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U.S. Geological Survey
Oklahoma Department of Mines
Oklahoma Mining Commission

The University of Oklahoma
Norman
1999

OKLAHOMA GEOLOGICAL SURVEY

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Cover Photo

Aerial view of Meridian Aggregates Co. quarry in the Long Mountain Granite. Quarry is in the Wichita Mountains of southwestern Oklahoma (from p. 34 of this volume).

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Preface and Acknowledgments

The Forum on the Geology of Industrial Minerals is an annual meeting during which representatives of industry, government, and universities discuss the problems of geology, exploration, evaluation, and production of our important industrial minerals (stone, sand, clay, cement, gypsum, salt, and other nonmetallic rocks and minerals). Each year the Forum is held in a different state or province, and in 1998 Oklahoma was privileged to host the 34th Forum. The meeeting was attended by a total of 177 people from the United States, Canada, England, Chile, Greece, and Turkey.

The 34th Forum was organized and supported by the following agencies and individuals:

Oklahoma Geological Survey
Charles J. Mankin, *Director*

U.S. Geological Survey
Aldo F. Barsotti, *Chief*
Industrial Minerals Section

Oklahoma Department of Mines
Mary Ann Pritchard, *Director*

Oklahoma Mining Commission
J. Welton Kelley, *Chairman*

The following companies and agencies provided additional financial support as co-sponsors of the 34th Forum:

Activation Laboratories, Ltd.
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Kansas Geological Survey
Material Producers, Inc.
McCabe Industrial Minerals, Inc.
Meridian Aggregates Co. (a Limited Partnership)
New Mexico Bureau of Mines and Mineral Resources
New Mexico Geological Society
Republic Gypsum Co.
Unimin Corp.
U.S. Gypsum Corp.
U.S. Silica Co.

It was because of the generous contributions and support of all the organizers and co-sponsors listed above that we were able to provide such an excellent program and amenities for the attendees.

Appreciation also is expressed to the Forum Steering Committee for 1997–1998, and the 34th (Oklahoma) Forum Planning Committee, listed below:

Forum Steering Committee, 1997–1998

Richard B. Berg, *Chair*	(1996–1998)
Robert Ganis	(1997–1999)
Stan D. Bearden	(1998–2000)
Kenneth S. Johnson	(1998 host)

34th (Oklahoma) Forum Planning Committee

Kenneth S. Johnson	*General Chair*
LeRoy A. Hemish	*Posters*
Michelle J. Summers	*Registration*
Tammie K. Creel	*Registration*
Judy A. Schmidt	*Registration*
Connie G. Smith	*Publicity*
Betty D. Bellis	*Guest Program*
Dorothea J. Johnson	*Guest Program*

Technical sessions for the 34th Forum were held in Norman, Oklahoma, at the Oklahoma Center for Continuing Education on the campus of The University of Oklahoma. A one-day, pre-Forum field trip was conducted in the Arbuckle Mountains, where participants examined the following: (1) high-purity silica sand (Ordovician Oil Creek Formation), operated by U.S. Silica Co. (Edwin Lips, Manager) north of Mill Creek; (2) granite with diabase dikes (Precambrian Troy Granite), mined for railroad ballast by Meridian Aggregates Co. (Joel Livingston) south of Mill Creek; (3) high-purity dolomite (Cambrian Royer Dolomite), mined by Unimin Corp. (David Rush) south of Mill Creek; and (4) display of *Acrocanthosaurus atokensis* (an enormous, Late Cretaceous meat-eating dinosaur), at Goddard Youth Camp (Wayne Edgar) south of Sulphur.

In addition, a two-day, post-Forum field trip to northwest Oklahoma focused on evaporite deposits and brines at the following sites: (1) high-purity gypsum (Permian Blaine Formation), mined for wallboard and plaster manufacture by U.S. Gypsum Co. (Bill Weber and Roger Sharpe) at Southard; (2) high-purity gypsum and anhydrite (Permian Blaine Formation), mined for surface material on dirt roads by Western Plains Material Co. (Richard Shore) south of Bouce Junction; (3) iodine-rich brines (pumped from Pennsylvanian Morrow sands, 7,000 ft deep), produced as source of iodine by Woodward Iodine Co. (Bill Gerber) north of Woodward; (4) solar salt (brine pumped from Permian Flowerpot salt, 50–150 ft deep), produced for water softeners and agricultural products by Cargill Salt Co. (Greg Joachims) west of Freedom; (5) a visit to Alabaster Caverns State Park (Permian Blaine Formation), south of Freedom; and (6) collect hourglass-selenite crystals (formed in Recent alluvium by evaporation of brine flowing from underlying Permian red beds and evaporites), at Great Salt Plains National Wildlife Refuge east of Cherokee.

We are indebted to the many authors and co-authors who presented talks and posters at the Forum. Of the 32 talks and 18 posters presented during the Forum in Oklahoma, a total of 45 papers and 5 abstracts have been contributed to this proceedings volume.

Technical editing of this volume was done by Thomas W. Henry, Lakewood, Colorado; layout and production was done by Sandra Rush, Denver, Colorado.

A hearty "thanx!" is extended to all the contributors mentioned above, for it is through their generosity and efforts that the 34th Forum was so successful.

KENNETH S. JOHNSON
General Chair, 34th Forum

Annual Meetings of the Forum on the Geology of Industrial Minerals

1st	1965	Columbus, Ohio
2nd	1966	Bloomington, Indiana
3rd	1967	Lawrence, Kansas
4th	1968	Austin, Texas
5th	1969	Harrisburg, Pennsylvania
6th	1970	Ann Arbor, Michigan
7th	1971	Tampa, Florida
8th	1972	Iowa City, Iowa
9th	1973	Paducah, Kentucky
10th	1974	Columbus, Ohio
11th	1975	Kalispell, Montana
12th	1976	Atlanta, Georgia
13th	1977	Norman, Oklahoma
14th	1978	Albany, New York
15th	1979	Golden, Colorado
16th	1980	St. Louis, Missouri
17th	1981	Albuquerque, New Mexico
18th	1982	Bloomington, Indiana
19th	1983	Toronto, Ontario, Canada
20th	1984	Baltimore, Maryland
21st	1985	Tucson, Arizona
22nd	1986	Little Rock, Arkansas
23rd	1987	North Aurora, Illinois
24th	1988	Greenville, South Carolina
25th	1989	Portland, Oregon
26th	1990	Charlottesville, Virginia
27th	1991	Banff, Alberta, Canada
28th	1992	Martinsburg, West Virginia
29th	1993	Long Beach, California
30th	1994	Fredericton, New Brunswick/ Halifax, Nova Scotia, Canada
31st	1995	El Paso, Texas
32nd	1996	Laramie, Wyoming
33rd	1997	Quebec City, Quebec, Canada
34th	**1998**	**Norman, Oklahoma**
35th	1999	Salt Lake City, Utah
36th	2000	Bath, England
37th	2001	Victoria, British Columbia, Canada
38th	2002	St. Louis, Missouri

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Geology and Industrial-Mineral Resources of Oklahoma

Kenneth S. Johnson
Oklahoma Geological Survey
Norman, Oklahoma

GEOLOGY OF OKLAHOMA

Oklahoma is a region of complex geology where a mobile belt of Paleozoic geosynclines and uplifts on the south abuts against the margin of the North American craton to the north. The state contains many classic areas where fundamental concepts of sedimentation, stratigraphy, structural geology, historical geology, mineral investigation, and petroleum exploration have been formulated through the years. In the southern Oklahoma mountain belts, there are exposed a great variety of igneous and sedimentary rock units seen at few other places in the Midcontinent area.

Major geologic provinces of Oklahoma (Fig. 1) include: (1) the cratonic and relatively stable northern shelf areas, including the Ozark uplift; (2) the Ouachita geosyncline (now the Ouachita Mountain belt) and associated Arkoma basin in the southeast; and (3) the southern Oklahoma aulacogen (geosyncline), comprising the area of Anadarko, Ardmore, Marietta, and Hollis basins, as well as the Arbuckle and Wichita Mountain uplifts. The three principal fold belts, the Ouachitas, Arbuckles, and Wichitas, all originated from a series of Pennsylvanian orogenies (about 300 million years ago) in the two Paleozoic geosynclines.

Most of the outcropping rocks in Oklahoma are of sedimentary origin, and most of these units are of Paleozoic age (Fig. 2, map). The thickness of Paleozoic section ranges from 2,000 to 10,000 ft in cratonic shelf areas of the north, and is 30,000–40,000 ft in deep basins of the south (Fig. 2, cross sections). Sedimentary rocks overlie a basement of Precambrian to Middle Cambrian igneous rocks, Precambrian metamorphic rocks, and mildly metamorphosed Precambrian sedimentary rocks. Limestone and dolomite make up most of the Upper Cambrian to Lower Mississippian strata and attest the early and middle Paleozoic crustal stability in most of Oklahoma prior to the Pennsylvanian episodes of mountain building. Thick units of shale and sandstone predominate in the Upper Mississippian and Pennsylvanian sequence. Permian sediments are characterized by red-bed shale and sandstone, with interbedded gypsum and salt. Triassic, Jurassic, and Tertiary deposits are mostly thin units of conglomerate, sandstone, and shale; Cretaceous deposits are similar but also include limestone units.

Oklahoma's three mountain regions have been the subject of much study. The Arbuckle Mountains in south-central Oklahoma make up an area of low to moderate hills containing 15,000 ft of folded and faulted sedimentary rocks ranging in age from the Late Cambrian to the Pennsylvanian. About 80% of these sedimentary rocks are limestones and dolomites, and the remainder are shales and sandstones. Rocks in this part of the southern Oklahoma aulacogen were thrust upward and were folded and faulted during several mountain-building episodes during the Pennsylvanian Period. The sedimentary cover has been eroded from the underlying Precambrian granites and gneisses in a 150-mi^2 area in the southeastern part of the Arbuckle Mountains, making this the largest exposure of Precambrian rocks in the state. The Arbuckles contain the most diverse suite of mineral resources in Oklahoma—limestone, dolomite, glass sand, granite, sand and gravel, shale, cement, iron ore, lead, zinc, tar sands, and oil and gas. All of these minerals are or have been produced commercially.

In the Wichita Mountains of southwestern Oklahoma, granite, rhyolite, and gabbro are the dominant outcropping rocks. These igneous rocks are of Middle and possibly Early Cambrian age and are flanked by scattered outcrops of Late Cambrian and Ordovician limestones and dolomites like those of the Arbuckle Mountains. The Wichita fault blocks were thrust upward and slightly northward during several Pennsylvanian uplifts, at which time the cover of pre-Pennsylvanian rocks was eroded. The exposed igneous rocks now form hills and mountains that rise 500–1,000 ft above a surrounding plain of Permian red beds. The Wichita Mountains have been mined for granite, rhyolite, gabbro, limestone, and sand and gravel. They have been prospected (with only limited success) for kaolin, montmorillonite, gold, silver, copper, lead, zinc, aluminum, titanium, and iron ores. Oil and gas have been produced from sedimentary rocks that surround the mountain area.

The Ouachita (pronounced "Wa´-she-tah") Mountains of southeastern Oklahoma and western Arkansas make up an arcuate belt of forested mountain ridges and subparallel valleys. Rocks making up the Ouachitas are mostly thick units of Upper Cambrian through Lower Pennsylvanian deep-water sandstones and shales, with lesser amounts of chert and novaculite (a

Johnson, K. S., 1999, Geology and industrial-mineral resources of Oklahoma, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 1–12.

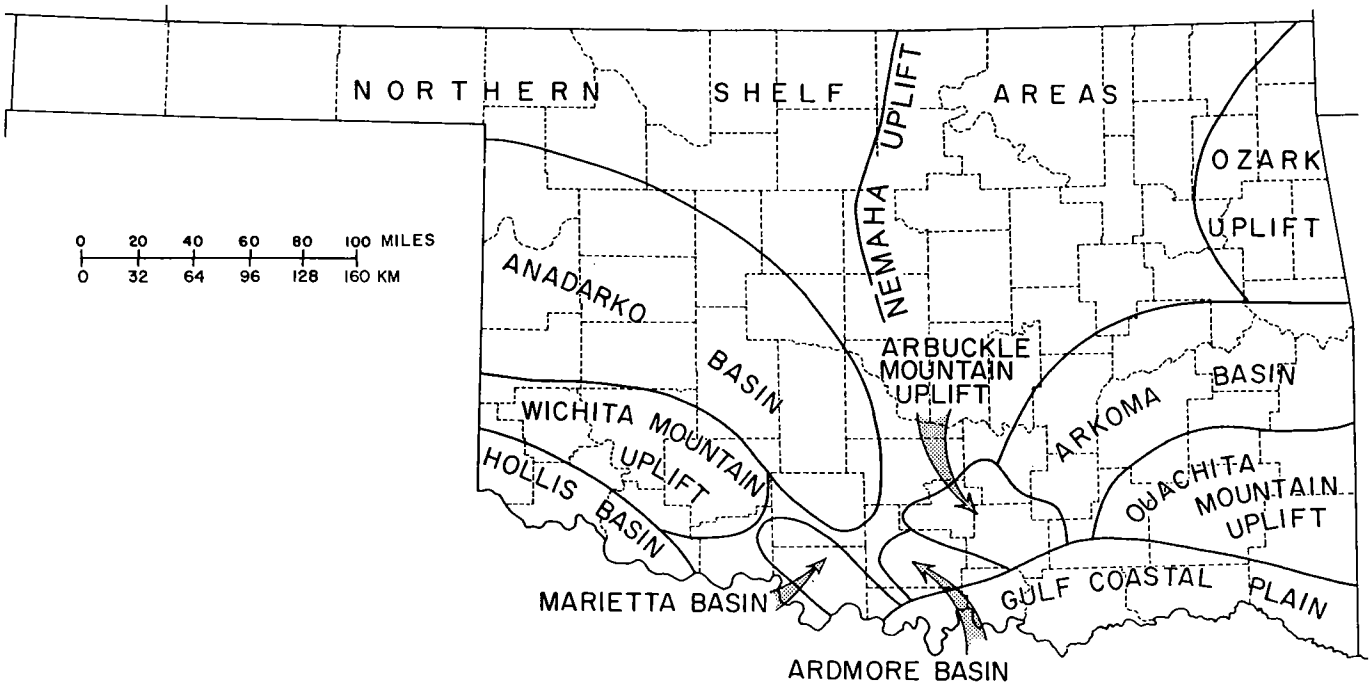


Figure 1. Major geologic provinces of Oklahoma.

fine-grained, light-colored silica rock, similar to flint). These strata, deposited in a geosyncline, have an aggregate thickness in excess of 40,000 ft. The area was then folded and faulted during the Pennsylvanian, producing a series of broad anticlines and synclines, and a number of major thrust faults with as much as 50 mi of northward displacement. Resistant beds of sandstone, chert, and novaculite now form long, sinuous mountain ridges that tower 500–1,500 ft above adjacent valleys formed in easily eroded shales. Mineral resources that are, or have been, produced in the Ouachitas include limestone, quartzite, sand and gravel, asphaltite, copper, lead, and oil and gas.

Outcropping Paleozoic rocks outside the mountain regions are essentially horizontal, with dips of 10–50 ft per mile being most common. Eastern Oklahoma Paleozoic rocks are chiefly Mississippian limestones and cherts in the Ozark uplift and Pennsylvanian sandstones, limestones, and shales elsewhere. In western Oklahoma, Paleozoic rocks are mainly red beds and evaporites (gypsum/anhydrite and salt). All these Paleozoic strata typically form gently rolling hills and plains, although the thick shale units form broad, flat plains and valleys. In places, resistant sandstones and limestones cap cuestas and hills 100–500 ft high. Badlands, sinkholes, and caves are common in the gypsum-hill regions of western Oklahoma, and deeply dissected cavernous limestones and cherts are typical of the Ozark uplift in the northeast. Surface rocks dip to the west across northeastern and central Oklahoma and dip toward the axes of sedimentary basins in other parts of the state. Minerals produced from Paleozoic strata outside the mountain regions are quite diverse; they include limestone, dolomite, sandstone, shale, gypsum, salt, building stone, sand and gravel, tripoli, iodine, asphalt, chat, lead and zinc (the Tri-State District), copper, coal, and oil and gas.

Cretaceous strata of the Gulf Coastal Plain in the southeast generally consist of loose sands, gravels, limestones, and clays that dip gently southward toward the Gulf of Mexico. The sediments are only slightly dissected by streams, and they commonly form gently rolling hills and plains. Minerals produced from Cretaceous strata are limestone and sand and gravel.

Tertiary deposits in the west are loose sands, gravels, and clays deposited by ancient streams and rivers draining the Rocky Mountains. They now constitute a featureless, flat upland surface, which is part of the High Plains. Tertiary mineral deposits include sand and gravel, clays, and limestone (caliche).

Quaternary sediments are chiefly unconsolidated sand, silt, clay, and gravel deposited by Pleistocene and Holocene rivers and lakes; typically they are 25–100 ft thick. Mineral resources being mined are extensive deposits of sand and gravel and scattered accumulations of volcanic ash derived from volcanoes in western United States.

Our knowledge of Oklahoma geology has come about largely through intensive investigations of the state's petroleum and nonpetroleum mineral resources, and through the cooperative exchange of information by all agencies and companies interested in construction and earth materials. The drilling of more than 500,000 wells in search of oil and gas (a statewide average of seven wells per mi^2!) has provided basic data in all geologic provinces. Although Oklahoma is well known as an oil state, its nonpetroleum resources (limestone, clay, coal, gypsum, salt, etc.) represent a vast mineral reserve needed for future industrial development and construction.

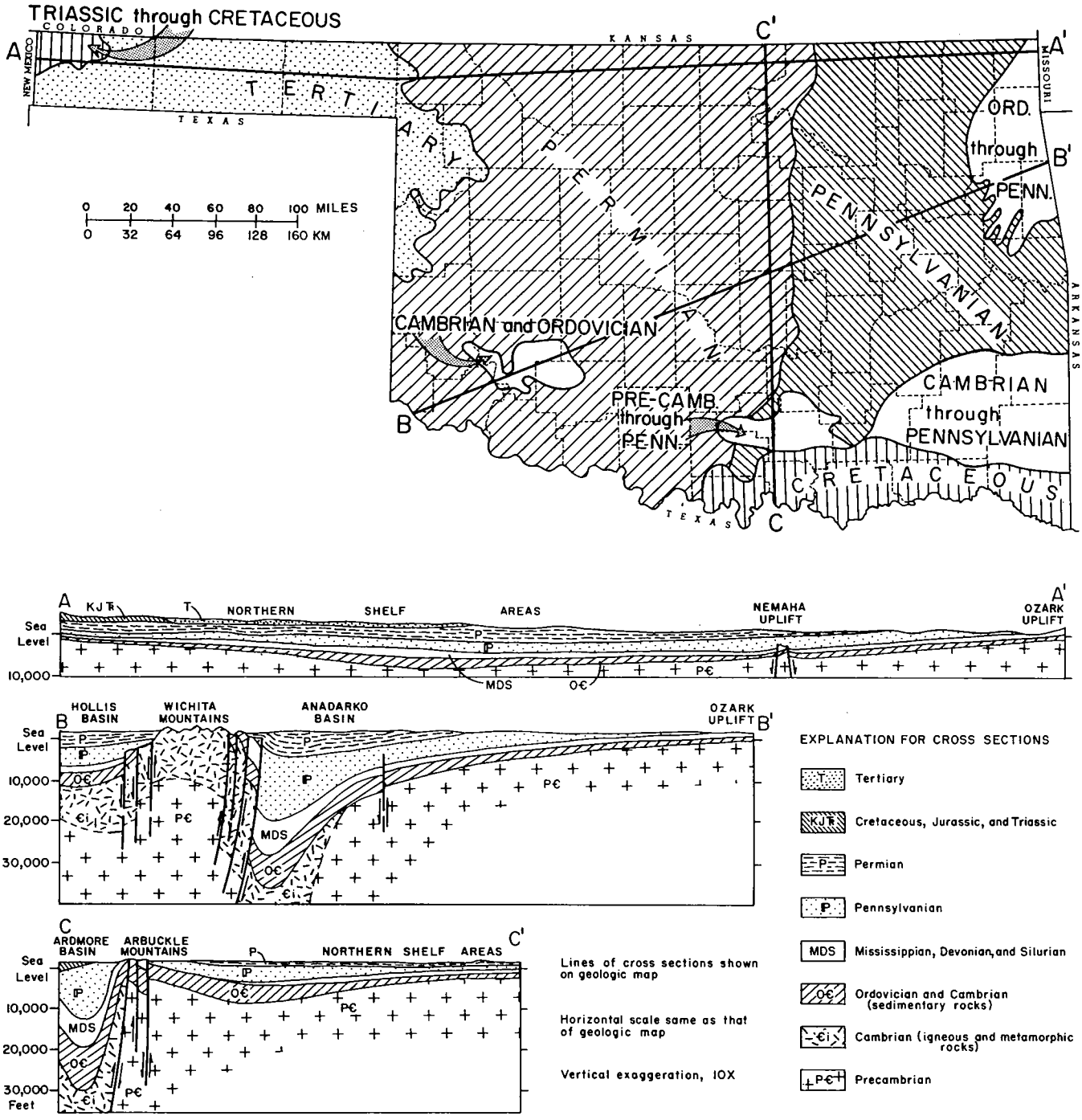


Figure 2. Generalized geologic map and cross sections of Oklahoma.

INDUSTRIAL MINERALS OF OKLAHOMA

Industrial minerals (which are the nonfuel, nonmetallic minerals that have potential for economic use) are widely distributed in Oklahoma (Fig. 3), and many of them are being mined for local, regional, and national markets. Numerous and varied industrial-mineral industries are active in 69 of Oklahoma's 77 counties. Although such activity is widespread in the state, some of the most important regions are the Wichita, Arbuckle, and Ouachita Mountain uplifts in the south, and the Ozark uplift in the northeast (Figs. 1–3); it is in these areas that some of the state's unique rock and mineral deposits have been uplifted and are now exposed at the land surface. For one such important region, Neman (1999, this publication) describes the character and uses of some of the major industrial-mineral resources in the Arbuckle Mountains.

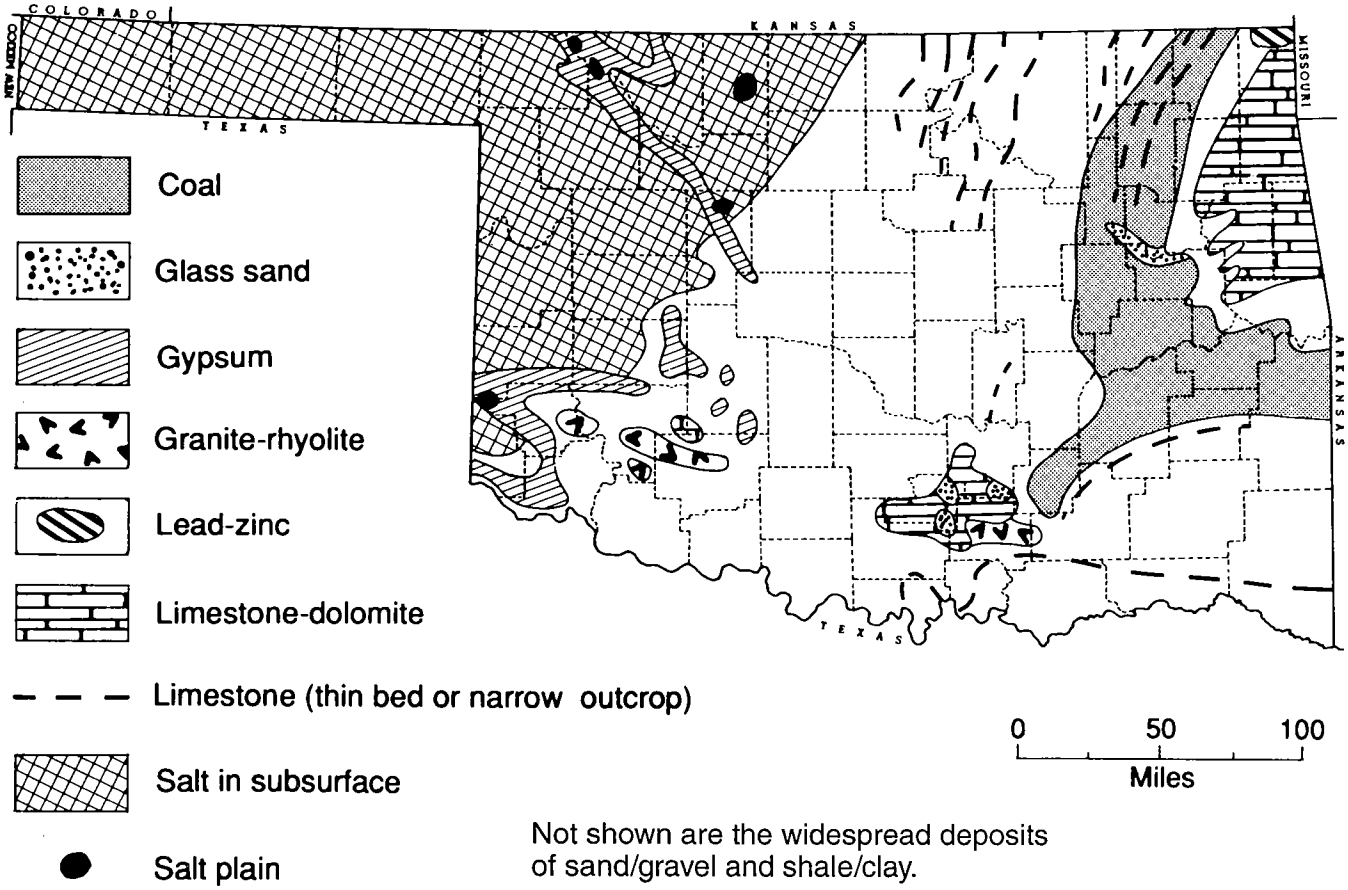


Figure 3. Selected nonpetroleum-mineral resources of Oklahoma.

Crushed-stone and building-stone resources include limestone, dolomite, granite, and rhyolite; other major construction resources are cement (made from limestone and shale) and the extensive sand and gravel deposits along modern and ancient river ways. Glass sand (a high-purity silica sand) is used for glass making, foundry sands, ceramics, and abrasives. Enormous resources of gypsum in the western part of the state are mined for wallboard, for plaster, as retarder in portland cement, and as soil conditioner. Thick layers of rock salt underlie most of western Oklahoma, and natural springs emit high-salinity brine to the several salt plains. Oklahoma iodine, produced from deep-subsurface brines in the northwest, is the nation's sole domestic supply. Other important industrial minerals in Oklahoma include clays and shales (to make brick and tile), and tripoli and volcanic ash (abrasive and/or absorbent materials). Gemstone production includes freshwater mussel shells and freshwater pearls.

The total value of industrial-mineral production in Oklahoma during 1997 was $386 million (Table 1), and the state ranked 32nd in the nation. Leading nonfuel commodities during 1997 were portland and masonry cement ($138 million), crushed stone ($112 million), sand and gravel ($29 million), glass sand ($28 million), iodine ($20 million), and gypsum ($17 million) (Table 1).

As an aid to present and future mining operators in Oklahoma, a symposium was held in 1992 to document the resource base, rules, regulations, and environmental issues related to wise development of Oklahoma's industrial minerals. The resulting publication (Johnson, 1993a) presented the major factors involved in starting up and operating an industrial-mineral mine; these factors include exploration, leasing, permits, quality control, transportation, marketing, inspections, water quality, wetlands, air quality, reclamation, and future developments. A further discussion of the regulatory requirements for mining industrial minerals in Oklahoma is given by Johnson and Schooley (1999, this publication).

The remainder of this report, modified from Johnson (1993b), is a description of the state's industrial minerals, arranged alphabetically. Many of the data are based upon reports by Johnson (1969a, 1977), Morris (1982), and the Oklahoma Department of Mines (1994); the reader is referred to these reports, as well as other reports that are referenced separately for several of the commodities. The many companies that mine Oklahoma's mineral resources are listed in a "Directory of Oklahoma Mining Industry" (Arndt and Springer, 1993), and maps from that report are reproduced here (Figs. 4–7) to show the number of mining operations for various commodities in each county during 1993.

Table 1.—Industrial-Mineral Production in Oklahoma[a]
(thousand metric tons and thousand dollars unless otherwise specified)

Mineral	1995		1996		1997	
	Quantity	Value	Quantity	Value	Quantity	Value
Cement:						
Masonry	95	$7,248	101	$8,849[b]	89	$6,499[b]
Portland	1,740	110,096	1,745	117,591[b]	1,898	131,530[b]
Clays						
Common	674	3,579	799	4,090	653	4,426
Fire	—	—	23	W	—	—
Gemstones	NA	W	NA	603	NA	354
Gypsum, crude	2,831	17,003	2,694	16,549	3,099	17,484
Iodine, crude (metric tons)	1,207	12,466	1,274	14,617	1,321	19,640
Sand and gravel:						
Construction	7,800	25,107	7,905	27,686	8,254	28,999
Industrial	1,249	25,363	1,349	27,189	1,379	28,231
Stone:						
Crushed[c]	31,053	124,784	28,330	117,366	31,871	112,056
Dimension (metric tons)	9,172[c]	2,354[c]	9,710	2,220	5,773	995
Combined value of feldspar, helium (crude, Grade-A [1996–97]), lime, salt, stone (crushed shell and traprock [1995–96], crushed shell, traprock, and misc. [1997], dimension quartzite and sandstone [1995]), tripoli, and values indicated by symbol W	XX	28,676	XX	32,339	XX	35,817
Total	**XX**	**$356,676**	**XX**	**$369,099**	**XX**	**$386,031**

Source: U.S. Geological Survey.
Dashes (—) indicate that no production was reported.
NA = Not available.
W = Withheld to avoid disclosing company proprietary data; value included with "Combined value" data.
XX = Not applicable.
[a]Production as measured by mine shipments, sales, or marketable production (including consumption by producers). Data are rounded to three significant digits; may not add to totals shown.
[b]Estimated.
[c]Excludes certain stones; kind and value included with "Combined value" figure.

Asphalt

Asphalt is an oil-based commodity, but, because it has been used mainly as a road-surfacing and tar material in Oklahoma, it is considered herein as a nonfuel mineral resource. Asphalt forms where crude oil migrates upward near the land surface. There, the lighter hydrocarbons evaporate, leaving a thicker, heavy residue that impregnates the rocks as rock asphalt or that fills voids as a tar-like substance called asphaltite.

The major sources of rock asphalt and asphaltite are in sedimentary rocks in and around the Arbuckle and Ouachita Mountains of southern Oklahoma (Jordan, 1964). Additional smaller deposits occur in sedimentary rocks surrounding the Wichita Mountains and in northeastern Oklahoma. From the state's large resources, about 3 million tons of asphalt were produced between 1891 and 1960, chiefly from asphaltic sandstones and limestones in the Sulphur and Dougherty districts of the Arbuckle Mountains. Principal mines for asphaltite were operated near Page, Sardis, and Jumbo in the Ouachita Mountains; these shaft mines and surface mines operated between 1890 and 1916.

Most of the rock asphalt mined in Oklahoma was used as paving material for roads in Oklahoma and adjacent states. Petroleum refineries now produce the large quantities of asphaltic material needed for road construction and maintenance, and all natural-rock-asphalt quarries currently are inactive. Asphaltite was used mainly in making roofing pitch, paints, varnishes, rubber substitutes, and electrical-wire insulation. Future demands for asphaltic materials and/or heavy oils can readily be satisfied by the vast resources that remain in the state.

Cement

Raw materials for the manufacture of portland cement and masonry cement are limestone and clay or shale. Oklahoma has an abundance of both these resources, and they are discussed separately elsewhere in this report. Three cement plants currently are operating, one each in Mayes, Pontotoc, and Rogers Counties. Production in 1997 was 2.0 million metric tons, with a value estimated at $138 million (Table 1).

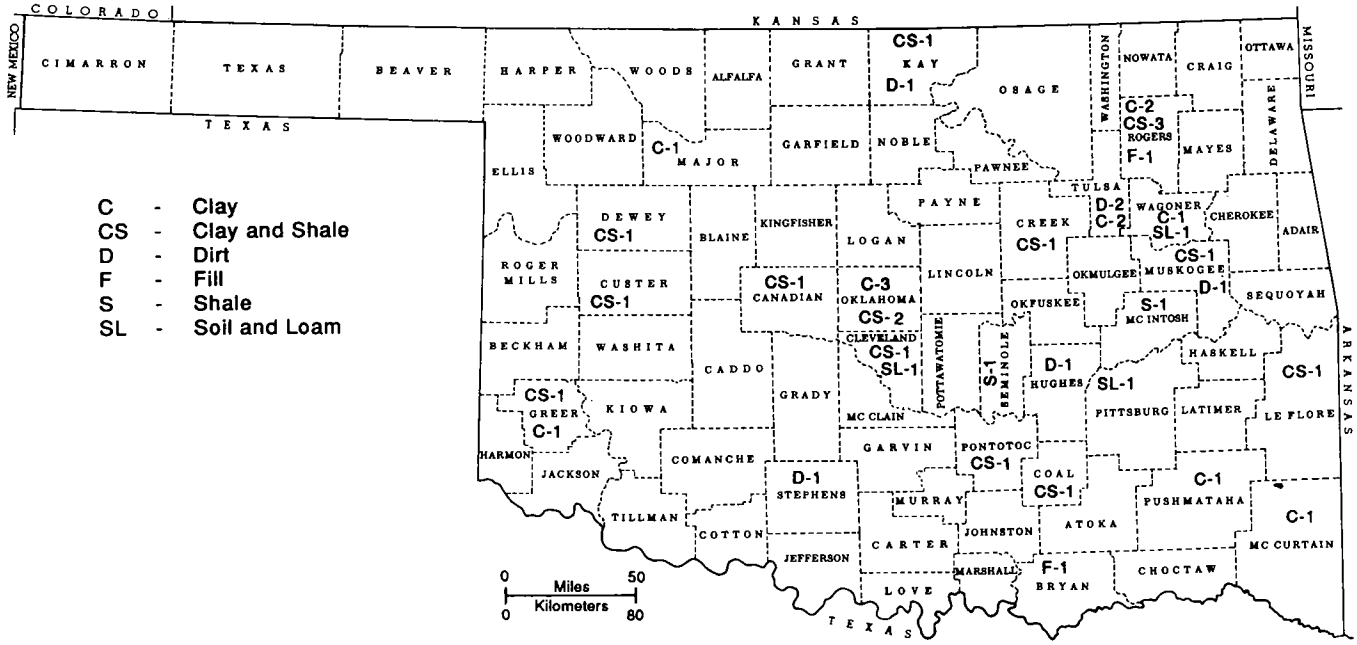


Figure 4. Number of clay, shale, and soil pits in each of Oklahoma's counties in 1993 (from Arndt and Springer, 1993).

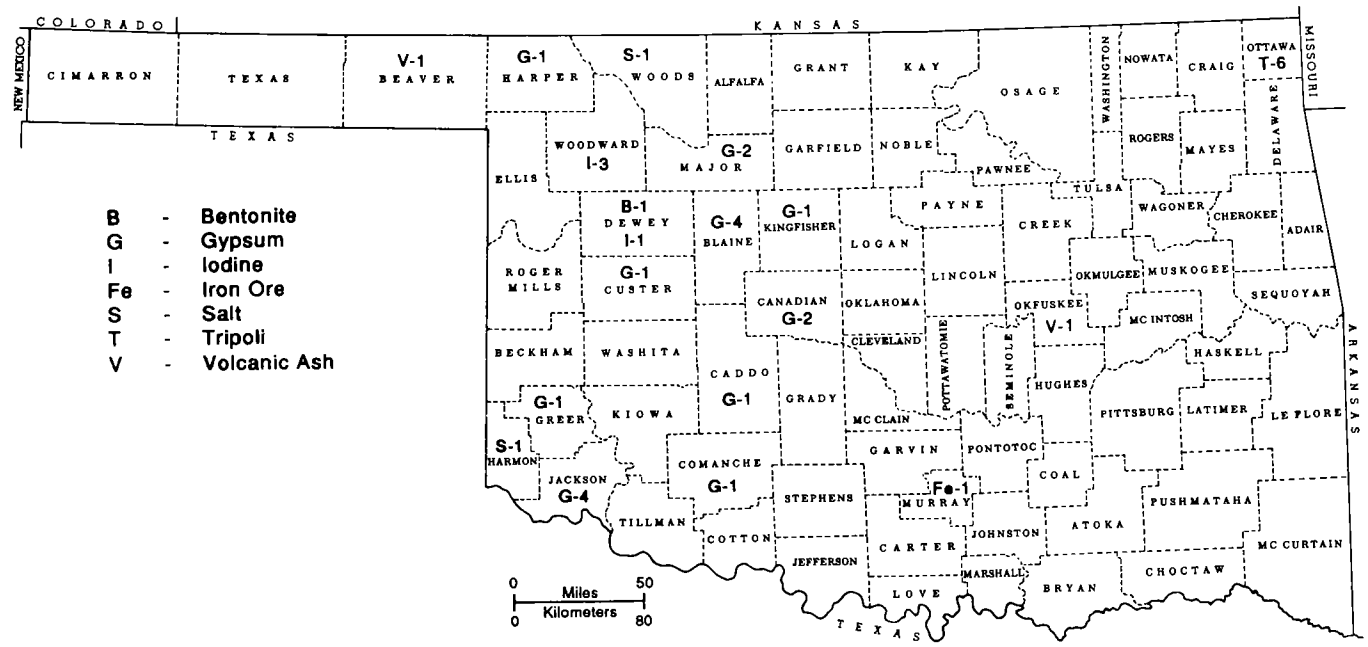


Figure 5. Number of bentonite, gypsum, iodine, iron ore, salt, tripoli, and volcanic-ash operations in each of Oklahoma's counties in 1993 (from Arndt and Springer, 1993).

Chat

Chat, which consists of crushed limestone, dolomite, and chert, was produced as a waste by-product of mining and milling of lead/zinc ores in the world-famous Tri-State District of northeastern Oklahoma. The material, which now exists in large piles in the Miami-Picher area of Ottawa County, has been used as road metal, railroad ballast, concrete aggregate, and rock fill.

Chemical Raw Materials

Oklahoma has vast resources of certain high-purity minerals suitable as raw materials for various chemical industries (Johnson, 1969b). Major deposits of limestone, dolomite, and glass sand are in the south-central and eastern parts of the state, whereas gypsum and salt are widespread in the west; these individual resources are discussed elsewhere in this report. The abundance and purity of these minerals should enable

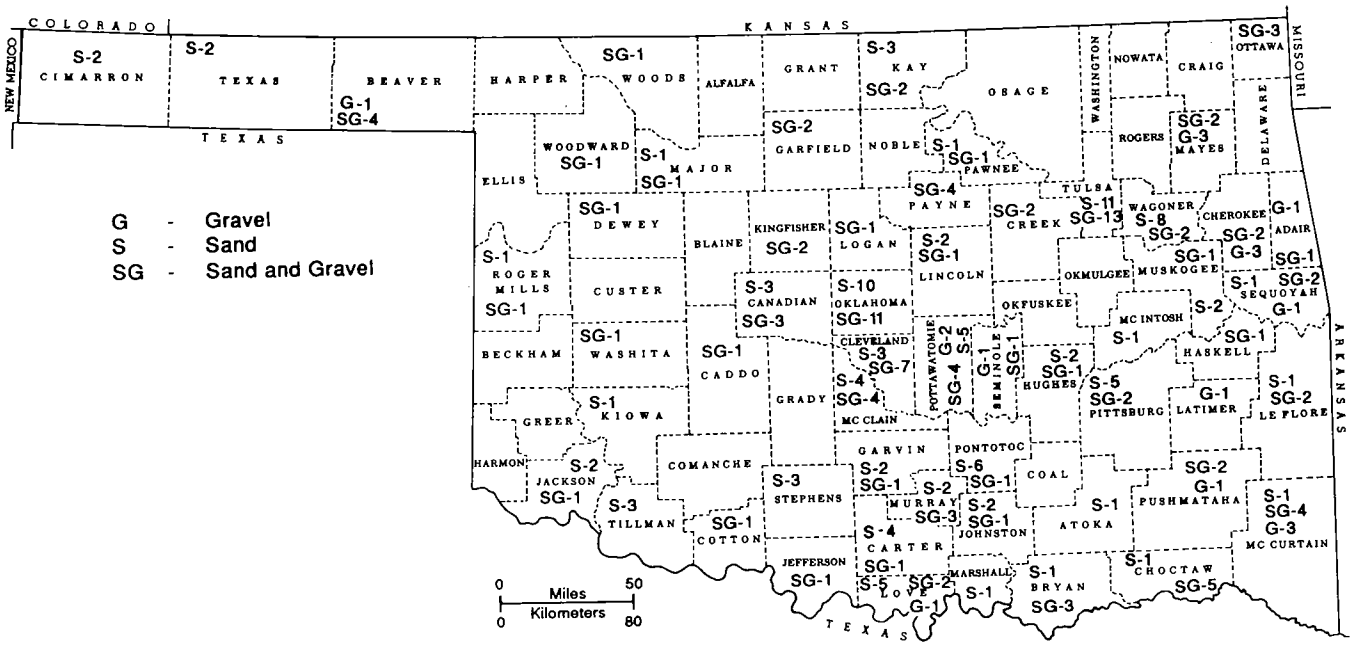


Figure 6. Number of sand and gravel operations in each of Oklahoma's counties in 1993 (from Arndt and Springer, 1993).

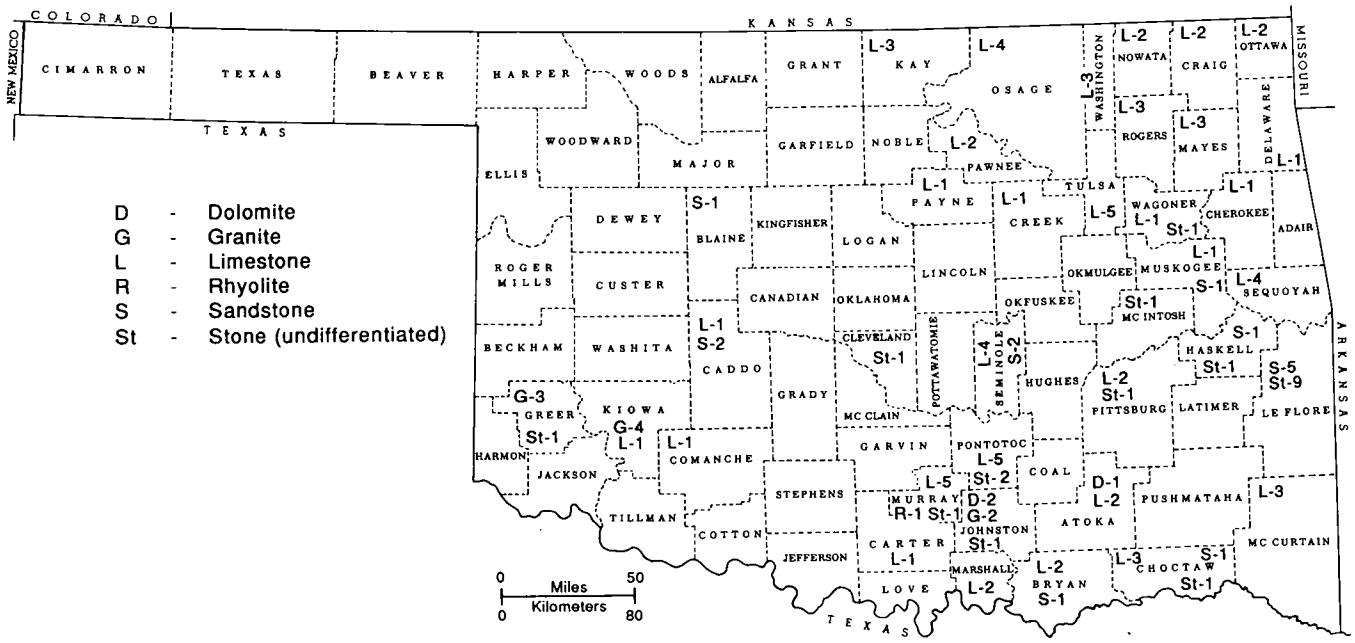


Figure 7. Number of stone quarries in each of Oklahoma's counties in 1993 (from Arndt and Springer, 1993).

manufacture of caustic soda, soda ash, chlorine, sulfur, sulfuric acid, lime, sodium silicate, and other chemical products. Oil, natural gas, and water, needed in the manufacture of these chemical products, are plentiful in most parts of the state, and bituminous coal is abundant in eastern Oklahoma.

Clay and Shale

Clay and shale are present in almost every county in Oklahoma, and deposits suitable for manufacture of red brick and tile products are widely distributed (Fig. 4). Light-firing clays, low-grade refractory clays, and clays suitable for making pottery are present at a few localities, and clay suitable for making lightweight aggregate is common in the eastern portion of the state.

Most of the shale deposits in Oklahoma contain illite as the dominant clay mineral, and the illite is associated with varying mixtures of clay-sized quartz and other clay minerals. Chlorite, kaolinite, montmorillon-

ite, and mixed-layer clays generally are less important, although each of these clays is predominant in certain localities. In addition to these common shales, there are several types of specialty clays in parts of Oklahoma: small to moderate-sized deposits of bentonitic clay (montmorillonite) are associated with, and altered from, volcanic ash, mainly in northwestern Oklahoma. Recent reports on clays and shales in Oklahoma are by Bellis (1972) and Johnson and others (1980). In addition, Luza and Hemish (1999, this publication) have described the characteristics and potential uses of the Croweburg coal underclays in the eastern Oklahoma coal field.

Shale has been an important part of the construction industry in Oklahoma since before statehood. More than 120 brick plants have operated since 1888, with most of them being in the central part of the state (Morris, 1982). Also, shale is one of the major ingredients at the three cement factories now operating in the state. In 1993, 21 companies were producing clay and shale in many different parts of Oklahoma (Oklahoma Department of Mines, 1994), and in 1997 the state produced 653,000 metric tons of clay and shale valued at about $4.4 million (Table 1).

Dimension Stone

Oklahoma has a variety of sandstones, limestones, dolomites, and granites suitable for building and ornamental purposes, and native stone has been used extensively in residence and building construction. The quality of some sandstones in eastern Oklahoma and of oolitic limestone in southern Oklahoma compares favorably with any in the nation, and several of the limestones and dolomites have unusual beauty and texture. The various types of dimension stone are discussed further in this report under the rock names. In 1997, Oklahoma produced about 5,773 metric tons of dimension stone, valued at about $1.0 million (Table 1).

Dolomite

Large resources of high-purity Cambrian dolomite are present in the Arbuckle Mountains (Ham, 1949); the stone is quarried for high-purity material at one site and is quarried for crushed stone at two other sites in the Arbuckle Mountain region (Fig. 7). The high-purity Royer Dolomite is about 500 ft thick in the area, and other dolomite units are also 400–500 ft thick. Smaller deposits or thinner beds, generally of lower purity, are known in the Wichita Mountains, in Delaware and Osage Counties, and in widely scattered Permian outcrops of western Oklahoma; several of these deposits are worked for dimension stone and/or for crushed stone.

Current and potential uses of dolomite are for fluxing stone, glass manufacture, refractories, dolomitic lime, magnesium metal, fertilizers, feeds, and as a soil conditioner. Quantity and value of current production are included within the estimates for crushed and dimension stone (Table 1).

Gemstones

Gemstone production consists of the harvesting of freshwater mussel shells from lakes and rivers, chiefly in eastern Oklahoma. The shells then are cut up and rounded, and the shell pellets are implanted in oysters for creating cultured pearls. Small quantities of freshwater pearls are also recovered from the mussels, but these are only a minor by-product of the shell production. Three firms are currently buying freshwater mussels from independent divers in Oklahoma, and almost all the shell material is being exported to Japan. The value of freshwater mussel shells and pearls harvested in 1997 was $354,000 (Table 1).

Although there are about 300 species of freshwater mussels, only about 15–20 are suitable for use as shell pellets for implanting. Also, about 100 species are already declared endangered species, or are proposed for such a listing. Thus, great care must be exercised in harvesting shells. Licensing of divers and shell buyers is carried out by the Oklahoma Wildlife Conservation Department.

Glass Sand

Large deposits of high-purity silica sand (Ordovician Simpson Group) are worked at two places (Johnston and Pontotoc Counties) in the Arbuckle Mountains region (Ham, 1945), with plant-run sands containing 99.8% silica and normally only 0.01–0.03% iron oxide. The origin of these multicycle sands that have undergone eolian transport is described by Denison (1999, this publication). Ordovician sand almost as pure is present in northeastern Oklahoma, and scattered exposures of Cretaceous sands with 98.5–99.5% silica are reported south and east of the Arbuckles. Alluvial sand from the Arkansas River is being specially treated in Muskogee County to produce a high-purity feldspathic sand for glass manufacture. The processed sand includes about 75% quartz (silica), about 25% feldspar, and less than 0.04% iron oxide. In 1997, Oklahoma's production of glass sand (reported as industrial sand in Table 1) was 1.38 million metric tons, with a value of about $28 million.

A number of glass-manufacturing plants in eastern and central Oklahoma produce a variety of glass products, including bottles, jars, window panes, tumblers, tableware, and pyrex glass. Sand also is shipped from the state for glass making, foundry sands, ceramics, and the manufacture of sodium silicate. One glass-sand plant produces ground silica for use in ceramics and abrasives and as an inert filler.

Granite

Granite and similar igneous or metamorphic rocks of the Wichita and Arbuckle Mountains of southern Oklahoma (Figs. 1,3) are extensively produced as dimension stone for the monument and building trades; crushed granite and rhyolite are also produced, mainly for railroad ballast (stone in the railroad bed) and intermittently for aggregate and rip-rap. Granite and similar rocks in Oklahoma are Precambrian and Cambrian in

age. Colors are red, pink, gray, and black, and the textures range from fine to coarse crystalline. The character and uses of granite and rhyolite in Oklahoma recently have been described by Gilbert and Denison (1999, this publication).

At present, eight companies are regularly producing granite and rhyolite from quarries in Greer, Kiowa, Jackson, Johnston, and Murray Counties (Fig. 7), and the state produced about 3.6 million short tons of granite and rhyolite in 1993 (Oklahoma Department of Mines, 1994). The major production (2.7 million tons) was from Johnston and Murray Counties, where granite and rhyolite are being quarried for railroad ballast. The value of granite and rhyolite production is divided among several categories (dimension stone and crushed stone) in Table 1.

Gypsum

Enormous resources of high-purity Permian gypsum crop out in western Oklahoma (Fig. 3). The gypsum beds of the Blaine Formation are 5–30 ft thick and 95–99% pure in the northwest and southwest, and the Cloud Chief gypsum of Washita and Caddo Counties is 25–100 ft thick and 92–97% pure. Anhydrite crops out only locally, but is present underground where overburden is 25–100 ft, or more.

Total gypsum resources in Oklahoma are estimated at 48 billion short tons (Johnson, 1978). These resources are well suited for open-pit mining or quarrying, because gypsum typically forms hills in the semiarid climate of western Oklahoma, and the gypsum layers are nearly flat lying, without folds or faults. Sharpe and Schroeder (1999, this publication) recently described the gypsum resources and products of Oklahoma.

Oklahoma ranks first among the United States in crude-gypsum production, with about 3.1 million metric tons produced annually by 14 companies in 9 western counties (Fig. 5). The value of gypsum produced in 1997 was about $17 million (Table 1). Present uses are for plaster, for wallboard, as retarder in portland cement, and as soil conditioner. In the future it may be used as a source of sulfur.

Helium

Helium, a colorless, odorless, and nonpoisonous gas, is the second lightest of all elements. Helium was extracted for many years from natural gas at the U.S. Bureau of Mines plant near Keyes, in Cimarron County, but production has ceased. The helium-producing field is largely depleted, although some resources still remain.

Iodine

Iodine is a grayish-black, nonmetallic element that is a solid at ordinary temperatures. In Oklahoma, it is dissolved in iodine-rich natural brines (>300 ppm iodine) 6,000–10,000 ft below the land surface in the Woodward, Vici, and Dover areas in the northwestern part of the state (Johnson, 1994; Johnson and Gerber, 1999, this publication) (Fig. 5). The major production is in the Woodward and Vici areas, where iodine occurs in Morrow sandstones (basal Pennsylvanian) preserved in a south-trending paleovalley, informally called the "Woodward trench." Other iodine production comes from several Paleozoic sandstones, limestones, and dolomites, as a by-product of oil and gas production. Iodine-rich brines are produced from wells drilled into these rock units, and the iodine is then treated chemically and precipitated from the brine. After being stripped of its iodine, the waste brine is treated and then reinjected into the same producing formation (Cotten, 1978). The Oklahoma brines range from 100 to 1,560 ppm iodine; they average 300–350 ppm iodine in most of the producing wells, and are the richest-known iodine brines in the world (Johnson, 1994; Johnson and Gerber, 1999, this publication).

Oklahoma's production of iodine began in 1977, and, with the cessation of iodine production in Michigan in 1987, Oklahoma is now the sole source of iodine in the United States. The U.S. (Oklahoma) produces about 9% of the world's annual output. At present, three companies operate three major plants and one miniplant in northwestern Oklahoma, and annual production is about 1.3 million kg, valued at about $20 million (Table 1). A new plant was built in Woodward to make about 50 iodine-derivative products from the iodine being produced. Major uses of iodine include catalysts, stabilizers, animal feeds, disinfectants, pharmaceuticals, photography, and colorants.

Lime

Quicklime, made by calcining high-purity limestone, has many chemical and industrial uses, as well as being used in construction and agriculture. High-calcium limestone is being mined to produce lime in Sequoyah County, and other deposits of high purity are present in northeastern, south-central, and southeastern Oklahoma.

Limestone

Limestone is abundant in northeastern Oklahoma, in the Wichita and Arbuckle Mountain areas, and in southeastern Oklahoma (Rowland, 1972) (Fig. 3). It is used mainly as aggregate (crushed stone) in concrete, in building roads, and in other construction, and it also is used in making cement, dimension stone, and chemical-grade lime. In the western and Panhandle districts, extensive deposits of caliche are acceptable substitutes for some purposes, and at other places dolomite is quarried for crushed stone.

Major limestone formations of the Arbuckle and Wichita Mountains are several hundred to several thousand feet thick, and, because they crop out over large areas, they are an almost unlimited resource of stone. The principal market for stone from these two areas is the Oklahoma City metroplex, although some stone also is shipped to major cities out of the state. Usable limestones in the southeastern, northeastern, and north-central parts of the state commonly are 10–

50 ft thick, and they are quarried to provide stone mainly for local markets. A report by Bliss (1999, this publication) characterized a number of Oklahoma limestones, and he showed that the lower Paleozoic carbonates are best suited for use as aggregates.

More than 30 companies are quarrying limestone at various sites in Oklahoma (Fig. 7), and the production in 1993 was 25–30 million tons (Oklahoma Department of Mines, 1994). Most of the limestone production is reported as crushed stone in Table 1, and the value of crushed stone produced in 1997 was about $112 million.

Salt

Thick sequences of Permian rock salt (NaCl) underlie most of western Oklahoma (Fig. 3), at depths ranging from 30 ft to more than 3,000 ft (Jordan and Vosburg, 1963). Individual salt beds are 5–25 ft thick and are interbedded with thinner layers of shale and anhydrite. The depth and thickness of salt beds in the region make them suitable for either underground or solution mining. No attempts have been made at opening a conventional underground dry mine in Oklahoma, but such mines have operated in the same salt beds for many years in Kansas, just 60 mi north of the state line. Solution mining of salt has been carried out intermittently near Sayre, in Beckham County, with marketing either of high-salinity brine or of salt that is precipitated from the brine by evaporation of water.

A number of major natural salt plains and salt springs are present along the rivers of western Oklahoma. Saturated brine, formed by dissolution of salt in the shallow subsurface, is discharged at 11 natural salt springs or salt plains in the state, with emissions ranging from 150 to 3,000 tons of salt per day at each salt plain. These natural springs have been used commercially since the beginning of this century, and even earlier by Native Americans. Several small salt producers have tapped salt plains in the northwestern and southwestern parts of the state in the past, and each company produced about 2,000–10,000 tons of solar salt per year. At present, a single major producer of solar salt, Cargill Inc., is operating on Big Salt Plain near Freedom, in Woods County (Joachims, 1999, this publication), and a small company operated until recently in Harmon County (Fig. 5).

Oklahoma's vast salt resources, estimated at 20 trillion tons (Jordan and Vosburg, 1963), are virtually untapped. Production from the one solar-salt plant in Woods County during 1993 was about 125,000 tons (Oklahoma Department of Mines, 1994). The salt was used primarily in recharging water softeners and for stockfeed, but other potential uses include chemical industries (chlorine, caustic soda, soda ash, and sodium), human consumption, and snow removal.

Sand and Gravel

Sand and gravel, which are essential to almost all types of construction, are widespread and available in most parts of Oklahoma. Principal deposits are along present-day major rivers, in terrace-like remnants of Pleistocene river beds, and in Tertiary deposits covering much of the northwest. Gravels are common in the western third of the state, as well as in and around the Wichita and Arbuckle Mountains, and in Cretaceous rocks south of the Arbuckle and Ouachita Mountains.

Sand and gravel are used in the building industry chiefly as aggregate, which is the term used for inert and hard, fragmental material that is bound by a cementing material to form concrete, mortar, or plaster. In the paving industry, sand and gravel are used as aggregate in both asphaltic mixtures and portland-cement concrete.

In 1993, more than 170 companies operated sand and gravel pits in 53 of Oklahoma's 77 counties (Oklahoma Department of Mines, 1994; Fig. 6). Construction sand and gravel produced in 1997 was 8.2 million metric tons, and it was valued at about $29 million (Table 1). Industrial sand and gravel consists mainly of glass sand, described elsewhere in this report.

Sandstone

Sandstone is a common rock type in most parts of Oklahoma. Deposits in the eastern half of the state are mostly hard, are gray, brown, or buff, and some are suitable for dimension stone or aggregate. Those in the western half of Oklahoma are mostly soft or friable, are reddish-brown, and are only locally suitable for building material. Sandstone is quarried as dimension stone at several sites in east-central Oklahoma, and has been quarried for riprap and aggregate at several places in the eastern half of the state (Fig. 7).

Stone

The state has many types of stone that can be used in the construction industries. Sandstones, limestones, dolomites, and granites are widely distributed in most parts of Oklahoma, and each of these resources is discussed separately elsewhere in this report.

Tripoli

Tripoli is a white or cream-colored, microcrystalline form of high-purity silica that is porous, lightweight, and friable. It is derived from a partly siliceous parent sedimentary rock from which soluble carbonate minerals have been leached (Quirk and Bates, 1978). Important tripoli deposits are present in northeast Oklahoma, with the first mine having been opened in the Missouri-Oklahoma tripoli district in 1869. Tripoli deposits typically are 2–20 ft thick, and they occur in Mississippian cherty limestones beneath 2–10 ft of overburden.

After quarrying, tripoli is dried, crushed, and screened to various grain sizes. Ground tripoli is used mainly as a mild abrasive or in buffing-and-polishing compounds. It is prized for its abrasiveness, porosity, permeability, absorption, and low specific gravity. One company operated a number of pits during 1993 in Ottawa County (Fig. 5).

Volcanic Ash

Small to large deposits of uncemented volcanic ash occur in western and east-central Oklahoma (Burwell and Ham, 1949). They result from local accumulations of ash and dust blown from volcanoes that erupted in New Mexico, Wyoming, and other western states during Tertiary and Pleistocene times. Some of the ash deposits are altered in part to bentonite clays.

Volcanic ash is used as an abrasive, mainly in polishing powders, scouring soaps, and cleansing powders; it also can be used as an admixture in pozzolan cement and as an insulating compound. In recent years, two companies have been mining volcanic ash in Beaver and Okfuskee Counties (Fig. 5); production from 1990 to 1993 ranged from about 100 to 700 tons (Oklahoma Department of Mines, 1994), but both companies are currently inactive.

Miscellaneous Minerals

Several other industrial minerals are present in small or low-grade deposits, described below.

Barite nodules, veins, and concretions are sparingly present in some shales and sandstones south of the Wichita Mountains and in central and south-central Oklahoma (Ham and Merritt, 1944). At a few localities there are surface concentrations of high-grade nodules that may have possibilities for limited production.

Celestite and minor amounts of strontianite are associated with dolomite and gypsum in eastern Washita and Custer Counties, but these deposits are quite small and apparently are not commercial.

Diatomite deposits are small and of low grade, and are widely scattered in western Oklahoma.

Phosphate occurs as nodules, plates, and lenses in several limestones and black shales of eastern Oklahoma and the Arbuckle Mountains (Oakes, 1938). The P_2O_5 content of these nodules and plates is generally 15–30%, whereas that of selected whole rocks is commonly 1–10%.

Quartz occurs as large vein deposits and some well-formed crystals in the Ouachita Mountains, especially in central McCurtain County (Honess, 1923).

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Origin of High-Purity Simpson Sands in the Arbuckle Mountains

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INTRODUCTION

The Middle Ordovician Simpson Group in the Arbuckle Mountains of southern Oklahoma contains sandstones of unusual purity. These have been exploited as glass sands since 1913 (Ham, 1945). Where quarried, the sandstones are uncemented or weakly cemented, greatly facilitating mining and processing. The origin, sedimentary setting, and lack of cementation of these valuable sands has been the source of much discussion.

The lowest of the sandstone units in the Simpson is at the base of the Oil Creek Formation. The basal Oil Creek sandstone is exposed in a series of accessible quarries north of the town of Mill Creek in Johnston County. Virtually all conclusions and generalizations concerning origin of the Simpson sandstones are based upon observations made in these quarries. The three Simpson sandstones overlying the Oil Creek share many of the same distinctive qualities, and there is an assumption that they share a common origin.

THE SETTING

In the Late Cambrian and Early Ordovician, Oklahoma lay near the southern edge of a peritidal carbonate platform of exceptional size and stability (Fig. 1). In Oklahoma the domination of carbonates of the Arbuckle Group was almost complete. The source of potential terrigenous material was so distant and the transportation across the platform so difficult that Oklahoma received only a trivial amount of sand and clay during this period. The carbonate thickness in the future Arbuckle Mountains is at least two times thicker in southern Oklahoma because a northwest-trending Cambrian rift zone, the southern Oklahoma aulacogen, allowed the crust to sink at a faster rate (Ham, 1969; Johnson and others, 1988; Denison, 1997). Near the end of the Early Ordovician, there was a significant lowering of sea level. For the first time since the basal Paleozoic transgression, the continent was drained and the vast peritidal platform was exposed—except for the aulacogen site in southern Oklahoma, where a finger of the sea remained (Fig. 2).

THE SIMPSON GROUP

During the ultra-regional post-Arbuckle sea-level lowering, the Joins Formation, the oldest unit in the Simpson Group, was deposited in the finger of sea remaining in southern Oklahoma (Denison, 1997). Strata within the Simpson represent the first introduction of significant terrestrial material into the depositional system since the Cambrian transgression. Sandstones of unusual thickness and purity are conspicuous in this sequence. The following discussion is taken mostly from the classic outcrop study of Decker and Merritt (1931).

The Simpson Group consists of five formations within the aulacogen area and was deposited over a period of about 25 million years, representing all of the Whiterockian and the earlier part of the Mohawkian. A comparison of the thickness, lithology, and distribution of the units with the Simpson are shown in Figure 3. The Joins Formation is followed by four similar formations, each characterized over most of the area by a distinctive basal sandstone.

The Joins Formation consists of thin, grainy limestones and shales. The Joins distribution in the Arbuckle Mountains extends just beyond the aulacogen. It is absent over most of the Hunton anticline apparently through nondeposition. Each of the four overlying formations of the Simpson Group shares a common lithologic sequence—a basal sandstone overlain by limestones containing variable amounts of shale. Within the Arbuckle Mountain area, there are also local sandstones, some quite substantial, within the middle parts of the McLish and Oil Creek Formations. Each of the four formations shows major differences in both thickness and composition inside and outside the aulacogen (Fig. 3).

THE SANDSTONE

McPherson and others (1988) gave the first detailed description of the features seen in the crucial quarry exposures. The basal Oil Creek sandstone is best seen on fresh, wet surfaces in the quarries. The glass sand in the quarries consists of regularly stacked horizontal beds 3–25 cm thick. The bedding is laterally continuous, even for the thinnest beds, over many tens of meters. Each bed consists of a sharp base with uniform sand size throughout. Illitic clay coats each sand grain and imparts a pale greenish color. The clay coats increase in thickness toward the top but never exceed a few microns. Some beds have a clay cap that may be up to several millimeters thick. It is the pattern of clay

Denison, R. E., 1999, Origin of high-purity Simpson sands in the Arbuckle Mountains, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 13–17.

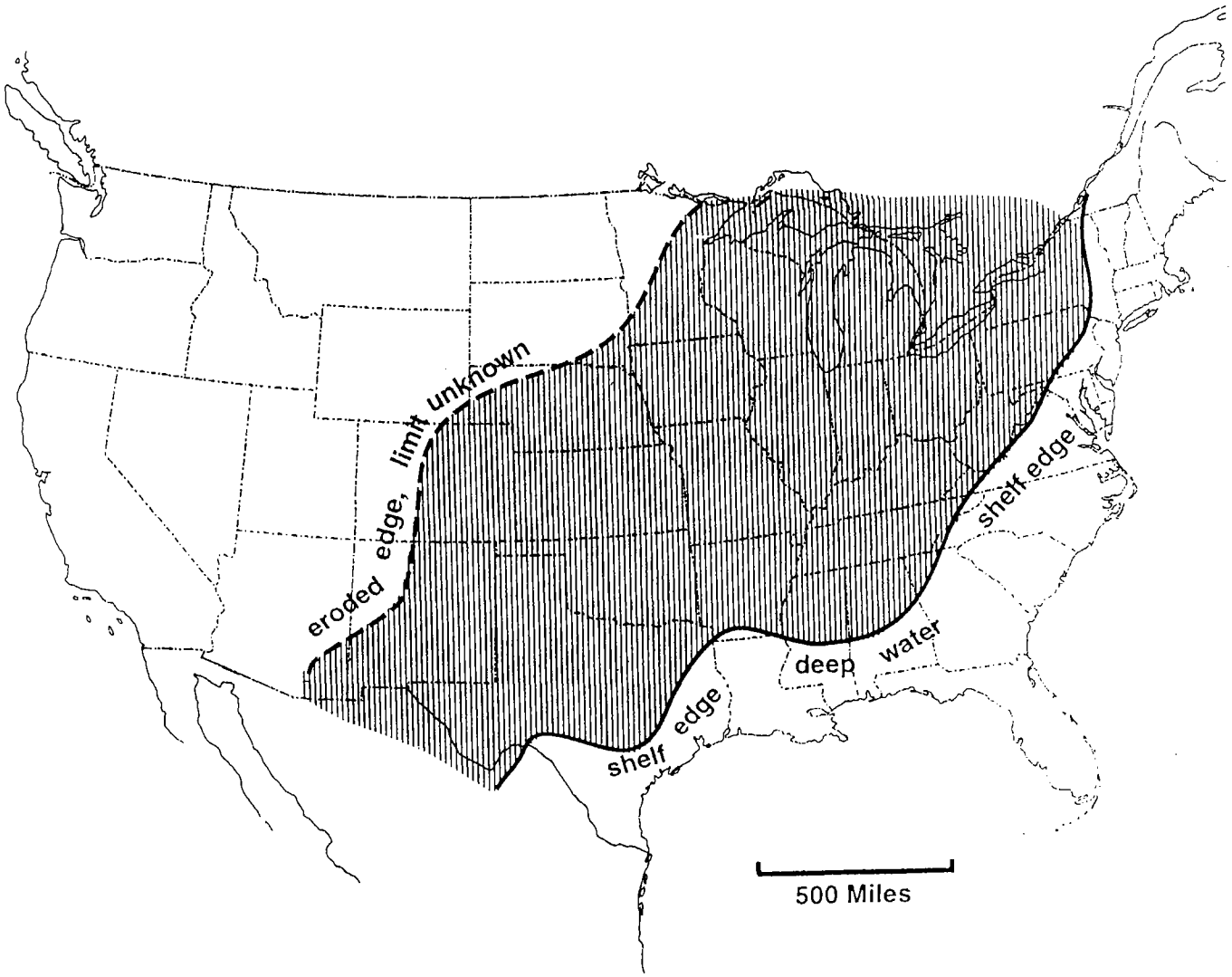


Figure 1. The Late Cambrian–Early Ordovician carbonate platform, on which the Simpson sandstones were deposited, covered a vast area in the United States. Interpreted from Cook and Bally (1975).

distribution that defines bedding (Fig. 4). Some beds have dewatering structures and fluid-escape pipes at the base (McPherson and others, 1988). There is no large-scale cross-stratification or evidence of bioturbation.

The sand grains are composed almost entirely of single quartz crystals, with traces of microcline, zircon, tourmaline, and garnet. Secondary pyrite (now completely oxidized) occurs as scattered cement that forms nodules several centimeters in diameter. The McLish sandstone contains tiny disseminated pyrite crystals. Ham (1945) gives a more complete discussion of mineral composition of the sands. The sand is very fine to fine grained, well sorted, and well rounded. The individual sand grains show surface frosting and crescent percussion marks (Fig. 5). The specifics of sand quality, sorting, and rounding are given by Ham (1945). The sand, washed to remove the illite, is >99.5% SiO_2.

DEPOSITION OF THE SIMPSON SANDSTONES

Over most of the area, each of the post-Joins formations has a remarkable basal sandstone. Sandstones of similar composition and age are distributed from Minnesota to Oklahoma (the St. Peter problem of Dake, 1921) and into West Texas. Each sandstone is overlain by a sequence of shale and limestone. Because most of the sandstone is poorly cemented, few outcrops expose the internal sedimentary structures that might be definitive in establishing an environment of deposition. Attempts to core the poorly consolidated sands are invariably unsuccessful. The limestones overlying the sands were deposited in a shallow-water, peritidal environment. The purity of the Simpson sandstones has been exploited for glass sands. The sandstones are composed of supermature, multicycle sand. Beds of dolomite- or calcite-cemented sandstone up to 1.8 m thick are present within the Oil Creek sandstone.

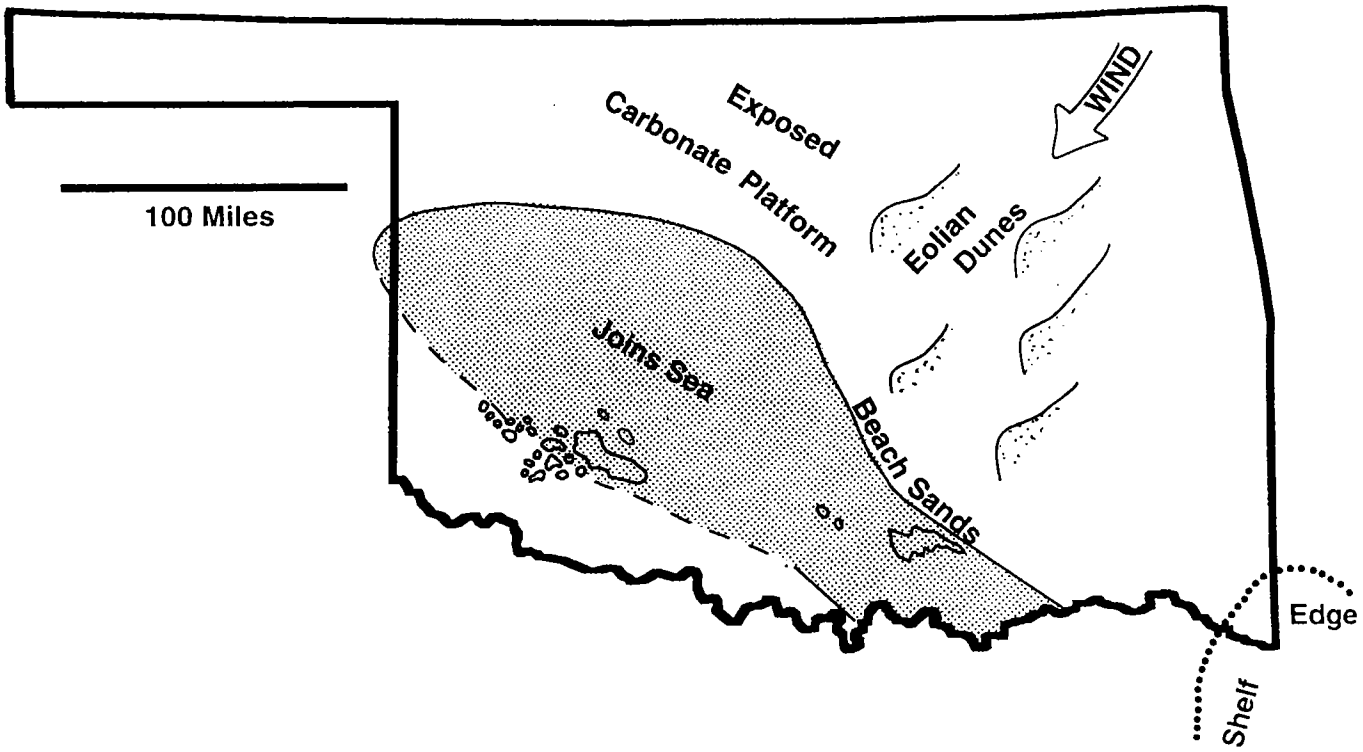


Figure 2. Approximate extent of the Joins sea and the transportation of eolian sands across the exposed carbonate platform during the post-Arbuckle ultraregional unconformity. Joins sea limits shown in relationship to present basement outcrops. From Denison (1997).

The origin of these sands, how were they transported to the deposition site, and the environment of deposition have been subjects of much speculation. The sands must have originated outside the vast limits of the underlying carbonate platform, at least hundreds of kilometers away (Fig. 1). Dapples' (1955) regional study showed that the sandstones were transported from the north. With the extreme flatness of the platform, what mechanism transported the sand to the depositional site? The pitting and frosting of the sand grains (Fig. 5) has long been regarded as a criterion of wind transport. However, the few exceptional quarry exposures of the Simpson in the Arbuckles do not show eolian sedimentary structures. The simple, uniform horizontal bedding seen in quarries is defined by the occurrence of varying amounts of green illite clay as coatings on the sand grains (Ham, 1955; Denison and Ham, 1973).

McPherson and others (1988) showed that outcrops in Oil Creek quarries north of Mill Creek were the result of repeated storm deposition. Each of the horizontal beds represented a single storm episode that transported the sand and clay from shallow, nearshore localities to deeper water to be deposited below storm-wave base. Their model brought the sands across the exposed Arbuckle carbonate plain as eolian dunes during a post-Arbuckle lowstand until the sands reached the edge of the Joins sea. There, the sand was deposited in a beach and shallow-marine environment, later to be reworked during a subsequent transgression into deeper water during storms (Figs. 2,6).

The McLish, Tulip Creek, and Bromide Formations that overlie the Oil Creek all have a basal sandstone overlain by peritidal limestones interbedded with shale. The upper four formations are, in fact, so similar on the outcrop that Ham (1945) could distinguish the units only on the basis of fossil content and stratigraphic position. Because the post-Joins formations are so similar, a common depositional model may well be appropriate for them. The Oil Creek is considered a general model—sand brought from a great distance by wind during a lowstand. The subsequent marine transgression redistributed the sands into a marine environment. Eventually, eolian sand transport is shut off, and the system evolves into a peritidal carbonate platform with interbedded clays brought in suspension from distant sources.

ORIGIN AND PRESERVATION

The high-purity quartz sand is clearly due to multiple sedimentary cycles during which less stable minerals were systematically eliminated from the system. The eolian transport caused the unusually good sorting and rounding and the percussion marks. The deposition below storm-wave base allowed the clays to filter into the just-deposited, uncompacted sands to coat each grain (Fig. 6). It is the lack of bottom-feeding organisms

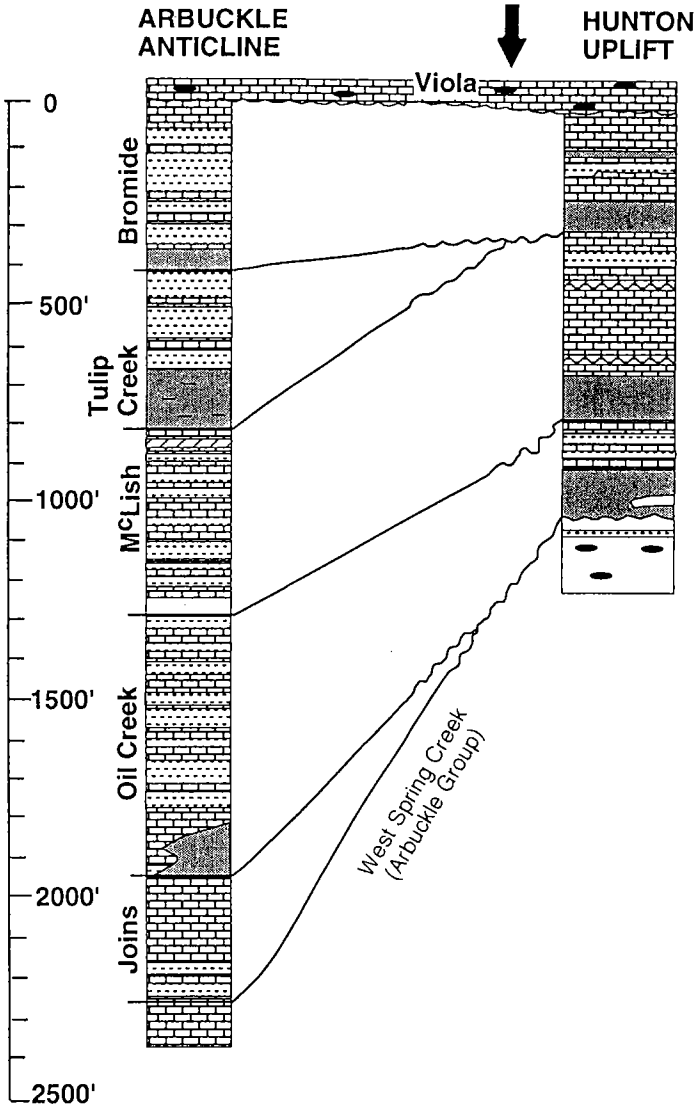


Figure 3. Contrast in thickness and composition of Simpson-age strata overlying Arbuckle Group rocks of the West Spring Creek Formation. Arrow shows the approximate location of quarry exposures. Based on Ham (1955).

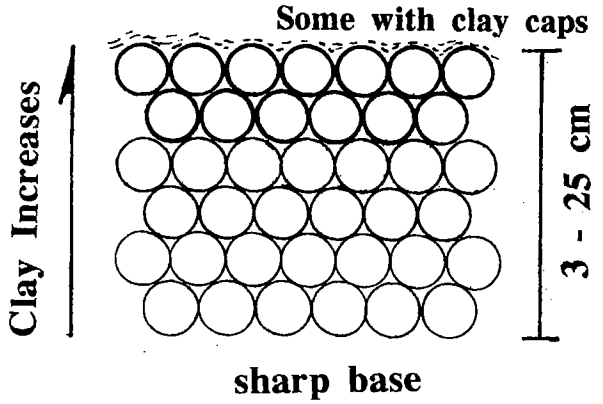


Figure 4. Schematic representation of horizontal storm deposits that make up most of the Oil Creek sandstone in quarries north of Mill Creek, Johnston County.

and currents that allowed the clay coats to remain undisturbed. The maintenance of the clay coats is crucial in preventing cementation during later diagenesis. The clay coats effectively "poisoned" the surface of the sand grain, precluding subsequent overgrowths and cementation. When the clay coats are removed or disrupted, the consequences are dramatic. This can be seen along small faults and fractures in the quarries where silica overgrowths result in tightly cemented sandstones. Certain beds within the Oil Creek, up to a few meters thick, are tightly cemented by carbonate. These beds floor some quarries. Internal structure of these cemented beds commonly shows delicate crossbedding that is the evidence of bottom currents that removed or prevented the deposition of the clay coats.

It is only by understanding the regional setting of the source, transportation, and deposition that there can be a true appreciation of fortuitous circumstances leading to the preservation of the original character of these remarkable sandstones.

ACKNOWLEDGMENTS

Access to the important Oil Creek quarries has been generously given by U.S. Silica over a period of years. Study to these remarkable exposures has benefited countless geologists and students of all levels. Ed Lips of U.S. Silica provided information in understanding operations within the quarry and plant. Jock Campbell and Doug Kirkland read the manuscript and offered helpful suggestions for improvement and clarity.

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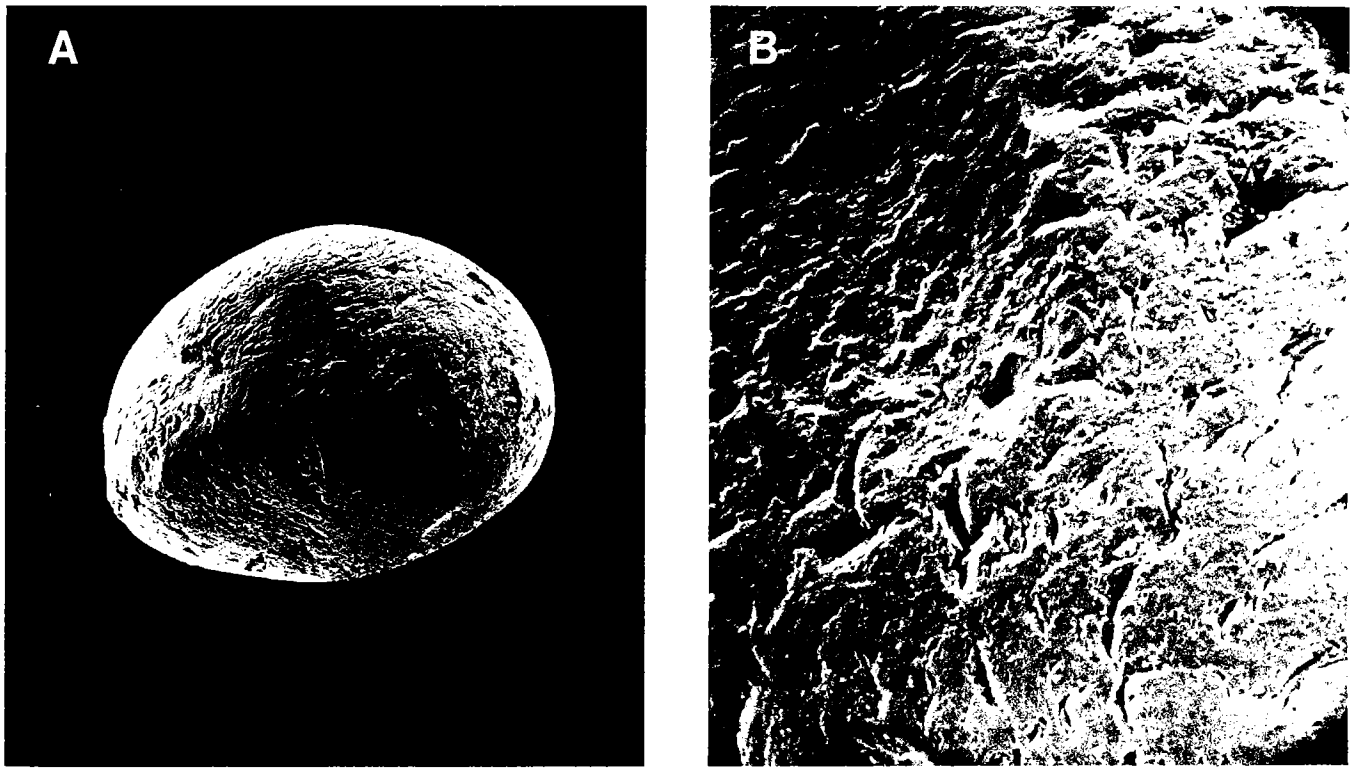


Figure 5. Scanning-electron micrographs of Oil Creek sand grains. (A) Single grain showing excellent rounding. Mild depressions are caused by pressure solution at grain contacts. Grain is 0.3 mm in diameter. (B) Enlarged view of grain surface showing percussion marks developed during an eolian cycle. Field width is 85 microns. Taken from Denison and Ham (1973, fig. 4B).

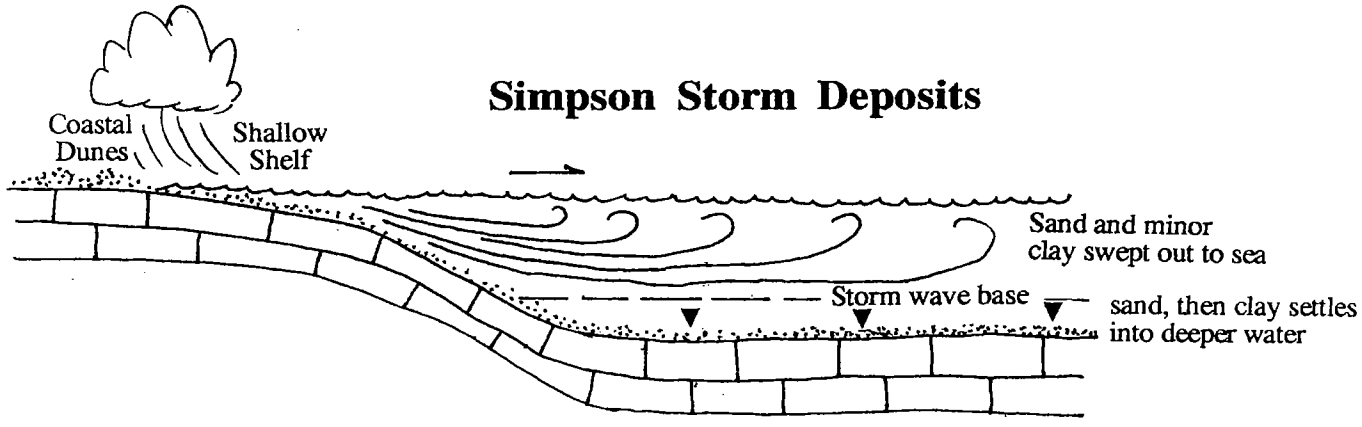


Figure 6. Simplified development of the horizontal beds where sand and minor clay are swept from the shore and shelf during storms into deeper water, below storm wave base.

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Economic Geochemistry of Industrial Minerals in the Arbuckle Mountains, Oklahoma

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INTRODUCTION

Southern Oklahoma (including the Arbuckle Mountains) has outcrops of rocks representing Precambrian, Paleozoic, and Cretaceous ages. Thus, rocks of every geologic age in the Paleozoic and Mesozoic Eras, except the Jurassic and Triassic Periods, are present in south-central Oklahoma. With rocks of such an enormous age range present in a relatively small geographic area, it is little wonder that a wide variety of economic rock and mineral resources are locally present. This report will describe the occurrence, mining, processing, and end-uses (dictated by chemical and physical properties) of the Precambrian Troy Granite, the Cambrian Royer Dolomite and Fort Sill Limestone, Ordovician silica sands of the Simpson Group, Ordovician limestones of the Viola Springs and Welling Formations, and Ordovician Sylvan Shale. In general, the more the end-use depends upon chemical composition and purity, the greater the price that can be demanded for such minerals. The not-so-successful attempts to mine zinc, manganese, copper, and iron from the Arbuckle Mountains also will be discussed briefly, and I will provide a sermonette on analytical chemistry and its usefulness to corporate CEOs.

I may be one of the few persons at this Forum on the Geology of Industrial Minerals who is not a professional geologist. I am an analytical chemist specializing in geochemistry. In particular, I investigate trace elements in rocks and their consequences in industrial processes. As such, I have consulted to the mining industry (and their clients) for two decades, always with the intent of improving service and product quality.

INDUSTRIAL MINERALS IN THE ARBUCKLE MOUNTAINS

The major industrial minerals that occur in the Arbuckle Mountains are silica sand, granite, limestone, shale, and dolomite (Table 1). Silica sand is mined at two localities by two different corporations, U.S. Silica Co. (at Mill Creek) and Unimin Corp. (at Roff). However, the geological differences in the two Ordovician units, the Oil Creek and McLish Formations, dictate their economic end-uses. The older Oil Creek Formation is purer than the McLish (e.g., less iron by a factor of 10), and, therefore, can be used in applications that call for high-purity silica, such as flat glass, optical glass, and lenses for microscopes, telescopes, etc. The McLish Formation's higher iron content dictates that the chief end-use is container glass. Although the two corporations operate sand pits only 10 mi apart, the purity, as dictated by trace-element content, determines the chief end-use of the ore. Both pits are mined by hydraulic methods. However, the less-pure sand (McLish Formation) has to be floated with a surfactant before being sold; the Oil Creek sand does not.

The Precambrian Troy Granite is mined by Meridian Aggregates Co., just south of Mill Creek, chiefly for use as ballast rock by the Burlington Northern Santa Fe Railroad. The "fines" resulting from the crushing process have limited use as sand-blasting grit. Rock chemistry is not generally important in this quarry, because physical properties (resistance to abrasion and wear) are more important in railroad ballast. West of Davis, another quarry has been opened by Western Rock Products, Inc., in the Cambrian Colbert Rhyolite to produce railroad ballast, but for a different track of the Burlington Northern Santa Fe Railroad. In the early 1980s, the (then) Santa Fe Railroad investigated the use of the Cambrian Royer Dolomite south of Mill Creek for ballast but concluded that it was inferior to granite for that purpose.

Limestone and shale are important industrial minerals in south-central Oklahoma. Whereas the ubiquitous limestone is used primarily for aggregate (road-base material), it also is used by the glass, cement, and filler industries. The Holnam, Inc., cement plant near Ada mines the Ordovician Viola Springs and Welling (Fernvale) Limestones of the Viola Group and Sylvan Shale to produce cement. Cement manufacture requires using a calcium-rich limestone; dolomite, with its high magnesium content, cannot be used because it retards the setting time of cement. Therefore, magnesium is an impurity in limestone as far as the cement industry is concerned. Glass manufacturers need to know the silica (SiO_2) content of limestone, but, as long as it is fairly consistent, they can use almost any limestone containing up to about 7% silica.

Neman, R. L., 1999, Economic geochemistry of industrial minerals in the Arbuckle Mountains, Oklahoma, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 19–23.

Table 1.—Industrial Minerals in the Arbuckle Mountains of Southern Oklahoma

Quarry/Owner	Location	Analyzed for	Impurities	Age/Description/Use
Meridian Aggregates Co., south of Mill Creek	Sec. 1, T3S, R4E	None	Clay	Cambrian Ft. Sill Limestone and Royer Dolomite/road aggregate
Unimin Corp., south of Mill Creek	Sec. 36, T2S, R4E	Ca, Mg, Al, Fe, K, Na, LOI, Si	Clay, SiO_2, Fe_2O_3	Royer Dolomite, Upper Cambrian/high-purity dolomite for glass, filler, ag lime
Meridian Aggregates Co., Mill Creek	Sec. 29, T2S, R5E	None	None	Precambrian Troy Granite/ballast rock for railroad
U.S. Silica Co., north of Mill Creek	Sec. 14, T1S, R4E	Fe, Ti, Al	Fe	Ordovician Oil Creek Formation/high-purity sand for optical glass, container glass
Mill Creek Mining (bankrupt)	Sec. 27, T1N, R4E	Fe	Gold? (They sure weren't mining Fe!)*	Ordovician West Spring Creek and Kinblade Formations (Arbuckle Group)
Unimin Corp., at Roff	Sec. 18, T2N, R5E	Ca, Mg, Si, Al, Fe, Ti	Fe, Ca, Mg	Ordovician McLish Formation/high-purity sand for container glass, foundry sand
Holnam Inc., Ideal Cement Division, south of Ada	Sec. 25, T3N, R5E	Ca, Mg, Fe, Al, Si, S, K, CO_3, Na	Mg	Ordovician Viola Springs and Welling Limestones and Sylvan Shale/manufacture cement

* I was told there was a "part-per-million" of gold in the iron. When the operators were told that this was not a Colorado placer deposit, and that any gold present was in the form of a compound (a sulfate, chloride, etc.), they went out of business as quickly as they could.

One of the nation's few high-purity dolomite deposits occurs in the Arbuckle Mountains. Whereas dolomites and dolostones occur worldwide, the Cambrian Royer Dolomite approaches the theoretical composition of dolomite (55% $CaCO_3$ + 45% $MgCO_3$). This deposit has been mined since 1948 and now is mined by Unimin Corp. Its chief uses are in glass manufacture, as agricultural lime (ECCE over 100%), and as filler for the composition-shingle industry. These fillers serve to add weight and provide flame retardation to composition shingles. The PVC (polyvinyl chloride) industry also uses considerable quantities of filler, but generally limestone is employed because of its lower cost and because limestone typically is whiter than dolomite. Ironically, another local company (Meridian of Denver, Colorado) is mining the Royer Dolomite and Fort Sill Limestone for different purposes; their chief product is aggregate for the Dallas–Fort Worth area. Thus the same formation is being mined by two different corporations for two entirely different end-purposes; Unimin does not market aggregate, and Meridian does not deal in industrial chemicals. The chief impurities in the Royer Dolomite are those that concern the glass industry—iron, aluminum, and silica. At the request of the companies involved, representative amounts of impurities and other data (such as price per ton) are not given in this paper; these figures are considered proprietary.

In the early part of this century, attempts were made to mine copper, zinc, iron, and manganese from small, localized deposits located throughout the Arbuckle Mountains; none proved profitable, and consequently none have survived. They are now of interest only to mineral and rock collectors.

SAMPLING AND ANALYTICAL METHODS

As an analytical chemist concerned with both the bulk composition and the impurities in industrial minerals, it concerns me that I have seen (all too often!) decisions made and money (lots of it!) spent on bad data. The analytical work was not bad, but the methodology prior to a sample arriving in my laboratory was highly suspect. As a consultant to the geochemical industry, I have seen boxcars of industrial minerals re-

turned to the mine because people at the receiving end did not know that granular products settle and that there is a right way and a wrong way to sample a boxcar. I have seen core samples selectively isolated because they "look good." Likewise, rather than truly sampling a quarry, I have watched CEOs (who ought to know better) selectively choose rock specimens from a quarry highwall for analysis. Therefore, the analysis was of selected specimens and was not representative of the quarry as a whole. But the problem I cannot abide in the "real world" of corporate geochemistry is that of the CEO wanting to hear only what they already believe about their quarry or product. I have lost clients because I refused to tell them what they already believed and wanted to hear.

If corporate management were more knowledgeable about what happens in a chemical laboratory and the steps involved in an analysis (including sampling, reducing the sample to a workable size, processing, measuring a chemical parameter, reporting, and interpreting this report), then the work of a geochemist would be easier and the CEO generally would be happier and understand more about his raw material. Of all the steps involved in analytical chemistry, sampling is the most important. To this end, the remainder of this paper will be a personal sermonette to managers and CEOs to help them better understand their operations.

A sample from your quarry is taken and submitted to your own laboratory, or mailed for analysis. Several hours (or days) later, you receive a report, which may read as follows:

LOI	47.27%
Na_2O	0.027
K_2O	0.058
CaO	30.49
MgO	21.28
Fe_2O_3	0.118
Al_2O_3	0.28
SiO_2	0.48
TOTAL	100.003%

Knowledge of what has transpired since the sample was taken and submitted to the laboratory, along with a general overview of the nature of analytical chemistry, are both useful in helping the laboratory do a successful job and in helping management appreciate and understand the results.

Whereas the general discussion that follows is applicable to most kinds of rock analyses, the examples will be taken from actual analyses of dolomite, normally composed of about 55% calcium carbonate ($CaCO_3$) and 45% magnesium carbonate ($MgCO_3$) with traces of sodium (Na), potassium (K), iron (Fe), and aluminum (Al) as the chief impurities.

Analytical chemistry is generally concerned with: (1) obtaining a suitable sample and reducing it to a manageable size; (2) selecting an appropriate analytic method; (3) preparing the sample for analysis, a process normally involving a weighing procedure, dissolution in some liquid, and adjustment of some factors, such as pH; (4) separation of the appropriate constituents from one another; (5) determining some property about the desired constituents, such as weight, volume, etc.; (6) calculating results; and (7) reporting and interpreting them. Very often, replicate analyses are performed for verification of results.

Several comments about these various steps are in order. First, the analysis can be no better than the sample taken. If the sample is not representative of the product actually going through the plant, or, for example, of the first 20 ft of a test hole, the results are largely meaningless. Commonly, the laboratory personnel do not take their own samples and must rely upon others to make sure that the analysis is not biased at the outset.

The chemist will grind the product to a powder of about 60 mesh and, through a series of splittings, reduce the sample to a manageable size, normally about 1 gram. (For comparison, a U.S. nickel weighs about 5 grams.) Thus, a 100-ton boxcar of material is normally analyzed on the basis of 1 gram of product, a weight-reduction factor of about 90 million! Sampling is very important.

The lab can analyze either for one particular constituent or for all constituents that react similarly to a given reagent. For example, analyzing for Fe and Al together, called a *proximate (approximate) analysis*, is reported as an R_2O_3 analysis, where R = Al + Fe + any other element reacting similarly. The sample can be analyzed "as received," or on a dry basis after driving off the trace of water contained in most samples.

Selection of analytical method is commonly determined by what the analyst expects to find and in what quantity he expects to find it. In all cases, a property of the material must be measured—weight, for a gravimetric analysis; volume, for a titration procedure; or some physical property, such as light absorbed or emitted, for an instrumental method. In the analysis of dolomite, high calcium and magnesium content dictate that gravimetric methods would work best, whereas instrumental techniques, such as atomic absorption (AA), work well for the trace quantities of Na, K, and Fe. Loss-on-ignition (LOI) must, by its very nature, be determined by a weighing procedure, generally by heating a preweighed sample in a furnace at 1,000°C for about an hour, then reweighing when cool. LOI represents traces of water and organic matter that are present and the conversion of carbonates to oxides, with the corresponding loss of CO_2.

Other factors, such as economics, equipment available, time, the accuracy required, and the number of analyses to be performed all play a role in the selection of a method. Commonly, several methods are available, and the author frequently correlates one method against another for verification of the results.

When considering the calculation and interpretation of results, it must be realized that an analysis generally can be reported in several different ways. For example, if a sample of impure sodium sulfate is submitted to

four different laboratories, the results might come back looking like this:

Lab #1:	59.42% Na_2SO_4
Lab #2:	40.20% SO_4
Lab #3:	33.50% SO_3
Lab #4:	13.42% S

Which is correct? Answer: they are all correct. The laboratories simply chose to *report* the results in different ways. I once worked about a week to verify a water-hardness test done by another lab, only to find that the other lab was reporting the percentage of CaO, whereas my lab was reporting the parts per million (ppm) of calcium. Although we were both correct, I had lost a week over a reporting problem, not a chemical analysis (my client lost time and money!).

Rock and mineral analyses generally are reported as percent metallic oxide. If other forms of reporting are needed or wanted, the following conversion factors will be helpful. To convert % oxide to % metal, multiply by the appropriate factor, shown below:

Fe_2O_3	×	0.6999	=	Fe
CaO	×	0.7147	=	Ca
MgO	×	0.6031	=	Mg
Na_2O	×	0.7419	=	Na
K_2O	×	0.8301	=	K
Al_2O_3	×	0.5292	=	Al
CuO	×	0.7988	=	Cu
ZnO	×	0.8034	=	Zn

Thus, if your analysis reads 30.51% CaO, it contains 21.80% Ca; and 21.36% MgO corresponds to 12.88% Mg. Obviously, the table can be utilized in the reverse manner; if the %Fe is divided by the factor 0.6999, the %Fe_2O_3 is obtained.

If a sample contains 0.047% K, this is equivalent to 0.047 g of K per 100 g of sample; this in turn is equal to 470 g of K per million g of sample, or 470 ppm. Thus, percentage multiplied by 10,000 is equal to ppm, and ppm divided by 10,000 is equal to percent.

Several techniques are available to determine the *precision* and *accuracy* (they are not the same, as discussed below) of analytical work. Two different methods of analysis of Fe—atomic-absorption and visible-absorption spectrophotometry utilizing phenanthroline as the color developing reagent—should correlate nicely. A complete analysis should total up to 100.00% ±0.050%. A check on analytical work also can be obtained by submitting the analysis to an independent laboratory.

What is meant by *precision* and *accuracy*? Results may be precise and agree with themselves without necessarily being accurate. An analogy illustrating the difference between precision and accuracy can be made if a target at which a marksman has taken five shots is envisioned. If the shots are all in the "bulls eye," they are both precise and accurate. If they are all clustered about the two-o'clock position, they are precise, but hardly accurate. If they are scattered randomly about the target, they are neither precise nor accurate.

I have taught analytical chemistry and consulted for the mining industry since the mid-'70s. If identical answers to multiple analyses are reported to me, I immediately suspect that something is not right. It is almost humanly impossible to reproduce analytical answers that agree perfectly. After all, the analytical balance is good to only the nearest 0.0001 gram, a buret can be estimated to only the nearest 0.01 mL, calibrated glassware is not perfect, a calibration curve (to be described later) is not perfectly linear at all times, and it is commonly difficult to remove all interferences. Reagents are never perfectly pure, and seldom is routine analytical work performed under temperature-corrected situations. Thus, for these reasons and many more, not the least of which is that imperfect people are performing the analyses, exact duplication is virtually impossible.

Analytical chemists operate under the philosophy that large errors occur seldomly and small errors (both positive and negative) occur frequently. Thus, a slight variation in duplicated work is to be expected, and is even desirable. It can be shown mathematically that an analysis of a dolomite whose percentage of CaO is 30.00% could have a true value anywhere in the range 29.95–30.05%, simply because of the limitations on the accuracy of the best measuring equipment available. In my classes, any replicate analyses that result in identical answers are immediately suspected of being analyzed by the well-known "graphite" method or the equally well-known "pencil titration" technique (also known as "copying").

Chemists are trained to report all numerical digits of which they are sure, and the first digit that is doubtful. Unfortunately, bias, prejudice, and a desire to "tell the boss what he wants to hear" are not unheard of in the analytical world, and the reporting of data is often not all that it should be.

Once the sample has been taken, ground, reduced to manageable size, and weighed accurately on a balance (that may have cost several thousands of dollars), it must be dissolved. For limestones and dolomites of any type, dilute hydrochloric acid (HCl) works nicely. It destroys the carbonate structure, releasing carbon dioxide and solubilizing the metallic elements:

$$CaCO_3 + MgCO_3 + 4HCl \rightarrow Ca^{++} + Mg^{++} + 4Cl^- + 2CO_2 + 2H_2O$$

Only quartz sand (SiO_2) and clay-type silicates are impervious to attack by HCl. They are filtered off and weighed as the acid-insoluble fraction. If SiO_2 analysis is desired, the acid-insoluble fraction is subjected to a treatment of hydrofluoric acid (HF), the only acid known to attack silica and silicates. From knowledge of the amount of material dissolving in the HF, the percentage of SiO_2 can be calculated. It always will be slightly smaller than the acid-insoluble fraction.

The acid-soluble fraction of the rock or mineral is generally diluted to a specific volume, and then is split into several smaller portions (aliquots) for analysis of

both the major and minor constituents. Ca and Mg are generally reacted with reagents that will cause them to precipitate. Calcium precipitates as the oxalate, CaC_2O_4, and the magnesium as the pyrophosphate, $Mg_2P_2O_7$. These solids are weighed after drying and reported as the oxides CaO and MgO, respectively. There are other ways to analyze for Ca and Mg, notable among them a double-indicator titration with EDTA; this method is quicker and cheaper, but suffers from a slight loss in accuracy. As a general rule in analytical chemistry, the "quick and dirty" analyses are not normally the most accurate.

Trace elements generally are determined by methods involving some physio-chemical property, such as light absorbed or light emitted by an excited sample. These methods encompass visible and ultra-violet spectrophotometry, flame-emission spectrophotometry, atomic absorption, and an interesting technique called inductively coupled argon-plasma spectrophotometry, or ICP for short. This technique will be described shortly.

Iron generally is determined by reacting the element with phenanthroline after some prior adjustment of parameters such as pH. An orange-red solution results, and the intensity of its color is directly related to the concentration of iron in the system. When light of a certain wavelength is passed through the system, a photocell records the amount absorbed, and the amount of iron is calculated. Calibration standards are used and the aliquots compared with them.

Atomic absorption (AA) is also concerned with the absorption of light when a liquid sample is sprayed into a flame. AA techniques are relatively commonplace now, and AA instruments can be found pretty much industry-wide. Related to this, but operating on the principle of light emission, is the ICAP instrument. If a sample is sprayed into a plasma of argon nuclei and electrons, which is held at a temperature of about 10,000°C, light is emitted by excited atoms. If we surround the hot plasma with its emitting elements with a variety of photocells, we can obtain qualitative and quantitative data on many elements simultaneously. The instrument operates well over concentration ranges from tenths of ppm to several thousands ppm. Data from these high-powered instruments commonly are corrected for interferences and tabulated by an onboard computer. Although expensive, they save many hours of time in the laboratory. Regardless, for any instrumental method, extensive preparation work must be performed. An instrumental method does not mean that traditional analytical chemistry should be avoided.

As an example of data generated by either AA or ICAP methods, if the potassium content of a 100.00 mL aliquot of a 1.0000 g sample were reported as 4.70 ppm (mg/L), then:

$$4.7 \text{ mg/L}(0.1000 \text{ L})\left(\frac{1.0000 \text{ g}}{1000 \text{ mg}}\right)(100\%)/1.0000 \text{ g sample}$$

$$= 0.047\% \text{ K}$$

$$= 0.057\% \text{ } K_2O$$

As an example of the power and value of an ICAP analysis, a recent sample of dolomite was found to have the following parts per million of trace-metallic elements: 0.6 Mn, 0.5 Cu, 0.05 Ni, 1.56 Zn, 0.3 Ba, and that cobalt, molybdenum, arsenic, selenium, cadmium, beryllium, antimony, chromium, silver, lead, mercury, lithium, tellurium, germanium, and vanadium were below the limit of detection of the instrument, generally 0.01 ppm.

CONCLUSIONS

In conclusion, when a sample is submitted for analysis, the chemist has had to make literally hundreds of operations, ranging from grinding and weighing to manipulation of mathematical formulas to arrive at the set of answers. The chemist normally uses pure reagents and complex equipment, valued at tens of thousands of dollars, if not hundreds of thousands of dollars, in some cases. It is hoped that the role of the chemist in performing rock analyses (not to mention other purely physical tests, such as particle-size analysis) is better understood by all who use analytical data, for the more one understands about the data generated by the chemist, the better one is able to make intelligent decisions regarding product quality and service.

Exposed Basement Rock of Oklahoma: Geology and Economic Use

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ABSTRACT.—Basement rocks in southern Oklahoma are divided into two groups. One group is the Lower Cambrian Wichita Igneous Province, a diverse igneous suite that crops out in the western Arbuckle Mountains and in the Wichita Mountains. These largely bimodal igneous rocks were emplaced in an intracratonic-rift environment. The other group, the older, is a set of Precambrian rocks of the Eastern Arbuckle Province, yielding ages between 1,350 and 1,400 Ma, exposed in the core of the eastern Arbuckle Mountains. These are deeply eroded mesozonal granitic rocks and associated granitic gneisses cut by numerous dikes ranging in composition from diabase to rhyolite.

The southern Oklahoma igneous rocks have long been utilized mostly as dimension and crushed stone. Most of the early quarries were in granite of various red hues for monuments and facing stones. Large crushed-stone quarries are now exploiting both granite and rhyolite, which is used chiefly as aggregate and railroad ballast. The exposed basement rocks in Oklahoma represent an underdeveloped and accessible resource.

INTRODUCTION

Two principal outcrop areas of basement in Oklahoma expose igneous and metamorphic rocks—the Arbuckle Mountains (AM) of south-central Oklahoma and the Wichita Mountains (WM) of southwestern Oklahoma. The basement rocks have been divided into two groups by Ham and others (1964). One group is represented by the Wichita Mountains area, which contains a bimodal sequence of felsic and mafic rocks of Early Cambrian age (~530 Ma). These consist of prominently layered gabbroic anorthosites, less strongly layered anorthositic gabbros with primary biotite, a series of variably grained granites, and mostly massive rhyolites. This terrane is part of the southern Oklahoma aulacogen (Gilbert, 1982, 1983; Gilbert and Denison, 1993).

Both groups crop out in the Arbuckle Mountains. The felsic extrusives of the aulacogen are exposed in the western Arbuckles. The other group outcrops in the eastern Arbuckles and is known as the Eastern Arbuckle Province (EAP) or Arbuckle basement. These rocks yield ages between 1,350 and 1,400 Ma. They are related to rocks that seem to form most of the basement buried in the eastern and northern parts of the state and consist of medium- to course-grained mesozonal granitic rocks cut by numerous dikes.

Both the WM and AM are exhumed older topographies, which means that most of the rocks have been subjected to more than the present cycle of weathering. The felsic rocks, particularly, show evidence of oxidation to considerable depths (20–30 m) (Price and others, 1998), but this has not noticeably affected the desirability of the rock for quarrying. Most quarries have not penetrated beyond these depths.

Granites from Oklahoma have been quarried since statehood (1907). Taylor (1915) provides the necessary background for this early period. The tombstone industry has favored those granites that are coarser and have more textural homogeneity and continuity. Because most Oklahoma granitoids are oxidized, they have distinct red to pink colors, which have been found desirable. Most of the historical monuments in Oklahoma using granite, as well as the newer "welcome" signs on the interstate highways, are made from the Reformatory Granite from the Wichita Mountains. However, some of the most active quarries today are producing crushed-rock aggregate for railroad ballast and concrete.

Table 1 gives a simplified stratigraphic section of the principal basement rock units and indicates which of these units currently is being quarried. In this paper, the fundamental geology and petrology of the Arbuckle and Wichita Mountains will be reviewed, with special

Gilbert, M. C.; and Denison, R. E., 1999, Exposed basement rock of Oklahoma: geology and economic use, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 25–36.

Table 1.—Lithostratigraphy of Exposed Basement of Southern Oklahoma

Group	Constituent units	Lithology[a]
Late Proterozoic (?)–Early Cambrian		
Wichita Granite Group	East: Quanah	Fine- to medium-grained granite
	Cache	Fine granite
	Saddle Mountain	Fine granite
	Mount Scott	Fine granite (widespread)
	Rush Lake	Fine granite
	Medicine Park	Fine granite
	West: Lugert	Fine granite
	Cooperton	Fine granite
	Long Mountain[b]	Fine granite
	Reformatory[b]	Medium granite
	Headquarters	Fine granite
??	Cold Springs Breccia	Fine mafic to fine granitic (including local diorite)
Carlton Rhyolite Group	Bally Mountain section	Layered
	Blue Creek Canyon section	Layered
	Fort Sill section	Massive and layered
	East Timbered Hills section	Cut by fine granite
	West Timbered Hills section[b]	Massive and volcanic breccia (including significant mafic components)
Raggedy Mountain Gabbro Group	Roosevelt Gabbros	Fine to medium anorthositic gabbro (subtly but distinctly layered) (some of these units may be younger than some granites)
	Mt. Baker	
	Iron Mountain	
	Glen Creek[b]	
	Sandy Creek	
	Mt. Sheridan	
	Glen Mountains Layered Complex[b]	Medium gabbroic anorthosite, generally noticeably layered at several scales
	K-L-M-N zones	
Proterozoic (~1,400 Ma)		
Arbuckle basement	Tishomingo Granite	Coarse two-feldspar granite
	Troy Granite[b]	Medium two-feldspar granite
	Burch Granodiorite	Medium granodiorite to quartz diorite
	Blue River Gneiss	Mixed lithology (age relative to other Arbuckle basement members unknown)

[a]Fine, medium, coarse refers to average grain size (rock texture). [b]Rock bodies currently being quarried.

attention given to those units being quarried. The closing sections of this paper will look to the future and the economic potential for basement rocks.

ARBUCKLE MOUNTAINS BASEMENT ROCK

Basement rocks in the Arbuckle Mountains are divided into two groups (Ham and others, 1964). The oldest are massive Precambrian rocks of the Eastern Arbuckle Province. These rocks, yielding ages between 1,350 and 1,400 Ma, are exposed in the core of the eastern Arbuckle Mountains. These are deeply eroded mesozonal granitic rocks associated with granitic gneisses. These massive granitic rocks are cut by numerous dikes ranging in composition from diabase to rhyolite. The Early Cambrian Wichita Igneous Province is a diverse igneous suite that crops out the western Arbuckle Mountains and in the Wichita Mountains.

Western Arbuckle Mountains

The Colbert Porphyry (=Carlton Rhyolite of Table 1), part of the Wichita Igneous Province, is exposed in the core of the Arbuckle anticline. The two small exposures of rhyolite represent part of a vast volcanic field developed during Early Cambrian rifting. A large quarry for crushed stone in the largest of the two exposures reveals a complicated rock sequence. Rhyolite flows make up most of the core exposures; however, an igneous breccia is conspicuous in the quarry. This explosive breccia contains a diverse suite of rhyolite, microgranite, diabase, and monzanite-syenite set in a basal-

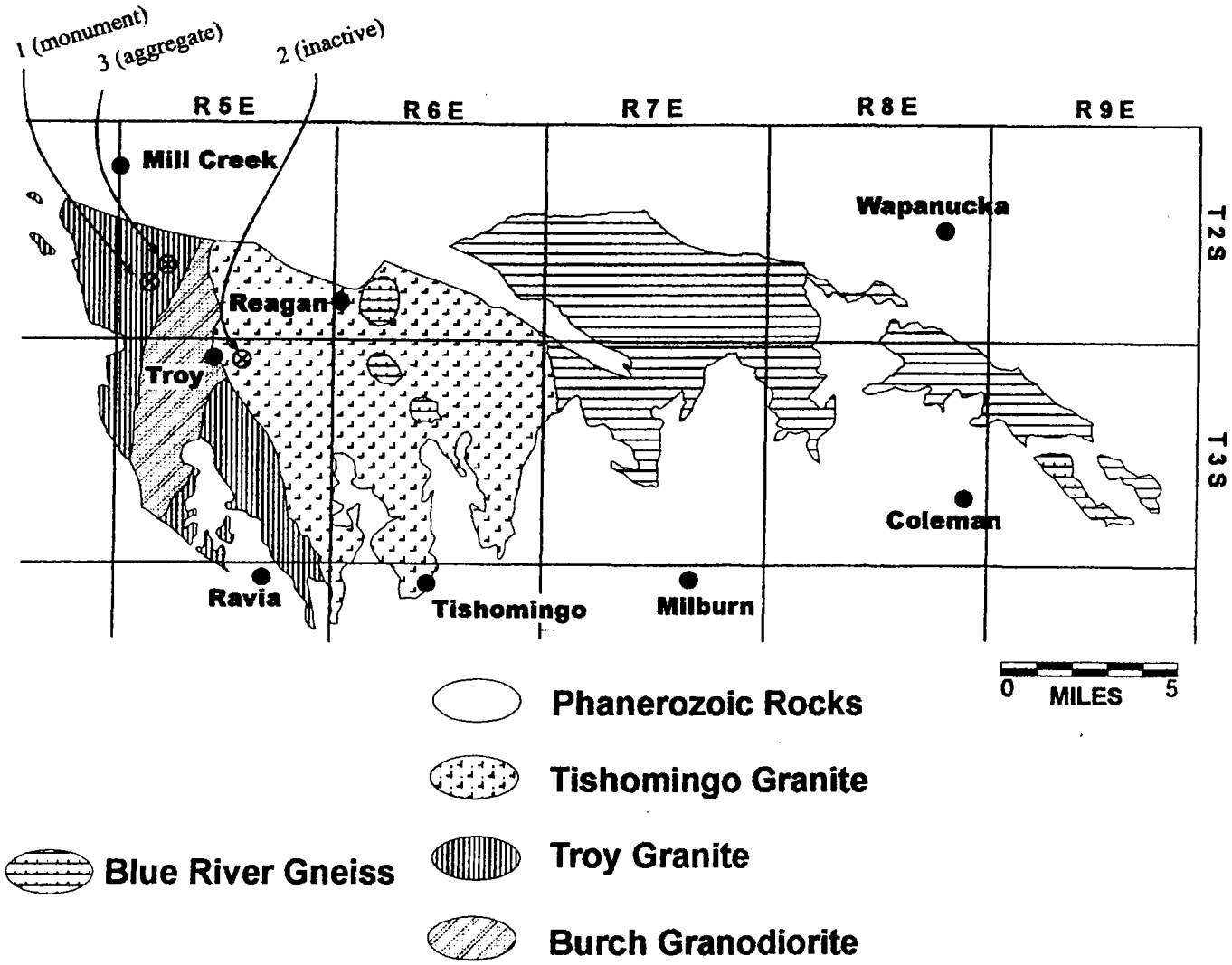


Figure 1. Geologic map of the Eastern Arbuckle Province basement (after Denison, 1994; Lidiak and Denison, 1999). Three of the noteworthy quarries are shown.

tic matrix. The volcanic sequence is cut by undeformed diabase dikes.

Eastern Arbuckle Mountains

The core of the eastern Arbuckle Mountains, the Tishomingo-Belton anticlines, exposes massive Precambrian rocks that were uplifted and eroded during the Late Pennsylvanian. Frankly, one might expect the core to be topographically more impressive. It is, after all, one of the most deformed areas (along with the Wichita Mountains some 160 km to the west) in the central interior of the United States. The ravages of Cretaceous peneplanation have left the igneous and meta-igneous rocks in the core of the eastern Arbuckle Mountains unimpressive at best. The maximum relief is only about 150 ft (45 m) over a distance of 0.25 mile (400 m). The relief rarely exceeds 50 ft (15 m) over most of the core area.

Four major rock units are recognized in the eastern Arbuckle Mountains (Table 1; Fig. 1). The youngest major map unit, the Tishomingo Granite, effectively separates differently appearing rocks to the east and west.

To the west, the Tishomingo intrudes the Troy Granite and the Burch Granodiorite. The Troy is seen to intrude the granodiorite at several widely separated localities, with minor chilling. The Tishomingo is strongly chilled for a distance of up to 200 m away from the contact with the granodiorite. Granodiorite and gneissic xenoliths are common in the chilled zone. The Troy-Tishomingo contact has not been seen but can be traced to within approximately a meter of one another. Minor diminution of grain size is present, but no extensive chilled zone was developed in the Tishomingo at the contact with the Troy.

To the east, the Tishomingo intrudes the Blue River Gneiss. The intrusive contact is irregular with minor chilling and numerous xenoliths of the gneiss within the Tishomingo. Mappable isolated masses of the

gneiss are found in the eastern half of the Tishomingo exposure. These are interpreted as roof pendants.

The granitic rocks are cut by numerous dikes. The following discussion of these dikes is taken largely from Denison (1995). The majority of the dikes are four basic types: diabase, rhyolite, granite, and microgranite porphyry. Only five diorite and quartz-diorite dikes were identified in the field. The diabase dikes are mostly vertical and are estimated to make up more than 90% of the dikes. The diabases vary from a foot or so (0.3 m) to about 100 ft (30 m) in thickness, although most are estimated to be 5–15 ft (1.5–4.6 m) thick. The diabases are of two ages—some near the age of the host rock and others clearly of Cambrian age. The two ages of diabases are petrographically indistinguishable, and there is no meaningful way to estimate relative abundances of the two dike suites. All diabase dikes show a very strong preferred N60°W strike direction. The Cambrian diabases are of two different ages. Most dikes are believed to be the earliest manifestation of the rift that led to the subsequent igneous activity. Another set of diabases, indistinguishable except for context, represent the youngest of all Cambrian igneous activity. The distinctive brick-red rhyolite dikes are of Cambrian age. They are few in number, strike generally N60°W and may represent feeder dikes for the Colbert Porphyry (Carlton Rhyolite). The granite dikes are mostly local, rarely large, and show no systematic attitude. The microgranite-porphyry dikes, although not numerous, are conspicuous. Most are greater than 10 ft (3 m) in width, and some can be traced for several miles along strike. The dikes form slight linear hills cutting the Troy and Burch but have never been identified in the Tishomingo and therefore are thought to be post-Troy and pre-Tishomingo in age. The microgranite-porphyry dikes show a clear N60°W preferred strike direction and are the best evidence for the early establishment of this zone of weakness, about 1,375 Ma ago.

Burch Granodiorite

The oldest map unit west of the Tishomingo Granite is a distinctive igneous rock, the Burch Granodiorite, originally called the "unnamed granodiorite" by Denison (1973). The Burch has a fairly uniform appearance but varies considerably in mineralogy, particularly in microcline-perthite content, so that the intrusion ranges from granodiorite to quartz diorite in composition. The rock is evenly grained, has medium crystallinity and, when fresh, has a dark green and white speckled appearance that is in clear contrast to the pink color of the other units.

Most of the rock is made up of plagioclase (50%), quartz (18%), and microcline perthite (12%) with the remainder composed largely of biotite (10%) and hornblende (5%). Opaque minerals, sphene, zircon, and apatite are minor minerals. Chlorite, feldspar alterations, and epidote are found as nearly ubiquitous secondary minerals. Microcline-perthite content varies from 1% to 20%. The texture is hypidiomorphic and does not appear to have been modified from the original crystallization fabric even near the contact with the younger Troy. The color index averages nearly 17, more than two times greater than the other granitic units.

No evidence indicates what the host for the Burch may have been. The granodiorite carries a few foliated and schistose xenoliths, but these are sparse. The Burch Granodiorite represents an unusual occurrence in the Precambrian of the south-central United States, where rocks of intermediate composition are rare. Thomas and others (1984) determined a concordia age of 1,397±7 Ma on zircons from the granodiorite.

Troy Granite

The Troy Granite occupies most of the outcrop area west of the Tishomingo contact (Fig. 1). The granite is mostly uniformly medium grained. The texture is hypidiomorphic and shows no evidence of post-crystallization modification other than minor deuteric alteration and remelting along major diabasic dikes. It is composed mainly of plagioclase (39%), perthite (29%), and quartz (25%) with lesser amounts of biotite (3%) and small to trace amounts of opaque minerals, sphene, apatite, zircon, and hornblende. Secondary minerals include feldspar alterations, chlorite, and epidote. The average color index is less than 5, although a darker, more biotite-rich phase of the Troy has an index near 10. The darker phase of the Troy is gradational with the normal Troy over a distance of a few centimeters. The biotite-rich Troy also contains proportionally more plagioclase and less perthite and approaches a granodioritic composition. The Troy can be seen to intrude that Burch Granodiorite at several places where minor chilling occurs and the grain size is reduced by half at the contact. Bickford and Lewis (1979) determined a concordia age of 1,399±95 Ma on zircon from the Troy.

Blue River Gneiss

Taylor (1915) mapped the area east of the Tishomingo Granite as the Troy. Although some outcrops bear a strong resemblance to the Troy, the granitic rocks are clearly different, and Denison (1973) used the name Blue River for this unit. Lidiak and Denison (1999) presented an extended discussion of the geology and composition of the Blue River. This complicated unit is not well exposed. The bulk composition of the most gneiss outcrops is similar to that of the Troy or Burch—from a quartz diorite to a granite. A third common phase of the gneiss is a fine-grained (<1.0 mm average), weakly or nonfoliated gneiss, a granofels. It is composed almost entirely of quartz and feldspar—a curious aplitic-looking rock. Where the color index is high enough in any of the gneiss types, a pronounced foliation and locally a banding is seen. In the more leucocratic phases, foliation is not discernable. However, on some weathered surfaces when the light is at the proper angle, a subtle dimensional orientation can be seen in the quartz and feldspar. In some outcrops, otherwise homogeneous-appearing granite gneiss contains scattered K-feldspar megacrysts (relict and modified phenocrysts or porphyroblasts) that show a dimen-

sional orientation. In thin section, every sample shows a clear and complete recrystallization during regional metamorphism. Bickford and Lewis (1979) determined a concordia age of 1,396±40 Ma on a gneiss sample.

The average composition is dominated by the more abundant granite gneisses, with plagioclase (40%), quartz (30%), and microcline (22%) making up most of the rock. Feldspar alterations, mostly after plagioclase, make up about 3% of the gneisses. Biotite, opaque minerals, sphene, apatite, and zircon are consistent accessory minerals. Muscovite is uncommon but locally well developed, and some hornblende occurs in the intermediate gneisses. The average color index is about 5 but shows a large variation, with many of the more silicic gneisses having an index in the 2–3 range.

The origin of the heterogeneous Blue River Gneiss remains illusive. It appears to be a suite of igneous rocks that has undergone profound regional metamorphism and is intruded by the undeformed Tishomingo Granite. The Blue River has undergone a metamorphic event not recorded in the other granitic rocks. Geologic reasoning, therefore, would assign an older age to the Blue River, but the zircon age of 1,396±40 Ma reported by Bickford and Lewis (1979) is within the error of the undeformed granitic rocks.

Tishomingo Granite

The Tishomingo intrudes older rocks to the east and west and is clearly the youngest major Precambrian unit of the Arbuckle Mountains. The granite is remarkably uniform in appearance and composition over the area. It carries conspicuous, pink microcline-perthite phenocrysts (averaging about 2 cm but ranging to 5 cm in length) and forms smooth, unjointed outcrops that are very difficult to sample. The granite is composed mostly of plagioclase (33%), quartz (30%), and microcline perthite (26%). Biotite, opaque minerals, sphene, apatite, and zircon are the other common minerals. Feldspar alterations, chlorite, and epidote are ubiquitous secondary minerals. Hornblende is not common but does occur in small amounts in scattered samples. Sphene, the most unusual and conspicuous accessory mineral, is found as resinous, euhedral, wedge-shaped crystals. The quartz contains rutile needles, a feature unique to the Tishomingo. The color index averages about 8. The original igneous texture is unmodified.

To the east, the Tishomingo intrudes the Blue River Gneiss. Minor chilling is seen, and numerous Blue River xenoliths of all sizes exist in the Tishomingo near the contact. Near the Burch Granodiorite, the Tishomingo is strongly chilled and contains numerous xenoliths of granite gneiss, diorite, and granodiorite. The intrusive contact with the Troy has never been seen, but it clearly is much less chilled and, although poorly exposed, does not appear to carry xenoliths. The chilling at the Tishomingo-Burch contact indicates that the Burch was significantly cooler than the Troy and Blue River at the time of Tishomingo intrusion. Bickford and Lewis (1979) determined a zircon age of 1374±15 Ma on the Tishomingo Granite.

Economic Potential

The basement rocks in the Arbuckle Mountains have been and continue to be an important source of industrial minerals (Table 2). The main uses have been for dimension stone, crushed aggregate, and gravel. Attempts to exploit mineralization were made in the early days of statehood, but these never achieved any success.

Dimension stone has been successfully quarried from both the Troy and Tishomingo Granites. The Tishomingo was quarried for the base of the Oklahoma state capitol at Ten Acre Rock (NE¼ sec. 3, T. 3 S., R. 5 E.). The quarry has not operated since about 1916. A quarry north of the town of Tishomingo (NE¼ SW¼ sec. 28, T. 3 S., R. 6 E.) was used to supply building stone for the Chickasaw Council House and the Harris Bank in that town. The quarry has not operated since about 1915. The Troy Granite was quarried largely for memorials from a number of sites south of Mill Creek in Johnston County. The Troy takes a nice polish and has a number of subtle color differences, depending on the location. No dimension stone has been taken from the Blue River, and it is probably not suitable for most purposes due to inhomogeneity.

Crushed stone, used largely for railroad ballast, is produced from a large quarry along the railroad south of Mill Creek (NW¼ sec. 29 and SW¼ sec. 20, T. 3 S., R. 5 E.). This quarry exposes a remarkable diabase-dike swarm (Fig. 2). The host rock is largely Troy Granite but minor Burch Granodiorite also is exposed. In addition to the diabase, a few dikes of a distinctive microgranite porphyry also cut the Troy. The diabases are believed to be the manifestation of the Cambrian rifting and the microgranite dikes are near the age of the host rocks. The coarser-grained Tishomingo is probably not as suitable as the medium- and even-grained Troy for aggregate. The Blue River Gneiss should be an excellent source of aggregate. Chemical analyses of some of the rock types are given in Table 3.

The granites all weather to a gravelly soil or grus. This material, particularly from the Tishomingo Granite, is an inexpensive and accessible source of road metal used along county section line roads. Numerous shallow pits have been opened to fill this need. These pits feature conspicuous residual boulders of the original granite that have been left behind. Some of these are exceptionally fresh.

SOUTHERN OKLAHOMA AULACOGEN

Framework

A large rifting event cut diagonally into the North American plate (Laurentia) from its Proterozoic southern boundary, starting approximately at the position of Dallas, northwestward through southwestern Oklahoma to Amarillo, Texas. The tectonic setting for this rift has been described as an aulacogen (see Gilbert and Denison, 1993), or alternatively as part of the transform-fault system (Thomas, 1991). Most current workers prefer to treat the WM outcrops as part of an

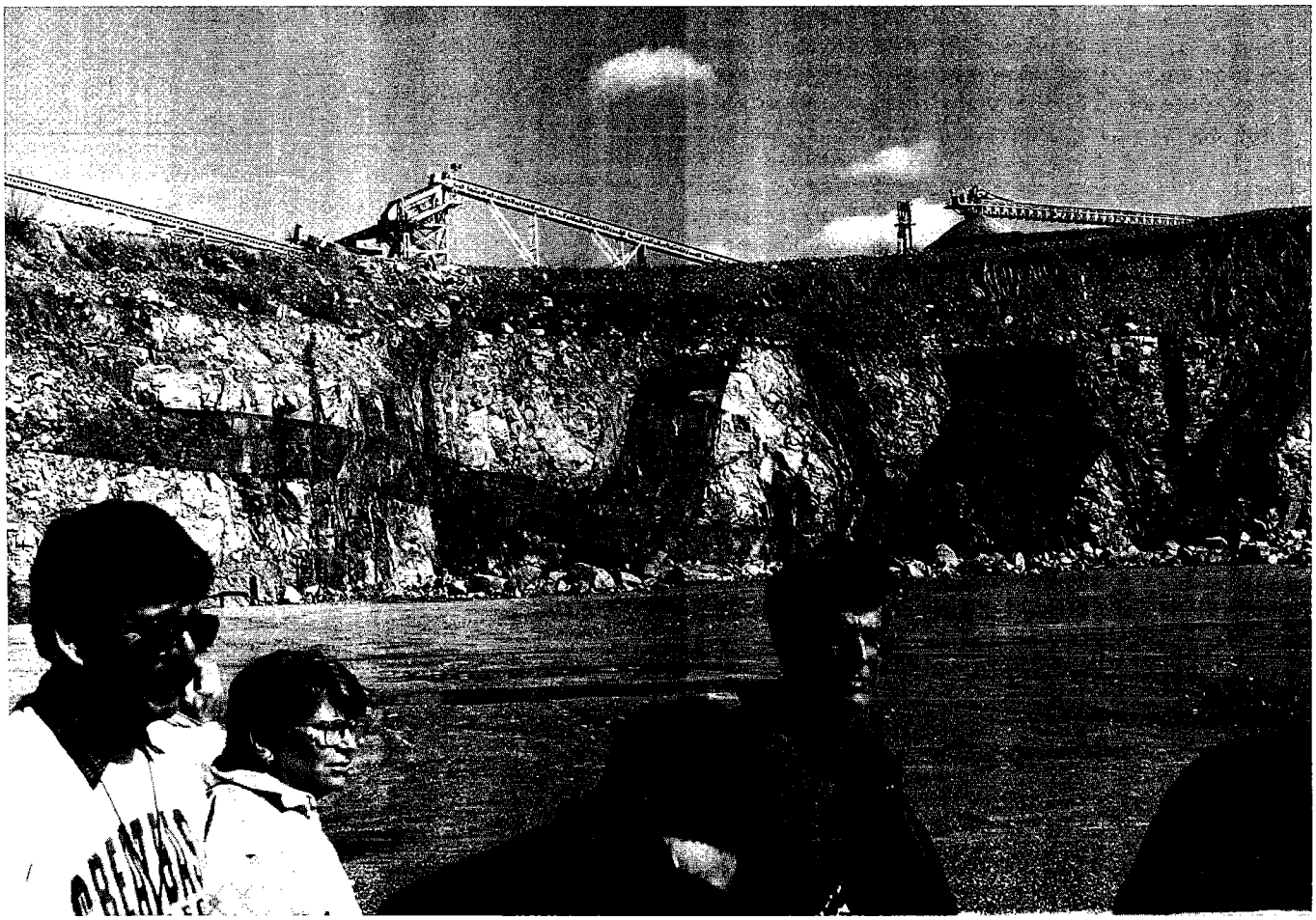


Figure 2. Meridian Quarry, Johnston County, taken in March 1998. This quarry is set in the Troy Granite and produces aggregate. Large diabasic (basaltic) dikes cross-cut the granite.

aulacogen (Gilbert and Denison, 1993; Hogan and Gilbert, 1998).

The rift has been modeled as being about 50 km wide and about 400 km long. McConnell and Gilbert (1990) estimated the extension at about 10–20 km. Because the rifted zone appears to be mostly filled with bimodal igneous materials, it is concluded that it occurred at high temperatures. Based on ages from igneous rocks in the aulacogen, the age of rifting is Early Cambrian. The largest intrusive mass is the Glen Mountains Layered Complex. It outcrops in the Wichita Mountains, and that unit, or similar ones, can be further delineated through their strong gravity and magnetic signature. The geophysical signature provides the best evidence of the extent of the rift and its fill. Ham and others (1964) mapped part of the subsurface extent of gabbroic rocks from drill-hole records through much of southern Oklahoma. There, Pennsylvanian erosion uncovered the basement section which is now overlain by <1 km of Permian cover.

Ham and others (1964) argued that, subsequent to the emplacement of this large mafic unit, uplift occurred allowing Cambrian erosion to decapitate the top of the intrusion. On this unconformity, rhyolitic materials began to erupt and build up. Shortly after this event, felsic magmatism started, and some of the rising felsic liquid intruded as sheet granites between the substrate gabbroic rocks and the overlying rhyolites. Hogan and others (1998) provided a mechanical model that explains a cyclic "rhyolite to granite to rhyolite to granite" sequence utilizing the formation of a near-surface, crustal magma trap (Hogan and Gilbert, 1995) along with variations in the source depth of the magmas. The rocks of the southern Oklahoma aulacogen appear to have formed in a fairly tight time interval of 530–540 Ma (Hogan and Gilbert, 1998). All of the igneous units studied thus far were emplaced at very shallow crustal depths in an intracratonic environment. Records from any deep-seated parts of the rift are not available.

The sedimentary sequence that overlies these igneous rocks is the Upper Cambrian Timbered Hills Group, which is well dated paleontologically and is about 505 Ma. Thus, subsequent to the emplacement of the igneous units, an erosional interval of at least 20 Ma occurred. Considerable stripping of part of the

Table 2.—Locations of Prominent Basement Quarries in the Arbuckle Mountains

Map no.	Quarry names	Rock types	Location	Product
1	Meridian	Troy Granite	Johnston County, OK NE¼ sec. 30, T. 3 S., R. 5 E.	Aggregate (esp. railroad ballast)
2	Capitol Quarry (inactive)	Tishomingo Granite	Johnston County, OK NE¼ sec. 30, T. 3 S., R. 5 E.	Facing stone for Oklahoma State Capitol
3	Meridian	Troy Granite	Johnston County, OK NW¼ sec. 29, and SW¼ sec. 20, T. 3 S., R. 5 E.	Aggregate (esp. railroad ballast and asphalt highways)
4	Western Rock Products	Carlton Rhyolite Group	Murray County, OK NE¼ sec. 10, T. 1 S., R. 1 W.	Aggregate (esp. railroad ballast)

Table 3.—Representative Major Element Compositions of Basement Rocks of Southern Oklahoma

Oxide %	Burch Granodiorite[a]	Troy Granite[a]	Troy Granite[b]	Tishomingo Granite[b]	Reformatory Granite[c] (10)	Mount Scott Granite[c] (6)	Long Mountain Granite[d] (4)
SiO_2	61.05	72.01	73.59	71.60	75.38	73.56	75.00
TiO_2	0.74	0.24	0.26	0.39	0.25	0.45	0.19
Al_2O_3	16.55	14.61	14.08	14.05	12.57	12.59	11.90
Fe_2O_3	↓	↓	0.70	1.17	2.37	3.82	2.30
FeO	5.52	1.31	0.66	1.10	↑	↑	↑
MnO	0.09	0.06	0.04	0.05	0.05	0.08	0.03
MgO	2.80	0.43	0.55	0.20	0.36	0.34	0.20
CaO	4.97	1.32	1.28	1.65	0.50	1.17	0.39
Na_2O	4.30	4.54	4.00	3.47	4.01	3.73	3.70
K_2O	2.21	4.41	4.63	5.20	4.91	4.30	4.60
P_2O_5	0.20	0.07	0.06	0.15	0.03	0.08	0.01
$H_2O\pm$	—	—	0.19	0.25	—	—	0.57
LOI	0.68	0.53	—	—	—	—	—
Total	99.11	99.53	100.02	99.79	100.43	100.12	98.89

Note: ↑↓ Total Fe expressed as one oxide. ( ) Number of analyses averaged.
[a]From Lidiak and Denison (1998, table 1).
[b]From Ham and others (1964, table 18).
[c]From Hogan and Gilbert (1998, table 4).
[d]From Myers and others (1981, table 7).

Early Cambrian igneous sequence was possible and is probable (see Donovan and others, 1998).

Quarried Units in Wichita Mountains

Figure 3 is the geologic map of the pre-Permian Wichita Mountains area showing the location of currently quarried basement-rock units that are identified in accompanying Table 4. The quarries are mostly in units of the Wichita Granite Group. The granites of this group are known as A-type, being low in CaO, high in SiO_2, and are hypersolvus quartz-perthite rocks. The color index is 4–7%, the chief mafic minerals are amphiboles, biotite, and magnetite. Most of these units were emplaced at low pressures and high temperatures resulting in fine grain sizes of the constituent minerals and widespread granophyric texture.

One quarry is working in both gabbroic units of the Raggedy Mountain Gabbro Group: the Glen Creek member of the Roosevelt Gabbros, and the M-zone of the Glen Mountains Layered Complex. Both of these units are plagioclase-rich. The following discussion

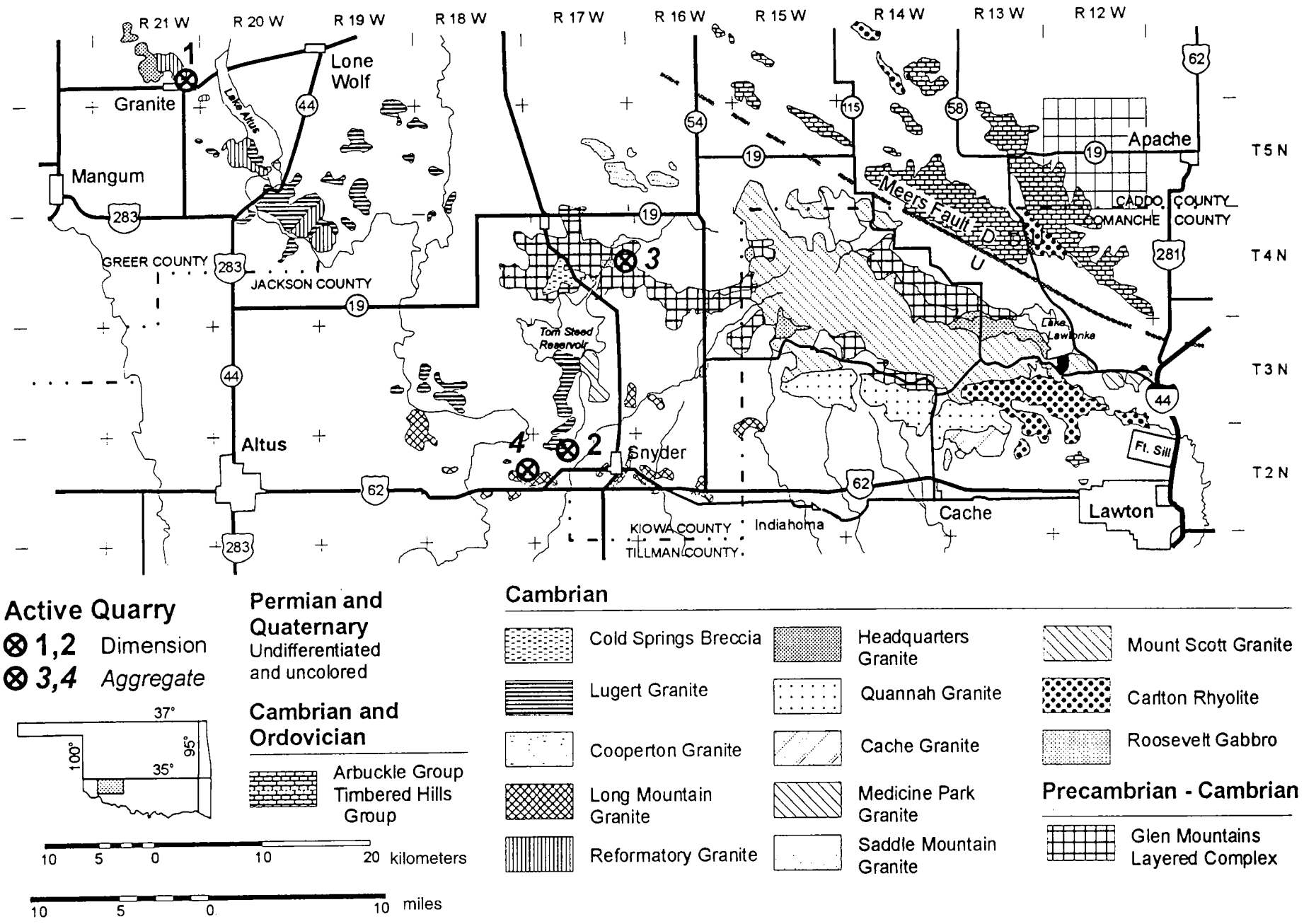


Figure 3. Geologic map of the Wichita Mountains Igneous Province basement (after Powell and others, 1980; Myers and others, 1981; Hogan and Gilbert, 1998). Locations of active quarries are shown.

Table 4.—Locations of Prominent Basement Quarries in the Wichita Mountains

Map no.	Quarry names	Rock types	Location	Product
1	Willis Granite Products	Reformatory Granite	Granite, Greer County, OK NE¼ sec. 26, T. 6 N., R. 21 W.	Facing stone and tombstone
2	Oklahoma Granite Company (formerly Roosevelt Granite Company)	Lugert Granite	Snyder, Kiowa County, OK SW¼ sec. 4, T. 2 N., R. 17 W.	Facing stone and tombstone
3	Kiowa County Blue Rock Pit	Glen Creek Gabbro, and Glen Mountains Layered Complex	Roosevelt, Kiowa County, OK NE¼ sec. 14, T. 4 N., R. 17 W.	Aggregate for county roads
4	Meridian Aggregate (Snyder Division)	Long Mountain Granite	Snyder, Kiowa County, OK NW¼ sec. 13, T. 2 N., R. 18 W.	Aggregate (esp. railroad ballast and asphalt highways)

will concentrate on those rock units being quarried with some later comments on those units with future potential. Bulk chemical analyses are given for some of the granitic rock units in Table 3.

Reformatory Granite

The Reformatory Granite is the most coarsely crystalline granite of the Wichita Granite Group, with the feldspars ranging up to 2 cm in size and showing some zoning (Merritt, 1958). The rock description is a hypersolvus, leucocratic, amphibole-biotite alkali-feldspar granite. It is about 67% feldspar and 33% quartz. The Reformatory Granite can have a seriate texture that is normally developed near contacts or around inclusions of other preexisting rock types. Certain areas of the Reformatory outcrop contain large and noticeable inclusions of rhyolite and the older, distinctly finer-grained Headquarters Granite. The Reformatory Granite is relatively uniform where quarried. Minor and accessory minerals include ferro-edenitic hornblende, annitic-biotite, magnetite, titanite (sphene), fluorite, zircon, apatite, sparse ilmenite, and possibly allanite or chevkinite. Riebeckite (a sodic amphibole), calcite, hematite, and chlorite all occur as common subsolidus-alteration products.

The Reformatory may be the most-used Oklahoma granite. It is extremely common as tombstones and widespread as historical and event markers. The Willis Co., which mines this granite at Granite, Oklahoma, locally pioneered the use of images, designs of varying types, and scenes etched onto polished slabs, which promote this kind of use.

Long Mountain Granite

The Long Mountain Granite crops out prominently just west of Snyder, Oklahoma. This granite is typically a granophyric microporphyry with hornblende being the dominant mafic phase. The Long Mountain, or variants of it, has been quarried for some time. The biggest current quarry operation is the Meridian Quarry on the north side of Long Mountain itself (Fig. 4). This quarry produces aggregate material for railroad ballast, highway construction, and other uses.

The old Roosevelt Granite Co. Quarry, which produced tombstones, has been sold and is to be operated as the Oklahoma Granite Co. It will continue to produce facing stone.

Glen Creek Gabbro/Glen Mountains Layered Complex

The quarried area in this complex now cuts across two rock types. The Glen Creek Gabbro was the center of the original quarry. This body is a small elongate intrusion of biotite-bearing anorthositic gabbro (outcrop area ~1.5 × 0.4 km). This gabbro has a hypautomorphic-granular texture, with large (up to 5 cm) anhedral, ophitic to subophitic augite grains enclosing lath-shaped labradorite crystals and rounded olivine grains. Magnetite, ilmenite, and phlogopitic biotite are present. Hastingsitic amphibole also occurs. The ultramafic segregations (olivine + magnetite) prompted the original excavations. However, the main reason for the quarrying is that much of the Glen Creek Gabbro at the level of exposure was sufficiently altered to be able to dig it out with mechanical shovels without blasting. This altered material makes excellent pads for set-up of large petroleum drill rigs and for road metal. Roadways layered with this altered gabbro hold up well for vehicular travel under wet conditions. Kiowa County acquired the property some time ago and now uses it to surface county roads.

Because all the easily available altered gabbro has now been removed, most of the quarrying is directed northward to the enclosing M zone of the Glen Mountains Layered Complex. This rock is anorthosite, being predominately plagioclase with less pyroxene than Glen Greek Gabbro and no primary hydrous phases. It



Figure 4. Aerial photo of the Meridian Aggregate Quarry, Kiowa County. Quarry is situated on the north side of Long Mountain in the Long Mountain Granite. The photo was taken looking south-southwest on December 16, 1998.

is distinctly layered at several scales. Importantly for the quarrying operation, it does not alter the same way Glen Creek does, and thus is harder to extract. It may not be as effective as road metal.

Dikes of four types cross-cut the quarried area—microgabbro (related to the Glen Creek body), Cold Springs Breccia (consisting of a mafic component called the Otter Creek Microdiorite intermingled with a microgranitic to microgranodioritic component), Late Diabase, and microgranite. These dikes have not proved bothersome to excavation activities or to the uses to which the altered rock material has been put. Other areas showing less diking could be chosen if rock for facing stone were to be quarried.

WICHITA MOUNTAINS UNITS WITH QUARRYING POTENTIAL

Roosevelt Gabbros (especially Mt. Sheridan Gabbro)

The Glen Creek Gabbro is quarried for aggregate, but other members of the Roosevelt Gabbros have properties that would make desirable facing stones or tombstones. The Mt. Sheridan Gabbro, which has the largest outcrop of any of the Roosevelt Gabbros, was quarried for facing stone in the 1960s on the Rowe Ranch (C sec. 32, T. 4 N., R. 13 W.). Although this gabbro has subtle mineralogical layering and some pegmatite development, it has nearly uniform character over lateral distances of 100+ m. The rock is very dark on fresh surfaces, relatively fine grained for a gabbro, and contains 60–70% plagioclase + clinopyroxene (augite) + orthopyroxene (hypersthene) + magnetite + phlogopitic biotite ± olivine.

Cold Springs Breccia

The Cold Springs Breccia was quarried sporadically until the 1940s. The rock unit consists of two mixed components—a felsic end member and a mafic end member. Mixing has been complete enough in some areas that a locally uniform gray quartz diorite/diorite has formed. However, mineralogical and textural continuity are too local for a large quarry operation unless these variational properties are desired.

Mount Scott Granite

The Mount Scott Granite is the most widespread granite in southwestern Oklahoma. The largest part of its outcrop is in the Wichita Mountains Wildlife Refuge, a part of the Fish and Wildlife Service, U.S. Department of the Interior. As such, this area is not available for commercial exploitation. However, at least one quarried site, the old Ira Smith Quarry (SE¼ sec. 4, T. 3 N., R. 15 W.), has yielded blocks that were processed for tombstones. The resultant polished stone has an appearance that is distinctive and might well be desired commercially. Although this old quarry is too close to the Wildlife Refuge to sustain more development, other privately held outcrops nearby might be useful. In addition, outcrop areas of Mount Scott Granite northwest of Mountain Park and east of Cooperton could be evaluated for possible quarry sites.

The Mount Scott has a micro-Rapakivi texture, rounded phenocrysts of alkali feldspars rimmed by sodic plagioclase. The cores of these phenocrysts are dark colored. Although the color index of the rock is not high (~6), the combined effect of the mafic minerals and the dark feldspar cores gives an interesting darker red rock than is found in most of the rest of the Wichita granites.

Cooperton Granite

The Cooperton Granite is a fine-grained rock with a very uniform composition and character over its outcrop area (see Fig. 3). It is a granophyric microporphyry with biotite as the dominant mafic phase. The outcrops of this granite occur as isolated hills to which access would be easy.

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Quantitative Models for Aggregate: Some Types and Examples from Oklahoma Carbonate Rocks

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ABSTRACT.—Evaluation of data for three engineering variables—absorption, bulk specific gravity, and freeze-thaw durability (350 cycles)—was made for quarries in carbonate rocks in Oklahoma that supply aggregate. It was found that lower Paleozoic carbonate rocks (Cambrian through Devonian) are likely to make a better quality aggregate than upper Paleozoic (Mississippian to Permian) carbonate rocks. In addition, freeze-thaw durability can be forecast from absorption and is exemplary for lower Paleozoic carbonate rocks.

PURPOSE OF STUDY

Quantitative models of the kind considered in this report are expected to be particularly useful in evaluating (or quantitatively assessing) the possible types and amounts of aggregate that may be present in a region. Although there is a long history of quantitative assessments of various resources, an assessment of this type for aggregate has been envisioned but not yet executed (Bliss, 1998).

Models can be powerful tools, because they help make forecasts about postulated situations concerning future aggregate resources. Models also systematically organize data about aggregates by their geology and other attributes in ways that help us recognize both interrelationships and groupings of geotechnical characteristics. Relationship can be empirical.

This study is focused on developing models of geotechnical characteristics of carbonate rocks of Oklahoma, particularly those quarried and processed for aggregate.

WHAT ARE MODELS?

Four general types of models are used in regional aggregate assessment:

1. *Descriptive models* use text to provide a description about a geologic entity in sufficient detail so that it can be used for recognition. A simple example would be a description necessary to allow a geomorphologist to recognize an alluvial fan, even though the reader had never seen one before. Examples of the geologic entity can be expected to contain one or more distinctive characteristics that are shared by other members of the geologic feature.
2. *Distribution models* use statistical distributions of geologic, economic, geometric, and geotechnical variables for a grouping of geologic features,
3. *Relationship models* use statistical links, like regression analysis, that tie geologic variables to other variables expressing ease of extraction, suitability for end uses, and economics of extraction and use.
4. *Spatial models* use statistical distributions of geologic, economic, geometric, and geotechnical variables in two or three dimensions.

The quantitative models (nos. 2–4, above) will be more useful for data systematically grouped using descriptive models. However, this not necessarily a precondition for using these models.

Both distribution models (no. 2) and relationship models (no. 3) will be used in the analysis of the geotechnical characteristics of carbonate rocks of Oklahoma. The study was primarily one of data exploration (an expanded discussion is given below) where descriptive details about the rocks were not formally codified. Groupings of carbonate rocks can be relatively simple, as used here. They can also be very complex; however, that generally requires more data than are available for this study. Spatial-modeling requirements were not met by the type of data that are readily available.

DATA EXPLORATION

Introduction

Data exploration is a fundamental activity for anyone trying to make sense of a mass of data either self determined or collected by others. Remarkably, data are commonly not fully examined. Some data are viewed as meeting just a single need, and other information that they contain about the phenomenon under investigation is not addressed. This focused approach is

Bliss, J. D., 1999, Quantitative models for aggregate: some types and examples from Oklahoma carbonate rocks, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 37–45.

not without merit, because data analysis can consume resources without necessarily providing reward. One goal of the data-exploration exercise undertaken here was to develop distribution models and relationship models.

There are numerous ways that data may be explored. Basic statistics can be quite effective. Perhaps one of the important parts of data exploration is the search for natural groupings that can subsequently be summarized using statistical methods. Grouping of geologic data may be done using one or more geologic variables, including lithology, stratigraphy, age, and other recognizable features. Age is commonly a proxy for differing geologic processes that were operating at different times or at different rates. If the model is expected to link to economic-type variables, a number of other factors need to be included.

Exploration Tools and Statistical Analysis

Four basic diagrams are used to examine and display data in this study. They are the histogram, boxplot, and the normal curve shown in both standard and cumulative formats.

Histograms, or frequency-distribution diagrams, are familiar to most people as an easy way to display data (Fig. 1A). Deceptively simple, histograms have shapes that are very sensitive to both the number of intervals and interval width. In the example, the number of values within each interval are counted. Another possible display option is showing a percentage of observations in each interval. Some statistical programs make cumulative histograms as well.

The boxplot is an extremely useful diagram for detecting asymmetry and the presence of extreme values (Rock, 1988), as well as comparing the distribution among different data sets. The boxplot in Figure 1B is constructed for the same data set used to make the histogram in Figure 1A. The box is divided by an internal line, which is the median value (2.64; Fig. 1A), the value halfway through the data set. The left and right boundaries of the box contain 25% of the values above and below the median. Whiskers extend out from the box on both sides to vertical lines (called fences). The fences bound 40% of the values above and below the median (Fig. 1B)—that is, 80% of the observations are between the fences. Data beyond the fences are shown as points and account for the lowest 10% of the values and the highest 10% of the values in the data set.

Two or more boxplots may be displayed together, which commonly is done in this study. When boxplots are not particularly well aligned, one might suspect that the data sets are different from one another. What are the chances that the differences between two boxplots is not due to chance? Because the data sets in the study are small, nonparametric methods for analysis are used. Standard parametric methods can be sensitive to small departures from normality or other underlying assumptions about the data. Small data sets are particularly vulnerable to these types of departures. Nonparametric tests do not operate on the values

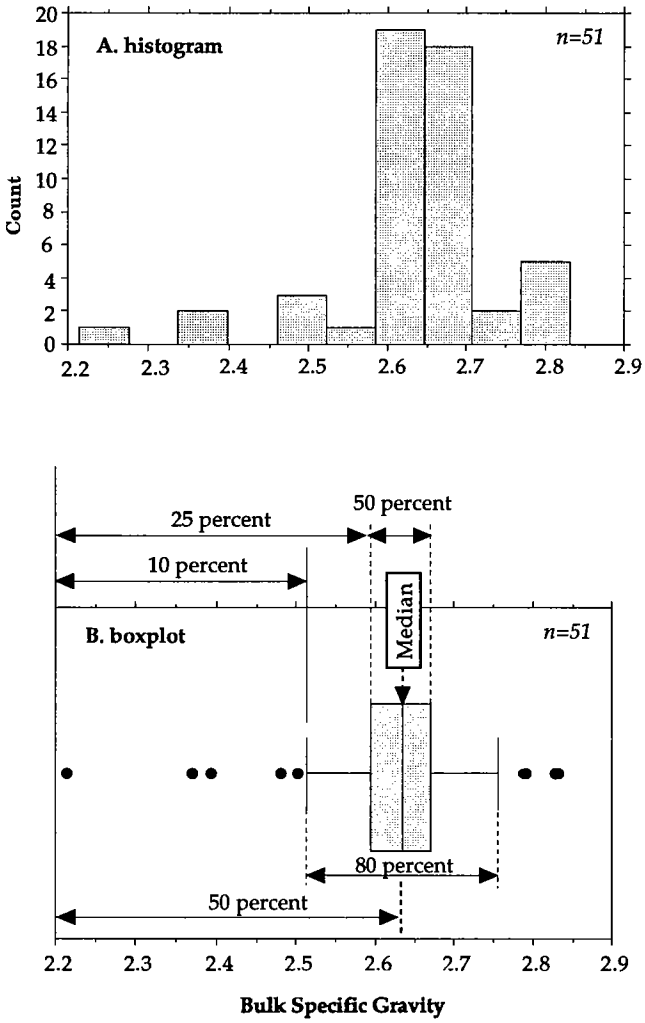


Figure 1. Examples of a histogram (A) and a boxplot (B) using the same data. Data from ODOT (1997).

directly. Each value assumes the rank of its position in the data set. The effect of extremely small or large values is greatly reduced. Tests are then run on the ranks. The nonparametric test used in this study to compare two data sets is the Mann-Whitney U test. This test operates under the assumptions that the two data sets come from continuous distributions and that they are independent of each other (Gibbons, 1976).

One of the best-known and often-observed frequency distributions in larger data sets is the normal distribution. It is one of the most commonly reported population distributions in geology (Krumbein and Graybill, 1965). Data with a normal distribution have a predictable bell-shaped frequency distribution when plotted in a histogram (Fig. 2A). Histograms of large data sets with small intervals and having a normal distribution will have outlines similar to the normal distribution curve (Fig. 2A). However, it can be difficult to determine if the normal distribution can be used to describe a small data set. A particularly useful statistical procedure for checking this is the Lilliefors test, a special

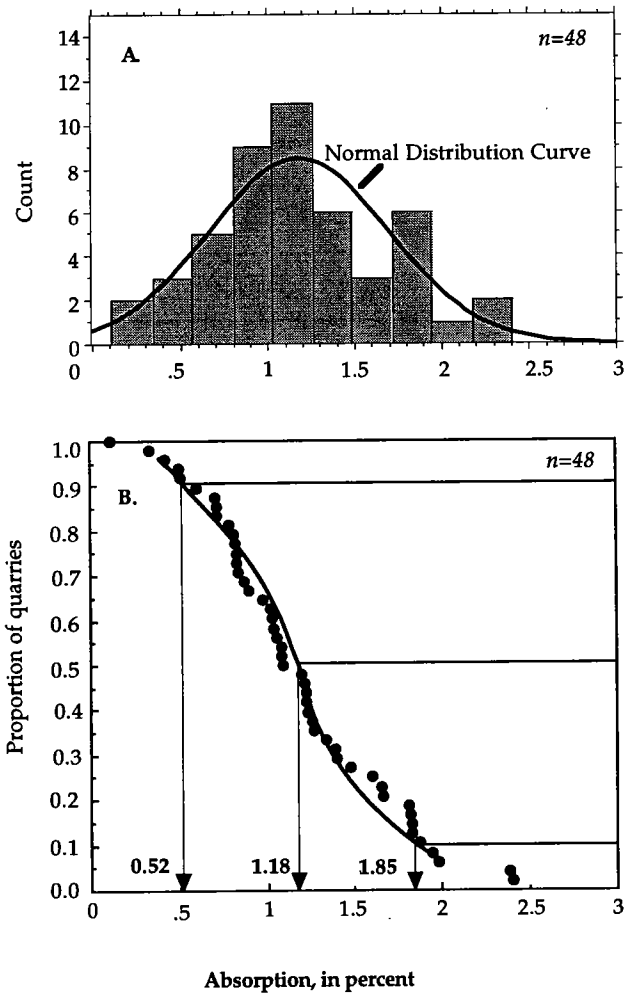


Figure 2. Example of histogram with a normal distribution curve (A) and model (B) use the same absorption data. Data from ODOT (1997).

form of the Kolmogorov-Smirov test (Rock, 1988). Moderate-sized (on the order of 35 to 100 values) and larger data sets that fail to have normal distribution may suggest that the data contain more that one population, or can be better described using a different distribution.

A normal distribution also can be displayed in a cumulative format (Fig. 2B) where the data points are shown in descending order from smallest to largest. Here, the data are cumulated so that larger values are at the lowest percentage of observed quarries. For example, 90% of the quarries in the data set have absorption of 0.52 or greater, 50% of the quarries have absorption of 1.18 or greater, and 10% of the quarries have absorption of 1.85 or greater. The format in Figure 2B is one commonly used to display data distributions for computer simulation and referred to as a model. In this example, it is an absorption model. Although a normal distribution was used in the example, models can also be developed using data having other types of distributions or none at all.

DATA SOURCE AND QUALIFICATIONS

Three sources supplied the basic data used in this study—Woolf (1953), Rowland (1972a), and Oklahoma Department of Transportation (ODOT, 1997). Some of the data reported in Woolf (1953) were collected as early as 1909.

Results taken from the ODOT (1997) report were averages of all tests for each coarse-aggregate quarry located in carbonate rock. ODOT (1997) also notes on the cover of the compilation that:

> The test results of the samples taken by the Department, as set out in this report, represent only the aggregates that are present at the time of sampling. In as much as this sampling represents a limited amount of the production from the quarry, the test results should not be interpreted to imply that the Department warrants that the material produced from this site is acceptable to be used in work performed under the Department's construction contracts. The Department makes no claim that this information is complete or accurate. This information is subject to change without notice.

Clearly, there are no guarantees that either quarry or sample locations are representative of the carbonate rocks in which they are located or sampled.

Determination of the geology of quarries in carbonate rocks involved using regional overviews of carbonate rocks (Rowland, 1972b), the 1:750,000 scale mineral map by Johnson (1969), and the directory of Oklahoma mining industry by Arndt and Springer (1993). Maps from the 1:250,000-scale hydrologic atlas of Oklahoma were particularly useful: they were prepared by Marcher (1969), Marcher and Bingham (1971, 1983), Hart (1974), Bingham and Moore (1975), Carr and Bergman (1976), Havens (1977), Morton (1980), and Bingham and Bergman (1991).

OKLAHOMA CARBONATE ROCKS

Carbonate rocks, particularly limestone, are widespread in Oklahoma. Limestones and dolomites with greatest thicknesses (100–1,000 ft) are found in the Arbuckle Mountains in south-central Oklahoma and the Wichita Mountains in southwest Oklahoma. Other limestone units in the state are notably thinner, typically 10–50 ft (Johnson, 1993).

Insufficient data on individual carbonate formations prevent them from being modeled separately. Therefore, grouping of carbonate units had to be made. Data for a few quarries in rocks not of Paleozoic age are too few and were excluded from the analysis. Two groups were eventually developed for Paleozoic carbonate rocks, based on preliminary data-scatter plots (not shown) of the geotechnical characteristics under review (and discussed below) and from the evaluation of the major trends of depositional history of the Paleozoic section, as summarized in Johnson and others (1988). The two groups are defined as follows: (1) Lower Paleozoic carbonate rocks are formations of Cambrian to Devonian age, and (2) Upper Paleozoic carbonate rocks

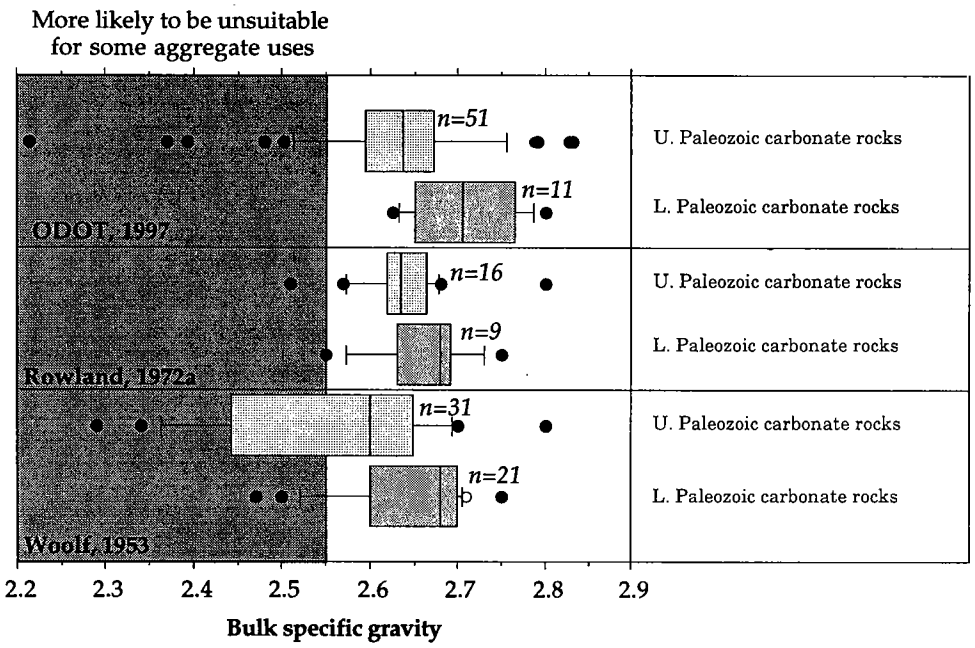


Figure 3. Bulk specific gravity boxplots of three reports. Upper Paleozoic carbonate rocks are Mississippian to Permian age. Lower Paleozoic carbonate rocks are Cambrian through Devonian age.

are formations of Mississippian to Permian age. These groupings are used in the discussion that follows.

MODELING DISTRIBUTIONS

Introduction

Analysis began with boxplots to help identify groupings of geotechnical data from carbonate-rock quarries that could be treated as a single population and then modeled using ODOT (1997) data. Two earlier compilations of data (Rowland, 1972a; Woolf, 1953) also were examined to verify the differences seen in the ODOT data. In general, the pattern found in the ODOT data is also found in the earlier work. As the data were collected and determined using different techniques and sampling protocol, they cannot be directly combined for analysis. Following evaluation with boxplots, distributions were determined and models were developed, where possible.

Bulk Specific Gravity

Bulk specific gravity of coarse aggregate is the ratio of the weight of dry aggregate in air to the weight of water of equal volume. Verhoef and Van de Wall (1998) suggest that density is one of the two best indicators of aggregate quality. As a general rule, material suitable for aggregate should have a specific gravity >2.55.

Three studies of carbonate rocks in Oklahoma (Woolf, 1953; Rowland, 1972a; ODOT, 1997) all show that bulk specific-gravity measurements of lower Paleozoic carbonate rocks are greater, on average, than those of upper Paleozoic carbonate rocks (Fig. 3). The upper Paleozoic carbonate rocks have a greater probability of being less suitable because of their lower specific gravity.

A model was developed for the distribution of specific gravity of lower Paleozoic carbonate rocks (ODOT, 1997); these data have a normal distribution and are shown in Figure 4A as a cumulative proportion of quarries. Also shown is a histogram of the data used, overlain by a calculated normal-distribution curve (Fig. 4B). The model, based on the sample quarries, suggests that 90% of lower Paleozoic carbonate-aggregate quarries have a specific gravity of 2.63 or greater, and 50% have a specific gravity of 2.71 or greater. Only 10% of the quarries have a specific gravity of 2.78 or greater. A better model would be possible if more data were available, and the model, therefore, must be considered preliminary.

Analysis of bulk specific-gravity data for upper Paleozoic carbonate rocks suggests that multiple distributions may be present, and no model can be developed without additional data refinement.

Absorption

Verhoef and Van de Wall (1998) suggest that one of the two best indicators of aggregate quality is absorption, and that absorption values less than 3% are desirable based upon ASTM Test Method C 127 (Goldman, 1994). Note that the data used in this study are absorption measurements derived by using AASHTO Test No. T-85 for those measurements that were made by ODOT (1997) and by unidentified procedures in the reports by Woolf (1953) and Rowland (1972a). The three studies of carbonate rocks in Oklahoma show that absorption of lower Paleozoic (Cambrian to Devonian) carbonate rocks is, on average, less than that of upper Paleozoic (Mississippian to Permian) carbonate rocks (Fig. 5).

Initial analysis of absorption (ODOT, 1997) of lower

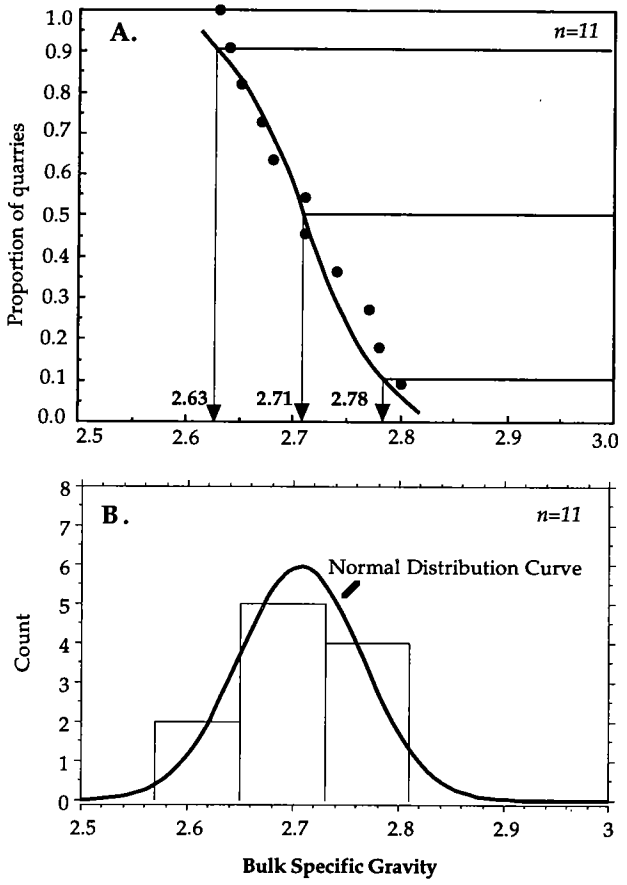


Figure 4. Bulk specific gravity shown as a preliminary distribution-type model (A) and as a histogram (B) with a normal distribution curve of lower Paleozoic carbonate rocks, Oklahoma. Data from ODOT (1997).

and upper Paleozoic carbonate rocks suggests that two separate models can be developed (Figs. 6,7). Lower Paleozoic carbonates have a distribution that is limited by zero absorption, and a distribution was achieved by fitting an exponential curve with an r-squared of 94%. This means that the regression line explains 94% of the observed variation in proportion of quarries from the absorption data (Fig. 6A). A histogram of the data is shown in Figure 6B. The model is read in the same fashion as described for specific gravity. A better model would be possible if more data were available, and therefore the model must be considered preliminary.

Upper Paleozoic carbonate rocks have absorption values with a distribution that can be successfully described using a normal-distribution model (Fig. 7A). A histogram of the data is shown in Figure 7B. The model is read in the same fashion as for specific gravity. This is the most robust model of those in this study.

MODELING RELATIONSHIPS

Freeze-Thaw Durability

The freeze-thaw durability (FWD) test is a measure of an aggregates resistance to deterioration during cyclic freezing and thawing. ODOT (1997) uses AASHTO Test No. T-161, with a test run for 350 cycles of freezing and thawing. The study of FWD shows that lower Paleozoic carbonate rocks have a higher durability than those of upper Paleozoic carbonate rocks (Fig. 8). Note that lower Paleozoic carbonates are likely to be of better quality.

FWD testing is a lengthy process. Can other tests be used that might forecast FWD? For lower Paleozoic carbonate rocks, FWD is found to be highly dependent on absorption. FWD can be forecast for lower Paleozoic

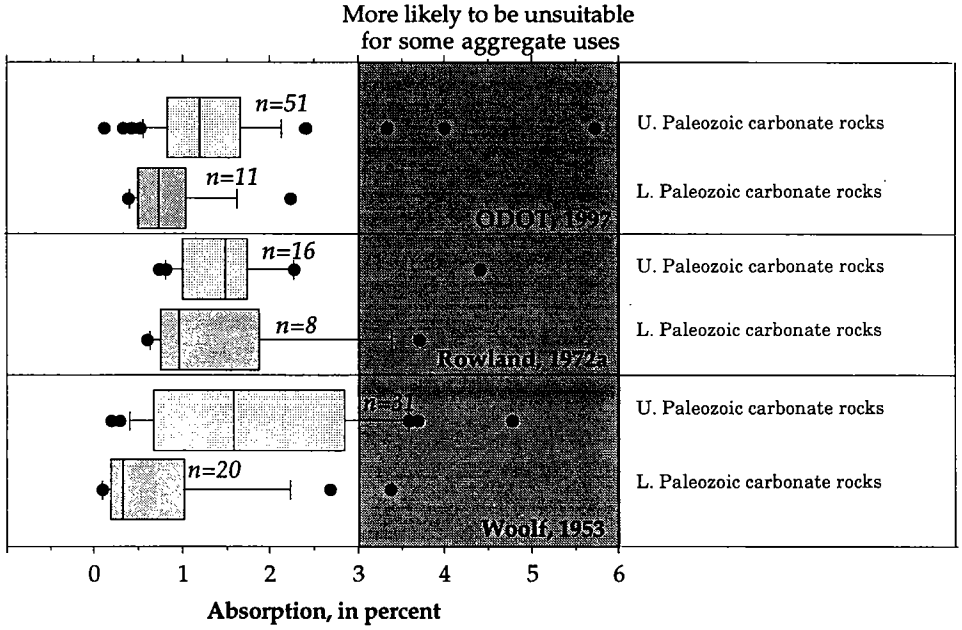


Figure 5. Absorption shown as boxplots of data from three reports on carbonate rocks in Oklahoma. Upper Paleozoic carbonate rocks are Mississippian to Permian age. Lower Paleozoic carbonate rocks are Cambrian through Devonian age.

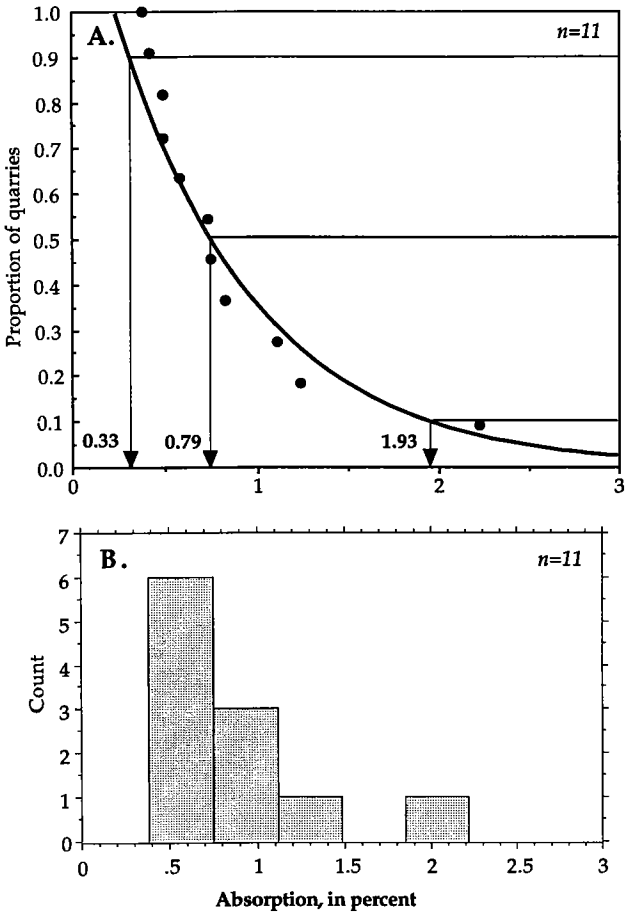


Figure 6. Absorption shown as a preliminary distribution-type model (A) and as a histogram (B) of lower Paleozoic carbonate rocks, Oklahoma. Data from ODOT (1997).

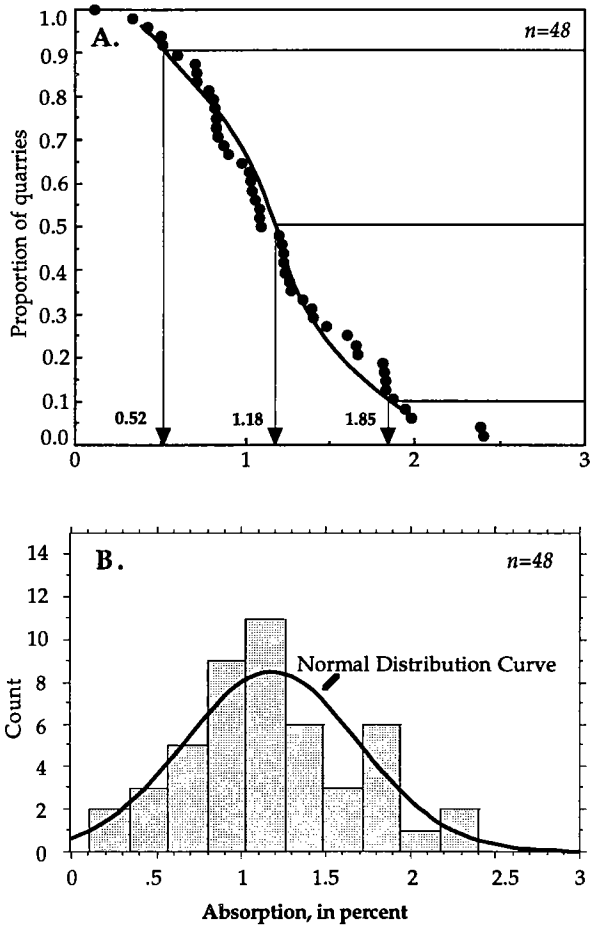


Figure 7. Absorption shown as a distribution-type model (A) and as a histogram (B) with a normal distribution curve of upper Paleozoic carbonate rocks, Oklahoma. Data from ODOT (1997).

carbonate-rock quarries from absorption by using this regression equation (Fig. 9):

$$FWD = 106 - (50 \times Absorption) \quad (1)$$

The regression on absorption (Fig. 9, line A) explains 95% of the observed variation (at the 1% level of significance) in FWD, based on data from nine quarries. The small size of the data suggests that care needs to be used when applying the model.

For upper Paleozoic carbonate rocks, FWD is also dependent on absorption. In this situation, FWD can be forecast for upper Paleozoic carbonates from absorption by using the following equation (Fig. 10):

$$FWD = 93 - (31 \times Absorption) \quad (2)$$

The regression on absorption (Fig. 10, line B) explains 80% of the observed variation (at the 1% level of significance) in FWD, based on data from 22 quarries. More variability is seen for upper Paleozoic carbonate rocks (Fig. 10) when compared with lower Paleozoic ones (Fig. 9).

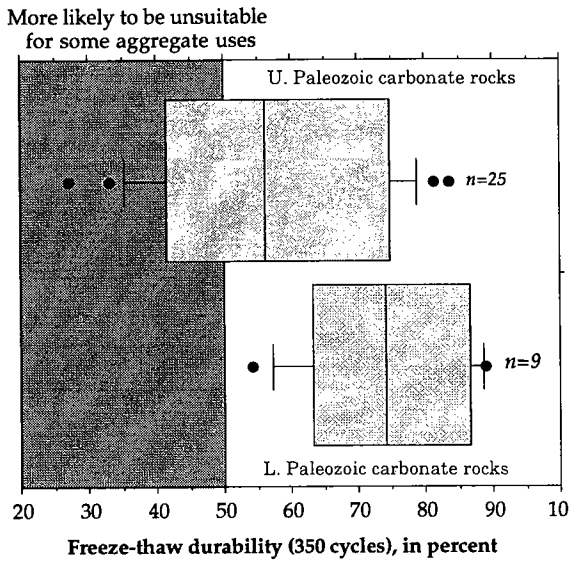


Figure 8. Freeze-thaw durability (350 cycles)—boxplots of lower Paleozoic carbonate rocks and upper Paleozoic carbonate rocks. Data from ODOT (1997).

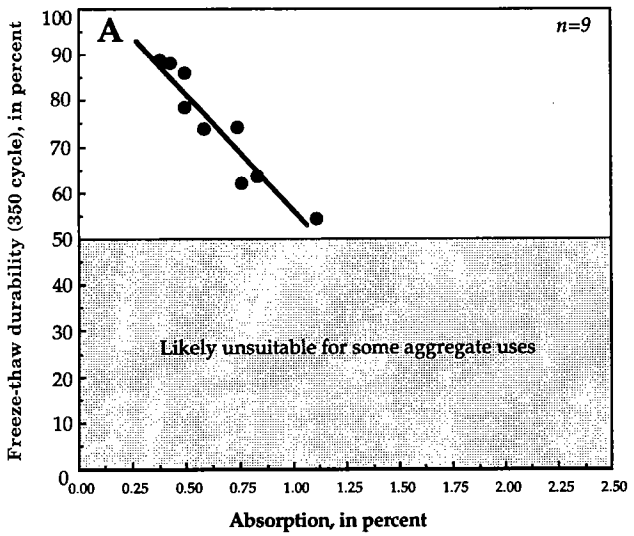


Figure 9. Regression of freeze-thaw durability (350 cycles) on absorption of lower Paleozoic carbonate rocks. See text for regression equation A. Data from ODOT (1997).

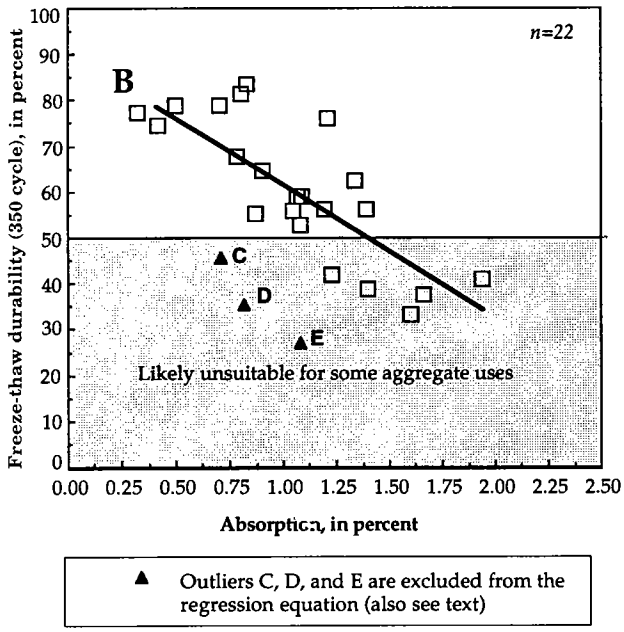


Figure 10. Regression of freeze-thaw durability (350 cycles) on absorption of upper Paleozoic carbonate rocks. See text for regression equation B. Data from ODOT (1997).

Outliers Classification

Three outlying data points are present and excluded from the regression equation (eq. 2), and are noted as C, D, and E on Figure 10; they are discussed below. As noted in Rock (1988), outliers can be classified into four types. The first type is the true (geological) outlier. The observation is, in fact, real, but is discordant with the rest of the data. True outliers are reproducible observations. They can be valuable indicators of possibly unrecognized relationships outside the norm of the situation under investigation.

The second type of outlier is called a bizarre outlier (Rock, 1988). Bizarre outliers may be due to contamination. However, bizarre outliers are reproducible. Misclassification of a rock as a "carbonate" rock, when in fact it is not, may result in a bizarre outlier; it may also be due to inclusion of an extreme or unrepresentative value or values in an average value taken for samples collected at a mine or quarry. This is particularly problematic when only a few samples are collected.

The third type is the false outlier (Rock, 1988). These are mistakes of one type or another that are not reproducible. For example, a FWD test that was executed incorrectly may give a value that may be a false outlier. The same result is not likely to be obtained on repetition, because the second test probably would be run correctly on a split of the same field sample. Bad sampling and incorrect sample preparation can also cause false outliers.

The fourth type is the statistical outlier. It is one identified by "purely statistical means" (Rock, 1988, p. 114) and will also be true, bizarre, or false. Both true and bizarre outliers may give insight during geologic-data exploration. It is only the false outlier that is not of use. Geologic data are complex, and, commonly, a geologic reason is apparent for excluding a given outlier with individual inspection. However, there is no guarantee that a geologist will be successful in classifying an outlier as true, bizarre, or false. Perhaps a fifth type of outlier is needed in this classification scheme—the enigmatic outlier.

Outliers Evaluation

The outliers (C, D, and E) in Figure 10 may result for a situation shared by all data in this study. There are few FWD observations per quarry; this situation may result in bizarre outliers. Some quarries are also represented by few absorption values. As noted above, the FWD test is lengthy. The number of absorption observations are far more numerous. Is the FWD average value (ODOT, 1997) for each pit representative? Additionally, the average value of absorption for each pit may have come from different (and certainly more) samples. Therefore, the FWD results from samples may not be representative of those in samples used for absorption measurement.

Outlier C is a data point from a quarry thought to be from the Pennsylvanian Atoka Formation. Classification of the formation is queried. The bedrock is identified as a cherty limestone (ODOT, 1997). Only two FWD tests have been run. Six tests have been conducted for absorption. The average FWD is 45.8%. The result of the last test run on April 21, 1992, was 27.9%, which is extremely low given an absorption of 0.47% (Fig. 10). Given that only two FWD results are available, the other FWD result would have a value of 63.3%; this is more consistent with other observations for absorption of 0.71% (Fig. 10), the average for six samples. The average absorption for outlier C should not be used in the regression, because the differences in

the two absorptions are too great to be likely representatives of the quarry as a whole.

Outlier D is a data point from a quarry in the Pennsylvanian Hoxbar Formation. The bedrock is identified as a limestone (ODOT, 1997). Twelve FWD tests have been run and 56 tests were made for absorption. This quarry is data rich, contrasted to most quarries examined in this study. The average FWD is 35.4%; the average absorption is 0.82%. The number of observations strongly suggests that the averages are typical for the quarry, so the outlier is likely not false. It has been noted that the limestone at this quarry contain faults that have been recemented, and the bedding is not horizontal; this means that quarried rocks come from several different parts of the geologic section and this results in high variability from one part of the quarry to next. Outlier D is bizarre and can be excluded from the regression. Post-depositional processes apparently have modified the limestone in ways that have affected the overall FWD and absorption relationship for the quarry as a whole.

Outlier E is a data point from a quarry in the Pennsylvanian Fort Scott Formation. The bedrock is identified as a limestone (ODOT, 1997). Only one FWD test has been run (on 11/26/90), as compared to six for absorption. The FWD value is 27.1%. The average absorption is 1.1%. However, absorption for the last result for a sample measured on December 5, 1994, was 1.34%. A point plotted using this absorption value and the single FWD value would fall with the rest of the data (Fig. 10), although it is unlikely the test was run on the same sample. This outlier is bizarre and was computed from too few observations; it needs to be excluded from the regression-equation computation, because it is not representative of the quarry geology as a whole.

CLOSING REMARKS

This study confirms the long-held observation that rock porosity (here expressed as absorption) is useful in forecasting rock durability. The paper by Ordóñez and others (1997) proves one example. For Oklahoma carbonate rocks, this study found that absorption can be used to predict FWD. It also suggests that the relationship is better for carbonate rocks from the lower Paleozoic carbonates (albeit based on a small data set) than for upper Paleozoic carbonates. What rock characteristics, in addition to absorption (as a measure of porosity), are more prevalent in the younger carbonate rocks? Can heterogeneities of absorption and FWD within quarries (perhaps more prevalent in upper Paleozoic carbonate rocks) be a contributing factor? What role does the limited number of observations play? Absorption is possible in carbonate rocks with voids, particularly where they are interconnected by microfractures or secondary minerals (Fookes and others, 1988). Texture and compactness are other petrographic properties of carbonate rocks that can be expected to influence freeze-thaw test results (Fookes and others, 1988). West (1998) suggests that a rock's texture and mercury-intrusion-porosimetry values (used to measure pore-size distribution) appear to be a highly effective way of gauging aggregate durability, including freeze-thaw loss.

FUTURE RESEARCH

Freeze-thaw durability is dependent on other rock characteristics beyond those measured using absorption. Some of the more important characteristics are suggested in the closing remarks. Why samples of lower and upper Paleozoic carbonate rocks differ in terms of their FWD-absorption-relationship models needs to be examined.

ACKNOWLEDGMENTS

Thanks to the Oklahoma Department of Transportation (ODOT) Materials Division for geotechnical data and to John Quigley, in particular, for providing insight on methods of data collection and analysis. Thanks to Ken Johnson, Oklahoma Geological Survey, for helping to identify the literature useful in classifying the quarries, as well as suggesting in which geologic formations quarries are more likely to be located. However, conclusions (and mistakes) in analyzing and interpreting these data are my own and should not be attributed to either the ODOT Materials Division or the Oklahoma Geological Survey.

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Evaluation of the Croweburg Coal Underclay for Possible Commercial Utilization

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ABSTRACT.—Underclays are associated with coals found in eastern Oklahoma. These coals are of bituminous rank and are in beds of Middle and Late Pennsylvanian age. They occur in an area of about 8,000 mi^2, within the southern part of the Western Interior Coal Region. The rocks of the area consist of a thick series of sandstones, shales, underclays, coals, and limestones.

There are more than 40 beds of bituminous coal in the state, but only 12 of these have been mined over large areas. The 12 are, from oldest to youngest: the lower Hartshorne, upper Hartshorne, McAlester (Stigler), upper McAlester, Cavanal, Rowe, Secor, Weir-Pittsburg, Mineral, Croweburg, Iron Post, and Dawson coals. None of the underclay associated with these coal beds is known to have been exploited commercially.

Nine samples of underclay from beneath the Croweburg coal were collected over a wide area in the eastern Oklahoma coal field for evaluation. The underclays are usually shades of gray with brown or orange iron-oxide staining. Although soft and plastic in some places, they are generally hard and slickensided, and contain abundant carbonized plant fragments.

Bulk chemical analyses, clay mineral identification, and ceramic tests were performed on each underclay sample. The dominant clay minerals are illite and kaolinite with some mixed-layer clays. Silica (SiO_2) ranges from 45.96% to 59.03% and alumina (Al_2O_3) varies from 14.98% to 23.60%. The U.S. Bureau of Mines Tuscaloosa Research Center conducted the ceramic evaluations. Samples were slow fired from 1,000°C to 1,250°C in 50°C intervals. Bulk density, color, percent linear shrinkage, and percent absorption were determined for each slow fire test. All Croweburg underclay samples are best suited for building brick.

INTRODUCTION

A program to evaluate the chemical and firing properties of Oklahoma underclays began in the early 1980s. This program was conducted simultaneously with the Oklahoma Geological Survey's (OGS) coal program. The northeastern Oklahoma coal program, under the direction of LeRoy Hemish, was an extensive study of the coal resources in that part of the coal field.

Sixty-six samples of underclay from 18 different named coal beds were collected over a wide area in the eastern Oklahoma coal field for evaluation (Luza and Hemish, in preparation, "Evaluation of Selected Oklahoma Underclays for Possible Commercial Utilization"). The Croweburg coal underclay was selected for this paper to represent the information compiled during the study mentioned above.

Underclay is an argillaceous rock that is commonly found beneath beds of coal. It is generally nonbedded, light colored, and contains plant roots (such as *Stigmaria*) and randomly oriented slickensides (Rimmer and Eberl, 1982). A sharp contact commonly exists between the underclay and the overlying coal, and the lower contact typically is gradational (Gresley, 1887). Underclay is generally a few inches to 3 ft thick, but may be 18 ft thick or more (Grim and Allen, 1938).

Underclay beds commonly are classified by the following clay types: (1) flint, (2) semiflint, (3) plastic, and/or (4) some combination (Hosterman, 1972). Underclay color, which varies from light gray to dark gray, is generally caused by varying amounts of organic matter in the clay (Hosterman, 1972). Flint clay is a hard, nonplastic refractory clay with high alumina (Al_2O_3) content. High-grade flint clays have firing temperatures that range from 1,760°C to 1,810°C (Hosterman, 1972). Semiflint clay is gradational between flint and plastic clay with maximum firing temperatures from 1,680°C to 1,745°C (Hosterman, 1972). Plastic clay,

Luza, K. V.; and Hemish, L. A., 1999, Evaluation of the Croweburg coal underclay for possible commercial utilization, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 47–55.

which has the lowest alumina content, has a maximum firing temperature below 1,670°C (Hosterman, 1972).

A comprehensive discussion of underclay origin(s) is beyond the scope of this paper. Several origin theories have been proposed since Logan presented his fossil soil theory in 1842. McMillian (1956), Huddle and Patterson (1961), Hosterman (1972), and Rimmer and Eberl (1982) gave excellent literature summaries of the various origin theories since Logan (1842). Bolger and Weitz (1952) and Burst (1952) proposed that some underclays are formed from colloidal material derived from subaerial erosion and deposition in swamps. Seiders (1965) and others proposed that some underclays form from the alteration of volcanic ash beds. Other authors propose that in situ leaching of fine-grained sediments in acid swamps is an important process. The origin of underclay has stimulated a number of studies by geologists and clay mineralogists for more than 150 years, and their work suggests a complex origin.

PREVIOUS INVESTIGATIONS

Significant clay/shale reserves occur throughout central and eastern Oklahoma. In 1997, Oklahoma produced 772,000 metric tons of clay/shale with a value of $3.55 million (Johnson, 1998). The clay was produced from 10–12 mines mostly in central and eastern Oklahoma. Oklahoma clay/shale is primarily used in the manufacture of cement and brick.

Snider (1911) did the first comprehensive study of clays/shales in Oklahoma. Ceramic firing tests were performed on more than 80 samples. Six samples, clay numbers 10, 45, 47, 172, 286, and 287, were collected beneath coal seams in eastern Oklahoma (Snider, 1911). Sheerar (1932) presented ceramic test fire data for more than 200 shale samples collected throughout the State of Oklahoma. Knox (1948) and Chase and Burwell (1952) conducted clay studies of kaolin and montmorillonite clays in the Wichita Mountains in southwestern Oklahoma. Several of the more comprehensive and/or detailed studies of clays and shales in Oklahoma include Bellis (1972), Bellis and Rowland (1976), Laguros (1972), Funnell (1949), and several student theses.

GEOLOGIC SETTING

Figure 1 (index map) shows the eastern Oklahoma coal belt, and delineates its two general regions: (1) the northeastern Oklahoma shelf area, and (2) the Arkoma basin. Figure 2 is a generalized geologic column showing Pennsylvanian coal-bearing strata in northeastern Oklahoma.

The Croweburg coal underclay is one of the principal underclays of eastern Oklahoma. These coals are of bituminous rank and are in beds of Middle and Late Pennsylvanian age. They occur in an area of about 8,000 mi^2, within the southern part of the Interior Coal Province (Fig. 1) (Averitt, 1967; Friedman, 1974, 1978; Wood and Bour, 1988). The rocks of the area consist of a thick series of sandstones, shales, underclays, coals, and limestones.

The Croweburg coal occurs only in the extreme northwestern part of the Arkoma basin (Hemish, 1994, 1998a). However, it is present, and has been mined extensively by both surface and underground methods throughout the northeastern Oklahoma shelf area (Hemish, 1986, 1989, 1990, 1994, 1998a,b). The Croweburg coal and its underclay have not been investigated south of the Okfuskee county line. The Croweburg coal splits into several beds just north of the Hughes-Okfuskee county line, and in that area has little commercial potential owing to interstratified shale layers (Hemish, 1988a, 1994). However, core-drilling by the OGS shows that the Croweburg coal underclay is 1.6–2.5 ft thick in this area (Hemish, 1988a).

In general, rocks of the shelf area dip to the west and northwest away from the axis of the Ozark uplift at about 25–50 ft/mi (Huffman, 1958). Strata in the Arkoma basin are much more faulted and folded, and, in many areas, the coal beds are not as amenable to surface mining as they are in the shelf area.

STRATIGRAPHY OF THE UNDERCLAYS

There are more than 40 beds of bituminous coal in the state (Friedman, 1974; Hemish, 1987), but only 12 of these have been mined over large areas. The 12 are, from oldest to youngest: the lower Hartshorne, upper Hartshorne, McAlester (Stigler), upper McAlester, Cavanal, Rowe, Secor, Weir-Pittsburg, Mineral, Croweburg, Iron Post, and Dawson coals (Fig. 2). None of the underclay associated with these coal beds is known to have been exploited commercially.

Nine samples of the underclay from beneath the Croweburg coal bed were collected over a wide area in the eastern Oklahoma coal field for purposes of this study (Fig. 3; Table 1). The Croweburg coal underclay occurs in the Senora Formation within the Cabaniss Group of the Desmoinesian Series (Fig. 2).

SAMPLE COLLECTION AND ANALYSES

Channel samples of underclay were collected at active-coal-mine locations, whenever possible, to minimize the effects of surface weathering. The sampling procedures as outlined by Friedman (1978) were followed.

The Chemistry Section of the OGS analyzed the Croweburg underclay samples. Values in percent of oxides of silica, alumina, iron, magnesium, calcium, sodium, potassium, and manganese are given in Table 2, along with the percent of water and loss on ignition (LOI).

The types and relative abundances of clay minerals were determined by X-ray diffraction methods. Oriented and unoriented slides were prepared and analyzed on a Norelco diffractometer using Cu-Kα radiation and scanned over the interval from 2 through 50 degrees 2 theta. All oriented slides were treated with ethylene glycol to test for the presence of expandable clay. No attempt was made to determine the amount of individual mineral constituents present in each sample.

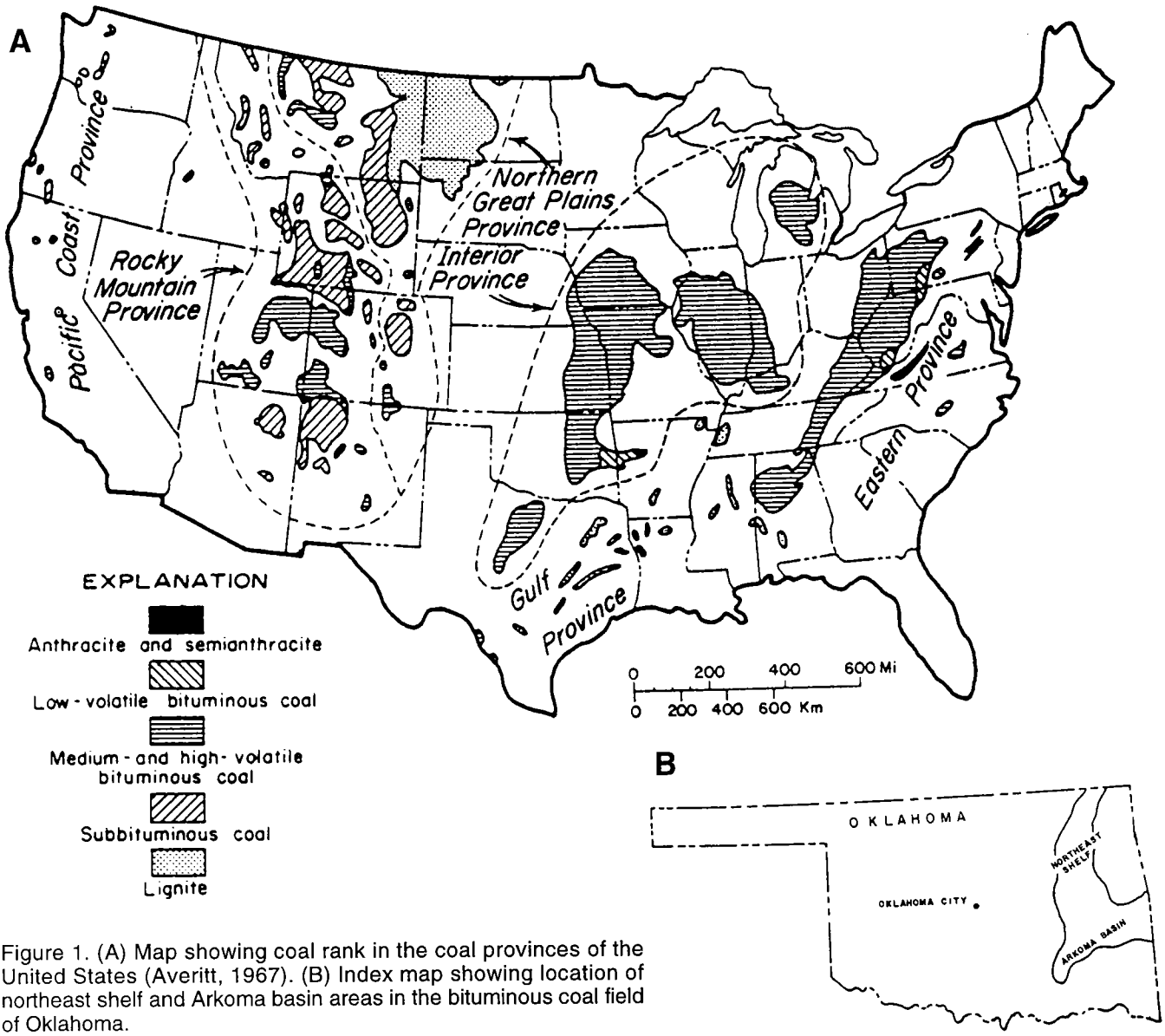


Figure 1. (A) Map showing coal rank in the coal provinces of the United States (Averitt, 1967). (B) Index map showing location of northeast shelf and Arkoma basin areas in the bituminous coal field of Oklahoma.

Underclay samples were submitted for ceramic evaluation to the U.S. Department of Interior Bureau of Mines Metallurgy Research Center in Tuscaloosa, Alabama. The test procedures are described by Liles and Heystek (1977). Raw properties include water of plasticity, working properties, color, drying shrinkage, dry strength, pH, and effervescence (HCl) for each sample. Samples were slow fired from 1,000°C to 1,250°C in 50°C intervals. Bulk density, color, percent linear shrinkage, and percent adsorption were determined for each slow-fire test. A preliminary bloating test was conducted on each sample. Potential commercial use (or uses) for each underclay sample were included with the test results.

CROWEBURG UNDERCLAYS

Nine samples of underclay from beneath the Croweburg coal were taken for chemical, mineralogical, and ceramic evaluation (Fig. 3; Tables 2–5). For comparison, these samples were grouped into the following three regions: north, central, and south. The sample sites begin on the shelf in the northern edge of the Oklahoma coal field and end in the Arkoma basin.

North

Map numbers, 1, 4, and 19 comprise the north group of samples (Fig. 3; Table 3). These samples were collected from active coal mines in Rogers County. The underclays, which vary from light gray to dark gray, are 9 in. to >12 in. thick in this region. The dominant clay minerals in samples 1 and 4 were illite and kaolinite. The principal clay minerals in sample number 19 were illite, kaolinite, and mixed-layer clays (Table 1). The SiO_2 content for these samples ranges from 50.39% to 56.42%, and the Al_2O_3 contents were about 20% (Table 2).

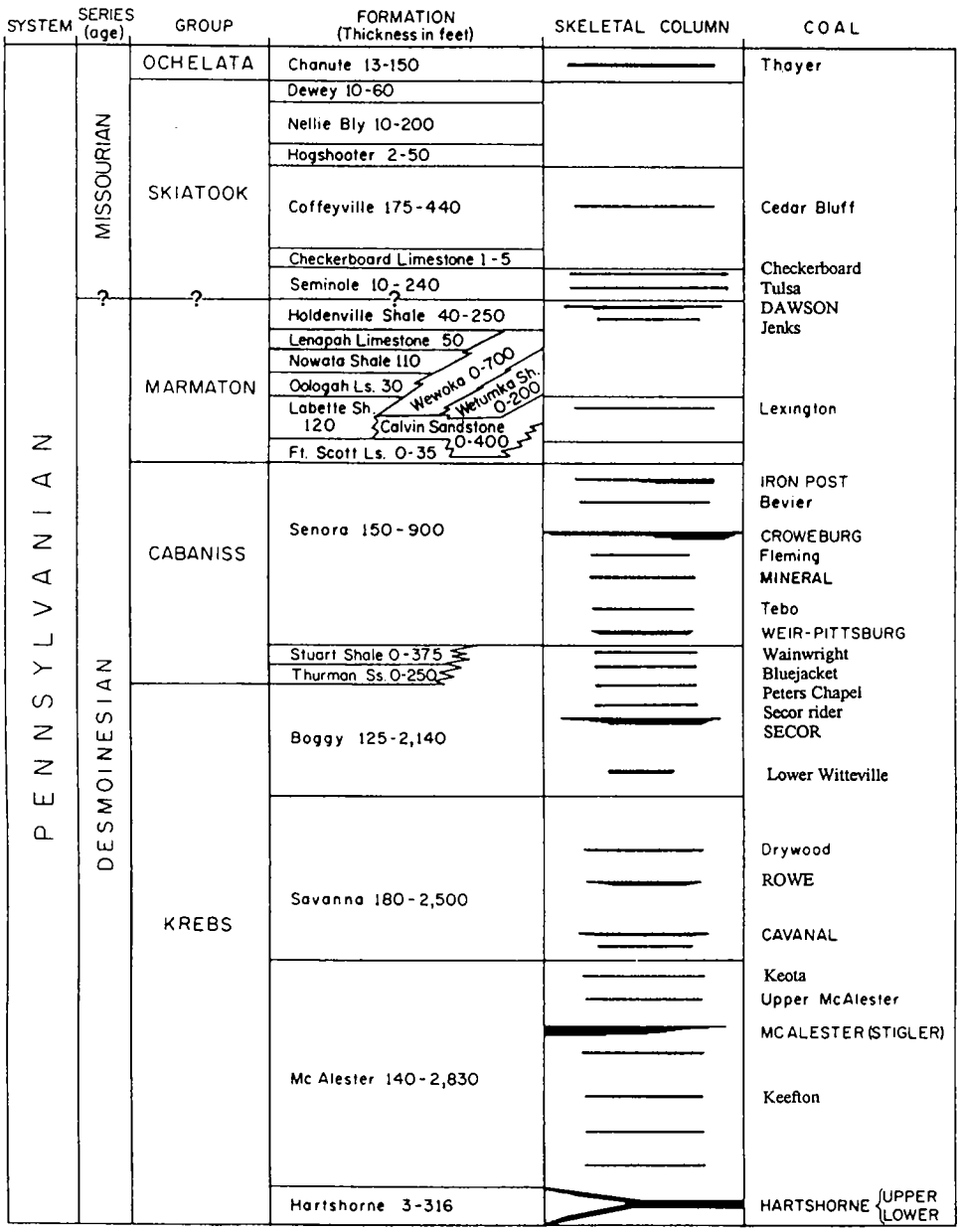


Figure 2. Generalized geologic column showing sequence of coal beds of Pennsylvanian age in Oklahoma. Coal beds containing identified coal resources are shown in capitals (modified from Friedman, 1974).

Firing-test data are summarized in Table 3 for the Croweburg underclay samples from the north group. The data indicate potential use as building brick in the general firing range of 1,050–1,100°C. All three samples had abrupt vitrification between 1,100°C and 1,150°C.

Central

Map numbers 12, 14, and 22 comprise the central sample group (Fig. 3; Table 4). Samples 12 and 14 were collected from abandoned coal mines in Wagoner County. Sample 22 was collected at an active coal mine in Okmulgee County. The underclay thickness ranges from >12 in. to 18 in. and varies in color from light to medium gray. Illite and kaolinite are the principal clay minerals in sample 12. In samples 14 and 22, the dominant clay minerals are illite, kaolinite, and mixed-layer clays. Sample 22 had the lowest SiO_2 content (45.96%) and the highest Al_2O_3 content (22.88%) (Table 2). Sample 14 had the highest SiO_2 content (59.03%) and the lowest Al_2O_3 content (16.55%) (Table 2).

Firing-test data for the central group of samples are summarized in Table 4. The data indicate potential use as building brick in the general firing range of 1,050–1,100°C for samples 12 and 14. Both of these samples had abrupt vitrification between 1,100°C and 1,150°C. Sample 22 showed good firing characteristics

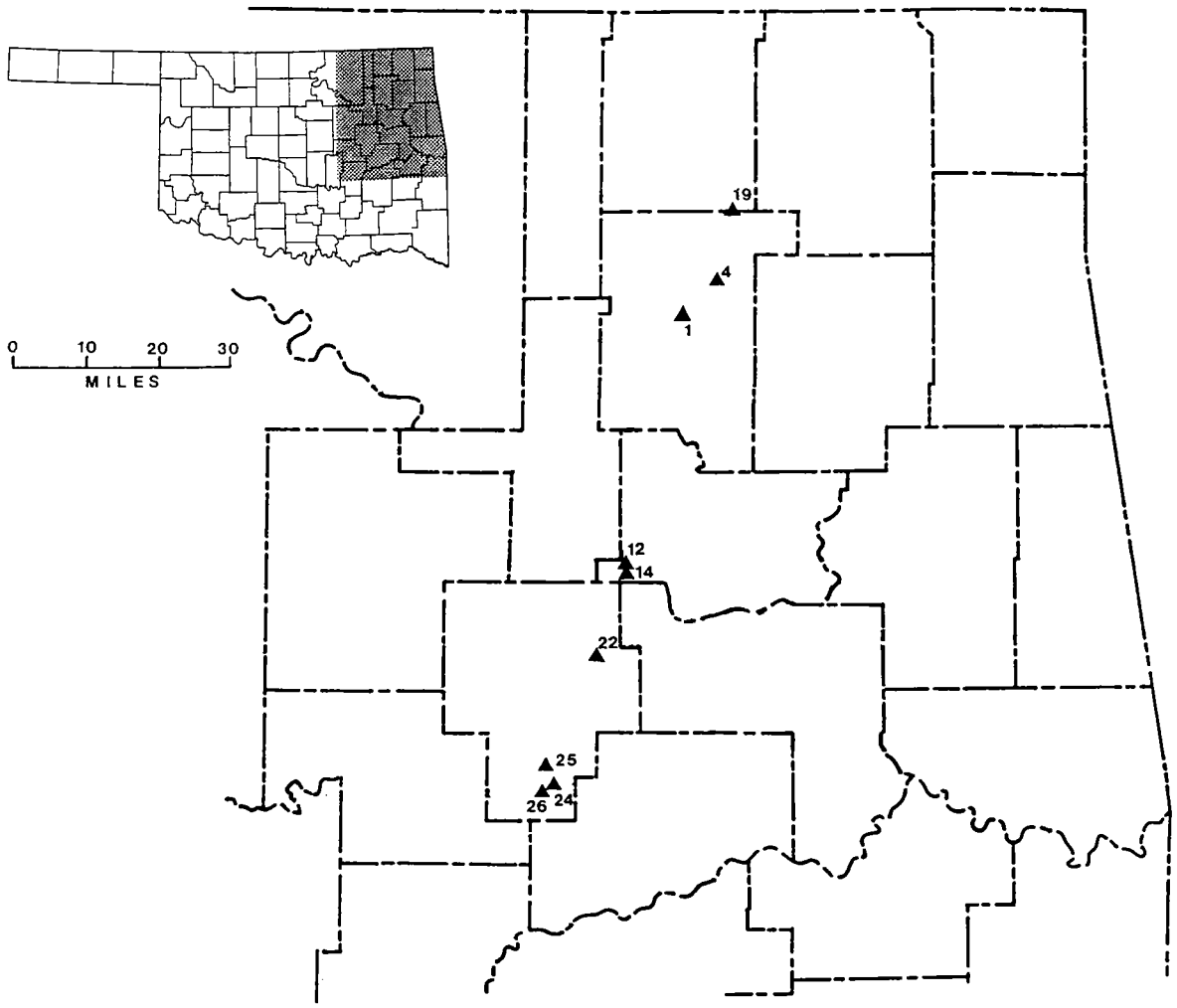


Figure 3. Locations of Croweburg coal underclay samples in the northeastern Oklahoma coal field. Map numbers correspond to those shown in Tables 3, 4, and 5.

at 1,050°C and vitrification between 1,050°C and 1,100°C.

South

Map numbers 24, 25, and 26 comprise the south sample group (Fig. 3; Table 5). All samples were collected from active coal mines in Okmulgee County. The light-gray-to-gray underclay varies from >12 in. to >14 in. thick. The principal clay minerals are illite, kaolinite, and mixed-layer clays in all three samples. Sample 26 had a slightly higher chlorite content. Sample 24 had the lowest SiO_2 content (48.89%) and the highest Al_2O_3 content (23.60%). Samples 25 and 26 had approximately 20% Al_2O_3. However, sample 25 had the highest SiO_2 content (58.98%) (Table 2).

Firing-test data for the Croweburg underclays in the south sample group are summarized in Table 5. The data indicate potential use as building brick at 1,050°C for samples 24 and 26. Vitrification occurred between 1,050°C and 1,100°C for these samples. Sample 25 had a slightly higher firing range, 1,100–1,200°C, and potential use as building brick.

DISCUSSION AND CONCLUSIONS

All the Croweburg coal underclay samples indicate potential use as building brick. The general firing range was between 1,050°C and 1,150°C. The alumina content (Al_2O_3) of the underclay samples varies from ~15% to 23.6%. In contrast, the Olive Hill clay in Kentucky, which is used to manufacture fire brick and other specialty products, has alumina content as high as 40% (Crider, 1913). Chemical and firing data for the Croweburg coal underclay are based on laboratory tests that are preliminary in nature. More research will be needed to determine what, if any, additives could be mixed with the Croweburg underclays to improve firing properties.

Because Oklahoma has large reserves of clay and shale deposits at or near the surface that are suitable for the manufacture of brick, it is unlikely that underclays will ever have much, if any, commercial potential. Limited areal distribution, relative thinness, and high stripping ratios preclude Oklahoma's underclays from becoming a viable resource unless underclay mining could be done in conjunction with surface mining of

Table 1.—Croweburg Underclay Sample Information and Clay Mineralogy

Map no.[a]	Sample no.	Collection date and type of sample site	Location	County	Coal bed thickness[b]	Underclay thickness[b]	Description	Clay mineralogy[c]
NORTH								
1	80U01H	09-18-80 active coal mine	SE¼SE¼NW¼SE¼ sec. 17, T22N, R16E	Rogers	22	>12	Light gray, "soapy" feeling; upper 12 in. of a bed of undetermined thickness	Illite, kaolinite; chlorite, mixed layer
4	80U04H	09-18-80 active coal mine	SE¼NE¼SE¼SE¼ sec. 19, T23N, R17E	Rogers	18	9	Dark gray with black carbonized plant compressions, becomes very hard and light gray in lower 2 in.	Illite, kaolinite; mixed layer, chlorite
19	80U23H	11-26-80 active coal mine	SW¼SW¼NE¼NE¼ sec. 4, T24N, R17E	Rogers	12	>12	Light gray; upper 12 in. of a bed of undetermined thickness	Illite, kaolinite, mixed layer; chlorite
CENTRAL								
12	80U16H	11-06-80 abandoned coal mine	SE¼SE¼NW¼SE¼ sec. 6, T16N, R15E	Wagoner	22	13	Light gray with orange bands	Illite, kaolinite; mixed layer
14	80U18H	11-13-80 abandoned coal mine	SW¼NW¼SW¼SE¼ sec. 7, T16N, R15E	Wagoner	18	18	Light gray with orange banding, black carbonized plant material abundant	Illite, kaolinite, mixed layer; chlorite
22	81U02H	10-29-81 active coal mine	NW¼NE¼NW¼SW¼ sec. 9, T14N, R14E	Okmulgee	12	>12	Medium gray with black carbonized plant fragments; upper 12 in. of a bed of undetermined thickness	Kaolinite, illite, mixed layer, chlorite
SOUTH								
24	81U05H	11-30-81 active coal mine	NE¼SW¼SW¼NE¼ sec. 9, T11N, R13E	Okmulgee	36	>12	Light gray with some black carbonized plant fragments; upper 12 in. of a bed of undetermined thickness	Illite, kaolinite, mixed layer; chlorite
25	81U06H	12-09-81 active coal mine	NW¼NE¼NW¼SW¼ sec. 28, T12N, R13E	Okmulgee	36	>10	Gray, hard; upper 10 in. of a bed of undetermined thickness	Illite, kaolinite, mixed layer; chlorite
26	82U01H	03-15-82 active coal mine	NW¼SE¼NE¼NW¼ sec. 17, T11N, R13E	Okmulgee	35	>14	Light gray with black carbonized plant compressions; upper 14 in. of a bed of undetermined thickness	Illite, kaolinite, chlorite, mixed layer

[a]Map numbers correspond to numbers used in Figure 1.

[b]Thickness in inches.

[c]Clay minerals listed in the order of abundance; semicolon separates major and minor occurrences; mixed-layer clays include illite-montorillonite, illite-vermiculite, and illite-chlorite.

Table 2.—Chemical Analyses of Croweburg Coal Underclays

Map no.	Sample no.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	H_2O[a]	LOI	Recovery (%)
NORTH														
1	80U1H	56.42	20.21	1.34	1.33	1.13	0.13	0.80	3.11	0.92	0.01	7.64	6.65[b]	99.69
4	80U4H	53.94	19.80	1.32	1.83	1.41	0.82	0.68	3.48	0.90	0.02	6.10	8.35[b]	98.65
19	80U23H	50.39	20.39	2.21	4.08	1.30	0.37	0.55	4.01	0.87	0.05	6.22	8.10	98.54
CENTRAL														
12	80U16H	56.81	16.55	5.60	0.39	0.78	0.49	0.84	3.31	1.01	0.01	9.50	6.47	101.76
14	80U18H	59.03	14.98	2.62	1.28	1.28	0.13	1.04	2.85	0.92	0.02	8.91	6.28	99.34
22	81U2H	45.96	22.88	1.78	2.42[b]	1.94	0.20	0.39	3.62	0.89	0.03	7.91	9.66	97.68
SOUTH														
24	81U5H	48.89	23.60	2.64	1.53	1.76	0.25	0.31	3.87	0.93	0.03	4.44	9.87	98.12
25	81U6H	58.98	19.58	1.41	2.69	1.50	0.18	0.90	3.16	1.02	0.03	2.75	5.79	97.99
26	82U1H	51.78	20.20	1.85	2.32	1.70	0.14	0.63	3.40	0.93	0.03	9.44	6.69[b]	99.11

Note: Values given as weight percentage.

[a]110°C.

[b]Indicates the reported value is the mean of two replicates.

Table 3.—Physical Properties of Croweburg North Underclays

		Unfired characteristics					Ceramic property tests			
Map no.	Sample no.	pH	Color	Water of plasticity (%)	Drying shrinkage (%)	Firing temperature (°C)	Color	Total fired shrinkage (%)	Absorption (%)	Bulk density (gm/cm³)
1	80U1H	6.9	gray	20.1	2.5	1,000	light orange	2.5	19.2	1.74
						1,050	light orange	5.0	16.6	1.83
						1,100	orange	5.0	13.6	1.93
						1,150	dark brown	10.0	4.8	2.17
						1,200	—	melted	—	—
4	80U4H	5.2	gray	21.6	2.5	1,000	reddish yellow	5.0	18.5	1.76
						1,050	reddish yellow	5.0	13.8	1.91
						1,100	reddish yellow	7.5	10.4	2.01
						1,150	reddish brown	7.5	2.1	2.21
						1,200	—	melted	—	—
19	80U23H	5.4	gray	19.4	5.0	1,000	reddish yellow	5.0	14.6	1.94
						1,050	reddish yellow	7.5	11.0	2.07
						1,100	reddish yellow	10.0	7.8	2.17
						1,150	—	melted	—	—

Table 4.—Physical Properties of Croweburg Central Underclays

		Unfired characteristics					Ceramic property tests			
Map no.	Sample no.	pH	Color	Water of plasticity (%)	Drying shrinkage (%)	Firing temperature (°C)	Color	Total fired shrinkage (%)	Absorption (%)	Bulk density (gm/cm³)
12	80U16H	5.3	tan	22.8	5.0	1,000	light red	5.0	17.3	1.80
						1,050	red	7.5	12.6	1.96
						1,100	red	10.0	9.8	2.05
						1,150	reddish brown	12.5	1.6	2.28
						1,200	—	melted	—	—
14	80U18H	4.5	tan	21.5	2.5	1,000	light red	2.5	23.2	1.64
						1,050	light red	5.0	20.5	1.72
						1,100	light red	5.0	18.3	1.79
						1,150	reddish brown	12.5	4.3	2.20
						1,200	—	melted	—	—
22	81U2H	7.3	gray	24.8	5.0	1,000	pink	5.0	18.6	1.76
						1,050	pink	7.5	13.7	1.92
						1,100	pink	10.0	4.9	2.19
						1,150	yellowish red	12.5	1.2	2.29
						1,200	—	melted	—	—

Table 5.—Physical Properties of Croweburg South Underclays

		Unfired characteristics					Ceramic property tests			
Map no.	Sample no.	pH	Color	Water of plasticity (%)	Drying shrinkage (%)	Firing temperature (°C)	Color	Total fired shrinkage (%)	Absorption (%)	Bulk density (gm/cm³)
24	81U5H	4.1	gray	25.6	5.0	1,000	light orange	5.0	18.8	1.75
						1,050	reddish orange	7.5	12.9	1.91
						1,100	reddish brown	12.5	3.6	2.14
						1,150	—	melted	—	—
25	81U6H	5.2	gray	20.4	2.5	1,000	reddish yellow	2.5	19.5	1.73
						1,050	reddish yellow	5.0	16.7	1.83
						1,100	red	7.5	10.9	2.02
						1,150	reddish brown	10.0	5.1	2.21
						1,200	brown	10.0	1.1	2.27
						1,250	—	melted	—	—
26	82U1H	6.2	gray	22.7	2.5	1,000	reddish yellow	2.5	19.8	1.73
						1,050	light red	5.0	15.2	1.85
						1,100	light red	10.0	7.1	2.14
						1,150	reddish brown	10.0	1.2	2.31
						1,200	—	melted	—	—

coal. Extraction of the underclay thus could be done immediately upon removal of the overlying coal and prior to reclamation.

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Oklahoma's Gypsum Resources—An Overview of Geology and Manufacturing of Value-Added Products

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ABSTRACT.—Oklahoma contains extensive resources of high-purity gypsum that were deposited in the Anadarko and Hollis basins during Permian time. The gypsum resources and reserves are estimated to be about 48 billion short tons and are located in the western portion of the state. Oklahoma is the largest producer of gypsum products in the United States.

The Blaine Formation and the Cloud Chief Gypsum contain several beds of minable thickness. Four stratigraphic units in the Blaine Formation are quarried in Oklahoma. The Shimer, Nescatunga, and Medicine Lodge Members are quarried in northwest Oklahoma. The Van Vacter Member, consisting of three gypsum beds, is quarried in southwest Oklahoma. The Cloud Chief Gypsum is quarried in the west-central part of the state. The gently dipping gypsum in the Blaine Formation generally crops out along low escarpments and is covered in the downdip direction by increasing overburden, consisting of sand, shale, and/or dolomite. Anhydrite occurs in the downdip direction under the thicker overburden. The Cloud Chief Gypsum crops out as hills, which are eroded remnants of a more widespread, massive sulfate unit. All of the gypsum produced in Oklahoma is extracted using quarrying methods.

A variety of products are made from gypsum quarried in Oklahoma. The products are manufactured from uncalcined, calcined, and deadburned gypsum. Products vary from raw, ground gypsum used for agriculture, to high-value-added industrial plasters, cements, and fillers produced from calcined gypsum. A sampling of the many products manufactured from Oklahoma gypsum includes: (1) *agricultural*—soil amendment; carrier for insecticides, pesticides, and herbicides; calcium supplement in animal feeds; (2) *gypsum wallboard*—common, fire-resistant, and water-resistant varieties; (3) *industrial gypsum plasters*—art and casting, pottery and ceramic, molding and tooling, crayons, wall patching; (4) *industrial gypsum cements*—oil-well cement, high-strength statuary, high-strength tooling, fiber-reinforced architectural, road and bridge repair; (5) *food and pharmaceutical*—filler and binder in aspirin and other medicines, yeast activator in brewing of beer, moisture absorbent in bread and pizza dough; and (6) *portland-cement retarder*—ground with clinker to control setting time.

INTRODUCTION

Oklahoma is the largest producer of gypsum products in the United States (15% of the total national production). In 1997, 3.4 million short tons were produced with a value of $17.5 million (U.S. Geological Survey, 1998). There are enormous resources of gypsum in Oklahoma. Johnson (1978) estimated the resources at 48 billion short tons. A great variety of gypsum products are produced in Oklahoma, varying from low unit-value crushed gypsum that is used for road-base material, to high-value-added products, such as food and pharmaceutical fillers. This paper will discuss briefly the geological relationships of gypsum in Oklahoma, and, more specifically, will highlight various products manufactured from the state's vast gypsum resources. The reader is referred to Johnson (1978), Jorgensen (1994), and Kebel (1994) for more complete discussions of the geology and processing methods of gypsum.

GEOLOGIC SETTING

Economic deposits of gypsum occur in Permian rocks in Oklahoma. The stratigraphic and structural relationships of the evaporites in Oklahoma have been described by Ham and Curtis (1958), Fay (1964), and Johnson (1978). The following description of the geo-

Sharpe, R. D.; and Schroeder, W. A., 1999, Oklahoma's gypsum resources—an overview of geology and manufacturing of value-added products, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 57–67.

logical relationships of economic gypsum in Oklahoma is based upon Johnson (1978).

During the Permian, a vast epicontinental sea extended northeastward across portions of New Mexico, Texas, Oklahoma, and Kansas. Marine carbonates were deposited in the Permian basin in western Texas, and evaporites were deposited in northwestern Texas, western Oklahoma, and extending into southwestern Kansas. Terrigenous fresh-water to brackish-water clastic rocks were deposited along the margin of the basin. The distribution of gypsum outcrops and gypsum-bearing strata is shown in Figure 1.

Four evaporite sequences, with a total thickness of about 5,000 ft, occur in Permian rocks in Oklahoma. Evaporite deposition in Oklahoma occurred mainly in the Hollis and Anadarko basins, which are separated by the Wichita-Criner uplift. The four evaporite sequences are the Wellington, Cimarron, Beckham, and Cloud Chief evaporites, in ascending order. The evaporite sequences are 100–1,300 ft thick and consist mainly of gypsum, anhydrite, and/or rock salt. Interbeds of dolomite, shale, and sandstone are common. Production of gypsum in Oklahoma is currently limited to the Beckham and Cloud Chief evaporite units.

Blaine Formation

The Blaine Formation occurs in the middle portion of the Beckham evaporites. In the Anadarko basin of northwestern Oklahoma, economic gypsum deposits occur within the Shimer, Nescatunga, and Medicine Lodge Members of the Blaine Formation. The stratigraphic relationships of these gypsum beds are well exposed in Salt Creek Canyon, just north of Roman Nose State Park, in Blaine County (Fig. 2). Economic gypsum occurs in the Van Vacter Member of the Blaine Formation in the Hollis basin of southwestern Oklahoma.

Individual Oklahoma evaporite beds generally are 10–30 ft thick. Gypsum within the Blaine Formation typically has a purity of 95–99%. Interbeds of shale, with a thickness of 2–30 ft, separate the gypsum units. The gypsum beds typically are underlain by thin dolomite beds. Anhydrite lenses, commonly present within the gypsum beds, increase in thickness in the downdip direction under increasing overburden thickness.

In the semiarid climate of Oklahoma, gypsum and anhydrite are resistant to erosion and crop out as benches and dissected escarpments. In northwest Oklahoma, the gypsum beds dip gently southwestward at a rate of 10–40 ft/mi (<0.5°). Near the outcrop, the upper surface of the gypsum has been affected by groundwater solution. Irregular bed thickness and clay-filled solution cavities and fractures occur where overburden is thin to absent. Anhydrite increases in the downdip direction under increasing overburden. Hydration of anhydrite appears to have been from the top down and the bottom up, leaving a wedge or lens of anhydrite in the middle of the gypsum units. In some areas, the upper surface of the gypsum has been buckled upward from expansion of rock during hydration from anhydrite to gypsum (26% volume expansion), forming what is known locally as "bear dens." In the Southard area of Blaine County, solution vugs containing long bladed selenite crystals have been found.

In northwestern Oklahoma, overburden consists of Pleistocene fluvial sand terraces of the Canadian River, and shales/mudstones and thin dolomites of the upper Blaine Formation. In southwestern Oklahoma, the Van Vacter Member is overlain by thin shale overburden.

Cloud Chief Gypsum

The Cloud Chief Gypsum is the uppermost of the evaporite sequences deposited in the Permian basin in Oklahoma. The Cloud Chief Gypsum outcrops in west-central Oklahoma in the central portion of the Anadarko basin.

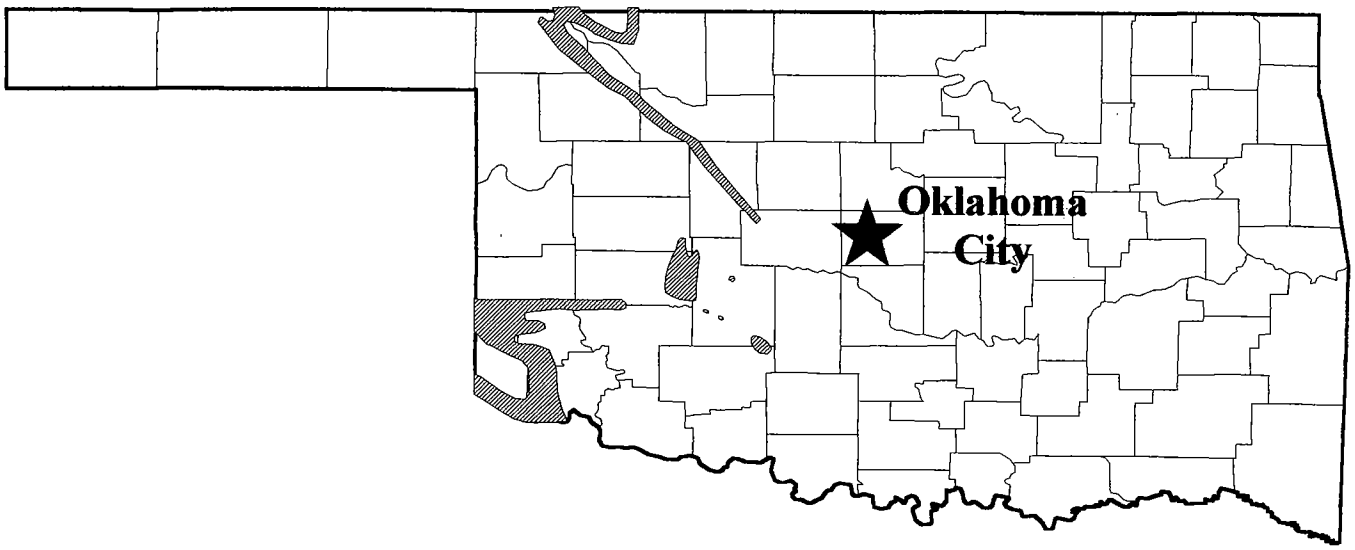


Figure 1. Distribution of gypsum resources in Oklahoma (Johnson, 1978).

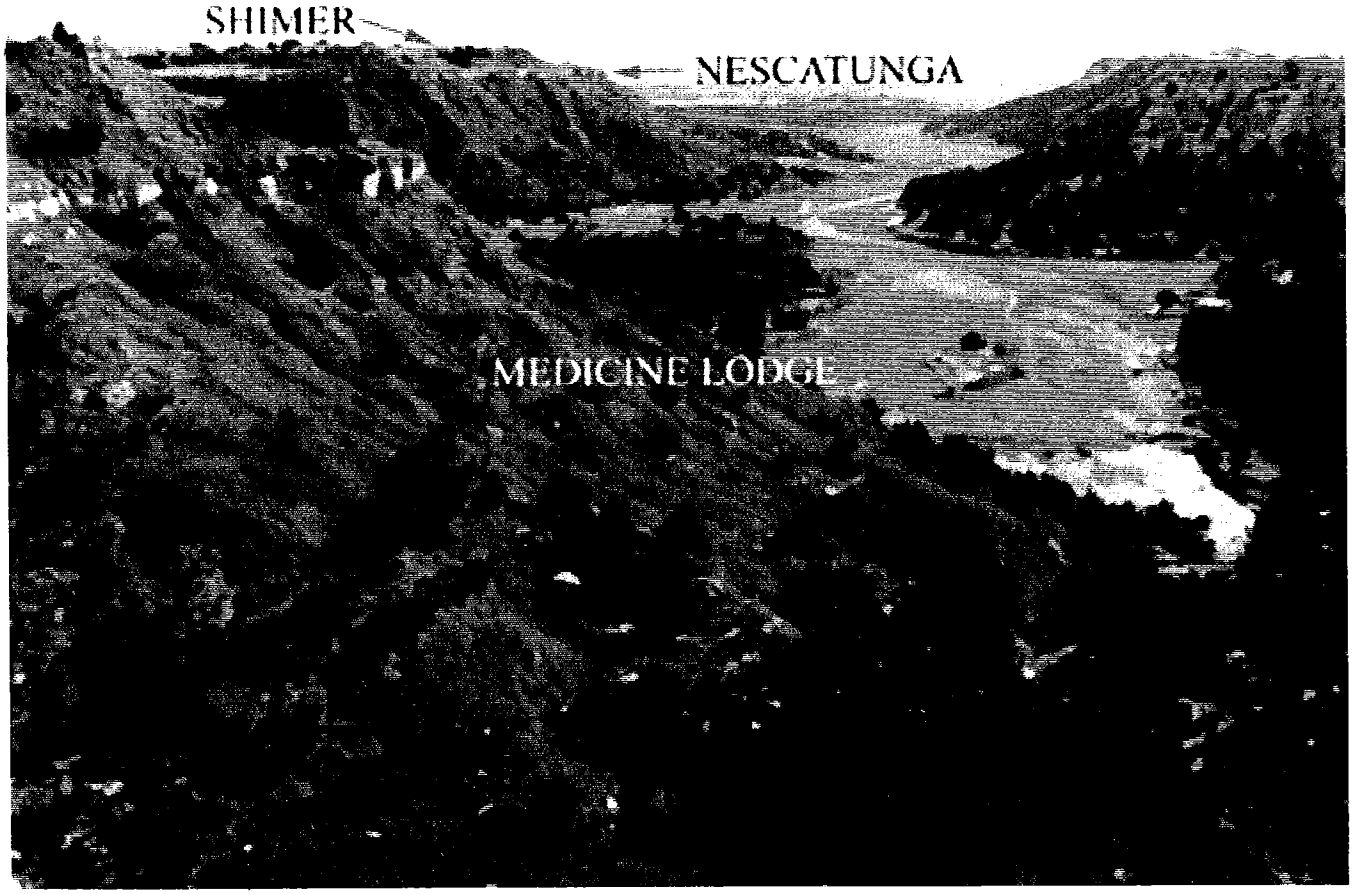


Figure 2. Exposure of the Shimer, Nescatunga, and Medicine Lodge Members of the Blaine Formation in Salt Creek Canyon, Blaine County.

The Cloud Chief Gypsum has a total thickness of about 100 ft. The sulfate bed has been partially eroded, resulting in a hilly terrain with 20–75 ft of gypsum. The lower portion of the sulfate unit typically contains anhydrite up to 40 ft thick; the upper part consists of 25–70 ft of massive gypsum.

The purity of the gypsum is high, about 97%, but this is reduced to 93–95% during quarrying due to the presence of clay and soil that fill solution cavities in the upper surface. Anhydrite is not present in the Harrison Gypsum operation, but occurs as residual lenses in the Temple-Inland gypsum deposit (Johnson, 1978).

GYPSUM PROCESSING AND PRODUCTS

Gypsum is a very versatile mineral, which can be used in the manufacture of several hundred products. Processing methods vary from simply grinding and sizing of quarry-run gypsum to the calcination of sized gypsum in closed pressure vessels.

Uncalcined Gypsum

Gypsum that has been processed only by grinding and sizing is known as landplaster, portland-cement retarder, and Terra Alba. Landplaster is used for agricultural gypsum and is a raw feedstock for manufacturing wallboard and plasters. Portland-cement retarder is used in the manufacture of portland cement. Terra Alba is used in food and pharmaceutical applications.

Agricultural Gypsum

Ground gypsum provides several benefits in agriculture. As gypsum dissolves it provides a source of elemental calcium (25% by weight) and sulfur (20% by weight). Gypsum has a neutral pH (7.0) and is 150 times more soluble than ground limestone. Finely ground agricultural gypsum permits rapid dissolution and absorption of its elements by plants. Long-term availability of these elements during a growing season may be accomplished by the application of agricultural gypsum consisting of multiple particle sizes. Finely ground gypsum can also be dissolved in irrigation water for easy application.

Agricultural gypsum aids in the growth of Oklahoma crops such as peanuts and cotton. It can also be used in the production of fruits, such as apples, strawberries, and blueberries. It is used in the growth and maintenance of lawns and golf courses.

Gypsum loosens and aerates heavy clay and wet soils. The gypsum particles act as nuclei for the floccu-

lation of clay particles, producing more granular and well-drained soils. Gypsum aids in reducing the alkalinity of soils by cation replacement of calcium for sodium. Application of gypsum prevents crusting of soils, where low-electrolyte irrigation water is used, or where the soil contains a high sodium content. Soil crusting results in excessive runoff and erosion in sloping terrain or standing water on more level ground.

In dairy-farm applications, gypsum can be applied to manure piles to prevent the loss of nitrogen by reacting with nitrogen to produce ammonium sulfate. An additional benefit is the reduction of ammonia odors.

Gypsum can be applied to bodies of water with high total suspended solids, such as muddy ponds. The gypsum acts as a flocculating agent to settle the suspended clay particles.

Portland-Cement Retarder

Gypsum and anhydrite are used as a source of SO_3 in the manufacture of portland cement. The SO_3 acts to control the setting time and strength of the finished product, as well as controlling shrinkage during drying. Approximately 3–6%, by weight, of gypsum or a gypsum and anhydrite mixture is ground with clinker to produce portland cement.

Portland-cement rock is produced by two companies in Oklahoma (Fig. 3). The United States Gypsum Company produces portland-cement rock at the Southard Plant, in Blaine County. The United States Gypsum Company also acquired the H&B Gypsum Company, located near Watonga, in 1998. The Harrison Gypsum Company operates a quarry near the town of Cement in Caddo County.

Terra Alba

Terra Alba is a white, high-purity, uncalcined gypsum that has numerous uses in the food and pharmaceutical industries. Terra Alba is made by fine-grinding and air-separation of gypsum with a purity of greater than 97%. Terra Alba has a calcium content of 23% (by weight).

Terra Alba is produced by the United States Gypsum Company at the Southard Plant in Blaine County and by Harrison Gypsum Company in Caddo County. Some of the beneficial uses for this high-purity product are described below. Deadburned gypsum, which is described later in this paper, shares some of the same characteristics and applications as Terra Alba.

1. *Beer Brewing.* Calcium ions, derived from the Terra Alba, buffer the pH and reduce the hardness of water used in the beer-brewing industry. The yield of the main mash is increased by promoting the proper gelatinization of the starch in the cooker mash, as well as protein degradation and starch conversion. Flocculation and precipitation of undesirable protein complexes is achieved by the addition of Terra Alba. These effects produce beer with improved stability and shelf life.

2. *Baking.* Terra Alba is used in the baking industry as a source of supplemental calcium. It is used in enriched flour and breads, pasta products, baking powder, yeast foods, and bread conditioners. Calcium enrichment of bakery products, in addition to providing supplemental calcium, also counteracts the effects of excess phosphorous in a person's diet. Many foods are high in phosphorous, but few foods are good sources of calcium. A deficiency of calcium causes the dough to be soft and sticky.

3. *Pharmaceuticals.* Terra Alba is used as a dilutent and inert extender in pharmaceutical products, such as aspirin tablets. As described above, it also provides a source of dietary calcium.

4. *Other Food Applications.* Terra Alba is also used in the production of canned vegetables, cheeses, and artificially sweetened jellies and preserves.

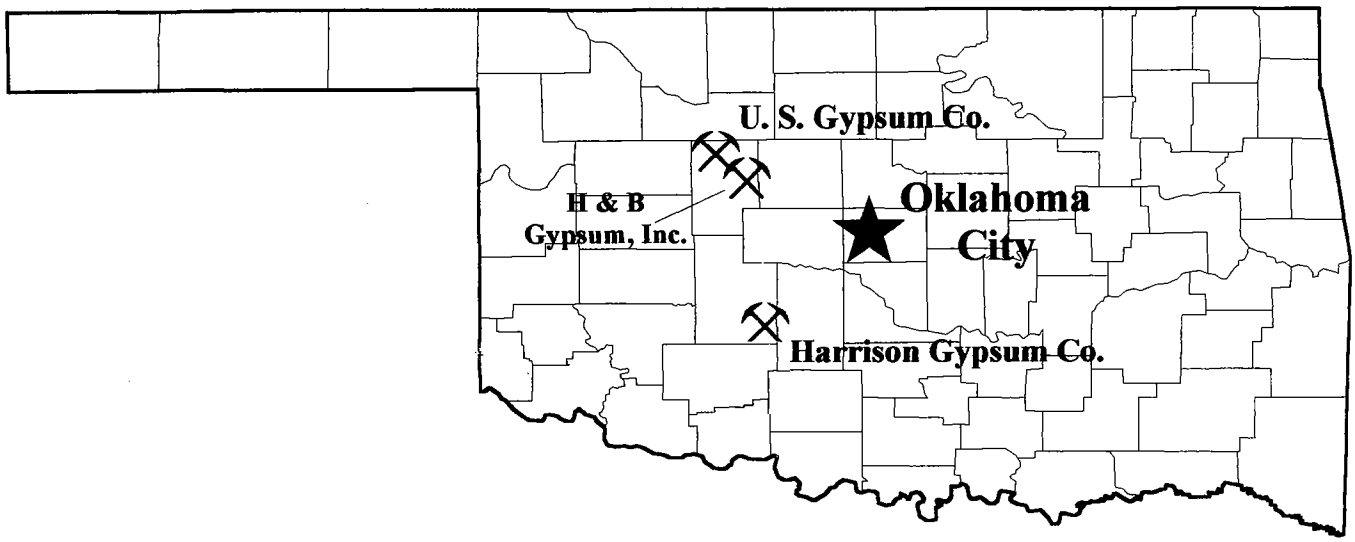


Figure 3. Location of portland-cement-rock producers in Oklahoma.

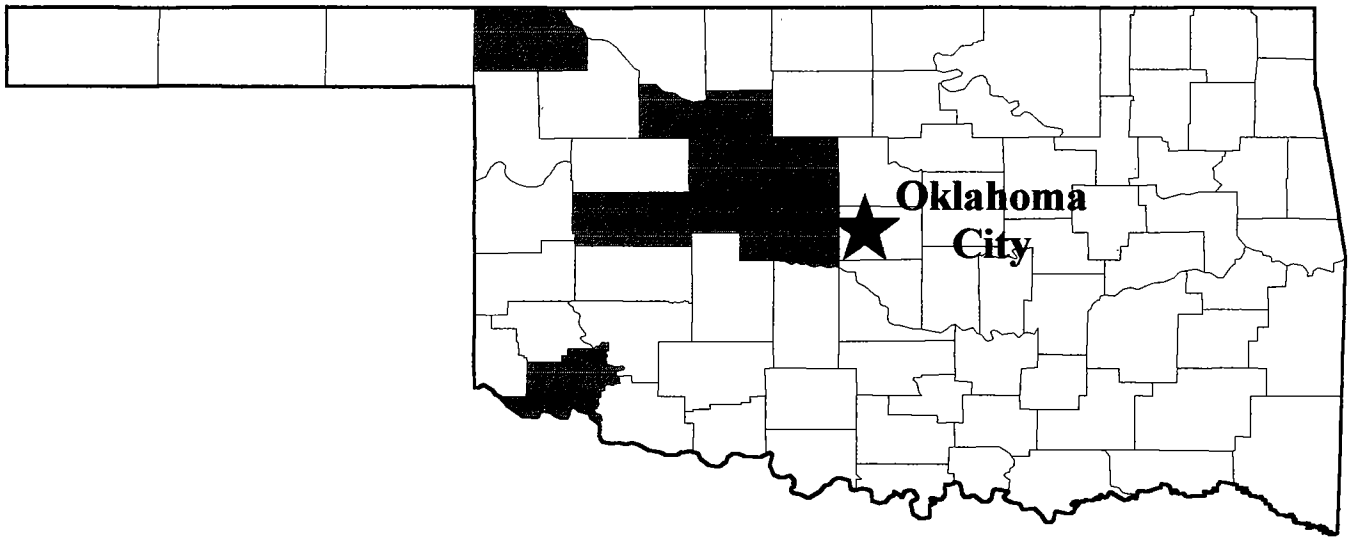


Figure 4. Counties that produced gypsum or anhydrite for road base, road surfacing, and drill pads in 1992.

Road-Base Material

Northwest Oklahoma does not have suitable aggregates for use as a road-base material. Gypsum and anhydrite are produced in several counties for use as surface material on unpaved county roads and on oil- and gas-well access roads and drillpads (Fig. 4). Gypsum and anhydrite cannot be used as concrete aggregate. A mixture of gypsum and anhydrite produces well-compacted unpaved roads.

Gypsum and anhydrite for use as road-base material is produced by the United States Gypsum Company, Western Plains Material, and H&B Gypsum, Inc. The 1992 directory of Oklahoma mineral producers (Arndt and Springer, 1992) listed several small companies producing road-base material. Some small borrow pits may be operated by local county highway departments.

Calcined Gypsum

Gypsum, which has been transformed chemically through the application of heat and/or pressure, thus removing three-fourths of the water of crystallization, is known as calcium sulfate hemihydrate, stucco, and Plaster of Paris. Calcination produces two products, *beta hemihydrate* and *alpha hemihydrate*, depending upon the processing method used. However, the chemical reaction for both products is the same:

$$CaSO_4 \cdot 2H_2O + \text{heat} = CaSO_4 \cdot \tfrac{1}{2}H_2O + 1\tfrac{1}{2}H_2O$$

Many different products may be manufactured from either alpha or beta hemihydrate, or a mixture of both. The products are further mixed with portland cement, fiberglass, plastic resins, and other materials to produce products with high strength and density, fire and water resistance, and other specialized characteristics.

Beta Hemihydrate

Beta hemihydrate is produced by calcining finely ground gypsum (95% minus 100 mesh) in vertically oriented, cylindrical, steel kettles at atmospheric pressure. The calcination can be done in a continuous process or in a batch process. Continuous calcining of landplaster is used predominantly for producing stucco for wallboard. Batch calcining is used predominantly for manufacturing construction and industrial plasters. The beta-hemihydrate calcining process produces rough, fractured, fragmented particles as shown in Figure 5. The predominant products manufactured from beta hemihydrate are described below.

In the continuous calcining process, landplaster is introduced into the top of the kettle. As the molecular

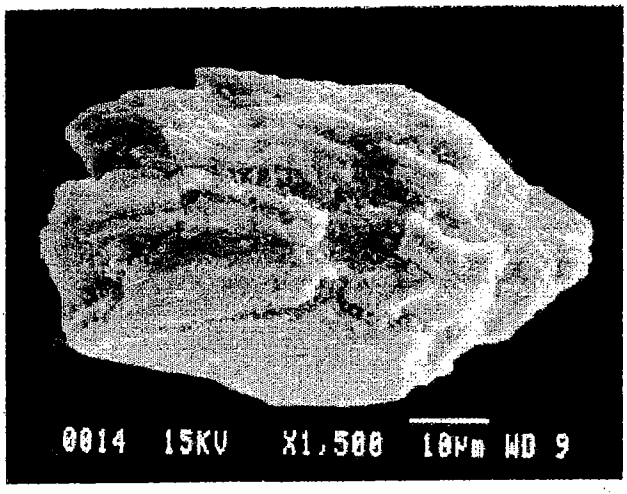


Figure 5. Electon micrograph of beta hemihydrate (magnification ×1,500).

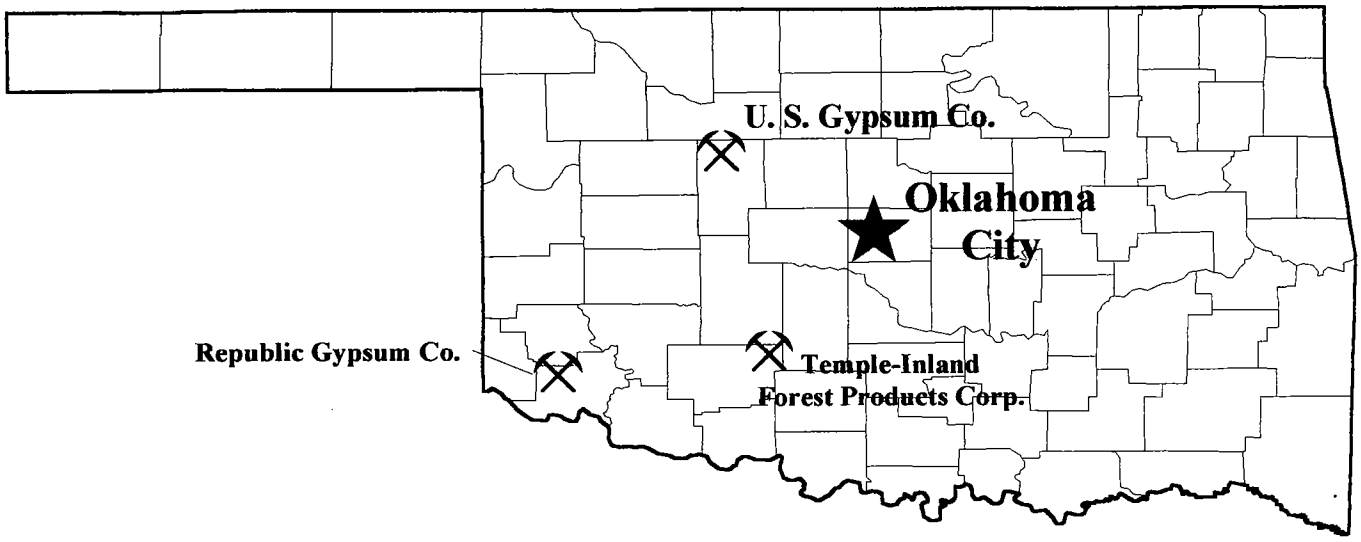


Figure 6. Location of gypsum-wallboard plants in Oklahoma.

water is removed during calcination, the beta hemihydrate becomes less dense and rises toward the top of the kettle. The beta hemihydrate overflows the top of the kettle into a hotpit where calcination is completed and entrapped steam is released. The beta hemihydrate is discharged from the continuous kettle at a temperature of 280–309°F.

In the batch kettle process, the calcining is done on a measured amount of landplaster, then the entire batch is dumped into a hotpit for the completion of calcination and release of entrapped steam. Batch calcining produces beta hemihydrate with high plasticity, high strength, and high density. The product from batch calcination is used for construction and in some industrial plasters. Batch calcining is performed at a temperature of 300–330°F.

Gypsum Wallboard

Gypsum wallboard is produced by three companies in Oklahoma (Fig. 6). All gypsum produced in Oklahoma is quarried by open-pit methods. Several different types of wallboard are manufactured, including the common variety and specialized varieties, such as fire resistant, water resistant, and plaster lath.

Gypsum wallboard is manufactured by mixing beta-hemihydrate stucco, water, and other additives to form a slurry. Additives, such as asphalt emulsion, vermiculite, chopped fiberglass, and paper fiber, impart to the wallboard characteristics such as water resistance, fire resistance, and strength. The slurry is discharged onto a continuous roll of paper; the edges of the paper are folded upward, and another sheet of paper applied to the top forms a soft, gypsum "sandwich." The gypsum sandwich travels along a conveyor for several hundred feet until the stucco slurry has recrystallized to gypsum. The continuous stream of wallboard is cut into lengths varying from 8 to 14 ft, which then enter a multi-deck drying kiln to remove excess water. Upon exiting the kiln, the wallboard is packaged into two-sheet bundles, stacked, warehoused, and shipped to customers (Fig. 7).



Figure 7. Typical gypsum-wallboard products produced in Oklahoma.

United States Gypsum Company.—The United States Gypsum Company, a subsidiary of USG Corp., operates a wallboard-manufacturing plant at Southard in Blaine County. A gypsum-calcining mill was founded under the name of Independence Plaster Company by George L. Southard in 1905. The United States Gypsum Company acquired the operation in 1912. The United States Gypsum Company products are known by the trademark SHEETROCK™.

The Shimer and Nescatunga Members of the Permian Blaine Formation are quarried at the Southard Plant. The gypsum members are overlain by as much as 70 ft of sand and shale. To the south of the Southard Plant, the overburden consists of shale and thin dolo-

mite. North of the plant, the shale overburden is overlain by unconsolidated Pleistocene terrace sands of the Canadian River.

The Shimer Member is 10–16 ft thick. The Shimer and Nescatunga Members are separated by about 30 ft of shale interburden. The upper few feet of the interburden consists of argillaceous dolomite. The Nescatunga Member is 12–15 ft thick. The Nescatunga Member is underlain by the Medicine Lodge Member, which is not quarried at the Southard Plant. The Medicine Lodge Member varies in thickness from 1 to 15 ft and increases in thickness from south to north.

Republic Gypsum Company.—Republic Gypsum Company, a subsidiary of the Republic Group Inc., operates a gypsum-wallboard-manufacturing plant at Duke, Jackson County. Republic Gypsum Company was founded in 1961 by the Simpson family, which had been involved in the manufacturing of building products in Texas and the Southwest since the 1880s.

The quarry is located about 5 mi from the manufacturing plant. Republic Gypsum Company operates its own fleet of trucks. The company-owned Hollis and Eastern Railroad connects the Duke plant to major rail carriers.

Three gypsum units within the Van Vacter Member of the Blaine Formation are quarried by Republic Gypsum. The three units, labeled Bed 1 (9 ft thick), Bed 2 (17–21 ft thick), and Bed 4 (9 ft thick), in ascending order, are separated by shale intervals that are about 9 ft thick.

Temple-Inland Forest Products Corporation.—The Temple-Inland Forest Products Corporation, a subsidiary of Temple-Inland, Inc., operates a gypsum-wallboard-manufacturing plant at Fletcher, Comanche County. The company was formerly known as the Texas Gypsum Company.

Temple-Inland Forest Products quarries gypsum from the Permian Cloud Chief Gypsum. The Cloud Chief Gypsum consists of approximately 100 ft of sulfate rock, overlain and underlain by red shale and sandstone. In the Fletcher area, the top of the Cloud Chief Gypsum is partially eroded, leaving 20–75 ft of gypsum as remnant hills.

Pottery and Ceramic Plasters

Plasters used in the manufacturing of pottery and ceramic products may be either alpha hemihydrate, beta hemihydrate, or mixture of both crystal phases. White art plasters used in schools and arts-and-crafts classes are made from beta hemihydrate.

The process of manufacturing pottery and ceramic products involves several steps, from preparation of an initial model to the final product. An original block mold is manufactured from the finished model of the product to be manufactured. Then a case mold is made from the block mold. The case mold becomes a die for fabricating multiple-working or production molds. The block-and-case molds are typically manufactured from alpha hemihydrate. The use of alpha hemihydrate allows for the production of dense, hard, strong, and durable molds, which can be intricately detailed. Working molds, which are used for mass production, are manufactured from a blend of alpha and beta hemihydrate or from alpha hemihydrate (Fig. 8). Industrial manufacturing processes for pottery and sanitary ware involve three major types of working molds: slip-cast molds, jigger molds, and press molds.

In slip casting, a relatively fluid mixture of clay and other ceramic raw materials, called "slip," is poured into a mold, which may consist of several individual pieces. The excess water in the slip is absorbed by the plaster mold. Slip-cast molds are generally manufactured from a mixture of 15–20% alpha hemihydrate and 80–85% beta hemihydrate. Examples of slip casting include the manufacture of sinks and toilets.

In jigger casting, a relatively soft, plastic clay mixture is placed on a rotating bottom mold. As the mold rotates, an upper molding template moves downward and forces the clay to fill the bottom mold. The upper molding template also impresses or cuts the desired design elements into the clay. This method is not very labor intensive and is used to manufacture lower priced dinnerware items. Jigger-cast molds generally are manufactured from a mixture of 70% alpha hemihydrate and 30% beta hemihydrate. The alpha hemihydrate gives the mold durability and hardness for use in longer production runs.

In press casting, the clay mixture is formed into the final product by hydraulically pressing a lump of clay between the two halves of a mold. This method is used to produce products such as dishes, ashtrays, some cups, and bud vases. This method of casting is also relatively fast and low cost. The molds are manufactured entirely from alpha hemihydrate.

Alpha Hemihydrate

Alpha hemihydrate is produced by calcining sized gypsum, or "lump rock," in an autoclave at elevated steam pressure in a batch process. This method of calcination produces dense, orderly, well-formed crystals (Fig. 9). Alpha hemihydrate may be used alone or mixed with additives such as beta hemihydrate, portland cement, resins, and fiberglass to produce very durable products. Alpha hemihydrate is used in the following applications:

Industrial Prototypes and Models

Gypsum-based plaster has been used for pattern, model, and mold making for over a thousand years. Alpha-hemihydrate cements are used to meet the specialized needs of the aircraft, automotive, foundry, plastics, and other industries. The characteristics of the alpha-hemihydrate cements allow for the manufacture of molds and patterns with high accuracy, high strength, high surface hardness, and low expansion during drying and curing. Patterns and molds may be made to close tolerances, such as required by the aircraft industry.

One of the latest innovations in the preparation of industrial prototypes and models is the development of a machinable alpha-gypsum cement. This product was

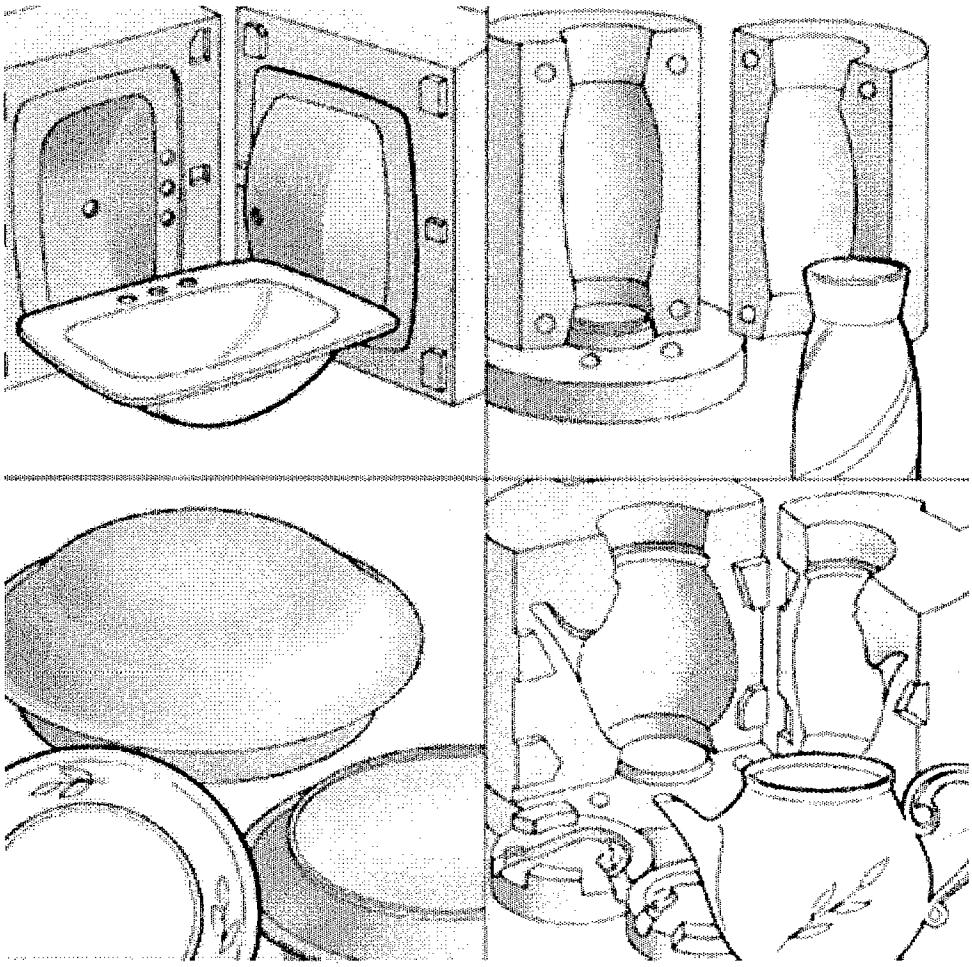


Figure 8. Pottery and ceramic plasters used for casting of sinks, toilets, dishes, and pots.

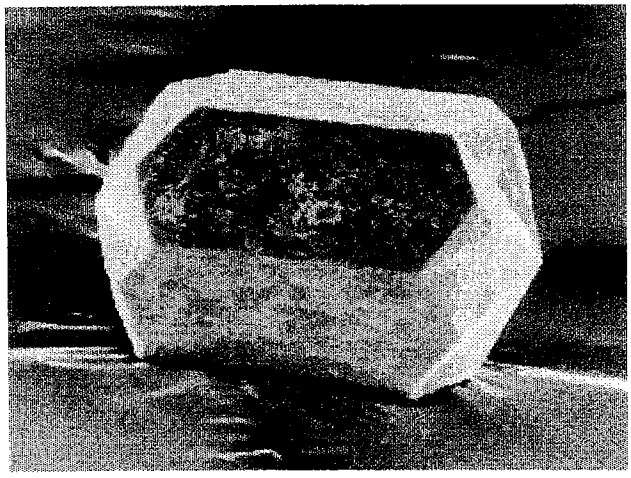


Figure 9. Electon micrograph of alpha-hemihydrate crystal (magnification ×1,500).

developed by the United States Gypsum Company in the 1990s to meet the needs of the rapid prototype-tooling industry and serves as a replacement for preformed polymer-based boards (Kaligian, 1997). The castable alpha-gypsum cement may be poured into containment vessels or molds of any size, and it hardens in about one hour. Dimensional stability is achieved after three hours.

Alpha-hemihydrate cement typically is used with computer-controlled numerical-milling machinery to produce prototypes and models (Fig. 10). The material also may be used to produce forms for vacuum molding of sheet plastics. Milling of cast blocks of this material produces chips, rather than dust, and does not require lubricating fluids.

Art and Statuary

Alpha-hemihydrate-gypsum cement and plaster is used to manufacture dense, durable, three-dimensional art and statuary products (Fig. 11). Art and statuary cement and plaster may be modified by the addition of polymers and glass fibers to produce resilient and chip-resistant castings. These products may be used to produce solid figurines, lamp bases, and hollow statuary.

Traffic-Surface Repair

Traffic surfaces, such as expressways, bridges, ramps, and commercial concrete floors that carry high volumes of traffic may be repaired with a mixture of

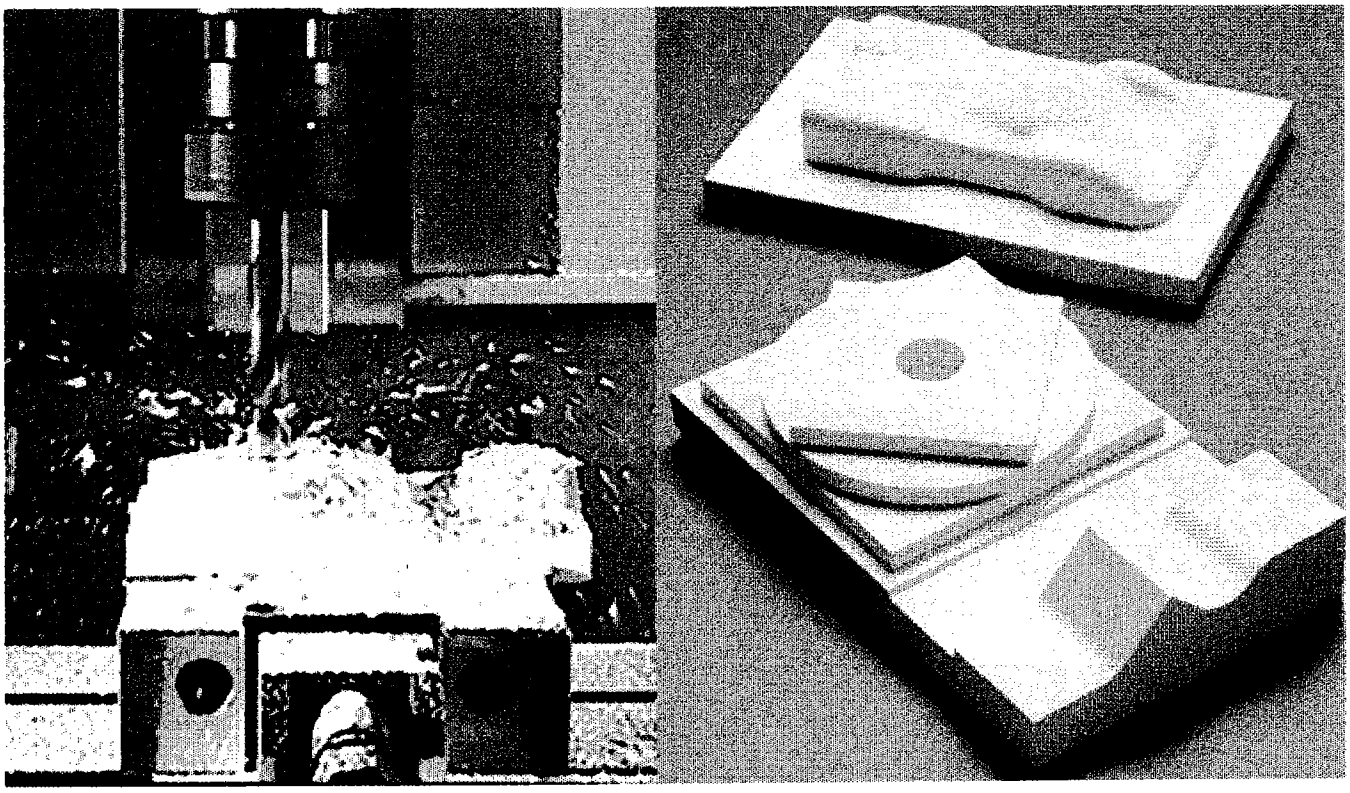


Figure 10. Numerically controlled milling of alpha-hemihydrate cement to product industrial prototypes and models.

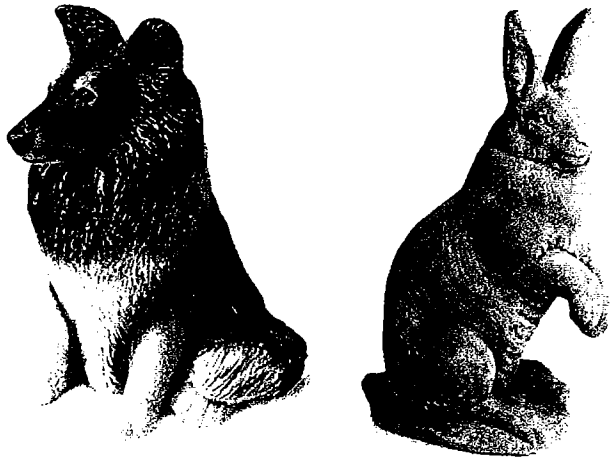


Figure 11. Three-dimensional art and statuary products made from alpha-hemihydrate-gypsum cement.

alpha hemihydrate, portland cement, and a suitable aggregate. This is a quick and effective method to repair or replace traffic surfaces that cannot be out of service for a significant period of time. The United States Gypsum Company manufactures Duracal™ at the Southard Plant, near Watonga in Blaine County.

Traffic-surface-repair cement expands upon setting to insure a tight contact with the surrounding pavement. This characteristic protects reinforcing steel by restricting the seepage of water and salt. The product sets quickly, and it rapidly develops relatively high compressive strength. The total process of repair or replacement of sections of pavement can be completed in less than five hours. The traffic-surface-repair cement will develop a compressive strength of 3,200 to 4,100 psi within about one hour. The compressive strength after 28 days reaches approximately 10,000 psi.

The Central Artery in Boston, Massachusetts, carries approximately 200,000 vehicles per day. Duracal™ was used to repair or replace road surfaces and bridge decking during the nighttime hours without disrupting normal rush-hour-traffic flow (Fig. 12). During a two-year period, approximately five million pounds of Duracal™ were used to repair large portions of the roadbed. Warehouse floors may be repaired and driven over by loaded fork trucks within just a few hours.

Architectural Applications

Fiberglass-reinforced alpha-hemihydrate cement (FGR) is used to fabricate highly detailed interior architectural features. The United States Gypsum Company produces HYDROCAL™ FGR Gypsum Cement at the Southard Plant. Strong, resilient, high-strength architectural details can be produced with a thickness of as little as 0.1 in. Column capitals and covers, light coves, medallions, cornices, coffers, and wall and ceiling moldings are examples of details that can be fabricated from this material. Architectural-detail elements can be pre-cast offsite from original pieces with exacting



Figure 12. Rapid repair of roadway with a mixture of alpha-hemihydrate-gypsum cement and portland cement.

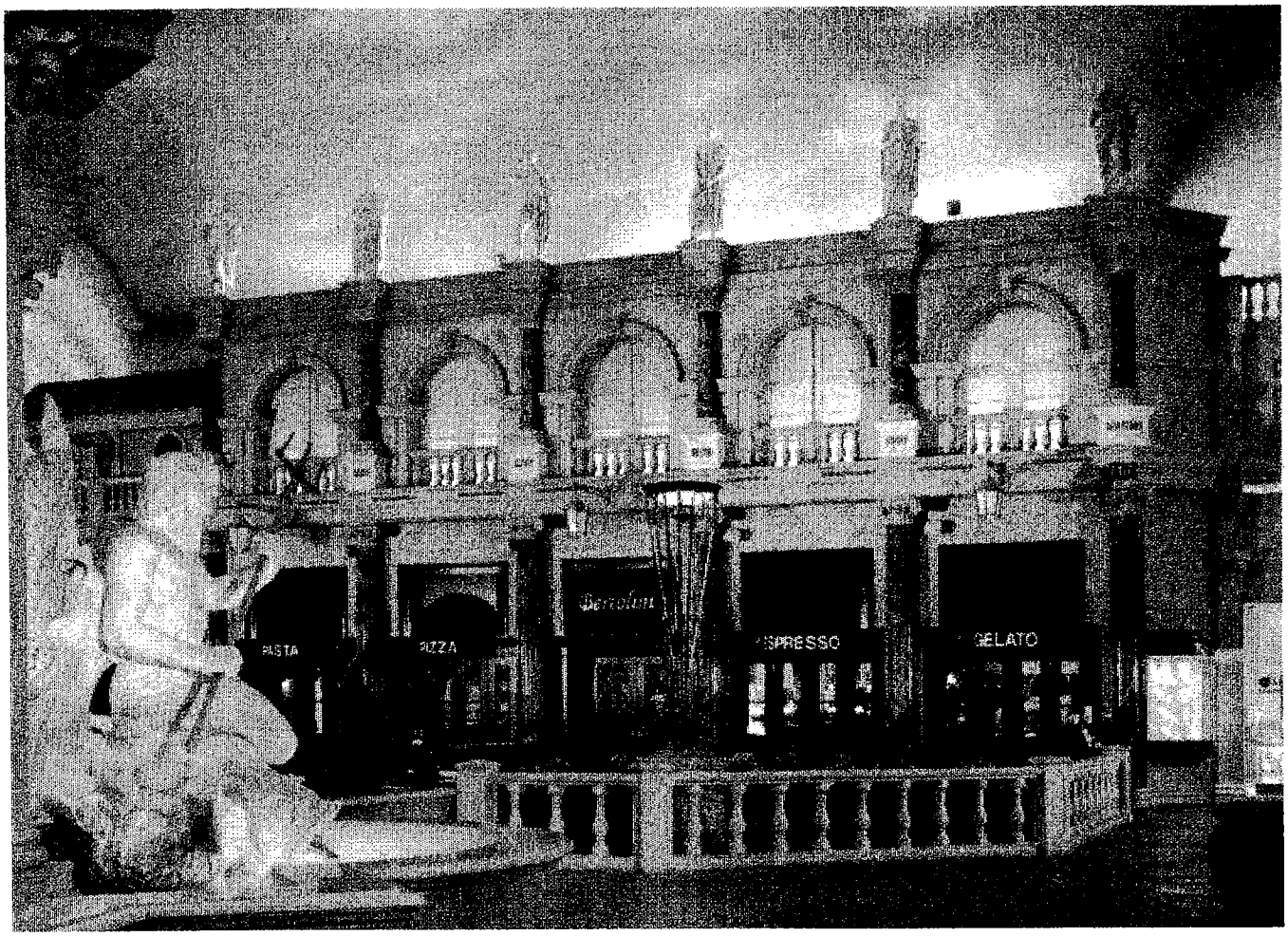


Figure 13. Intricate architectural details produced from fiber-reinforced gypsum cement. Interior view of Caesar's Palace Hotel in Las Vegas, Nevada.

detail. Historical architectural elements can be easily replicated with stronger, lightweight, FGR Gypsum Cement. Figure 13 shows the application of FGR cement in the creation of molded architectural and artistic elements at Caesar's Palace, Las Vegas, Nevada. The view includes molded features such as columns, balustrades, statuary bases, and cornices.

Deadburned Gypsum

Gypsum that has been calcined at a temperature above 400°C loses both molecules of the water of crystallization, forming a deadburned calcium sulfate ($CaSO_4$). Although it has the same chemical formula as anhydrite, deadburned gypsum is relatively inert and insoluble. Deadburned gypsum is almost anhydrous, with more than 99.6% of water of crystallization being removed during calcination. The deadburned gypsum has a high calcium content (29% by weight).

Deadburned gypsum has several high-value-added uses. It is used as an inert filler in plastics. It also is used in agricultural products as a binder or as a carrier for herbicides and pesticides. Deadburned gypsum is used in pharmaceutical products, such as aspirin tablets. It is also used in pizza dough and other bakery products, acting as a desiccant and a source of calcium. The deadburned gypsum absorbs moisture in products such as pizza dough, which can be manufactured and then stored for a period of time before use. Deadburned gypsum also is used as a filler in thermoplastics, such as PVC. These PVC products include vinyl siding, window frames, moldings, conduit, and pipe. The filler imparts special characteristics, such as acid resistance and low electrical conductivity. It also is used in food packaging.

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Solar-Salt Production in Northwest Oklahoma

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INTRODUCTION

Composition of salt in the Permian Flowerpot Shale in northwest Oklahoma suggests that the salt in this formation was deposited in the early phase of solar evaporation. Brine produced through natural dissolution of the subsurface salt has netted very pure brines, with relatively low concentrations of magnesium salts that should result from late-stage precipitation of salt deposits from sea water.

Over the last 100 years, extensive studies of sea-water evaporites, in relation to brine density, have been a topic of discussion. The development of evaporation models has facilitated the increased production and purity of solar salt (salt produced through evaporation of brine by the sun's energy). Conversely, this information can be utilized to gain an understanding of how rock-salt formations were precipitated from sea water by analyzing the elemental constituents of the rock salt and of the resulting brine. By evaluation of well-documented, phase-curve tables of sea-water evaporation, a basic theory can be formulated on how the Flowerpot salt unit was formed.

Whereas the evaporation of sea water has netted consistent and predictable results around the world, utilization of saturated brine formed by dissolution of the Flowerpot salt has yielded some unusual results. Crystallization of basic elements (such as calcium sulfate) known to precipitate from brines of lower densities has been identified in these saturated brines. Until recently, there was little understanding as to how and why these elements could remain in solution at such high densities.

The purpose of this paper is to present general observations based upon salt-production activities in northwest Oklahoma. Whereas the Big Salt Plain has long been a source of salt, there has been little study of the brine constituents formed by dissolution of the Flowerpot salt in this area.

DISCUSSION

The Big Salt Plain, located in northwest Oklahoma (Fig. 1), has been a documented source of salt production since early written records of the area. The salt flats consist mainly of alluvial sands of the Cimarron River. Big Salt Plain is flanked by the Cimarron Gypsum Hills, where high escarpments of red Flowerpot Shale are capped by gypsum beds of the Blaine Formation (Johnson, 1972).

Solar-salt production results from pumping saturated brine from the Flowerpot salt to the surface (Fig. 2). Specialized earthen pans are designed to maximize use of the prevailing winds to enhance evaporation. The earthen pans were constructed by leveling the sandy flood plain, building a series of earthen embankments to contain the brine, and then lining the ponds with reddish clays from the surrounding hills.

Harvesting of the salt is conducted annually in the fall, after the summer heat and winds have facilitated precipitation of salt in the earthen pans. The salt is removed, washed of impurities, and stockpiled for further processing. The processing plant produces a variety of products for water-conditioning, industrial, and agricultural uses.

The Flowerpot salt is located 80–100 ft below the land surface and consists of rock salt intermixed with lesser amounts of red and gray shale. Natural groundwater has dissolved small channels atop the salt unit, and these channels convey brine upward through fractured Flowerpot Shale and into the alluvium. Extensive drilling data indicate that the channels atop the salt unit are much like small "streams" that flow at the contact between the shale and salt. Hydraulic pressure and flow are considerable in these channels, and force the nearly saturated brine up to within a few feet of the surface.

Precipitation of minerals from evaporating sea water follows a basic phase curve, as shown in Figure 3.

Brine utilized for salt production at Big Salt Plain is chiefly from the upper surface of the Flowerpot salt, which should contain the highest amounts of magnesium chloride, if the precipitation of the salt went to late-stage crystallization from sea water. However, this is not the case, because magnesium chloride is lacking. Operations in West Texas and the Texas Panhandle that utilize other Permian salts do recover magnesium chloride, thus supporting the idea that Flowerpot salt formed in the early phase of solar evaporation.

The resulting salt produced is 99.5–99.8% pure sodium chloride (NaCl). The main impurities are calcium sulfate ($CaSO_4$) and wind-blown sand. As stated earlier, calcium sulfate (gypsum) typically is precipitated at lower densities prior to salt production,

Joachims, Greg, 1999, Solar-salt production in northwest Oklahoma, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 69–71.

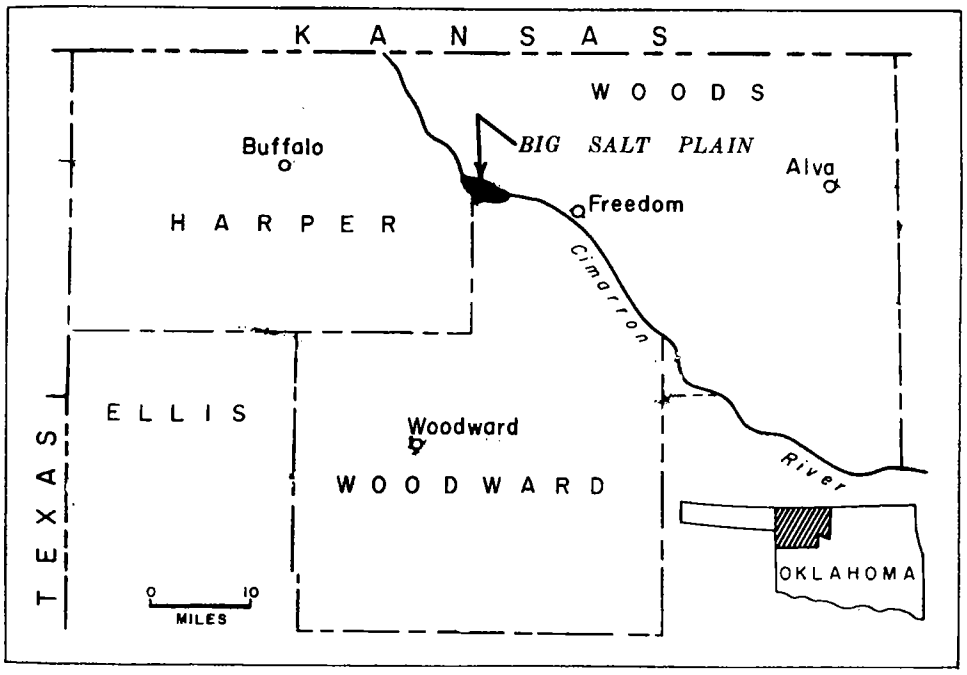


Figure 1. Location of Cargill's solar salt plant on Big Salt Plain in northwestern Oklahoma (from Johnson, 1970).

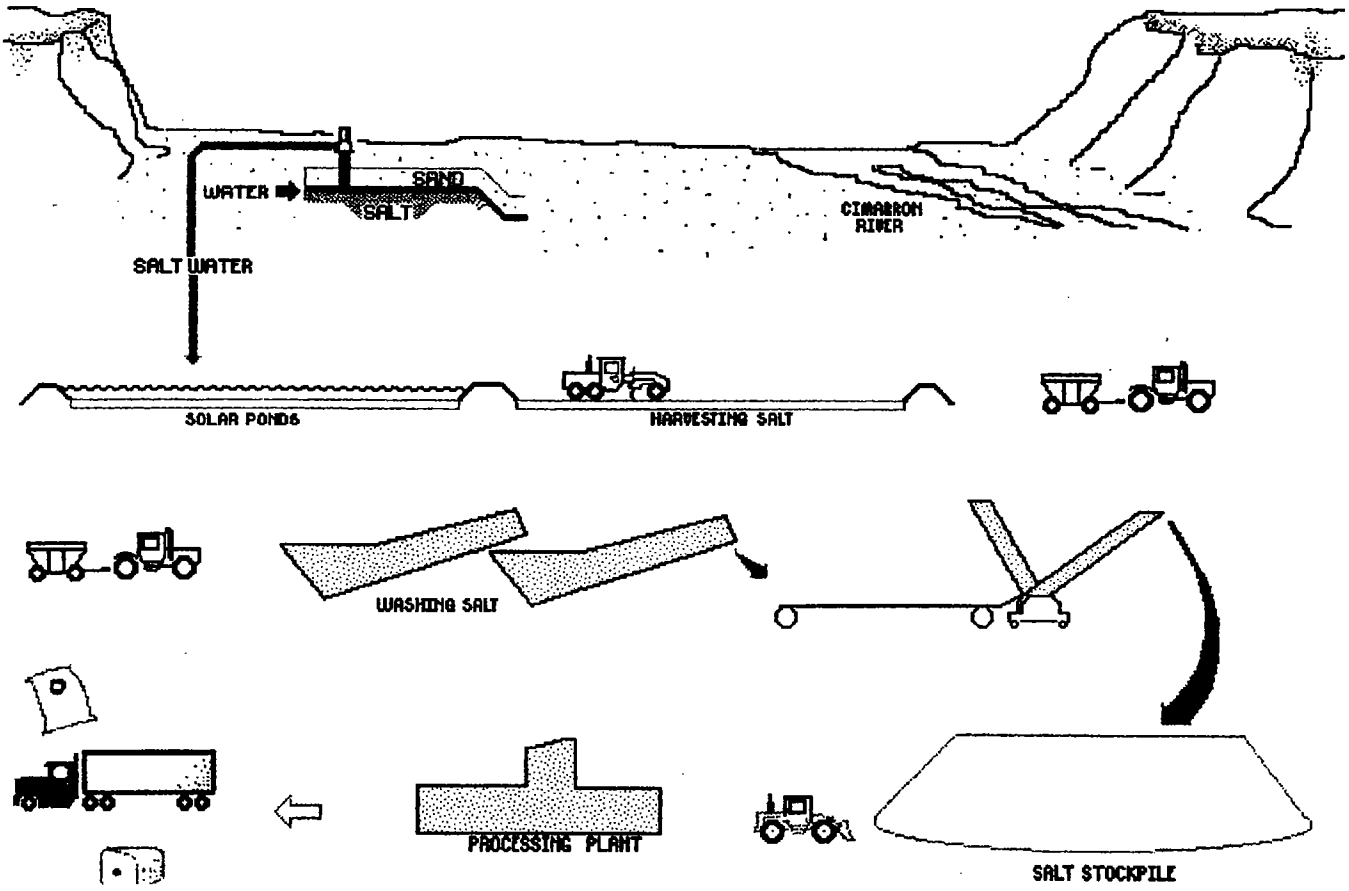


Figure 2. Schematic diagram showing production of solar salt at the Cargill, Inc., salt plant near Freedom, Oklahoma.

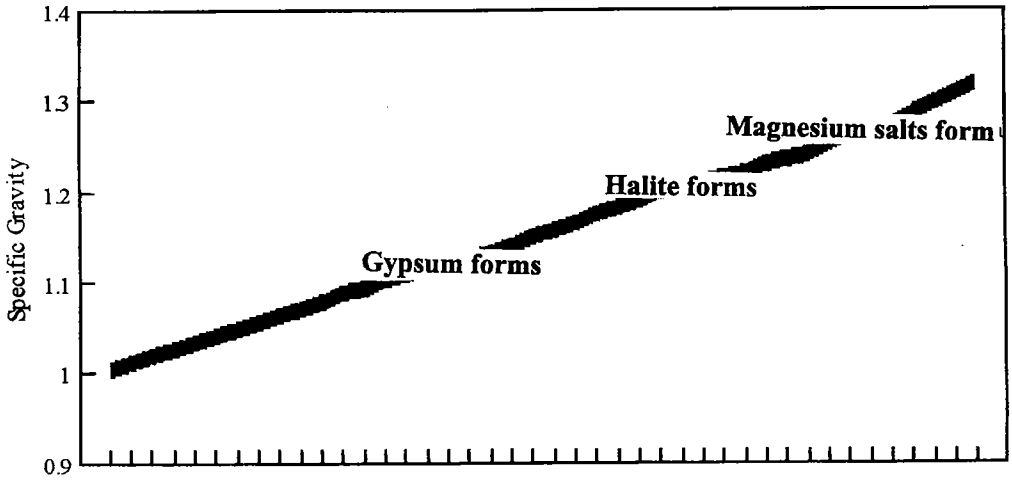


Figure 3. Graph showing the various minerals that normally crystallize from sea water with increasing specific gravity.

although continued analysis of brine has indicated differently.

The source of calcium sulfate is chiefly from dissolution of the gypsum beds in the Blaine Formation. As meteoric water flows through the cavernous gypsum hills and then down into the Flowerpot salt, gypsum ($CaSO_4 \cdot 2H_2O$) is dissolved, forming a hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$). The calcium-sulfate-rich water then continues to move underground, where it dissolves the Flowerpot salt to form brine.

The saturated brine does not readily precipitate the calcium and sulfate in a hemihydrate state. However, during rainfall events, the density of the brine may drop to a specific gravity of less than 1.2, allowing excess H_2O to combine with the hemihydrate and thus form gypsum that is precipitated across the earthen pans.

Solar-salt production on the Big Salt Plain has served to improve the economy of northwest Oklahoma and also to reduce the natural chloride degradation of the Cimarron River.

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Iodine Geology and Extraction in Northwestern Oklahoma

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ABSTRACT.—Oklahoma is the only state in the nation that is currently producing iodine. The iodine is extracted from iodine-rich natural brines being pumped from deep wells drilled into Pennsylvanian sandstones in the Anadarko basin of northwestern Oklahoma. Woodward Iodine Corp., started in 1977, was the first plant in the United States built for iodine recovery since the 1930s. At present, three companies are operating four iodine-producing facilities in northwestern Oklahoma. The combined production of these facilities, 1,321,000 kg in 1997, is about 26% of the U.S. annual consumption.

Iodine is present in concentrations ranging from less than 100 ppm (parts per million) to as much as 1,560 ppm in brines in various Paleozoic strata in the subsurface of northwestern Oklahoma; these concentrations are exceptionally high, and are well above those of any other known brines in the world. Strata with the highest iodine content in the area (Mississippian limestones) have low permeabilities, and thus would yield only small amounts of brine. On the other hand, the lower Morrow sandstones (Lower Pennsylvanian) have a relatively high permeability and are capable of yielding large quantities of brine that average 300–350 ppm iodine. The Morrow brine reservoir was deposited in shallow-water-marine and intertidal-shelf environments and now is buried 6,000–10,000 ft below the land surface. Production is localized to Morrow channel deposits confined to an Early Pennsylvanian paleovalley that is 1–2 mi wide, is about 70 mi long, and is referred to informally as the "Woodward trench." All three companies are producing iodine-rich brines from Morrow sandstones in three different parts of the Woodward paleovalley, and one of the companies also is extracting iodine from oil-field brines coming from several petroleum reservoirs near Dover, about 80 mi east of Woodward.

The basic extraction method employed by Woodward Iodine Corp. was used in Louisiana and California operations in the late 1920s. This method is commonly called the air-stripping process. Lower Morrow brine containing dissolved sodium iodide is pumped to the plant through a series of pipelines, where by-product natural gas is separated and processed. The brine is then acidified and subsequently oxidized with chlorine to convert the iodide to iodine. The iodine is air stripped and reabsorbed with sulfur dioxide and water, converting it to hydriodic acid, or process liquor. The process liquor is then processed, using chlorine once again, to crystallize the iodine as a solid. This is then melted and frozen to form a solid product, which is packaged in 110-lb (50-kg) drums and shipped to end users throughout the world.

HISTORY AND GEOLOGIC SETTING

This brief discussion about the history of iodine production in the United States and the geologic setting in northwestern Oklahoma is essentially reproduced from Johnson (1994), with updates from the U.S. Geological Survey (USGS, 1998a,b).

Iodine was first produced in the United States between 1917 and 1921, from seaweed harvested in California. However, anomalously high concentrations of iodine in brines is known in a number of major sedimentary basins in the United States (Fig. 1). The first commercial production of iodine from these U.S. brines was in Louisiana, between 1928 and 1932; some of

Johnson, K. S.; and Gerber, W. R., 1999, Iodine geology and extraction in northwestern Oklahoma, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 73–79.

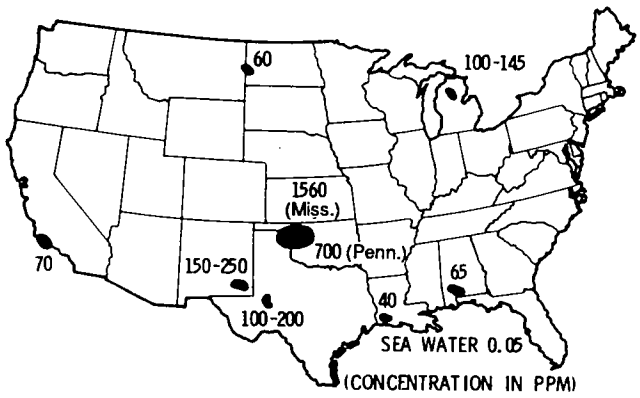


Figure 1. Areas of known iodine concentrations in the United States (from Cotton, 1978). Exceptionally high iodine concentrations in northwest Oklahoma are in Mississippian (Miss.) and Pennsylvanian (Penn.) strata.

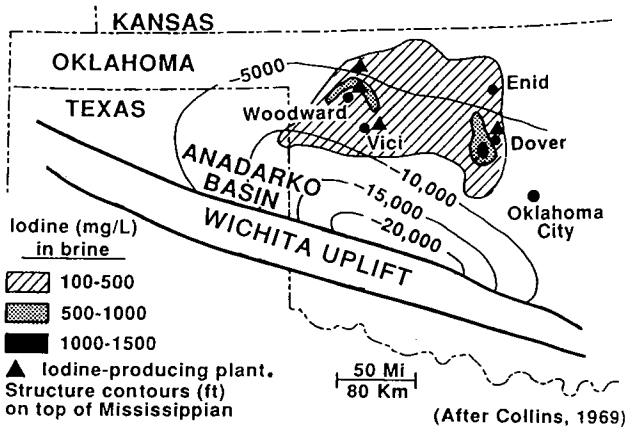


Figure 2. Map of western Oklahoma showing area of high iodine concentrations on the north flank of the Anadarko basin (after Collins, 1969). Structural contour lines are in feet below sea level.

the Louisiana oil-field brines contained about 35 ppm iodine (Lyday, 1986). Oil-field brines in parts of California contain 30–70 ppm iodine, and these were produced at various times between 1928 and 1966. In Michigan, natural brines containing an average of 15–30 ppm iodine were processed mainly for bromine, and by-product iodine, by Dow Chemical Company, until the wells were plugged and abandoned in 1987.

With closure of Dow's Michigan operation, iodine production in the United States now comes completely from iodine-rich (production brines average about 300–350 ppm iodine) natural brines in the deep subsurface of the Anadarko basin of northwestern Oklahoma (Figs. 2,3). Oklahoma production began in 1977, and three companies currently operate three major plants and one miniplant for the recovery of iodine. Total production from the three companies was: 1,207,000 kg (valued at $12.5 million) in 1995; 1,274,000 kg ($14.6 million) in 1996; and 1,321,000 kg ($19.6 million) in 1997 (USGS, 1998b). World production of iodine was 13,400,000 kg in 1995, 15,600,000 kg in 1996, and 15,500,000 (estimated) in 1997; the reported consumption of iodine in the United States in 1997 was 5,140,000 kg (USGS, 1998a). Therefore, in 1997 Oklahoma produced an estimated 9% of the world's output and 26% of the United States' reported consumption.

Oklahoma's first iodine operation was the Woodward Iodine Corp. It opened early in 1977 as a joint venture between Amoco Production Co. and Houston Chemicals, a subsidiary of PPG Industries (Cotton, 1978). In 1984, the company was purchased by Asahi Glass Co. of Japan (Lyday, 1986) and then was sold to Ise Chemical Industries Co. Ltd. of Japan in 1994 (USGS, 1998a). Discovery of these iodine-rich brines near Woodward resulted from a 12-year program of analyzing brine samples collected by Amoco (Cotton, 1978). Amoco noted unusually high concentrations of iodine from several formations in the Woodward area, with concentrations as high as 1,560 ppm iodine in low-permeability Chester (Upper Mississippian) limestones and up to 700 ppm in the more porous Lower Pennsylvanian Morrow sandstones.

The basal Pennsylvanian Morrow sandstones are as much as 200 ft thick in the area and are preserved as channel sands in a south-trending paleovalley (informally referred to as the "Woodward trench") that was cut into the underlying Chester limestone surface (Figs. 4,5). Although iodine concentrations are higher in the Chester limestones, these strata have low permeabilities and do not yield large volumes of water. On the other hand, Morrow sandstones here have a much higher porosity (about 14%) and permeability (about 20–40 millidarcies) and yield large volumes of brine averaging about 300–350 ppm iodine; production wells yield 5,000–10,000 barrels of brine per day (200,000–400,000 gal per day).

The Woodward trench has an average width of 1–2 mi and a known length of about 70 mi (Cotton, 1978). Woodward Iodine Corp. operates 20 production wells, extracts iodine from the brine at their Woodward plant, and then injects the waste brine back into Morrow sandstones within the trench through nine injection wells (Fig. 6). The main plant is located about 8 mi north of Woodward. Brine-production wells and injection wells are 7,000–8,200 ft deep at Woodward.

A second iodine-recovery plant in Oklahoma was started in late 1987 by Iochem Corp. of Japan. The Iochem plant, located near Vici, about 20 mi south of Woodward, also produces iodine-rich brines from Morrow sandstones at depths of 9,850–10,440 ft, in a southern extension of the Woodward trench. The company has 11 production wells and 5 injection wells.

North American Brine Chemicals operates the two remaining iodine-recovery plants in Oklahoma. The company built a major facility about 20 mi north of Woodward in 1989, where they produce iodine-rich brine from Morrow sandstones in a northern extension of the Woodward trench. This facility operates three production wells and three injection wells, all about 6,000 ft deep. The company also operates a miniplant near Dover where they extract iodine from oil-field brines collected from about 50 oil and gas wells that

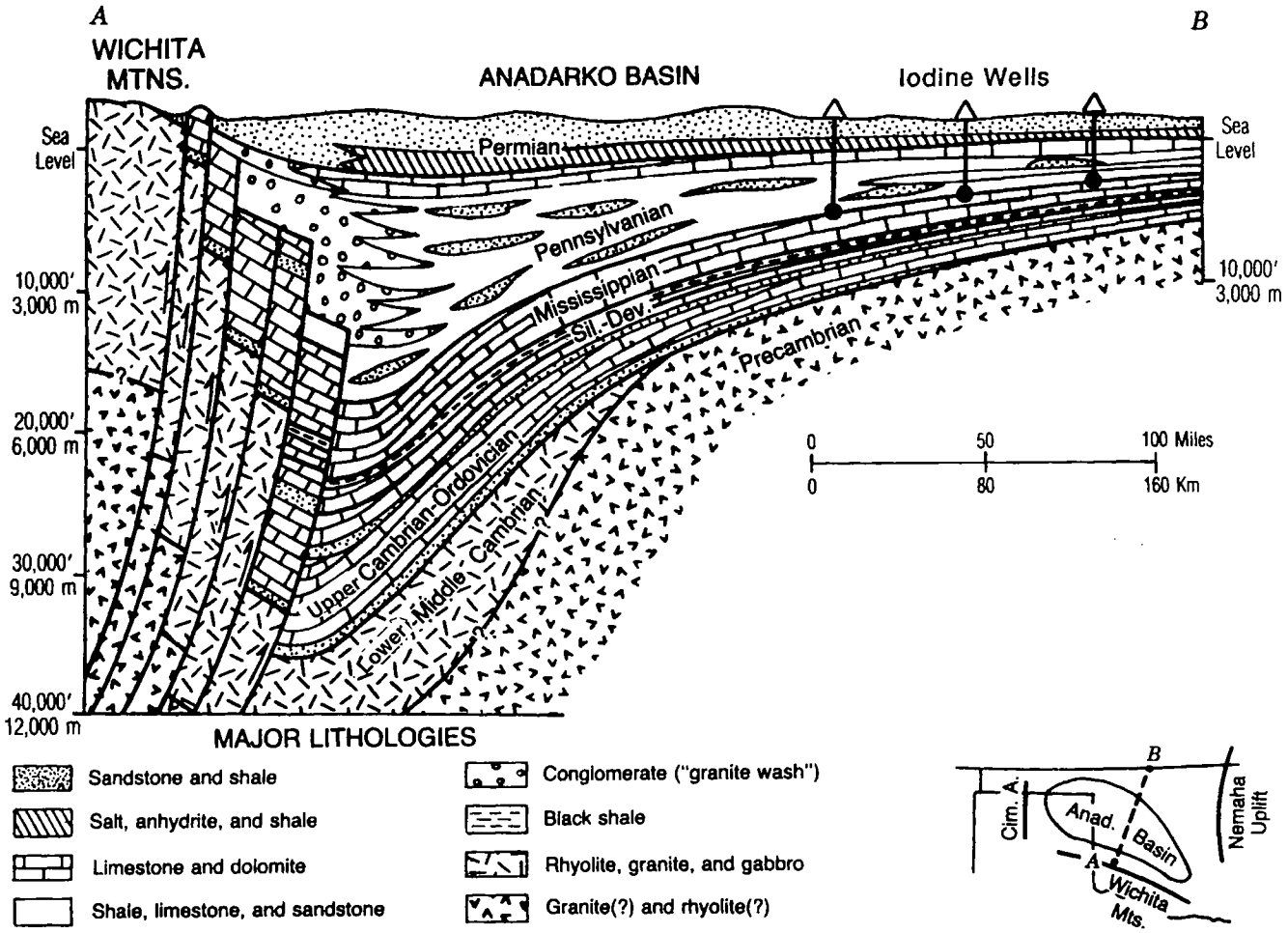


Figure 3. Generalized north-south structural cross section (A–B) through the Anadarko basin of western Oklahoma (modified from Johnson, 1989). Iodine-rich brines are produced from basal Pennsylvanian (Morrow) sandstones on northern flank of the basin.

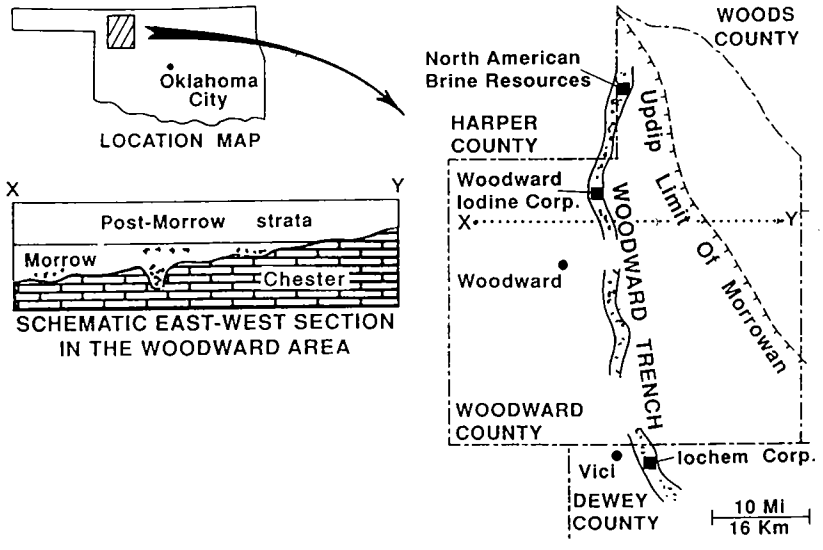


Figure 4. Map and schematic cross section (X–Y) showing relationship of Morrow strata to the paleovalley referred to as the Woodward trench.

produce from several formations in nearby parts of northwestern Oklahoma. Iodine, present in concentrations of from 100 ppm to more than 1,000 ppm, is stripped from the brines, and the waste water then is injected into the subsurface in a brine-disposal well. North American Brine Chemicals is a joint venture of Beard Oil Co. (40% share) and two Japanese firms (Godoe, Ltd., 50% share, and Mitsui and Co. Ltd., 10% share).

To capitalize on these four iodine-producing operations, another company, Deepwater Chemical, opened a new plant at Woodward in 1994 to manufacture a range of inorganic and organic compounds from the crude iodine.

The origin of the iodine-rich brines on the north flank of the Anadarko basin has been an enigma for many years. Recent work on iodine-isotope ratios by

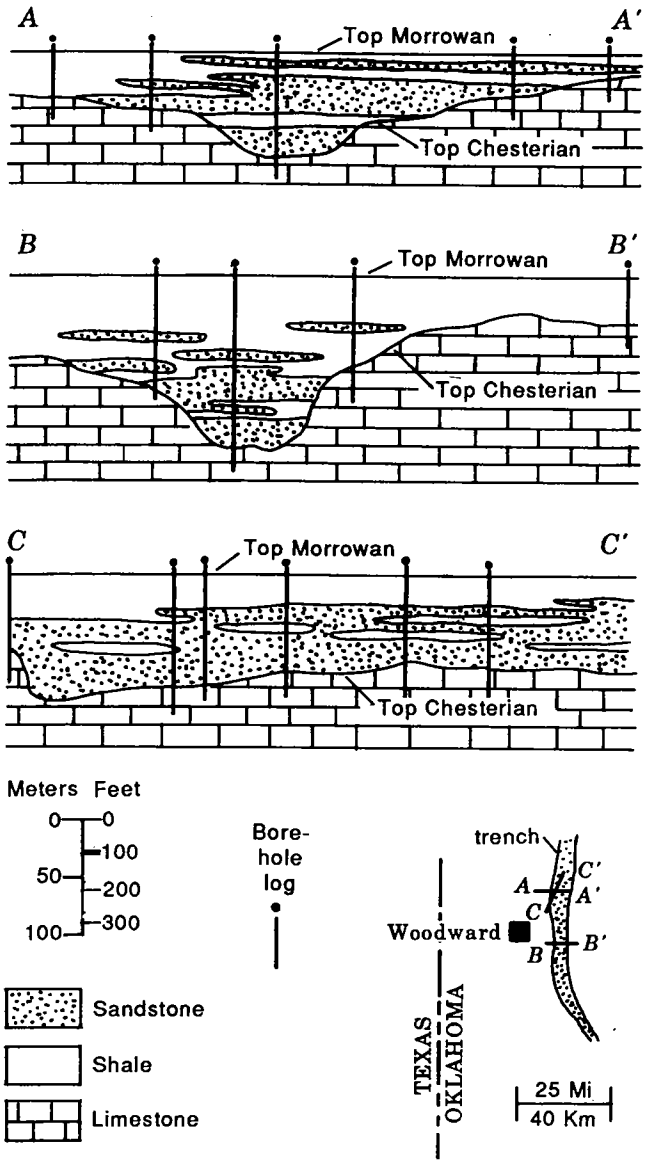


Figure 5. Cross sections showing iodine-bearing Morrow channel sandstones preserved in the Woodward trench that has been cut into the underlying Chester limestones (from Johnson, 1994; modified from Cotton, 1978). Datum is top of Morrow strata. Length of A–A′ and B–B′ is about 10 km; length of C–C′ is about 15 km.

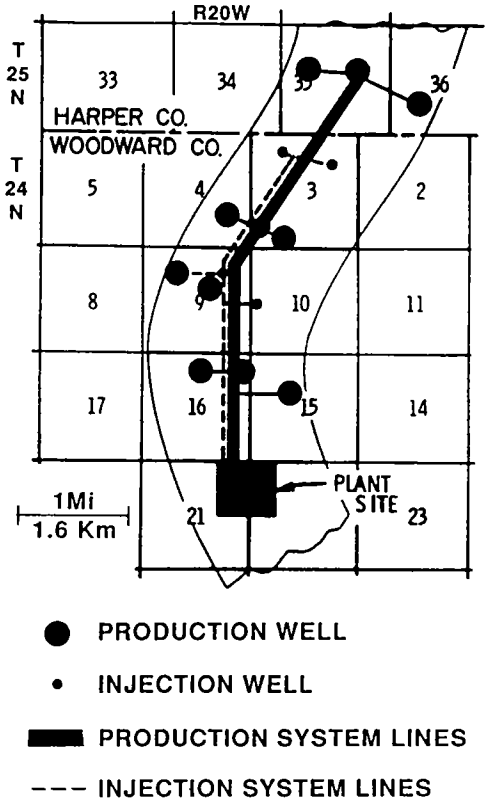


Figure 6. Map showing wells and production system for part of the Woodward Iodine Corp. plant north of Woodward (from Cotton, 1978).

Moran (1996) indicates that the Woodford Shale (an Upper Devonian–Lower Mississippian, organic-rich shale) is the probable source formation for these high iodine concentrations, and that iodine-rich brines migrated from the Woodford Shale into a number of brine reservoirs in northwestern Oklahoma.

EXTRACTION METHOD AT WOODWARD IODINE CORP.

The following description of extraction methods is modified from an internal company report of Woodward Iodine Corp. by R. S. Cook.

The basic extraction method employed at Woodward (Fig. 7) was used in Louisiana and California operations in the late 1920s. This method, now used by Japanese iodine producers, is commonly called the air-stripping process. One of the major advantages that Woodward brine has over other domestic and many foreign reserves is its relatively high iodine concentration, which is several times the concentration of most other known reserves. Consequently, capital-investment requirements and operating costs compare favorably with those of other producers.

Bringing Brine to the Recovery Plant

The technology of the Woodward facility was tailored by PPG's technical staff for the character of the Woodward brine. Environmental safeguards and corrosion-resistant construction materials were major items considered in the design of the Woodward facility. The process provides for total containment and recovery of iodine and other chemical vapors, resulting in no emissions to the atmosphere. The process equipment was built using advanced materials of construction that can cope with the extremely corrosive materials handled. From an environmental point of view, the plant is designed to provide total containment of the iodide-bearing waters by re-injection of the depleted brines into the same formation (Morrow sandstones) from which they were produced. Land subsidence is thereby

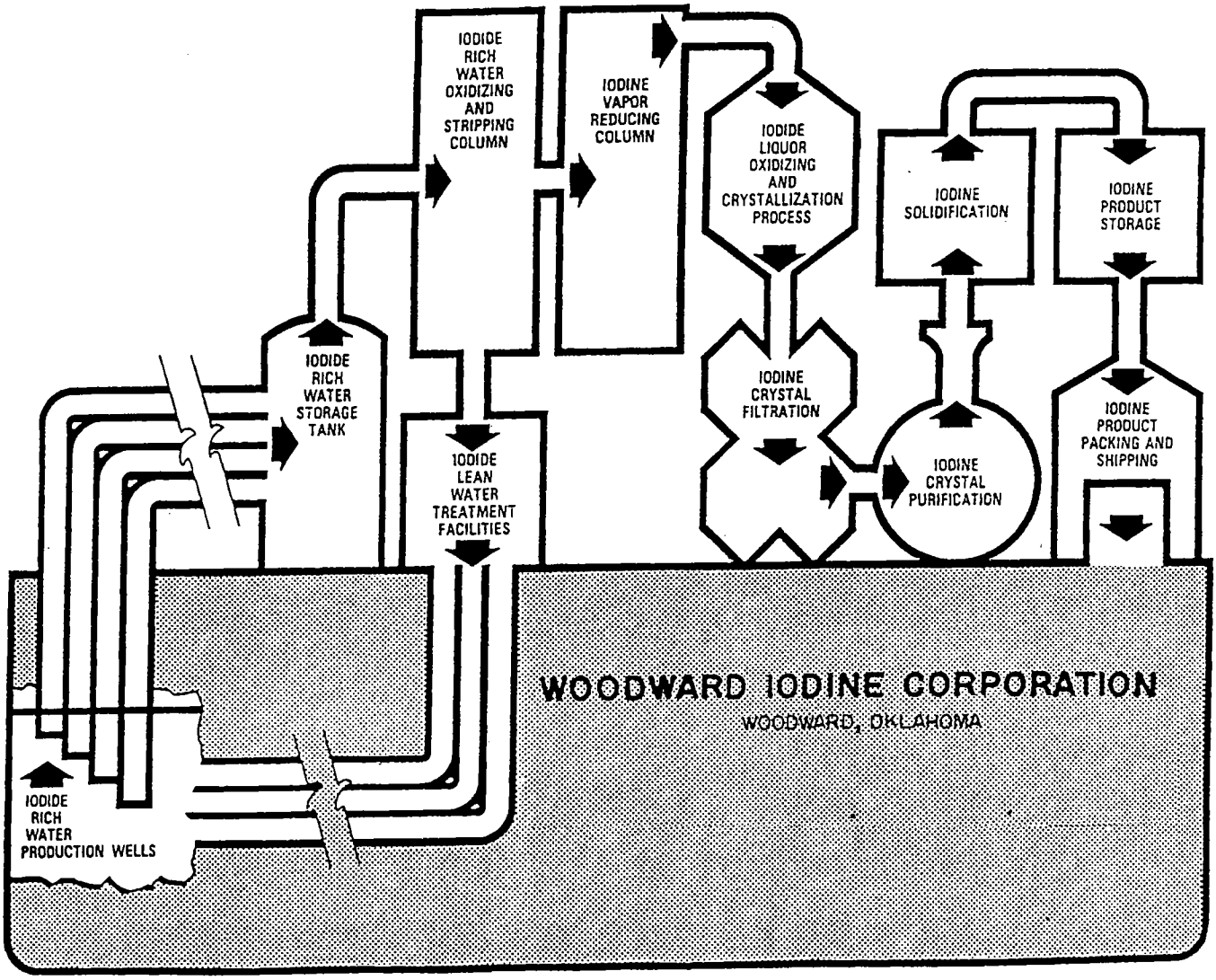


Figure 7. Flow sheet for the iodine process used at the Woodward Iodine Corp. plant north of Woodward.

avoided, and fluid pressures in the reservoir are maintained. Amoco developed the waterflood methods used to raise iodine-rich brine to the recovery plant and to then dispose of waste brine after iodine has been removed. Amoco also set up a gas-processing method to remove by-product natural gas contained in the brines handled by the iodine-recovery plant. PPG Industries' Chemicals Group's experience in chemical-plant design and operation enables efficient removal of the iodine from the brine.

Extracting Iodine from Brine

Iodine occurs in the natural brines as a soluble compound, sodium iodide. After natural gas (primarily methane) is flashed from the brine, some sulfuric acid is added to maintain the pH below 4.0 to ensure efficient iodine liberation in the oxidation and stripping process. Gaseous chlorine serves to oxidize the iodide in the brine to iodine. After the oxidation stage, the brine passes through a packed column where free iodine is stripped from the brine as it is exposed to large volumes of air. The depleted effluent that leaves the stripping column is then treated and returned to the original formation. The iodine vapor is carried by the air-process stream from the stripping column to an absorbing column, where a reducing atmosphere is maintained by the injection of gaseous sulfur dioxide and water. The basic chemical reactions that take place in the oxidation and reduction stages of the stripping and absorption steps are as follows:

Oxidation: $2I^{-1} + Cl_2 \rightarrow I_2 \uparrow + 2Cl^{-1}$

Reduction: $I_2(air) + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$

Absorbing-tower concentrations are controlled at optimum hydriodic-acid levels by the continuous addition of water and withdrawal of hydriodic- and sulfuric-

acid solution. This solution is kept in an interim-storage vessel.

In acid solution, chlorine gas reacts with hydriodic acid to form crystalline iodine. The process liquor accumulated in the interim-storage vessel is processed through the oxidizing and crystallization steps. The crystallizer vessel contains agitated absorbed liquor into which gaseous chlorine is injected. The rate and quantity of chlorine addition are precisely controlled to avoid particle contamination, over-oxidation, and resultant product loss. The best available oxidation/reduction-potential instruments are used to control this step. The reaction taking place here is:

$$2\,HI + Cl_2 \rightarrow I_2 \downarrow + 2HCl$$

The oxidized crystallizer liquor is a mixture of water, sulfuric acid, hydrochloric acid, and iodine crystals.

Converting Iodine Crystals to Flakes

After the crystallization step, it is necessary to separate the crystals from the mother liquor. This is done through batch filtration, followed by vacuum drying of the filter cake. The filtrate is recovered and reused at the front end of the plant, where the sulfuric and hydrochloric acids serve to acidify incoming brine. Wet iodine filter cake is transferred to a heated purification vessel containing molten iodine under a layer of hot, concentrated sulfuric acid. As the filter cake settles through the hot sulfuric acid, the acid effects additional drying of the crystals. The diluted acid is withdrawn and replaced with fresh 93% sulfuric acid. The diluted sulfuric acid withdrawn from the purification vessel is recovered and reused at the front end of the process to acidify the incoming brine. The molten iodine accumulated in the purification vessel is processed through a final solidification step designed to produce flakes. The iodine flakes are packaged in 110-lb (50-kg) fiber drums and stacked on pallets for shipment.

USES OF IODINE

The following discussion of uses is from Lyday (1989a,b), as presented by Johnson (1994).

Iodine was discovered in 1811 and identified as a new element in 1813. Iodine products were first used commercially in the late 19th and early 20th centuries as a remedy for goiter, as a disinfectant for cuts and abrasions, and for sanitation. Since then, iodine has been used in a variety of specialty chemicals for many commercial applications. Major uses include disinfectants, pharmaceuticals, stabilizers, catalysts, animal feeds, colorants, and photography.

Disinfectants

The major use of iodine is in the manufacture of disinfectants. Iodine is an effective germicide for many microorganisms, and its compounds are used in dairies, laboratories, food-processing plants, and dish washing in restaurants. Iodine also is used as a disinfectant in swimming pools and in water supplies.

Pharmaceuticals

Pharmaceuticals are another major use of iodine, mainly as radiopaque media that are injected into the blood stream for producing X-ray photographs of the internal structure or blood circulation of the body. Potassium iodide is widely used in cough medicines as an expectorant, and iodine compounds are used in the synthesis of amphetamine, methamphetamine, and ethylamephetamine.

Stabilizers

A third major use is as a stabilizer in the manufacture of nylon for tire cord and carpets, and for converting rosins, tall oil, and other wood products to more stable forms.

Catalysts

Another important use of iodine is in catalysts. With development of the Monsanto process for producing acetic acid (using an iodine-promoted rhodium complex as catalyst) in the 1960s, most new acetic-acid producers used this process. Iodide catalysts also are used in the dehydrogenation of butane and butene to butadiene, and in the preparation of stereo-regular polymers.

Animal Feeds

Another important use of iodine is in the form of additives for animal feeds. Cattle and sheep are fed iodized salt and other iodine compounds to reduce certain livestock ailments, such as soft-tissue lumpy jaw and goiter.

Colorants

Iodine is a coloring agent in some red dyes used in foods and on materials. Red food coloring has been used in carbonated soft drinks, powdered drinks, gelatin desserts, icings, and pet foods, whereas red dyes are used in dyeing and/or printing of cotton, half-silk, jute, and straw products.

Photography

Photography is one of the oldest industrial uses of iodine. As much as 7% of the silver salt in the emulsions of negatives is iodide, and ammonium iodide is used as a photographic developer.

Other Uses

Iodine is also used in: (1) the modification of selenium to make semiconductors; (2) the manufacture of high-purity metals, such as titanium, zirconium, boron, and hafnium; (3) the production of motor fuels; (4) making additives for rechargeable dry cells; (5) production of smog inhibitors; and (6) as cloud seeders to induce rainfall.

End uses for iodine in 1996 were estimated, from a USGS (1998a) canvass of consumers, as follows: sanitation (39%); pharmaceuticals (24%); heat stabilizers (13%); catalysts (9%); animal feeds (7%); and other

(8%). The "other" uses included inks and colorants, photographic chemicals, laboratory reagents, production of batteries, high-purity metals, motor fuels, and lubricants.

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Industrial Minerals and Regulatory Requirements in Oklahoma

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INTRODUCTION

The regulatory landscape has changed considerably since the first passage of Oklahoma's land-reclamation requirements in 1968 (Open Cut Reclamation Act of 1968). The Oklahoma Legislature revised the reclamation requirements in 1971 with passage of the Mining Lands Reclamation Act. With the passage of this Act, the Legislature empowered the Oklahoma Department of Mines with jurisdiction for permitting and regulatory authority over non-coal (industrial-minerals) mining operations. This act required all operators to file with the State, through the Department of Mines, a written application for a permit to engage in non-coal mining. Each application consisted of a mining plan, which included location maps of the proposed mining area along with a reclamation plan for the area to be covered. Additionally, a reclamation bond is required prior to issuance of a permit to ensure that the site would be reclaimed.

Since 1971, the Act has been amended to include public notification and public participation in the review process of any application. Also, the operator can request that the Department review the mining plan based on the *Life Expectancy* of the mine, instead of the original one-year plan (HB 1409 in 1993). Even though the operator is granted a mining plan tied to the "Life Expectancy" of the site, the permit is reviewed annually for compliance as required by law.

In 1983, the Department promulgated a set of "Rules and Regulations for the Non-Coal Division of the Department of Mines" (Section 460:10, subchapters 1–37). These rules consist of permitting and bonding requirements, reclamation-release procedures, and State authority and inspection requirements. In 1994, the rules were revised to require more information with respect to an operator's reclamation plan. This detailed plan includes a plan for permanent vegetation, best management practices to assist in erosion control and off-site siltation, and a handling plan for any settling ponds and tailings-disposal areas on the permitted land. The revised rules require each company to submit its plan in a narrative form, with an accompanying *reclamation map*, which documents the referenced plan, outlines the areas affected, and shows the planned post-mine usage (460:10-15). In addition to new permitting guidelines for all non-coal operations, the rules outline strict conditions for operating in the watershed of a *scenic river* (460:10–13). In June 1998, the Legislature passed a new law that requires public display of the mining application near the proposed site, to allow more public access to the permitting process.

Although one might assume that the new regulations and permitting guidelines would cause the industrial-minerals industry in Oklahoma to suffer a decline, the opposite is quite true. The Department administers more than 400 mining permits on an annual basis. The production reported to the Department for last calendar year (1997) reached a new peak at 57,342,990 tons of industrial minerals mined in the State.

PERMITTING REQUIREMENTS

The State of Oklahoma environmental requirements for non-coal (industrial-minerals) mining are administered by more than one regulatory agency. Air and water issues are regulated by agencies other than the Department of Mines. The Oklahoma Department of Environmental Quality (ODEQ) regulates, through permitting and inspection, the Storm Water Run Off Program and the Point Source and Non-Point Source water discharges, under Oklahoma Pollutant Discharge Elimination System permitting activity. The ODEQ also regulates the fugitive dust from mine sites through the Air Quality Program. The U.S. Army Corps of Engineers, along with the ODEQ, issues permits to allow non-coal mining in the rivers and streams of the State, providing that such actions comply with Section 404 of the Federal Clean Water Act and Section 401 of the Federal Pollution Control Act. Each respective agency has specific jurisdictional boundaries. There is no overlap or duplicate enforcement, and these environmental regulations are concurrent with each other. For the purpose of this paper, only the permitting responsibility of the Oklahoma Department of Mines will be outlined.

Johnson, Steven; and Schooley, Douglas, 1999, Industrial minerals and regulatory requirements in Oklahoma, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 81–83.

APPLICATION PACKAGES

Specific statutory requirements for permitting of non-coal mining operations are found under Title 45, Chapter 8A, of the Mining Lands Reclamation Act, Sections 721 through 738. Non-Coal Rules and Regulations, Oklahoma Administrative Code 460:10, Sections 1 through 31, covers the permitting process, the posting of bonds, and the blasting plan. The required documents for an *application package* follow.

Formal Application Section

This section is used to disclose the operator's name, address, and phone number, as well as the method of mining, legal description, bonded and permitted acreage disclosure, and bonding instrument used. A *Landowner Disclosure and Public Information* page is located in this section. This form references the legal estate status of the site and also outlines the additional permits needed from other regulatory agencies. An attachment to this section of forms is the *Compliance Information* document, which requests disclosure of past practices and operations, and corporate or individual disclosure. An instrument of legal estate verification is a required attachment to be included with this section. A *Statement of Certification*, pertaining to legal right of entry and the accuracy of the information contained in the application, must be attached to the application, executed and sworn to by the applicant.

Reclamation Section

This section discloses and justifies the post-mine land use of the permit area. The reclamation standards for permitting disclosure were revised in 1994 to require a detailed process for reclamation. The *Reclamation Plan Section* must include, to the extent applicable, the following six items:

1. The methods to prevent or eliminate conditions that will be hazardous to animal or fish life in or adjacent to the affected land;
2. The methods for rehabilitating settling ponds;
3. The method for the control of contaminants and disposal of the refuse, including tailings;
4. The method to provide safety to persons and adjoining property owners;
5. The plan for permanent revegetation, including soil tests, site preparation, and seeding;
6. Best management practices that will be used on the mine site.

In addition to the required site maps, a map that describes and justifies the post-mine reclamation should be submitted with the plan. Useful attachments for the plan can be topographic maps, flood plain area maps, soil data, and/or reclamation cross sections and maps.

Mapping Requirements

State law requires grid Location Maps to be filed with the application. Additionally, the application must contain a Site Map. This map must be an accurate representation of the requested acreage to be permitted. This map must have, as a minimum, the plotted location of the plant site, processing area, stockpiles, sediment ponds, excavation locations, haul roads, scale house, and all support facilities. This map must be scaled to accurately represent the acreage being disclosed. These maps will have the permit area outlined, as well as the bonded area indicated; this should include any property setbacks as required by law. Transmission, electrical, fluid, or gas lines must be plotted on these maps. The maps utilized for this purpose should be aerial photos, topographic maps, or a metes-and-bounds survey.

Blasting Plan

A *Blasting Plan* (only required with explosives) must be submitted on those locations where explosives will be used as part of the mining procedure. A *Blasting Plan* requires disclosure of the blaster's name and State Certification Number. Types and amount of explosives are to be referenced, as well as procedures for control of site, and the plans for blasting signals and blasting procedures. Procedures include the use of a seismograph or the utilization of the Standard Weight Distance formula outlined in the Department's Rules and Regulations for Non-Coal Mining. A copy of the blaster's recording form is to be attached to the plan for retention requirements of each shot fired.

Reclamation Bond

Statutory law requires an operator to post a Reclamation Bond to insure reclamation of the permit site. The bond is conditioned for performance of the documented Reclamation Plan. The State will accept either a surety bond or a collateral bond. Each bond amount, form, and duration must be accepted by the Department prior to permit issuance.

AFTER COMPLETION OF PERMITTING APPLICATION

Figure 1 is a flow chart that represents the permitting procedures that are followed. Once all permitting documentation has been received, and the application is considered complete, a copy of the documents is submitted to the appropriate County courthouse for public access and viewing. When the application is filed for public review, the applicant must publish a *public notice* disclosing the intent of the applicant, the legal location of the mining operation, and the location of the public-inspection copy. Said notice must be published once a week for four consecutive weeks. The public notice will state that comments, objections, or a hearing on the application will be allowed by qualified protestors. Once the notice is published, an *affidavit of publication* must be submitted to the Department to document this action.

All hearings and conferences requested will be held in accordance with the Department's Non-Coal Rules and Regulations, the Department's Rules of Practice and Procedure, and the Oklahoma Administrative Procedures Act. The Department's rules do allow for an

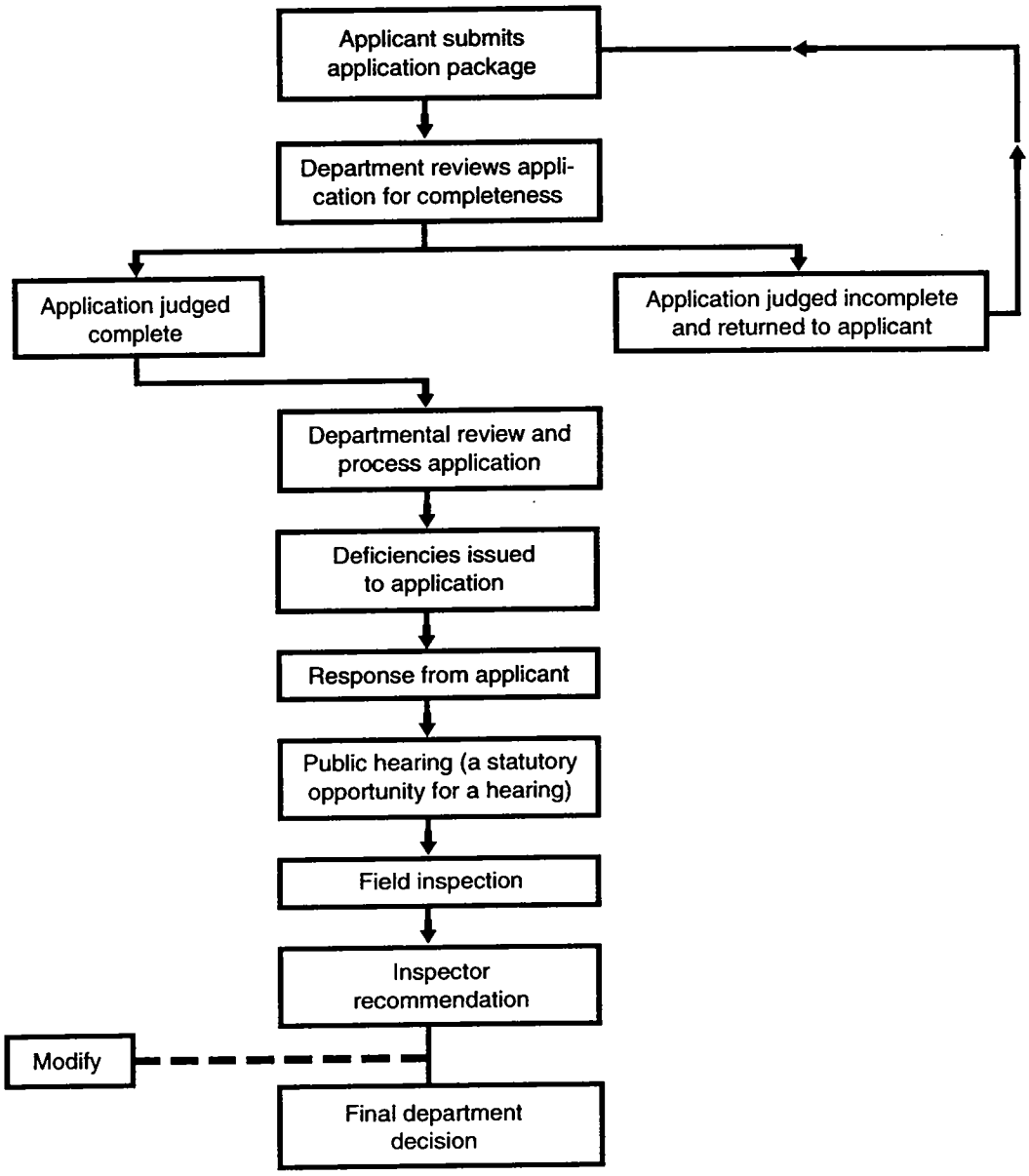


Figure 1. Flow chart showing industrial-minerals-permitting procedures of the Oklahoma Department of Mines.

internal appeal of the conference officer's findings. A formal hearing will be provided for those who have appealed, allowing for adjudication in a formal setting in front of an administrative-law judge.

Even if a hearing is not requested, a field inspector reviews the application, prior to any permit issuance, and inspects the proposed location for site evaluation and recommendations. Based on this field inspection or a hearing determination, the plan may be modified or conditioned. All permits issued by the Department are approved by the Director, and are considered final orders of the Department.

Geology of Crushed-Stone Aggregate Resources in Arkansas

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ABSTRACT.—Rock suitable for crushed-stone aggregate is almost entirely restricted to the Highlands region of Arkansas, mostly from Paleozoic sedimentary units, but also from a few Cretaceous igneous plutons. Reserves in the state are sufficient for local needs, and Arkansas is geographically well situated for export markets to the south, where resources for crushed-stone aggregate are lacking. A study of 423 quarries, test pits, and exploration sites in Arkansas has been completed to evaluate the relative quality of bedrock units for producing crushed aggregate. Of these, 274 sites have records of engineering tests for stone evaluation done by the U.S. Army Corps of Engineers and/or the Arkansas State Highway and Transportation Department (AHTD). Of the 1,775 sample records from these sites, the most commonly reported parameters are the LA abrasion test and the Na-sulfate soundness test. Many records also have absorption and specific-gravity data, and, for some, petrographic information helps identify the potential for alkali-silica reactivity in portland-cement concrete. By determining the bedrock sources of the tested samples, comparison is made between the various geologic mapping units as to their relative quality for crushed stone.

INTRODUCTION

The crushed-stone industry is important to the economy of Arkansas in terms of both domestic needs and out-of-state trade. Stone aggregate is essential for maintaining existing infrastructure in the state and for expansion to meet the needs of a growing population. Arkansas, with abundant near-surface hard rock that is suitable for construction aggregate, is also strategically located for supplying this material to neighboring Gulf Coast states that lack this resource. The national movement to "Superpave" specifications in road design is increasing the role of crushed aggregate, as opposed to river gravels, in highway construction (Cominsky and others, 1994), thus heightening interest in Arkansas as a base for exports.

To meet the growing demand for information regarding stone resources in Arkansas, a project was conceived to determine the suitability of the various bedrock sources for crushed-stone construction aggregate in the state, as well as to identify problems and/or special benefits peculiar to specific bedrock units. Preliminary results from that project were presented at the 31st Forum on the Geology of Industrial Minerals (Kline, 1996). A full report on the completed project is now in press for publication by the Arkansas Geological Commission. The report presented here is a summary of these results.

METHODS OF STUDY

A number of techniques have been devised to test stone for its suitability in construction (Marek, 1991). Both the AHTD and the U.S. Army Corps of Engineers have used considerable amounts of stone produced in Arkansas and have required testing to qualify stone for use in their projects. Test records dating back to the 1940s were obtained from the Corps of Engineers, and records starting from 1970 were obtained from AHTD. These records provide the basic data used in the present study to evaluate the geologic bedrock units that have been utilized in Arkansas.

The most commonly reported test data from the two sources were results from the LA abrasion test (American Society for Testing and Materials test ASTM C 131) and the sodium sulfate (or magnesium sulfate) soundness test (ASTM C 88). These tests evaluate a stone's durability in different ways. The LA abrasion test measures the stone's ability to resist degradation by abrasion and impact (Marek, 1991). The Na-sulfate soundness test simulates freeze-thaw conditions; a material susceptible to freeze-thaw degradation should fare poorly in the test. Mg-sulfate soundness test results can be converted to approximate Na-sulfate soundness equivalents by dividing by a factor of 1.5.

Besides these two tests, specific gravity and absorption were reported enough to be used in the present

Kline, S. W., 1999, Geology of crushed-stone aggregate resources in Arkansas, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 85–93.

study. Specific gravity (SG) is helpful in determining suitability for use as riprap and is also an essential parameter used in asphalt-mix design. Absorption indicates how much bituminous binder will be absorbed by the aggregate in asphalt-pavement mixes; materials with high absorption will require more binder, increasing costs. Petrographic data were also included in a number of Corps of Engineers data sheets, supplying information regarding potential for alkali-silica reactivity (ASR) in portland-cement-concrete (PCC) applications.

To apply the stone test data to geologic bedrock units, sample source locations were first determined and plotted on 7.5-minute topographic quadrangles. For most of the tests, information regarding the site location was included, but inaccuracies were found, especially in the older AHTD records. Where locations were questionable, field visits were made to resolve the conflicts by finding the site and plotting its position, using a Global Positioning System (GPS) receiver as an aid. The quadrangle locations were then transferred to geologic maps to assign the sample tests to mapped rock units. The maps employed were "geologic worksheets" available through the Arkansas Geological Commission, which are photo-reduced 7.5-minute quadrangles that include mapped contacts between bedrock units.

Once all the sites were accurately determined, the test data were compiled according to bedrock units, and histograms were constructed for comparing the relative performance of rock from these units on the engineering tests. The results of these comparisons are presented below. In addition to the analysis of the raw data, some matters related to the suitability of stone from the various formations are addressed, based on personal observations and discussions with AHTD personnel, quarry operators, and other professionals.

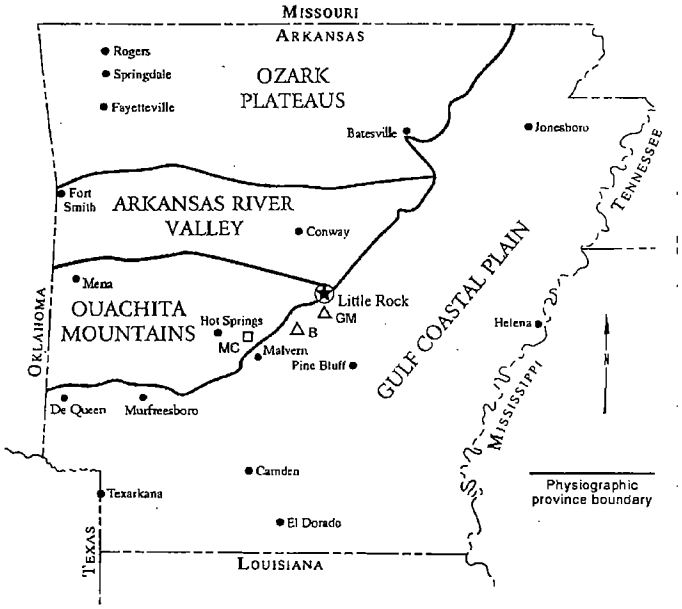


Figure 1. Map of Arkansas showing general physiographic divisions. Well-lithified sedimentary rocks of Paleozoic age occur in the Ozark Plateaus, Arkansas River Valley, and Ouachita Mountains. Generally unconsolidated sediments of Cretaceous and younger age occur in the Gulf Coastal Plain. Two prominent nepheline-bearing syenite plutons are designated with triangles (GM = "Granite Mountain"; B = the pluton near Benton). The Magnet Cove alkaline-intrusive complex is shown with a square designated MC.

RESULTS

The various bedrock units as aggregate sources will be discussed in sections according to the physiographic regions of the state (Fig. 1). Each section of this discussion will begin with a brief introduction to the general geology of the region. Only the "Highlands" portion of the state, which contains all the "hard rock," will be covered (Ozarks, Arkansas River Valley, and Ouachitas), because the Gulf Coastal Plain has only unconsolidated sediments, with a limited amount of gravels that are coarse enough for producing crushed aggregate.

Ozark Plateaus Region

Bedrock in the Ozark Plateaus region consists of generally flat-lying, bedded sedimentary rocks ranging from Ordovician to Pennsylvanian age. A slight southerly regional dip causes lower parts of the section to be exposed in the north and upper parts to crop out toward the south. The lower part of the section is dominated by carbonates, both limestone and dolostone, with minor shale and sandstone. The upper part is dominated by shale with some sandstone and limestone. The only structural disruptions are a few normal faults and very gentle folds. The topography of the Ozarks is composed of dissected plateaus, expressed in the northern part of the region as rolling hills with isolated mountains, and in the southern part as the Boston Mountains, formed by deep dendritic erosion of the highest plateau. For the distribution of lithologic units, readers are referred to the Geologic Map of Arkansas (Haley and others, 1993).

LA abrasion and Na-sulfate soundness data compiled from the AHTD and the Corps of Engineers from sites in limestone bedrock units are presented as histograms in Figure 2. The LA abrasion and soundness restrictions of 40% and 12% loss shown as reference lines on Figure 2 are recommended pass/fail values for first-class aggregate used in asphalt surfacing and PCC pavements (Nichols, 1991; White, 1991). These standards are employed for many aggregate applications in AHTD jobs. They are not, however, universally applied throughout the United States.

Of the limestone units that have been used for aggregate, the Pitkin Limestone shows the most consistent favorable results (Fig. 2B). This unit extends from east to west across the entire Ozark region, but its outcrop belt is for the most part narrow, because it is a bluff-forming unit in rather mountainous terrane over most of its extent.

The most widely utilized rock unit in the Ozarks is the Boone Formation, which is mostly limestone. This high degree of utilization is both because durable limestone is produced from it (Fig. 2A) and because it has a

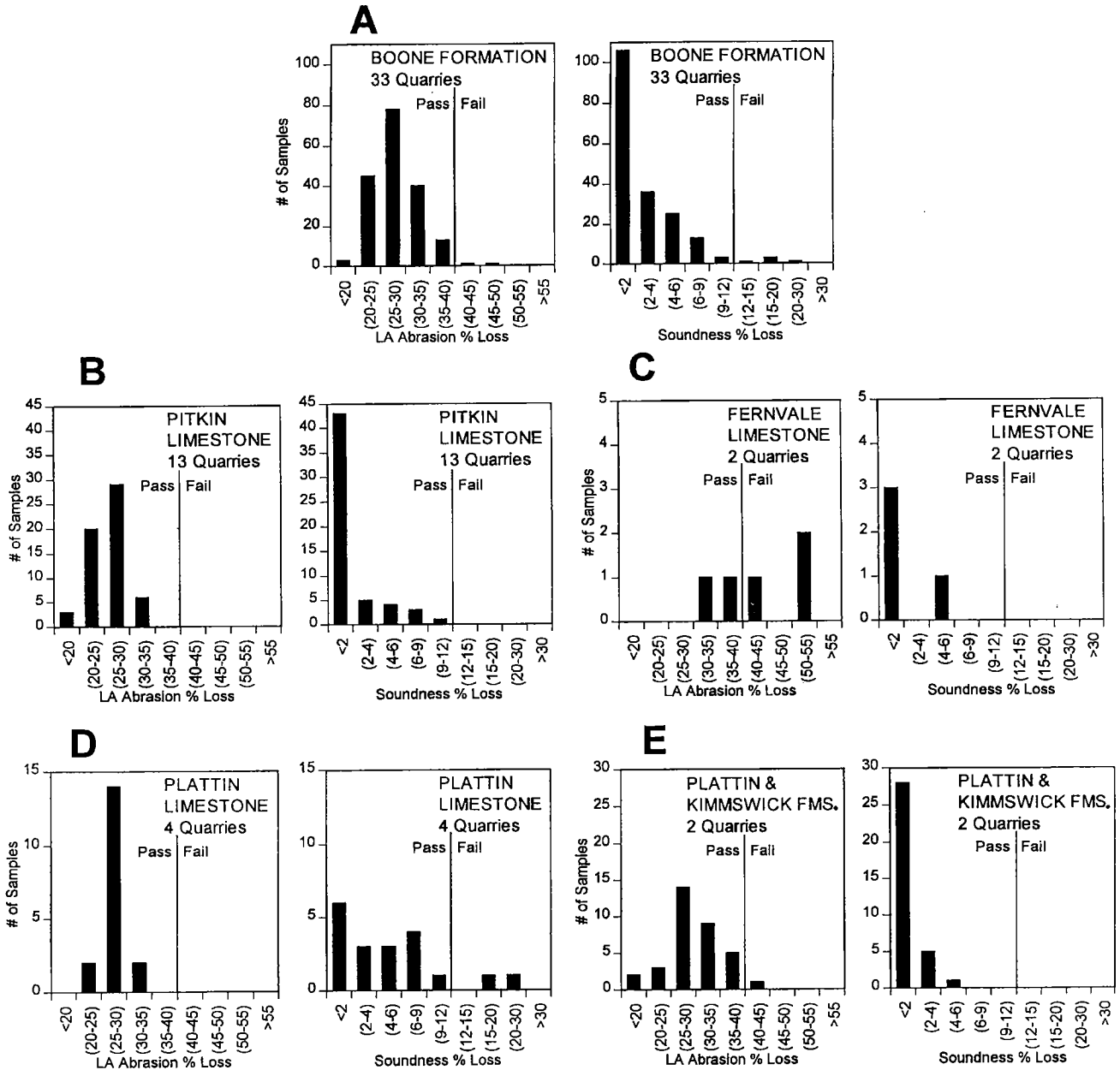


Figure 2. Histograms showing combined AHTD and Corps of Engineers test results on crushed stone from limestone-dominated formations of the Ozark region. For each formation, two histograms are given—one for results of the LA abrasion test and one for the Na-sulfate soundness test. A commonly employed pass/fail limit for each test is given (see text).

favorable stratigraphic position with respect to topography, which places it as the surface bedrock unit across an extensive plateau. However, there are problems occasionally encountered with the Boone Formation that are not readily apparent from the LA abrasion and soundness data. These problems are related to the presence of chert nodules. The abundance of chert in the Boone can vary from a few percent to nearly 100%, and the variation occurs both laterally and vertically, although a chert-free lower member, the St. Joe Limestone, crops out in some areas. The main problem with the chert is that, in places, it is unusually porous, leading to high absorption and low SG. However, in many areas, the chert is hard, and the porous chert is either not present or is avoidable. The median absorption value for aggregate produced from the Boone, based on data compiled in this study, is 1.42%, with a high incidence of values below 2%. However, 9% of the samples had absorptions between 5.5% and 8.27%; these came from sites having the porous chert. Clearly, such stone should be avoided for production of aggregate for asphalt jobs.

The samples that had high absorption had low SG, ranging to as low as 2.12. Low SG is undesirable for

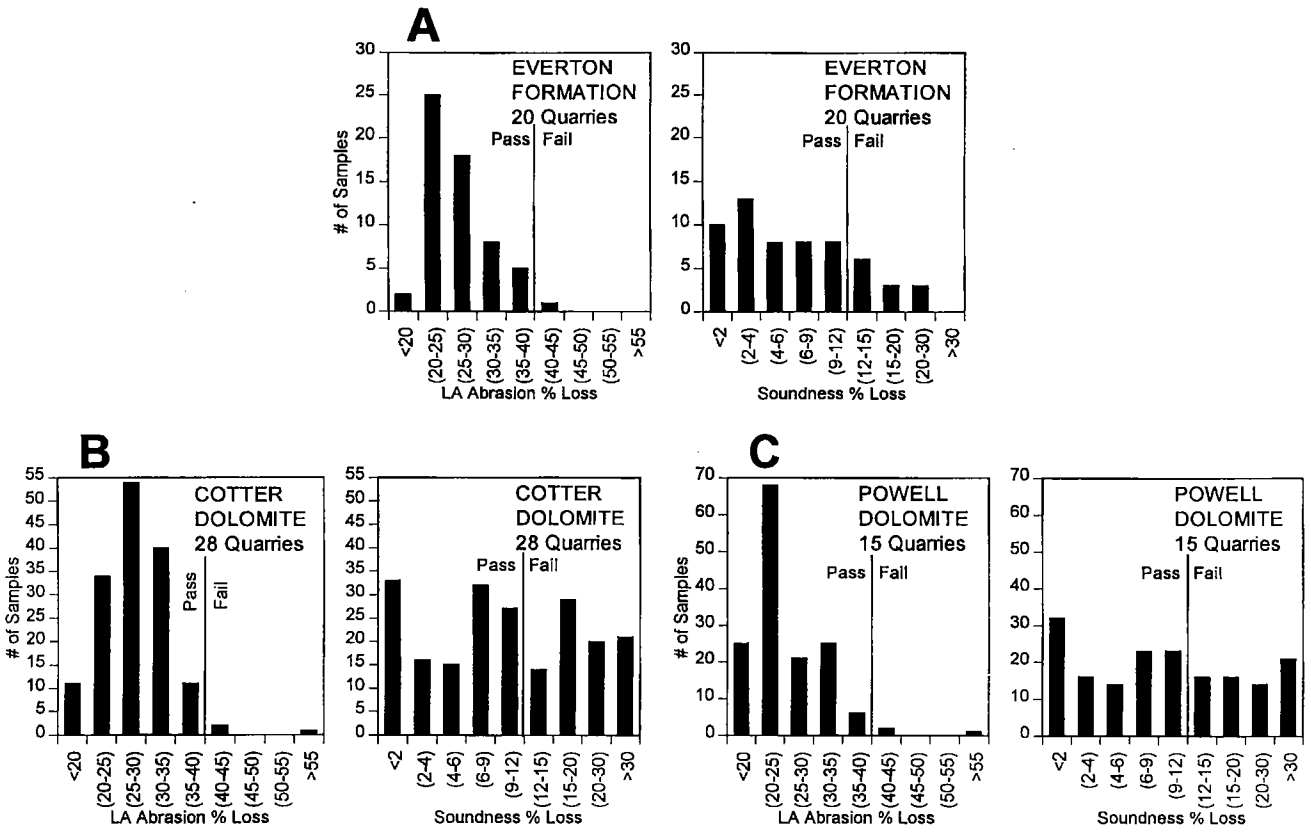


Figure 3. Histograms showing combined AHTD and Corps of Engineers test results on crushed stone from dolomite-dominated formations of the Ozark region.

riprap, but consistency in aggregate SG is also important in construction of PCC structures and pavements (White, 1991), asphalt pavements (Marek, 1991), and road base (Nichols, 1991). Some problems have occurred with material from quarries in the Boone that have lateral or vertical variations in porous chert content (W. J. Pay, personal communication, 1997). No problems are recognized with absorption or SG from limestones of the Plattin, Kimmswick, or Pitkin.

The data for the Plattin Limestone (Fig. 2D) are too few to be conclusive, but there appears to be a difference in its behavior in the soundness test as compared to the limestones of the Boone and Pitkin. Both the Boone and Pitkin have strong modes in the lower part of the range of soundness values, whereas the Plattin has a flatter distribution across the range. The distribution of Plattin soundness values is more like that of the dolostones (Fig. 3). There are some lithologic similarities between the Plattin (laminated-micrite facies) and the dolostones (laminated dolomicrites, discussed below) that may relate to the similarity in soundness results.

Two quarries have used a combination of the Plattin and Kimmswick Limestones with acceptable results (Fig. 2E). One of these quarries also includes the Fernvale Limestone. In constructing Figure 2E, an attempt was made to choose samples that appear to have come from levels in the quarry without the Fernvale, or where friable portions of the Fernvale (discussed below) were removed by processing. Samples from that quarry that were from the Fernvale are included in Figure 2C, along with samples from another quarry exclusively in the Fernvale.

Although the test data (Fig. 2C) are sparse, they suggest a problem with the LA abrasion test for the Fernvale, especially since "failing" tests are not restricted to one of the quarries. It has been recognized (W. J. Pay, personal communication, 1997) that much of the Fernvale crumbles to sand-sized particles during the crushing process. This tendency may be a result of its grain size. The Fernvale is made up mostly of echinoderm plates, which are, individually, single crystals of calcite, and which commonly have calcite cement as an overgrowth that enlarges the grains. The resulting rock is an intergrowth of coarse calcite crystals. It may be that the strong mineral cleavage of calcite becomes a breakage factor when coarse-grain sizes are involved.

Histograms for LA abrasion and Na-sulfate soundness tests from dolostone rock units are shown in Figure 3. No significant problems are recognized in the LA abrasion data, but all three formations from which dolostone samples were taken show problems with the soundness test. Furthermore, analysis of the data indicates that the poor overall results are not attributable to a few quarries, but rather that the problem is widespread.

The cause of the common unacceptable soundness values in dolostones may be related to a high clay content in many of the dolostones. D. W. Lumbert of AHTD (personal communication, 1996) reports that a study done on dolostone with soundness problems from a quarry in Missouri indicated clay in the dolostone as a possible factor. Laminated dolomicrites with clay-bearing parting surfaces are common in Arkansas dolostone formations, and of the quarries included in the present study, the one that had the poorest soundness results also had the greatest abundance of laminated dolomicrite. A consulting chemist, R. L. Neman (personal communication, 1998), has seen a positive correlation between soundness values and acid-insoluble residue (mostly clays) in dolostones. However, J. Bliss of the U.S. Geological Survey (personal communication, 1998) plotted Na-sulfate soundness against insoluble residues using data from Rowland's (1972) study of 26 carbonate-rock quarries in Oklahoma, and found no correlation. Whatever the cause, it would be useful to find mappable stratigraphic intervals without soundness problems, because dolostone is the sole aggregate source in much of the Ozarks.

Except for the Boone Formation, the dolostones have the greatest tendency for variation in absorption and SG. For example, from the Powell Dolomite, 20% of the absorption values were in the 3–5% range. However, all the samples that had values in that range were from two out of the nine quarries represented in the absorption data; all the rest of the samples had lower values, and the majority were less than 2% absorption. From the Everton Formation, one sample had 6.05% absorption; however, of the remaining 25 samples from 10 quarries, only 5 had values from 2–3%, and the rest were lower. Therefore, absorption is not a major problem with the dolostones, but some caution is warranted in using dolostone for asphalt applications.

All the carbonate formations are vulnerable to solution cavities, but the Boone Formation has the highest incidence. The distribution of such cavities can be unpredictable. The cavities are commonly filled with clay washed in from the weathered regolith above the bedrock and may extend 10 m or more into the subsurface. Clay in a batch of aggregate will spoil it for high-dollar applications. Cavities also can affect production blast efficiency during quarry operations.

Another problem that is fairly common in Arkansas carbonates concerns excess dust-sized fines created during the crushing process, causing the aggregate to exceed a "dust ratio" requirement for base-course aggregate (AHTD, 1993, p. 303). This appears to be related to micritic dolostones and limestones. At many quarry sites, sand must be brought in from external sources to mix with the aggregate to lower the dust ratio. To overcome this problem, one quarry operator blends a proportion of Fernvale Limestone, which produces an abundance of sand-size particles upon crushing, with Plattin and Kimmswick Limestones. Another obtains sand by crushing the friable St. Peter Sandstone, which crops out near the main quarry.

Because aggregate composed of carbonate rock is susceptible to wear, AHTD requires that asphalt surface pavements have at least 40% siliceous materials (such as sandstone, chert, or igneous rock) in the aggregate. There is a paucity of such materials in the bedrock of the northern part of the Ozarks, and chert from river gravels is becoming less available because of public concern for the ecology of the region's rivers. Most producers now must ship in siliceous materials for surface-coat asphalt. There may be stratigraphic intervals in the Boone Formation with chert that is durable enough and abundant enough for this purpose, but such intervals are probably rare. Exploration for such occurrences might be worthwhile.

Sandstones of the Ozark Plateaus and Arkansas River Valley

The Arkansas River Valley region (Fig. 1) may be considered as geologically transitional between the undeformed Ozarks and the highly folded and thrusted Ouachitas. Much of the Arkansas River Valley is underlain by horizontal strata, but broad anticlines and synclines are developed in places, and bedding can be gently to moderately dipping or nearly vertical.

Sandstone units throughout most of the Ozarks region are either too thin or too friable to be utilized for aggregate (e.g., the St. Peter Sandstone). However, in the southern part of the Ozarks, portions of the Hale and Bloyd Formations, which are generally mapped together, contain sandstones that are thick and durable enough to support aggregate quarries. Another unit with durable sandstones, the Atoka Formation, crops out in the southern Ozarks and extends into the Arkansas River Valley, where two other units with durable sandstone occur, the Hartshorne Sandstone and the Savanna Formation. These sandstones are, except for a few Bloyd/Hale occurrences, silica-cemented sandstones. Their test data are presented together in Figure 4.

With few exceptions, samples from the Atoka, Hartshorne, and Savanna Formations performed well on the LA abrasion and Na-sulfate soundness tests. Of these three units, the Atoka and the Hartshorne are the more extensive, and many quarries have been located in them, including sites on the Arkansas River, which are advantageous for utilizing this transportation option for export to the south. The few "failing" tests from these units were probably from occasions when quarry operators included too much near-surface weathered material. However, there is a greater tendency toward failing values on the LA abrasion test among Bloyd/Hale samples, and it appears to be a problem with the rock itself. Most of the poorer results were from two quarries, and the poor results were not restricted to shallow rock layers (W. J. Pay, personal communication, 1997). It may be that original cementation in the Bloyd/Hale units was incomplete or that parts were cemented by calcite and are thus more susceptible to weathering. In spite of these problems, most of the quarries in these formations have suitable stone.

Although the sandstones from these four units are favorable for aggregate, most geologic maps would be of only limited value in exploration for new quarry sites in the Bloyd/Hale, Atoka, or Savanna Formations. Each of

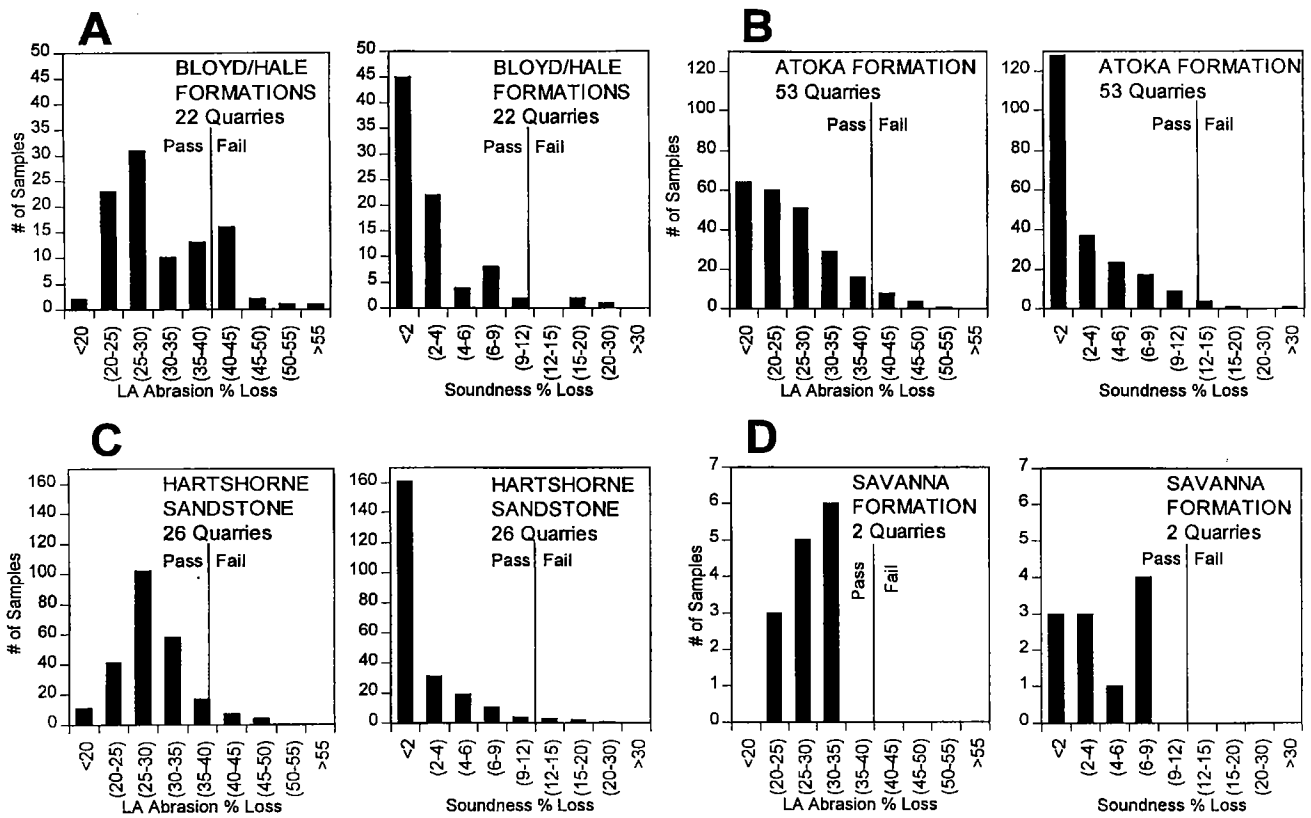


Figure 4. Histograms showing combined AHTD and Corps of Engineers test results on crushed stone from sandstones of the southern part of the Ozarks plus the Arkansas River Valley region.

these formations is dominated by shale, and areas of thick sandstone are not distinguished on most available geologic maps. In the areas underlain by these formations, topographic interpretation can be used to find portions that are occupied by the hard sandstones. For example, where strata are inclined, hogback ridges indicate areas of hard rock.

All these formations, being sedimentary, are susceptible to lateral facies changes into shale-bearing horizons. This is perhaps especially true of the Hartshorne Sandstone, which is a fluvial sandstone and, therefore, subject to the kinds of lateral variations associated with that environment.

Ouachita Mountains Region

As mentioned previously, the Ouachita Mountains region is characterized by highly deformed sedimentary rocks. Consequently, mining methods must be adopted that accommodate the generally steep dips that are encountered. In a number of places, folds are within the scale of a quarry, and dip changes also must be considered. A wider variety of rock types suitable for aggregate occur in the Ouachitas than in the other two hard-rock regions of the state. Results from tests on stone from the Ouachitas are presented in Figure 5.

The most extensively quarried bedrock unit in the Ouachitas is the Jackfork Sandstone (Fig. 5A). The Jackfork includes both sandstone and shale, but sandstone is the dominant lithology. The sandstones in the Jackfork are silica-cemented and constitute a very durable stone in most places. Some of the few cases of marginal or "failing" LA abrasion test results may be from zones of deep weathering. In the area of the southern portion of the Ouachitas, many of the rocks that are at or near the surface today were also near the surface during parts of the Cretaceous and early Teritary as well, resulting in weathering profiles over 30 m deep in places (C. G. Stone, personal communication, 1998). Variations in cementation also occur in the Jackfork that are associated with subfacies; these may account for some of the poorer abrasion values. The Jackfork was deposited as submarine fans in a deep basin. A tendency for poorer cementation in the coarser, more-poorly sorted channel facies, as contrasted to the fan-lobe facies, is discussed by Pauli (1994). The channel facies is also more likely to contain lateral transitions into shale-bearing sequences than the fan-lobe facies of the Jackfork (C. G. Stone, personal communication, 1998). In general, greater rock-type consistency occurs where the present trend of outcrop is parallel to the trend of the original depositional system. There are, however, no geologic maps available showing the distribution of these stratigraphic relationships.

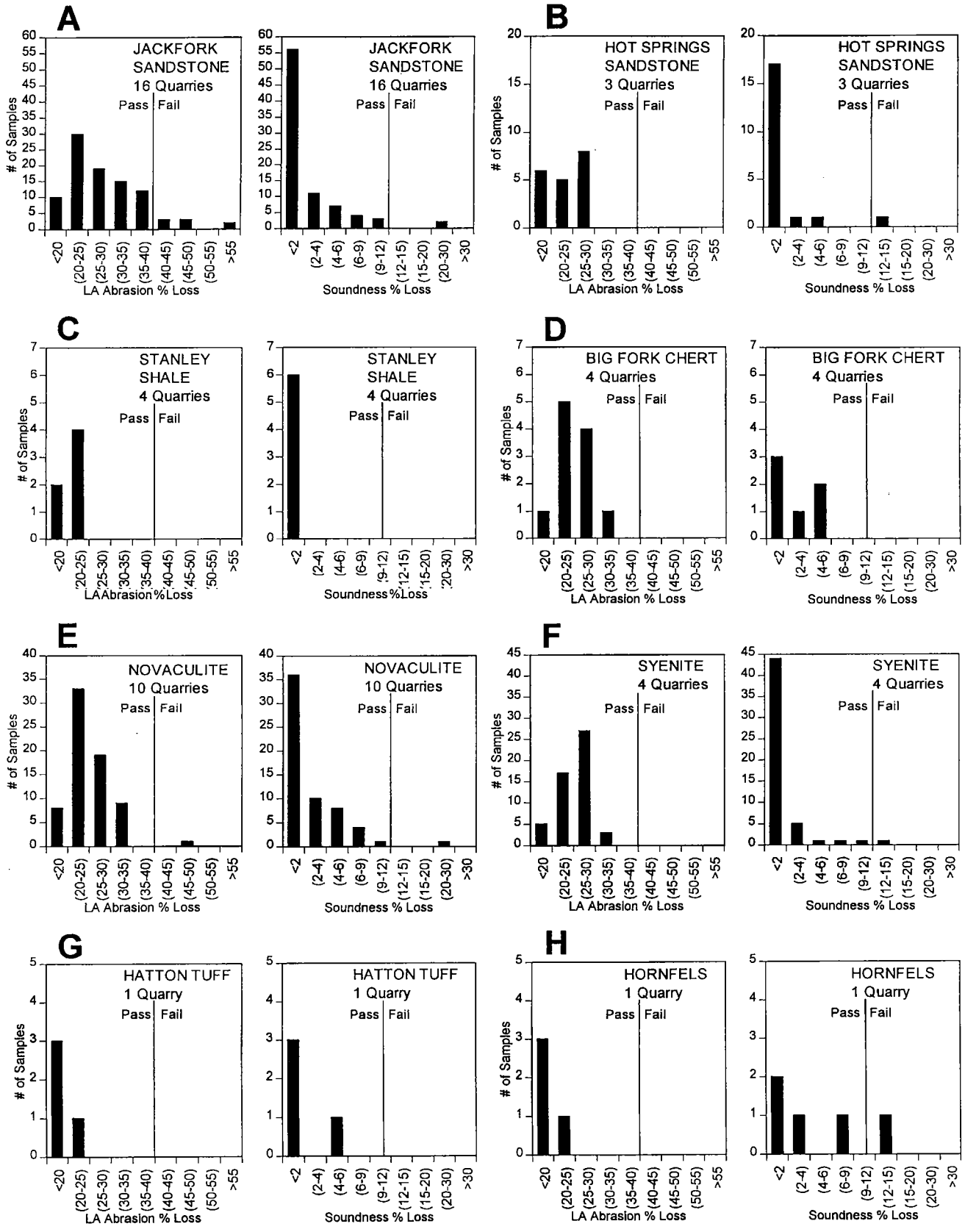


Figure 5. Histograms showing combined AHTD and Corps of Engineers test results on crushed stone from rocks of the Ouachita Mountains region.

Another sandstone resource in the Ouachitas is the Hot Springs Sandstone Member of the Stanley Formation, which occurs near the stratigraphic base of the formation in the eastern portion of the Ouachitas in the vicinity of Hot Springs. This thick sandstone has silica cement and is very durable (Fig. 5B). The other four sites in the Stanley Formation indicated in Figure 5C were Corps of Engineers quarries developed for riprap. Although durable sandstones were mined at these sites, shale interlayers are ubiquitous, as they are in other parts of the Stanley other than the Hot Springs Sandstone Member, generally rendering the Stanley Formation unsuitable for most aggregate applications.

Another member of the Stanley Formation that produces stone that is suitable for high-quality construction aggregate is the Hatton Tuff Lentil (Fig. 5G). The Hatton Tuff occurs in the lower part of the Stanley and is considered the most extensive of five tuff beds that have been indentified in the Ouachitas of western Arkansas and eastern Oklahoma (Miser and Purdue, 1929; Niem, 1977). The Hatton Tuff is not shown as a separate unit on the Geologic Map of Arkansas (Haley and others, 1993), nor is it shown on the geologic worksheets, but its distribution is shown on the map in Miser and Purdue's (1929) report. Niem (1977) indicates that the Hatton thins to the north and to the east from its primary area of occurrence in western Arkansas. However, a 15-m-thick tuff bed, tentatively correlated with the Hatton, has been identified and mapped in the vicinity of Hot Springs (Danilchik and Haley, 1964). Although the data in Figure 5G are few, the highway department in Texas obtains similar excellent results on their tests of the Hatton Tuff (C. N. Fu, personal communication, 1995). Tuffs are commonly suspect with regard to potential alkali-silica reactions in PCC applications (Smith and Collis, 1993, p. 210), but the Hatton, being Mississippian in age, is fully devitrified to crystalline substances that are not associated with alkali-silica reactions (Niem, 1977; Kline, 1996).

Another sedimentary unit widely utilized for crushed aggregate in the Ouachitas is the Arkansas Novaculite. Novaculite is a form of chert that has a granular microcrystalline texture that is coarser than typical chert. The Lower Division of the formation has the thickest beds, the least shale, and the most consistent durability. All the important quarries supported by this formation come from the outcrop belt on the southern limb of the Benton uplift; the formation thins to the north, where facies changes reduce the abundance of the favorable stone. Durability tests on the Arkansas Novaculite (Fig. 5E) show very good results. It should be noted, however, that this material is probably the most troublesome with respect to wear on mining and processing equipment. It is very abrasive in crushing equipment, and its tendency to break with conchoidal fracture causes it to be hard on handling equipment that use rubber tires.

The data from AHTD include several tests of samples from the Bigfork Chert (Fig. 5D). Although the data look good, the samples for these tests must have been obtained by careful and selective quarrying. This unit is actually not suitable for applications with rigorous restrictions on soft particles, due to a pervasive occurrence of thin shale interlayers. However, material from this formation is easily quarried with earth-moving equipment (not requiring blasting), and it packs well and sets up hard, so it is widely used for gravel roads.

Closely associated with the Ouachita Mountains, but marginal to them, are Cretaceous nepheline-bearing syenite plutons southwest of Little Rock and the Magnet Cove alkaline intrusive complex near Hot Springs (Fig. 1). The pluton which occupies "Granite Mountain", near Little Rock, has been extensively quarried because of its excellent performance (Fig. 5F) and its proximity to the most populous part of the state and to transportation routes by rail and the Arkansas River. Except for some old small workings, the pluton near Benton and the Magnet Cove intrusive complex have not been exploited for aggregate. However, adjacent to the Magnet Cove intrusion, a quarry has operated in the contact-metamorphic aureole, where baked shales and sandstones of the Stanley Formation now are a durable hornfels (Fig. 5H).

CONCLUSIONS

Overall, Arkansas has abundant resources for crushed-stone aggregate in the Interior Highlands including the area associated with the Cretaceous intrusive complexes. These resources are presently adequate to supply the needs of Arkansas as well as neighboring states that lack such resources. Although every part of the Highlands region has some bedrock units that have proven suitable for a variety of construction applications, the units have differences in their specific performance. Geologic maps can be used along with the information in this report to locate the best stratigraphic units available in a particular area.

ACKNOWLEDGMENTS

I wish to thank W. J. Pay, J. M. Howard, J. D. McFarland, and C. G. Stone for constructive reviews of a longer manuscript, which formed the basis of this report. All of these were also very helpful throughout the course of the study. R. R. Cohoon and C. G. Terry reviewed the present manuscript.

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Summary of USDA Forest Service Assessment of Minerals, Geology, and Mining within the Ozark–Ouachita Highlands Assessment Area, Arkansas, Missouri, and Oklahoma

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The Ouachita, Ozark–St. Francis, and Mark Twain National Forests are located within the Ozark and the Ouachita Mountains regions of southern Missouri, central and northern Arkansas, and eastern Oklahoma—an area generally referred to as the Ozark–Ouachita or Interior Highlands. These national forests share many similarities in geography, biotic resources, and areas of shared public, market, and user interests. The three national forests have joined together to evaluate the natural resources within the Highlands and to study the impacts of the forests on local and regional economies and on the people who use these national forests and their resources. Other federal, state, and local government agencies and universities have joined with the Forest Service in this project, broadening the assessment area beyond the national forest boundaries to include 107 counties in Arkansas, Missouri, and Oklahoma. The diverse, resource-related data for the assessment area address social, economic, terrestrial, and aquatic issues and conditions throughout the Highlands. The assessment report currently is being developed by the Forest Service and will include an accompanying CD-ROM.

The Ozark–Ouachita Highlands assessment has provided a forum for minerals- and geology-related resources, industries, social significance, and potential to be profiled and discussed along with other critical assessment resources. The state geological agencies in Arkansas, Missouri, and Oklahoma were active contributors to this effort. Their reports and other key data bases developed and used for the minerals sections of the published assessment report will be available either as a supplemental CD-ROM or on the Internet. Updated information on the progress of the assessment report can be found at the Ouachita National Forest Website, at <http://www.fs.fed.us/oonf/ouachita.htm>. This will also include a matrix displaying the minerals in the assessment area, their occurrence by assessment-area counties, and a potential ranking, as well as information on interesting geologic features. The state and federal reports, resources, and data bases, have helped answer key questions concerning mineral resources and related issues in the Highlands:

- Historically, what Highlands minerals have been important, to whom, and why?
- In assessment area communities, what is the current reliance on and projected demand for Highlands minerals and mining?
- What are current national and global uses of and reliance on the mineral resources in the assessment area, and what is the projected demand for them?
- What are the current and projected recreational and educational uses for Highlands minerals?
- What are the current status and potential effects of activities associated with the exploration and extraction of Highlands minerals on the aquatic resources within the assessment area?

Table 1 shows the percentage of mines, mining-related employees, and lands within the Ozark–Ouachita Highlands Assessment area. The following are the key minerals-related findings that are discussed extensively in the assessment report, in chapters on social and economic conditions (Chapter 7), and on aquatic and atmospheric conditions (Chapter 4) within the assessment area:

1. Of the mineral resource extraction operations (mining and processing plants) within Arkansas, Missouri, and Oklahoma, 60% occurs within the assessment area, accounting for a mineral value in 1996 of approximately $1.2 billion.
2. Of 76 known minerals and mineral materials within the assessment area, 33 currently are being mined.
3. In terms of U.S. production volume, the assessment area contains the top 10 production sites for 14 of the numerous mineral commodities produced throughout the United States.
4. The portion of Missouri within the assessment area contains the largest concentration of lead mineralization in the world. Mines located in the assessment area are the leading producers of lead in the United States and, until recently, were the world's leading lead producers.

Nichols, J. C., 1999, Summary of USDA Forest Service assessment of minerals, geology, and mining within the Ozark–Ouachita Highlands assessment area, Arkansas, Missouri, and Oklahoma, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 95–96.

Table 1.—Ozark–Ouachita Highlands Assessment: Percent of Mines, Mining-Related Employees, and Lands Located within the Assessment Area Portion of Arkansas, Missouri, and Oklahoma*

1996	Mines within assessment	Mines statewide
Arkansas	169	202
Missouri	217	391
Oklahoma	78	219

1996 Highlands	Mines within assessment (%)	Employees within assessment (%)	Land within assessment (%)
Arkansas	84	84	54
Missouri	55	58	48
Oklahoma	36	32	17
Total	58	59	41

*Percent based against all mines, mining-related employees, and land acreage within each of the three states.

Note: Information compiled from records maintained by the U.S. Department of Labor Mine Safety and Health Administration for mines and employees throughout each of the three states, from the state mining divisions for Arkansas, Missouri, and Oklahoma, and from the USDA Forest Service for operations conducted on national forests within each state.

Between 75% and 80% of U.S. lead production comes from the Mark Twain National Forest—it is a leading source of the world's lead production.

5. The assessment area contains three world-class lead- and zinc-producing districts (in Missouri) and was a past world leader in zinc (Oklahoma) and barite (Arkansas and Missouri) production.
6. The Ouachita Mountains are the only source for electronic-grade, high-quality quartz in North America. All of the U.S. production is from the Ouachita National Forest in Arkansas.
7. The Ouachita Mountains are one of the leading world producers, and are the leading U.S. producer of quartz crystals for aesthetic and jewelry uses. Production occurs from both private and Ouachita National Forest lands.
8. Missouri is the leading U.S. producer of fire clay, much of which is mined from within the assessment area.
9. Coal from the Oklahoma portion of the assessment area is used to generate power for 150,000 homes in eastern Oklahoma.
10. The Ozark National Forest has 66 producing gas wells in areas that have a high potential for additional exploration and development.
11. In 1996, the minerals industry employed approximately 10,500 persons within the assessment area and was responsible for approximately 50,000 more assessment-area jobs that depend in part or in whole on Highlands' mineral production.
12. In 1996 alone, extraction of mineral resources from the three national forests within the assessment area generated almost $6,000,000 in federal revenue.
13. The national forests within the assessment area have a high potential for discovery of additional reserves of the minerals currently being mined on them and in some cases those mined in the past as well. The demand to access the national forests for mineral exploration is expected to continue and increase.
14. The assessment area and the three national forests within it have unique geologic features that attract people from across the United States and throughout the world for research, education, rockhounding, and mineral collecting.
15. Numerous extractable minerals that are important to society are present in the 50 watersheds that make up the Ozark-Ouachita Highlands assessment area. At least 76 different minerals and mineral commodities known to be present in the assessment area have been or are being explored or developed to various degrees.
16. Mining and exploration currently are taking place for 33 minerals and mineral commodities, including building stone, crushed stones and aggregates, gravel, quartz and other gems, coal, natural gas, metallic minerals, clays, novaculite, tripoli, and others. All operations within the assessment area are surface operations with the exception of the underground lead mines in the Missouri Ozarks.
17. Present-day exploration and mining activities on the three national forests are primarily involved with extracting the following commodities: lead and zinc (Mark Twain National Forest in Missouri); natural gas, building stone, and aggregate materials (Ozark National Forest in Arkansas); quartz, building stone, and aggregate materials (Ouachita National Forest in Arkansas and Oklahoma).
18. The primary mining activities are surface-mined, common-variety-mineral materials, much of which goes into the building and road-construction industry within the assessment area.
19. Several abandoned, historic mine sites continue to contribute to chemical and metals leaching and runoff, increasing acidity in some cases, and affecting some aquatic resources within the assessment area.
20. Effects on aquatic resources from present-day mining activities primarily are associated with increased sedimentation of streams caused by in-stream gravel and sand extraction.

Summary of the 1990s Exploration and Testing of the Prairie Creek Diamond-Bearing Lamproite Complex, Pike County, Arkansas

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ABSTRACT.—Holes cored through the Prairie Creek lamproite volcanic complex at the Crater of Diamonds State Park by companies interested in the site's commercial diamond potential give an opportunity to redefine the size and shape of the Prairie Creek pipe. Relationships of cored rock sequences and the discovery of a previously unrecognized major rock type allow a reinterpretation of the sequence and type of intrusive activity. Trench sampling of diamondiferous rock units yielded a diamond content far below what was anticipated based on an estimate from historical records. Inadequacies of shallow bulk-testing methods for a diamondiferous pipe are examined.

PURPOSE

The Cretaceous sedimentary units of southwest Arkansas were mapped and defined beginning in the late 1800s (Hill, 1888; Dane, 1929; Miser and Purdue, 1929; Ross and others, 1929). The volcanic vent near Murfreesboro was noted as early as 1842 by Powell and was recognized as similar to African kimberlite pipes by 1889 (Branner and Brackett, 1889). Diamonds were first discovered on the Prairie Creek vent by John Huddleston, a land owner and local farmer, in August of 1906.

Early investigations and the history of the property, mining efforts, and most of the pipes (Fig. 1) discovered in the area through 1990 are well summarized in previous papers (Miser and Purdue, 1929; Krol, 1988; Kidwell, 1990). In 1916, Miser mapped the site and determined it to be some 73 acres in extent (Miser and Purdue, 1929). The U.S. Bureau of Mines conducted a drilling project on the Prairie Creek pipe in the 1940s, including sampling with a 30-in. rotary bucket drill. The holes averaged only 27 ft in depth. The samples washed totaled 435 tons, producing 21.389 tons of concentrate from which 32 stones (total weight 8.4 carats) were recovered. This effort only touched the surface of the pipe and did not define the subsurface shape of the body.

On the basis of mineralogy, Scott-Smith and Skinner (1984a,b) recognized that the Prairie Creek pipe was more closely related to lamproite than kimberlite. (Editor's note: the Appendix for this paper contains definitions of some of the igneous-rock terms that are used in this report and with which the reader may not be familiar.) Morris (1987) included a summary of chemical and mineralogic data for Prairie Creek samples, which also indicated that, though the igneous phases were not identical to previously identified lamproites (Argyle pipe, Australia), the rock units were more similar to lamproite than to African kimberlites. Mitchell and Bergman (1991) discussed the absence of typical kimberlite indicator minerals and the lack of diatreme facies. During the 1980s, company investigations on several small pipes in Pike County resulted in publications showing these pipes also to be of lamproitic affinity (Waldman and others, 1987; Candless and others, 1994; Griffin and others, 1994). Because the Prairie Creek complex is publicly owned (Crater of Diamonds State Park), there is a wealth of information available about the recent testing process that normally would not be available under a private business arrangement.

PHASE I TESTING

Administration

In 1987, the Arkansas Legislature passed Act 793, permitting the Arkansas Parks, Recreation, and Tourism Commission to enter into lease arrangements for testing to evaluate the feasibility of commercial production of diamonds at the Crater of Diamonds State Park (the Prairie Creek vent). A Task Force was established by the Governor to debate the issue and receive public comment. The Task Force made its recommendations to the Parks Commission in October of 1988, which then authorized the Department of Parks and Tourism to proceed with the testing of the Prairie Creek pipe in

Howard, J. M., 1999, Summary of the 1990s exploration and testing of the Prairie Creek diamond-bearing lamproite complex, Pike County, Arkansas, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 97–104.

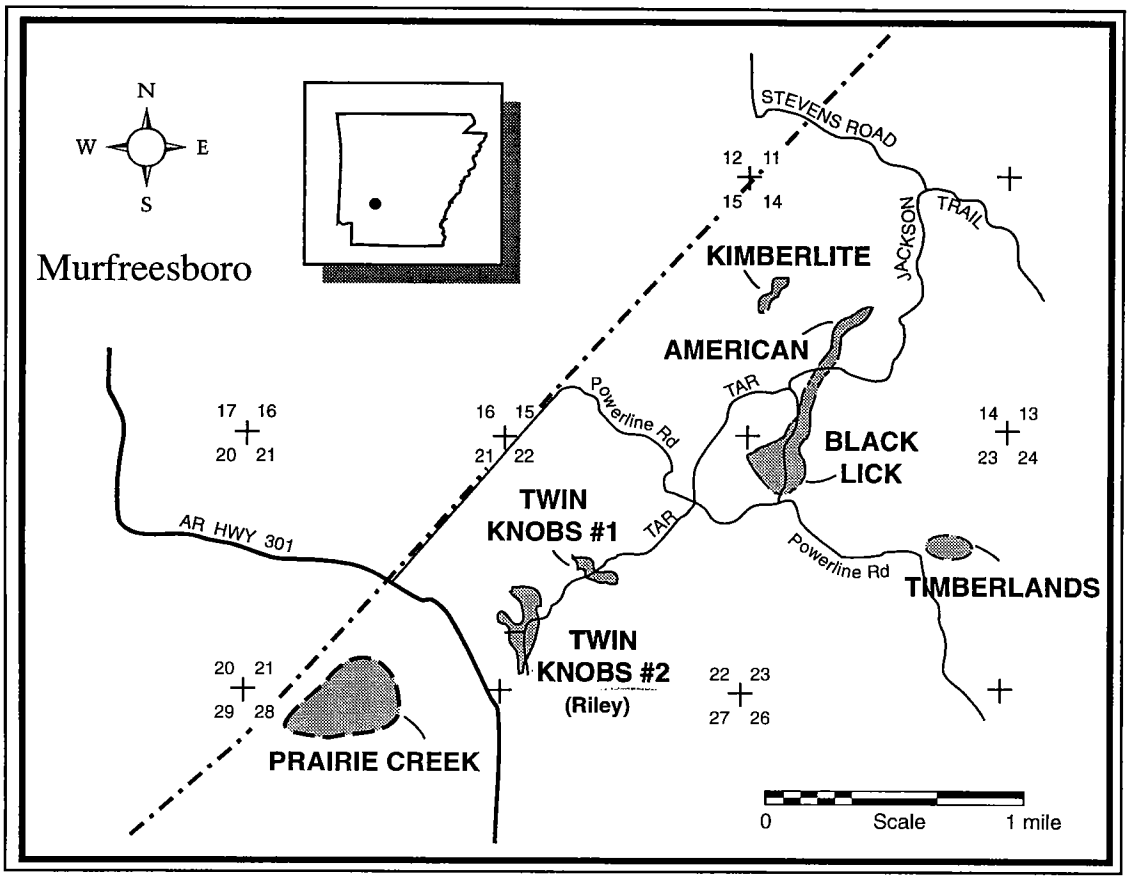


Figure 1. Lamproite pipes near Murfreesboro, Pike County, Arkansas. Base by W. D. Hanson, Arkansas Geological Commission.

phases, Phase I being authorized. The Department selected a project manager, Morgan Mining and Environmental Consultants, Ltd., of Lexington, Kentucky. Four companies—Capricorn Diamonds, Ltd., of West Perth, Australia; Kennecott Corporation of Camden, South Carolina; Arkansas Diamond Development Corporation of Dallas, Texas; and Continental Diamond of Little Rock, Arkansas—were accepted from approximately 100 applicants to participate in the testing. Drew F. Holbrook was chosen as the on-site geologist. Phase I was estimated to cost $350,000. Each company provided $87,500 to be administered by the Department of Parks and Tourism; no taxpayer money was spent. A "temporary non-conforming use" permit was approved by the U.S. Department of Interior, National Park Service (NPS), to allow Phase I to proceed. This permit was necessary because the State of Arkansas had utilized $750,000 from a special NPS fund in the early 1970s to build the present State Park museum and visitor's facilities.

Boyle Brothers of Murfreesboro, Tennessee, was selected to do the drilling. The Arkansas Geological Commission (AGC) was selected to receive the drilling samples of Phase I coring as well as Phase II concentrates from bulk sampling, the materials to be stored in a separate secured area in the N. F. Williams Well Sample Library in Little Rock. The completed Phase I report, along with a report by the four companies, was submitted by the Program Manager (1993) to the Technical Advisory Committee (TAC) in December of 1992, although it bears a January 14, 1993, release date. The TAC was composed of both company and various state agency representatives, including the Department of Parks and Tourism, AGC, Arkansas Department of Finance and Administration, Arkansas Game and Fish Commission, and Arkansas Department of Pollution Control and Ecology. Of the TAC members, only company representatives had voting rights. The TAC recommended the presentation of the reports to the Parks Commission, which was done in January of 1993. The reports were accepted by the Parks Commission and a motion made to vote on proceeding with Phase II. The motion was approved at the next Parks Commission meeting.

After completion of the Project Manager's Report in 1993, and before the start of Phase II, the first two companies (listed above) dropped out of the project, leaving Arkansas Diamond Development Corporation and Continental Diamond as the two participants. Also, Continental Diamond was purchased by Texas Star (now Star Corp.) of Houston, Texas. If the Prairie Creek vent was demonstrated to be commercially viable, only those companies remaining in the process would be allowed to bid on the mining rights. Had either of the two re-

maining companies dropped out, the entire process would terminate, since no competitive bidding would be possible.

Procedures and Results

Work during Phase I included surface mapping and drilling of core holes to determine the size and shape of the body and to allow correlation of rock types encountered during surface mapping. Surface mapping was accomplished concurrent with drilling and was a collaborative effort between the project geologist and geologists of the participating mining companies. Drilling began on July 8, 1990, after a series of court delays. The core drill was a Mobil™ Model B53 mounted on a 20-ft by 8-ft skid. It was towed to each site by a John Deer™ 455 bulldozer. Initially, a water truck with a tank was used to supply the drilling fluid (water). However, after protest by environmentalist groups of excessive ground compaction, a water-line system was devised and use of the water truck ceased. Drilling was done on a predetermined surveyed-grid system under the full inspection and scrutiny of State Park and government officials, environmental activists, tourists, and news media. Each drill site was fenced for safety and security reasons. No drilling was allowed on Sundays. Core was removed to a secured trailer in the Park for detailed logging by the project geologist. Phase I called for 30 holes, totaling 6,600 ft. Phase I was finished in the summer of 1992, after many delays and after additional environmental lawsuits were resolved. For the second part of Phase I drilling (after the removal of a permanent court injunction), several changes in drill equipment and procedures were made to lessen the ground compaction effect. A smaller, self-propelled, track-mounted drill, a Teremac™ 1000, was utilized and a smaller skid was used to supply fuel and materials. These changes resulted in a reduction in size of the fenced security area. Modifications on the muffler system of the drill resulted in significant noise reduction. A Case™ 55E bulldozer, equipped with wider tracks than the previous bulldozer, also assisted in limiting surface disturbances. Twenty-six holes were completed for a total of 8,699 ft, of which 3,926 ft of vertical core and 3,845 ft of slant-hole core were recovered, and 928 ft of rotary drilling were completed. Core hole depths ranged from 41 to 669 ft. With the exception of two holes, core recovery averaged 95%. Holes #15 and #19 encountered difficult rock conditions, particularly vertical fracturing and clay interlayered with very dense lamproite. Core recovery dropped below 60% and was deemed unacceptable. Core samples were transported from Phase I drilling to the AGC facility after they had been logged by the project geologist.

The results of Phase I testing include a renaming of all the major rock types and the discovery of a previously unrecognized map unit at this location—maar epiclastics (Fig. 2). Renaming of the rock types (see Appendix) follows: intrusive peridotite was termed magmatic lamproite; kimberlite breccia and fine-grained breccia tuff are now grouped together and mapped as pyroclastic (olivine- and phlogopite-rich)

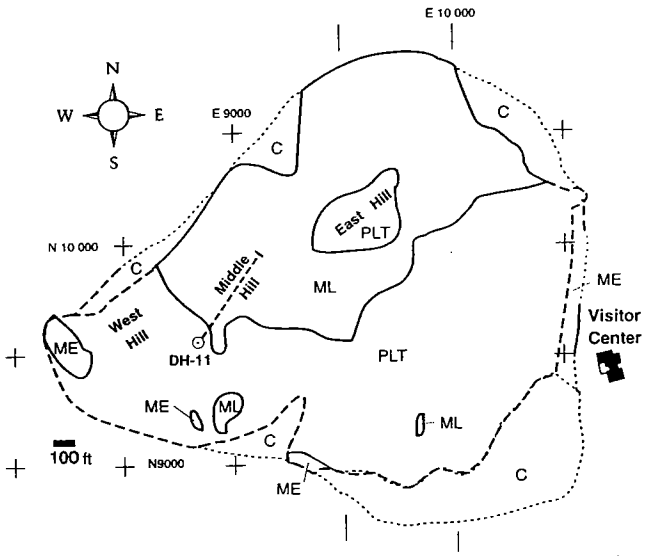


Figure 2. Generalized Phase I geologic map, modified from Holbrook. PLT–Pyroclastic Lamproite Tuff; ML–Magmatic Lamproite; ME–Maar Epiclastics; C–Cretaceous and Quaternary (alluvium/colluvium) cover.

lamproite tuff; and outcrops on the east side of the body, previously mapped as "Jackfork Sandstone(?)" by Miser and his colleagues over a 25-year period, were determined to be the surface outcrops of maar epiclastic material. Drill cores show the erratic nature of the distribution of epiclastic rock in the body of the pipe. The pyroclastic lamproite tuffs, in particular those that had been mapped as kimberlite breccias by Miser, are the principal source of the diamonds collected on the plowed field of the State Park (about 35 acres). Surface mapping indicated that the pyroclastic lamproite tuffs and the epiclastic units make up about 59% of the pipe's surface exposure. Maar epiclastics probably constitute less than 10% of the pipe's volume and are highly erratic in occurrence, except along the eastern margin of the vent.

The original surface exposure map, plane-tabled by Miser in 1916 and later published (Miser and Purdue, 1929), proved to be reasonably accurate despite the differences in rock nomenclature. Drill data from Phase I indicated that Quaternary sediments (alluvium-colluvium) cover several acres along the contact of the vent complex and the Trinity Group (Cretaceous), particularly along the southeast margin. By projection of Phase I drill-hole data, the Prairie Creek vent was determined to extend over 80.3 acres, some 10% larger than previously calculated.

Before Phase I drilling, any attempt at modeling the vertical configuration of the pipe was a matter of speculation. If kimberlitic, the pipe should have a shape similar to a carrot in the subsurface. If lamproitic, it should be shaped like a champagne glass, being a shallower body with a narrow feeder pipe, therefore having less potential reserve of diamond-bearing rock. Knowledge of the actual shape of *any* ore body is necessary to calculate the tonnage of potentially valuable rock at hand. However, when dealing with a high-value commodity

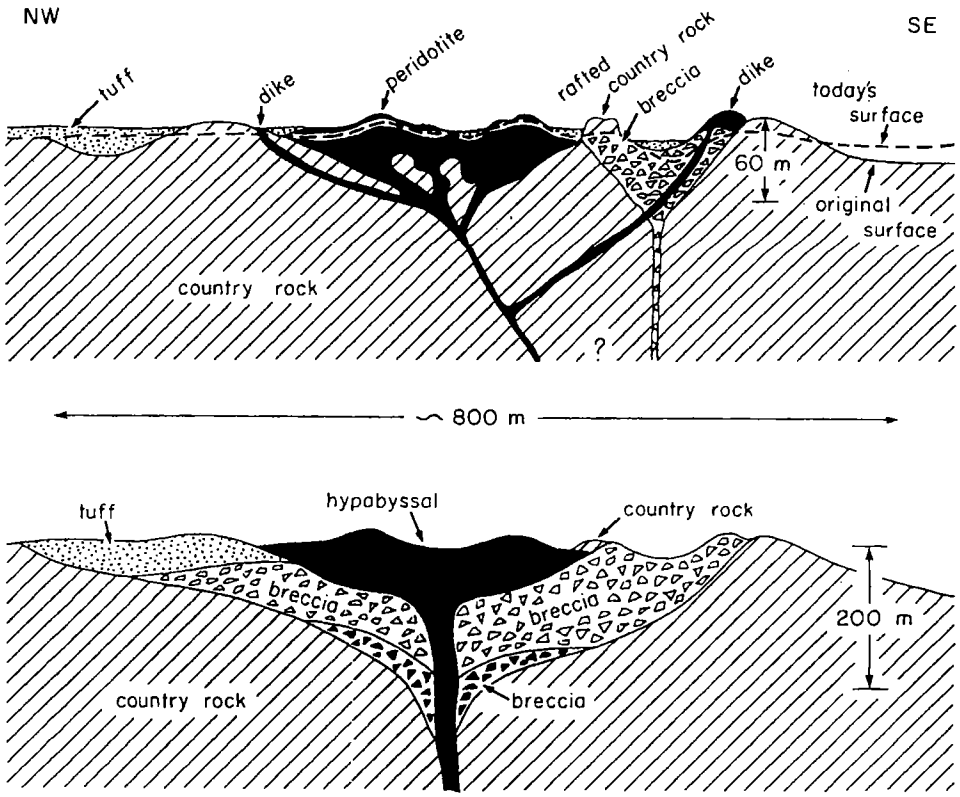


Figure 3. Previously published stylized cross-sectional models of the Prairie Creek complex. Upper: Bolivar (1977, 1984), Lower: Mitchell and Bergman (1991). Modified from Mitchell and Bergman (1991, p. 148).

like diamonds, where mining involves moving and processing rock that may contain less than 1 part per million of sought-for mineral, it is critical. Idealized cross-sectional models of the Prairie Creek complex by Bolivar (1977, 1984) and by Mitchell and Bergman (1991) were radically different (Fig. 3) and were based on meager subsurface information. The only subsurface data available to these workers was from the U.S. Bureau of Mines shallow drilling in the 1940s. From Phase I drilling, the shape of the intrusion was determined to be similar to a martini glass with contacts sloping inwards at about 45° toward a small feeder pipe.

One angle drill hole, #11, revealed a particularly important rock relationship. This hole was started in lamproite tuff and slant-drilled N.35°E. at about 40° under Middle Hill (Fig. 2). It failed to encounter magmatic lamproite, remaining in pyroclastic tuff units to a cored distance of 600 ft. Horizontally, this hole extended some 460 ft to near the center of Middle Hill. This hole was drilled because two attempts at drilling vertically through the magmatic lamproite on Middle Hill had been unsuccessful, due to ground conditions. The determination that Middle Hill, which at the surface is magmatic lamproite, is underlain by pyroclastic units necessitated revising previous interpretations of the sequence of emplacement. Instead of a magmatic event followed by an explosive phase, the general intrusion sequence is one of an initial large explosive eruption resulting in crater formation followed by a sequence of lesser eruptions, airfalls of tuff, the deposition of maar epiclastics during quiescent times, and the late intrusion of a marginal hypabyssal body of magmatic lamproite, as displayed in the new cross-sectional model (Fig. 4). It is possible that much of the pyroclastic sequence was covered originally by a thin lava flow or lava lake, which originated from the magmatic lamproite. The true sequence is undoubtedly more complicated than presented here, as suggested by the several varieties of pyroclastic tuffs encountered. Features, such as crossbedding of fine-grained tuffs, had been noted by previous workers, leading to speculation that the pipe possibly erupted in shallow water. The formation of maar epiclastics is now interpreted as sedimentary units deposited in ephemeral shallow crater lakes during quiet times between eruptive activity. The epiclastic units consist of sediments derived from the intruded Cretaceous Trinity Group, primarily quartzose sand, mixed with pyroclastic breccias and tuff materials. This interpretation adequately explains the presence of cross-bedding of these units reported by Miser and Purdue (1929). Mitchell (1993) presented the results of a petrographic study of thin sections from six cores and his petrologic interpretation of the Prairie Creek vent in Appendix C of the Phase I Report. He noted that crater facies composed the entire pyroclastic sequence and that this sequence was highly complex, with samples displaying many varieties of air-fall pyro-

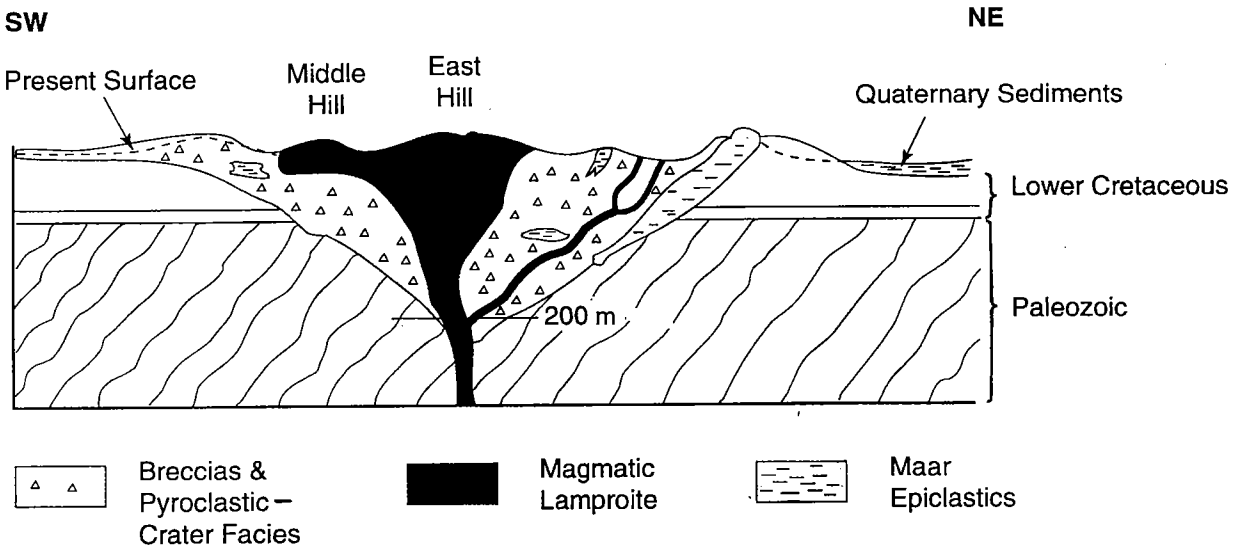


Figure 4. Stylized cross-sectional model of the Prairie Creek complex as interpreted from Phase I mapping and drilling.

clastics, including welded, collapsed-pumice fragments. Olivine lamproite breccia represents rapidly quenched brecciated magmatic material. Several varieties of epiclastics are present, including epiclastic lamproite and epiclastic lamproite breccia. Late olivine lamproite dikes were noted crosscutting the pyroclastic-breccia-tuff units in the core and during surface mapping. Mitchell (1993, p. 16) summarized his interpretation of the formation of the volcanic pipe, from which the artist's sketch (Fig. 5) is derived:

> Examination of the cores reveals that the crater does not exhibit any simple volcanic stratigraphy. Each core contains pyroclastic and epiclastic rocks which cannot be correlated with those found in other cores. The changing character . . . indicates that the crater was formed by the eruption of several distinct batches of magma. . . . Each episode of volcanism was complex, with many distinct eruptions and periods of quiescence. It is possible that each episode of volcanism originated at a different vent. The original volcano may be envisioned as a series of interlocking tuff cones. Tuffs originating at each cone would drape over pre-existing pyroclastic cones and their associated deposits. Slumping of pyroclastic deposits into ephemeral lakes would give rise to intercalated epiclastic units. . . . A single vent would be unlikely to generate this complexity [of stratigraphy recorded in the cores].

From the drilling and surface mapping, it was conservatively estimated by the project geologists that 78.5 million tons of diamond-bearing pyroclastic rock (including maar epiclastics) and 24.1 million tons of magmatic lamproite (nondiamond bearing) compose the Prairie Creek pipe, to a depth of 650 ft. The Phase I report recommended a composite sample of 4,400 to 11,000 tons of material be removed in order to retrieve at least 1,000 carats of diamonds for evaluation.

Phase Ib

Between Phase I and II, the TAC determined that a planning phase, termed Phase Ib, was necessary to consider various methods of bulk sampling and determine which method best fit the testing project. Several techniques of bulk sampling were considered, including large-diameter churn drilling, a single trench across the entire exposure, a series of small pits, mini-trenches, and a tunnel. Mini-trenches, a modification of pit and trench methods, were chosen for a variety of reasons, but primarily because the smallest amount of ground would be disturbed at any given time because of lower earth-moving costs.

PHASE II TESTING

Administration

Phase II testing was to determine, by bulk sampling, the concentration of diamond in each rock type tested and, if 1,000 carats were recovered, to allow for the gemstone evaluation of the pipe by modern means. It was estimated from historical records that the pipe grade should contain between 9.1 and 22.7 carats per 100 tons. A 10-ton per hour plant, owned by Texas Star Resources and located some 3 mi to the northeast of the State Park, was chosen to process the bulk material. This plant uses a combination of heavy-media-separation and Sortex™ methods to recover diamonds. Bulk sampling during Phase II was to consist of a series of mini-trenches, measuring 4 ft wide, 100 ft long, and 40 ft deep. The top 10 ft of material was to be set aside and, after backfilling, placed back on top of the trench site. The sites for the mini-trenches were chosen on the basis of the surface mapping and drilling data provided by Phase I testing. Before Phase II testing could begin, a temporary noncompliance use

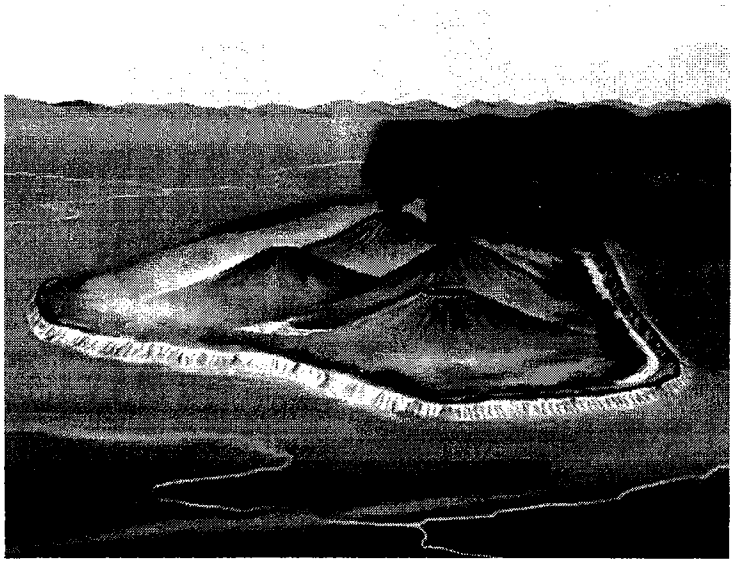


Figure 5. Lesser pyroclastic eruptions inside initial explosion crater, looking north during the early Late Cretaceous. Vance Pleasant, artist, Arkansas Geological Commission.

permit was again needed. This permit was delayed for over a year until a court case in California, which considered whether trenching, drilling, and other typical exploration activities should be legally considered mining, was resolved. When the courts found that such activities do not meet the legal definition of mining, the permit for Phase II was issued and testing proceeded.

Procedures and Results

From the 13 mini-trenches, 9,600 tons of rock was processed, which yielded a total carat weight of 45.748 carats of diamond or less than 1/20th of the expected yield, based on the estimates from the historical records. Also notable was the fact that no diamond over 2 carats was recovered, despite the history of recovery of larger stones by previous mining and tourist activity. Only one diamond was recovered between 1.5 and 2 carats and only three between 1.0 and 1.5 carats. The average size of the stones recovered was about 20 points.

During the period of bulk testing, six additional drill holes were cored on the north side of the vent in an area that had been considered environmentally sensitive during Phase I. These holes were cored with a small track drill along the path of a new nature trail that the companies agreed to fund, so that the northern border of the intrusion could be better defined. Both slant and vertical holes were cored. These holes confirmed that there was no extension of the pipe to the north and that the wall contact was basically as had been determined from Phase I drilling, that is sloping at about 45° to a narrow feeder pipe in the subsurface. The feeder pipe is now thought to be somewhere under East Hill (Fig. 2).

After completion of the bulk sampling and core drilling, all the samples from Phase II, excluding the diamonds, were retained at the N. F. Williams Core Sample Library of the AGC in Little Rock. The samples include all core samples from Phase I and II and all processed heavy mineral concentrates from the processing facility. Even periodic floor-sweepings, plant recovery cleanup, and cleanup slimes were retained. The parcel of recovered diamonds is held in the possession of officials of the Arkansas Department of Parks and Tourism. The 210 diamonds, weighing 45.748 carats, were sent to New York for evaluation. The recovered diamonds range in value from $100 per carat to $1 per carat, with an average value of $12.30 per carat. Of these diamonds, about two-thirds (147) with a combined weight of nearly one-half of the stones (22.448 carats) graded as industrial bort, having a value of $1 per carat. All samples, including the diamonds, are the property of the Arkansas Department of Parks and Tourism. Access to the materials has, to date, been limited to company and project geologists, who are approved by the Parks Department. The Project Manager's (1997) Report for Phase II concludes with the statement that the pipe is uneconomic, the contained value of diamond per ton being 12 cents as calculated from the 45+ carat parcel.

THE FUTURE

Some thoughts as to the future of diamond mining and exploration in the region are in order. The Prairie Creek complex, the largest known pipe in the region and the eighth largest in the world (some 80.3 acres), has been shown by the recent testing to have subcommercial quantities of diamond present in the host rock in the zone from 10 to 40 ft in depth. No evaluation as to the commercial viability of this diamond deposit can be made, considering the small recovery of diamonds (<46 carats). An examination of the gem percentage of diamond versus industrial stones, and quality of gem-grade diamonds has been made on the 45+ carats of diamond recovered from Phase II bulk sampling. In the strictest sense, any conclusions from Phase II data concerning diamonds from this body represent only a sample from the upper 40 ft of crater facies in a highly complex body known to extend to a depth of 650 ft. Mitchell (1993) noted that "the complexity of the volcanic stratigraphy. . . suggests that evaluation of the diamond grade of the whole intrusion will not be a simple task." Each pyroclastic vent in the crater, depending on its own magmatic history, will carry its own grade and content of diamond. It cannot be predicted which vent will be higher or lower in diamond content and crystal size. These details must be established empirically. Testing of the upper 10 ft of regolith and soil was neither proposed nor done during the project, due to the decision that this material should not enter into the evaluation; the presumption being that the surface material would be

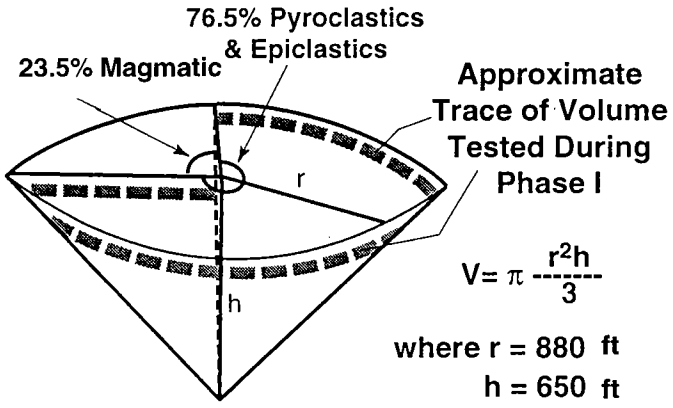


Figure 6. Cone volume model, displaying horizon of testing and relationship of the tested horizon to the entire calculated volume of the pipe.

removed and located elsewhere on State Park property for tourists' use should the pipe be mined at a later date.

The bulk-sample results from the mini-trench testing has proven inadequate to describe the commercial potential of the Prairie Creek vent, given the complexity of the pyroclastic system. Consider Mitchell's (1993) comments (above) and the simplistic approach of the shallow bulk-sampling method used in Phase II. Calculations, based on the volume of a simple cone some 880 ft in radius and 650 ft in depth as a model (Fig. 6), show that, by testing only near-surface material (upper 10 to 40 ft) during Phase II, less than 5% of the total volume of the body was evaluated. If one allows for 23.5% of the total volume of the cone to have very low potential (this number comes from the calculations of the volume of magmatic rock as given in the Phase I Report (Project Manager, 1993), then the volume of the tested zone represents about 8%. Looking back, a more valid method of bulk sampling would have been to include several, perhaps as many as five large-diameter bore holes to a depth around 300 ft. Certainly this additional method would have increased the costs of Phase II, but at least some volume of rock from depth and its diamond content would have been included in the evaluation calculations.

It is known that since 1906, when the first gemstones were discovered, that many diamonds, between 100,000 and 400,000 and weighing up to 42 carats individually, have been recovered by shallow mining and tourist efforts (Kidwell, 1990). Over 20,000 stones have been recovered since 1972. Therefore, the original upper 10 ft of material, which was not tested, must represent a notable concentration of diamonds when compared with the underlying 30 ft of tested rock. Until the final results of bulk sampling were known, some geologists believed that the Prairie Creek vent had only recently been exhumed by erosion and no significant surface concentration of diamonds had taken place. That assumption now appears false. On Monday, April 20, 1998, it was reported that a diamond from the Crater of Diamonds State Park was cut which graded as a perfect stone. The finished diamond weighs 1.093 carat and is valued at $33,730 (Thompson, 1998, p. 1B and 3B). The possibility of the presence of such quality stones never entered into the potential economic evaluation of the Prairie Creek deposit.

Opportunities for commercial ventures within the Crater of Diamonds State Park will be dormant for the next 20 years. This was a condition of the agreement between the U.S. Department of Interior (National Park Service) and the State of Arkansas that allowed the testing to take place. If the testing indicated the site to be noncommercial, the state may not consider any additional commercial ventures in the Park for a period of 20 years. This does not mean that scientific studies are to be hampered, but that commercially oriented activities will not be allowed for this period. Evaluations of the other small pipes and dikes in the region have, to date, indicated that they are not commercially viable, even though most are diamond-bearing. Until the Prairie Creek vent is adequately tested or additional pipes are discovered in southwest Arkansas, the potential for the start up of a modern diamond-mining operation in Arkansas is significantly reduced, due to the negative results of the testing program. Even after proper testing and evaluation, the Prairie Creek volcanic complex may not prove commercially viable. But for now, commercial viability cannot be ruled out. The Prairie Creek vent is 80.3 acres; the Argyle pipe in northwest Australia is 123 acres. So far, about $3.5 million was spent on testing and evaluation on Prairie Creek, compared to $165 million for evaluation of Argyle. It is granted that positive results were obtained initially at Argyle and as the evaluation process proceeded. However, only slightly more than 2% of the costs of a major evaluation program on a comparable size body elsewhere has been incurred by the companies involved at Prairie Creek. On the results from only shallow testing, the project manager concluded that the entire Prairie Creek deposit is noncommercial.

In the past, minor exploration efforts by companies for commercial-grade alluvial diamond deposits in the area have produced negative results. Little evidence is available concerning the possible existence of alluvial diamond deposits in Arkansas.

ACKNOWLEDGMENTS

Thanks to Drew. F. Holbrook, project geologist, for his critical review and Robert Allen for reviewing this paper and discussions during and after the testing.

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APPENDIX: DEFINITIONS OF SELECTED TERMS

diatreme—volcanic pipe that is filled with breccia formed by a gaseous explosion.

epiclastics—volcanic breccias. In the case of Prairie Creek, the epiclastic units also include a significant proportion of admixed sediment, predominantly sand and clay, derived from the Cretaceous wall rock.

kimberlite—porphyritic alkalic peridotite with abundant phenocrysts of olivine (commonly heavily altered), the mica phlogopite (commonly chloritized), and other minerals, set in a fine-grained groundmass of calcite and second-generation mafic minerals. An ultramafic rock. Name derived from Kimberly, South Africa.

lamproite—group rock name for dark-colored shallow-intrusive rocks or extrusive rocks that are rich in potassium and magnesium. Ultrapotassic igneous rock; compare with the ultramafic rock, kimberlite.

maar—a broad, low-relief volcanic crater that is formed by shallow volcanic explosions and that is commonly filled with water.

pipe—vertical conduit below a volcano through which magmatic materials have passed; generally filled with volcanic breccia and fragments of older rock.

pyroclastics—clastic rocks (breccias) formed by lateral volcanic explosion or aerial expulsion from a volcanic vent; generally, material is very hot when it settles and may partially re-fuse to form a welded tuff.

Celestine (Celestite) in Southwest Arkansas

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ABSTRACT.—Celestine (celestite) ($SrSO_4$), the primary ore mineral of strontium, is present in the DeQueen Limestone Member of the Trinity Group (Lower Cretaceous) in Sevier, Howard, and Pike Counties, southwest Arkansas. Two mappable celestine beds have been identified. One bed is commonly 3–5 in. thick, but ranges up to 18 in. in thickness; the other bed is generally 2–3 in. thick. The beds are concordant within the DeQueen Limestone and were formed by precipitation from periodically restricted sea water.

Reports concerning celestine date back to 1929, when Hugh D. Miser and A. H. Purdue mapped the geology of the DeQueen and Caddo Gap quadrangles. A small amount of celestine was produced in the early 1940s in Howard County. During 1941, the J. W. Hintze Company collected 1,500 pounds of celestine for testing purposes. In 1942 and 1943, 750 test holes were drilled by the Bennett-Clark Company in Howard County. Afterward, approximately 90 tons of celestine was open-pit mined and shipped to Texas for processing. Since then, no mining of celestine in Arkansas has taken place.

INTRODUCTION

Celestine ($SrSO_4$), also called celestite, is the primary ore mineral for strontium. It occurs in the DeQueen Limestone Member of the Trinity Group (Lower Cretaceous) in southwest Arkansas. The Trinity Group consists of beds of clay, sand, gravel, limestone, gypsum, and celestine (Miser and Purdue, 1929). The unit dips approximately 1° to the south and thickens southward under the Upper Cretaceous units. The DeQueen Limestone Member consists of limestone, gray and green calcareous clays, gypsum, and celestine. The DeQueen Limestone Member is exposed from Plaster Bluff on the Little Missouri River in Pike County, westward to the Arkansas-Oklahoma border west of DeQueen, Sevier County, Arkansas. This member is approximately 140 ft thick at the active Highland Gypsum quarry in sec. 16, T. 8 S., R. 26 W., near Highland in Pike County. Gypsum beds within this member pinch and swell and are occasionally nodular. Sand-dominated members of the Trinity Group are present both above and below the DeQueen Limestone Member. In the subsurface of south Arkansas, the DeQueen Limestone corresponds in part to the massive Ferry Lake anhydrite.

A number of celestine-bearing horizons have been identified in the DeQueen Limestone, and two beds have been mapped. One bed is commonly 3–5 in. thick and ranges up to 18 in. in thickness; the other bed is generally 2–3 in. thick. The bedded celestine is coarsely crystalline, vuggy, and interbedded with a gray or green calcareous clay. Nodular celestine horizons also are present within the limestone beds. This form of celestine seems to be associated with a higher calcite content.

Figure 1 is an outcrop map of the bedded-celestine deposit south of Dierks in Howard County. Table 1 presents descriptions of celestine on numbered sample sites in Figure 1. This deposit, roughly 3 mi^2 in extent, has easily traced exposures of celestine as well as being the thickest known bed. The celestine bed at this location is about 35 ft above the base of the DeQueen Limestone Member (McElwaine, 1972) and occurs *below* the gypsum-bearing horizons.

Elsewhere, other beds of celestine occur *above* the gypsum-bearing horizon—for examples, in the inactive portion of the Highland Gypsum mine (sec. 21, T. 8 S., R. 26 W.) in Pike County and in the James Hardie Gypsum mine, formerly known as Briar Plant Gypsum, (sec. 14, T. 8 S., R. 27 W.) in Howard County. Figure 2 is the stratigraphic section in the active portion of the

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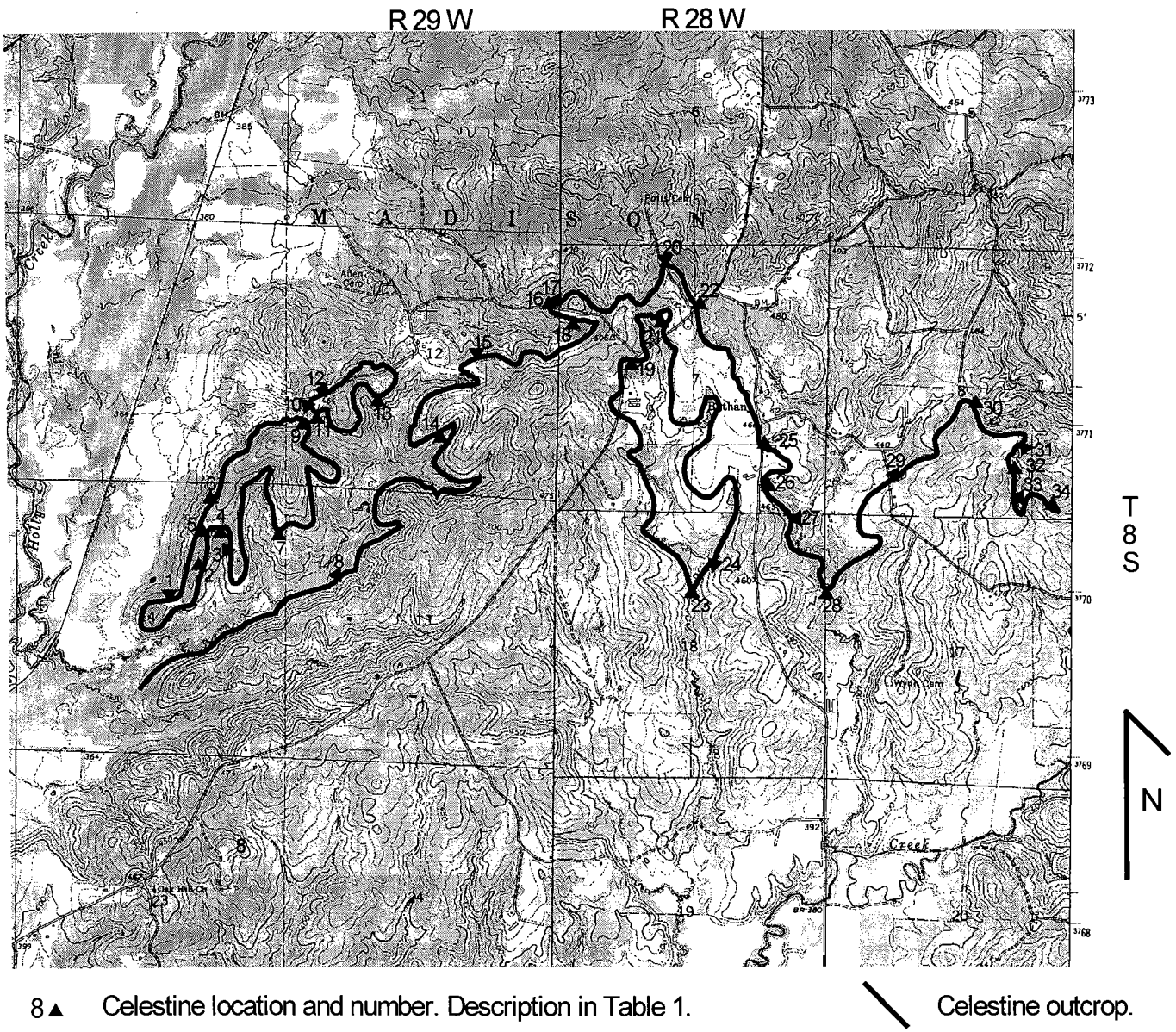


Figure 1. Outcrop map of celestine deposit near Dierks, Howard County, Arkansas. Base map from Dierks 7½ -minute quadrangle, reduced to scale 1.6 in. = 1 mi.

Highland Gypsum mine (sec. 16, T. 8 S., R. 26 W.) in Pike County, and Figure 3 is the stratigraphic section in the inactive James Hardie Gypsum mine (sec. 14, T. 8 S., R. 26 W.) in Howard County.

ANALYSES

Analyses were performed on celestine samples collected from Sevier and Howard Counties in southwest Arkansas. Much of the unpublished data cited below is from the open-file reports of the Arkansas Geological Commission (1998). Table 2 shows analyses of individual hand samples collected from various locations as well as an analysis of a 536-lb bulk sample collected by one of us (McElwaine) in 1957. This bulk sample was analyzed by Bruce Williams Laboratories the same year and yielded a composite $SrSO_4$ value of 46.37% (Table 3), and values of $SrSO_4$ in size fractions ranging from 22.94% to 78.44%. Selected and grab samples collected and analyzed in 1969 by the U.S. Bureau of Mines had a $SrSO_4$ content ranging from 5.5% to 97.0% (Stroud and others, 1969). Samples, collected south of Dierks in Howard County, analyzed by Bruce Williams Laboratories during 1954, yielded $SrSO_4$ contents ranging from 85.45% to 91.62%. Samples collected at the inactive James Hardie Gypsum mine and analyzed by Richard H. Olson in 1978 had $SrSO_4$ contents ranging from 10.90% to 38.30%. A sample collected in Sevier County, Arkansas, by Mr. Volk in 1979 and analyzed in 1980 by Gaston F. Bell of the Arkansas Geological Commission Laboratory, had a $SrSO_4$ content of 79.1%.

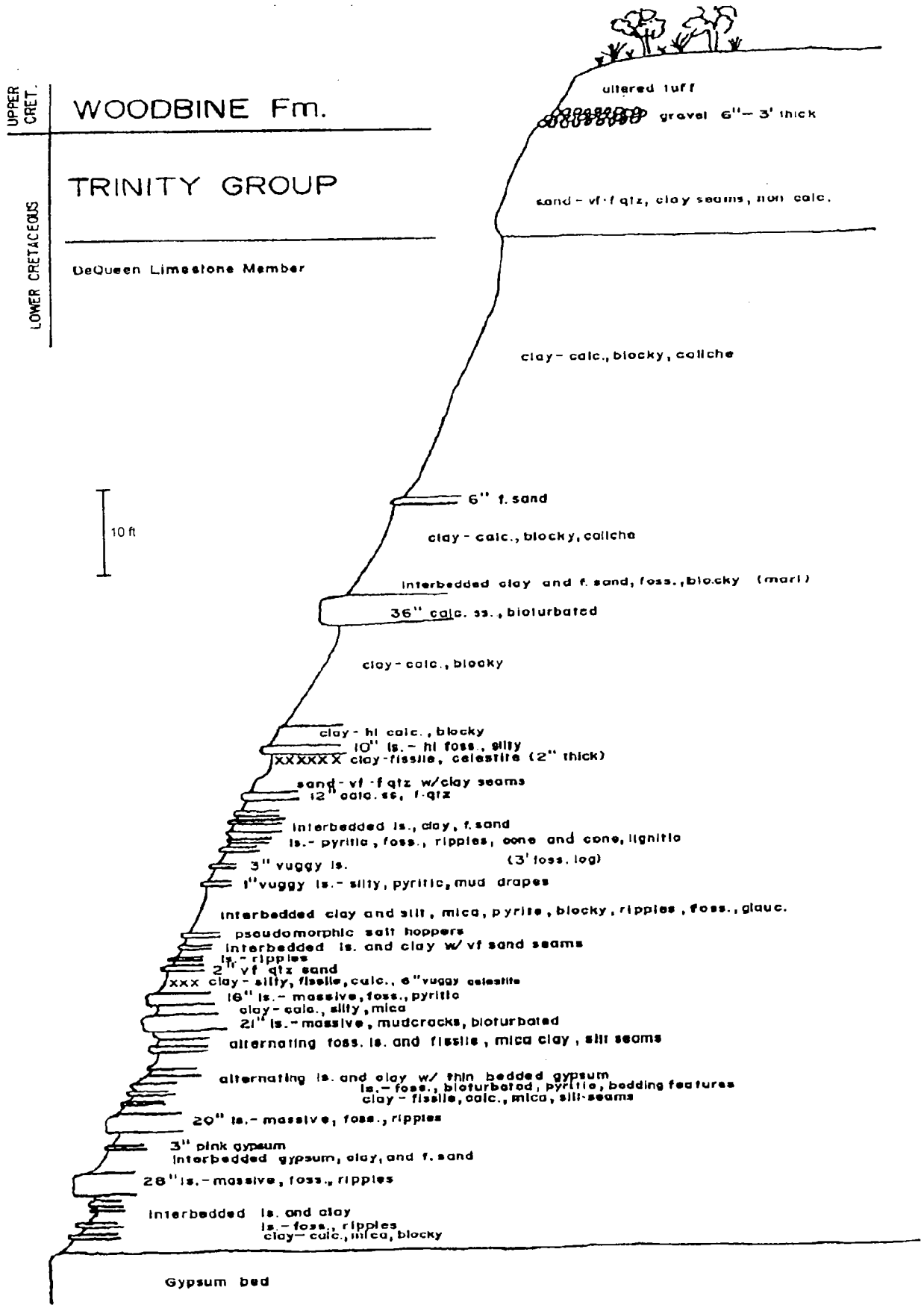


Figure 2. Stratigraphic section measured in active portion of Highland Gypsum quarry, SW¼SW¼ sec. 16, T. 8 S., R. 26 W., Pike County, Arkansas.

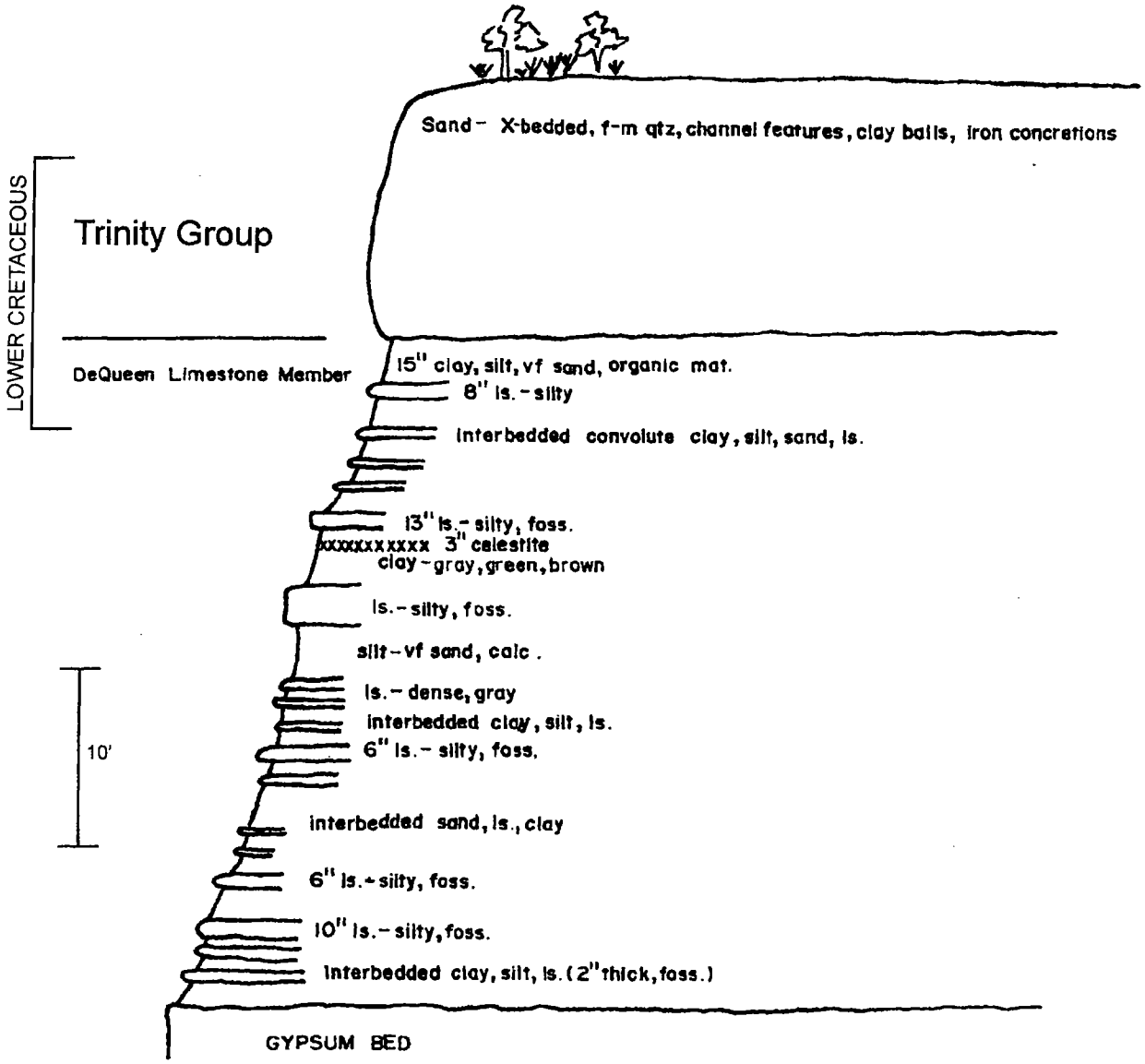


Figure 3. Stratigraphic section measured in the inactive James Hardie Gypsum mine, SW¼SW¼ sec. 12, T. 8 S., R. 27 W., 0.10 mi east of Nathan/Corinth Road.

ORIGIN

The celestine beds appear concordant within the strata, and their vugginess and coarse crystallinity suggest that the celestine precipitated from periodically restricted sea water and formed as an evaporite deposit. The association of gypsum and barite in the DeQueen Limestone Member also suggests that the celestine is an evaporite deposit. The thinner celestine unit may have a different mode of formation, as suggested by its nodular form and higher content of calcite, implying concentration of fluids after burial.

USES

The primary use for strontium is to block X-ray emissions from color-television sets and other devices containing cathode-ray tubes, such as computer monitors. Additional uses include ceramic ferrite magnets, pigments and fillers, small direct-current motors, and pyrotechnic applications (fireworks). Of the 53,708.5 tons (48,724,000 kg) of celestine imported into the United States in 1990, approximately 89% originated in Mexico and 10% was from Spain. Rated production capacity for the United States on December 31, 1990, was 22,000 tons. The average value for total strontium imports during this period was approximately $85/ton (Ober, 1994).

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Table 1.—Description of Celestine Locations in Figure 1

Location no.	Description	Location no.	Description
1	4 ft below gap celestite outcrop and float	18	celestite outcrop
2	celestite outcrop and float	19	4–6 in. celestite outcrop
3	surface celestite outcrop in gap	20	3 in. celestite float
4	celestite float	21	4 in. celestite outcrop
5	celestite outcrop and float	22	celestite in weathered clay
6	celestite float	23	celestite float material in creek
7	8 in. interbedded celestite outcrop (thickest bed 1.5 in.)	24	4 in. celestite outcrop
		25	5 in. celestite outcrop
8	5–6 in. celestite outcrop	26	18 in. interbedded celestite outcrop (thickest bed 3 in.)
9	18 in. interbedded celestite outcrop (thickest 3 in.)		
10	celestite outcrop	27	18 in. interbedded celestite outcrop
11	celestite outcrop	28	4 in. celestite outcrop
12	celestite outcrop	29	3 in. celestite float
13	celestite float material	30	celestite outcrop
14	celestite float material	31	4 in. celestite float
15	celestite outcrop — mixed areas (trenches)	32	4 in. celestite float
16	celestite outcrop	33	celestite outcrop
17	celestite outcrop	34	3 in. celestite float

Table 2.—Analyses of Celestine Hand Samples (%)

Sample ID	Location	$BaSO_4$	$SrSO_4$	$CaSO_4$	$CaCO_3$	SiO_2	Sp. Gr.	Analysis by and when
1	SE¼ sec. 7, T. 8 S., R. 28 W.	0.08	85.45	9.10			3.81	Bruce Williams Laboratories, 1954
2	SE¼ sec. 7, T. 8 S., R. 28 W.	1.00	86.36	7.28			3.74	Bruce Williams Laboratories, 1954
3	SE¼ sec. 7, T. 8 S., R. 28 W.	2.67	90.94	2.91			3.86	Bruce Williams Laboratories, 1954
4	SE¼ sec. 7, T. 8 S., R. 28 W.	0.95	91.62	4.86			3.88	Bruce Williams Laboratories, 1954
5	SE¼ sec. 7, T. 8 S., R. 28 W.	1.50	90.78	6.07			3.83	Bruce Williams Laboratories, 1954
Volk	SE¼ sec. 17, T8S, R29W	0.29	79.10	17.40				G. F. Bell, AGC, 1980
RHO-76C-8	NW¼ sec. 14, T. 8 S., R. 27 W.	0.26	15.00					Richard H. Olson, 1978
RHO-76C-9	NW¼ sec. 14, T. 8 S., R. 27 W.	0.38	10.90		74.90			Richard H. Olson, 1978
RHO-76C-10	NW¼ sec. 14, T. 8 S., R. 27 W.	0.64	27.70		65.90			Richard H. Olson, 1978
RHO-76C-11	NW¼ sec. 14, T. 8 S., R. 27 W.	0.86	31.80		47.90			Richard H. Olson, 1978
RHO-76C-12	NW¼ sec. 14, T. 8 S., R. 27 W.	1.03	38.30		35.90			Richard H. Olson, 1978
McElwaine	Howard County?	0.90	66.90	14.50		10.50		?
USBM-Ranges		0.2–3.0	5.5–97.0	0.4–1.4	0.5–56.0			U.S. Bureau of Mines, 1969

Table 3.—Analyses of Celestine Bulk Sample SE¼ sec. 7, T. 8 S., R. 28 W.

Product	Wt. (lb)	Wt. (%)	$SrSO_4$ (%)	$BaSO_4$ (%)	CaO (%)	SiO_2 (%)	Sp. Gr.
>2 inches	37.31	6.96	72.19	1.19	7.58	0.64	3.73
>1½ inches	15.56	3.09	64.42	1.19	12.50	0.78	3.52
>1 inch	26.00	4.85	52.74	0.95	18.43	1.05	3.35
>¾ inch	13.31	2.48	54.16	1.02	18.05	1.74	3.38
>½ inch	22.50	4.20	62.99	1.00	13.33	1.60	3.64
>⅛ inch	67.56	12.60	78.44	1.10	6.60	0.52	3.73
>4 mesh	33.12	6.18	69.24	0.95	9.03	1.62	3.72
>16 mesh	63.56	11.86	76.21	1.31	6.73	1.29	3.71
>30 mesh	26.00	4.85	73.29	1.38	6.40	1.56	3.69
>50 mesh	10.06	1.87	73.23	1.77	6.35	1.48	3.71
>80 mesh	3.44	0.64	68.26	1.58	4.98	2.41	3.73
>100 mesh	1.19	0.02	63.53	1.33	4.40	5.25	3.56
(–100 mesh)	4.66	0.87	54.95	1.17	5.23	14.75	3.30
Fine sand	82.77	15.44	22.94	0.33	9.47	39.39	2.85
Slimes*	128.39	24.11	0.90	0.12	9.65	46.71	2.61
Heads (totals)	536.00	100.00	46.37				

*R_2O_3 of slimes = 41.45%.

Note: Analysis by Bruce Williams Laboratories, 1957. Collected by R. B. McElwaine.

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Development, General Geology, and Economic Resources of the Kansas River Corridor

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ABSTRACT.—Divided opinions concerning dredging-permit locations and boating uses on the Kansas River in northeastern Kansas led to a study of the recreation potential on the river by a legislatively mandated interagency group (five agencies) that included the Kansas Geological Survey (KGS). In addition, the KGS conducted its own study of the river corridor, encompassing the development, geology, and economic resources of the corridor (Brady and others, 1998). The corridor area is 12 mi wide and 140 mi long (171 river miles). Included in the study was the potential impact of restrictions to river dredging.

The Kansas River and its floodplain in northeastern Kansas are underlain by Lower Permian and Upper Pennsylvanian limestones and shales. The river and its floodplain are the major sources of sand and gravel for northeastern Kansas, and the limestones along the river bluffs supply crushed stone and building stone. The population of the 10-county area bordering the river has grown by 20% since 1980, and now comprises nearly 40% of the state's population (U.S. Bureau of the Census, 1996). Projections (Floerchinger, 1992) indicate close to 50% of the Kansas population will reside in these counties by 2025, with a continued increase in the demand for aggregates.

Factors such as floodplain width, price and availability of land, and overburden ratios tend to favor river dredging on the lower part of the river, and floodplain or pit dredging on the upper portion. The use of alternate sources of sand and gravel such as the Missouri and Arkansas Rivers would increase sand prices due to transportation costs to much of the 10-county area. In 1996, river and pit dredges along the Kansas River supplied more than 3 million tons of sand and gravel valued at about $8 million to northeastern Kansas.

As a result of its study, the KGS had concerns with the idea of large recreation zones on the river that excluded river dredging in areas of presently large population and projected population growth. This controversial issue is likely to recur elsewhere.

INTRODUCTION

In July 1974, Victory Sand and Gravel applied to the U.S. Army Corps of Engineers for a permit to dredge in the Kansas River a few miles northwest of Lawrence, Kansas, in an area of the river that historically had not been used for dredging. In the subsequent public hearings, the usual opinions were expressed by neighbors about traffic, noise, roads, etc.—factors that are commonly associated with NIMBY ("not in my back yard"). Also, concern was expressed about the location being a short distance upstream from an old landfill. In the months that followed, numerous newspaper articles appeared that referred to the poor water quality of the river. Such articles also mentioned dredging, and, to the general public, the implication was that dredging was somehow related to the poor water quality. Strong opposition to any dredging on the river was expressed by recreational and environmental groups, specifically the Kansas Canoe Association and Friends of the Kaw. Eventually, a two-year moratorium on any new dredging in the river was proposed. Although the measure failed to gain the necessary support, the legislature mandated an interagency committee to study the recreational potential on the river. The Kansas Geological Survey (KGS) was a member of this committee. Realizing the importance of the sand-and-gravel resources associated with the river, and recognizing the attempts to eliminate or restrict the Kansas River as a source of economic minerals, the KGS launched its own study of the river.

Grisafe, D. A.; and McCauley, J. R., 1999, Development, general geology, and economic resources of the Kansas River corridor, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 111–117.

OBJECTIVES

The objective of this paper is to provide a better understanding of the Kansas River as a geologic resource by discussing the physical and cultural geography of the river valley, the geologic setting, and the economic minerals associated with the river, especially sand and gravel. The study focuses on a Kansas River corridor that we defined as that area within 6 mi of the river, from its source in Junction City to its mouth in Kansas City, an area of roughly 1,700 mi^2.

The Kansas River is a major natural resource in northeast Kansas; in fact, it is many different resources. First, it is a transportation resource and is still classified as a navigable stream, although that is primarily a bureaucratic description rather than a practical one. Its river valley cuts through the Flint Hills and the Osage Cuestas and is still an important transportation corridor with roads and rail lines parallel to the river. Second, the river is an important water resource. This resource is not only the river itself but also its alluvial aquifer, which is the major aquifer in northeastern Kansas. Third, the rich bottom lands of the river are an important agricultural resource. Fourth, the Kansas River is the largest river in the state, and its riparian habitat represents an ecological resource. Fifth, as one of three public waterways in the state, the Kansas River is an important recreational resource. And, finally, but not least, because it is the source of industrial minerals, mainly sand and gravel, the Kansas River is an important mineral resource; this subject will be the major topic of this paper.

GEOGRAPHIC AND GEOLOGIC SETTING

The Kansas River officially begins in Junction City at the confluence of the Smoky Hill and Republican Rivers (Fig. 1). It flows 170 mi east to the Missouri River in Kansas City. The actual drainage area of the Kansas River extends 500 mi west from Kansas City onto the high plains in northeastern Colorado. The river drains an area of 60,000 mi^2, an area larger than the state of Iowa. Major tributaries to the river include the Smoky Hill, Saline, Solomon, Republican, and Big Blue Rivers, Soldier Creek, Delaware River, Wakarusa River, and Stranger Creek. All the large tributaries of the Kansas River are impounded by federal reservoirs, and 18 such reservoirs occur in the basin. The Kansas River itself is dammed at Lawrence by Bowersock Dam, a low hydroelectric dam.

The Kansas River flows near the southern limit of glacial advance into Kansas during the Pleistocene Epoch, a period of time known informally as the Ice Ages and which occurred fairly recently in geologic time. The Kansas glacier entered Kansas several hundred thousand years ago and played a major role in the formation and location of the Kansas River. Since that time, the Kansas River has been cutting into the underlying bedrock, which dates to the Pennsylvanian and Permian Periods (270 to 300 million years old). The bedrock is predominately limestone and shale with a few sandstones and thin coals interbedded. This bedrock forms the bluffs and the uplands that border the Kansas River. Scattered throughout the uplands are glacial-drift deposits that include clay, silt, sand, gravel, and boulders, especially the large pink quartzite boulders so common to northeastern Kansas. The areal geology of the river corridor is shown in Brady and others (1998).

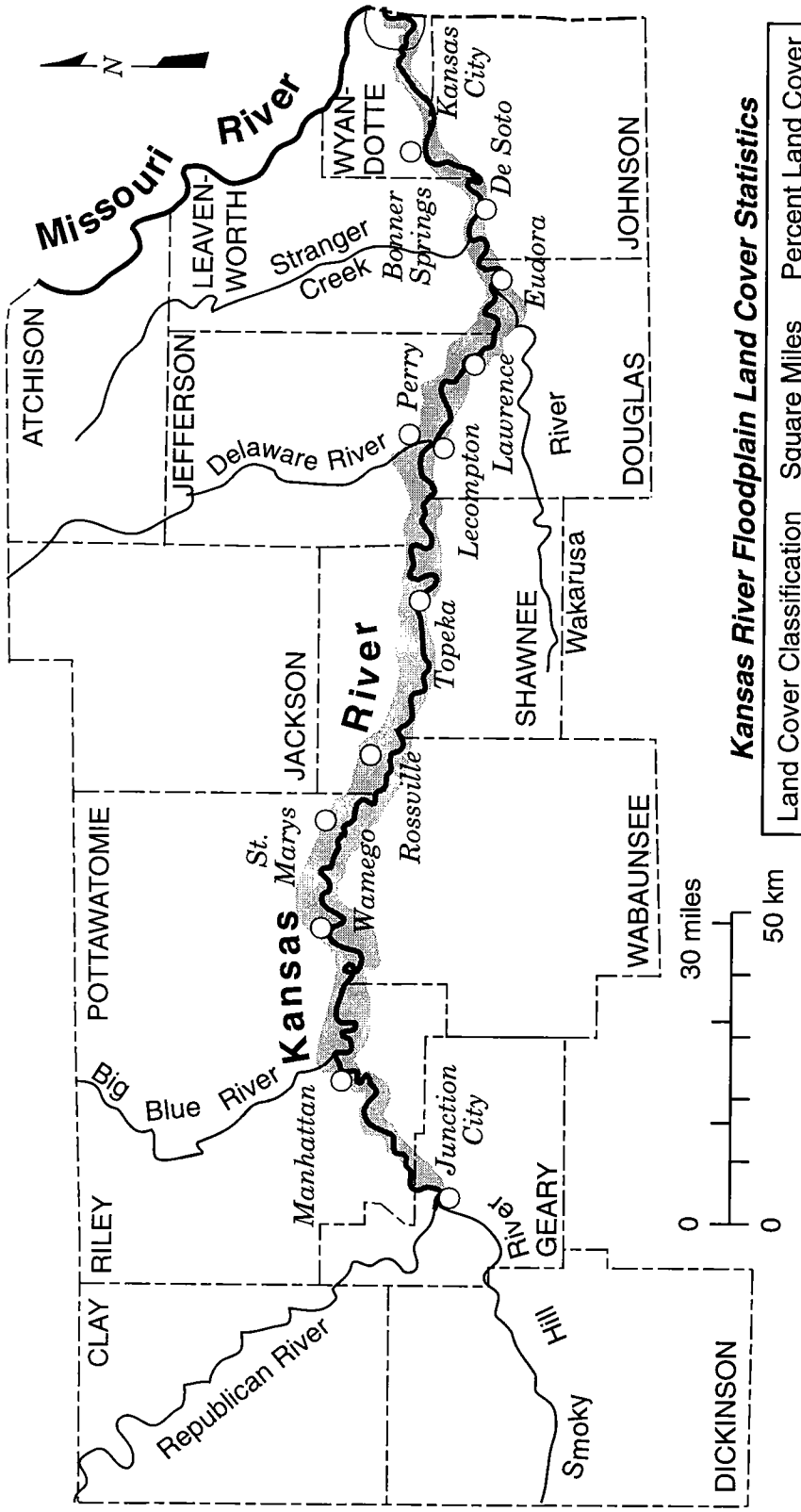
Today, the Kansas River has formed a deep, bedrock trench that is partially filled up with silt, sand, and gravel, material collectively known as alluvium. In places, this alluvium is as much as 95 ft thick. Away from the river are slightly elevated terraces. These represent floodplain deposits that formed when the river flowed at higher levels following periods of glacial melt. In general, the Kansas River is said to be at equilibrium or slightly degrading. A study done in 1984 by Simons, Li, and Associates, estimated that roughly 1.67 million tons of sediment per year passed the De Soto gauging station (Fig. 1). Such measurements are made with a high degree of uncertainty. The 18 federal reservoirs in the Kansas River basin do two things: they control floods, and they trap sediment. By reducing the size of floods along the Kansas River, these reservoirs reduce the maximum grain size that can be transported by the river. As a result, today, much of the gravel that is taken from this river cannot be replenished, because it is moved only during very large floods.

The Kansas River valley is 138 mi long and has a gradient or slope of about 2.5 ft/mi. The river proper takes a more tortuous course of 170 river miles and has a gradient of about 2 ft/mi. The average width of the Kansas River floodplain is 2.6 mi. However, it is 3 mi or wider in numerous places above Eudora. The widest stretch of the floodplain is in the Wamego to Rossville area (Fig. 1), where it is equal to or slightly more than 4 mi in width. The narrowest stretch of the Kansas River is from Eudora to its mouth where it is less than 1.5 mi in width and in some places less than 1 mi. From Junction City to Lawrence, the Kansas River seems to prefer the south side of its valley touching the south valley walls in numerous locations. Below Lawrence, the river shows no preference for either side of its valley and meanders from bluff to bluff. Also, very few terraces occur in this stretch of the river from Eudora to Kansas City (Fig. 1).

The general nature of the Kansas River floodplain is shown in Figure 1. Statistics for the types and percentages of land use in the floodplain are presented in the table that is shown as part of Figure 1. A summary of the land use in the river corridor is given in Brady and others (1998). Almost three-quarters of the land use is agricultural—cropland (60%) and grassland (14%).

POPULATION

The Kansas River touches on or passes through 10 counties along its course (Fig. 1). Those are Riley, Geary, Pottawatomie, Wabaunsee, Shawnee, Douglas, Jefferson, Leavenworth, Johnson, and Wyandotte. These 10 counties had a population of slightly less than one million in the 1990 census according to the U.S. Bureau of the Census (1996). This represents 40% of the state's 2.5 million population. Eight of these 10



Kansas River Floodplain Land Cover Statistics

Land Cover Classification	Square Miles	Percent Land Cover
Commercial/Industrial	14.1	4%
Cropland	201.4	60%
Grassland	48.6	14%
Other	15.0	4%
Residential	10.4	3%
Urban-Grassland	4.8	1%
Urban-Water	0.2	0%
Urban-Woodland	0.5	0%
Water	19.1	6%
Woodland	24.1	7%

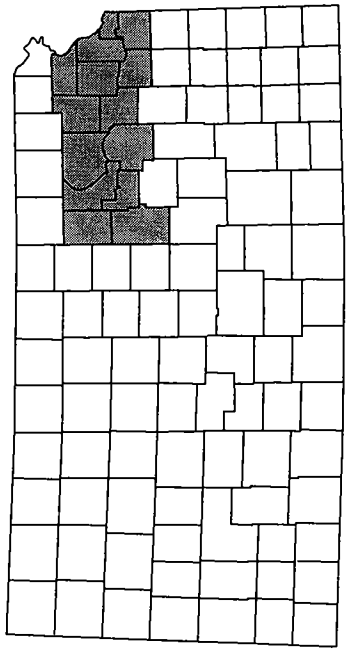


Figure 1. Map showing counties, communities, and major drainages along the Kansas River. The shaded area along the river denotes the floodplain area, and the table below the map lists the land uses within the floodplain (data from Brady and others, 1998).

counties gained population between the 1980 and 1990 census years, and the net gain of these 10 counties equals 97% of the state's net gain in population between those two census years. The population density of the 10-county area is 182.3 people per mi^2. This is six times as dense as the state as a whole, which has an average density of 30.3 people per mi^2. Although there are roughly one million people in the Kansas River valley now, by the year 2025, it is projected that the population of these 10 counties will be 1.3 million (Floerchinger, 1992), which will be nearly 50% of the state's projected population. Such growth demands new infrastructure and new construction, and one resource necessary for that new construction is aggregates.

AGGREGATES

Although aggregates are an inexpensive and, in places, an abundant natural resource, they are like most of the earth's resource—not distributed in a uniform or equitable manner. This inequitable distribution of the earth's resources is one reason there are disputes, lawsuits, wars, and geologists. The two main types of aggregates used in Kansas are sand and gravel and crushed stone. Most of the crushed stone in Kansas is produced from the limestones that crop out from the Flint Hills eastward. In the Kansas River valley are roughly 75 named limestone units. However, only a few of these limestone units meet the rigid specifications of the Kansas Department of Transportation (KDOT) and other users of aggregates for purity and physical character for use in concrete construction. A recent article in the Kansas City Star (Anonymous, 1998) dealt with the problem of crumbling concrete in the Kansas City area and laid the blame on the use of crushed limestone from eastern Kansas. Today, more sand and gravel is being substituted for crushed stone. The average aggregate mixture in highway concrete is 65% sand and gravel and 35% crushed limestone. KDOT estimates that a 1-mi concrete highway, two lanes wide and 9 in. thick, uses 3,400 tons of sand and gravel alone, at a cost of $12,350. Data from the U.S. Bureau of Mines and U.S. Geological Survey for northeastern Kansas were used to calculate 10-year averages from 1986 to 1996 listed by Blechinger (1997) that included: concrete aggregate (50%), asphalt aggregate (21%), fill sand (14%), road base and covering (11%), and other uses such as treatment for icy roads, fill, sandblasting, and raw material for fiberglass production (4%). Of the sand and gravel produced in the Kansas River corridor, 25% is used by the KDOT.

PRIMARY SOURCES OF SAND AND GRAVEL

The primary sources of sand and gravel in Kansas are: (1) the Kansas River, including the lower portions of its tributaries such as the Republican, Big Blue, and Smoky Hill Rivers; (2) the Arkansas River, which is extensively mined in the Wichita area and other places; and (3) the Missouri River. Sand from the latter source has a drawback, because its sand contains lignite, the dark particles of which may discolor the concrete and also lead to accelerated weathering. The Neosho River is mined occasionally for cherty gravels that are found along its course.

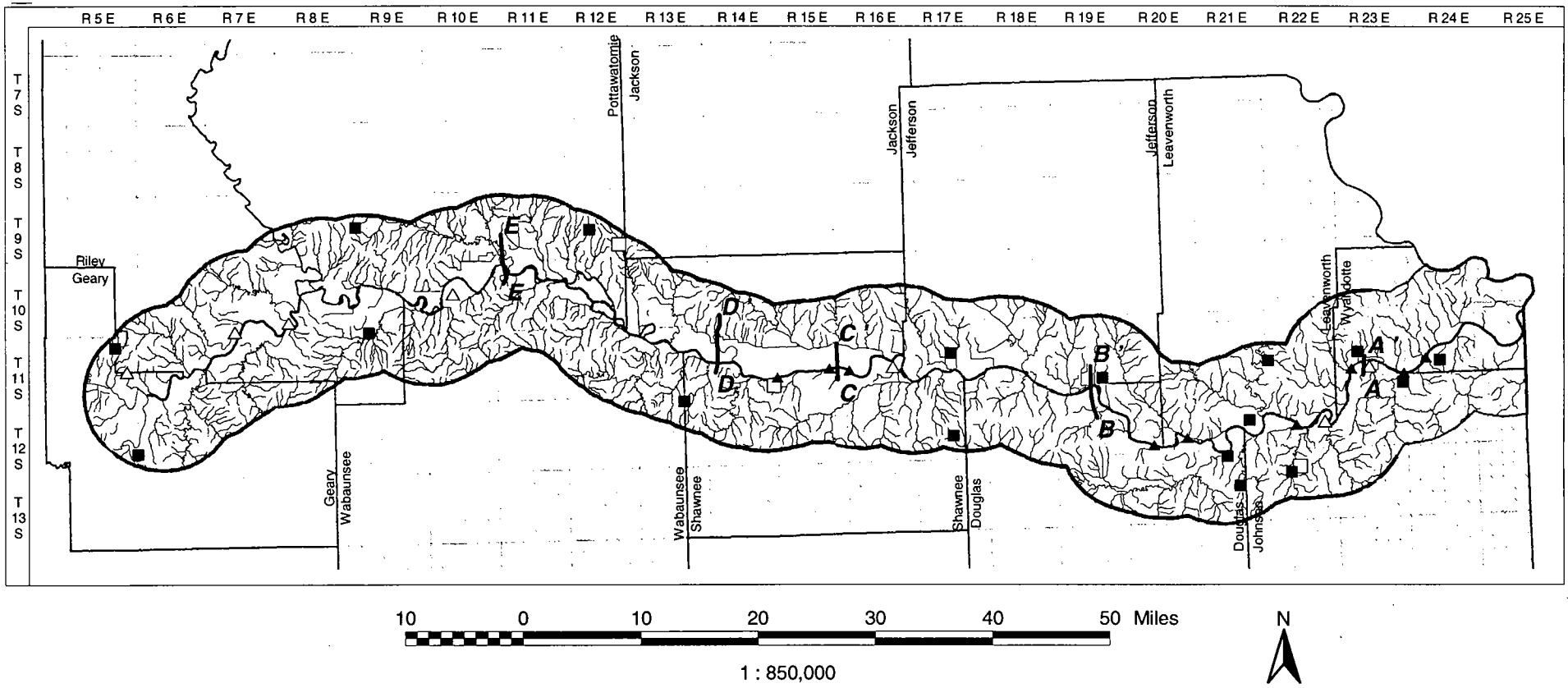
Another source of sand and gravel is in western Kansas, where Ogallala and younger deposits of sand and gravel are mined in dry pits generally located above the water table. The ultimate source of sand and gravel mainly comes from two sources. The first source comes from glacial drift, which was left behind in northeast Kansas by the glaciers that carried material into the state from Canada and the north-central parts of the United States. The second source is the sand-and-gravel deposits of the High Plains that were washed into Kansas from the west and the Rocky Mountains. Rivers that do not drain these two areas, the glaciated area, and the Ogallala-type deposits of western Kansas, generally do not have economic deposits of sand and gravel in their river beds.

DREDGING

The Kansas River is a major source of sand and gravel in northeastern Kansas. Sand and gravel is produced by two dredging processes: river dredges and floodplain or pit dredges. A colored map of the Kansas River valley given in Brady and others (1998) shows the river corridor, permits for dredging, exclusion zones to river dredging such as bridges and pipelines, and river miles. The occurrence of numerous exclusion zones in the lower portion of the river removes a significant amount of sand-and-gravel resources.

River dredges are the main method of dredging in the Kansas River area, particularly with respect to tonnage. They mine the bed material of the river, which is generally sand and small gravel. In general, the Kansas River contains very little mud or clay; therefore, there is very little waste. Nearly all the material taken from the river can be used as a commercial product. This results in some of the best-quality, least-expensive sand in the United States. Data from an Engineering News Record report (Anonymous, 1997) showed that U.S. prices for sand at the plant ranged from $3.00 to $15.00 a ton. In Kansas City, sand at the plant cost on average $3.60 per ton. In 1996, 2.4 million tons of sand and gravel were produced from the Kansas River. This represents 75% of the sand and gravel produced in the 10-county area along the Kansas River. Producers pay a $0.15 per ton royalty to the state on sand taken from the Kansas River, and, in 1996, this resulted in $360,000 paid to the Kansas treasury.

Floodplain dredges or pit dredges operate on the floodplain of the river at some distance from the river and mine the alluvial fill of the river valley. Figure 2 shows industrial-mineral operations along the Kansas River corridor, including river and pit dredges, crushed limestone, and building limestone. Also, shown on Figure 2 are stratigraphic-section lines that cross the Kansas River. These are lines along which cross sections have been presented in previous KGS reports. The thickest sequence of alluvium shown on these cross sections is roughly 90 ft or so shown on the Topeka cross section (C–C′), along the north side of the Kansas

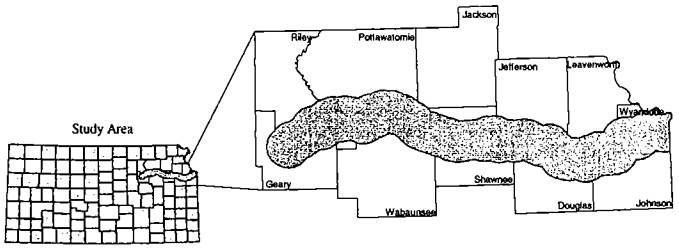


Primary Features:

- Streams and Rivers
- Cross-Section Locations (A - A')
- River Dredge Locations
- Pit Dredge Locations
- Crushed Limestone
- Building Limestone

Base Map Features:

- County Boundaries
- City boundaries
- Township boundaries
- Section corner points



Citation Information:

Base map information (County boundaries, City Boundaries, Township boundaries, Section Corner Points, and Hydrography were obtained from the State of Kansas Data Access and Support Center (DASC) at the Kansas Geological Survey (KGS)

Pit dredge locations were obtained by converting legal descriptions to geographic coordinates. River dredge locations were plotted using river mile markers as a reference

Projection Information:
Lambert Conformal Conic (Clarke 1866)

Central Meridian	-98 15 00
Reference Latitude	36 00 00
Standard Parallel 1	33 00 00
Standard Parallel 2	45 00 00

Figure 2. Industrial-mineral operations and cross-section locations along Kansas River Corridor. For statistics on land-use in area, refer to Figure 1.

River valley. These cross sections show the typical sequence of materials encountered within the river floodplain. The uppermost part of the floodplain and much of the terrace deposits are composed of over-bank deposits, generally consisting of fine-grained materials such as clays and silts that were deposited at times of flood at some distance from the river channel itself. The soil and these fine-grained materials represent overburden that must be removed and used as fill or possibly as topsoil. There is limited market for this material. The next material commonly encountered is fine-grained sand. Much of that is also unusable; however, a small amount can be used and sold as masonry sand. The deeper layers on down to bedrock commonly contain large amounts of medium- to coarse-grained sand and gravel, and this is the desired material. However, within this sand and gravel sequence may be lenses of clay or silt that again have very little market value. The overburden must be removed down to the water table in order to float the dredge that will then dig up the sand and gravel.

PIT DREDGING VERSUS RIVER DREDGING

Pit dredges are permitted by the State Conservation Commission with approval from the appropriate county commission. River dredges are permitted by the U.S. Army Corps of Engineers with approval of plans by the Division of Water Resources of the Kansas Department of Agriculture. In addition, county commissioners approve areas where the plant and handling facilities are located. At the time of this paper, seven pit dredges and nine river dredges were operating in the Kansas River corridor (Fig. 2). All the river dredges operated from just west of Topeka downstream to the river's mouth (Fig. 1).

A pit dredge requires much more land. At a minimum, it is estimated that 100 acres are required for a successful pit-dredge operation, and this land is commonly expensive bottom land. A river dredge requires only about 10 acres of land necessary for the screening and storage of material, and this is generally located along the river bank. A pit-dredge operation generally requires drilling or some sort of exploration program to ensure that adequate supplies of sand and gravel are available for mining. This generally is not necessary for the river dredge. With a pit dredge, overburden must be removed at some cost and the pit must be excavated down to the water table, which may be at a considerable depth below the surface. On a river dredge, there is no overburden, and no unnecessary excavation is needed. Unused material produced by pit dredging incurs some cost for removal or disposal. With a river dredge, there is very little in the way of unusable material. Pit dredges also require reclamation. With river dredges, there is no reclamation. In addition, when a pit dredge is shut down, a large hole is left in the floodplain in which the water table is exposed, creating a potential avenue of pollution and also a potential loss of water resources through evaporation. In general, in the lower Kansas River area, sand produced by pit dredging is 50% more expensive than sand produced by river dredges.

Blechinger (1997), in a master's project in Civil Engineering at the University of Kansas, did an analysis of sand-mining alternatives along the Kansas River. He evaluated most of the water-well logs located at the KGS for wells drilled in the Kansas River valley. For these, he determined overburden ratios (defined as the ratio of overburden in volume to tons of underlying sand and gravel) for each mile-square section for which information existed. After analyzing various factors affecting the cost, 74 potentially profitable pit dredging sites in the Kansas River valley whose overburden ratios were 0.18 or less were identified. Most of these are in the upper part of the Kansas River valley from Shawnee County westward. Forty-nine occur in Shawnee, Pottawatomie, and Wabaunsee Counties, where the floodplain is quite wide (Fig. 2). Only nine potentially profitable pit-dredging sites were found downstream of Douglas County.

CONCLUSIONS ON DREDGING

Conclusions regarding dredging in the Kansas River follow. In general, the Kansas City to Lawrence stretch of the river favors river dredging. There, the floodplain is much narrower, and the land available for pit dredging is tightly restricted by commercial development, railroad yards, highways, pipelines, and expensive farmland. In addition, the overburden—that unusable material lying above the commercially valuable sand and gravel—is thicker in this portion of the river valley.

The Lawrence to Topeka stretch of the river (Figs. 1,2) is slightly more conducive to pit dredging. There, the floodplain is a little bit wider; however, the overburden is still thick. In addition, much of the land in this area is farmed and more expensive and difficult to obtain. The Topeka to Junction City stretch of the river (Figs. 1,2) appears to be the most likely area for successful pit dredging. There, the floodplain is quite wide making available more less-expensive land. Commercial and industrial usage of the floodplain is less than in areas downriver. In addition, the overburden is thinner. Presently, all of the dredges operating above Topeka in the Kansas River valley are pit dredges.

ALTERNATIVE SOURCES OF SAND AND GRAVEL

A major expense in the use of sand and gravel is its transportation costs. Ten cents per ton-mile is an average cost for transporting sand and gravel, but this may range from $0.08 to $0.25 per ton-mile. Most producers do not haul sand and gravel farther than 50 mi. They find that longer runs are less profitable than shorter hauling distances. This effectively rules out the Arkansas River as a source for sand and gravel in the Kansas River area except in unusual circumstances. In 1993, such unusual circumstances occurred when flooding along the Kansas River caused the dredges, both river and floodplain, to shut down. Then, some sand and gravel was shipped into the Kansas River area from the Arkansas River, and this sand and gravel was selling

for $15.00 a ton. This contrasts to $3.60 a ton average for Kansas River sand at plants in the Kansas City area.

If circles are drawn around each sand-and-gravel source with radii of 50 mi, the following results are obtained for two scenarios. First, if river dredging were removed from the Kansas River, the few pit dredges on the narrow floodplain of the lower Kansas River valley would be inadequate to meet the demand in that rapidly growing area, and pit dredges in the upper Kansas River valley would be too far away, and transportation costs would be very high. Consequently, more Missouri River sand would have to be used. Even after attempts are made to remove the troublesome lignite from the latter source, it is still not suitable for some construction jobs. Second, if no sand were removed from the Kansas River, only the lower parts of its tributaries and the Missouri River would be sources in northeastern Kansas. This scenario shows that Topeka would lie outside 50-mi arcs drawn around these sources, and, as a result, transportation costs to this area would be large.

CONCLUSION

Continued growth in the 10-county area along the Kansas River will guarantee a strong demand for aggregate. Between 1980 and 1996, there was a 20% increase in population in these 10 counties. This compares with a 9% increase for this state as a whole during this same period. It is important that adequate reserves of aggregates are available to meet this increasing demand. However, under the present conditions, including opposition to river dredging, restricted production by river dredges, limited floodplain reserves, and limited available floodplain land, a shortage of sand and gravel is likely to develop in the lower portion of the Kansas River area in the future.

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Industrial Uses of Lamproite from Silver City Dome, Woodson and Wilson Counties, Kansas

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ABSTRACT.—Lamproite occurs in two locations in southeastern Kansas that are in close proximity to each other. In both locations, the lamproite is restricted to northeast-elongated, ellipsoidal depressions measuring about 3 mi by 1.5 mi. At the surface and in the shallow subsurface, lamproite occurs as sills that were intruded into Middle and Upper Pennsylvanian rocks consisting of shale, limestone, and minor sandstone. Isotopic age determinations by Zartman and others (1967) indicate that the lamproite was intruded during the Late Cretaceous (88–91 my).

Drillholes for hydrocarbon exploration down to a depth of about 1,400 ft (top of the Mississippian) and numerous shallow drillholes (mostly 200–300 ft) by the Kansas Geological Survey in the northern portion of Silver City dome helped to understand the structural complexity and extent of the near-surface sills. Numerous radial faults showing small apparent vertical offsets limit the lateral continuation of individual sills. Concentric faults are believed to mark the edge of the depression.

Wagner (1954) mapped the geology of Silver City dome in considerable detail and recognized a northward dipping, 120-ft-thick, lamproite sill exposed at the surface along the northeastern edge of the dome. The upper 40–50 ft of the sill weathers olive-brown and has a soft, clayey consistency in which only the phlogopite mica is recognizable. The weathered material has been mined by Micro-Lite LLC since 1982 from the exposed sill in an open-pit that measures about half a mile extending in an east-west direction. The bulk of the material, about 98%, is used as an additive in mineral supplements for cattle feed.

INTRODUCTION

Lamproite is a peralkaline, ultrapotassic, mantle-derived porphyritic rock consisting of abundant phenocrysts of phlogopite, serpentine pseudomorphs after olivine, and lesser amounts of microphenocrysts of potassic richterite, diopside, and chrome spinel set in a groundmass composed mostly of serpentine.

Lamproite occurs at or close to the surface at Silver City dome and Rose dome south of the town of Yates Center in southeastern Kansas (Fig. 1). Silver City dome, situated in T. 26–27 S., R. 14–15 E., straddles the Wilson-Woodson county line. Rose dome is located about 6 mi to the northeast in Woodson County. The designation of these two features as "domes" is somewhat misleading in that both are topographically defined, northeast-trending, elliptical depressions, about 2.5 mi long by 1.5 mi wide. Lamproite occurs at the surface in the form of detached sills only in the northeastern part of Silver City dome.

The area originally drew attention in the early 1870s, fueled by erroneous reports of silver occurring in the area. Originally, the lamproite was believed to be a slightly metamorphosed sedimentary rock (Mudge, 1881). However, its igneous nature was soon recognized by Hay (1883). Attention was drawn briefly to the area in the 1940s when the lamproite was considered to be a potential source for vermiculite, bauxite, chromite, and road ballast. The lamproite was mined again intermittently between 1961 and 1982. For the first five years of this period, the weathered lamproite was marketed as an insulating material, and after that mainly as a complete fertilizer. Only small amounts of weathered lamproite were mined in an open pit from an exposed sill along the northern perimeter of the dome. A full-scale open-pit mine, owned and operated by Micro-Lite LLC, headquartered in Chanute, Kansas, started at this location in 1982. Since that time, the company has been mining the soft, weathered lamproite, starting in the original open-pit on the west end of the sill and extending its operations in an easterly direction for about half a mile.

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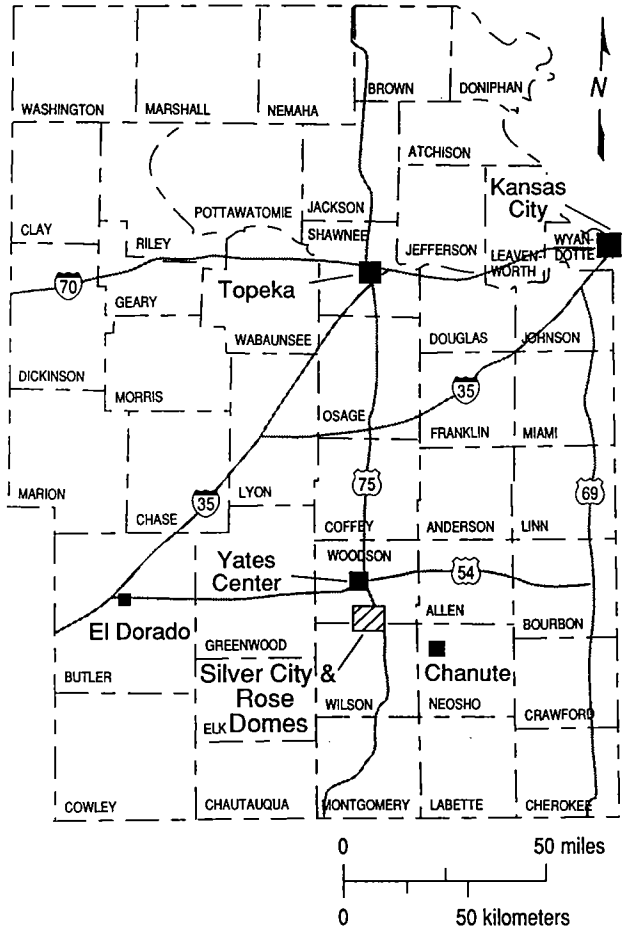


Figure 1. Index map showing the location of Silver City dome in southeast Kansas.

ERA	PERIOD	SERIES	GROUP/FORMATION
CENOZOIC	Quaternary		
	Tertiary		
MESOZOIC	Cretaceous	Upper	
		Lower	
	Jurassic		
	Triassic		
PALEOZOIC	Permian	Leonardian	Sumner Group Chase Group Council Grove Group
		Wolfcampian	Admire group
	Pennsylvanian	Virgilian	Wabaunsee Group Shawnee Group Douglas Group
		Missourian	Lansing Group Kansas City Group Pleasanton Group
		Desmoinesian	Marmaton Group Cherokee Group
		Atokan	
		Morrowan	Basal Penn. Cgl.
	Mississippian	Chesterian	Mississippian Limestones
		Meramecian	
		Osagian	
		Kinderhookian	Chattanooga Shale, Misener Sandstone
	Devonian		Upper "Hunton" Group
	Silurian		Lower "Hunton" Group
	Ordovician	Upper	Maquoketa Shale Viola Limestone
		Middle	Simpson Group
		Lower	Arbuckle Group
	Cambrian	Upper	Reagan, Lamotte Ss.
		Middle	
		Lower	
PRECAMBRIAN			Fractured Basement Rocks

Figure 2. Generalized stratigraphic column.

STRATIGRAPHY OF THE SILVER CITY DOME

Sedimentary rocks assigned to the Lansing and Douglas Groups of Pennsylvanian age constitute the surface rocks in and around Silver City dome (Fig. 2). Approximately 1,500 ft of Pennsylvanian strata underlie the area, followed downward by about 300 ft of Mississippian limestone, dolomite, and minor shale of Mississippian age and about 800 ft of Cambro-Ordovician limestone and dolomite, which overlies the Precambrian basement. Epizonal granite, the dominant basement rock, is encountered at about 2,600 ft.

The Lansing Group is comprised of three formations (Fig. 3), of which only the youngest, the Stanton Limestone, is exposed in the center of the dome. The Stanton Limestone is subdivided into five members consisting of alternating limestone and shale units. Only the top two limestone units, the South Bend Limestone Member and the underlying Stoner Limestone Member, are exposed. The intervening Rock Lake Shale Member is not recognized at the surface, but can be identified in core in the subsurface. The typical thickness of the rocks comprising the Stanton Limestone is on the order of 75–100 ft, but it can differ substantially as a result of local algal-bank build-ups.

Completely surrounding rocks of the Stanton Limestone inside the elliptical depression that defines Silver City dome is shale of the Weston Shale Member of the Stranger Formation of the Douglas Group. The Weston Shale Member generally consists of unfossiliferous medium-gray shale and siltstone with minor amounts of fine-grained, micaceous sandstone in the upper part. This member reaches a total thickness of about 180 ft. The shale and siltstone weather yellowish gray to light olive gray. In a normal sequence, overlying the Weston Shale Member are the successively younger Iatan Limestone and Tonganoxie Sandstone Members of the Stranger Formation (Fig. 3). However, the Iatan Limestone is not present in this area. The Tonganoxie Sandstone forms a rim, generally about 50 ft higher in elevation, around the elliptical depression outlining the dome. The Tonganoxie Sandstone Member is on average 50 ft thick and consists of massive, fine-grained, micaceous sandstone in the lower part overlain by a sequence of alternating fine-grained, micaceous sandstone and siltstone.

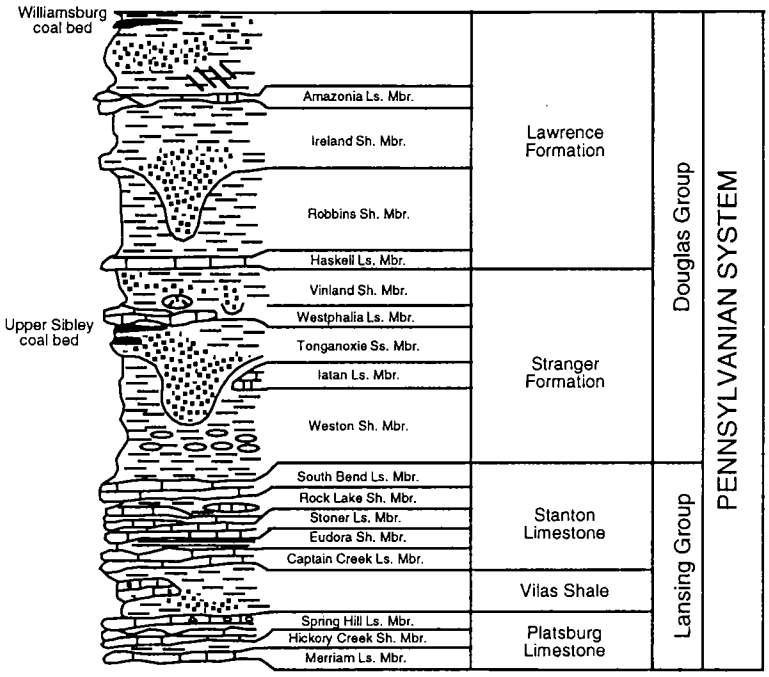


Figure 3. Stratigraphic column of the surface rocks exposed around Silver City dome.

LAMPROITE

About 10 years after the initial flurry of mining activity, Hay (1883) recognized that intrusive igneous activity took place at Silver City dome, but it took another 50 years before this conclusion was widely accepted (Knight and Landes, 1932; Weidman, 1933). The name Hills Pond peridotite was proposed by Wagner (1954) for the igneous rock that crops out 500 ft east and 100 ft south of the CNL of sec. 32, T. 26 S., R. 15 E., and it was designated the type locality. On the geologic map of the Fredonia 7½-minute quadrangle, Wagner (1954) shows the outcropping peridotite as an elongate body extending about 1 mi in a west-northwest direction (Fig. 4). Based on mapping and drillhole data, Wagner (1954) speculated that the peridotite extended to great depth, but near the surface is sill-like and fan-shaped having an average thickness of 70 ft. A small fault bounds the peridotite to the north and provided the pathway along which the peridotite magma intruded the Pennsylvanian sediments (Fig. 4; Wagner, 1954). In addition to this larger body, two smaller patches of peridotite were identified on the surface farther south in sec. 32 by Wagner (1954). These were believed to be part of a northward-dipping sill originating at the fault (Figs. 4,5).

Defined above in the Introduction to the current paper, the term lamproite was applied first by Niggli (1923) to unusual mafic rocks having a high potassium and magnesium content. The name lamproite is derived from a Greek word meaning "glistening" and refers to the reddish-brown, shiny flakes of phlogopite always present in this rock type. As more detailed mapping and sophisticated chemical analyses of these rocks took place through the years, lamproites were subdivided into a number of rock types all belonging to the lamproite clan (Mitchell and Bergman, 1991). Petrographic studies and chemical analyses of fresh material from drill cores indicate that the alkalic and ultrapotassic rocks at Silver City dome are lamproites (Cullers and others, 1985). The lamproites are porphyritic and contain 14–25% euhedral to subhedral, reddish-brown phlogopite, 7–34% anhedral serpentine pseudomorphs after olivine, and generally <5% euhedral to subhedral phenocrysts of diopside or diopsidic augite, chrome spinel, and potassic richterite, set in a groundmass composed mostly of serpentine. Significant variations in the mineral content occur between sills and within sills (Cullers and others, 1985), the nature of which currently is not well understood. Fresh lamproite is dark gray to black, but, where the sills are exposed to weathering, lamproite becomes soft and takes on an olive-brown color as a result of extensive alteration to clay minerals. Depending upon topography and possibly other factors, the zone of alteration may be as thick as 35 ft. Whenever hard, fresh lamproite is exposed to the surface, it takes only a relatively short time (months) for the upper foot or so to disintegrate.

During the last 10 years, the Kansas Geological Survey has drilled about 50 holes in the eastern portion of Silver City dome (Fig. 4). Most of these holes were drilled to a depth of less than 300 ft in sec. 32, T. 26 S., R. 15 E., with the exception of one hole in sec. 5, T. 27 S., R. 15 E., which reached a depth of 825 ft. In addition to these drillholes, more than a dozen wells have been drilled to the top of the Mississippian limestones to test the oil potential of the sandstones in the Pennsylvanian Cherokee Group. Lamproite sills are encountered in most drillholes within Silver City dome. The number of lamproite sills occurring in a particular drillhole differs, but it is not uncommon to encounter up to six sills in the Pennsylvanian part of the section. The thickness of individual sills ranges from about 10 ft to as much as 120 ft in the exposed sill along the northern perimeter of the dome at the site of the Micro-Lite LLC mine.

The lamproite is estimated to have intruded into the country rock at temperatures in the neighborhood of 800°C and pressures as low as 225–300 bars (Franks and others, 1971). Wagner (1954) reported that the sedimentary rocks were metamorphosed up to 1,000 ft away from the contact with the lamproite sills, but examination of core indicates that the distance is more on the order of 100 ft. Sandstone and shale have been transformed into quartzite and hornfels, respectively, suggesting contact metamorphism up to the sanidinite facies (Franks and others, 1971) close to the contact. The effect on limestone is less obvious, but apatite vein-

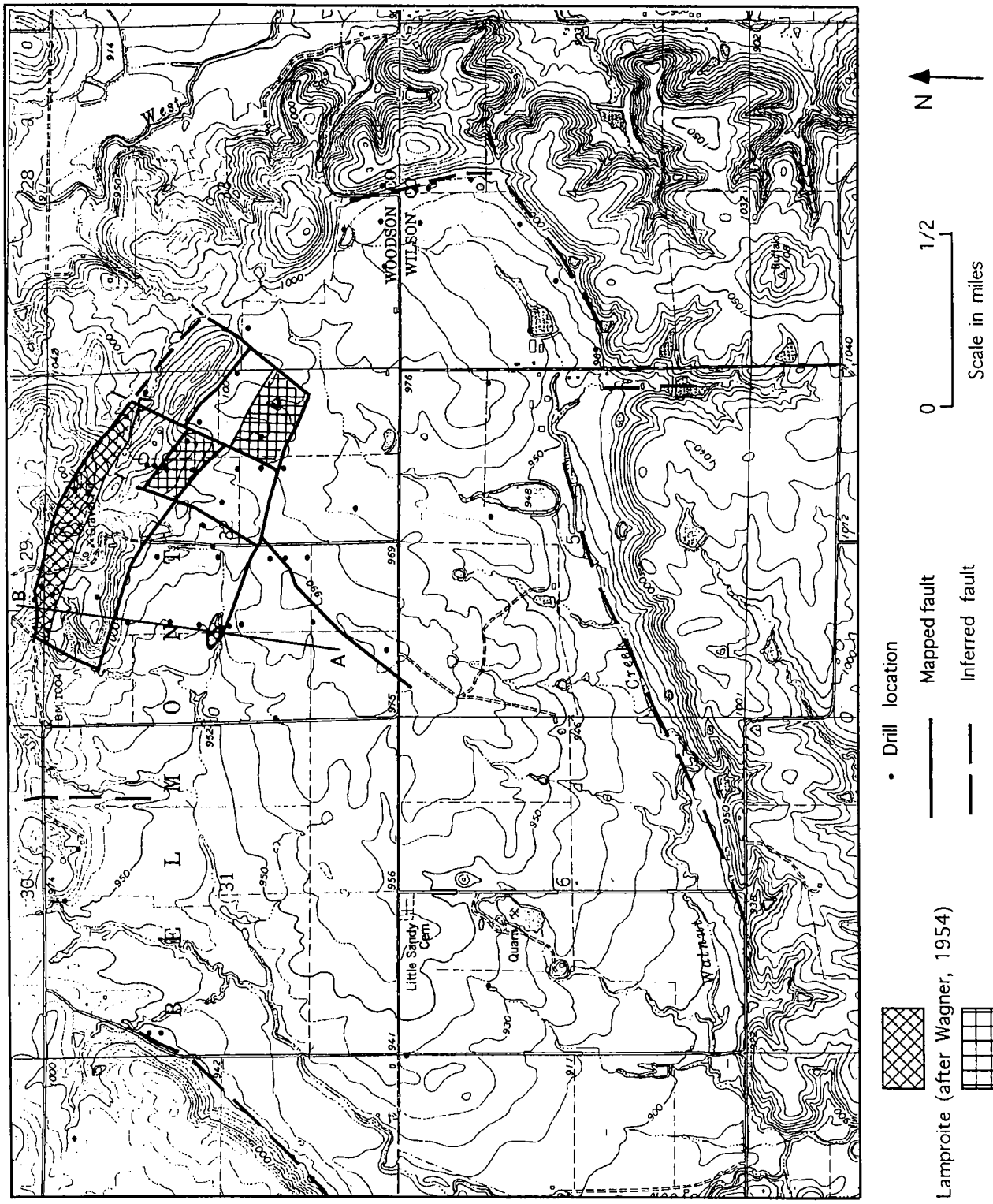


Figure 4. Location of exposed lamproite at Silver City dome.

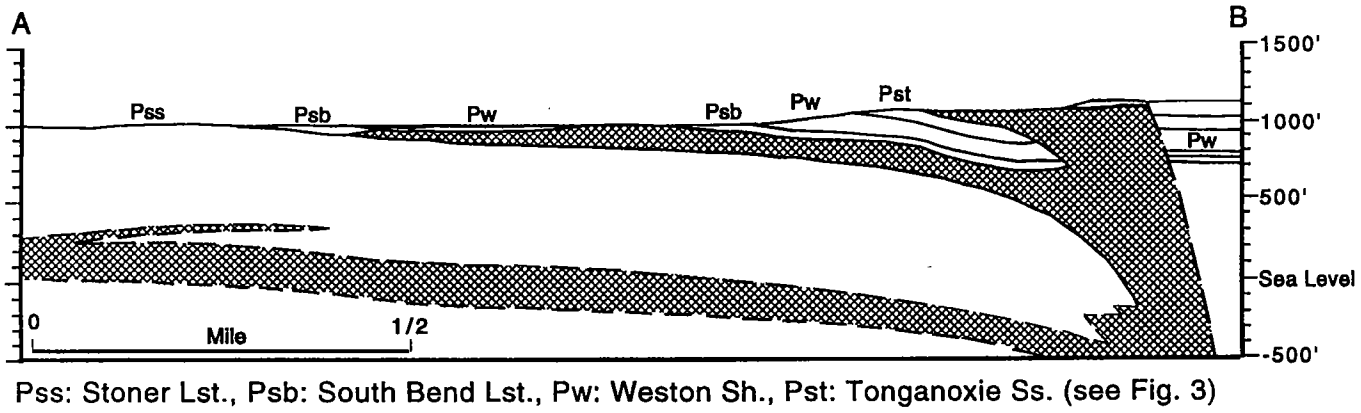


Figure 5. Generalized cross-section along line A–B (Fig. 4), showing intrusive nature of lamproite.

lets locally transect the rock at Silver City dome (Wagner, 1954).

Potassium-argon age determinations of about 90 my on biotite (probably phlogopite) from two samples at Silver City dome (Zartman and others, 1967) indicate that the lamproite is Late Cretaceous.

STRUCTURE

Morphologically, the Silver City dome resembles a small crater, of the type typically formed by small volcanic explosions caused by lava that is highly charged with gas. The Silver City dome is elliptical in shape and is surrounded by a rim that stands about 75–100 ft above the floor of the dome (Fig. 4). In most places, the rim is held up by sandstone of the Stranger Formation (Fig. 3) that has been transformed to quartzite by contact metamorphism. The quartzite is well exposed along the northeastern rim of the dome in the open-pit mine of Micro-Lite LLC. The surface elevation in the central part of the dome is 10–20 ft higher than along the edge of the dome inside the rim. Furthermore, bedrock exposed in the center of the dome is older than bedrock along the inner rim of the dome, suggesting uplift in the center of the dome.

Interpretation of information obtained from drilling (mostly in sec. 32, T. 26 S., R.15 E.) indicates the presence of several radial and concentric faults inside the dome (Fig. 4). All faults are high angle and can change from normal to reverse. Based on current available information, the offset on individual faults is relatively small. The lamproite sill mapped by Wagner (1954) dips at an angle of 5–10° to the north and is bounded by the mapped fault that defines the northern boundary of the dome (Fig. 4). Wagner (1954) mapped the sill as extending to the east into the western part of sec. 33, T. 26 S., R. 15 E. Data obtained by drilling indicates that the sill does not extend into sec. 33 but is cut off by a northeast-trending fault. The west end of the sill also is terminated by a north-northeast–trending fault. In addition to the major sill mapped by Wagner (1954), two other sills have been identified in sec. 32, T. 26 S., R. 15 E. These two sills, both dipping at an angle of 5–10° to the northeast, have minimum thicknesses of 80 ft. Because they have similar thicknesses, they may be the same sill, but, because they are fault bounded, this cannot be established with certainty. Wagner (1954) mapped two additional small exposure of lamproite in the C, W½ sec. 32, T. 26 S., R. 15 E (Fig. 4). Only one, located in the east-west drainage has been verified. This exposure represents the outcrop of a 45-ft-thick, north-dipping sill that can be traced northward in the subsurface to the low east-west–trending ridge where it terminates against a fault. This sill also can be traced to the south to at least the C, SW¼ sec. 32. However, the dip of the sill changes to horizontal in the east-west–trending drainage. Whether this is the result of faulting or not is difficult to ascertain.

There is a subtle but recognizable correlation between surface topography or morphology and interpreted faults, especially in secs. 32–33, T. 26 S., R. 15 E. Applying these observations to the other portions of Silver City dome, it may be speculated that numerous radial and concentric faults characterize the structure of the dome.

MINING AND PROCESSING

Micro-Lite LLC, headquartered in Chanute, Neosho County, Kansas, operates an open-pit mine centered on the lamproite sill that is exposed on the surface along the northern perimeter of Silver City dome (Fig. 4), which was mapped by Wagner (1954). Up to this time, practically all of the material used has been the weathered, olive-brown lamproite. A scraper is utilized to mine the soft lamproite and haul it to a stockpile at the edge of the open-pit. From here the material is fed to a rotary kiln for drying with temperatures of 200–212° F. Retention time in the kiln is about seven minutes.

The dried lamproite is hauled by truck to the processing and packing plant in Buffalo, a small town about 7 mi to the southeast. In the plant the lamproite is classified according to size. All the processed material is shipped by truck to customers throughout the Midcontinent.

APPLICATIONS

The bulk of the material, about 98%, is used as an additive in mineral supplements for cattle feed. Potential new applications are being tested and include using finely ground, fresh, dark-colored lamproite as a filler in plastics. Potentially, it also can be used as a component material in ceramics and possibly as an additive in adhesives.

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Defining Models and Measuring Aggregate Quality for Gravel Deposits of the Front Range Urban Corridor, Colorado

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ABSTRACT.—In this paper, we present a physiographic classification of gravel deposits, identify some field measures of aggregate quality, and describe sampling strategies for mapping aggregate quality in the Front Range Urban Corridor of Colorado.

Gravel occurs in four types of deposits along the Front Range of Colorado: (1) piedmont alluvial fans, (2) high dissected terraces, (3) high (continuous) terraces, and (4) floodplains and low terraces. The four deposit types are the basis for definition of gravel-deposit models, which differ in geologic environment, deposit characteristics, deposit size, environmental impacts of mining, and post-mining use. Of the four types, floodplains and low-terrace deposits have been exploited most for gravel. High terraces also have been mined. Deposits of high dissected terraces and dissected alluvial fans have produced minor amounts of gravel, mostly for use as local fill.

Studies to identify useful field measures of aggregate quality and to determine the appropriate scale for sampling were conducted on gravel deposits beneath the floodplain and low terraces of the South Platte River north of Denver and the Cache la Poudre River between Ft. Collins and Greeley. Gravel deposits of the South Platte were selected for study because they represent the last major resource of gravel for aggregate in the Denver metropolitan area. The Cache la Poudre valley is the primary source of gravel aggregate for rapidly urbanizing areas around Ft. Collins and Greeley.

Of all the field measures of gravel quality, the most important is particle size. Various parameters that measure particle size were investigated, but the easiest to determine, and the most useful to the aggregate industry, are measures of the proportion of coarse sizes. Particle size varies widely in gravels of the urban corridor. Gravel lithology, particularly the presence of deleterious particles such as reactive volcanic rocks and decomposed rocks, must be determined to assess aggregate quality. Studies of South Platte and Cache la Poudre gravels have not revealed large proportions of deleterious lithologies. Studies of particle shape revealed only small numbers of physically weak shapes in both the South Platte and Cache la Poudre gravels. Particle shape does not appear to vary from place to place in the gravels. Rounding, or the absence of angular corners, may play a role in the tendency of loose gravel to yield under load. South Platte and Cache la Poudre gravels are rounded, and rounding tends to increase upstream.

Before the quality of gravel in a valley can be assessed, the stratigraphy of the gravel must be known because it affects sample design. If only a single gravel layer is to be studied, only the thickness of the gravel must be known before sampling. If, however, more than one layer of gravel—distinguished by particle size, sorting, or lithology—is present, sampling must take into account the thickness and distribution of each layer. For example, three gravel layers of different particle size underlie the floodplain and low terraces of the South Platte. The tributary Cache la Poudre, on the other hand, contains gravel layers that can be distinguished only locally and vary slightly in particle size.

Sampling experiments were conducted on gravel bars in the South Platte River and in gravel pits on the floodplain and low terraces of the South Platte and Cache la Poudre Rivers. Experimental results indicate that, even where sample error is large, regional and stratigraphic variation may be measured if it is large relative to sample error. Using vertical trench samples weighing an average of 40–90 pounds, downstream decrease in coarse particle size was mapped for Cache la Poudre gravel, and differences among superposed gravel beds were measured for South Platte gravel.

Lindsey, D. A.; and Langer, W. H., 1999, Defining models and measuring aggregate quality for gravel deposits of the Front Range Urban Corridor, Colorado, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 125–137.

SCOPE AND PURPOSE OF STUDY

Investigations of gravel-deposit models were undertaken to classify and describe gravel deposits in part of the Front Range Urban Corridor of Colorado (Fig. 1), as part of the U.S. Geological Survey's Front Range Infrastructure Resources Project (FRIRP). Major areas of gravel mining in the valleys of the South Platte River north of Denver (Lindsey and Shary, 1997; Lindsey and others, 1998a,b) and the Cache la Poudre River from Ft. Collins to Greeley, Colorado, were selected for initial studies of gravel aggregate quality (Fig. 1). Floodplain and low-terrace deposits like the ones studied have been the largest source of gravel aggregate in the Front Range Urban Corridor and still provide most of the gravel used in the corridor.

In studying gravel-aggregate quality, we have emphasized measures that can be obtained readily in the field or from small samples returned to the office. Data were collected on gravel stratigraphy, particle size, lithology, particle shape, and rounding. While collecting data on aggregate quality, we experimented with sampling plans to improve the reliability of the data. Measurement and sampling methods developed during study of the South Platte and Cache la Poudre gravels are being applied to map gravel-aggregate quality in the rest of the Front Range Urban Corridor.

This paper summarizes the classification of gravel deposits in the Front Range Urban Corridor, describes and compares the usefulness of field measures of aggregate quality, and describes sampling methods for obtaining reliable data to map gravel-aggregate quality.

GRAVEL-DEPOSIT MODELS

Gravel-deposit models are descriptions of deposits that may be mined for natural aggregate. Commonly, a mineral-deposit model consists of a systematic arrangement of information that summarizes the features of a group of similar deposits (Cox and others, 1986). Deposits in each group are thought to have formed in more or less the same manner and to share similar features. The information in deposit models is descriptive; however, judging the significance of information may depend on an understanding of how the deposit formed. By comparing features specified by mineral-deposit models with the characteristics of an area of interest, models can be used to explore for mineral deposits, assess potential for undiscovered deposits, anticipate the effect of mining on the environment, and investigate alternatives for reclamation and land use after mining.

Models of gravel deposits in the Front Range Urban Corridor are classified and named for their physiographic setting (Fig. 2). The physiographic setting of each deposit is the result of its entire geologic history, beginning with deposition of gravel and extending through successive episodes of erosion to the present. The resulting deposits have characteristic landforms, such as dissected alluvial fans and river terraces at various levels. From highest to lowest in elevation (and oldest to youngest in age of deposition), the four models are: (1) piedmont alluvial fans, (2) high dissected terraces, (3) high (continuous) terraces, and (4) floodplains and low terraces (Fig. 2).

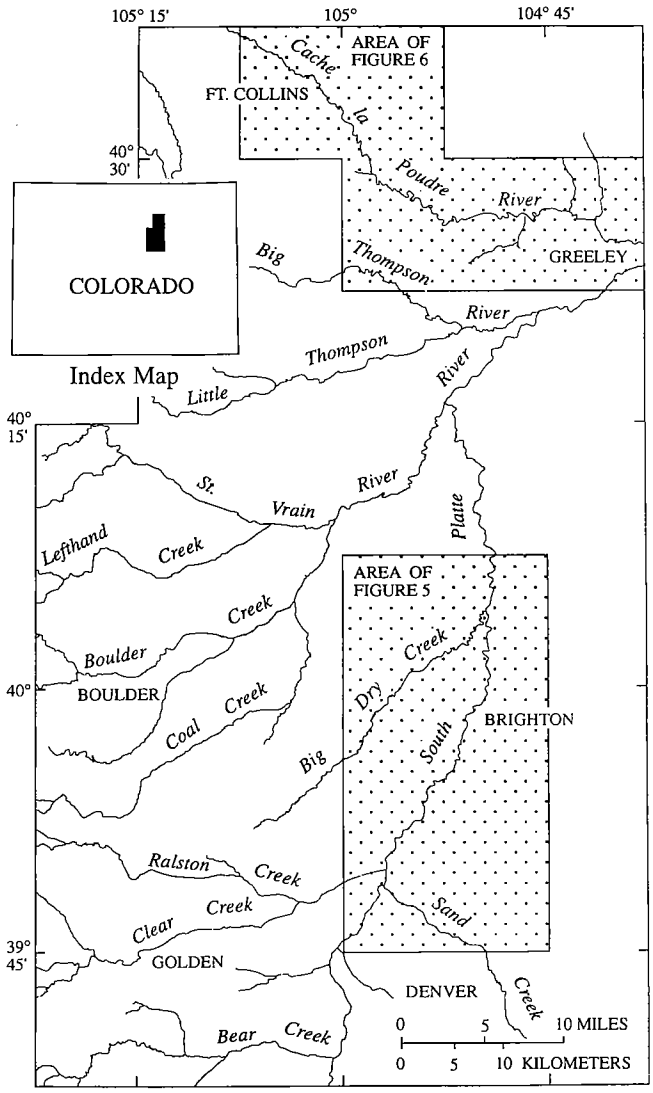


Figure 1. Map showing demonstration study area in the Front Range Urban Corridor, Colorado, and initial study areas (dot pattern) for gravel-aggregate quality.

For the deposit models of the Front Range Urban Corridor, we tabulated information about geologic environment, deposit characteristics, deposit size, possible environmental effects of mining, and post-mining land use (Table 1). Geologic environment includes both the sedimentary environment in which the deposit formed (Langer, 1988; Smith and Collis, 1993) and the subsequent geologic history of the site of the deposit. Deposit characteristics include information on physical properties, such as sedimentary features, and information that is relevant to aggregate quality or suitability, such as particle size and composition (Langer and Knepper, 1998). Deposit size is measured in areal extent, thickness, and volume of gravel in entire geologic units, such as alluvial terraces, and may be modeled statistically (Bliss, 1998). Environmental effects of mining take into

Table 1.—Characteristics of Gravel Deposit Models, Front Range Urban Corridor, Colorado[a]

Geologic environment	Deposit characteristics	Deposit size	Environmental effects	Post-mining use
	DISSECTED ALLUVIAL FANS			
Piedmont alluvial fan, interfluvial surface	**Low quality:** massive flash-flood deposits, poorly sorted, weathered	Small to medium	Visual impact	Landfill; reclamation to grassland
	HIGH DISSECTED TERRACES			
Eroded alluvial fill, interfluvial surface	**Low quality:** channel gravel, well-sorted, weathered	Small	Minor visual impact	Reclamation to grassland
	HIGH TERRACES			
Alluvial fill, above stream level	**High quality:** channel gravel, well-sorted, weakly weathered	Large	Visual and traffic impact during production	Landfill, urban development
	FLOODPLAINS AND LOW TERRACES			
Alluvial fill, near stream level	**High quality:** channel gravel, well-sorted, unweathered	Large	Visual and traffic impact during production, lower water table	Water storage, recreation, open-space, wetlands

[a]Includes information compiled from Schwochow and others (1974a,b), Colton and Fitch (1974), and Trimble and Fitch (1974).

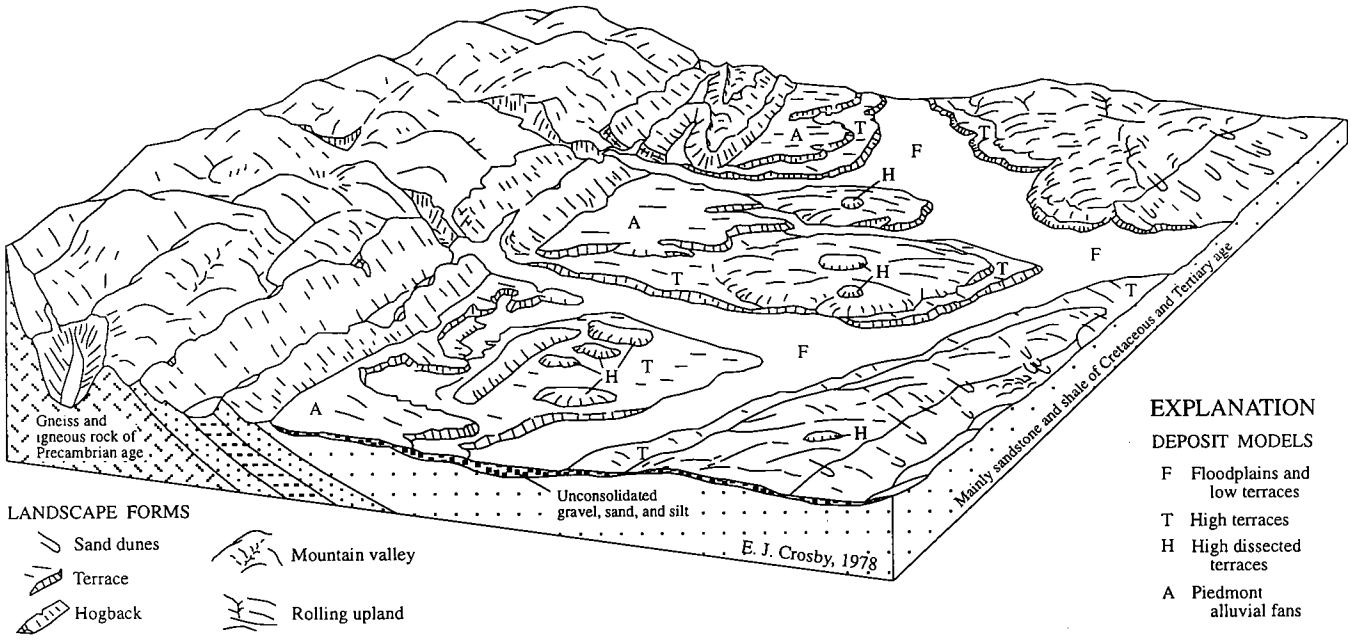


Figure 2. Block diagram (from Crosby, 1978) showing simplified physiographic setting of gravel-deposit models in the Front Range Urban Corridor, Denver to Ft. Collins, Colorado.

account the size of the area affected, mining methods, overburden, depth to water table, and production of fine-grained waste. Post-mining land use considers alternatives for beneficial use, such as water storage and recreation. The characterization in Table 1 is brief and preliminary, based on survey of the literature and general knowledge; it is intended to be illustrative rather than comprehensive.

Gravel deposits of alluvial fans (model 1) and high dissected terraces (model 2) underlie surfaces of Pleis-

tocene age (Scott, 1965). These deposits are typically weathered and, near the mountains, poorly sorted. Although fan deposits underlie surfaces sometimes considered pediments, they reach tens of feet in thickness (Robson, 1996), and are clearly not veneers on erosional surfaces. Deposits of high dissected terraces typically cap small hills and drainage divides; these deposits are small in size and weathered, making them suitable mainly for local fill. Dissected-terrace deposits are probably the downstream equivalents of piedmont alluvial fans, and indeed have been mapped and correlated as such (Scott, 1965; Colton, 1978; Trimble and Machette, 1979).

Gravel deposits that underlie high continuous terraces (model 3) and floodplains and low terraces (model 4) comprise the principal resources of high-quality gravel aggregate in the Front Range Urban Corridor. In the South Platte River and its major tributaries, both types of deposits contain well-sorted, unweathered, coarse gravel more than 20 ft in thickness. Only those valleys that were fed by ice-age glaciers (Wayne and others, 1991) contain significant resources of terrace and floodplain gravel. Evidently, the combination of erosion by glaciers and flushing by high-discharge meltwater streams was necessary to transport and deposit large amounts of coarse gravel downstream. Subsequent reworking of glaciofluvial gravels by the smaller post-glacial streams that now occupy valleys east of the Front Range has produced somewhat finer-grained gravel in the South Platte River valley (Lindsey and others, 1998a,b). Valleys of tributary streams that do not head in glaciated terrane, such as Ralston Creek and Big Dry Creek (Fig. 1), lack large amounts of coarse gravel.

GRAVEL STRATIGRAPHY

The physical stratigraphy of gravel deposits affects the quantity and quality of aggregate resources and, ultimately, mining operations. Stratigraphic information is essential to estimation of the quantity of a gravel resource. Physical stratigraphy must be known before an appropriate sampling plan for gravel quality can be implemented. If a single gravel layer is to be sampled, only the thickness of the gravel must be known. If more than one layer of gravel is present—distinguished by particle size, sorting, or lithology—sampling must take into account the thickness and distribution of each layer.

Information on physical stratigraphy of floodplain and terrace gravels in stream valleys of the Front Range Urban Corridor is available from drillhole logs (Schneider, 1961, 1962; Smith and others, 1964; Schwochow and others, 1974b), which we compiled into sections showing the thickness and stratigraphy of valley fill (Fig. 3). Sections prepared from drillhole logs have serious limitations, dependent on sample recovery and the skill of the logger. Logs must be consistent to permit construction of valley sections. Logs of adjacent holes recorded by different observers commonly do not match. We have relied primarily on logs prepared under past drilling programs of the U.S. Geological Survey.

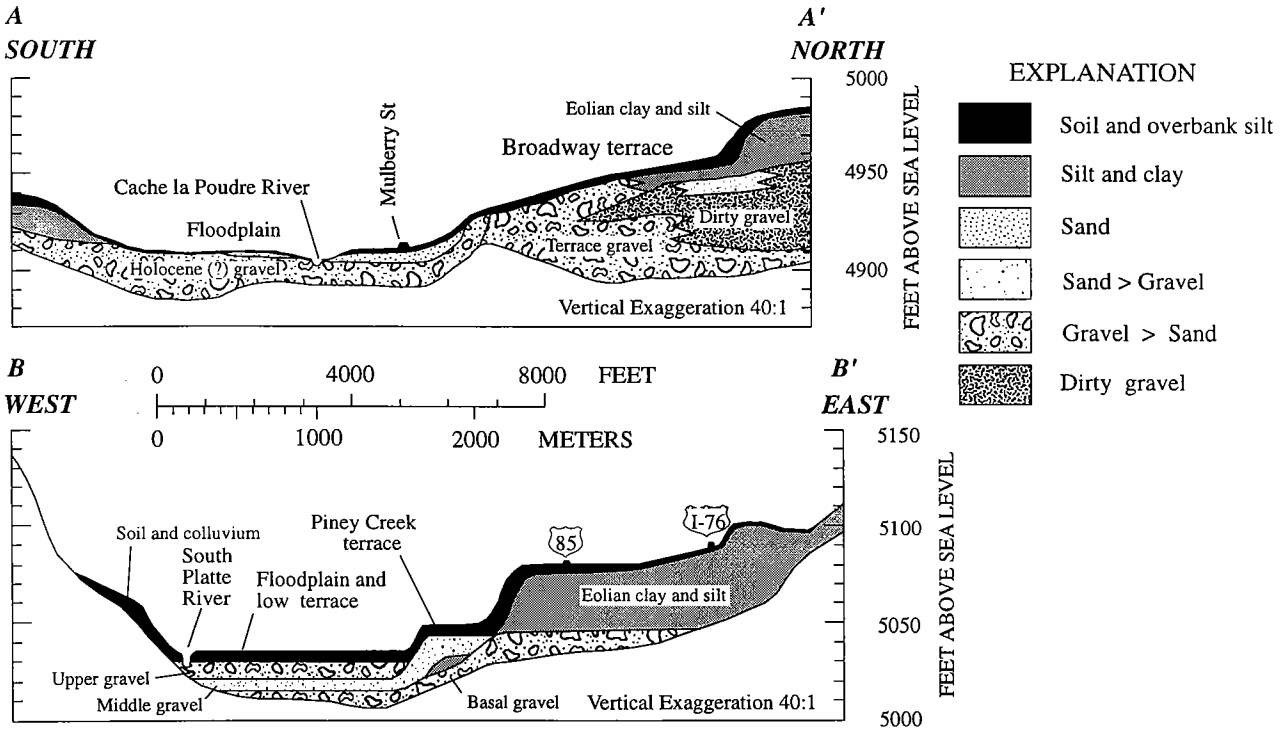


Figure 3. Stratigraphic sections showing valley fill in the Cache la Poudre River east of Ft. Collins (*A–A'*), Colorado, and in the South Platte River north of Denver, Colorado (*B–B'*). Sections drawn from drillhole logs in Schneider (1961, 1962). Lines of sections located in Figures 5 and 6.

The best information on stratigraphy of gravel deposits comes from observation of fresh walls in gravel pits; such information can be used to supplement and interpret logs of nearby drillholes. We used this strategy in the South Platte valley north of Denver to construct a detailed set of sections where drillholes are widely scattered (Lindsey and others, 1998a). Pit walls also permit direct observation of important local features such as clay lenses, which impede gravel mining (Lindsey and others, 1998c). Finally, sedimentologic observations from pits can aid in interpretation of the depositional environment of gravel deposits and lead to better understanding of individual deposit models.

Sections of alluvial gravels in the Front Range Urban Corridor reveal two distinct stratigraphic styles (Fig. 3). In valleys of tributary streams near the mountains, such as the Cache la Poudre River, gravel beneath the floodplain and low terraces forms a single homogenous unit (Fig. 3, section *A–A′*). Individual layers can be distinguished only locally and vary slightly in particle size. In contrast to tributary streams, the floodplain and low terraces of the South Platte River valley north of Denver are underlain by three gravel layers of differing particle size (Fig. 3, section *B–B′*). The stratigraphy of floodplain and low terrace gravels in both streams is not continuous with deposits of the high terraces, which have their own stratigraphy. In both the Cache la Poudre and the South Platte valleys, eolian clay, silt, and sand locally cover high terraces.

Through mapping of pit walls, sedimentologic observations, pollen identification, and radiocarbon dating of wood in gravel, we established the probable age and depositional history of gravel deposits beneath the floodplain and low terraces of the South Platte valley (Lindsey and others, 1998a). The uppermost gravel layer beneath the floodplain of the South Platte is a recent deposit of the river. It was deposited in a meandering to braided channel much like that of the South Platte today. The middle gravel is probably of Holocene age, also. It was deposited in a shallow braided channel that probably did not have banks of fine sediment. The coarse basal gravel of the South Platte valley is regarded as a glaciofluvial deposit of late Pleistocene age.

FIELD MEASURES OF GRAVEL-AGGREGATE QUALITY

Particle Size

Particle size, composition, and shape are among the properties that affect the suitability of a gravel deposit for a specific commercial use (Marek, 1991; Smith and Collis, 1993; Langer and Knepper, 1998). Particle size can be determined by sieve analyses or, for coarse sizes, by direct measurement at the deposit site. Methods are discussed by Krumbein and Pettijohn (1938). Size can be specified in broad categories, such as fines (silt and clay), sand, gravel, and oversize (cobbles and boulders). Data on gravel-size particles are of greatest interest to the gravel industry and are easiest to collect. Accordingly, we adopted the standard use of sieves to collect and weigh the percent of gravel in size fractions greater than 3/16, 3/8, 3/4, 1½ and 3 in. All material that passes through the 3/16-in. sieve is classified as "sand." Particle size is measured in inches and fractions of inches by the aggregate industry; however, it is convenient to convert data into millimeters for calculating some size parameters, such as median and quartile sizes. Accordingly, both English and metric units are used to express particle size. Examples of the application of particle size data to aggregate quality are discussed later, under "sampling gravel deposits."

Particle Composition

Composition refers to rock types, contained minerals, and chemical constituents, which are all important to determining aggregate quality. Certain volcanic rocks contain unstable silica minerals (opal, cristobalite, and tridimite) that react with portland cement, resulting in rapid deterioration of concrete (Langer and Knepper, 1998). Abundant clay minerals can indicate strongly weathered gravel with weak particles. Other deleterious materials include iron- and manganese-oxide minerals, calcium-carbonate minerals, and gypsum; these substances commonly coat particles and fill interstices and cracks. Pebble counts, which are tabulations of various rock types identified in gravel, are simple measures of composition. Pebble counts are available for gravels in part of the Front Range Urban Corridor (Colton and Fitch, 1974). We collected new data on pebble composition in the South Platte and Poudre study areas.

The lithology of South Platte gravel north of Denver is remarkably uniform among layers and locations (Lindsey and others, 1998b). Pooled estimates of pebble lithology in the South Platte valley show about 25% granite, 23% gneiss, 31% pegmatite, 8% quartz, and about 13% minor rock types, including mafic rocks, volcanic and shallow intrusive rocks (porphyry), sandstone, quartzite, and chert (Fig. 4). Among the rock types, only the minor mafic rocks, porphyry, and chert are potentially deleterious to aggregate quality. Easily weathered mafic rocks, a minor constituent, are least abundant in the youngest gravel. Among volcanic rocks, welded tuff may contain reactive volcanic glass, but it makes up less than 1% of the gravel. Los Angeles degradation tests show that the major rock types in South Platte gravel are about equal in durability (Lindsey and others, 1998b). Thus, even if variations in proportions of major rock types did occur, they would not affect gravel quality.

Particle Shape and Roundness

Particle shape, roundness, and surface textures affect strength (Marek, 1991). A detailed discussion of shape, roundness, and surface textures of particles is provided by Pettijohn (1975). Shape is defined by the ratios of the three dimensions of a particle: particles tend to be spherical, rod-shaped, disc-shaped, or blade-shaped. The tendency for equidimensional shape, termed "sphericity," can be calculated from the long (A), intermediate (B), and short (C) axes of particles (Krumbein, 1941). Thin, blade-shaped particles with

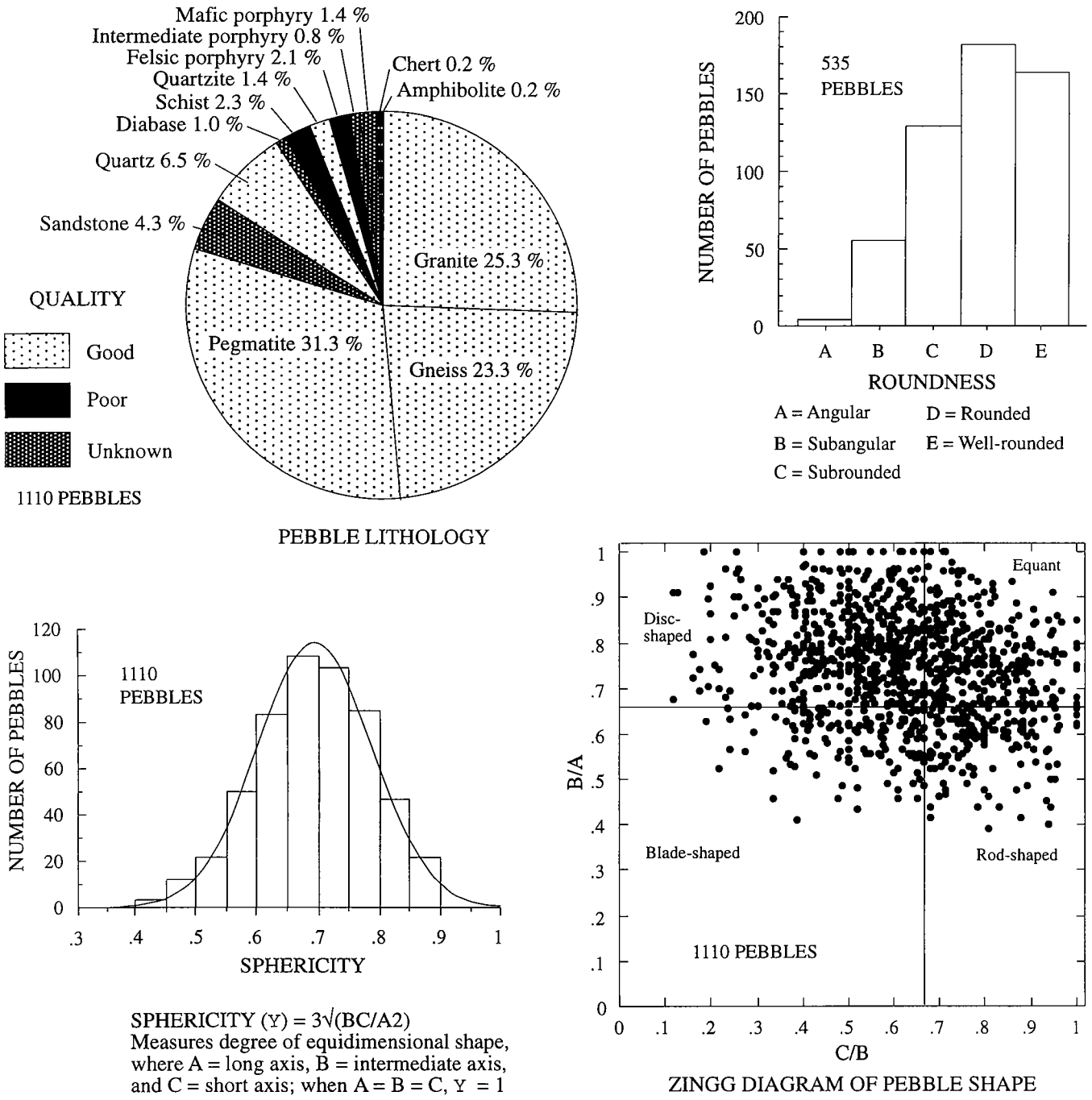


Figure 4. Graphs showing selected field measures of aggregate quality for gravel deposits beneath the floodplain and low terraces of the South Platte River north of Denver, Colorado.

axial ratios of less than 0.5 tend to be weak, whereas equidimensional particles tend to be strong. Roundness refers to the degree to which a particle lacks angular corners; the greater the roundness, the greater the tendency of loose particles to shift under load. The degree of roundness is determined by visual comparison with particle images assigned to a roundness scale, ranging from very angular to well-rounded.

Analysis of pebble shape in gravels of the South Platte valley north of Denver (Fig. 4) indicates that shape will not adversely affect aggregate quality there (Lindsey and others, 1998b). Pebble shape is dominantly equidimensional, with some tendency to form thick disc shapes. Rod and blade shapes comprise 16% and 15% of the pebble size fraction, respectively, but even these shapes have axial ratios mainly above 0.5, suggesting that they are not a significant source of weak particles. Shape shows little significant variation

among gravel units and sampling sites. Comparison of pebble shape with rock type (particle composition) shows no variation in shape among the major types. Only two of the least abundant rock types, mafic rocks and schist, tend to form disc and blade shapes.

Although no cases are known where roundness affects the suitability of South Platte gravels for loose aggregate such as road base, gravel particles are mostly rounded to well-rounded (Fig. 4). Roundness of gravel pebbles shows a pronounced tendency to decrease downstream, a relationship also observed in modern stream gravels in the South Platte River (Lindsey and Shary, 1997). The origin of downstream decrease in gravel roundness is not well understood, but selective abrasion and breakage during transport in the river may cause it. Among rock types represented in pebbles, pegmatite has the lowest roundness values.

SAMPLING GRAVEL DEPOSITS

Methods of Sampling

Samples are the basis for estimating many of the measures of aggregate quality. Measurement of entire populations, such as the particle size of gravel in a river valley, is rarely possible. Sampling provides a way to estimate aggregate quality of a gravel deposit. The goal of sampling is estimation with sufficient precision to be useful and with sufficient efficiency to be time- and cost-effective. The present discussion will be restricted to particle size, but the principles apply to any measure of aggregate quality, such as composition, shape, and roundness.

Vertical trench samples (Krumbein and Pettijohn, 1938) are well suited to collect data representative of gravel deposits because they permit averaging and weighting the effects of stratification. We collected trench samples by using a shovel or hoe to scrape gravel from a vertical indentation cut in a clean pit face. All of the gravel that falls is caught in a bucket. Gravel can also be collected on a tarpaulin placed at the foot of the indentation and mixed and quartered on the tarpaulin if the amount is too large to sieve.

In general, the required sample size is considered to vary with particle size, with samples weighing as much as 70 lbs recommended for coarse gravel (Wentworth, 1926). In practice, coarse gravel cannot be sampled without taking samples sufficiently large to collect representatives of the coarsest size. During sampling of coarse gravel with abundant cobbles near Ft. Collins, we collected trench samples weighing as much as 200 lbs to obtain material of all sizes. Likewise, coarse gravels require large-diameter sieves. After one sampling program using 8-in.-diameter sieves on the South Platte River, we switched to 12-in.-diameter sieves.

Target Variation and Sample Error

Samples can be taken at any distance interval where measurement of variation is of interest (Krumbein and Graybill, 1965). Our sampling of gravel deposits has been directed toward individual gravel layers and sites located along the length of a valley to assess variation in particle size and other measures of aggregate quality as a function of stratigraphic level and downstream distance. In general, such measurements include both the variation among layers and sites (the target of investigation) and variation due to sample error.

In sampling gravel deposits, target variation and sample error should be estimated separately. When variation is expressed as variance (square of the standard deviation), individual components of variance are additive if the frequency distribution is normal and variances are homogenous:

$$S_T^2 = s_t^2 + s_e^2 \quad (1)$$

where S_T^2 = total variance, s_t^2 = target variance (among layers or sites), and s_e^2 = error variance (among samples). In the case of replicate sampling, used by us, error variance includes analytical variation due to procedures such as sieving and weighing the sample as well as differences among samples taken from the same trench. Replicate samples instead of sample splits are preferable because measurements on replicates can provide estimates of the real error of sampling (which includes analytical error), whereas measurements on splits of the same sample provide estimates of analytical and splitting error.

In our studies of gravel in the Front Range Urban Corridor, we estimated sample error in three experiments (Table 2). Measures of sample error (expressed as standard deviation), for particle sizes greater than 3/16 to 3 in., were typically about 2–9%. (For example, an error estimate of 5% standard deviation for a mean value of 60 weight percent is equivalent to the statement that any measurement can be expected to fall within the range 55–65 weight percent two-thirds of the time.) Estimates of sampling errors reported here were made for a variety of situations, where particle size, sieve diameter, and sample weight vary. Our estimates show the magnitude of errors that can be expected for sampling pebble gravels where median particle size is 10–30 mm (0.4–1.2 in.) and samples weigh approximately 40–90 lbs.

In mapping target variation, the absolute size of sample error is not as important as the proportion of sample variance relative to target variance (Table 3). Although sample error accounts for a significant proportion of the variation in measurements of particle size and other measures of aggregate quality, target variation can be mapped if it is large relative to sample error. For most particle size parameters measured in gravel deposits along a 25-mi distance of the Cache la Poudre River, sample error accounted for 23–79% of total variance. For first-quartile particle size, sample error accounted for 100% of the variance of trench samples. The best parameters for mapping particle size have a high ratio of target-to-sample variance; these parameters are all measures of the proportion of large sizes (Table 3).

Simply increasing the number of samples at each site can reduce sample error, because error is inversely proportional to the square root of the number of samples (Krumbein and Pettijohn, 1938). Although it is

Table 2.—Estimates of Sample Standard Deviation for Gravel Particle Size Parameters, South Platte and Cache la Poudre River Valleys, Colorado

Size Parameter	Eight samples from four gravel bars[a]		Twelve samples from six sections[b]		Five samples from one section[c]	
	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
PERCENT > 3/16 in.	59.7	8.6	74.5	4.2	78.7	2.5
PERCENT > 3/8 in.	—	—	65.0	5.3	70.4	3.5
PERCENT > 3/4 in.	29.8	6.4	53.0	5.7	61.3	4.9
PERCENT > 1.5 in.	—	—	33.2	6.0	44.2	7.6
PERCENT > 2 in.	11.4	3.4	—	—	—	—
PERCENT > 3 in.	—	—	6.9	5.5	13.4	7.7
Q1 (mm)	2.5	0.4	5.2	2.1	7.0	1.2
Median (mm)	13.9	6.8	21.8	5.0	32.2	8.0
Q3 (mm)	48.4	37.8	47.7	10.6	59.0	9.8
Estimated maximum size (mm)	131.5	135.6	92.9	23.3	98.0	19.2

Note: PERCENT >, cumulative weight percent for stated particle size; Q1, first quartile (25th percentile); Q3, third quartile (75th percentile); mm, millimeters; —, not measured; lbs, pounds.

[a]Sieve diameter, 8 in.; average sample weight, 38 lbs.

[b]Sieve diameter, 12 in.; average sample weight, 80 lbs.

[c]Sieve diameter, 12 in.; average sample weight, 86 lbs.

Table 3.—Variance Components for Gravel Particle Size Parameters, Cache la Poudre River Valley from Ft. Collins to Greeley, Colorado

Size parameter	Total variance	Percent of total variance		
		Between sites (8)[a]	Between sections[b] (1–3/site)	Between samples[c] (1–2/section)
PERCENT > 3/16 in.	24	0	38	62
PERCENT > 3/8 in.	35	17	4	79
PERCENT > 3/4 in.	49	43	0	57
PERCENT > 1.5 in.	91	67	0	33
PERCENT > 3 in.	121	77	0	23
Q1 (mm)	4	0	0	100
MEDIAN (mm)	60	58	2	40
Q3 (mm)	307	68	0	32
Estimated maximum size (mm)	1,215	67	0	33

Note: PERCENT >, cumulative weight percent for stated particle size; Q1, first quartile (25th percentile); Q3, third quartile (75th percentile); mm, millimeters. Average sample weight, 70 lbs; range, 36–203 lbs.

[a]Downstream variation.

[b]Local variation.

[c]Sample error.

sometimes efficient to take more than one sample from the same place to reduce sample error, attractive alternatives involve spreading sample locations over pit-scale distances, sampling clusters of pits, and controlling sample design to measure regional variation over a variety of distances.

Pilot Sampling

Pilot sampling is desirable to assure that the resulting data will be sufficiently reproducible for the purpose intended. After an initial pilot study, sampling procedures can be adjusted to produce estimates that are sufficiently stable to map or characterize a gravel deposit. For measurement of particle size, adjustments can be made through choice of sieves, sample weight, type of sample, and the number and spacing of samples. A procedure to optimize the number and spacing of samples, described by Miesch (1976) for geochemical investigations, can be adapted to sampling gravel deposits.

On the South Platte River (Fig. 5), a simple multilevel design was used for a pilot study of variation in aggregate quality of modern stream gravel. Two sites located 18 mi apart, representing points near the upstream and downstream limits of gravel mining in 1997, were selected for comparison (Lindsey and Shary, 1997). At each site, two successive gravel bars were selected for sampling. Spot samples were dug from the top foot of gravel at each end of the two gravel bars. At one end of each bar, one sample was recollected 5 ft from the first (for a total of three samples per bar). The sampling plan was used to estimate variation among replicate samples, ends of bars, successive gravel bars, and the 18-mi downstream distance. The variance model is an expansion of equation (1):

$$S_T^2 = s_\alpha^2 + s_\beta^2 + s_\gamma^2 + s_\varepsilon^2 \qquad (2)$$

where S_T^2 = total variance, s_α^2 = variance among sites, s_β^2 = variance among gravel bars, s_γ^2 = variance among ends of bars, and s_ε^2 = sample-error variance.

The results of the South Platte pilot study have implications for the design of other sampling plans (Lindsey and Shary, 1997). For example, the variance among bar ends was found to be negligible, so that sampling on the scale of ends of gravel bars could be eliminated. Variance among successive bars was large, however, so that sampling gravel deposits at intervals comparable to the distance between gravel bars might be important. Most important, the sampling plan should be sufficient to measure downstream variation between sites. For the cumulative weight percent of particles >4 mm (comparable to the 3/16-in. sieve openings used in other experiments), 62% of total variance is between the sites 18 mi apart, and the remaining 38% is distributed among various levels of sampling within sites. For median particle size, 37% of total variance is between sites, and 63% of the variance is within sites. For both weight percent >4 mm and median size, the sampling plan was not quite sufficient to distinguish particle size at upstream and downstream sites.

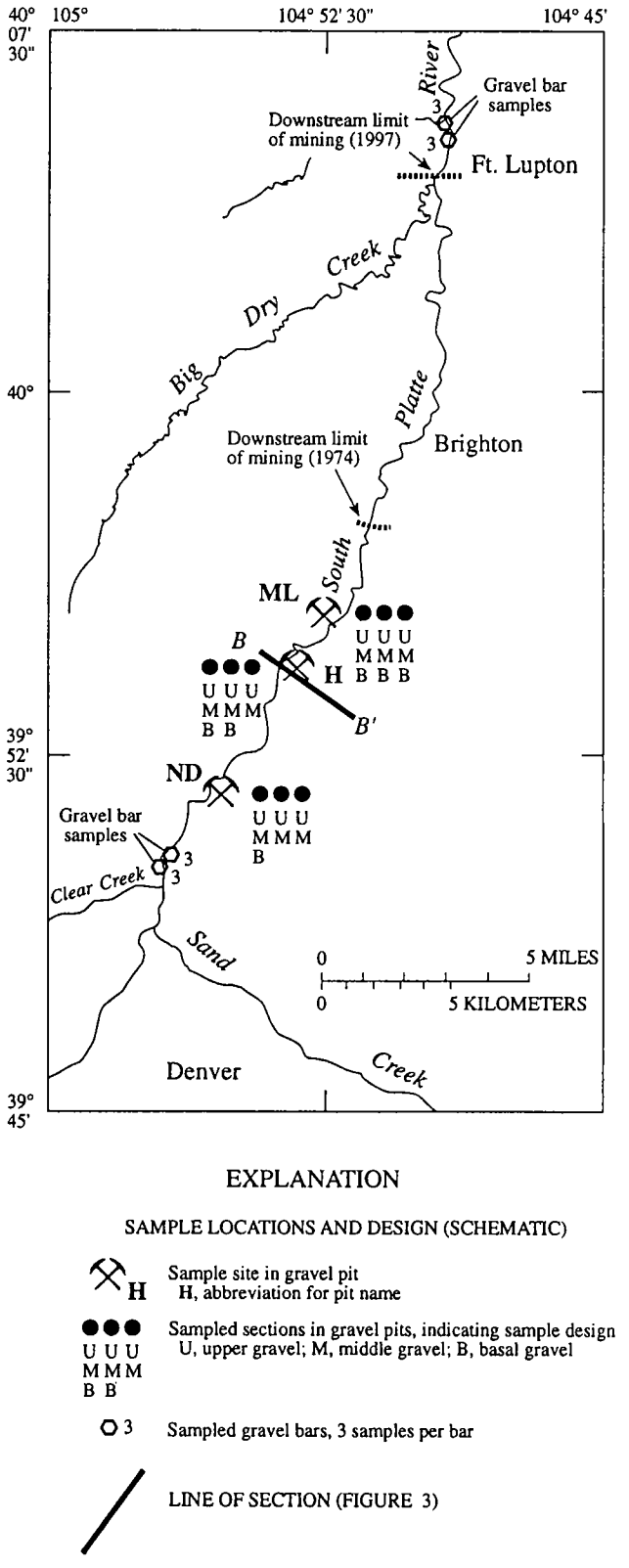


Figure 5. Study area for stream gravel (Lindsey and Shary, 1997) and gravel deposits (Lindsey and others, 1998a,b,c) in the South Platte River valley north of Denver, Colorado, showing sample locations and structure of sample plans. Gravel pits: ML, Western Mobile Mann Lake; H, Western Mobile Howe; ND, Cooley North Dahlia.

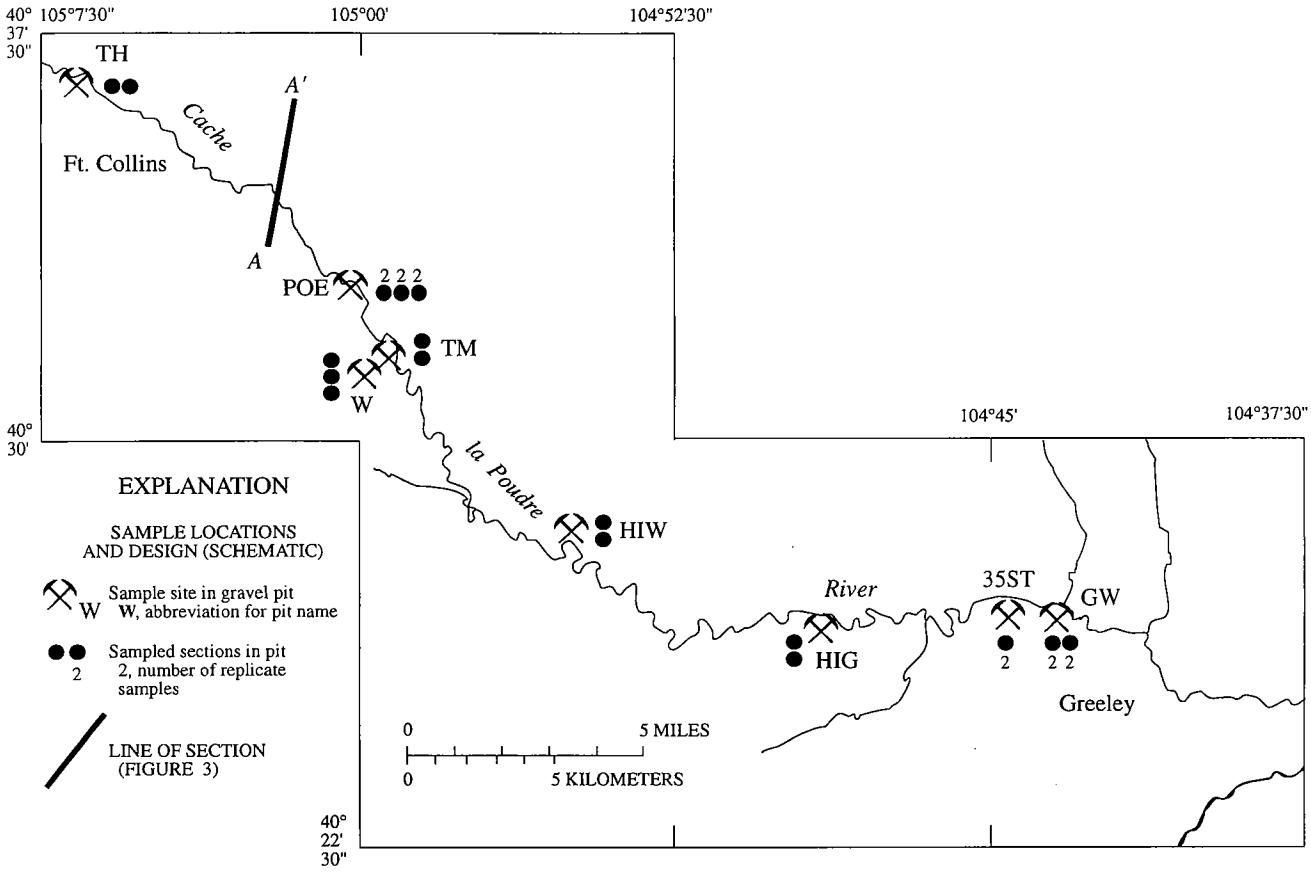


Figure 6. Study area for gravel deposits in the Cache la Poudre River valley between Ft. Collins and Greeley, Colorado, showing sample locations and structure of sample plans. Gravel pits: TH, Western Mobile Taft-Hill; POE, Western Mobile Port-of-Entry; TM, Western Mobile Timnath; W, Western Mobile Weitzel; HIW, Hall-Irwin Windsor; HIG, Hall-Irwin Greeley; 35ST, Western Mobile 35th Street; GW, Western Mobile Greeley West.

However, by comparing the ratio of between-site variance to within-site variance (method of Miesch, 1976), sample design could be adjusted to provide sufficient power to distinguish particle size between sites. A very efficient sampling plan, consisting of one sample from each of five adjacent gravel bars at each site, for a total of only 10 samples, would have been sufficient to distinguish particle size between the two sites 18 mi apart. In this way, a pilot study can be used to design a new sampling plan that will yield data of sufficient precision in a time- and cost-effective manner.

Sampling for Target Variation

Two sample designs were tested to measure variation in aggregate quality of gravel deposits of the Front Range Urban Corridor. In a study of gravel in the Cache la Poudre valley, downstream variation was selected as the target. In a study of gravel in the South Platte valley, stratigraphic variation was selected for measurement.

A multilevel-sample design similar to that used on gravel bars in the South Platte River was used to study gravel deposits beneath the floodplain and low terraces of the Cache la Poudre River (Fig. 6). The goal of the study was to map downstream variation in particle size and other properties. In the Poudre study, eight sites were selected at gravel pits from Ft. Collins to Greeley, representing about 25 mi of the Cache la Poudre valley. Although sites are more or less evenly spaced about 4–5 mi apart, distance between sites ranges from 1 to 3 mi for a cluster of three sites to 7 mi for the sites located at the upstream end. At all sites except one, two or three vertical sections through the entire thickness of gravel were located approximately 500 ft apart and sampled. At three sites, replicate samples were collected at individual sections to estimate sample error. Because stratigraphic units were only locally distinguished and did not differ appreciably or systematically in particle size, each sampled section represents the entire thickness of gravel. The equation for the variance model is:

$$S_T^2 = s_\alpha^2 + s_\beta^2 + s_\varepsilon^2 \quad (3)$$

where S_T^2 = total variance, s_α^2 = variance among sites, s_β^2 = variance among sections, and s_ε^2 = sample-error variance. The percent of total variance between sites (representing downstream variation) increases with increasing particle size, from zero for the cumulative

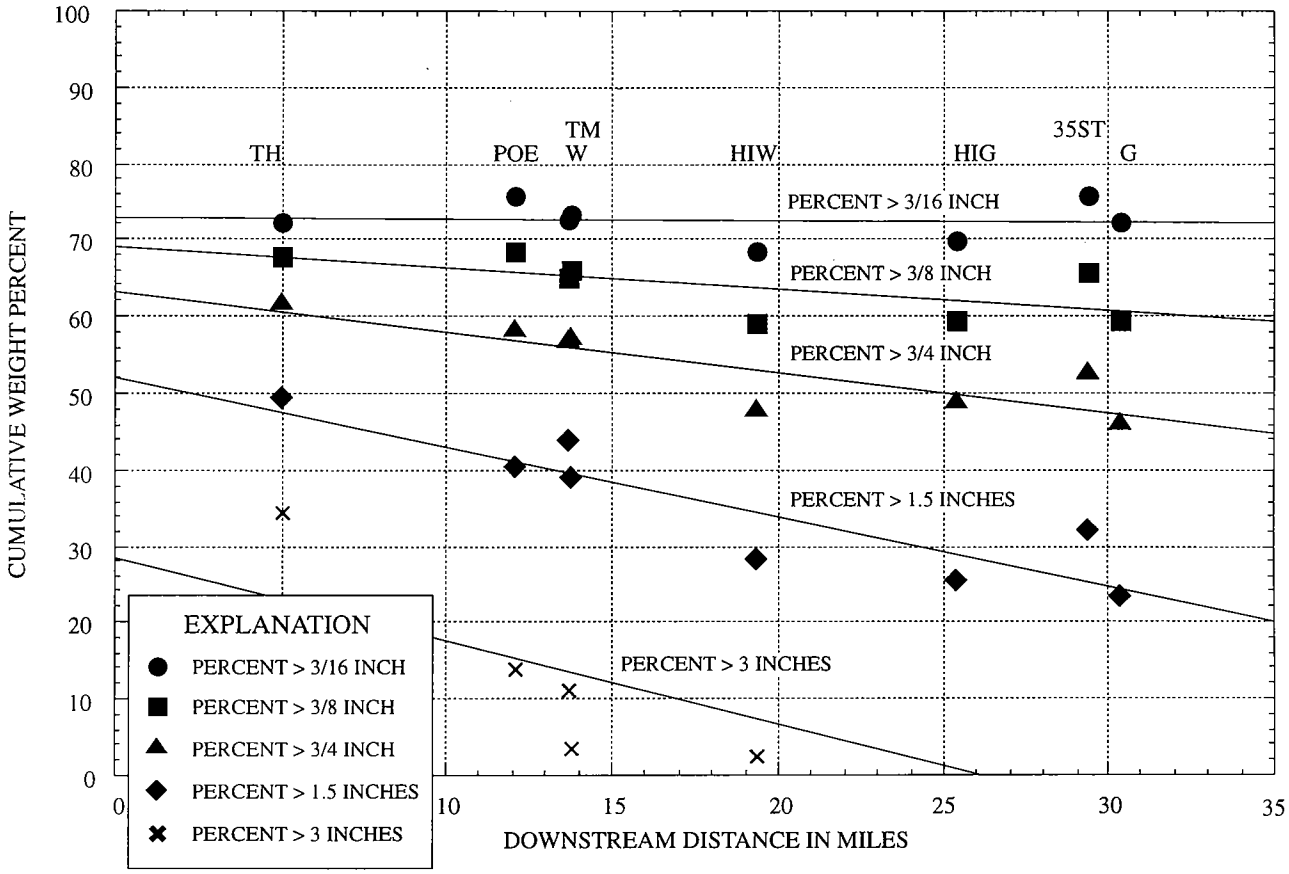


Figure 7. Graph showing downstream variation in particle size for gravel deposits beneath the floodplain and low terraces of the Cache la Poudre River, Ft. Collins to Greeley, Colorado. Gravel pits identified in caption, Figure 6.

weight percent of particles >3/16 in., to 77% for the cumulative weight percent of particles >3 in. (Table 3). Analysis of variance shows that the sample design was sufficient to distinguish cumulative weight percent of particle sizes >3/4 in. among sites. Thus, downstream trends for coarse particle sizes (percent >3/4 in. and greater, Fig. 7) are considered stable; trends for cumulative weight percent of particle sizes of >3/8 and >3/16 in. are not predictable, mainly because the cumulative values for these sizes do not vary appreciably downstream. For small particle size, the target variation is too small relative to sample error to measure with confidence. A second conclusion from the sampling is that, unlike the case of adjacent gravel bars in the South Platte River, particle size in sections spaced 500 ft apart at each site does not vary significantly in the Cache la Poudre gravels. Variation among sections consists mainly of sample error and could be used to measure the latter without collecting replicate samples at each section, thus increasing sample efficiency.

A second sample plan was used to estimate stratigraphic variation in particle size of gravel below the floodplain and low terraces of the South Platte River north of Denver (Lindsey and others, 1998b). In the plan, sampling was distributed among three sites at gravel pits located within a 5.5-mi segment of the valley, and the three gravel units (upper, middle, and basal) were sampled separately at sections spaced 500 ft apart (sites ML, H, and ND, Fig. 5). The spacing of sections was determined from the observation that, in river gravels of the South Platte, significant variation in particle size was noted among bars spaced 600–900 ft apart (Lindsey and Shary, 1997). Channel samples were taken from individual gravel units because differences in particle size among units were apparent. The sample design is called "factorial" (Snedecor and Cochran, 1967) because it attempts to measure the effects of two factors, location and stratigraphy, simultaneously. Replication in the design is provided by measurements at three sections per site and per gravel unit. Sample error was not estimated separately from variation among sections. The design was sufficient to measure average differences in particle size among units (Fig. 8), and in some cases, among sites. A practical application of the results is that the quantities of specific particle sizes could be estimated for each gravel unit; such estimates could be considered in mining plans.

CONCLUSIONS

Aggregate quality of gravel deposits can be measured and modeled by (1) classifying similar deposits

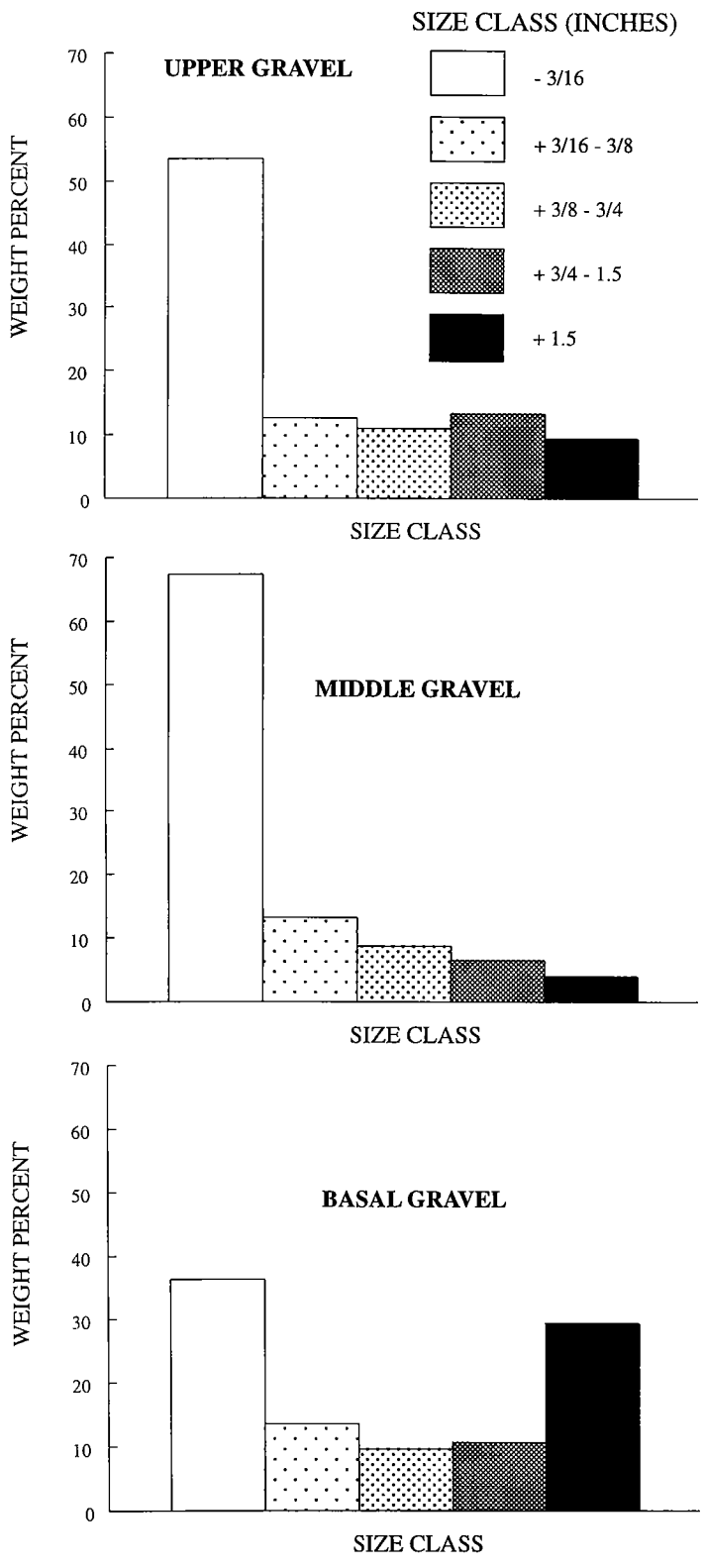


Figure 8. Histograms showing average values for particle size of gravel units at three sites beneath the floodplain and low terraces of the South Platte River north of Denver, Colorado.

into models that have predictive value, (2) constructing stratigraphic sections of deposits to define sampling targets, (3) identifying useful measures of aggregate quality, (4) conducting a pilot study to assure adequate sample design, and (5) implementing a sampling program to measure variation in aggregate quality.

ACKNOWLEDGMENTS

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A GIS and Decision-Support–System Demonstration of Aggregate Maps and Data for the Front Range Infrastructure Resources Project Area

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ABSTRACT.—The U.S. Geological Survey (USGS) recently initiated the Front Range Infrastructure Resources Project. This is a multidisciplinary study along the Rocky Mountain Front Range from Pueblo, Colorado, to Cheyenne, Wyoming, and is designed to collect, compile, and analyze new and existing data on natural aggregate (stone, sand, and gravel), as well as water, and energy resources.

To identify aggregate resources in the Front Range, a 1:500,000-scale reconnaissance map showing locations and quality of both bedrock and surficial sources of natural aggregate in the Front Range urban corridor was prepared by processing the digital geologic maps of Colorado and Wyoming. The first step of the process was to identify map units as either bedrock or unconsolidated material. Bedrock was classified according to type (i.e., limestone, granite, gneiss, etc.), which in turn was classified based on the suitability of the bedrock for use as crushed stone. Unconsolidated materials were classified according to relative age, with the older, more weathered materials being defined as less suitable for use as aggregate than younger materials. As a spin-off from the Front Range Project, the techniques developed for analyzing the Front Range geology have been modified and expanded to include all of Colorado and New Mexico.

More detailed digital aggregate maps (1:24,000 scale) are being prepared in collaboration with the Colorado Geological Survey (CGS). Maps from the CGS "Atlas of Sand, Gravel and Quarry Aggregate Resources, Colorado Front Range Counties" show the distribution of potential resources of sand and gravel and provide general information about the physical properties of the resources. These maps are being digitized and merged into a single Geographic Information System (GIS) data base. In addition, the project is adding more specific information to the maps about deposit thickness, volume, and quality. This additional information is being obtained through field-characterization studies and modeling activities. The GIS data base can be displayed and queried using off-the-shelf software such as ArcInfo™, ArcView™, and Map Professional™. In addition, the USGS is developing a decision-support system to assist users in analyzing various land-use options on resource availability.

INTRODUCTION

In 1997, the U.S. Geological Survey (USGS) initiated the Front Range Infrastructure Resources Project (FRIRP) in the area extending from Pueblo, Colorado, north to the Cheyenne, Wyoming (Fig. 1). The project addresses issues related to sustaining the availability of infrastructure resources (natural aggregate, water, and energy) in rapidly growing areas. In such areas, resource extraction commonly competes with other land uses and may be preempted by government mandate in response to local issues. The principal objectives of the project are to: (1) evaluate the region's infrastructure resources, (2) identify issues that may affect the availability of resources, and (3) provide decision makers with tools and data to evaluate alternatives leading to sustained access to infrastructure resources. During the first three years of the project, studies will be concentrated in the demonstration area. Studies will be conducted in the remaining part

Langer, W. H.; Lindsey, D. A.; Knepper, D. H., Jr.; and Faber, B. G., 1999, A GIS and decision-support-system demonstration of aggregate maps and data for the Front Range Infrastructure Resources Project area, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 139–146.

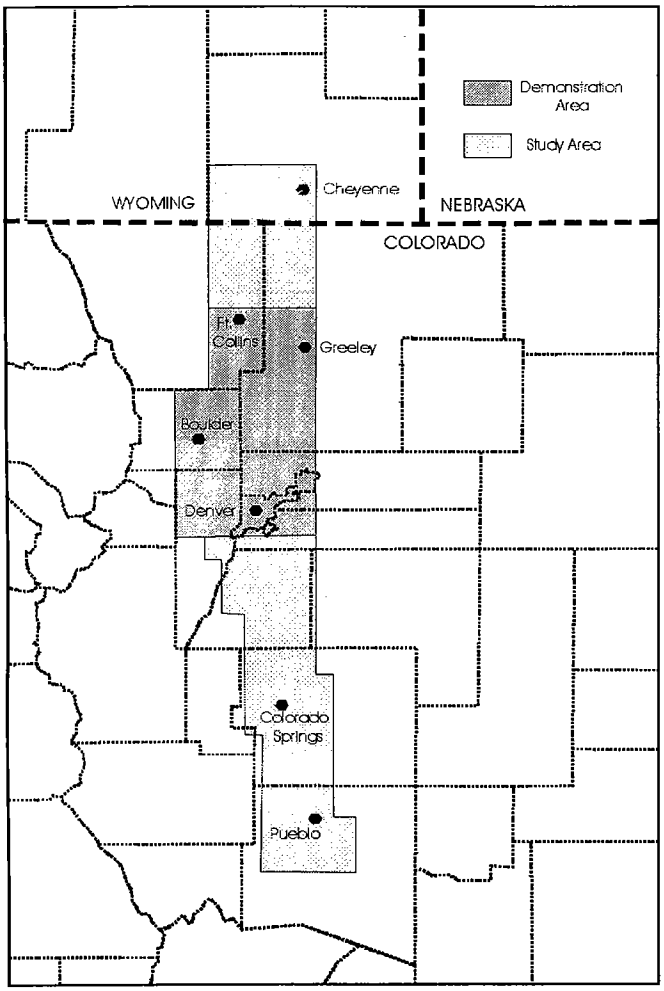


Figure 1. Index map showing Front Range Infrastructure Resources Project study area and demonstration area.

of the study area during the final two years of the project.

Aggregate studies include mapping, modeling, and characterizing aggregate resources using data obtained from conventional field mapping, as well as data acquired through geophysical and remote sensing techniques. In addition, the project addresses environmental aspects of aggregate mining, including the study of the reclamation of mined-out areas. The topic of this paper is aggregate characterization and mapping; deposit modeling and reclamation studies are discussed elsewhere in this volume.

HISTORICAL BACKGROUND

Aggregate Demand

Much of the Front Range infrastructure built during the 1950s and 1960s has deteriorated to a point that extensive repair and replacement are required. About half of Colorado highway miles are rated in poor condition. By the year 2015, traffic is expected to increase more than 50% (Rocky Mountain News, 1996). Rehabilitation and development of new infrastructure requires tremendous amounts of natural aggregate (stone and sand and gravel). During 1995, the Colorado Front Range communities consumed approximately 30,500,000 tons of sand and gravel and 8,000,000 tons of crushed stone, for a total of approximately 38.5 million tons. By the year 2000, aggregate consumption is projected to be approximately 45 million tons per year.

Restrictions on Aggregate Availability

Expansion of urban areas restricts the availability of sand-and-gravel and crushed-stone resources. This problem has affected the Denver area since the 1950s, when urban growth began to cover large deposits of prime gravel resources. In 1957, the Colorado Sand and Gravel Producers Association produced an air-photo publication to call attention to the diminishing sand-and-gravel reserves. The U.S. Bureau of Mines (Sheridan, 1967) predicted that restrictive zoning, lack of general public understanding of sand-and-gravel occurrence and mining operations, and conflicting land uses would cause a shortage of low-cost aggregate in Denver. Cooley (1971) restated the problem at the 74th National Western Mining Conference. In 1974, Soule published a report on gravel resources, urbanization, and future land use in the Colorado Front Range. That report reaffirmed Sheridan's predictions.

During 1973, the Colorado Legislature passed House Bill 1529. That act declared that "(1) the state's commercial mineral deposits are essential to the state's economy; (2) the populous counties of the state face a critical shortage of such deposits; (3) such deposits should be extracted according to a rational plan, calculated to avoid waste . . . and cause the least practical disruption to the ecology and quality of life of the citizens. . . ."

By 1980, it was obvious that H.B. 1529 was not working to protect resources in the Denver area (Schwochow, 1980). Gravel extraction had removed large amounts of the high-quality gravel. Most of what remained had been precluded from extraction by urbanization. The last major source of local gravel, the South Platte River valley north of Denver, was being mined. By 1997, mining had advanced downstream about 9 mi farther to the vicinity of Fort Lupton (Lindsey and others, 1998). The gravel-to-sand ratio of the deposits in that area is about 1:4 and decreases downstream. The economics of mining the deposits depends in part on marketing the high proportion of sand for use with crushed stone in asphalt.

Aggregate operations nearby to the north, along Boulder Creek, St. Vrain Creek, Big Thompson River, and the Cache la Poudre River, are likely to become sources of sand and gravel for the Denver metropolitan area. However, aggregate deposits along some of these rivers, particularly near the mountain front, also are being covered by urbanization.

Resources that are unavailable locally must be imported from more distant sources, generally at greater

cost. At Denver International Airport, for example, local shortages required one-fifth of the construction aggregate to be shipped approximately 100 mi from Wyoming. To further complicate supply, land-use decisions and restrictions by federal, state, and local governments precluded development of aggregate resources in many remaining areas and, thereby, eliminated extraction of resources in those areas. As available resources are consumed or preempted, the cost of maintaining or expanding the infrastructure increases, and the costs are passed on to the public as higher taxes or reduced services in other areas.

AGGREGATE CHARACTERIZATION AND MAPPING

Regional Map (1:500,000 scale) Showing Potential Sources of Aggregate

Aggregate assessments can be used to help plan for future aggregate requirements. An assessment of aggregate quality is determined by the physical and chemical properties of potential sources of sand and gravel and crushed stone and depends on the intended use of the aggregate. For example, to be used in portland-cement concrete, aggregate should be both physically satisfactory and chemically innocuous. For use as road base, aggregate commonly only needs to be physically satisfactory; chemical properties commonly are irrelevant. Similarly, aggregate used as road base can have somewhat lower physical properties than that used with a binding agent.

The FRIRP prepared a regional assessment (1:500,000 scale) of aggregate for the entire project area. The assessment is in the form of a digital map and data base that can be used to match specific properties of aggregate with specific uses. In other words, it is not a map that characterizes aggregate as good or bad. The user needs to define what is "good" or "bad" based on the end use of the aggregate.

The key to mapping potential sources of aggregate is an understanding of the geology of the region. This includes Quaternary geology for deposits of sand and gravel; stratigraphy, origin, and structural history of the region for crushed stone; and the subsequent weathering or alteration of both sand-and-gravel deposits or potential sources of bedrock for crushed stone. The Geologic Map of Colorado (Tweto, 1979) and the Geologic Map of Wyoming (Love and Christiansen, 1985) served as primary sources of information for determining the location of potential sources of aggregate.

Both maps were already available in digital form (Green, 1992, 1994). These two maps have been combined and processed into a map showing the distribution and quality of potential sources of aggregate for the Infrastructure Resources Project area (Langer and others, 1997). First, the project area was extracted from the two maps. The resulting digital-map files were assigned two sets of attributes. One set describes the geologic characteristics of the rocks in terms of mode of formation, composition, and texture of each mapped unit. The terminology and classification techniques used to define geologic characteristics are described in Knepper and others (1998). This attribute allows the files to be displayed as a lithologic map.

The second set of map attributes estimates the physical and chemical properties of each unit for use as aggregate. The terminology and classification techniques used to define aggregate resources on this map are briefly described below and are described in more detail in Langer and Knepper (1998). Physical quality is defined as satisfactory, fair, or poor. Satisfactory aggregate has physical properties that make it suitable for most purposes. It contains clasts that generally are strong, hard, relatively free from fractures, and not chiplike; capillary absorption is very small or absent; and the surface texture is relatively rough. Fair aggregate has physical properties that make it useful for many purposes, although it commonly cannot be used where engineering specifications are strict, such as in concrete or asphalt. It contains clasts that generally are friable, moderately fractured, and flat or chiplike; capillary absorption is small to moderate; and the surface is relatively smooth and impermeable. Poor aggregate has physical properties that greatly limit its use. It contains clasts that generally are weak, highly fractured, and friable. Thus, capillary absorption is moderate to high, and the surface is relatively smooth and impermeable. In many circumstances, potential sources of crushed stone can be processed to improve its quality to meet special requirements. Figure 2 shows the file displayed to show physical suitability for aggregate. Most of the figures in this report are screen prints of ArcView™ images. They are intended to show how GIS can be used for visualization and are not intended to show the details of the maps.

Chemical quality is defined as either innocuous or deleterious. Innocuous aggregate contains no constituents that dissolve or react chemically to a significant extent in the atmosphere, water, or hydrating portland cement, or while enclosed in concrete or mortar under ordinary conditions. Deleterious aggregate contains constituents in significant proportion that are known to react chemically under conditions ordinarily prevailing in portland-cement concrete or mortar. The reaction may produce significant volume change, interfere with the normal course of hydration of portland cement, or produce other harmful effects upon concrete. Figure 3 is an enlarged section of the map area that shows, as a ruled pattern, where rocks are likely to be reactive when used in portland-cement concrete.

As an extension of the Front Range project, the entire Colorado Digital Geologic Map is being processed in a manner similar to the FRIRP area. The final product will be a digital map file and supporting data base structured so that it can be imported into GIS programs, such as ArcView™ and Map Professional™. All of the descriptive information on the Colorado Geologic Map is contained in the digital data base. In addition to descriptive terms for aggregate, the data base contains descriptions of geologic units, including age, formational names, lithologic description and dominant rock type, mode of formation, and vertical and horizontal variability of the map units.

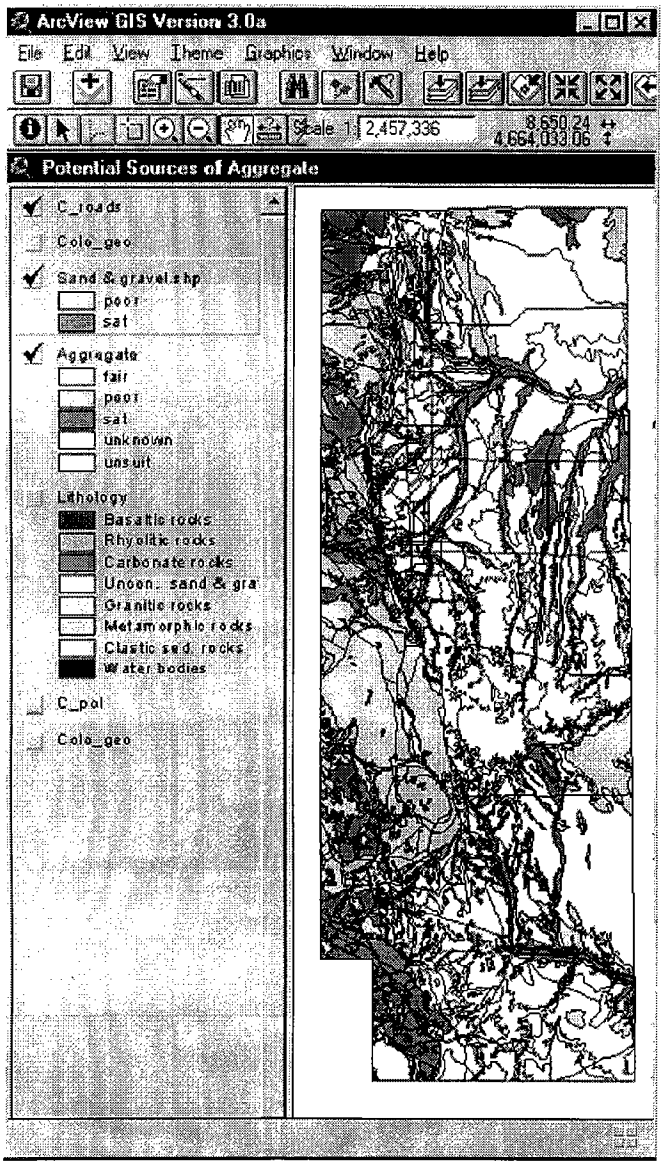


Figure 2. ArcView™ image showing potential aggregate resources for the Front Range Infrastructure Resources Project area.

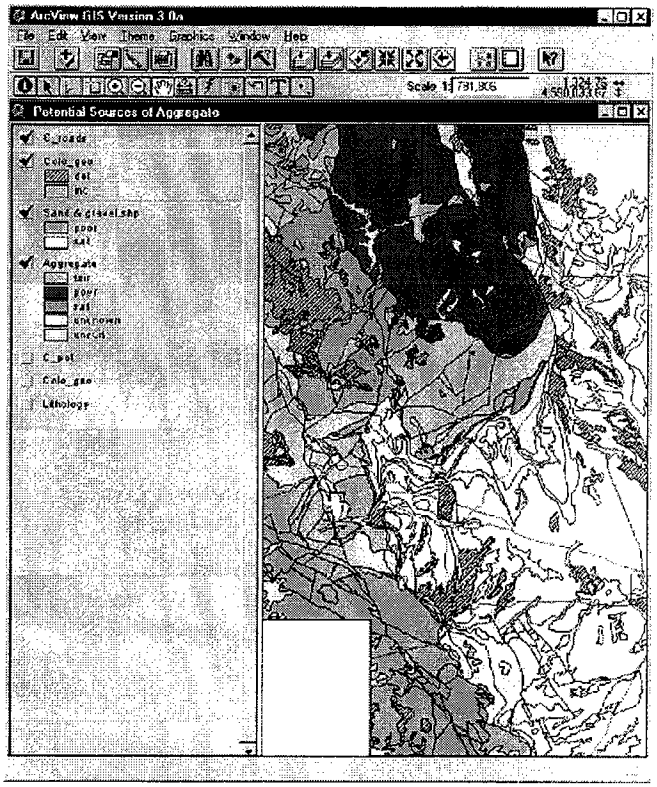


Figure 3. ArcView™ image of enlarged portion of Front Range Infrastructure Resources Project area showing, by diagonal pattern, rocks that are likely to be reactive when used as aggregate with portland-cement concrete.

Detailed Maps (1:24,000 Scale) Showing Potential Sources of Aggregate

One provision of Colorado House Bill 1529 charged the Colorado Geological Survey (CGS) to "contract for a study of commercial mineral deposits in the populous counties of the state in order to identify and locate such deposits. Such study shall be of sand, gravel, and quarry aggregate, and shall be completed on or before July 1, 1974, and shall include a map or maps of the state showing such commercial deposits, copies of which may be generally circulated."

The CGS completed those maps and released them (Schwochow and others, 1974a,b). Those maps describe geologic landforms and provide a resource classification of aggregate quality. The classifications relate to landform units and are based on whether or not a deposit is expected to have at least 30% coarse particles, as well as the presence, or absence, of unsuitable material such as fines, decomposed rock, and calcium carbonate. Information about thickness of deposits is contained as point data.

The USGS, in collaboration with the CGS, has completed digital files of all the maps contained in Special Publication 5-B, which includes all the counties within the Colorado portion of the FRIP area.

Although the maps contain some information about thickness and quality of the deposits, additional information regarding these subjects would allow for a more thorough analysis of aggregate deposits. The USGS is using the digital-map files as a basis for aggregate modeling as part of the FRIRP. New field studies are being conducted to determine deposit thickness, stratigraphy, and quality. Quality is being determined by measurement of grain size, pebble roundness, shape, and lithology. Field studies have been completed along the middle reach of the South Platte River and along the Cache la Poudre River (Fig. 4).

Certain properties of aggregate deposits are predictable and can be portrayed in map format. For example, the proportion of 0.75 in. and larger gravel varies with distance downstream. These attributes can be added to the map unit descriptions of the digital Colorado Geological Survey aggregate maps.

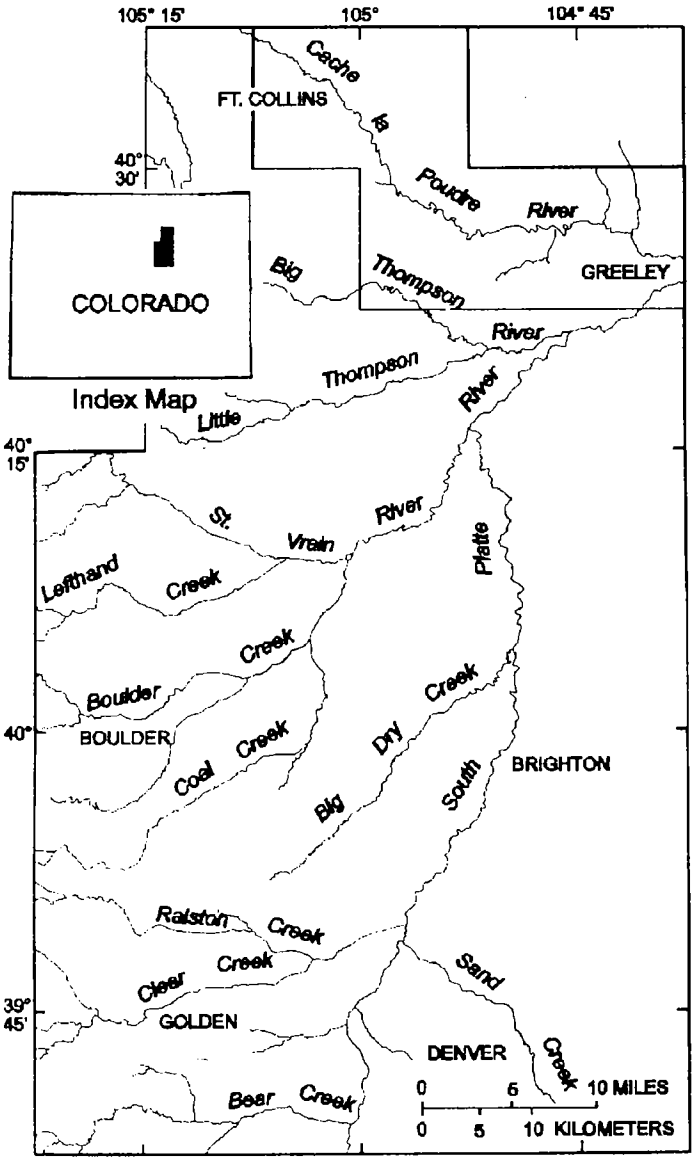


Figure 4. Index map showing geographic features in Front Range Infrastructure Resources Project demonstration area and location of the Cache la Poudre study area.

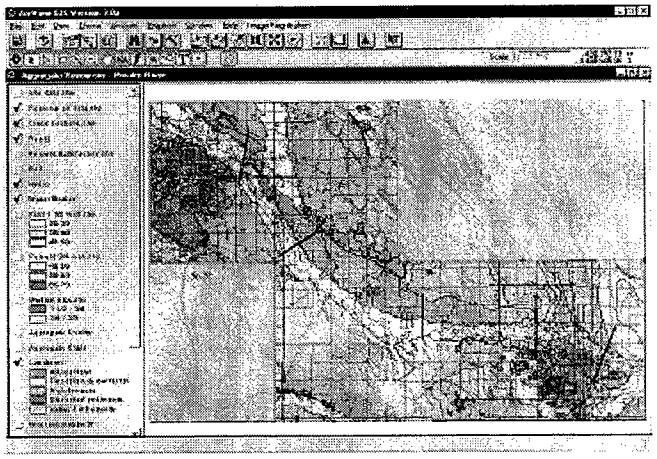


Figure 5. ArcView™ image showing landforms underlain with sand and gravel and lines of cross sections in the Cache la Poudre River area.

ArcView™ Presentation of Aggregate Data

One goal of the FRIRP is to educate decision-makers regarding the issues related to infrastructure resources. It is important for decision-makers to understand that aggregate occurs only in limited areas, that the quality of the aggregate, in part, controls its use, and that aggregate quality changes from deposit to deposit. GIS is a valuable tool for use in outreach. The aggregate-map data sets described above were imported into ArcView™ and can be displayed in combination with other digital data allowing users to interactively develop a variety of scenarios. The Cache la Poudre River from Ft. Collins to Greeley, Colorado, has been selected for this demonstration (Fig. 4).

A subset of the project data files was selected for the Cache la Poudre River area. An artificially sun-shaded relief image created from a digital elevation model, combined with highway and hydrological digital line graphs (DLG), serves as the base for the digital maps. Data showing landforms underlain with sand and gravel and cross sections are added as layers overlying the base map (Fig. 5).

The "hot-link" feature of ArcView™ has been employed to graphically demonstrate some of the geologic aspects of sand-and-gravel resources. The hot-link feature allows you to associate an image with a map feature. For example, cross sections were prepared along the river valleys to help demonstrate that the thicknesses of the deposits change from place to place. The locations of the cross sections were plotted in the data base, and the sections were connected to the section lines using the hot-link tool (Fig. 6). Likewise, other features of aggregate deposits, or even photographs, can be hot-linked to map locations.

It is important for decision makers to understand that gravel particle size affects the use of the aggregate. For example, most cement concrete requires gravel of at least 0.75 in. Most asphalt requires particles with angular faces (obtained through crushing), which commonly requires starting with gravel of at least 1.5 in. The downstream change in particle size can clearly be demonstrated by linking photographs of pit faces to pit locations along the stream valleys (Fig. 7). Statistical charts also can be used for similar purposes.

Smart-Places™ Decision-Support System

Smart Places™ is a decision-support system (DSS) that assists decision makers in assessing the implications and opportunities of alternate land-use plans. It was developed by the Consortium for International Earth Science Information Network , in collaboration with the U.S. Department of Agriculture, City and County of Denver, and a host of other collaborators. It

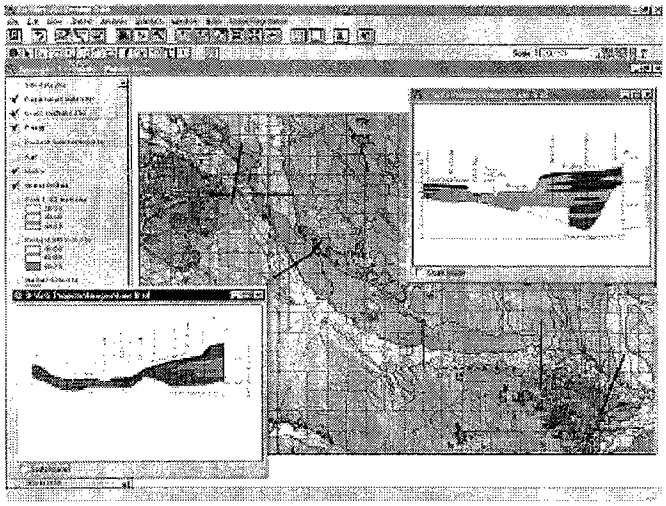


Figure 6. ArcView™ image showing images of cross sections that were linked to the section lines using ArcView™ "hot link" feature.

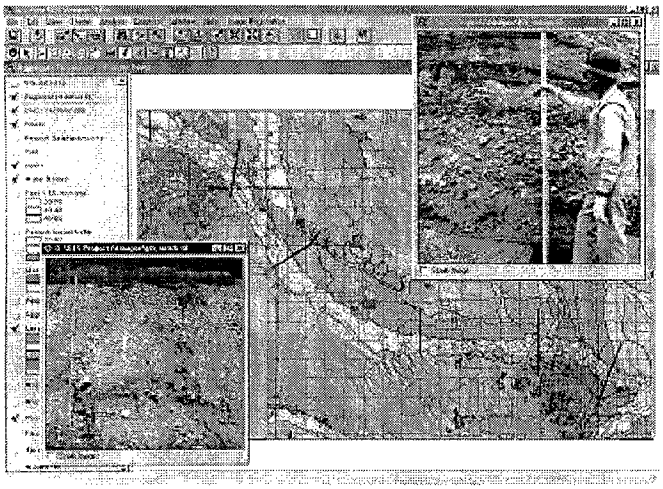


Figure 7. ArcView™ image showing photographs of gravel faces linked to gravel pits using ArcView™ "hot link" feature.

is written in Avenue (ArcView™ programming language) and executed as an ArcView™ extension. Smart Places™ offers new innovation to land-use planning through interactive design, evaluation, and illustration of proposed land-use change. The system can provide answers to resource development questions by running a series of geographic and empirical analysis models. The models are readily chosen and executed through a graphical user interface. Model results can be displayed in tabular or graphical format.

One function of Smart Places™ is to assist in the design of land-use scenarios. The ArcView™ FRIRP aggregate project described above provides some of the earth-science data and a platform for implementing the Smart-Places™ decision-making process. Using Smart Places™, we developed the scenario by adding three resource-related components to the data set; resource development, resource demand, and resource transportation. These components are editable and can be added or deleted for individual scenario exercises.

All three resource components are demonstrated in Figure 8. First, a polygon was drawn on the map view (using simple Smart-Places™ procedures) that identified a new development area. Smart Places™ calculated the aggregate required to construct the new houses, infrastructure, and supporting commercial development. The calculations were based on the size of the development area (determined by Smart Places™), the number of dwellings per acre (input by the user), and an average aggregate requirement per housing unit (provided by the scenario developer [the authors]).

Another polygon was drawn to identify a new aggregate extraction area. Resource reserves and pit life were calculated. Smart Places™ based the calculations on aggregate distribution and thickness and quality information derived from other ArcView™ data layers. It combined those data with information regarding production rates, which was input by the user. It calculated results using formulas and data supplied by the scenario developer (the authors).

Using the line-drawing function of Smart Places™, the route to transport the aggregate from the extraction area to the use area was identified. Smart Places™ queried the "new development area" to determine aggregate needed. It calculated the cost of transportation, accident exposure, fuel consumption, and emissions based on miles traveled (determined by Smart Places™), aggregate requirements ascertained for the new developments (determined by Smart Places™), and other data provided by the scenario developer (the authors).

An extremely versatile function of Smart Places™ is a feature that allows a user to create a polygon around an area of interest and return information regarding the contents of that polygon. We created four evaluation tools for this scenario (shown on the right side of Fig. 9). Those tools can summarize the results of various land-use options regarding aggregate resources, demand, and transportation, and can demonstrate the results either as numbers or as graphics. For this example we implemented the area summary tool. First, we zoomed in on a detailed part of the map and created a polygon around an area on the map (upper-left part of Fig. 9). Within that polygon are three different landforms that are underlain with gravel. By enabling the area evaluation tool (right side of Fig. 9), Smart Places™ identified what types of landforms were contained within the polygon, determined how many acres each landform comprised, and displayed the results in graphical format. Smart Places™ can query any layer of the map project, regardless of whether or not it is active or even visible.

SUMMARY

Many urban areas such as Denver, Colorado, are experiencing difficulties in obtaining adequate supplies of suitable sources of natural aggregate. It is helpful to

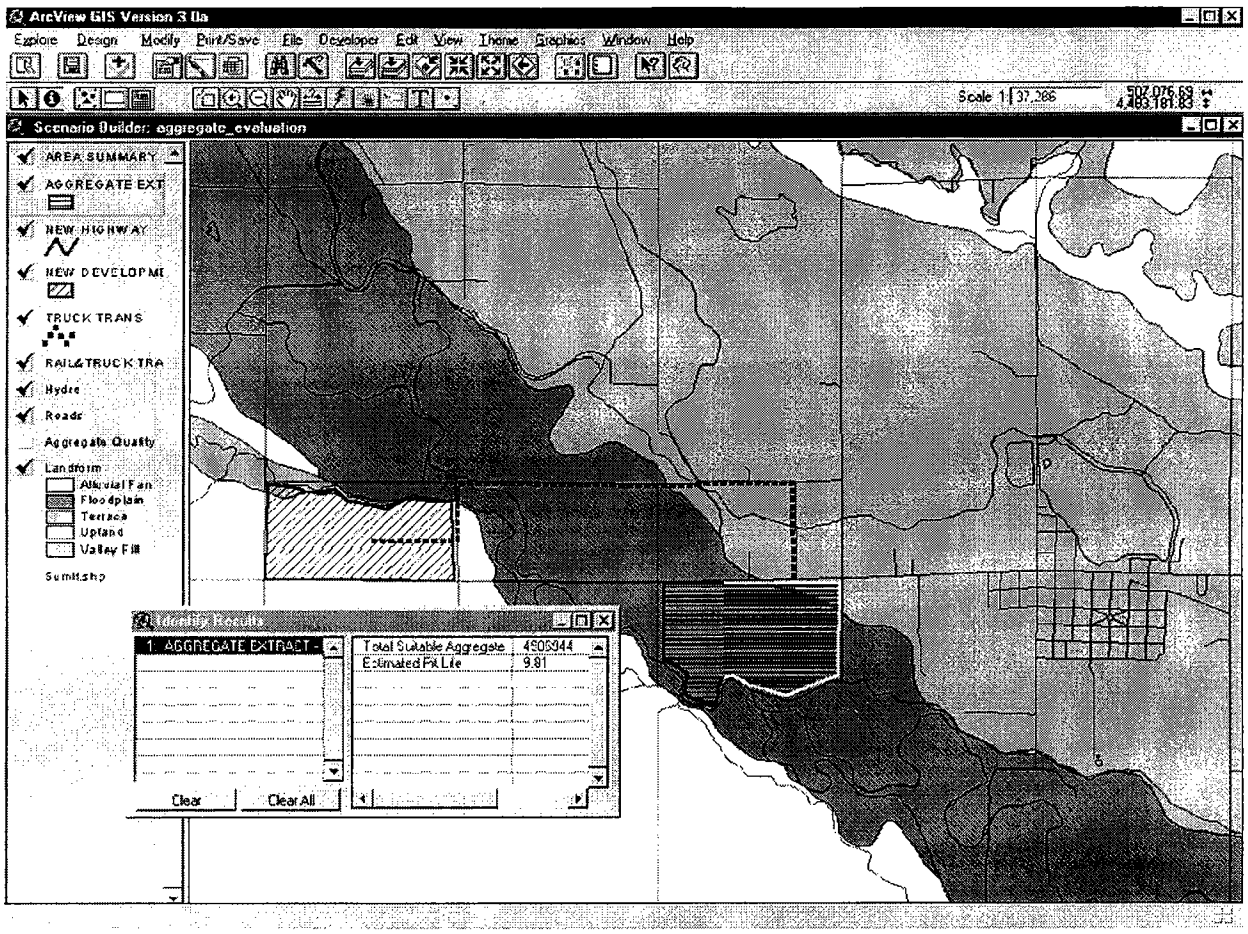


Figure 8. Smart-Places™ image showing three editable themes: (1) new development (diagonal-ruled area), (2) extraction area (horizontal-ruled area), and (3) truck transportation route between extraction and development areas (black dotted line). Summary information is shown for aggregate-extraction area.

have information about the distribution and quality of aggregate in order to manage available resources. However, many land-use decision makers are not extensively trained in dealing with technical data and maps. Geographic-information systems (GIS) and decision-support systems (DSS) are valuable tools for nontechnical users, not only to manage and analyze data but also to display and visualize data.

GIS such as ArcView™ can display maps showing the distribution and quality of aggregate resources. It can relate those data to other spatial information such as rivers and highways. Equally important, it can relate those data to information in the form of photographs, drawings, illustrations, tables, and charts. All of this information can help explain the three-dimensional variability of resources such as aggregate.

DSS such as Smart Places™ can help manage the technical data relating to aggregate or other resources. Smart Places™ can query various map layers or data bases. It can then use information obtained from those map layers in mathematical equations supplied by program developers to predict outcomes of various land-use scenarios.

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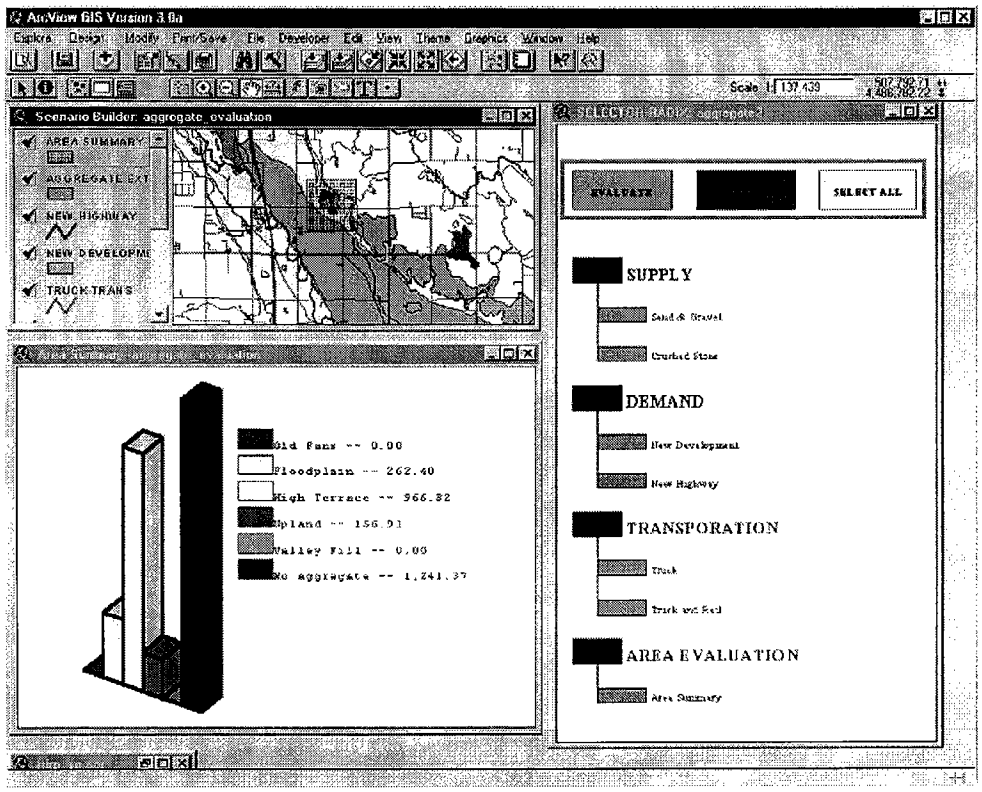


Figure 9. Smart-Places™ image showing summary area (upper left), area-evaluation tool (right), and graphical results of evaluation (lower left).

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Geophysics in Exploration for Sand and Gravel

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A geophysical investigation can provide valuable geologic information needed to characterize sand-and-gravel deposits and can be an attractive complement to more common characterization methods such as drilling. Although such investigations have been conducted already, a comparison of the different geophysical methods used in these investigations apparently has never been done. For this reason, a study was initiated by the Mineral Resources Program of the U.S. Geological Survey to determine the advantages and the limitations of different geophysical methods when used to evaluate alluvial sand-and-gravel deposits. The study is focused on those geophysical methods that are commonly available, because these are most likely to be used by industry. Furthermore, the study is focused on surface geophysical methods.

Heretofore, four different methods have been evaluated. Three of the four methods—time-domain electromagnetic (TEM) soundings, frequency-domain electromagnetic profiling, DC-resistivity soundings—are similar in that they all measure the electrical resistivity of the ground with depth. Ground-penetrating radar, however, maps changes in the dielectric permittivity and/or the electrical resistivity with depth. For all four methods, the objective is to relate the measured physical quantity to the stratigraphy of the alluvial sediments.

The study was conducted at two sites in the South Platte River valley, northeast of Denver, Colorado. One site was adjacent to an active sand-and-gravel pit, where the sediments and the underlying bedrock are well exposed. These alluvial sediments are roughly 7 m thick and consist of gravel, sand, and some clay. The bedrock beneath these sediments is mudstone. The water table is within the alluvial sediments—there are roughly 6 m of unsaturated sediments and 1 m of saturated sediments. The thickness of the unsaturated sediments was accurately determined with the time-domain electromagnetic soundings (Fig. 1) and the DC-resistivity soundings (Fig. 2); the thickness was determined moderately accurately with the frequency-domain electromagnetic profiling. The thickness of the saturated sediments could not be determined with any of the tested methods because its electrical conductivity is practically identical to that of bedrock. Sedimentary structures, such as foreset beds, were detected with ground penetrating radar; the bedrock surface possibly was detected when a low-frequency, high-power radar antenna was used.

The other site was a transect across the entire South Platte River valley, and the subsurface geology here had been determined from 12 test holes. The alluvial sediments consist of gravel, sand, and some clay, and the sediments are covered with soil that is 1 to 2 m thick. In the center of the transect, the sediments and the soil are between 9 and 16 m thick; on the western and the eastern sides, they are between 15 and 25 m thick. The underlying bedrock is mostly shale. Across the entire transect, the water table is believed to be 2 or 3 m below the ground surface. In the center of the transect, the combined thickness of the sediments and the soil was accurately determined with the time-domain electromagnetic soundings and the DC-resistivity soundings. However, on the western and the eastern sides of the transect, the thickness could not be determined with either method; rather, layers in the alluvial sediments that are not present in the center of the transect were detected. Ground-penetrating radar could not detect any sediments beneath the soil because the soil is clay-rich.

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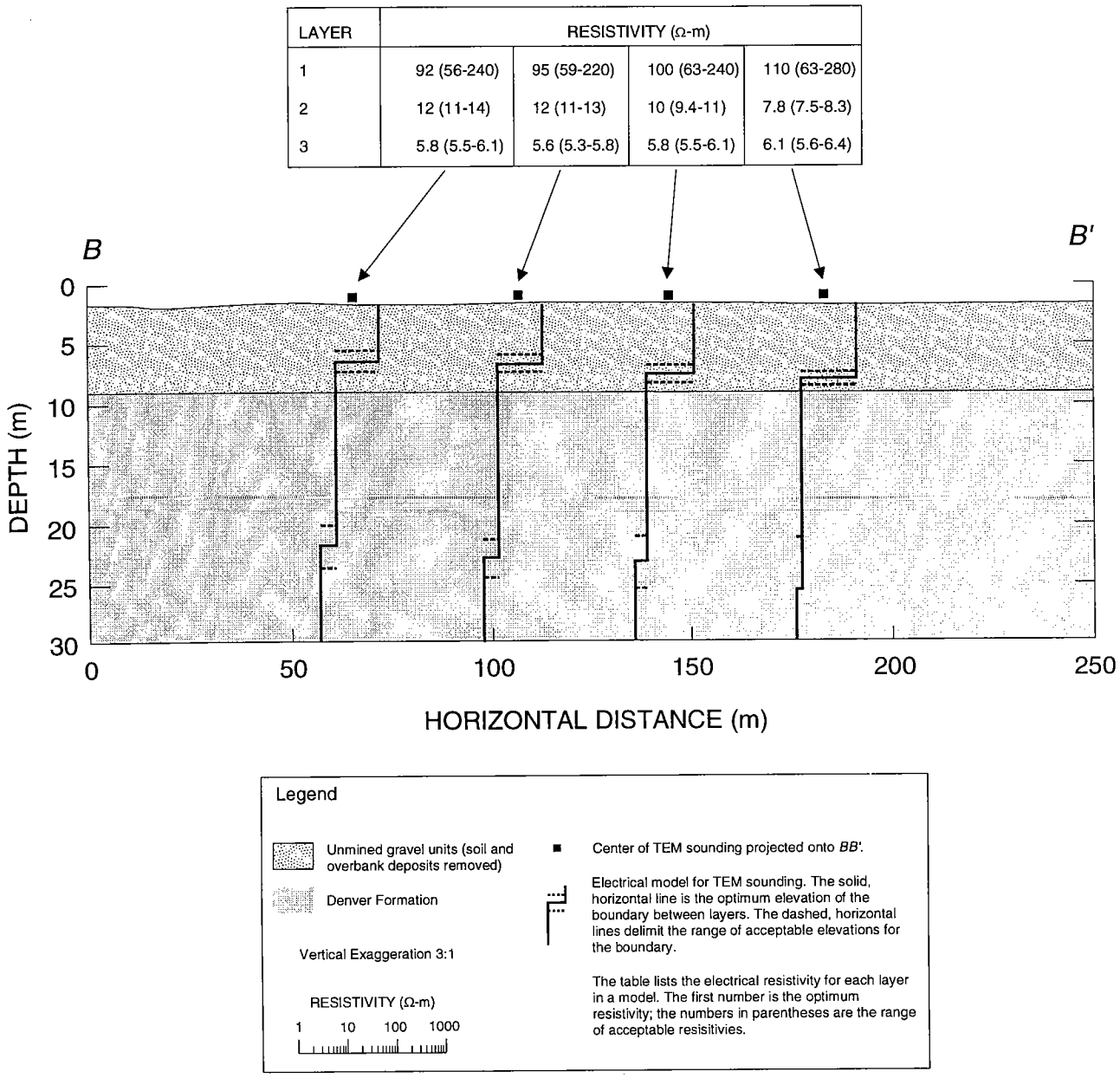


Figure 1. Cross section of the Howe Pit and the electrical models from the TEM soundings.

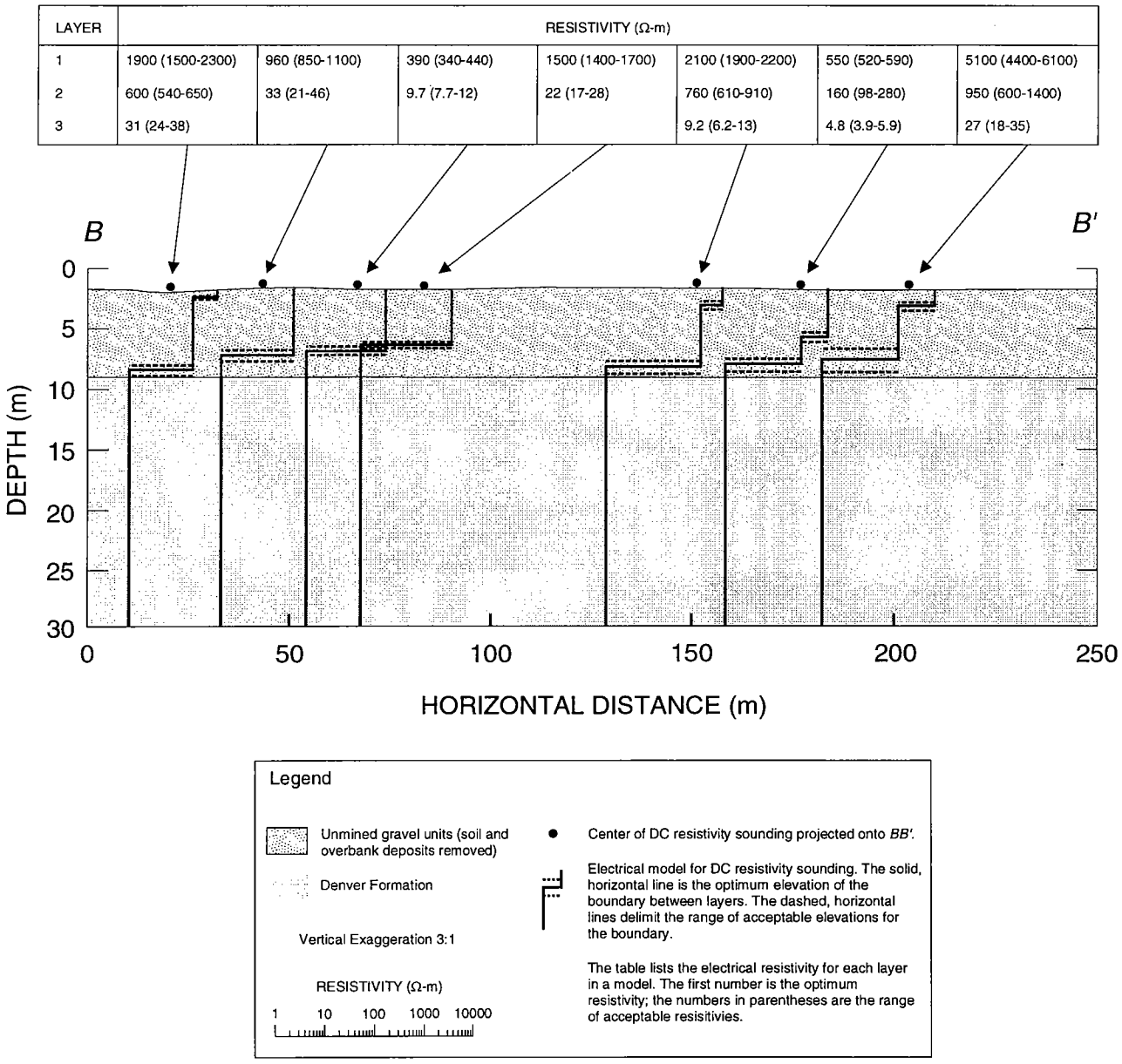


Figure 2. Cross section of the Howe Pit and the electrical models from the DC-resistivity soundings.

Processing Remotely Sensed Data for Industrial-Mineral Prospecting

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Denver, Colorado

The Front Range Infrastructure Resources Project (FRIRP) of the U.S. Geological Survey (USGS) is currently using Landsat Thematic Mapper™ and airborne-visible-infrared-imaging-spectrometer (AVIRIS) data along with planned thermal-infrared data and interferometry-synthetic-aperture radar (IFSAR) data to assess the industrial-minerals quality and quantity along the Colorado-Wyoming Front Range Urban Corridor and to characterize surrounding areas.

Landsat™ satellite data show synoptic views of the corridor, which may readily be used to identify potential regions of permissible terrain, such as river drainages, pediment surfaces, upturned lithology, and bedrock exposures, where various types of deposits may occur. Descriptive models of these deposit types are used to define the physical features that need to be recognized and characterized. In the case of Landsat™ data, the measured light is either reflected or partly absorbed by surface materials, depending on the wavelength of the light, which allows coarse mineral classifications to be made.

AVIRIS airborne data (Fig. 1) is being used to map specific minerals within selected sites. The AVIRIS instrument measures the intensity of light reflected

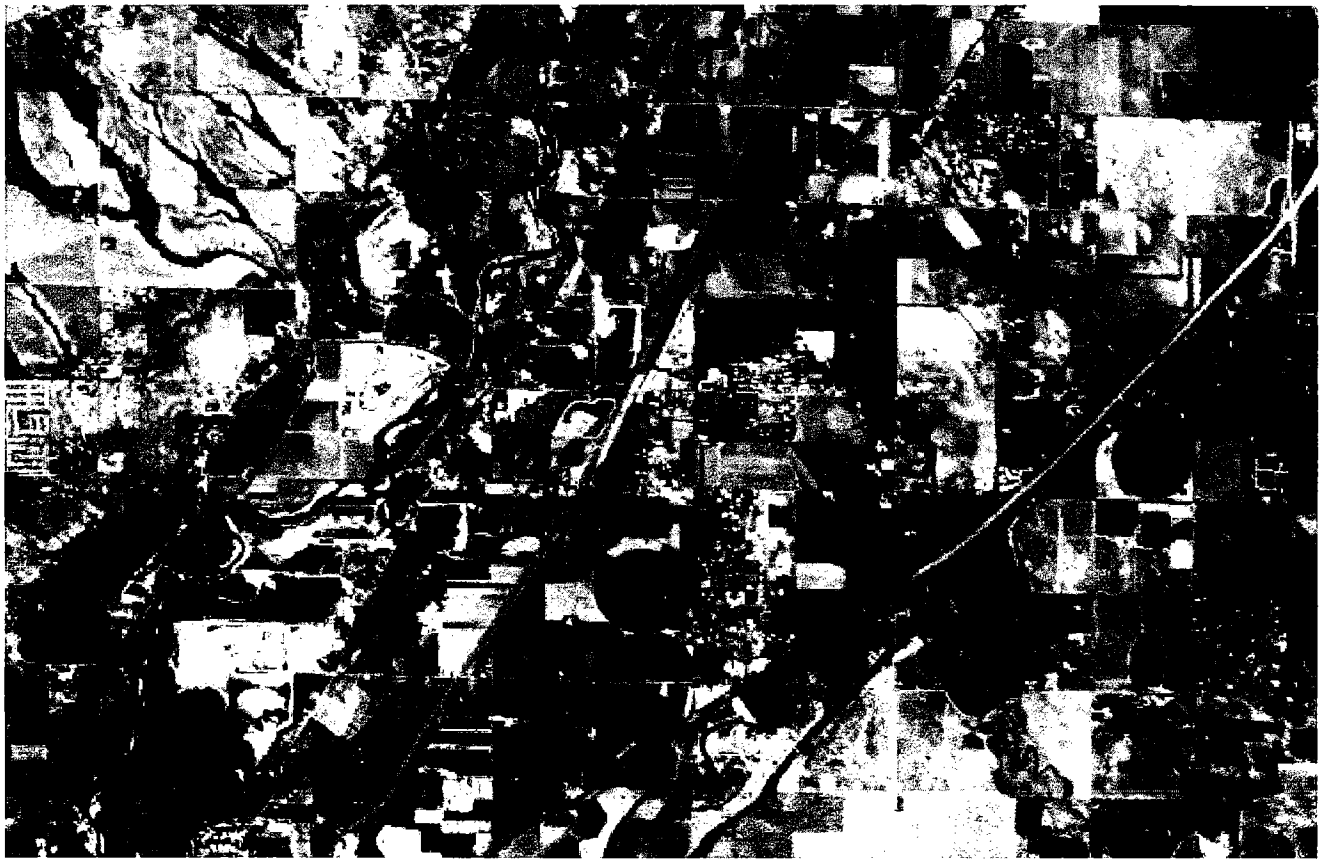


Figure 1. AVIRIS image of the Platte River southwest of Brighton, Colorado. Figure is oriented with north at top. Located in the southwest corner is Western Mobile's Howe sand and gravel pit.

Livo, K. E.; and Knepper, D. H., Jr., 1999, Processing remotely sensed data for industrial-mineral prospecting, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 151–152.

from the ground using 224 spectral channels with wavelengths that range from the visible to the near-infrared. Pixels within the AVIRIS data are processed to identify the most spectrally dominant mineral in the 1- and 2-micron-wavelength regions using USGS software. The method compares selected absorption features within a spectral library to each pixel spectrum and statistically either finds a match or rejects the identification.

Preliminary study results over several clay, sand-and-gravel, and crushed-stone quarries have identified the minerals kaolinite, montmorillonite, hematite, goethite, muscovite, and chlorite, which are minerals either being actively sought, as in the case of clay deposits, or are deposit impurities. A problem so far has been significant vegetation and other ground cover that limits exposure of soils and bedrock. Techniques are being developed in spectral unmixing to subtract these mixed pixel effects.

Future work will include acquisition and analysis of thermal-infrared data for classification of the rock-forming minerals feldspar and quartz. Combining the location of these minerals with the mapped clays, micas, iron oxides, and other minerals will enable a more precise characterization of the lithology of potential industrial-mineral deposits.

Development of Silica-Sand Resources of Wyoming

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ABSTRACT.—All of the major raw materials (silica, soda ash, limestone, and feldspar) needed to manufacture most grades of glass are found in Wyoming. Additional advantages for the manufacture of glass include the state's geographic location, a well-developed transportation network, a favorable tax structure (no corporate or personal-income tax), and low energy costs.

Inadequate local markets and prohibitive transportation costs to other markets have been the major obstacles to developing a glass industry in Wyoming, the least-populated state in the nation. The Rocky Mountain region only recently became a major market for glass, especially for the Colorado Front Range and Utah's Wasatch Front.

Currently, changing costs of the production of glass, an increased market for container glass in the Colorado Front Range, and innovative production and transportation ideas (e.g., production of selected types of glass and bulk shipments of specification-glass pellets) favor developing a glass plant in Wyoming. Thus, the Wyoming State Geological Survey (WSGS) and other state agencies have been conducting studies and contacting investors in an effort to attract a glass-manufacturing plant to the state.

Between 1987 and 1993, three locations of silica-sand and -rock deposits were studied in Wyoming (Cassa, Plumbago Creek, and John Blue). Funding was provided by the WSGS operating budget and local and state Department of Commerce economic-development grants. The reports on these areas were released between 1988 and 1993. In 1988–89, a California-based company conducted additional drilling and feasibility studies and prepared to construct a glass plant in Cheyenne, using the Cassa silica source. However, due to losses incurred by some of their other investments, the company did not proceed.

In 1997, the Wyoming Science, Technology, and Energy Administration (STEA) contracted a market study for glass manufactured in Wyoming, using information provided by the WSGS. The STEA contacted several major glass producers, and a major glass-producing company began feasibility studies in January 1998, for the construction of a glass plant. In June 1998, bids to supply brown beer bottles to the Budweiser brewery northeast of Fort Collins, Colorado, were submitted by at least two companies that were considering glass-plant sites in Wyoming.

INTRODUCTION

Wyoming contains several occurrences of industrial minerals that have long been underutilized due to Wyoming's low population and remote location in the Rocky Mountains, far from areas of high populations and markets. The industrial minerals currently produced in Wyoming are specialty products. These include trona, bentonite, and white-marble aggregate. Other products with a large regional market due to the strategic location of the material include: wallboard manufactured from gypsum and marketed in the Pacific Northwest, Colorado Front Range, and the Wasatch Front of Utah; sodium sulfate sold to a chemical plant in Chicago; and cement manufactured from local deposits of limestone, gypsum, marl, and iron additives. Other industrial minerals are marketed locally or regionally and include limestone for sugar-beet refining; construction aggregate, feldspar for ceramic glazes, leonardite (an organic product used in soil conditioners and as a coloring agent in wood stains and pigment), and decorative aggregate.

Industrial minerals with growth potential also are found in Wyoming. The Industrial Minerals section of the Wyoming State Geological Survey (WSGS) has targeted three of these for study to attract their development. These are decorative stone and aggregate,

Harris, R. E., 1999, Development of silica-sand resources of Wyoming, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 153–159.

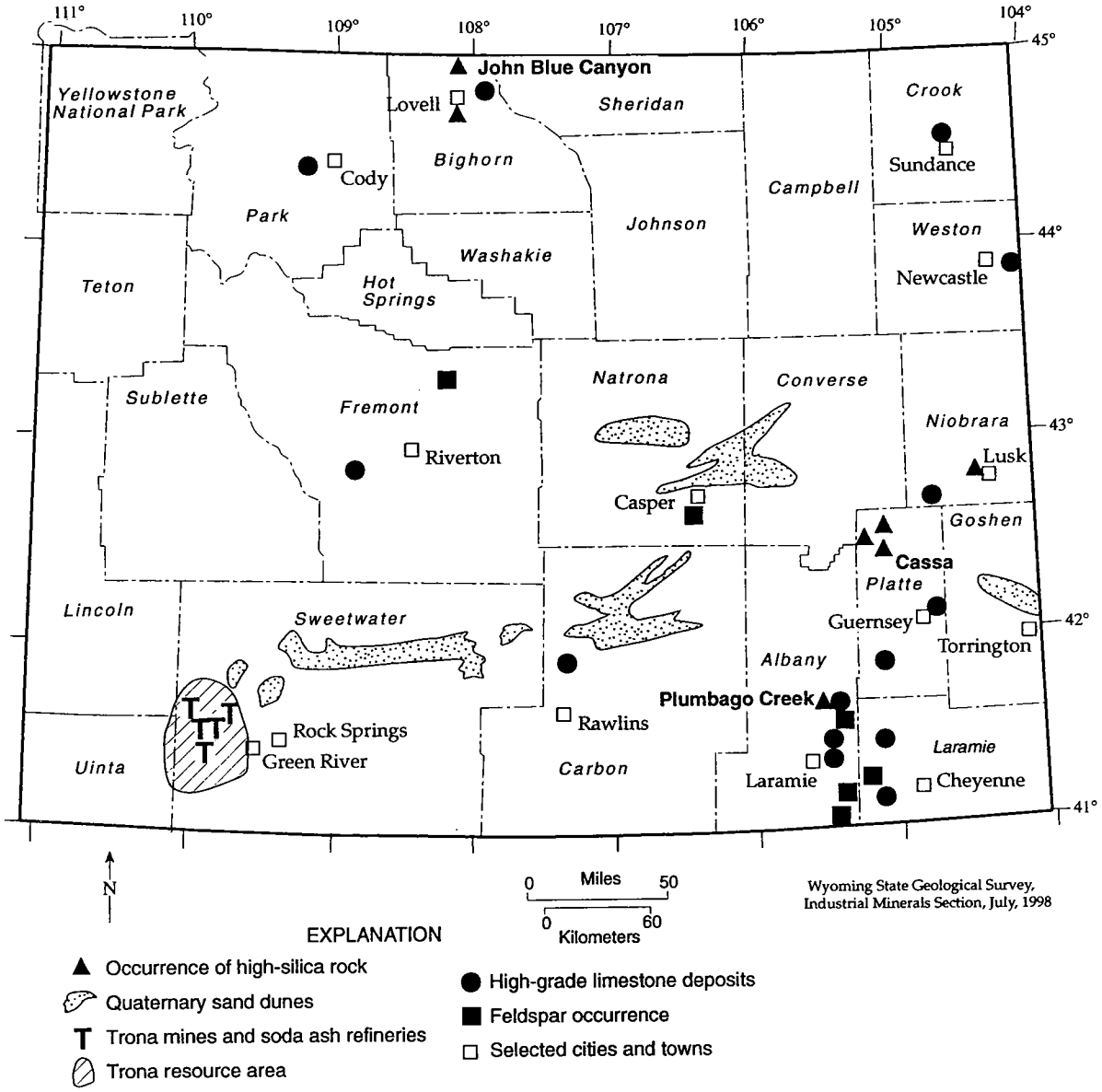


Figure 1. Index map of Wyoming showing possible sources of raw materials for glass manufacture.

zeolites, and glass raw materials. As a result of this effort, the following enterprises were initiated: (1) a quarry producing three different granites has started in Wyoming; (2) an Italian-based company currently is conducting a $500,000 feasibility study of potential quarries for dimensional limestone and granite quarry locations; (3) stone producers from the United States, Italy, and Saudi Arabia are conducting quarry-site and plant-feasibility studies; (4) numerous small decorative-aggregate and landscape-rock operations have begun; and (5) one zeolite company conducted small-scale mining operations in 1997 and currently is expanding its market.

Although Wyoming contains all of the raw materials necessary for the manufacture of glass, including soda ash produced from mined trona, producing glass in Wyoming has not been considered economic due primarily to the costs associated with transporting finished glass products long distances to markets. From the late 1870s until the 1920s, almost every community in Wyoming had a local glass works, producing bottles and window glass from locally derived silica sources. With the development of large efficient glass plants elsewhere, these plants closed. The last production of glass in Wyoming was in 1927 at Lovell (Osterwald and others, 1966, p. 78) (Fig. 1).

In the late 1980s, I presented innovative ideas regarding the production of glass to the WSGS and the Wyoming Department of Commerce, Division of Economic and Community Development (DECD). As a result, I studied several deposits of silica sand around the state and completed formal reports on these three: Plumbago Creek (Harris, 1988a), Cassa (Harris, 1988b), and John Blue Canyon (Harris and Warchola, 1992). The locations of these silica sand sources in Wyoming are shown on Figure 1.



Figure 2. Quaternary and Recent active sand dunes south of the Ferris Mountains in central Wyoming.

SILICA-SAND RESOURCES OF WYOMING

Silica-sand resources in Wyoming are found mostly in Cambrian, Pennsylvanian, Jurassic, and Cretaceous nearshore-marine sandstone or subaerial (dune) nearshore-sandstone deposits. Quaternary sand dunes in southwestern and central Wyoming (Figs. 1,2) have been tested for glassmaking, but none of these yet tested meet the specifications for glass, primarily due to a high iron content. Sand from the eastern, or distal end of the dune field contained 0.21% Fe_2O_3 (Carpenter, 1951).

Locally, the Cambrian Flathead Formation in central and western Wyoming is an orthoquartzite. The Cambrian Deadwood Formation near Lusk in eastern Wyoming is composed of 95% SiO_2, with the primary impurity being feldspar. The iron content of this unit ranges between 0.1% and 0.2%.

Pennsylvanian sandstones constitute one of the most important silica-sand resources in Wyoming. Locally, the Pennsylvanian Tensleep Sandstone in the Bighorn Basin, northwestern Wyoming, contains >90% quartz and has a low iron content. In and near John Blue Canyon north of Lovell, the wedge edge of the Tensleep Sandstone (Figs. 1,3) assays >98% SiO_2. However, the unit can be mined only by underground methods or by a borehole- or slurry-mining system (Harris and Warchola, 1992). Nearshore dune sandstones found locally in the Pennsylvanian Casper Formation near Laramie (Figs. 1,4) are an important potential source of silica sand. These units contain around 78% SiO_2 as quartz and may be upgraded by washing or hydraulic mining to ≥97% SiO_2 (Harris, 1988a).

The Canyon Springs Member of the Jurassic Sundance Formation locally contains as much as 88% SiO_2. It is also a lightly indurated sandstone, probably amenable to hydraulic-mining methods. In locations such as northwestern Platte County (Figs. 1,5) and in the Black Hills of Wyoming and South Dakota, this unit may be worth studying for its glass-sand potential.

Cretaceous rocks in Wyoming contain numerous sandstones deposited as beach- or nearshore-sand facies on the margin of the Cretaceous Interior Seaway. Unfortunately, most of these are too impure for use as a source of silica. However, the Cloverly Formation is locally an orthoquartzite with as much as 98% SiO_2, as at the Cassa locality (Figs. 1,6). This rock is well indurated with silica cement, and it is exposed at the surface over an extensive area and is near transportation routes (Harris, 1988b).

Some sandstones in the Upper Cretaceous Mesaverde Formation near Lovell, in north-central Wyoming (Figs. 1,7) contain >85% SiO_2, and are soft and probably amenable to hydraulic mining or washing. The Lovell glass plant used this unit as a source for its silica sand.

OTHER GLASS RAW MATERIAL RESOURCES IN WYOMING

Soda Ash

Perhaps the key to establishing a glass plant in Wyoming is its soda-ash production. In 1997, more than 18 million short tons of trona (sodium sesquicarbonate, $Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$) were mined (Wyoming State Inspector of Mines, 1998), constituting 90% of the soda ash produced in the United States. Five mines and refining plants west of Green River in southwestern Wyoming (Fig. 1) produce soda ash. Approximately 9 million short tons of soda ash were produced

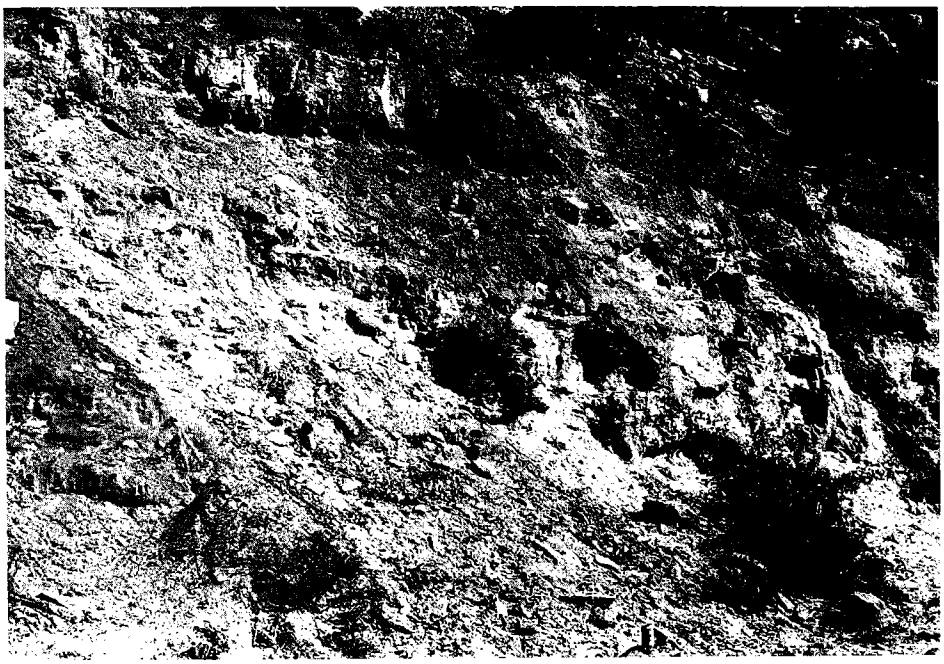


Figure 3. Near the wedge edge of the Pennsylvanian Tensleep Sandstone in John Blue Canyon, north-central Wyoming (soda-pop can, lower front center, for scale). The Tensleep in this area is only about 15 ft thick and thins to zero to the north and east of this locality.

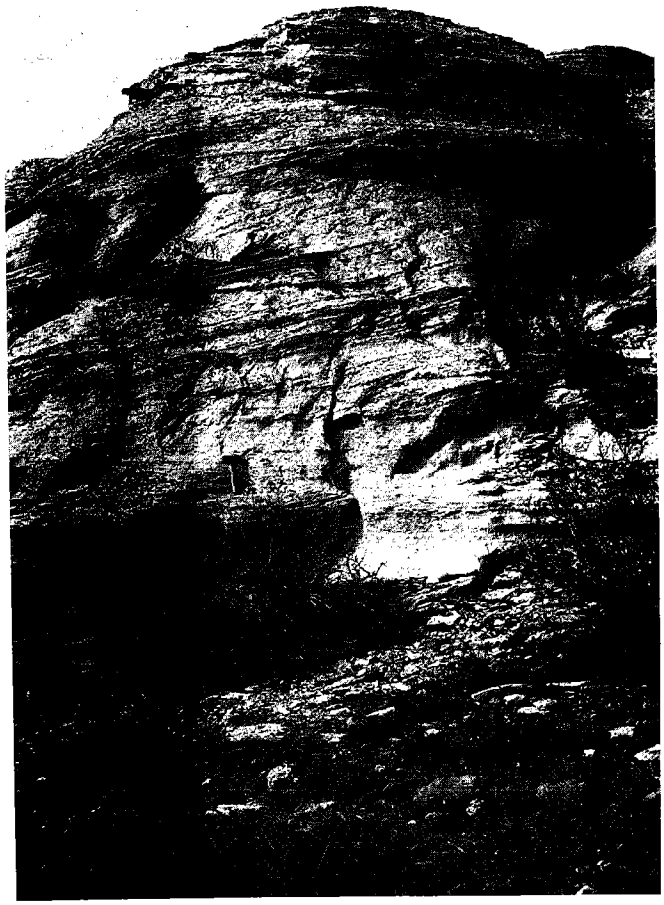


Figure 4. The Plumbago Creek silica-sand deposit, in the Permian-Pennsylvanian Casper Formation northeast of Laramie (hammer for scale).

from these mines in 1998. Most of this soda ash is shipped by rail or truck/rail to users, including existing glass plants. Utilizing this resource in Wyoming can reduce costs at the glass plant due to transportation-cost reductions. Wyoming's trona resource is enormous. About 127 billion tons of trona are found in beds more than 4 ft thick (Wiig and others, 1995).

Limestone

Wyoming contains resources of high-purity limestone sufficient to supply the needs of a glass manufacturer. Most of these resources are located in northeastern, northwestern, and southeastern Wyoming (Harris, 1996) (Fig. 1). Currently, high purity limestone is used at Laramie for manufacturing cement and in the Laramie River coal-fired power plant north of Wheatland for emissions control.

Feldspar

Wyoming produces small amounts of feldspar for manufacturing ceramic glazes at a plant in Pringle, South Dakota. The source is a pegmatite on Casper Mountain, south of Casper (Fig. 1). Feldspar has been produced from large pegmatites in southeastern and central Wyoming in the past. Adequate resources of feldspar are available for the manufacture of certain types of glass.

Energy Resources

Wyoming is a major producer of natural gas and is the world's leader in coal production. Associated with this abundance of energy resources are low energy costs. These contribute to the favorability of producing glass in Wyoming.



Figure 5. The Canyon Springs Sandstone member of the Jurassic Sundance Formation near Glendo, northwestern Platte County. Outcrop is about 40 ft thick.



Figure 6. The Cretaceous Cloverly Formation at Cassa. This outcrop has been drilled and shot to produce blocks suitable for dimensional stone. The outcrop pictured is about 30 ft thick.

CASE HISTORY AND CURRENT STATUS OF GLASS-PLANT STUDIES

The Plumbago, Cassa, and John Blue Canyon projects (Harris, 1988a,b; Harris and Warchola, 1992) were undertaken under the leadership of the Wyoming State Geological Survey after recognizing the potential for the production of glass in Wyoming. Funding for the drilling, sample analyses, and printing for these projects was obtained through community block grants from the Wyoming Department of Commerce to Albany County (Plumbago), Platte County (Cassa), and the Town of Lovell (John Blue).

In 1989, Owl Construction of Newport Beach,

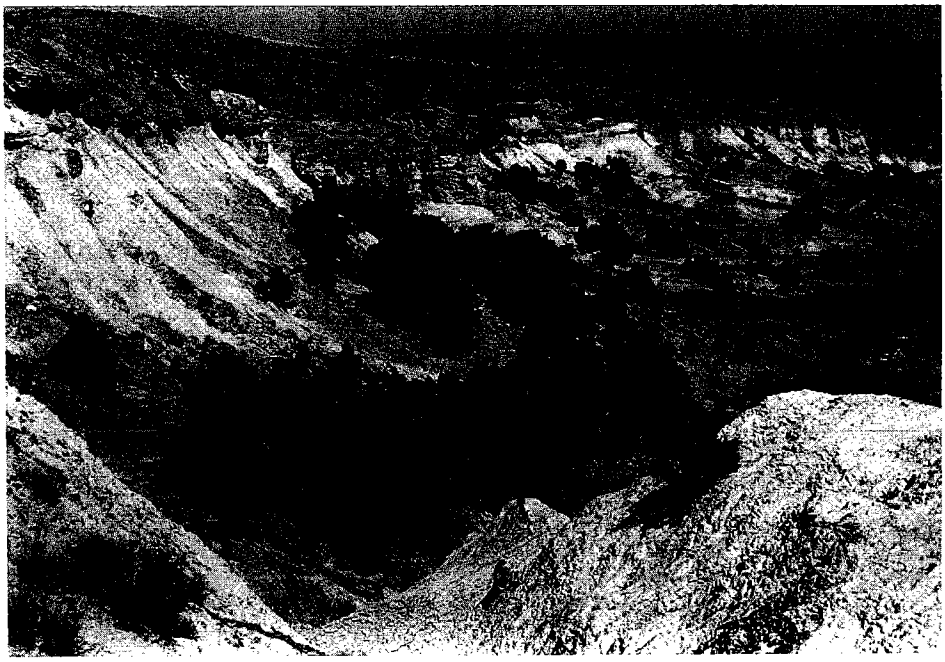


Figure 7. Sandstones of the Upper Cretaceous Mesaverde Formation south of Lovell.

California, acquired a lease on the Cassa site and conducted additional drilling and analyses. This drilling supported the conclusions from the 1988 report, and, by mid-1990, the company was negotiating the acquisition of a plant site. However, the company's other investments, particularly in low-head hydroelectric generation in California, were losing money. The winter of 1989–90 was a time of drought in California, the hydroelectric projects failed, and Owl Construction withdrew from the Wyoming glass project.

From 1990 until 1997, there was intermittent interest in producing glass in Wyoming, but no investor pursued additional studies. In 1997, acting on the recommendations in the WSGS reports, the Wyoming Science, Technology, and Energy Authority (STEA) commissioned a study to determine if a market for glass from Wyoming existed. This study identified the Budweiser brewery north of Fort Collins, Colorado, and only 30 mi south of Cheyenne, Wyoming, as a potential customer. The contract for the supply of brown bottles to this plant was to be renewed in 1998, and the existing supplier shipped the bottles to Fort Collins by rail from Oklahoma. The marketing report also identified the increasing demand for beer bottles in the Front Range area of Colorado. This area is growing rapidly, and the nation's two fastest growing counties are located in this area.

By mid-June 1998, at least two companies had submitted bids to supply the plant with bottles. However, due to the test marketing of plastic beer bottles by another beer brewing company in 1998 and 1999, the decision to construct a bottle plant in this area was postponed until the acceptance of plastic beer bottles could be evaluated. The final contract is not expected to be announced by Budweiser until after January 2000. Should plastic beer bottles become popular, construction of a new glass bottling plant could be postponed indefinitely.

SUMMARY AND CONCLUSIONS

Although a glass plant is not a reality in Wyoming as of this date (April 1999), there have been at least four industry studies regarding the siting of a glass plant in Wyoming. These have all been based on the original silica-raw-material studies conducted under the guidance of the WSGS. States desiring economic growth through the development of industrial minerals should examine the market trends for various materials known to exist in the state and determine if there are any underutilized or undeveloped resources. A geologic report and partnership studies with state economic development agencies may then produce results.

It is also important to realize that the time between completing technical reports and actual interest in the deposits can be long. Although there was one serious study undertaken within a year of the initial release of two of these reports, it has been 10 years since they were published. Serious interest continues but no construction has occurred yet.

Due to the changing transportation costs, increases in local, regional, and national market demand, and Wyoming's advantages in having nearby raw materials and low energy costs, a glass plant located in Wyoming seems likely to become a reality.

ACKNOWLEDGMENTS

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Industrial-Mineral Resources Associated with Salt Domes, Gulf of Mexico Basin, U.S.A.

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ABSTRACT.—Salt domes, their cap rocks, and the adjacent sedimentary strata represent a major economic resource in the Gulf of Mexico basin. Gulf Coast salt diapirs formed in response to sediment loading of the "mother" Louann evaporite sequence of middle Jurassic age, an effect that is caused by the buoyant nature of the lower density salt. Halokinesis progresses from nonpenetrative deformation that creates broad "pillow" structures into discrete high-amplitude diapirs. Because of its buoyancy, the top of the salt diapir remains near the land surface or the seafloor during much of its history as the basin floor subsides. The salt within the Gulf Coast diapirs is deformed complexly and commonly shows subvertical banding that represents modified sedimentary layers with different contents of nonhalite components. The most abundant impurity is anhydrite, which occurs as individual millimeter-scale crystals or as deformed clasts that generally form about 5% of most salt stocks. Many mature salt diapirs are mantled by a "cap rock" that consists of a lower anhydrite zone and an upper calcite zone, commonly separated by a discontinuous gypsum-bearing zone. The anhydrite zone forms as accreted layers of anhydrite grains and clasts that are left after episodes of halite dissolution. The calcite zone is a product related to petroleum destruction accompanying bacterial reduction of aqueous sulfate. Calcite-cemented siliciclastic strata occur above or alongside diapirs.

The mineral resources of the salt-dome setting are remarkably diverse. Major economic products of the salt-dome environment are salt and cap-rock–hosted native-sulfur deposits, as well as petroleum resources that occur on the dome flanks and in the cap rock. Native sulfur forms as a result of bacterial sulfate reduction accompanying petroleum destruction to form hydrogen sulfide, which is subsequently oxidized to elemental sulfur, major amounts of which have been produced by the Frasch process from Gulf Coast salt-dome cap rocks. Some cap rocks have produced limestone, gypsum, and anhydrite for a variety of construction uses. Although traditional industrial-mineral resource production from Gulf Coast salt domes is shrinking, some cap rocks host potentially commercial concentrations of celestite and barite, as well as the metals Zn, Pb, and Ag. Furthermore, caverns, excavated within the salt stocks, serve as major storage facilities for crude oil (including the Strategic Petroleum Reserve), liquefied petroleum gas, and natural gas.

These resources are products of fundamental geologic processes that are integral to the evolution of the Gulf of Mexico basin. Whereas production of some industrial-mineral resources, such as elemental sulfur, has declined in recent years, ample reserves of salt will allow production to continue into the foreseeable future. Further, there is potential for other mineral-resource production from cap rocks under favorable economic circumstances. Expanded use of caverns, excavated in the salt masses for material storage and disposal, is likely to continue into the next century.

INTRODUCTION

The Gulf of Mexico basin is one of the most intensively studied geologic regions of the world, in large part because of its contained mineral resources. Mineral-resource production was initiated by the spectacular concentrations of petroleum revealed by the drilling into the cap-rock reservoirs of the Spindletop dome in coastal Texas in 1901, an event that initiated the "age of liquid fuel"; a total of about 55 million bbl of oil were produced from the Spindletop cap-rock reservoirs (Halbouty, 1979). The development of the Frasch process for in situ production of cap-rock–hosted sulfur was necessitated by the generally unconsolidated nature of

Kyle, J. R., 1999, Industrial-mineral resources associated with salt domes, Gulf of Mexico basin, U.S.A., *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 161–178.

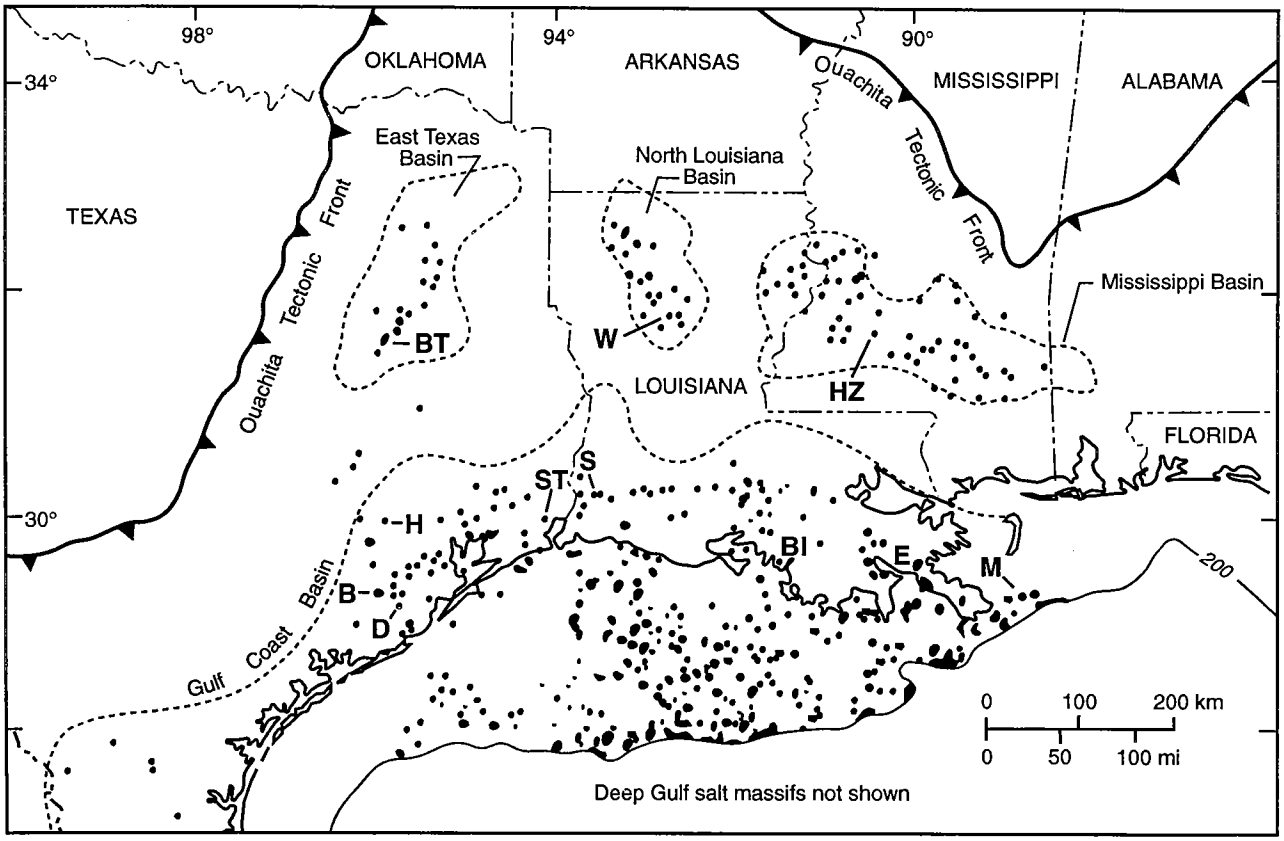


Figure 1. Geologic setting of the northern Gulf of Mexico basin. Black dots indicate position of individual salt diapirs, typically shown larger than actual size at this scale. Selected domes: B = Boling; BI = Belle Isle; BT = Butler; D = Damon Mound; E = Grand Ecaille; H = Hockley; HZ = Hazlehurst; M = Main Pass 299; S = Sulphur Mines; ST = Spindletop; W = Winnfield. Modified from Posey and Kyle (1988).

the enveloping sediments and the presence of toxic hydrogen sulfide that prohibited conventional mining. Salt-dome cap rocks became an early focus of petroleum exploration, with an eventual greater understanding of salt-dome geology and their contained resources. More scientific studies of salt-dome formation have evolved during this century, including the integration of the processes of mineral-resource concentration within the overall context of basinal processes. Recent developments include the identification of active salt diapirs on the present seafloor of the Gulf of Mexico, environments that are believed to represent modern cap-rock–forming sites. These active salt structures have topographic expression that is prominent enough to control the local depositional environments, which affect the diapirism process and the localization of diverse mineral resources.

As this century draws to a close, it is appropriate to review the history, current status, and future potential of nonenergy-mineral resource production associated with salt domes in the Gulf of Mexico basin of Texas and Louisiana. The origin of these mineral resources will be discussed within the context of the evolution of this remarkable sedimentary basin. Salt domes, their cap rocks, and the adjacent sedimentary strata represent a major economic resource in the Gulf Coast. Major products of the salt-dome environment are salt, caprock–hosted native sulfur, and oil and gas that occur on the dome flanks and in the cap rock. Some cap rocks have served as sources of limestone, gypsum, and anhydrite for a variety of local industrial purposes. Recent exploration has revealed concentrations of Zn, Pb, and Ag sulfides, as well as barite and celestite, in cap rocks. Caverns, remnant within the salt stock after brine production or specifically designed and excavated, serve as diverse product storage and disposal.

GULF COAST GEOLOGIC SETTING

The depositional framework of the Gulf of Mexico basin was initiated during the Triassic by crustal thinning and rifting along the former junction of South America and North America that created the proto–Gulf of Mexico (Fig. 1). Incipient rifting created smaller continental basins along the margin of southern North America. The Gulf area had become a series of rapidly subsiding, restricted marine basins in which the areally extensive Louann Formation and equivalent evaporites were deposited during the Middle Jurassic (Salvador, 1991). The Louann evaporites began to deform in response to sediment loading, thus initiating the development of the salt structures that are a domi-

nant geologic feature of the present Gulf of Mexico basin (Fig. 1). Diapirism continued throughout the late Mesozoic and the Tertiary, a period of time dominated by siliciclastic sedimentation that continues today. Except for Upper Jurassic and Lower Cretaceous marine-carbonate formations, the stratigraphic sequence in the Gulf of Mexico basin consists largely of prograding fluvio-deltaic complexes. These units dip gently regionally toward the Gulf, and their depositional architecture is influenced by down-to-basin growth faults.

The salt-diapir margins and the growth faults are major routes of fluid transport and play an important role in mineral-resource localization in the Gulf of Mexico basin. Thus, a brief review of halokinesis is appropriate. The reader is referred to the studies of Jackson and Talbot (1986) and Jackson and others (1990, 1996) for more complete discussions. The salt diapirs form in response to sediment loading of the "mother" Louann evaporite sequence, an effect that is caused by the buoyant nature of the lower density salt. Halokinesis progresses from nonpenetrative deformation that creates broad anticlines or "pillow" structures into discrete high-amplitude diapirs. After an individual salt diapir is detached from the salt-sequence source, it may continue to rise in response to sediment loading because of its buoyancy. The active salt structure may have topographic expression that is significant enough to control the local depositional environment. Sediments adjacent to the salt structure subside to form rim synclines as salt migrates from the source salt sequence (Jackson and Seni, 1983). Disruption of the bedded units along diapir margins creates potential avenues for fluid movement (e.g., Kyle and Agee, 1988; Land, 1991).

The salt within the Gulf Coast diapirs is complexly deformed and commonly shows subvertical banding due to the development of isoclinal folds. The banding represents modified sedimentary layers with different contents of nonhalite components. The most abundant impurity is anhydrite, which may occur as single millimeter-scale crystals or as deformed thin beds. Anhydrite may form as much as 10% of some salt stocks, although a few percent is more common, and salt is essentially devoid of significant amounts of impurities in some salt domes.

It is important to recognize that the environment in which cap rocks form (i.e., the top of the salt diapir) remains near the land surface or seafloor during much of its history. Many nearshore Gulf Coast diapirs have topographic relief above the surrounding coastal plain, a situation that made them preferred sites for Native American and later European settlers. Active marine calcite cap-rock–forming sites have been identified over shallow salt diapirs on the present Gulf of Mexico seafloor (Kennicutt and others, 1985; Roberts and others, 1990). These sites coincide with petroleum seeps, and the isotopic signature of the calcite that is present reflects a hydrocarbon source (Kennicutt and others, 1985). Barite-rich mounds occur in association with some of these seeps (Fu and others, 1994). Thus, it follows that cap-rock mineral-resource concentrations may form in the unconsolidated sediments near the contemporaneous surface or seafloor in sites of mixing of fluids discharged from the deep basin with shallow circulating fluids of marine or meteoric origin.

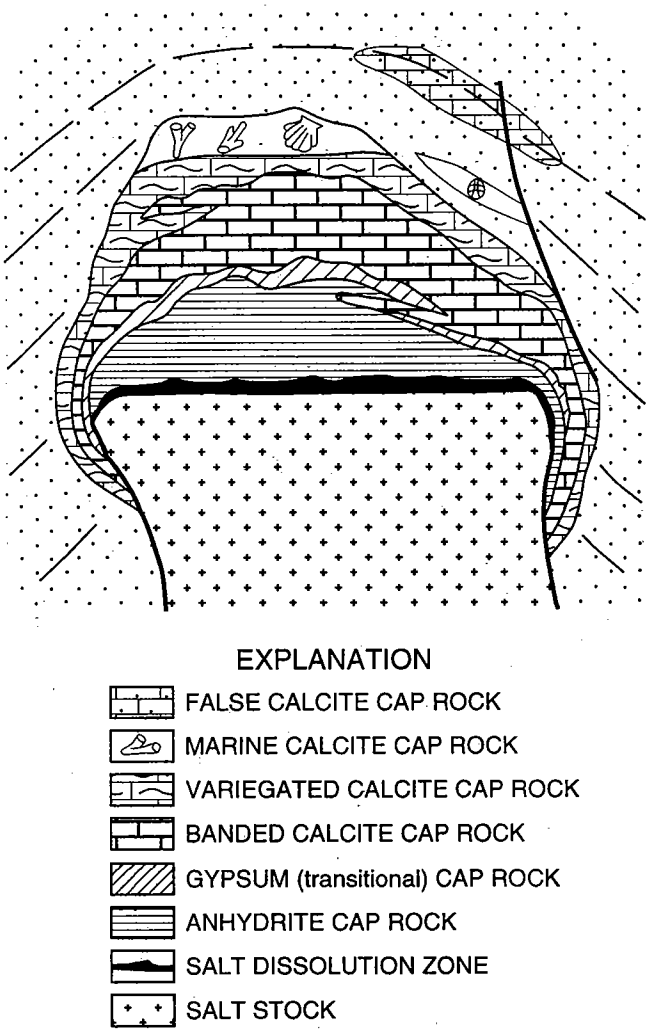


Figure 2. Generalized salt dome cap rock zones. After Posey and Kyle (1988).

NATURE AND ORIGIN OF SALT-DOME CAP ROCKS

Most mature Gulf Coast salt diapirs are mantled by a "cap rock" that consists of a lower anhydrite zone and an upper calcite zone, commonly separated by a discontinuous gypsum-bearing zone (Fig. 2) (see Kyle and Posey, 1991, and Kyle, 1995, for further documentation of cap-rock zones). Virtually all cap rocks contain anhydrite; however, gypsum and calcite may or may not be present. Lenses of calcite also appear to occur within the anhydrite, particularly near the diapir margins. Calcite-cemented clastic rocks commonly occur above or alongside diapirs and have been referred to as "false cap rocks."

Cap rocks commonly contain several accessory minerals, the most abundant being doubly terminated

quartz crystals, euhedral carbonate crystals, and clay minerals. These are residual from the salt mass and are encased during growth of the cap-rock zones. Various "exotic" minerals, including base- and precious-metal sulfides, alkaline-earth sulfates, and elemental sulfur, make up varying amounts of cap rocks and form at the same time and after their cap-rock hosts under the influence of externally supplied basinal fluids (e.g., Kyle and Agee, 1988).

Anhydrite Cap Rock

Diapiric salt contains a few percent anhydrite as crystals and deformed clasts. As halite at the top of a diapir is dissolved by halite-undersaturated formation waters, the less soluble anhydrite accumulates concurrently as a residual "sand" in a brine zone. As pressure is exerted on the cap rock by the rising diapir, the anhydrite crystals are fused to form a dense anhydrite cap rock. As more halite dissolves, additional anhydrite layers are progressively underplated to the overlying layers, creating an inverted stratigraphy. Petrographic evidence indicates that sulfide laminae form at the salt-anhydrite contact as the anhydrite cap rock grows by accretion (Ulrich and others, 1984; Kyle and others, 1987). Thus, these stratiform sulfide layers represent a paragenetic sequence with the sulfide concentrations in the upper anhydrite cap rock reflecting the oldest mineralizing events, and the sulfide laminae become progressively younger downward in the cap rock.

Calcite Cap Rock

The formation of calcite cap rock is a complex process that is controlled by several coincident chemical and physical parameters This process can be generalized as follows (Machel, 1989):

$$\text{Hydrocarbons} + SO_4^{2-} \rightarrow \text{Altered hydrocarbons}$$

$$+ \text{bitumen} + HCO_3^- + H_2S\ (+ CO_2?) + \text{heat}$$

Calcium is derived from the dissolution of anhydrite, and bicarbonate is derived through the oxidation of liquid or gaseous hydrocarbon compounds. The oxidation of crude oil or natural gas is a bacterial process that accompanies sulfate reduction at relatively low temperatures (≤70°C) (Feely and Kulp, 1957). Bicarbonate combines with calcium to precipitate calcite that has a light carbon-isotope signature inherited from the hydrocarbon precursor (e.g., Feely and Kulp, 1957; Posey, 1986). The carbon-isotope character of cap-rock limestones of all genetic types (Fig. 2) (–10‰ to –55‰) are distinct from ordinary marine limestones (+5‰ to –5‰). Calcite that forms from the bacterial degradation of crude oil has carbon isotope compositions ranging from about –10‰ to –30‰ (Posey, 1986; Posey and others, 1987b; Prikryl and others, 1988), whereas isotopically lighter calcite, –30‰ to at least –55‰, forms from gaseous hydrocarbons. Metal supply by formation waters to the H_2S-bearing cap rock may lead to precipitation of metal-sulfide deposits (Kyle and Agee, 1988; Kyle and Saunders, 1996). Conversely, H_2S may be oxidized subsequently to form extensive concentrations of native sulfur.

The calcite zones generally are thickest along the margins of the salt-dome cap rock, probably because this area is most susceptible to anhydrite dissolution and bacterial alteration related to pore fluids that bathe the sides of the salt diapir. Marine calcite cap rocks may be the earliest cap-rock zone to form overlying the locally uplifted seafloor that overlies a shallow diapir. This environment would be favorable for the development of marine communities, including a supply of nutrients related to petroleum destruction on the seafloor. The banded-calcite zone forms later, beneath the early calcite zones in an isolated environment, as the upper part of the anhydrite zone is progressively altered. Banded-calcite cap rock forms in a repetitious two-stage process of anhydrite replacement and open-space filling (Posey, 1986; Posey and others, 1987b; Prikryl and others, 1988). Partial dissolution and replacement of anhydrite takes place at the calcite/anhydrite interface. A layer of fine-crystalline dark limestone, containing the more resistant residues from the anhydrite, forms first and leaves a space between the new limestone layer and the overlying cap rock. Coarse-crystalline calcite precipitates in the open space. Repetition of this process forms the distinctly banded-calcite zone that in general becomes progressively younger downward.

CAP-ROCK–HOSTED MINERAL RESOURCES

General

Salt domes, their cap rocks, and the adjacent sedimentary strata represent a major economic resource in the Gulf Coast and elsewhere. The principal economic product of the salt-dome environment is petroleum that occurs in reservoirs within the cap rock, in strata overlying the dome, in pinchouts on the dome margins, and in peripheral stratigraphic traps that formed in response to salt movement within withdrawal areas (Seni and Jackson, 1984). Energy resources are not the focus of this review, but cap-rock petroleum is of historic interest, as the site of the first major oil production, as well as serving as a critical component for the origin of some industrial minerals in the salt-dome setting.

Other mineral resources include industrial rocks and minerals used for construction and chemical applications. Cap rocks have served as local sources of jetty stone and aggregate, including a unique use of anhydrite as a road material. Industrial minerals of traditional importance have been salt, produced from hard-rock mines and brine operations, and sulfur, produced by the Frasch method, which was developed to extract sulfur from salt-dome cap rocks. Furthermore, caverns excavated with salt diapirs serve as repositories for materials such as crude oil, liquefied petroleum gas, and natural gas.

Construction Materials

The surface materials in much of the Gulf Coastal Plain are Tertiary to modern unconsolidated sands and muds. Thus, local sources of hard materials, even of

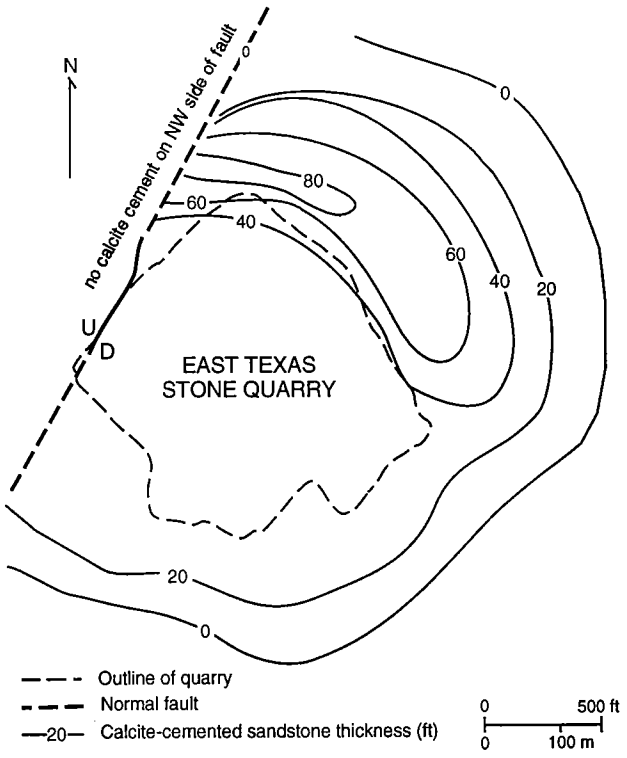


Figure 3. Calcite-cemented Carrizo Sandstone on the Butler dome periphery in the East Texas basin. Isopachs based on drill cores; no detailed information is available on thickness of the cemented zone within the quarry, but it typically varied between 40 ft and 60 ft. Modified after Smith (1996).

relatively poor quality, have served for a variety of industrial purposes. Near-surface cap rocks, including calcite-cemented "false cap-rock" sandstones, have provided this type of material.

The Butler salt dome in the East Texas basin is a slightly elliptical piercement stock with a 2.5-mi-long, northeast-trending major axis (Fig. 3). The dome lies about 300 ft below the surface at its center and deforms strata as young as the upper Eocene Claiborne Group. A traditional cap rock is not present above the salt stock, but a perched false cap rock of calcite-cemented Carrizo sandstone occurs about 2,100 ft above the salt associated with a radial fault on the northeast flank of the dome (Smith, 1996). The cemented sandstone cropped out and was exploited as an aggregate source in a quarry to a depth of about 300 ft, when production was terminated in 1995 (Fig. 4A). The cements essentially disappear within 2,000 ft of the fault (Fig. 3), and the Carrizo sand becomes friable, which is typical for the shallow uncemented sediments of the Gulf Coast Tertiary sequence.

The Damon Mound dome in coastal, south-central Texas is typical of geologically young salt diapirs that show topographic relief. The mound is elliptical in plan, measuring roughly 2 by 1.5 mi and rising about 80 ft above the surrounding land surface. The surface relief is a function of uplift since the late Pleistocene of the underlying salt diapir, which occurs presently about 600 ft below the land surface. Oligocene to Pleistocene units of marine, deltaic, and fluvial origin occur along the flanks and over the crest of the dome. Thick calcite cap rock occurs on the northwest side of the dome and has been exploited sporadically for construction materials, most recently in the late 1980s, when a quarry about 80 ft deep was developed (Fig. 4B). The calcite cap rock is up to 250 ft thick and is overlain locally by the Oligocene *Heterostegina* limestone. This coral reef is separated from the true cap rock by a several feet of mudstone and can be considered a marine cap rock (Prikryl and others, 1988)

The Winnfield dome in the North Louisiana basin has an irregularly circular outline, extending about 4,000 ft in a north-south direction and 3,500 ft in an east-west direction (Fig. 5). The top of the salt mass comes within 340 ft of the surface and is flat, varying in elevation from –250 ft to –265 ft (Belchic, 1960). The calcite cap rock cropped out and was first quarried in the late 1800s, when kilns were constructed for the production of lime. Later, the calcite cap rock was produced for aggregate and as a local building material; the quarry was reported to be operating at a daily capacity of 1,000 tons in 1926. The present quarry is more than 150 ft deep (Fig. 4C) and provides unique exposures of the calcite, gypsum, and anhydrite cap-rock zones for a Gulf Coast salt dome.

Beginning in 1936, the Winnfield cap rock was used as a source of calcium carbonate for use in the Solvay process to produce soda ash, caustic soda, chlorine, and many other related chemicals from calcium carbonate and salt. This operation was terminated in 1948 after most of the calcite cap rock had been exhausted. Total calcite–cap-rock production from 1936 through 1948 was reported to be 6.4 million tons (Belchic, 1960). A 838-ft mine shaft was completed in 1931 to the –620-ft elevation, more than 400 ft into the salt (Fig. 5). Salt production began in late 1932 and continued until 1965, when the mine was flooded.

Production of the underlying gypsum and anhydrite cap rock began in 1951, and 2.1 million tons of gypsum and anhydrite was produced for wallboard through 1959 (Belchic, 1960). Production of anhydrite as a road base (WinnRock) began in 1961 and probably is the only commercial use of anhydrite anywhere in the world. This unique use of anhydrite typically is not reviewed in discussions of crushed stone or gypsum and anhydrite (e.g., McCarl, 1994; Herrick, 1994; Jorgensen, 1994). Anhydrite aggregate is ideally suited for temporary and secondary roads in a region where the water table is essentially at the surface. Hydration of the aggregate margins and the matrix fines causes the material to expand and produces a tough, flexible "pavement" that far outlasts standard aggregate in the wet Louisiana climate. Anhydrite production is tied to local demand, including the lumbering and petroleum-drilling industries, and reached a maximum of about 600,000 tons per year in the late 1970s.

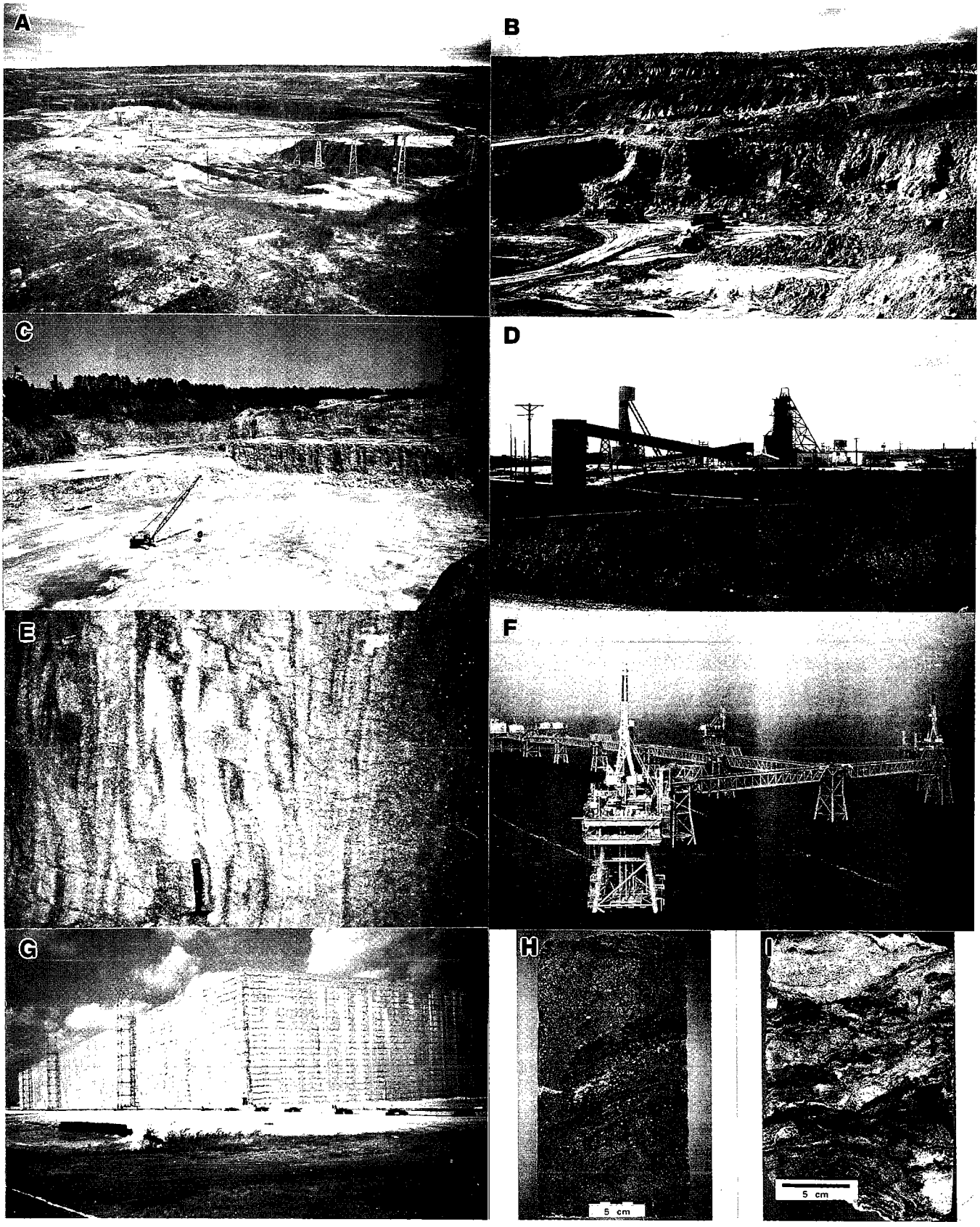

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Figure 4 (facing page). Geologic features of mineral resources associated with Gulf Coast salt domes. See Figure 1 for locations of sites illustrated. (A) East Texas Stone quarry in calcite-cemented Carrizo Sandstone at Butler dome, Texas. (B) Aggregate production from calcite cap rock at Damon Mound dome, Texas. (C) WinnRock quarry in anhydrite cap rock at Winnfield dome, Louisiana. (D) Salt mine shaft and production facilities at Weeks Island dome, Louisiana. (E) Banded and recrystallized salt at the Belle Isle dome, Louisiana. (F) Frasch sulfur-production facility at Main Pass 299, offshore Louisiana. (G) Block of elemental sulfur produced from Boling dome, Texas. (H) Massive sulfide concentrations in calcite cap rock, Hockley dome, Texas. (I) Barite concentrations in calcite cap rock, Hockley dome, Texas.

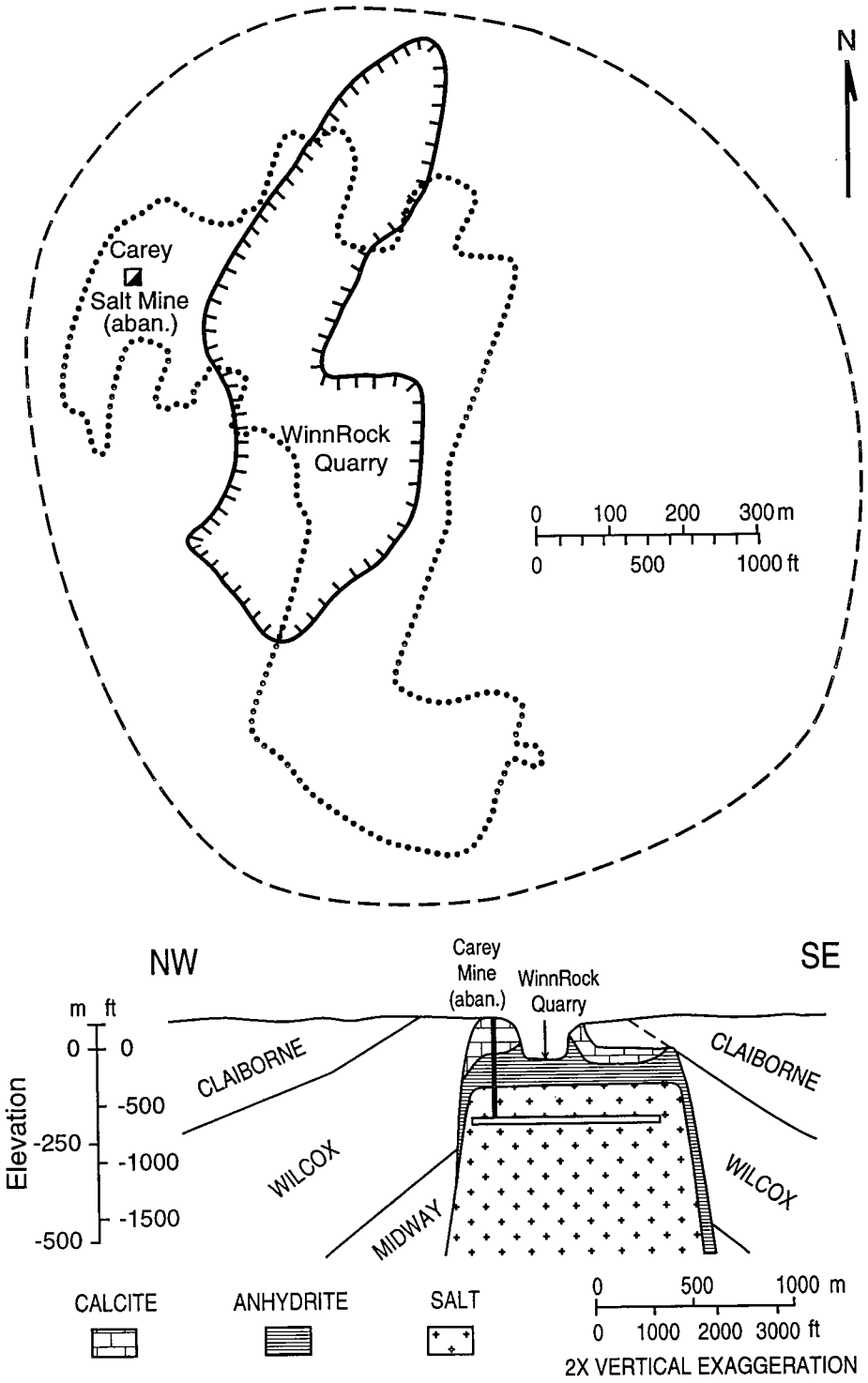


Figure 5. Geologic features and industrial-mineral production from the Winnfield dome, North Louisiana basin. Outline of salt stock is at –620-ft elevation. Minor amounts of gypsum occur at the contact of the anhydrite and calcite cap rocks and are included within the anhydrite zone on the cross section. After Kyle and Ulrich (1993).

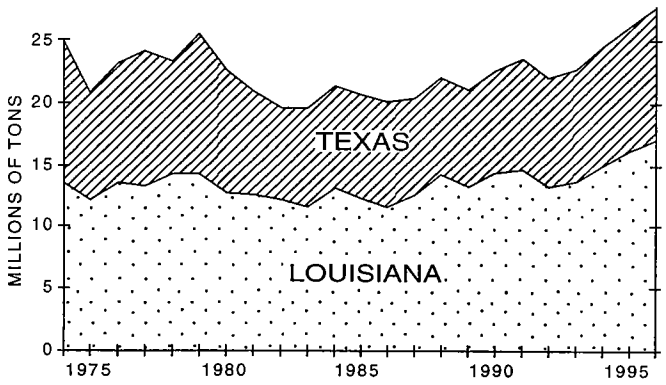


Figure 6. Louisiana and Texas salt production from 1974 to 1996. Data from U.S. Geological Survey (Anonymous, 1998a).

Industrial Minerals

Salt

Salt is a major industrial commodity that is used principally in the chemical industry (Kostick, 1994) and that clearly is a significant industrial-mineral product of the Gulf Coast salt-dome environment. Louisiana and Texas generally rank first and second among salt-producing states, with current annual production of 17.1 and 10.7 million tons, respectively (Fig. 6). Salt is produced in the Gulf Coast from conventional mines (Fig. 4D) and by solution mining. Rock salt is mined by the room-and-pillar method, and, because of the unrestricted vertical character of salt domes, rooms can be very high and approach 100 ft in some cases. Mining is typically by conventional mining methods involving a horizontal undercut of the mining face to produce a kerf (and a smooth floor for later operations), followed by drilling and blasting. The blasted salt is transported to a breaker-feeder, where it is crushed and screened to the desired sizes.

Solution mining involves the ancient technique of dissolving the salt by fresh water to produce a brine that is later desiccated to recover the halite. Recent developments involving hydraulic fracturing have greatly improved the effectiveness of solution mining of salt (Kostick, 1994). Solution mining produces the sodium-chloride feedstock for production of vacuum-pan salt and for the manufacture of synthetic soda ash, chlorine, and caustic soda.

Gulf Coast salt commonly shows subvertical banding that represents complexly deformed sedimentary layers that contain different amounts of nonhalite components (Fig. 4E). Dark layers contain the greatest concentration of impurities, whereas light-colored salt is typically relatively pure. The most abundant impurity is anhydrite, which may occur as single millimeter-scale crystals or as deformed thin beds. Anhydrite may form as much as 10% of some salt stocks, although a few percent is more common, and salt in some domes is essentially devoid of significant amounts of impurities. Salt from Gulf Coast diapirs is texturally a metamorphic rock, and thus commonly has coarse crystals, including local recrystallized zones with halite crystals several feet across.

Sulfur

The Frasch sulfur industry in the Gulf Coast has had a long and colorful history that spans more than a century (Fig. 7). However, in recent years large quantities of "non-discretionary/involuntary" sulfur have been recovered as a byproduct of the refining of metal sulfide ores, natural gas, and crude oil. Involuntary sulfur now accounts for more than 70% of all sulfur produced and threatens the future of the Frasch sulfur mining indus-

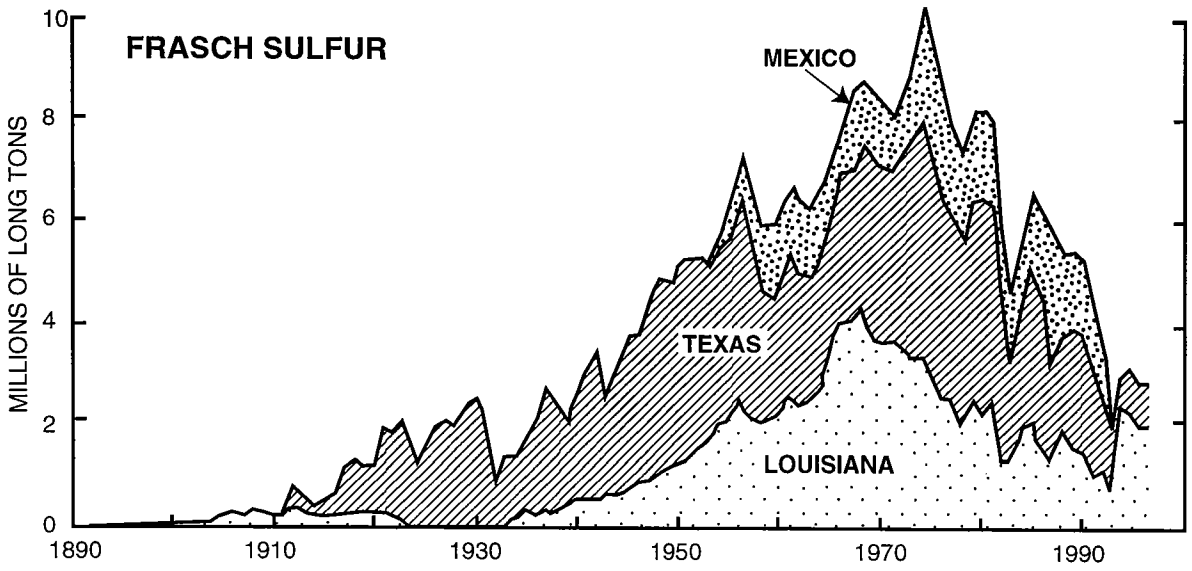


Figure 7. Frasch sulfur production from Texas, Louisiana, and Mexico from 1894 to 1997. Texas values include production from non-salt–dome sulfur deposits, that is, the bedded sulfur deposits of the Delaware basin in West Texas. Updated from Ellison (1991) with data supplied by Freeport McMoRan Sulphur, Inc.

try (Wessel, 1994). About 350 million long tons (lt) of sulfur have been produced by the Frasch process from Gulf Coast salt-dome cap rocks (Ellison, 1991). The majority of U.S. production has come from a distinct belt of domes near the Texas-Louisiana coast. The salt domes of the interior salt basins have not produced sulfur despite the common presence of cap rock that is similar to the host rock for the commercial sulfur concentrations. However, of the roughly 220 coastal domes in the U.S. Gulf Coast (Fig. 1), only about 20 have produced sulfur (Edwards, 1995). Main Pass 299 in offshore Louisiana is the only active sulfur-producing Gulf Coast dome (Danielson and others, 1995).

Attempts at mining sulfur from the Gulf Coast domes began with the Sulphur Mines dome at Sulphur, Louisiana, in the 1890s (Fig. 1). The presence of sulfur on this dome had been known for some time, but prior conventional underground mine production attempts had failed and fatalities had occurred due to hydrogen sulfide gas. In 1896, Herman Frasch began pumping superheated water into the sulfur-bearing formation through a nested-casing string to melt sulfur and then recover it through an inner-casing string. The Freeport Sulphur Company was formed in 1912 to mine the Bryan Mound and Hoskins Mound domes in Texas. Freeport developed the Grande Ecaille mine in Louisiana, a significant achievement because the dome was located in largely inaccessible marsh. Freeport became the first company to mine an offshore sulfur deposit in 1957 at Grand Isle dome in 50 ft of water about 6 mi offshore. Freeport designed an innovative power plant using sea water to mine the sulfur and a nested pipeline to bring molten sulfur to shore. Freeport developed additional offshore mines at the Caminada dome in 1973 and the Main Pass 299 dome in 1988, a deposit in 210 ft of water located approximately 15 mi offshore (Fig. 4F). The Texas Gulf Sulphur Co. (later renamed Texasgulf) was formed in 1918, and their flagship operation was the mine on the Boling dome at Newgulf, Texas, which they acquired in 1923. The Duval Sulphur Co. (later merged into Pennzoil Oil Co. as Pennzoil Sulphur) was organized in 1927 to mine sulfur at Palangana and Orchard domes in Texas. Orchard dome was the site of the deepest Frasch sulfur production in the U.S. at a depth of approximately 3,000 ft in a flank cap-rock zone. Duval also pioneered in development of Permian evaporite-hosted sulfur deposits in the Delaware basin. Pennzoil ceased to be a sulfur mining company when the Culberson mine in west Texas was purchased in 1994 by Freeport-McMoRan.

Boling dome is located about 60 mi southwest of Houston within the Houston diapir province (Fig. 1). Boling dome forms an elongate oval measuring about 15 mi^2 at the –4,000-ft elevation salt contour. The minimum depth to cap rock is 383 ft, and the cap rock is as much as 700 ft thick. Undifferentiated Miocene sands, muds, and limestone underlie the Plio-Pleistocene, and along with the underlying Oligocene Anahuac and Frio Formations have been the source of most of Boling's 35 million bbl of oil production (Halbouty, 1979). The first commercial quantities of sulfur were found in 1927,

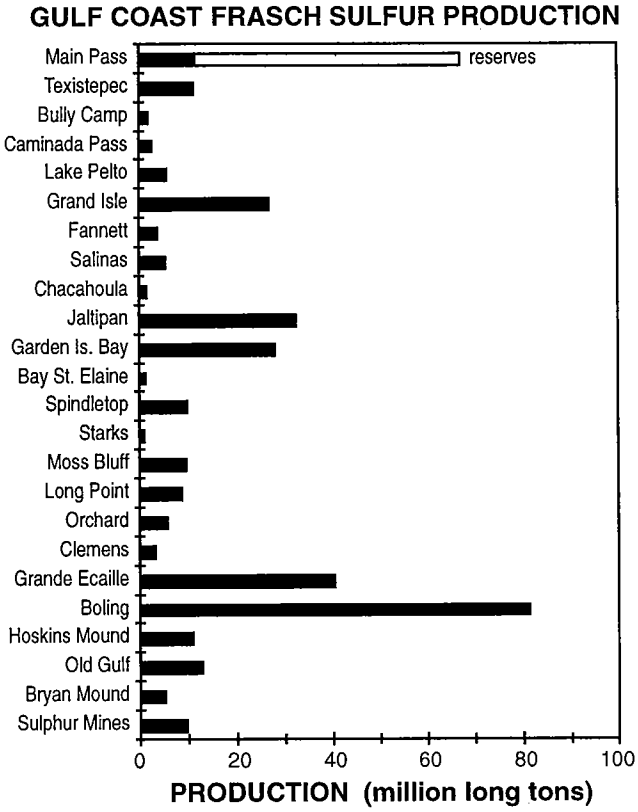


Figure 8. Major sulfur-producing salt domes in the Gulf of Mexico basin. Data from Davis and Detro (1992).

and Texas Gulf Sulphur drilled about 200 wells to define the largest single deposit of native sulfur in North America (Samuelson, 1992). Frasch sulfur production began in 1928 and continued until 1993 (Fig. 4G). Total sulfur production from Boling was about 86 million lt (Fig. 8), with average peak production of 8,376 ltpd in 1948. In 1985, Texasgulf started the first cogeneration facility operating at a sulfur mine. The natural-gas–fueled turbine generated 70 MW of electricity along with enough steam to produce more than 4 million gal of superheated water daily (Samuelson, 1992). The Boling cap rock consists of a typical zonation of an upper dense calcite zone that grades into a calcite and sulfur zone that overlies a dense anhydrite zone. The thickest calcite zone (>400 ft) coincides with the richest sulfur concentrations in the southeast part of the dome (Fig. 9).

Main Pass 299 is unique in that it is a world-class sulfur deposit contained in calcite cap rock that also contains significant petroleum reserves. Coordinating sulfur mining with oil and gas production under a single operator benefits both operations. Main Pass 299 dome is located in the federal offshore Gulf of Mexico about 90 mi southeast of New Orleans and 15 mi offshore in 210-ft water depths (Fig. 1). The dome is elongate to the northwest with dimensions of about 8,900 ft by 7,700 ft (Fig. 10). The shallowest point on the Main Pass cap rock is at 1,234 ft subsea. The Main Pass 299 salt-dome-sulfur deposit was discovered in December 1988, by a joint venture partnership composed of

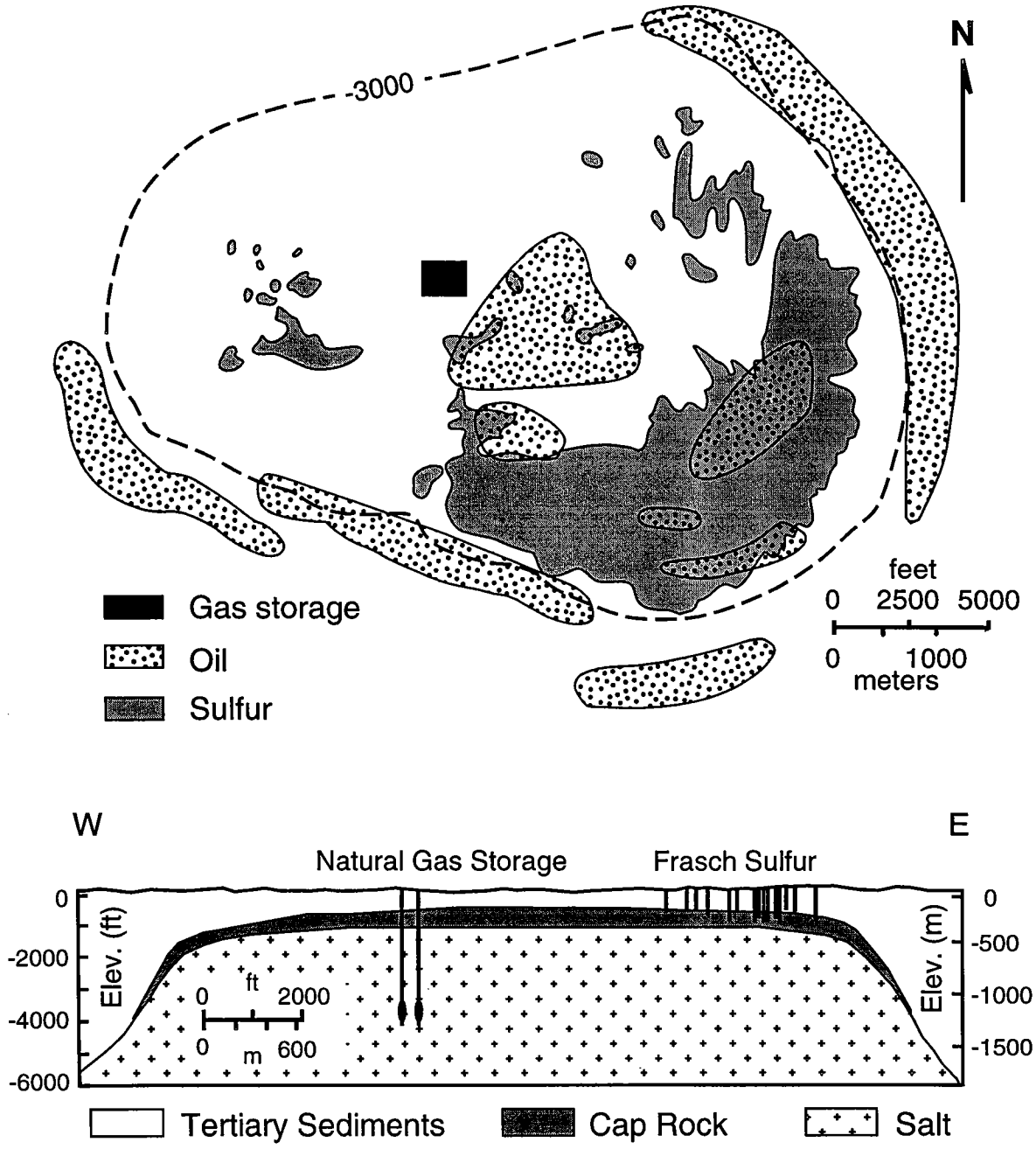


Figure 9. Geologic features and mineral production from Boling dome, Texas. After Samuelson (1992).

Freeport-McMoRan Resource Partners, IMC Fertilizer, and Homestake Mining Co. Exploration drilling delineated the second largest sulfur deposit in the United States with recoverable sulfur reserves of 67 million lt of sulfur (Fig. 8). Oil and gas reserves totaling 39.4 million bbl of oil and 9.1 billion cubic feet of gas were discovered in the limestone cap rock and overlying sandstones. An offshore Frasch sulfur-mine complex, consisting of 15 platforms and interconnecting bridges, was built (Fig. 4F). Oil production began in November 1991, at a rate of 25,000 bbl of oil per day, and averaged 18,000 bbl of oil per day through 1993 (Danielson and others, 1995). Sulfur production began in April 1992 and reached the design rate of 5,500 lt per day by December 1993. The Main Pass sulfur facility is designed to heat 10 million gal (250,000 bbl) per day of seawater to 325°F. Heat is confined to the sulfur-ore body by the overlying oil pool. A mine life of 34 years is projected for an average rate of 5,500 lt of sulfur per day, requiring almost 1,600 wells to recover the sulfur. The Main Pass cap rock is composed of three zones from bottom to top: (1) dense anhydrite; (2) calcite with native sulfur; and (3) calcite that is porous but is barren of sulfur (Danielson and others, 1995). The calcite cap rock varies from 33 ft to >475 ft in thickness and is thickest in the southwest part of the dome (Fig. 10). The calcite

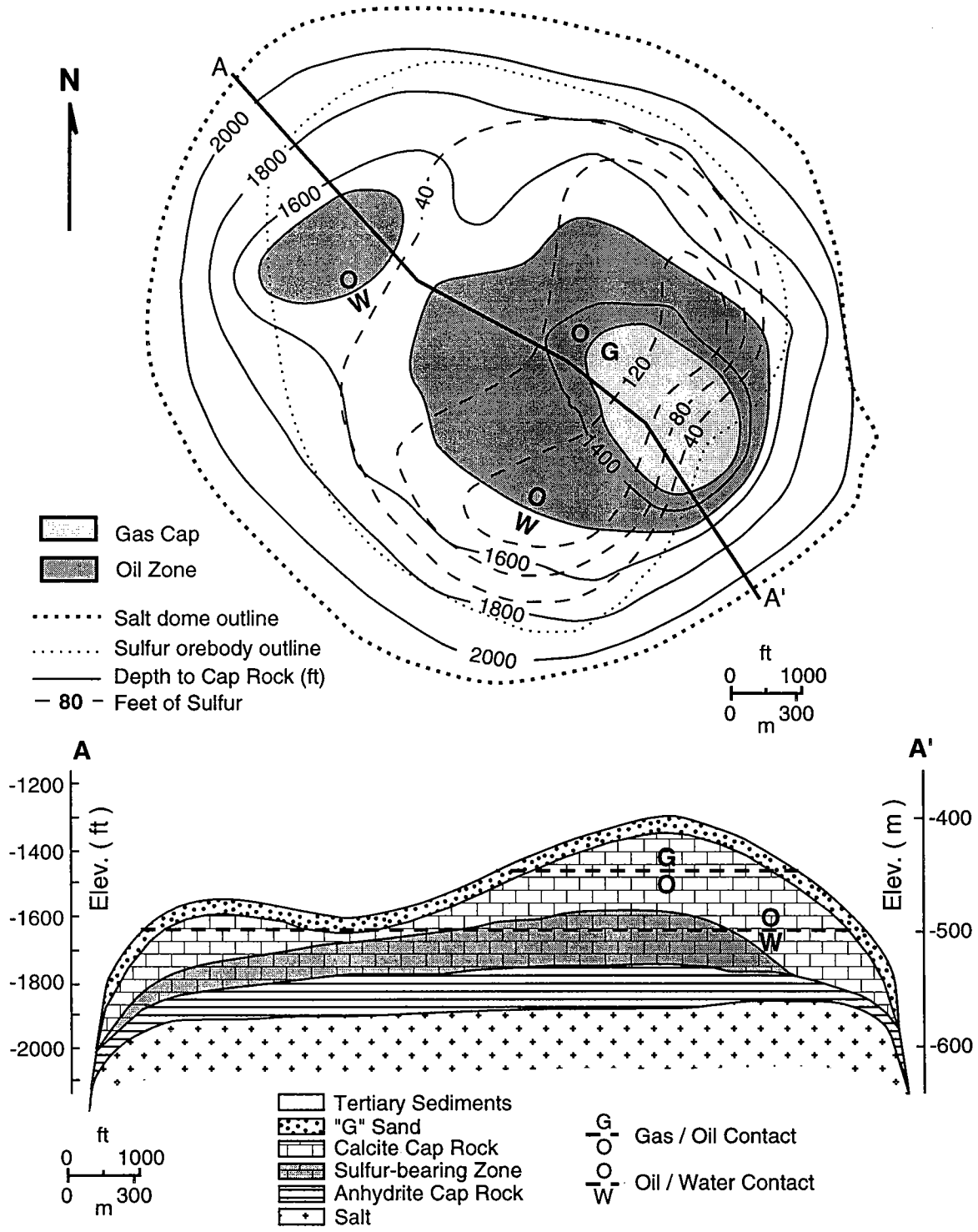


Figure 10. Geologic features and mineral production from Main Pass 299 dome, offshore Louisiana. After Edwards and others (1992) and Danielson and others (1995).

cap rock is light to dark gray, massive to banded, generally fractured to brecciated, with large and small pores commonly containing calcite and sulfur. Sulfur thickness varies from 18 ft to 247 ft, and sulfur grade averages 28%. The sulfur-bearing calcite cap-rock zone overlies anhydrite cap rock that varies from 2 ft to 135 ft thick (Danielson and others, 1995).

Material Storage and Disposal

Caverns excavated within the salt serve to store products as diverse as crude oil (including the Strategic Petroleum Reserve), liquefied petroleum gas, and natural gas. Initially, the caverns used for storage purposes were remnants from brine-production operations, but

more recent storage facilities have been designed and developed expressly for storage purposes. The caverns provide inert and sealed containers in which to store products, and potentially for disposal of oil-field and other waste materials (e.g., Millican, 1995).

The above factors, combined with a perceived tectonic stability of salt domes within the interior salt basins of east Texas, north Louisiana, and central Mississippi, led to the evaluation of selected domes in these areas for radioactive waste disposal following criteria established by the Nuclear Waste Policy Act of 1982. Many of the recent geologic studies of the salt domes in these areas are related to these evaluations (e.g., see articles in Posey and Kyle, 1988). Although none of these domes were selected as repositories for radioactive waste, Jackson and Seni (1984) concluded that there is "no characteristic generic to salt domes that precludes their use as a repository for nuclear waste."

Gulf Coast salt domes are used for product storage, principally of natural gas, crude oil, and liquefied petroleum gas. In Texas, 19 domes serve these storage purposes with more than 300 active caverns (S. Seni, personal communication, 1998). A particularly striking example is the Barbers Hill dome where nine gas companies have facilities with more than 100 caverns for liquified-petroleum-gas storage.

Another significant storage issue is the Strategic Petroleum Reserve that was created by the Energy Policy and Conservation Act of 1975. This act allows for the storage of a volume of crude oil representing a 90-day supply of imported oil (excluding Canadian imports). The Strategic Petroleum Reserve is stored in salt-dome caverns at Bryan Mound and Big Hill in Texas and West Hackberry and Bayou Choctaw in Louisiana (Anonymous, 1998b). Current capacity for crude-oil storage is 680 million bbl in 62 caverns; expansion to 1 billion bbl has been authorized should the need arise.

Potential Mineral Resources

Zn-Pb-Ag Sulfide Deposits

Many Gulf Coast salt-dome cap rocks contain Zn-Pb sulfides and other "exotic" minerals (Kyle and Price, 1986). The best documented metal-bearing domes are Hockley, Texas (Agee, 1990), Winnfield, Louisiana (Kyle and Ulrich, 1993), and Hazlehurst, Mississippi (Saunders and Swann, 1994). The Hockley dome cap rock is the only one to have been systematically evaluated for its contained metal contents. Hockley dome occurs within the Houston diapir province in south-central Texas and is emplaced into the Cenozoic siliciclastic sedimentary assemblage of the Coastal Plain (Fig. 1). The dome is elongate in a northwest-southeast direction, with dimensions of 12,000 ft by 10,000 ft at a depth of 1,000 ft (Fig. 11). Although the cap rock is within 40 ft of the surface, there is no topographic expression of the dome. The cap rock is composed of a typical sequence of calcite, gypsum, and anhydrite zones totaling as much as 900 ft. The relative thickness of each zone varies considerably throughout the dome, but the anhydrite zone generally is the thickest and is as much as 800 ft thick in the central part of the dome. Although discontinuous, the calcite portion is commonly several tens of feet in thickness and may be more than 100 ft thick. This zone is highly fractured and brecciated with vugs containing calcite, barite, and sulfur crystals; petroleum is present locally in the calcite zones. A deeper calcite zone is present in the southern part of the dome and appears to be enclosed within the anhydrite cap rock (Fig. 11); massive sulfide and barite concentrations occur within this calcite zone (Fig. 4H,I).

A total of 70 cores were drilled through the cap rock along a series of radial fences during an exploration program in the late 1970s and early 1980s (Fig. 11; Price and others, 1983; Kyle and Price, 1986; Agee, 1990). Initial exploration has defined a multimillion-ton resource of Zn-Pb-Ag ore of grades comparable to those mined elsewhere in the United States. These exploration results defined an annular zone of metal concentrations within the Hockley dome cap rock (Fig. 11). Metallic minerals occur in the calcite and anhydrite zones at depths ranging from 400 to 1,200 ft. Variable amounts of marcasite, pyrite, sphalerite, and galena range from trace components to local massive sulfide zones (Fig. 4H). Significant Zn+Pb intercepts include 18 ft of 7.1% and 40 ft of 4.2%. The maximum Ag assay of 550 ppm occurs within a 6-ft intercept averaging more than 200 ppm. Most high metal concentrations occur in massive sulfide lenses, generally in association with zones of bacteriogenic calcite. These massive sulfide lenses are vuggy, fractured, and brecciated. Salt-dome cap rocks and associated sedimentary strata provide excellent physical and chemical traps for the interaction of metalliferous formation waters with fluids containing reduced, partly oxidized, or oxidized sulfur species (see later discussion on origin).

Celestite and Barite

Many Gulf Coast salt-dome cap rocks contain "exotic" minerals (Kyle and Price, 1986), including celestite and barite, that generally are confined to the calcite cap rocks (Saunders and others, 1988; Kyle, 1994). None of the cap rocks have been evaluated for celestite or barite, but both are abundant in some domes and could represent an exploitable resource. The exploration project at Hockley dome intersected locally abundant barite with local concentrations of more than 60%. The barite content was not systematically evaluated, but several 20-ft intervals in the calcite cap rock average 30% barite (Fig. 12). High barite concentrations occur as intergrown crystal aggregates, which may be associated with sulfides (Figs. 4I, 11).

ORIGIN OF CAP-ROCK–HOSTED MINERAL RESOURCES

Geologic Evidence

The mechanism for producing elemental sulfur concentrations involving the bacterial reduction of caprock sulfate minerals has been well accepted following the experiments of Feely and Kulp (1957). Aqueous

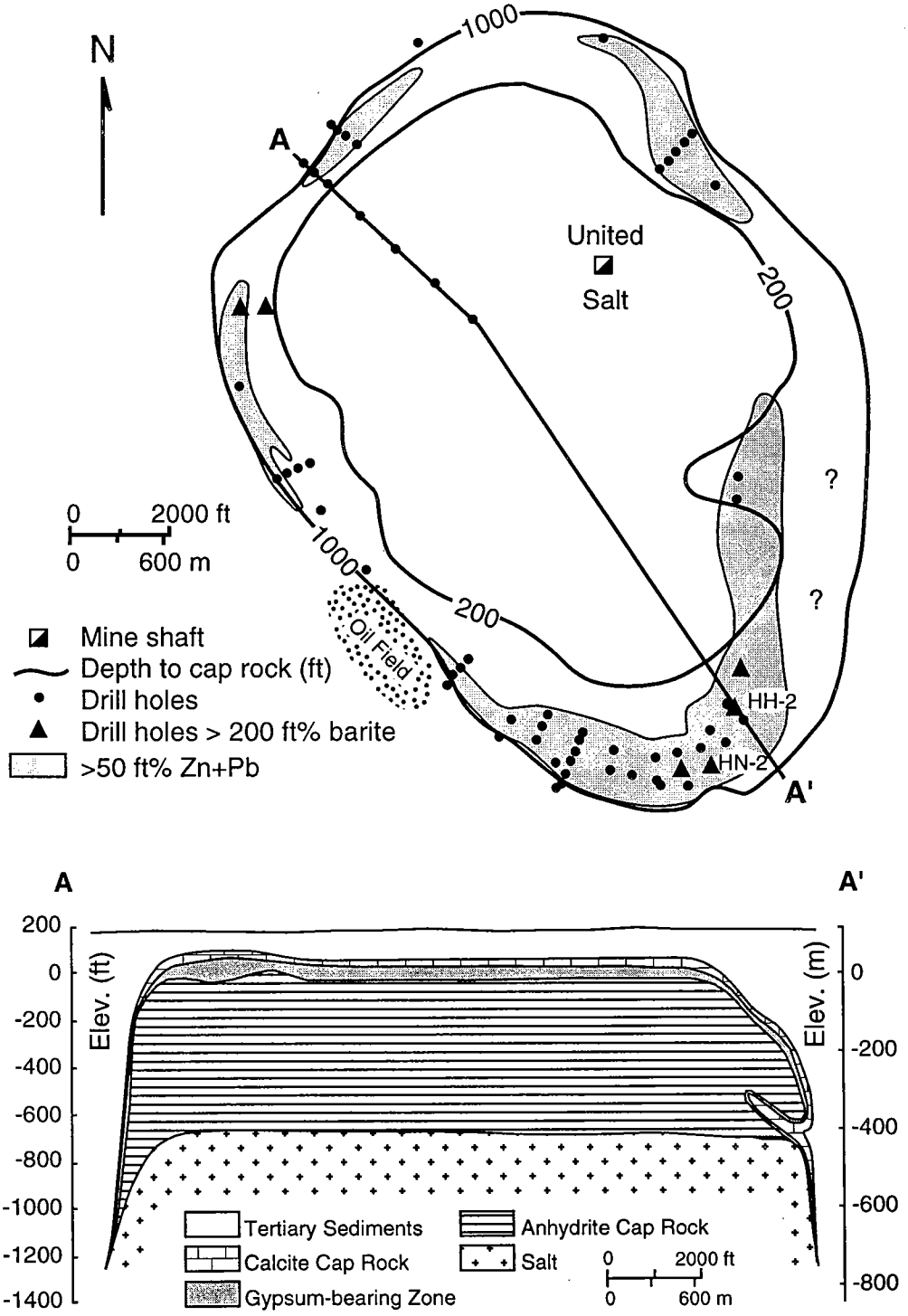


Figure 11. Geologic features and industrial mineral distribution at Hockley dome, Texas. After Agee (1990) and Kyle (1994).

sulfate derived from the anhydrite impurities in the salt stock are ingested by anaerobic sulfate-reducing bacteria that derive their energy from hydrocarbons to generate carbon dioxide and hydrogen sulfide. The bacterial mechanism, including petroleum degradation, is supported by the distinctive light-carbon-isotope composition of the calcite cap-rock host (although sulfur-barren calcite cap rocks are far more numerous than sulfur-productive ones). The mechanism of hydrogen-sulfide oxidation is less clear, but likely is caused by oxygen dissolved in ground water, a model supported by the shallow occurrence of cap rocks with major concentrations of sulfur and their localization near sites of major fluvial systems. Whatever mechanism is accepted, it is clear that a prolonged episode or repeated events of hydrogen sulfide generation and oxidation is

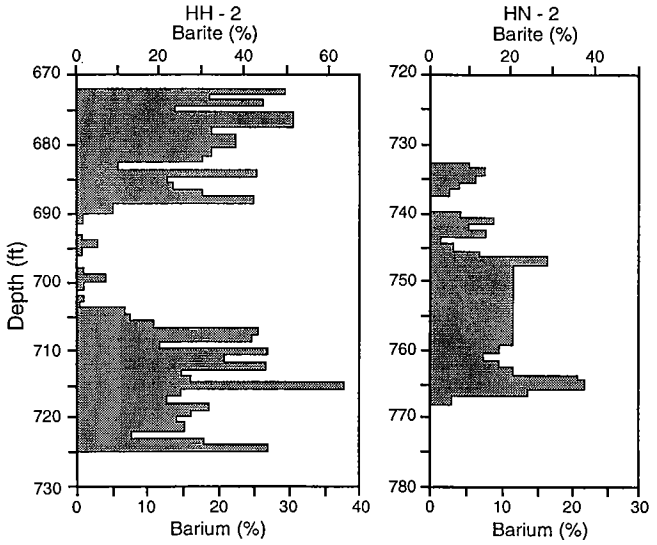


Figure 12. Barite distribution in the lower calcite cap-rock zone in the HH-2 and HN-2 drill cores at Hockley dome, Texas. See Figure 11 for drill-hole locations. From Kyle (1994).

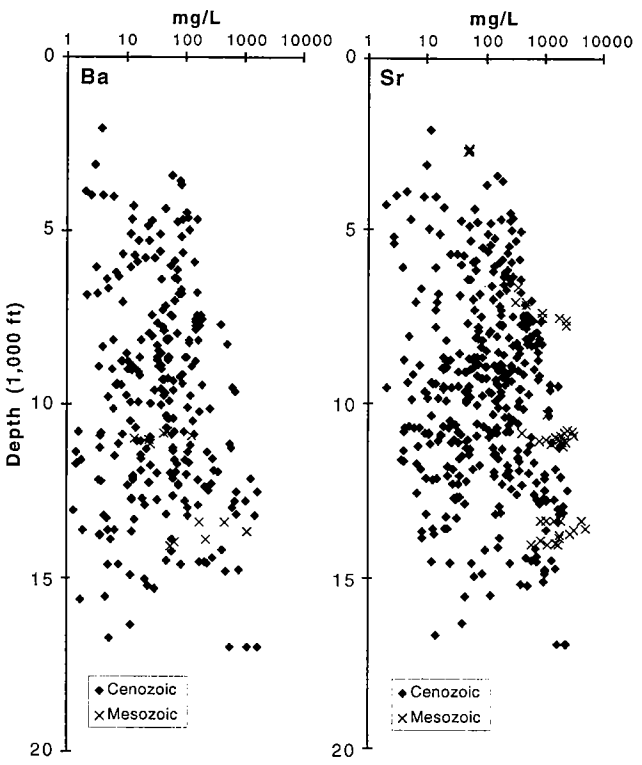


Figure 13. Barium and strontium concentrations in Gulf Coast formation waters. Data base of L. S. Land, University of Texas at Austin.

required to generate the enormous amounts of elemental sulfur present in some cap rocks (Fig. 8).

However, a paradox is apparent in attempts to extend this model to account for the sulfide and related minerals also present in some calcite cap rocks, including sulfur-bearing ones—e.g., the Boling dome (Samuelson, 1992). Even though some of the sulfide minerals are intimately intergrown with "bacteriogenic" calcite (e.g., Posey and others, 1994), the circa 100°C conditions believed to be appropriate for sulfide deposition is too hot for sulfate-reducing bacteria to function. Sulfate-reducing bacteria generally are believed to require conditions of less than 70°C (Feely and Kulp, 1957). Thus, how can the bacterial mechanism be justified as the source of the reduced sulfur in cap-rock–hosted sulfide concentrations?

Based principally on evidence from the Hockley dome, Kyle and Agee (1988) proposed that cap-rock mineralization was the result of the episodic mixing of a deep-sourced metal-rich brine containing minor H_2S produced by thermochemical sulfate reduction with the resident cool, dilute H_2S-rich solutions produced by bacterial sulfate reduction in the shallow cap-rock environment. Variable mixing of these two different H_2S sources accounted for the range of sulfur isotope values of the sulfide minerals. Additional support of this model is provided by paleomagnetic studies of timing of cap-rock formation (Kyle and others, 1987; Gose and Kyle, 1993), fluid inclusion studies (Saunders and Swann, 1994; Saunders and Thomas, 1996), reaction path geochemical modeling (Kyle and Saunders, 1996), and studies of active Gulf floor discharge sites (Roberts and Aharon, 1994; Fu and others, 1994).

Formation Waters

The close spatial association between Gulf Coast mineral concentrations and saline formation waters containing elevated amounts of metals indicate that the brines are likely mineralizing solutions in this setting (Kyle and Price, 1986; Saunders and others, 1988; Agee, 1990; Saunders and Swann, 1994). Formation waters of the Gulf Coast sedimentary basins have been the subject of numerous investigations, and Kyle (1994) summarized the available data (Carpenter and others, 1974; Carpenter and Trout, 1978; Land and Prezbindowski, 1981; Carpenter, unpublished data; Land, unpublished data) to illustrate the major- and minor-element relationships of oil-field brines. Existing data on Gulf Coast formation waters suggest general trends of increased metal contents with depth, temperature, and chlorinity of the reservoir fluids, but the correlation is weak. Zinc and lead show strong positive linear correlations in Gulf Coast formation waters, particularly in siliciclastic reservoirs, where the correlation coefficient is 0.92 (Kyle, 1994).

Barium contents of Gulf Coast formation waters show a considerable range and have a mean value of 96 mg/L for 101 available analyses (Kyle, 1994); barium concentrations of several hundred to a few thousand mg/L are not uncommon (Fig. 13). The sources of dissolved barium in formation waters have not been defined positively, but alteration of detrital potassium silicate minerals, largely feldspars and micas, during

diagenesis would be effective in releasing barium and other components from interior lattice sites (Hanor, 1979, 1987; Macpherson, 1989).

Barium contents of the formation waters of the Gulf Coast and elsewhere appear to be essentially unrelated to the major cation (Na, Ca, K, Mg) components of the brines, although good correlations of barium with strontium and barium with calcium are indicated for siliciclastic reservoirs. Hanor (1979) indicated that barium contents as high as 100 mg/L have been measured in dilute formation waters with salinities no greater than seawater (3.5%). Predictably, a strong negative correlation is indicated for barium and sulfate content of the formation waters, particularly for siliciclastic reservoirs; that is, elevated barium and sulfate contents of the same brine would promote precipitation of barite, thereby reducing the contents of each in the formation water.

Mixing of barium-containing formation waters with sulfate-rich water, typically during waterflood operations for secondary recovery of oil, results in the formation of considerable barite-rich well scale (Carpenter and others, 1974; Hanor, 1979). Barite scale formation in some deep wells may be due simply to adiabatic cooling during pumping of some brines from depth, indicating that some formation waters carry enough barium and sulfate in solution to precipitate significant quantities of barite on cooling (Hanor, 1979). Metalliferous formation waters also caused development of concentrations of barite and metallic sulfides in salt-dome cap rocks in the Gulf Coast (Kyle and Price, 1986; Posey and others, 1987a; Kyle, 1994).

Strontium contents of Gulf Coast formation waters show a considerable range, and concentrations of several hundred to a few thousand mg/L are common (Fig. 13). The sources of dissolved strontium in formation waters is not easily defined, but perhaps are somewhat different than barium. For example, the strontium content of biogenic calcium carbonate is typically very high, whereas the strontium content of ancient limestones is typically low (e.g., Bathurst, 1975), suggesting the release of considerable strontium to pore waters during diagenesis.

The presence of secondary strontium minerals in Gulf Coast sediments is seldom reported, but may be influenced by the difficulty of recognition. High celestite and strontianite contents of Gulf Coast cap rocks have been reported (Kyle and Price, 1986; Saunders and others, 1988; Werner and others, 1988).

Geochemical Modeling

The chemical composition and temperature of modern formation waters in the Gulf of Mexico basin are well established (e.g., Carpenter and others, 1974; Kharaka and others, 1987), thus allowing geochemical modeling of precipitation mechanisms that produced cap-rock mineralization (Saunders and Thomas, 1996; Kyle and Saunders, 1996). A representative metal-rich brine (Kharaka and others, 1987) was used by Kyle and Saunders (1996) to model cap-rock–mineral precipitation. The starting brine contains ~300,000 mg/L TDS; >300 mg/L Zn+Pb; 1,920 mg/L Sr; and 60 mg/L Ba at a reservoir temperature of 102°C.

The SOLVEQ/CHILLER™ programs (Reed, 1982) were used to model the effects of cooling the starting brine to 60°C to examine the effects of moving a deep-basin brine into the shallow cap-rock setting where bacterially derived H_2S and aqueous sulfate would be present (Kyle and Saunders, 1996). Ubiquitous cap-rock calcite suggests that ore precipitation was a consequence of bacterial reduction of sulfate sourced from cap-rock anhydrite. CHILLER was used to model the results of adding the products of coupled anhydrite dissolution and sulfate reduction (Ca^{2+}, HS^-, and HCO_3^-) to the brine. As previously demonstrated by Kharaka and others (1987), adding reduced sulfide to metal-rich brines caused most sulfide minerals to precipitate at the onset of mixing. The effectiveness of such a mixing process can explain why the main mineralized zones in the cap rocks have Zn/Pb ratios similar to present-day metal-rich formational brines (Agee, 1990; Saunders and Swann, 1994). Furthermore, modeling indicates that a mechanism of mixing H_2S with a fluid close to saturation with respect to Fe, Zn, and Pb sulfides would cause sulfide deposition, but without calcite deposition, thus perhaps accounting for sulfide mineralization in anhydrite cap rocks (Kyle and Saunders, 1996). Modeling also shows that simple cooling by 25°C to 50°C of a brine saturated with respect to the metal sulfides under reservoir conditions would lead to the precipitation of sulfides. Thus, cooling also may have played a role in sulfide precipitation for the cap-rock–hosted sulfides and barite. This effect is consistent with the formation of barite well scale in Gulf Coast wells that produce brines (Saunders and Rowan, 1990) and the widespread presence of barite in calcite cap rocks in the Gulf Coast (Kyle, 1994).

CONCLUSIONS

The salt-dome environment in the Gulf of Mexico basin has been a major producer of diverse energy and mineral resources for the past century. These resources are products of fundamental geologic processes that are integral aspects of the evolution of this sedimentary basin. Whereas some industrial mineral resources such as elemental sulfur have declined markedly in recent years in response to declining reserves and increased competition from other sources, ample reserves of salt will allow production to continue into the foreseeable future. Further, potential exists for other metal and industrial mineral production from cap rocks under favorable economic circumstances. Expanded use of caverns excavated into the salt masses for material storage and disposal is likely to continue into the next century.

ACKNOWLEDGMENTS

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Development of a Multimedia Tutorial for Gulf Coast Salt-Dome Geology and Mineral Resources

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A multimedia tutorial illustrating the geology and mineral resources of Gulf Coast salt domes has been developed as a pilot project for a course on Texas geology and resources at the University of Texas at Austin. The principal objective of the tutorial is to educate students with limited background in geological sciences about a major local geologic feature and its geologic and economic significance. The content of the tutorial represents materials generally covered in 4 hours of lecture and laboratory instruction. These materials are presented using a flattened hierarchy of topics, each accessible from a central menu, including salt-dome history, salt tectonics, anhydrite and calcite cap rocks, mineral resources, and geophysical character. Information concerning salt-dome geology is communicated using interactive software; sound and animation are used throughout to reinforce key concepts. Visual aspects include field views, hand specimens, and photomicrographs that were digitized from slides. Illustrations were created using a graphics program or scanned from available archives. Each visual element has an accompanying explanation, which in many cases is linked to other parts of the tutorial. Navigation is accomplished using hyper-links or a set of unobtrusive buttons. The program includes a glossary of the major minerals associated with salt domes available as a pull-down menu and digitized video footage of the Gulf of Mexico sea floor to illustrate the active environment of the formation of the salt-dome cap rock. In addition, a group of interactive questions is presented to assess the level of mastery.

Technical aspects were accomplished using a Power Macintosh™ 7100AV and a variety of commercial software. Actual linking of information was done with Authorware™ 3.0 Educational, an icon-based, multimedia authoring program. Graphic illustration was done with Adobe Illustrator™; image processing was accomplished using Adobe Photoshop™; video was captured, edited, and compressed using Adobe Premiere™. The interactive nature of the project was designed with regard to future means of dissemination, especially on the World Wide Web. This tutorial serves as a template to build additional modules covering the entire course. A modular approach to the coding of the project and extensive self-documentation should ensure the viability of the project by allowing other workers with moderate computer skills to complete other lessons within the curriculum framework.

Leslie, Stephen; and Kyle, J. R., 1999, Development of a multimedia tutorial for Gulf Coast salt-dome geology and mineral resources, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 179.

Variations in New Mexico Concrete through Time

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ABSTRACT.—Concrete is a mixture of a fine aggregate (sand), a coarse aggregate (gravel), cement, and water. Cement itself is the most expensive of the ingredients but generally amounts to only about 10% of the concrete mixture. Cement raw materials include calcium, alumina, iron oxide, silica, and gypsum. They are heated and chemically changed into clinker "minerals," which are then ground and shipped as cement. Each of the four main clinker minerals—tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite—impart specific strength and compositional properties to the final concrete product. During hydration of the cement, chemical changes produce new minerals that include calcium silicate hydrate gel (C-S-H, the main constituent of hydrated cement paste), calcium hydroxide, and calcium, sodium, potassium, and sulfate ions, among others.

Two main reactions can occur that may be deleterious to concrete. Normal cement pore solutions, in a hydrated cement, contain sodium hydroxide and potassium hydroxide. If these alkali concentrations are too high, they can react with the siliceous aggregate (alkali-silica reaction, or ASR) to form an alkali-rich calcium silicate hydrate gel (C–N+K-S–H), which, upon prolonged contact with water, can expand to crack the concrete. The other deleterious reaction occurs when the mineral ettringite ($Ca_6Al_2(SO_4)_3OH_{12} \cdot 26H_2O$) forms after the concrete is hardened (delayed ettringite formation) and cracks the concrete.

Many of the concrete bridges and structures built in New Mexico in the past 20 years are in need of replacement due to deterioration. Many others constructed very early on in the century are still sound. By collecting and analyzing samples of both old and new concrete and good and bad concrete, we compared their differences on both a microscopic and macroscopic scale.

Samples taken from concrete sidewalks, parking lots, drainage canals, spillways, and a railroad-trestle foundation have construction dates that range from 1923 to 1997. They were analyzed by electron microprobe and by petrographic microscopy. Cracks, air voids, and aggregate alteration were primary locations for investigation and analysis.

Using the electron microprobe, ettringite was found in voids of most of the samples, both in good and bad concrete. This leads us to believe that ettringite formation is not causing distress in the concrete. There was one exception in which ettringite was found lining a crack. In this instance, ettringite may have the ability to further the cracking and cause distress. No alkali-silica gel was identified with the microprobe. Using the petrographic microscope in cross-polarized light, a light-brown material was observed that lined some of the air voids and cracks; however, exact mineralogic identifications were not made. Although many instances of chalcedony and other deleterious quartz phases were found, no clear evidence of ASR-gel deterioration was present in our samples using these methods. However, positive identification of the ASR gel was made on an in-place concrete near one of our sample sites and in several sample cores using a newly developed chemical test for the soluble potassium ions associated with the gel. The chemical used in this test is sodium cobaltinitrite, $Na_3Co(NO_2)_6$.

Coose, K. E.; and Austin, G. S., 1999, Variations in New Mexico concrete through time, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 181–187.

INTRODUCTION

Many of the concrete structures built in New Mexico in the past 20 years must be replaced due to deterioration. A good deal of research by the New Mexico State Highway and Transportation Department and other engineers has been conducted to find a way to slow or stop concrete decay. Our approach is to sample existing concrete to determine exactly why certain concretes deteriorate in the first place.

Some concrete structures built early in the century are still very sound, and yet others built only a few years ago are badly deteriorated. Much controversy exists about different deleterious reactions being the cause of the deterioration. Today, concrete is made with numerous additives, from water reducers to pozzolans, that did not exist many years ago. The purpose of this research is to find some answers about the differences between old and new concrete and good and bad concrete on a microscopic as well as macroscopic scale.

BACKGROUND

Cement is made from five basic ingredients. These include calcium and iron oxide, alumina, silica, and gypsum. They come from a variety of raw materials. The most common sources of calcium are limestone, chalk, marl, and marine shells. Alumina and silica generally are supplied by clay, shale, slate, or blast-furnace slag (Bouge, 1947). Iron oxide comes from magnetite, hematite, or bottom ash—a by-product from coal-fired power plants. Other materials containing impurities are allowed, but they must be kept to strict minimum percentages to maintain the correct properties of the cement.

The proportioned raw materials are combined and heated to approximately 2,700°F in a large (~500-ft long) rotating, inclined kiln. This length and temperature allows time for the chemical changes to occur that produce the clinker "minerals." The material is cooled at a specified rate to ensure the stability of the clinker "minerals" and to stop the formation of glass, which forms from cooling too quickly. Gypsum is added, and all the material is ground to a fine powder in a ball mill. This material then is bagged and shipped.

The clinker "minerals" include tricalcium silicate, or C_3S, also called alite ($3CaO \cdot SiO_2$); dicalcium silicate, or C_2S, also called belite ($2CaO \cdot SiO_2$); tricalcium aluminate, or C_3A, ($3CaO \cdot Al_2O_3$); and tetracalcium aluminoferrite, or C_4AF, also called celite ($4CaO \cdot Fe_2O_3 \cdot Al_2O_3$) (Soroka, 1979). Each has its own properties and contributes differently to the strength and composition of the final concrete (cement + aggregate + water) product. The C_3S is perhaps the most important, as it is most abundant in the common types of cement. It sets up in about six hours, and attains maximum strength in a few days (Bouge, 1947; Soroka, 1979). The C_2S will hydrate only about 50% in 28 days and will continue to build strength over many years. Some research indicates that the C_2S continues to hydrate and harden for up to 50 years after initial mixing (Soroka, 1979). The C_3A will instantaneously hydrate. Gypsum is added to cement clinker to form the mineral ettringite ($Ca_6Al_2(SO_4)_3OH_{12} \cdot 26H_2O$) during hydration, which will coat the C_3A grains initially, then break up allowing the hydration to occur over time. This reaction is important to delay the instant set to allow time to lay and work with the concrete. The C_4AF sets up within minutes but imparts no significant strength to the concrete. Its main properties are to give the cement a gray color and to lower the clinkering temperature by acting as a flux (Soroka, 1979).

During the exothermic reaction of a hydrating cement, the clinker minerals change chemically as they react with the aggregate and the water added. One of the major compounds formed is calcium hydroxide ($Ca(OH)_2$), from the reaction of water and the C_3S and C_2S. A calcium silicate hydrate gel is formed (typically called C–S–H), as are hydroxyl ions (OH^{-1}), also from the reaction of clinker minerals and water. Other ions in the solution of cement paste from the clinker minerals and gypsum include calcium ions, alkalis (mainly potassium and sodium, K^{+1} and Na^{+1}), and sulfate (SO_4^{-2}) ions (Stark and others, 1993). As time goes on, the chemistry of both the pore solution and the minerals formed continues to evolve by using up the ions in solution.

A normal cement-pore solution contains a high amount of both sodium hydroxide (NaOH) and potassium hydroxide (KOH) after a day of hydration (Stark and others, 1993). Normally, the C–S–H gel that forms absorbs a small amount of the alkalis from the solution. However, if the cement hydrate solution has too great an amount of sodium and potassium, a very alkaline solution with high amounts of hydroxyl ions is created, which can chemically break down the siliceous aggregate occasionally used in concrete. According to Stark and others (1993), the result is an alkali-silica reaction (ASR), which forms an alkali-rich silicate hydrate gel (C–N+K-S–H). This gel will then swell in the presence of water and can cause the concrete to crack and deteriorate. A gel with a CaO content <53% and a SiO_2 content >40% will swell. The concentrations of the ions in solution and their reactions are altered by external and internal sources of ions. Additives such as silica fume, fly ash, water reducers, pozzolans, etc., and outside chemicals such as deicer salts and sulfates can cause changes in concentrations of ions or changes in pH that affect ASR. The additives, such as fly ash and pozzolans, have been reported to decrease the severity of ASR by allowing high calcium gels to form that will not swell. The pozzolans act as sacrificial silica by reacting and consuming the alkalis in solution, allowing for the reaction product to become richer in calcium. Certain outside chemicals such as sea salts tend to increase ASR (Stark and others, 1993).

Another deterioration problem may be due to delayed ettringite formation (DEF). Some ettringite formation during initial hydration is needed in order to delay the instantaneous hydration of the C_3A; however, ettringite that forms later in a hardened concrete may cause damage. The elongated ettringite crystals that form in DEF can be located by using the scanning electron microprobe (SEM) to look in the cracks, pores, and air voids where they commonly occur.

Table 1.—Sample Descriptions, Results of Soil pH Testing, SEM Comments, and Petrographic Microscopy Summary

Sample	Location	Structure	Age	Distress	Soil pH	Comments from SEM	Petrography
KC09001	Socorro, G. Austin's house	sidewalk	1960s	no	8.03	NA	high basalt, qtz
KC09002	Socorro, G. Austin's house	sidewalk	1960s	no	8.03	no ettringite found	NA
KC09003	Socorro, McCutcheon Ave.	sidewalk	WPA 1936	no	NA	no ettringite found	high rhyolite
KC09004	Socorro, NMT, library	sidewalk	1988	map cracking	7.77	ettringite in crack & voids	high paste, qtz
KC09005	Socorro, NMT, Brown Hall	sidewalk	1988	popouts	8.12	NA	high qtz
KC09006	Socorro, NMT, Brown Hall	sidewalk	1988	popouts	8.12	NA	high qtz
KC09007	Socorro, NMT, Brown Hall	sidewalk	1988	popouts	8.12	ettringite in voids & paste	NA
KC09008	Socorro, NMT, Golf/P=Plant	parking lot	1993	no	7.96	ettringite in voids	high qtz, voids
KC09009	Socorro, NMT, Workman	sidewalk	1997	no	7.76	no etringite found	high rhyolite
KC09010	Socorro, NMT, Weir Hall	sidewalk	WPA 1939	map cracking	NA	etringite in voids	high chalcedony
KC09011	Socorro, NMT, Gym, north	driveway	1988	popouts	7.53	etringite in voids	high chalcedony
KC10012	Gallup, train trestle	drainage	1923	no	NA	ettringite in voids - fibrous	NA
KC10013	Gallup, train trestle	drainage	1923	no	NA	NA	NA
KC10014	Gallup, train trestle	drainage	1923	no	NA	NA	high paste, voids
KC10015	Gallup, drainage channel	wall	1977–78	no	NA	no etringite found	high limestone
KC10016	Gallup, spillway into arroyo	drainage	1965–68	no	NA	etringite in voids	high voids, ls
KC10017	Gallup, spillway into arroyo	drainage	1965–68	no	NA	NA	NA
KC10018	Albuquerque, Gibson Blvd.	street	1979	no	NA	flyash, no ettringite found	NA
KC10019	Albuquerque, Gibson Blvd.	street	1979	no	NA	NA	NA
KC10020	Albuquerque, Gibson Blvd.	street	1979	no	NA	ettringite in voids	NA
KC10021	Albuquerque, Gibson Blvd.	street	1979	no	NA	NA	NA
KC10022	Albuquerque, Gibson Blvd.	street	1979	no	NA	NA	NA
KC10023	Albuquerque, Gibson Blvd.	street	1979	no	NA	NA	NA
KC10024	Albuquerque, Gibson Blvd.	street	1979	no	NA	NA	NA
KC10025	Albuquerque, Gibson Blvd.	street	1979	no	NA	NA	NA
KC10026	Albuquerque, Gibson Blvd.	street	1963	map cracking	NA	ettringite in voids	NA

Note: NMT = New Mexico Institute of Mining and Technology; NA = data not available; qtz = quartz; ls = limestone.

METHODS

The concrete samples were taken from a number of sources in New Mexico and range in date from 1923 to 1997 (Table 1). Samples 1 to 11 were taken from the New Mexico Institute of Mining and Technology (NMIMT) campus in Socorro and include sidewalks, driveways, and parking lots. Samples 12 to 17 were taken from the Gallup area, and include a railroad trestle support, a drainage ditch and a spillway. Samples 18 to 26 were taken from a section of Gibson Boulevard, in Albuquerque. With samples near soil or lawn, a soil sample was taken to determine the pH of the area. We could not find records of the alkali concentration of the cement used or the source of the aggregates for the concretes; therefore, we assumed a low alkali percent (<0.6%) for the cements and relied upon the petrographic analysis to determine aggregate mineralogy.

All concrete samples were drilled cores of 1-in. diameter, approximately 2–4 in. long. The drill used was a hand-held electric drill, converted to receive power from a 12-volt battery, with a water connection for cooling the bit. The cores were cut using a small water saw into circular sections for petrographic thin sections and electron microprobe slabs. The thin section samples were sent to Spectrum Petrographics, Inc., in Winston, Oregon, to be made into 30-μm thin sections. The SEM slabs were attached to 1-in. round glass slides with epoxy; the surface was polished with a 60-grit diamond wheel down to 2-μm diamond grit, and they were carbon-coated for the microprobe. A second set of microprobe slabs were left with a sawn surface from the water saw and coated with carbon.

The electron microprobe polished samples were analyzed using backscatter electrons (BSE). Some elemental maps were constructed of areas believed to be ettringite, or other crystalline phases. The sawn samples were analyzed by secondary electrons (SE). Some of these points were analyzed to determine chemical composition using wave dispersive spectrometer (WDS) analysis.

Petrographic analysis of thin sections of some of the core samples was done according to the specifications of ASTM C856-83 (Standard Practice for Petrographic Examination of Hardened Concrete), with the exception of the initial core-sample size. The results are shown in Table 2.

The procedure for identifying ASR gel using a set of chemical stains was developed by George Guthrie and William Carey from Los Alamos National Labs, New Mexico. The chemicals stain soluble potassium and calcium ions that are associated with the ASR gel. We used the chemical test for soluble potassium, a saturated solution of sodium cobaltinitrite ($Na_3Co(NO_2)_6$), to see if our samples contained the gel. In this test, the sample is rinsed with distilled water, the solution is applied, the sample is rinsed again with distilled water, and then it is allowed to dry (Guthrie and Carey, 1997).

Table 2.—Results of the Petrographic Analysis (ASTM C856-83) of Hardened Concretes

Sample	KC 09001	KC 09003	KC 09004	KC 09005	KC 09006	KC 09008	KC 09009	KC 09010	KC 09011	KC 10014	KC 10015	KC 10016
Rhyolite & trachyte	1.80	66.60	0.00	6.90	5.40	7.40	41.60	7.60	7.70	1.10	1.10	1.30
Andesite	0.00	0.00	tr	0.00	0.00	0.00	0.00	5.00	15.60	0.00	0.00	tr
Dacite & basalt	42.90	tr	tr	tr	tr	0.00	2.00	5.00	1.30	1.40	tr	4.60
Chert & chalcedony	0.0	0.00	tr	tr	8.50	6.00	4.20	31.80	16.80	2.00	tr	4.10
Quartz	21.00	9.10	22.60	26.70	34.60	54.00	19.00	9.20	14.20	14.10	8.00	12.50
Feldspar	5.50	4.20	11.90	7.50	8.10	4.10	6.10	7.30	7.60	11.00	5.00	7.90
Ferro-magnesian	tr	1.90	9.60	1.30	1.70	2.10	tr	tr	tr	1.70	tr	0.60
Opaque (Fe-rich)	1.06	tr	tr	2.10	1.10	1.10	2.80	tr	1.30	0.00	tr	0.00
Limestone	tr	tr	3.20	23.40	2.60	tr	tr	1.10	1.30	2.80	53.80	27.00
Voids	tr	2.80	tr	1.80	2.00	5.00	1.20	3.00	1.90	5.90	3.80	9.00
Cement paste	25.30	14.20	50.90	29.80	35.10	19.60	21.30	29.40	31.60	59.90	25.60	32.40
Total	97.56	98.80	98.20	99.50	99.10	99.30	98.20	99.40	99.30	99.90	97.30	99.40

Note: tr = trace, less than 1%.



Figure 1. SEM micrograph of ettringite crystals growing in an air void in concrete.

RESULTS

The condition of each area from which a sample was taken was noted, including water and drainage conditions, and any evidence of cracking or popout damage. The pH of soil samples ranged from 7.76 to 8.12. No observed correlation exists between the alkalinity of the surrounding soil and the condition of the concrete. The summary of the concrete conditions and the soil sample results are given in Table 1.

The scanning electron microprobe in SE mode enabled us to see ettringite crystals growing in empty air void spaces. Ettringite in voids occurred in samples of concrete that were both distressed with map cracking and popouts as well as those that showed no signs of distress. The age of the concrete also seemed to have no

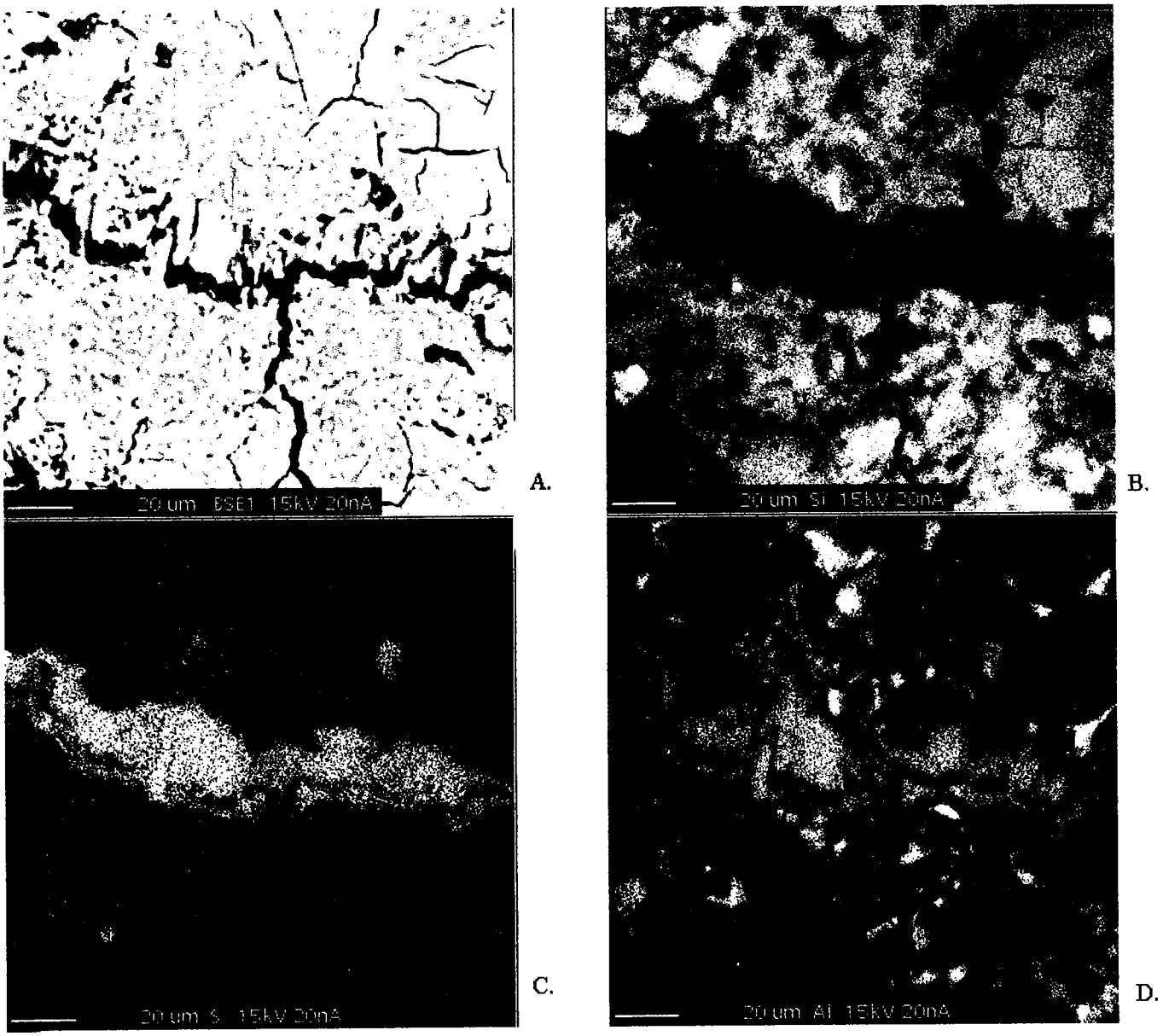


Figure 2. SEM micrograph of ettringite lining a crack in a highly distressed concrete. (A) Backscatter electron image where lighter colors indicate an atomically heavier element. (B) Element map of silica. (C) Element map of sulfur. (D) Element map of aluminum. In (B), (C), and (D), a lighter color indicates a greater amount of the element is present.

correlation with the occurrence or absence of the ettringite. The crystals were confirmed to be ettringite by the chemistry detected by the wave dispersive spectrometers (WDS). Using the BSE mode, an element map was made of a crack containing ettringite crystals that lined the space. The ettringite in the open-air voids tended to look nonstressing to the concrete (Fig. 1), but the ettringite in the crack could be causing stresses that are enlarging the crack and distressing the concrete (Fig. 2). No ASR gel was identified by us in our samples using the electron microprobe.

The concrete samples made into thin sections were used to determine the amounts and types of aggregate, and the amounts of air voids and cement paste. Many potentially reactive aggregates were found, including chalcedony, rhyolite, microcrystalline quartz, and other volcanics (Table 2). Using cross-polarized light, some light-brown rims lining air voids were seen, but positive identification was not made. These rims are assumed to be the ettringite that was seen lining air voids using the SEM.

The chemical test for soluble potassium ions was used to try to identify the presence of ASR gel. Using the chemical that stains soluble potassium yellow (sodium cobaltinitrite), a 0.125-in. halo surrounding a less than 0.125-in.-wide crack was displayed on a distressed

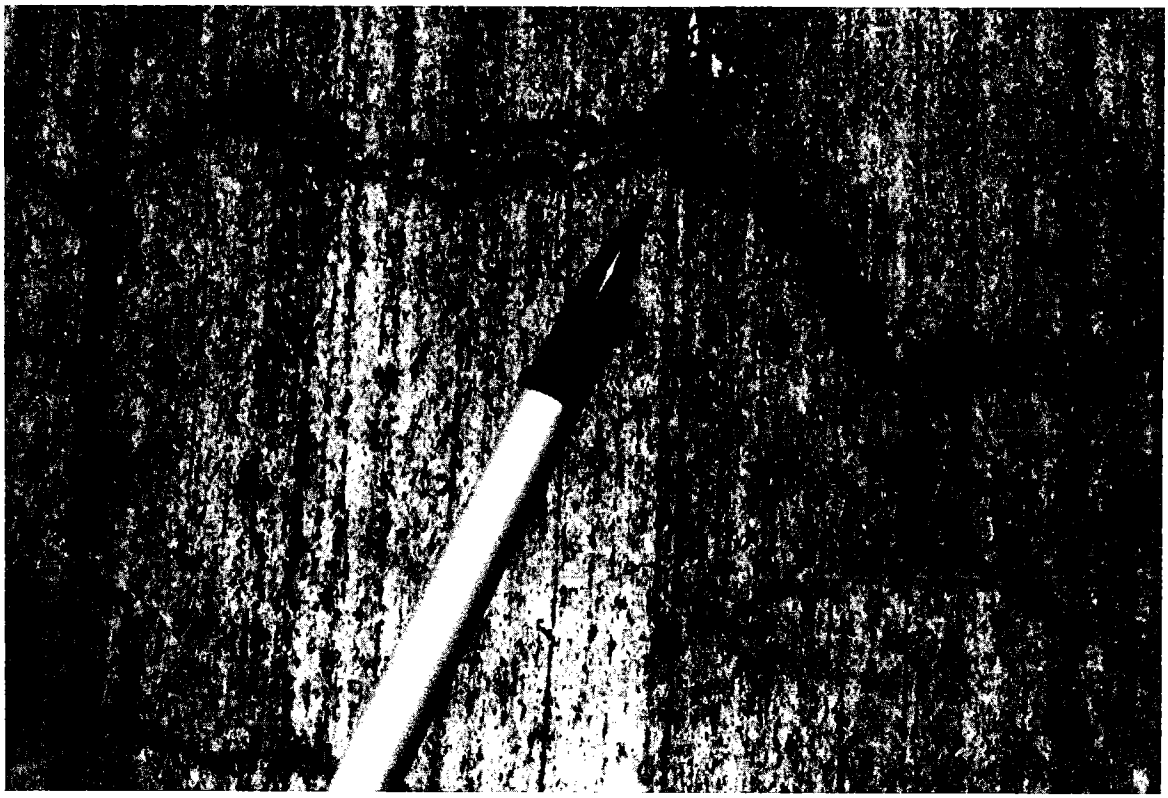


Figure 3. A sidewalk near the location where sample KC09004 was taken. It shows the stain from the sodium cobaltinitrite in the presence of potassium associated with the ASR gel. The photograph was enhanced with a blue filter to emphasize the stain on the black and white photo. The yellow stain forms a halo around the crack at the tip of the pencil.

sidewalk near a sample site (Fig. 3). The concrete sample cores were also tested with the chemical to identify the ASR gel (Table 3).

CONCLUSIONS

The SEM analysis of the ettringite shows that the majority of the ettringite that grows in open-air voids does not cause distress to the concrete. The only example of ettringite possibly causing distress was in the severely deteriorated sample in which the ettringite lined the crack. Therefore, in most cases, delayed ettringite formation does not seem to be a problem in these concretes.

The SEM did not show any positive evidence for the ASR gel in our samples. However, using the petrographic analysis, the potential for the reaction is present. Many of the aggregates used in these concretes are potentially deleterious. The sodium cobaltinitrite yellow stain for soluble potassium related to the ASR gel did give a positive test for some of our samples.

Although the SEM confirmed that the ettringite is not causing these concretes distress, it has not cleared up the problem of the expansive ASR gel. By using the other methods, ASR has been identified as a possible cause of the deterioration. More testing needs to be done to clearly show that the ASR gel is the main culprit of the concrete distress.

FUTURE WORK

Much more research is needed to determine the reason why New Mexico's concretes are deteriorating. Many other variables must be investigated and tested to be able to discover the true mechanism of concrete distress. Aggregate type and reactivity must be examined more closely, as well as the effects of additives and admixtures in the concrete mix. The problem of the rapid deterioration of some New Mexico concretes has not been completely solved.

ACKNOWLEDGMENTS

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Table 3.—Results of the Sodium Cobaltinitrite Chemical Testing of Concretes for Soluble Potassium Associated with the ASR Gel

Sample	Results	Comments
KC09001	NA	NA
KC09002	hi pos.	stain on and surrounding rhyolite and quartz
KC09003	med pos.	halo on rhyolite/granitic aggregate, in cavity of missing aggregate
KC09004	hi pos.	bright yellow in cavity, and halo on andesite
KC09005	NA	NA
KC09006	NA	NA
KC09007	low pos.	stain coats and forms halo on quartz or chert
KC09008	low pos.	stain halo on chert aggregate
KC09009	low pos.	slight yellow stain in paste
KC09010	med pos.	stain halo around aggregate, stains altered feldspars in aggregate
KC09011	neg.	only stains altered feldspar in aggregate
KC10012	NA	NA
KC10013	neg.	slight stain on surface of granitic aggregate
KC10014	NA	NA
KC10015	low pos.	slight stain around aggregates and altered feldspar
KC10016	NA	NA
KC10017	neg.	slight yellow aggregate
KC11018	NA	NA
KC11019	neg.	slight stain on quartz aggregate
KC11020	hi pos.	stain in cavity and on quartz aggregate
KC11021	low pos.	slight halo around quartz aggregate
KC11022	NA	NA
KC11023	hi pos.	stain on surface of aggregate and in cavity
KC11024	hi pos.	stain in cavity
KC11025	med pos.	stain in cavity
KC01026	neg.	very slight stain on quartz aggregate

staining method for the identification of the ASR gel. Our report was reviewed by Gretchen Hoffman and James Barker, and their comments greatly improved its readability.

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Raw Material in Cement Manufacture in California

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ABSTRACT.—California's annual production of >11 million tons of cement, at a value of over $640 million, comes from eight companies, which operate 11 plants. Cement is California's second most important mineral commodity, representing 25% of its total annual mineral production. Although most of the cement produced is consumed within the state, current export locales include the Pacific Northwest, Nevada, Arizona, Utah, and New Mexico.

An enumeration of the components required to produce cement is deceptively simple: calcium oxide (65%), silica (20%), alumina (4–5%), iron (3–4%), and calcium sulfate (4%) as a retardant admixture. The last, and most expensive, ingredient in cement manufacture is energy. Detrimental materials in cement mixes include excess magnesium, alkalis, heavy metals, sulfur, and other volatiles.

Each of the 11 cement plants in California requires a unique chemical solution of combined raw materials to produce a uniform product: portland cement. The geologist proposing solutions for the additive raw materials in cement manufacture must have a thorough knowledge of a particular cement plant's needs. In the California cement market, keeping the costs of additive raw materials down is one way to also stay competitive, and using a combination of natural and waste materials as additive raw materials allows cement producers to stay competitive.

INTRODUCTION

The basic raw material for cement manufacture, limestone or marble, is widespread and abundant in California. The additive raw materials, silica, alumina, iron, and calcium sulfate, are also abundant and widespread. The complicated decisions that determine the suitability of all additive raw materials include the physical properties and chemistry of the material, the location of the source, and the transportation, processing, and/or handling necessary to use that material in the cement-manufacturing process. Each of the 11 cement plants in California requires a unique chemical solution of combined raw materials to produce a uniform product: portland cement. These unique solutions demonstrate that it is imperative that the geologist proposing solutions for the additive raw materials in cement manufacture have a through knowledge of a particular cement plant's needs.

California has led the nation in cement production from 1958 to the present, with the exception of the 5 years between 1980 and 1985. Cement is California's second most important mineral commodity, after construction aggregate, and represents about 25% of California's mineral production.

California has experienced unprecedented growth in this century, and the present growth rate is estimated at about 2% (personal communication, California Department of Finance, 1998). About 75–80% of the cement produced in California is consumed in California. The remaining is exported to the Pacific Northwest, Nevada, Arizona, Utah, and New Mexico. Most of the plants in California have been modified and modernized, and current clinker capacity is estimated to be >12 million tons (California Cement Promotional Council, 1998). In 1997, California's annual production of >11 million tons of cement, at a value of over $640 million (Kohler-Antablin, 1998), came from eight companies operating 11 plants. Figure 1 shows the locations of the 11 operating cement plants in California. Eight of the plants are located in southern California.

The cement industry in California is highly competitive, and, because no one location provides all the necessary raw materials in the required tonnages and/or chemical properties, cement producers in California must use a combination of local and imported resources to create the proper chemistry for cement production.

Although California has an abundance of carbonate rocks, many of which are well suited to cement manufacture, plant location close to the market area is critical. With continued market growth supporting larger

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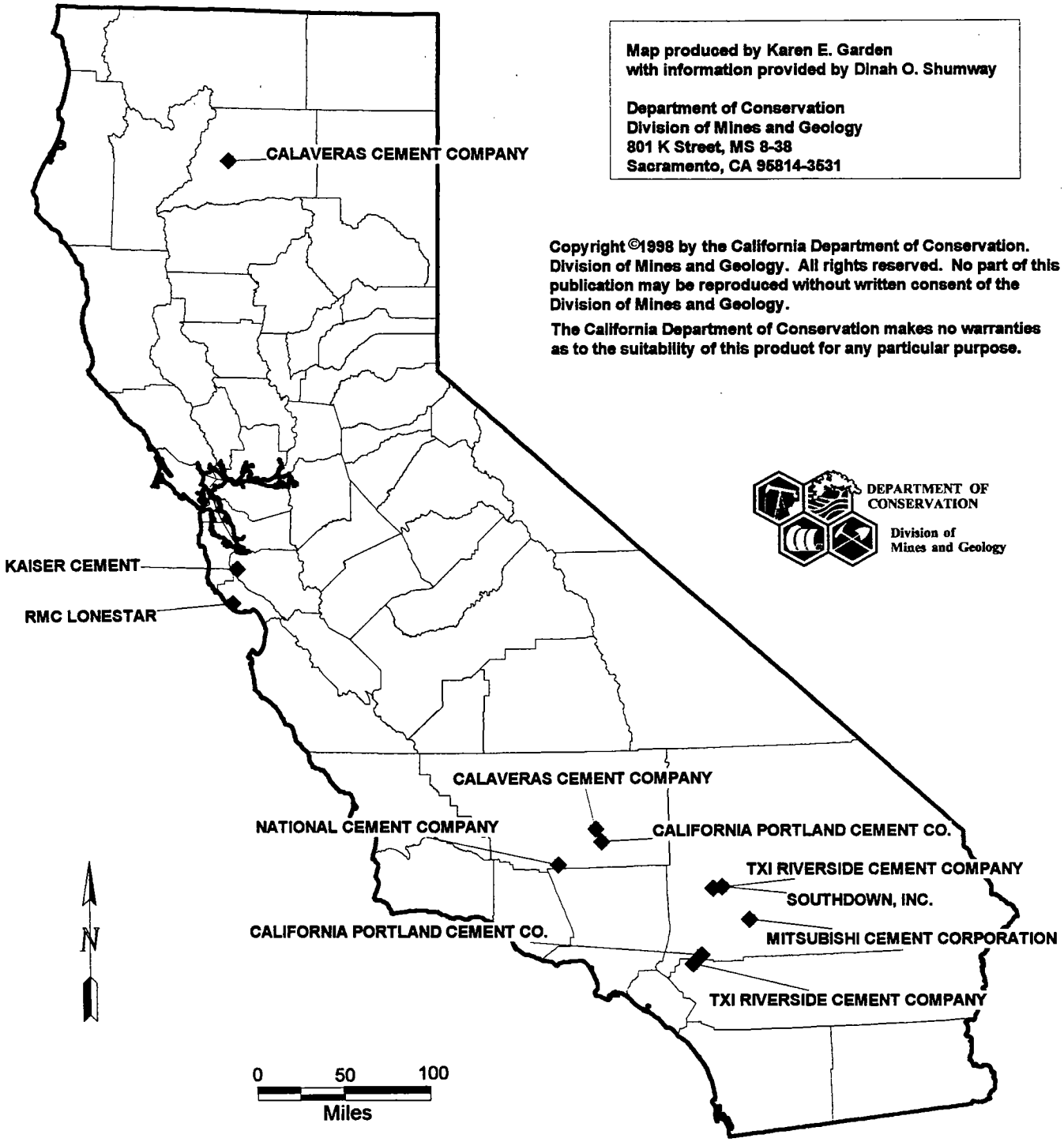


Figure 1. Location of cement plants in California. California Department of Conservation, Division of Mines and Geology, 1998.

plant capacities, large, chemically uniform calcium-carbonate sources are needed, with the potential to provide increased tonnages to support larger production.

The location of the cement plants plays an important role in the identification and acquisition of the other raw materials necessary in the manufacture of cement. The variety of geology within California and the region guarantees the availability of most of the additive raw materials necessary for cement production. However, the closest natural raw materials may not be the best or most economic solution to every additive problem.

In a competitive market, such as the cement industry in California, blending resources for optimum cement chemistry is critical in gaining and maintaining a competitive edge. Each cement plant is unique, and, because no source of the basic raw materials from lime-

stone or marble is the same, the chemical needs of a particular plant need to be considered when the geologist is looking for the additive raw materials for cement production.

CEMENT CHEMISTRY

An enumeration of the raw materials required to produce cement is deceptively simple (Table 1). Limestone or marble provides the largest constituent, calcium oxide (CaO), about 65% of the kiln feed. Additives required will be about 20% silica (SiO_2), 4–5% alumina (Al_2O_3), about 3–4% iron oxide, (Fe_2O_3). Magnesium oxide (MgO), a contaminant, has a fluxing benefit in the 2–5% range, but above 5% is a major detriment to cement production. About 4% calcium sulfate ($CaSO_4$) is added during the final grind to retard the setting time of concrete. Detrimental materials in cement mixes include excess magnesium, alkalis (generally not exceeding 0.6% by weight), heavy metals, sulfur, and other volatiles.

Energy in cement manufacture is critical and expensive. Traditional fuels include powdered coal, natural gas, and oil. Recent innovations in the industry have used alternative fuels, including biomass and waste tires to supplement fuels and to help reduce undesirable elements from emissions. The raw materials used to produce and supplement energy will not be discussed further in this paper.

Even though the list of chemical components in cement manufacture appears elementary, proportioning the raw materials to get the proper chemistry is complicated. The production of cement is an extremely technical process depending on detailed chemical analyses of a variety of materials that provide the basic ingredients. The simplified explanation of the process is that the raw materials are proportioned according to their individual chemical characteristics, blended to make the proper mixture, then ground to a fine powder, and reacted under high temperature to form a new compound, clinker, which is then combined with calcium sulfate, and ground up to a fine powder to make cement.

In the California cement market, keeping the costs of additive raw materials down is one way to stay competitive. Historically, California producers, like cement producers everywhere, have used a variety of materials as additives to provide the necessary raw materials for producing cement (e.g., Bowen and Gray, 1962). California producers currently use a combination of natural and waste materials as additive raw materials.

THE BASICS: CALCIUM CARBONATE ($CaCO_3$)

About 65% of the kiln-feed chemistry is calcium oxide: lime. Because the other additive materials are vitally important but needed in smaller volumes, they *can* be imported economically from a variety of locations. The lime-providing limestone or marble in the cement raw materials generally ranges from 80% to 95% of the weight total, depending on the grade of rock. Although the ideal cement-grade rock is rare on the west coast, a plant that has a cement-grade—or near "cement-grade"—rock as its primary raw material has a considerable economic advantage. A "cement-grade" rock, with a chemistry close to the kiln-feed chemistry shown in Table 1, can be characterized as a dirty limestone (or a marl) with a little silica, a little alumina and iron (both from a clay or shale component), a little magnesium oxide, and low total alkalis.

Table 1.—General Percentages of Major Oxides in Kiln Feed for Cement Manufacture

Oxide	Approximate %
CaO	65%
SiO_2	20%
Al_2O_3	4–5%
Fe_2O_3	3–4%
$CaSO_4$	3–4%

Table 2.—Selected Analyses of Calcium-Carbonate Raw Materials Used by California Cement Producers

Sample	1	2	4a	4b	5	7	8
SiO_2	3.60	6.30	8.19	10.21	3.00	5.87	18.0
Al_2O_3	0.80	0.80	0.57	0.32	1.00	0.00	3.5
Fe_2O_3	0.20	0.46	0.56	0.23	0.30	0.93	1.6
CaO	54.90	50.00	47.21	46.96	51.60	63.44	41.3
MgO	0.30	0.60	0.74	0.45	2.60	0.49	1.5
Na_2O	0.03	0.04	0.02	0.02	0.00	0.45	0.3
K_2O	0.15	0.09	0.10	0.05	0.20	0.24	0.5
LOI	40.00	40.66	42.58	41.75	41.10	27.92	32.3

Table 2 shows selected analyses of calcium-carbonate raw materials used by California cement producers. The lime component in a suitable "high-grade" carbonate rock can range from 50% to 56% (a calcite marble to a dirty limestone). About 44% of $CaCO_3$ is CO_2. Thus, 50% CaO represents a limestone or marble with about 90% $CaCO_3$. Samples 4a, 4b, and 8 in Table 2 are representative of typical "low-grade" carbonate rock. Cement producers generally blend "high-grade" and "low-grade" limestones. Blending proportions typically might be 20% "high-grade" and 80% "low-grade" limestone.

Selected analyses of calcium-carbonate raw material characterized by California cement producers as waste are shown in Table 3. Although low lime content is the major characteristic, contributing factors that make raw material unsuitable include minor element contents, especially alkalis (sodium and potassium) and

Table 3.—Selected Analyses of Calcium-Carbonate Raw Materials Characterized by California Cement Producers as Waste

Sample	1	2	4
SiO_2	36.5	35.9	26.84
Al_2O_3	4.8	9.4	2.6
Fe_2O_3	2.50	4.87	0.68
CaO	26.6	24.93	39.18
MgO	1.70	0.57	1.05
Na_2O	0.10	0.30	0.20
K_2O	1.22	0.97	0.17
LOI	24.0	22.26	29.12

magnesium. Excess silica, magnesium, and other detrimental components on occasion can be blended or diluted with other raw material additives or high-grade rock.

As a source of CaO, the lime component of cement, a "high-grade" limestone or marble, would at first seem the desirable raw material, and, in many locations in the central and eastern United States, that is the primary raw material of cement manufacture. Although using "high-grade" limestone as the only lime source will require less limestone, it also will require the addition of more additives to provide the other necessary oxides. If the additive materials are not available locally by nature of the regional geology, then the producer must import the necessary additives.

THE ADDITIVES

Some Initial Considerations

The additive materials for cement production are typical industrial minerals in that they generally have low unit values and can incur high transportation costs. In California, transportation of raw materials ranges from 10 cents to 17 cents per ton per mile (Public Utilities Commission, 1992); thus, if a California cement producer had to import all the additive minerals necessary to make cement, the cost could be prohibitive or at the least noncompetitive.

The grade of the material is also very important when considering the costs of the additive raw materials. For an alumina source, for example, a manufacturer would require twice as much clay at 25% alumina as that of a clay at an alumina content of 50%. Balancing the physical chemistry of the material, its location, transportation distance, and transportation mode (e.g., backhaul) is a complicated process that is subject to many variables requiring flexibility and rapid change.

Natural and Alternative Raw Materials

Raw-material additives that provide the other oxides necessary for cement manufacture generally can be characterized as *natural materials* (i.e., naturally occurring mined materials), or *alternative materials*. The term *natural raw materials* implies any raw materials that are used in the natural form without any beneficiation or prior use. *Alternative raw materials* include materials used from other manufacturing processes or waste materials. Alternative raw materials can include mining wastes or by-products from mineral production, manufacturing wastes, process wastes, or process by-products (with acceptance, it is conceivable that a "waste" can become a "by-product"). The use of alternative raw materials sometimes can reduce the costs of additive raw materials.

The use of alternative materials in cement manufacture is not new and has had a long history (e.g., Lesley, 1924, p. 77–79). Many recycled materials have been used for decades, for example slag, fly ash, and, in California, tailings from local gold mines (Bowen and Gray, 1962). Modern cement plants, notably in the eastern United States, employ elaborate and effective programs that use waste and recycled materials in cement manufacture (Biondo, 1994). In California, there has been a steady interest in using alternative raw materials for cement manufacture, and several of the California producers are more aggressively testing and utilizing some of these alternative raw materials.

Technology and regulation have made available "recycled materials" that can be used as raw-material substitutes, and the use of alternative materials as raw materials can be attractive to cement manufacturers for many reasons. Landfill limitations and a general movement in California to divert materials from landfills as well as the California hazardous-waste laws create incentives for manufacturing concerns and power producers to look for economic ways to get rid of their commonly useful wastes. The use of alternative materials can extend the life of natural raw materials. Using alternative materials can also be economic because of tipping fees charged by the cement manufacturer, or arrangements such as "we'll take it, if you haul it."

Tipping fees or hauling arrangements, however, are not enough to make an alternative raw material economic. A careful consideration of any plant modifications, permit constraints, or additional handling requirements as well as the strict chemical and tonnage requirements of the cement process need to be balanced against any fees received before a proper economic assessment can be made. Cement plants located in urban areas have much more access to materials from manufacturing processes with an opportunity for incurring less transportation costs.

Tonnage requirements are important. For example, a 1,000,000-tons-per-year plant requiring 3% iron additive would require about 30,000 tons per year of material. Using a natural raw material requires either purchase of the material and transportation, generally from a rural location, or the development and mining of a resource large enough to provide large tonnages at a consistent grade. The producers of alternative materials may not be able to provide the large tonnages necessary for modern high-capacity cement plants (Biondo, 1994).

When considering raw materials, it is important to know the chemistry of the basic calcium carbonate and the needs of the plant. For example, a high-silica, high-iron slag used as an iron additive would not be suitable for a cement plant using a high-silica limestone as a calcium carbonate source.

About the Tables

The following sections are a general overview of the raw-material additives that currently are being used as raw materials by California cement manufacturers. The following tables show only the major components that are critical to cement manufacture. The analyses shown in the tables were provided by the California cement producers and reflect individual plant processes and practices and are not reported in any uniform way. The analyses were selected largely for their general representative chemical nature.

Table 4.—Selected Analyses of Raw Materials Used Primarily as Silica Additives by California Cement Producers

Sample	2 quartzite	3 quartzite	5a quartz sand (Nev.)	9 quartz sand (S. Calif.)	5b mine tailings	5c diatomite filter	9 foundry sand
SiO_2	72.24	67.65	84.1	56.94	84.3	69.07	91.59
Al_2O_3	9.07	16.15	0.90	4.00	7.60	7.68	2.07
Fe_2O_3	5.35	4.38	0.10	7.98	3.10	1.84	3.05
CaO	1.69	3.93	6.30	15.09	1.30	1.25	0.00
MgO	1.04	0.70	0.60	1.48	0.40	0.75	0.21
Na_2O	0.50	4.16	0.10	0.23	0.20	2.07	0.24
K_2O	1.67	2.52	0.60	0.38	1.41	0.50	0.79
LOI	3.35		6.70	13.43	1.60	17.55	4.04

Table 5.—Selected Analyses of Raw Materials Used Primarily as Alumina Additives by California Cement Producers

Sample	4 altered anorthosite	5 shale	6 shale	6a bauxite	7 bauxite (Australia)	4 filter cake	4a foundry sand	5a spent petroleum catalyst
SiO_2	52.52	44.70	62.00	10.00	7.00	37.22	20.17	44.80
Al_2O_3	30.57	8.00	17.00	48.00	52.00	26.09	53.90	48.60
Fe_2O_3	1.45	3.50	6.00	15.00	16.00	1.53	2.56	0.50
CaO	8.73	22.60	30.00	0.00	0.70	8.03	3.64	0.30
MgO	0.23	1.60	3.00	0.00	1.40	0.24	8.31	0.50
Na_2O	2.91	0.50	1.50	0.05		2.49	0.87	0.30
K_2O	0.69	1.00	4.00	0.09		0.19	0.82	4.40
LOI	0.40	17.10				23.90	0.40	4.40

Silica (SiO_2)

About 20% silica is needed in the kiln feed to produce good cement. Although the silica fraction is sometimes contained in the limestone, most California producers must add some silica. A variety of natural materials have been used as a silica source including quartzite, silica sand, diatomaceous earth, igneous rocks, and schists of various types. These silica additives are generally resources located close to the plant. The raw materials that provide other oxides, such as clays, which provide the alumina, also can provide a portion of the silica fraction, as most clays have a significant silica fraction. Producers that use limestone with a high-silica content (for example samples 4 and 8 in Table 2) may not be required to add much if any silica, and, in fact, may get all the silica needed from other additives, such as a clay.

Some forms of silica raw materials incur additional costs. Quartzite, for example, may require additional costs of crushing and grinding. The producer is constantly balancing source-location considerations, costs of processing, and chemistry for optimum production.

Several alternative sources for the silica fraction in cement manufacture currently are used by California producers, including "waste" materials. Selected analyses of materials used as silica raw materials by California cement producers are shown in Table 4. Shown are several alternative silica additives. Tailings from an early gold operation (sample 5b) are located close to one plant and are from an early non-refractory, vein-hosted ore. Used diatomite filter material from local beer manufacture (sample 5c), colorfully called "Budcake," has been used in the last few years as a silica source. One manufacturer has been using foundry sand and brick as a silica and an alumina source (sample 9). Fly ash also is used as an alternative silica source by several California cement manufacturers.

Alumina (Al_2O_3)

Table 5 shows selected analyses of raw materials used as alumina raw materials by California cement producers. Most major clay districts in California have served at some time as an alumina source in cement manufacture, and clay from areas such as the Ione district of central California and the Temescal Valley of southern California continue to be sources of alumina for the cement industry. However, many clays, except for bauxite clays, tend to have elevated alkali contents, and many of high-alkali clays are unsuitable because of the institution of strict performance standards for cement.

Materials from offshore imported as alumina raw materials include bauxite from Australia and Malaysia (samples 6b and 7).

A hydrothermally altered anorthosite from the San Gabriel Mountains (sample 4) currently is used by several of the southern California manufactures as an alumina source. The white altered anorthosite also is suitable as a substitute for kaolin clay in the production of white cement. From the same location, a gabbro with iron content of up to 12% also is being used as a alumina and iron source.

Samples 4b, 4c, and 5 are recycled materials. Sample 4b is a filter cake from water-filtration processes and has some CaO content. Sample 4c, ACA (alumina cement additive), is dross from the aluminum-recycling process being used by at least one manufacturer. However, the chlorine used in the ACA washing process can cause some problems for cement manufacture. Other alumina sources include foundry brick and sand, which is a silica source, and clay tailings from a southern California clay district. The relatively high silica contents of samples 3, 4a, 5, 5a, and 6a also make these materials useful as silica additives.

Iron Oxides (Fe_2O_3, Fe_3O_4)

About 3–4% iron oxide is required to manufacture cement. Like the other additives, a variety of sources exist for the iron additive, and a portion of the iron fraction can be obtained from other additive materials such as shales, clays, and altered igneous rocks. Table 6 shows selected analyses of raw materials used primarily as iron additives by California cement producers.

Magnetite and hematite are mined in two locations in the California Desert. These are at California Portland's Baxter Mine (sample 5b) in the Cave Mountains and from the Kaiser Ventures' (KVI) Silverlake mine in the Avawatz Mountains near Baker. Tailings from the closed Iron Mountain Mine in Shasta County are used by at least one of the northern California cement producers. Some pure, natural iron resources, such as magnetite, have some of the same drawbacks as pure silica resources (e.g., the need to be crushed and ground) that adds to production costs.

An alternative material, the sinter mix from the now-closed Kaiser Steel Mill in Fontana (sample 2), is close to depletion. Located in the Inland area of Southern California, the Kaiser Steel Mill was the primary iron source for the southern California cement manufacturers. Another current alternative is a "doubly" recycled material. Sample 5c, slag from Arizona copper mines, is imported for use as an abrasive in shipyards of southern California and then used as an iron (and silica) source in cement manufacture.

Gypsum ($CaSO_4 \cdot 2H_2O$) and Anhydrite ($CaSO_4$)

A very small percentage, probably much less than 10%, of the gypsum or anhydrite mined in California is used in the cement industry. About 4% gypsum is added to the final ground clinker to retard setting and allow workability in concrete. Most of the southern California producers use natural gypsum supplied by U.S. Gypsum from its Fish Creek quarry in Imperial County in the southernmost part of the state. A smaller portion comes on back haul from Nevada sources. The northern California plants use a combination of natural gypsum from Nevada and by-products from petroleum-cracking plants and from scrubbers from coal-fired power plants. The precipitate from Ft. Cady Mineral's in situ borate production plant in the Mojave Desert has had limited use as a cement additive.

Table 6.—Selected Analyses of Raw Materials Used Primarily as Iron Additives by California Cement Producers

Sample	1 magnetite sand	2 iron ore (Calif.)	4a iron ore (Nev.)	4b shale mix	5 copper slag
SiO_2	2.40	14.0	1.70	5.80	31.6
Al_2O_3	0.90	4.80	9.00	1.64	10.40
Fe_2O_3	95.40	72.80	87.70	64.90	51.30
CaO	0.00	1.80	1.60	6.30	3.30
MgO	0.50	2.70	2.40	1.37	1.30
Na_2O	0.00	0.20		0.57	0.70
K_2O	0.10	0.20		0.32	0.00
LOI	0.00	3.20		21.60	0.00

CONCLUSIONS

California cement manufacturers currently use a variety of natural and alternative raw materials to provide the necessary oxides for cement manufacture. Both natural and alternative raw materials have advantages and disadvantages related to uniform chemistry, location, and transportation and handling costs, which affect the economic viability of the raw material in keeping a competitive edge. It is critical that all additive raw materials have the uniform chemical characteristics in addition to the tonnages necessary for modern high-capacity cement plants.

Natural raw materials, which can be mined or purchased and transported economically and which have the necessary chemical characteristics, are desirable but can incur additional costs (in crushing, for example). These materials, however, are nonrenewable, and new deposits of the required tonnages and uniform chemistry are expensive to identify, permit, and mine.

Using alternative raw materials extends the life of natural raw materials and can provide an environmentally sound way of recycling nonhazardous manufacturing wastes, such as foundry sands, or filtering media. Alternative materials, in addition, commonly have fine textures that can be compatible with the needs of cement manufacture and can be a source of additional revenue from tipping fees, thereby reducing the costs of raw materials.

Although using alternative raw materials has some distinct advantages, especially for plants located in urban areas, many factors must be considered when judging if an alternative material is economic. The generator of an alternative raw material may not be concerned if the waste or by-product material is not chemi-

cally uniform. However, in the cement industry, chemical uniformity is critical and must be monitored to ensure that the alternative raw material has uniform chemical characteristics. The cement manufacturer may incur costs associated with the evaluation of the materials, the time required for adequate analyses, additional personnel, and the maintenance of a laboratory capable of analyzing the materials (Biondo, 1994).

If a producer decides to make use of alternative materials, some process modifications may be necessary to handle new materials. Storage must be considered. California waste-management laws may require containment, protection of water tables, and dust suppression.

Undesirable constituents in the alternative materials, such as heavy metals, some trace elements, or volatiles, will be cause for rejection of the material. Chlorides, for example, can cause plugging in cyclones, and heavy metals, such as chromium, erode refractory or metal lining. Volatiles can lead to excess emissions and/or the formation of dust from a cement kiln.

Other characteristics that can lead to rejection of alternative raw materials are the physical characteristics of the material that may require special storage requirements or process modifications. Textural problems such as fineness can cause problems requiring special covered areas, silos, or covered conveyance. Material that is wet or sticky also creates additional processing and handling considerations. For example, wet material may need to be dried for viable transport. An awareness of the regulations concerning alternative raw materials is imperative. Such materials, for example, must be stored off the ground and may require special concrete bunkers or storage areas.

The California cement manufacturers produce a similar product that meets ASTM standards. Chemical uniformity of the raw materials is attained by using a variety of raw-material additives. These raw materials are a combination of natural and alternative raw materials. Both groups of raw materials have advantages and disadvantages that must be carefully considered in order to reduce the costs of raw materials and remain competitive. Geologists searching for raw materials for the cement industry should be aware of the particular needs of each plant before presenting raw materials for consideration.

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Adobe/Earthen Construction on the Northern Plains: Empowering Standing Rock Sioux Housing Choices

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ABSTRACT.—After a century of variable government-supplied housing on their cold, windswept lands, and facing extremely limited natural resources and no timber, the Standing Rock Sioux Tribe has launched a study into alternative housing approaches for their people. Considering that they have little more than the soil and limited river aggregates under their feet, the Tribe has elected to consider adobe and earthen-wall construction.

Earthen construction is no stranger to the Sioux lands. Smaller tribes, including the Mandan, Arikira, and Hidatsa, lived here among the Sioux in earthlodges for centuries. Such earthlodge structures were not unlike the Southwestern jacal style—a framework of upright branches and branches covered with mud—employed by the Anasazi about A.D. 700–900. Indeed, the Sioux people themselves evolved from earlier earthlodge dwellers.

Indigenous peoples in New Mexico, Arizona, and neighboring Mexico have used earthen-wall housing for many centuries, reinforcing Sioux observations that this is today an earth-friendly, cost-effective, and practical approach. The Cheyenne River and Pine Ridge Sioux Reservations also recently have conducted studies on earthen-wall construction.

This paper describes the search for and evaluation of potential raw-material resources for earthen-wall/adobe construction on the Standing Rock Reservation in North and South Dakota. Significant resources of clay/silt materials (8 million tons in the Striped Cloud clay bed) suitable as adobe binders and sand-and-gravel aggregate (2.5 million tons) that could support earthen/adobe construction have been identified throughout the Fort Yates Flat area on the Reservation. Also addressed is how adobe and rammed-earth construction could add to the diversity of reservation construction and address future Tribal housing and other building needs.

EARTHEN CONSTRUCTION FOR STANDING ROCK—BEYOND A DREAM?

Historical Perspective: The Sioux "Tepee" People

Traditional Sioux housing was principally tepee-oriented. The buffalo-skin tent structures were adequate year-round and well adjusted to the high-mobility lifestyle of the horse Indians. The Sioux generally kept together as communities or clans, remaining either in regular camping areas where they had a territorial claim, or at temporary sites if they were traveling, on warring forays, attending Tribal and ceremonial events, or on the run from hostile forces. The tepee was very much integrated into the cultural habits and religion of the Sioux people, and the tepee was much more than a roof under which to survive. Sioux rarely lived in earthlodges. When they did, it was principally due to changing food patterns, bitter winters, or shortages of horses that forced lifestyle changes.

The tepee commonly belonged to the Sioux woman. She built and maintained it, raised her children therein, and sheltered her elderly relatives in it as well. It was her responsibility to erect it, dissemble it, move it, and erect it again as well. Sioux women have lost but not forgotten their traditional control of the living arrangements.

Over the past century, since the conquest of the Sioux people, the American government (and the U.S. Cavalry) herded the Sioux tribes onto the Standing

Holmes, D. A.; and Archambault, David, 1999, Adobe/earthen construction on the Northern Plains: empowering Standing Rock Sioux housing choices, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 197–208.

Rock Reservation (Fig. 1) and other reservations to "civilize" them. The Sioux have struggled to adjust to major changes in lifestyle, diet, and shelter, but, with this, they have experienced a high mortality rate and a dismal record of housing reliability.

From early log cabins, solutions from the federal government have moved mostly to frame cabins or houses constructed in common designs over the whole Sioux Nation. These small frame homes or "stick houses" do not stand up well in the strong and frequent winds and the wide temperature variations of the North and South Dakota Plains. Further, such houses commonly are sited on exposed areas and in configurations that ignore the sheltering potential of hills and trees.

Certainly, the Bureau of Indian Affairs (BIA) has struggled in the past to provide adequate housing for reservation populations, but limited budgets and staff, Congressional indifference, power struggles, and reluctance to empower tribal peoples to solve the problems have drawn out the predicament. Today, the BIA is more realistic, less paternalistic, and more willing to help, if not demand, tribal involvement or leadership in problem solving.

Mobile homes and "double wides" have been a common nongovernment answer throughout the reservation, but these also fall short of adequate housing for poor families in the extreme cold and windy climate.

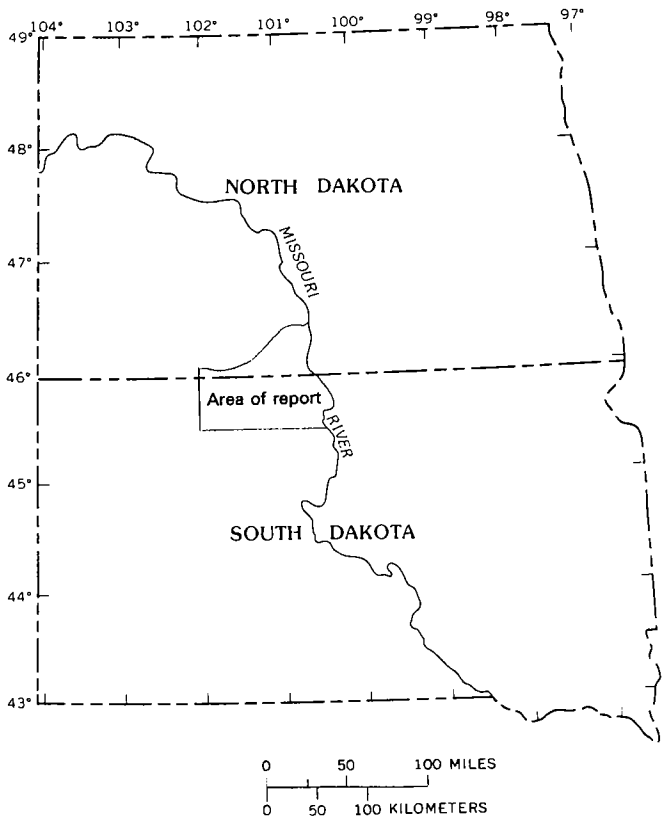


Figure 1. Index map showing location of Standing Rock Sioux Reservation in North Dakota and South Dakota.

Historical Perspective: The "Earthlodge" People

Within the Sioux territory were other tribes, the Mandan, Hidatsa, and Arikira (now collectively known as the Three Affiliated Tribes), who were more farmers and gatherers than hunters. They lived mostly in "earthlodges," mud-over-stick structures that were much more practical in the winter. Such huts were warmer and much roomier than tepees, but they were vulnerable to attack from the more warlike Sioux and, later, from the settlers and military. These earthlodge people infrequently occupied tepees or mobile shelter; they used these structures only when forced to by hunting forays or migrations.

The Pawnee Tribes to the south in present Nebraska and Kansas were an even larger earthlodge-culture people. To the northeast was a third group of linguistically related earthlodge tribes—the Omaha, Ponca, Oto, and others.

These earthlodge tribes held geomantic beliefs of their own that were not totally unrelated to Sioux beliefs. Their earthlodges were generally circular and oriented by very specific directional and star-pattern constraints, reflecting their religious and cultural beliefs. Whole villages followed the same geomantic logic with lodges arranged in circles and in special arrangements relative to gardens, water supplies, and natural topography. Villages tended to be carefully sited on sheltered locations.

For whatever reason, the federal government and missionaries particularly disliked the Indian desire to continue living in earthlodge communities. As Nabokov and Easton (1989) wrote in their now-classic *Native American Architecture*:

> By 1870 the buffalo were almost gone, and the trading post which helped stabilize the community was closed down. In 1887, the Federal policy of subdividing Tribal lands forced Indian families to abandon the village. The government program called for each Indian family to live like an Anglo household, farming 160-acre allotments, attending schools and churches, and dwelling in single family log cabins or wooden frame houses. Soon, the building of an earthlodge became almost an act of cultural defiance.

The earthlodge tribes have had an experience as dreary as the tepee Sioux in adjusting to the very different "stick house" culture of Anglo America.

Future Housing Needs

The tribal population of the Standing Rock Reservation (Fig. 1) is steadily growing, and, if it follows the national population trend, it will double sometime after 2060. Whereas some tribal residents may build their own homes, others face problems with severe poverty and bleakness of the land and are unable to afford any reasonable housing at all. Various programs of the Bureau of Indian Affairs as well as Housing and Urban

Development (HUD) support building of homes to care for this latter, less successful group.

It appears that the federal government will continue to build standard, small frame houses at Standing Rock and other Indian reservations, ignoring the realities of the severe wind and cold. Such housing is difficult and expensive to maintain, grants the residents little motivation to carry out simple maintenance, and has a relatively short structural life contrasted to earthen, masonry, and concrete structures.

Looking to New Mexico: Historical and Contemporary Solutions

The State of New Mexico offers a fascinating contrast in construction style to that of the Dakotas, as well documented by Austin (1989) and especially Smith and Austin (1989), in New Mexico Bureau of Mines and Mineral Resources Bulletin 127. While New Mexican earthen construction became more used and refined with time, Northern Plains earthen construction has been largely rejected and forgotten.

Adobe construction prevailed in the Southwest centuries before the first Europeans set foot in the area in 1598. Adobe construction was used for large, continuously occupied structures such as the Acoma Pueblo and the Taos Pueblo, for small individual houses on farms, and for comprising villages.

Indeed, the Spanish brought over a rich array of adobe-construction techniques from their Iberian and Moorish traditions that modified the indigenous pueblo designs to yield today's New Mexico style of architecture. Classic mud-brick adobe style and architecture, as we know them today, evolved during the Spanish and Mexican Colonial period (1598–1848). The Territorial period (1848–1880) and the American period (1880–present) brought changes in coatings (e.g., stucco), finishings (windows, fittings, roofs, wiring, and plumbing), and architecture.

Existing pueblo structures in New Mexico commonly date back centuries, and many are still occupied by indigenous peoples. Longevity of the structures is a function of intelligent design, careful siting, use of optimum high-aggregate adobe mixes, and periodic maintenance. Institutional adobe buildings such as tribal centers, churches, and schools have served local reservations well for many decades. Low-income Southwesterners, both rural and urban, have long cherished adobe houses for their low cost of construction, heating and cooling advantages, energy efficiency, and practical beauty. The occupants or their ancestors built many such homes.

Wealthy New Mexicans, and to a lesser extent wealthy Arizonans and Texans covet earthen-wall houses, most commonly constructed of mud-bricks. Drive around up-scale neighborhoods of Santa Fe and Albuquerque and you will find that earthen-wall is the predominant construction type. Affluent Southwesterners prefer earthen-wall construction for its attractive, traditional appearance, heating and cooling characteristics, energy efficiency, durability, and architectural versatility.

New Mexico offers an excellent example of how indigenous people can create their own housing—with originality and innovation.

Contemporary Earthen Construction: Examples around the World

Somewhat over 30% of the world's population today lives in homes of earthen construction. These are mostly in developing countries, which cannot afford to import costly construction materials such as wood. Let us consider typical earthen housing in a developing country. Many of the residents of North Africa today live in earthen houses, particularly in rural areas, but also in towns and cities away from the rising concrete and steel buildings that dominate "downtowns" everywhere. The principal reason for this is that there are very little alternative construction materials with which to build modest houses and smaller commercial and institutional structures. Concrete and steel and fired bricks are used only where required by construction of multistory or functional structures, or where more affluent citizens reside.

Even highly developed countries employ earthen construction. For example, Western Australia has excellent examples of contemporary use of earthen-wall construction for housing and institutional and commercial buildings in a highly developed country. Located on a continent with very limited timber supplies, local earthen, brick, and concrete construction are necessary. Earthen construction offers notable cost and insulation advantages compared to brick and concrete for permanent, long-term building construction.

An outstanding example is the Thomas More Roman Catholic Church in Margaret River, south of Perth, in western Australia. Built in 1979, this structure shows great creativity in architectural design and the interrelated used of rammed-earth, concrete, stone-facing, and wood construction to yield an attractive and very functional religious facility. Local high-alumina lateritic soils were used as the basic earthen raw material. Very little wear or weather deterioration is visible on the stabilized rammed-earth surfaces of this structure.

Other western Australian examples show a resourceful marriage of earthen-construction practices and solar-heating and insulation technologies. A newly constructed winery incorporates very thick rammed-earth walls to ensure constant temperatures in the winemaking and storage areas of the facility. Rammed-earth construction of a classic 19th-century Australian country house incorporates wide verandas to shield out high summer sunlight, but allows lower sun angles to shine on the massive walls for heat transfer during cooler winter months.

Earthen Construction: A Leading-Edge Alternative

Numerous books and articles have been written, some very recently, on earthen-wall construction. Most of these include basic construction techniques, and many extol earthen buildings for their durability, low costs, weather resistance, energy efficiency, and archi-

tectural beauty. Included in this list are Clough (1950), McHenry (1973, 1984), Smith and Austin (1989), Southwick (1994), Austin (1995), Austin and Goolsby (1996), Easton (1996), and King (1996).

Having demonstrated that earthen-wall construction can be a practical solution to home and other building in wood-free areas, we recommend that the Standing Rock community incorporate adobe and rammed-earth construction in its future building programs. We do not recommend switching to earthen construction as the solitary answer to the future housing and commercial needs of the Standing Rock Reservation, because, for example, some multistory buildings may require concrete and steel construction. Furthermore, temporary and more short-term housing or homes built in sheltered valleys or groves may best be pursued by frame housing or even mobile homes.

North and South Dakota lie in an area of North America regarded to have a 0 rating of earthquake frequency, in contrast to 2 to 4 ratings in the southwestern states. From a seismic standpoint, in the Dakotas, local vulnerability of earthen-wall homes to earthquakes would be nonexistent to very low.

TECHNICAL STUDIES

Organizing the Project

The basic goals of this project were (1) to identify adequate minable resources of aggregate (sand-and-gravel) and clay or clay-silt mixes on the Standing Rock Reservation, and (2) to establish that these resources were suitable as earthen/adobe raw materials.

To achieve these goals, the project was addressed in four individual tasks: Task 1: Resource Investigation; Task 2: Adobe-Processing Study; Task 3: Drilling and Testing Phase; and Task 4: Bulk-Sample Collection and Testing.

A detailed summary report was released on the completion of each task. Representative adobe bricks (mud-bricks) were made, tested in a commercial laboratory, and used to build a small demonstration wall at the Tribal Department of Water and Natural Resources office at Fort Yates.

Some Fundamentals about "Adobe" and Earthen Construction

More Than One Method of Earthen Construction

The term "earthen" and "earthen wall" are used herein to describe all types of unfired, nonconcrete, earthen-material construction. The term "adobe" is sometimes used to describe all such earthen construction materials, but more correctly refers to mud-brick products. We occasionally have used the term "adobe" in this paper as referring to all earthen construction.

Basically, three practical types of earthen-wall construction are considered in this report:

1. Mud-brick.—Individual bricks shaped from a slurry or soft, wet earthen mass and cured slowly while drying by sunlight and air.
2. Pressed Block.—Individual blocks or bricks mechanically or hydraulically pressed from a moist adobe mix and available immediately for construction.
3. Rammed Earth.—Construction by ramming moist adobe-type soil mixes into forms to yield thick, compacted, earthen walls. Sun and/or air drying and curing must follow.

Less common methods of earthen construction include:(1) puddled earth, (2) cast earth, (3) sprayed-on earth, (4) cut blocks, and (5) "quemados," or semifired adobe mud-bricks. The first three methods involve slurries of adobe mixes.

What Makes Adobe Work?

Contrary to popular belief, "adobe" and other earthen construction materials are not clay or clay-silt alone. They are generally a mixture of 50% or more aggregate (sand and gravel), 2–25% clay minerals, and the balance as silt or fine sand.

It is important to understand how adobe materials work to identify sources and to direct mining activities. An aggregate (sand-and-gravel component) gives body and strength to the mix, just as in concrete. The clay minerals, and to a lesser extent the silt, act as the cement or binder. Silt acts mostly as a filler and gives body, but relatively little strength, to the adobe mix.

The important characteristics of a potential adobe soil are: (1) whether it "works" as adobe (i.e., whether it can be shaped and hold its shape in an uncured state); (2) uncured- and finished-product strengths; (3) plasticity; (4) physical durability; (5) stability; (6) nonexpansive characteristics; (7) water-resistance; (8) particle-size range; and (9) clay mineralogy and content.

Meeting Specifications and Quality Requirements

The New Mexico Adobe Building Code and the 1997 edition of the Uniform Building Code (Anonymous, 1997) regarding "unburned masonry construction" are the two most widely accepted standards to follow in adobe construction. Local building codes rarely address adobe construction, except in New Mexico, Arizona, California, and Texas. Standard ASTM and soil tests may be used to evaluate physical properties of potential aggregate and clay raw materials.

Task 1: Resource Investigation

General Geology

Numerous papers have been written on the general geology, stratigraphy, and glacial history of southern North Dakota and northern South Dakota, including, to a degree, the area within the Standing Rock Reservation. These authors include Searight (1937), Rothrock (1947), Baldwin and Glass (1949), Stevenson (1956, 1960), Clayton (1966), Royse (1967), Frye (1968), Bluemle (1975, 1984, 1988), Moore (1976), Cvancarra (1976a,b), and Carlson (1982, 1983).

The entire known bedrock geologic section underlying the Reservation is more than 10,000 ft thick, ranging from Archean up to upper Tertiary, and consists of

diverse sedimentary lithologies above a crystalline Precambrian basement. Pleistocene continental glaciation over a portion of the Reservation area left both pre-Wisconsin glacial drift and outwash sediments in meltwater channels from both pre-Wisconsin and Wisconsin glaciers. Recent stream channeling has cut only slightly deeper into the topography, leaving valley alluvium along the major river and stream courses. Mapping by Howells (1982) of the U.S. Geological Survey provides the most comprehensive geologic map of the Standing Rock Reservation.

Geologic Structure

The Standing Rock Reservation lies on the southeast flank of the Williston basin. Regional geologic structure is very simple and has little influence on occurrences of earthen raw materials. The exposed bedrock section is relatively thin and essentially monoclinal with southeasterly dips typically of 2–4° and very little faulting. Local dip variations are due to small-scale folding, faulting, or flattening.

Bedrock Geology

The exposed bedrock on the Reservation consists mostly of fine-grained clastic sedimentary rocks in basically five formations ranging from the Upper Cretaceous to the Tertiary (mostly Paleocene) and comprising about 1,200 stratigraphic feet (Fig. 2). They are described below in descending order from youngest to oldest.

Tongue River Formation

The Paleocene Tongue River Formation is a nonmarine sequence (Royse, 1967) that is about 25 ft thick and occurs mostly as a mesa-capping unit in the northwestern part of the Reservation. It consists of light-gray to buff, fine-grained sandstones and clayey silts with some lignite beds. It is more highly cemented than underlying formations. Tongue River rocks show little or no promise as adobe raw materials. They have a high fine-grained sand content, and most of the clays are expansive.

Ludlow Formation

The Paleocene Ludlow Formation (Moore, 1976) forms the basal unit of the Cenozoic sequence on the Reservation and may attain 400 ft in thickness. This formation is also nonmarine and consists chiefly of light-gray to light-yellow and buff, fine- to medium-grained sandstones, silts, shales, and lignites. The Ludlow Formation shows little or no promise as a source for adobe raw materials due to its high content of fine-grained sand and expansive clay.

Hell Creek Formation

The Upper Cretaceous Hell Creek Formation (Frye, 1968; Moore, 1976) is a nonmarine unit that is about 25 ft thick and occurs mostly as a mesa-capping unit in the northwestern part of the Reservation. It consists of light-gray to buff, fine-grained sandstones and clayey

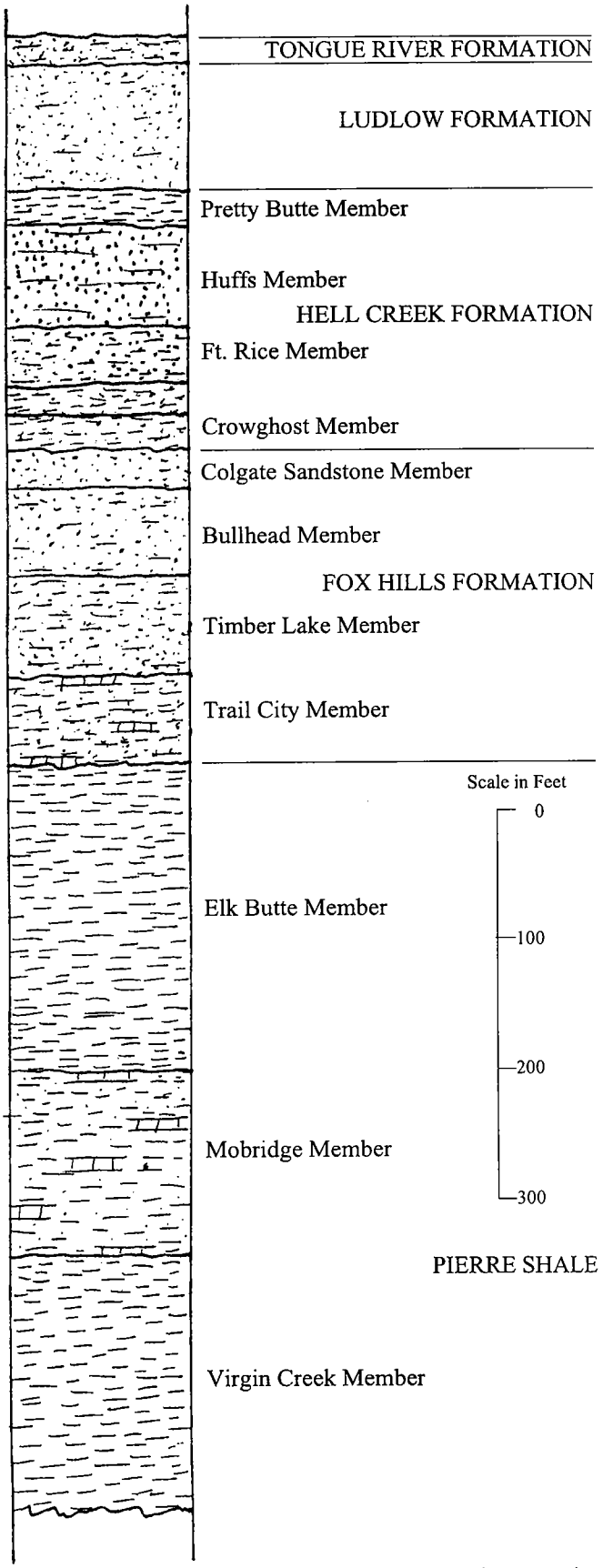


Figure 2. Stratigraphic column of bedrock section cropping out on Standing Rock Sioux Reservation, North and South Dakota.

silts with many lignite beds. It is more highly cemented than underlying formations. Hell Creek rocks show little or no promise as adobe raw materials because of their high fine-grained sand content and expansive clays.

Fox Hills Formation

The Upper Cretaceous Fox Hills Formation (Cvancara, 1976a) is a sequence of marine sandstones, shaly sandstones, and beach sediments. The formation underlies much of the eastern half of the Reservation and supports the better wheat and pasture growth. It is locally unconformable with the overlying Hell Creek Formation, contains no lignite, and locally reaches a thickness of 400 ft. Its soils are undesirable as mud-brick adobe or rammed-earth raw materials.

Pierre Shale

The Pierre Shale (Upper Cretaceous) is about 1,400 ft thick, but only the upper three members (comprising 570 ft stratigraphic thickness) are exposed on the Reservation (Searight, 1937; Rothrock, 1947; Baldwin and Glass, 1949; Clayton, 1966). The Pierre Shale is a deep-water marine sequence consisting predominantly of dark-gray to black shales and claystones, marls, and bentonite beds. It is exposed in the lower elevations of the eastern portion of the Reservation and forms rolling hills with gentle slopes. Pierre Shale outcrops weather very quickly to a sticky, swelling soil called "gumbo" by local farmers, who leave them mostly as untilled pasture land.

The upper three members of the Pierre Shale include, in descending order:

1. Elk Butte Member: 200 and 400 ft thick. Medium-gray, flaky shales and claystones with numerous basal bentonite beds, generally weathering to "gumbo" clay.
2. Mobridge Member: 150 ft thick. Buff calcareous to chalky claystone, shale, and sandstone.
3. Virgin Creek Member: 120+ ft thick. The upper part is a gray "gumbo" shale underlain by a lower part of medium-hard gray shale with numerous thin bentonite beds. The Virgin Creek Member is noncalcareous.

The strata of the Pierre Shale are too fine grained and expansive to offer on-site potential for earthen-wall construction. Certain strata might be selectively mined for their high-clay content to temper or "fatten" multi-source earthen raw-material mixes.

Quaternary Geology

Patchy outcrops of pre-Wisconsin Pleistocene bouldery till and poorly sorted outwash sediments are scattered over the higher ground of the Reservation. The thickness of this drift is generally less than 10 ft.

Wisconsin sand-and-gravel terraces and alluvial trains occur in late Pleistocene meltwater channels along the valleys of the Missouri River (Pantea, 1994), Grand River (Stevenson, 1956, 1960), Cannonball River, Oak (Wakpala) Creek (Baldwin and Glass, 1949), and Porcupine Creek, crossing the Reservation easterly to southeasterly. Howells (1982) mentions seven observable terrace levels along the Missouri River valley and three terraces along the Grand River. The extensive sand-and-gravel layer (C bed) underlying much of the Fort Yates Flats is probably related to a single flooding event durng the late Wisconsin.

Loess, consisting of fine-grained sand- and silt-size wind-blown sediment, accumulated as a patchy thin cover and small dunes over the region since the close of Pleistocene glaciation about 10,000 years ago. It masks the underlying soils, contains little or no clay and no aggregate, and has little if any earthen-wall raw-material potential.

Recent stream sediments consist of sand beds and pockets of sand and gravel along the Missouri River and other stream courses. Narrow bands of Recent alluvial sands and gravels occur in the beds of the Cannonball and Grand Rivers and are composed mostly of poorly sorted, fine- to coarse-grained sand with gravel lenses, which are commonly capped by silt or sandy clay.

Soil Zones and Colluvium

Soil zones are rarely more than a few feet thick throughout the Reservation and may be missing altogether due to erosion. They represent weathered rocks or thin surface layers developed on loess or outwash sediment and drift. They generally reflect the character of the original source rock more than the weathering process.

Colluvium is common at the foot of slopes and hillsides, generally representing the mixed lithologies of the uphill slopes. Sizeable bodies of colluvium occur on the Pierre Shale, where large areas have liquefied and flowed down into stream valleys or adjacent flatlands.

Analyzing Geology to Identify Resources

Resource investigation for earthen-construction raw materials on the Standing Rock Reservation started with an intensive literature search of the geology of the reservation and adjacent areas. Several papers (Howes, 1963; Foster and others, 1980; Pantea, 1994) addressed some of the mineral resources on the Standing Rock Reservation itself. However, none of these dealt with the potential for earthen-construction materials.

Although geologic information on the surface geology was sparse, one of us (Holmes) felt basically optimistic at the start of the project. There appeared to be numerous potential clay sources related to the shale and claystone occurrences in Tertiary and Cretaceous rocks, and there were numerous references to existing and possible aggregate sources in the Pleistocene and Recent drainages across the Reservation.

Weeks of field work, however, soon found that potential earthen-construction raw materials are indeed quite lean on the Standing Rock Reservation. The five bedrock formations exposed on the Reservation consist mostly of fine-grained sandstone and thin shale beds that do not weather to attractive soils. Further, the

dominant clay mineral in all five exposed formations is swelling bentonite.

The most promising adobe materials occur as the aggregates (sandy gravels) that overlie sandy loam soils and one silty clay deposit, all of which occur in the present and Pleistocene meltwater river channels on the Reservation. Raised river terraces are also a potential source of aggregates. Potential resources occur along the Missouri River bars and terraces and the meltwater channels of the Cannonball River, Grand River, Oak Creek, and Porcupine Creek.

The Fort Yates Flats offer the strongest promise for adobe-resource development on the Reservation. A layer of clayey silt loam overlies the sheet of sand and gravel that caps the Fort Yates Flats peninsula, just south and west of the town of Fort Yates (Fig. 1). This aggregate layer already is being developed for local highway and construction material. A thick layer of silty clay, designated herein as the Stripped Cloud clay, underlying the sand-and-gravel bed offers excellent potential as the needed clay-mineral binder.

Mineralogical content determined by x-ray diffraction (XRD) analysis for sample SC-01, a split of the bulk sample of Striped Cloud clay, was reported by The Mineral Laboratory Lab, Inc., and is shown in Table 1.

With the exception of the Fort Yates Flats, there are few sites where both aggregates and clay-silt fractions could be mined together on the Reservation. Separate sources might need to be developed and the mined raw materials transported to a common site for blending and processing. This is commonly done in New Mexico and also may allow some mixing with local soils at the building sites.

Two other substances could affect raw-material supply on the Standing Rock Reservation. Their addition would add strength and durability to otherwise marginal-quality materials. These are (1) addition of fly-ash (from regional coal-fired steam plants) and similar materials to give a pozzolan effect and enhanced binding characteristics to the adobe mix, and (2) addition of stabilizers such as asphalt emulsion or portland cement to inhibit disintegration from moisture and cold weather effects. Such stabilization locks in moisture and prevents any more from entering the adobe brick. It also strengthens the brick and reduces temperature change shock.

Table 1.—Mineralogical Content of Bulk Sample from the Striped Cloud Clay, Determined by XRD Analysis

Mineral	Approximate weight %
Quartz	36
Mica/Illite	16
Smectite	15
Chlorite	10
Plagioclase feldspar	6
K-feldspar	5
Dolomite	5
Calcite	<5
Unidentified	<5

Task 2: Adobe-Processing Study

The goal of this task was to determine if available adobe technology from the southwestern United States, principally New Mexico, could be applied to the Standing Rock Reservation in the wind-swept Dakotas. Information was gathered from published and unpublished literature, contractor schools, visits to friendly producers, and the substantial help of George W. Austin of the New Mexico Bureau of Mines and Mineral Resources. Discussions also were held with adobe contractors and architects.

Standing Rock Tribal managers and technicians could readily gain additional knowledge from New Mexico and Arizona sources by networking with earthen-wall contractors and architects, by visiting active adobe producers and construction sites, and through courses such those offered by the Solaradobe School in Bosque, New Mexico.

Much of the Southwestern adobe/earthen-wall technology is directly transferable to the Northern Plains environment, in spite of more prolonged winter cold, different wind and snow conditions, different raw materials, and a shorter construction season. The Reservation has a very short season for mud-brick making and more limited solar radiation for drying and curing. For this reason, pressed-earth blocks and rammed-earth construction may be much more practical.

Earthen/adobe raw materials are commonly blended and do not have to come just from site soils or special pits near the producing yard. Outside materials such as fly-ash, clays, irrigation-ditch dredgings, off-specification clay-plant wastes, and crusher fines could be brought in to supplement local raw materials. Using such outside materials may improve and increase the quality and variety of the product.

Task 3: Drilling and Testwork

Exploration prior to Task 3 had narrowed the most promising earthen-resource area down to the large alluvial flats of the Fort Yates area, where broad areas of clay/silt and aggregate suitable as earthen/adobe raw materials occur on Tribal lands.

Fifteen holes were drilled in secs. 13 and 24, T. 130 N., R. 80 W., Sioux County, to allow quantification of earthen/adobe raw material resources on a 40-acre parcel basis. Figure 3 is a map of a portion of the Fort Yates Flats area showing the drill-hole locations and other pertinent features. The 15 holes were core-drilled and ranged from 20 ft to 25 ft in depth. Geoserve, Inc., of Bismark, North Dakota, provided and operated a double-axle, truck-mounted drilling rig using hollow-stem augers and a split-barrel sampling tube to drill and sample the holes. The split-tube sampler was emplaced in the lowest hollow-auger stem and recovered core samples up to 60 in. long. The core had a diameter of 3 in. and was logged and placed in sample

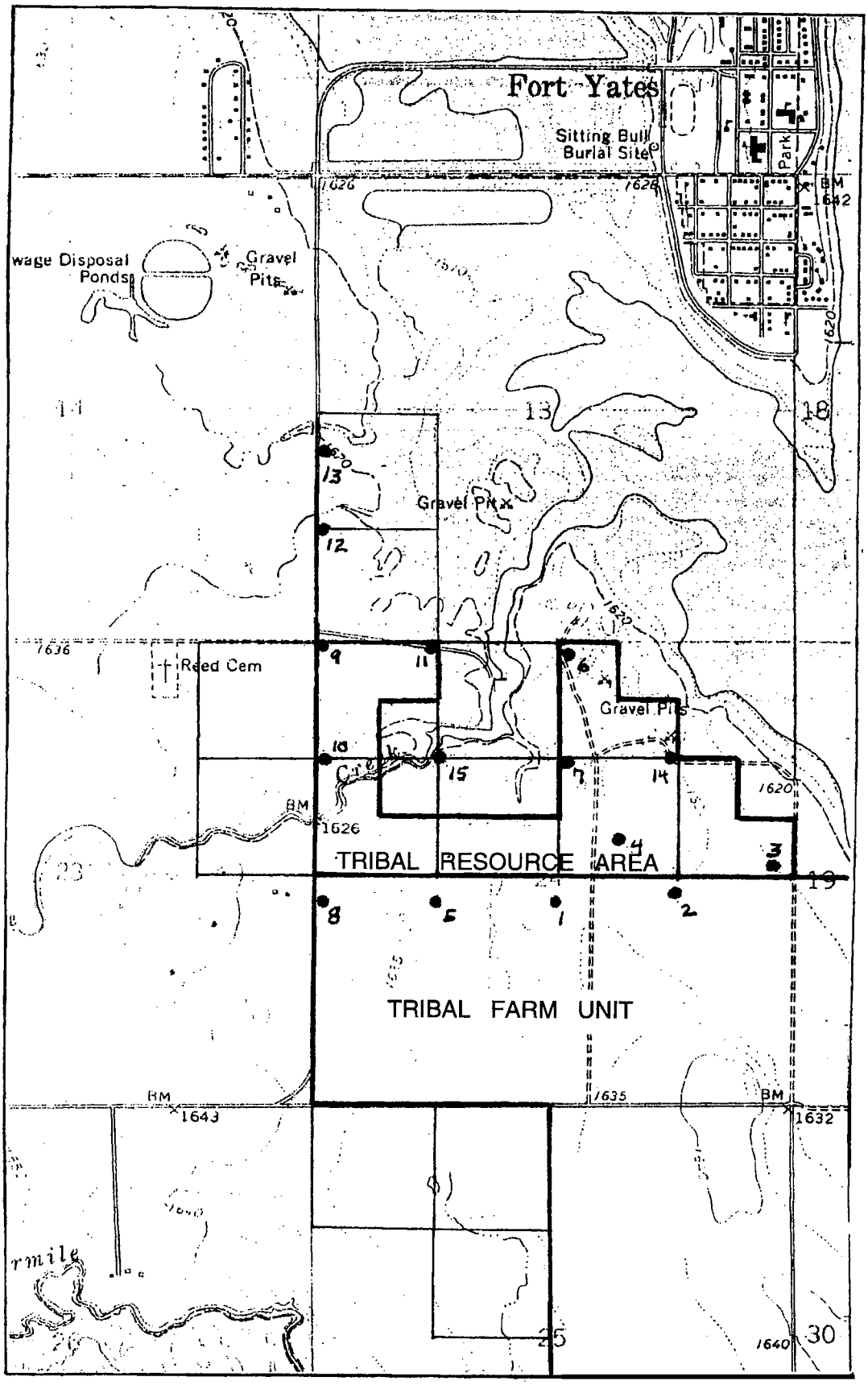


Figure 3. Map of portion of the Fort Yates Flats area, showing drill holes (black dots), boundaries of Tribal lands, location of sand-and-gravel mining, and high shoreline of Lake Oahe Reservoir.

bags immediately after recovery. Drilling logs show contact depths, lithology, sampling intervals, and drilling characteristics.

Due to budget constraints, only a limited number of aggregate samples were tested in the laboratory. Test methods included Gradation Analysis (ASTM C136-95a), Hydrometer Analysis (ASTM D422-63), Atterburg Limits Test (ASTM D4318-95a), and a Specific Gravity Test.

Drilling consistently penetrated a soil zone, followed by the B and C beds and the Striped Cloud clay, demonstrating that the shallow alluvial geology is predictable and measurable. It strongly suggests that these units are consistent over most of the Fort Yates Flats area, from the south tip of the peninsula to the gravel pits in the northern half of sec. 11, just north of a new HUD housing area. Outcrops of identical alluvial geology were observed on the western and eastern sides of the peninsula and at its southern tip.

Large tonnages of clay/silt materials suitable as adobe binders occur in the surface soil zone, the B bed, and the newly discovered Striped Cloud clay (also called the D bed). The fine-grained sediments of the Striped Cloud clay might also be valuable for use in civil-engineering applications or for fired brick-ceramic raw materials.

Significant tonnages of sand and fine-gravel aggregate present throughout the Fort Yates Flats area could support earthen/adobe construction. Areas of aggregate occurrence with low stripping ratios have been partially mined out, and some remaining resources may require more stripping than a commercial aggregate operation could afford. Earthen raw-material resources present on the Tribal Resource Zone lands in the southern Fort Yates Flats area are estimated to include indicated mineral resources of 8 million tons of clay/silt and 2.5 million tons of sand-and-gravel aggregates.

Task 4: Bulk-Sample Collection and Testing

Mini-bulk samples were collected from promising alluvial B and C beds and from the Striped Cloud clay bed at selected sites on the Fort Yates Flats. Testing and evaluation of these bulk samples used practical tests to analyze their potential as adobe raw materials and to guide small-scale blending studies. A specific range of promising adobe mixes was developed.

Informal test methods included a number of hands-on practical techniques employed by adoberos throughout the Southwest and Mexico. These are prosaically named the ball test, rope test, jar test, trowel test, knife-penetration test, damp test, etc., and are described by McHenry (1984), Smith and Austin (1996), and others in literature.

Twelve raw-material blends were selected for production-scale brick making, mixed in a standard heavy-duty masonry wheelbarrow, and poured as a thick slurry into wooden forms to make 10-in. × 14-in. × 4-in. mud-bricks. This is a common commercial adobe-brick size in New Mexico. Using a promising blend developed by this study, an additional 40 production-size test mud-bricks were made at a Fort Yates site and used to construct a demonstration wall. No straw was added to any adobe mix in this study. Handling practices were patterned on adobe-brick–making methodology employed by the Adobe Factory in Alcalde, New Mexico, and the Rio Abajo Adobe operation in Belen, New Mexico, to ensure compatibility with industry practices.

Limited laboratory testing indicates that adobe bricks of commercial quality can be made with local raw materials and labor. Test methods included the Compression Strength (ASTM C140-96) and Modulus of Rupture (C293-94).

On a practical level, sturdy adobe mud-bricks can be made from the Fort Yates Flats raw materials, specifically from blends of the B and C beds and the Striped Cloud clay, and utilizing a portland-cement stabilizer. All materials except the stabilizing agents come from Reservation sources. Pressed-block adobe and rammed-earth structures could also be constructed with local raw materials, based on this experience.

MATCHING RESOURCE DATA TO FUTURE CONSTRUCTION NEEDS

Standing Rock Reservation Has Earthen Construction Resources

Like the desert terrains of New Mexico and Arizona, the most promising earthen-wall raw materials of the Standing Rock Reservation occur in the Quaternary sediments along the current and old stream channels. Weathered bedrock is much less likely to yield soils with desirable binder or filler characteristics. Fresh, unweathered aggregate (sand and gravel) generally occurs only as Pleistocene and Recent sediments.

The Striped Cloud clay bed on Fort Yates Flats, and possibly at other sites along the Missouri River, represents an excellent binder source and can be extended by blending with the overlying clayey silts of the B bed.

The sand-and-gravel layer of the C bed will supply a reliable source of the aggregate fraction. Even old waste piles from previous sand-and-gravel operations could be incorporated into this supply, because the earthen-material specifications are much broader than concrete or state-highway aggregate specifications. Older Pleistocene terrace deposits of sand and gravel scattered along river valleys are also promising as smaller aggregate sources.

Some other bedrock clay beds on the Reservation might be tapped to supply bentonitic clays that would increase the plasticity of the earthen/adobe mixes. However, the amounts would have to be controlled carefully because their expansive clays would cause problems.

As noted above, earthen-raw-material resources on the Tribal Resource Zone lands in the southern part of the Fort Yates Flats area are estimated to include indicated mineral resources of 8 million tons of Striped Cloud silty clay and 2.5 million tons of sand-and-gravel aggregate. Resources could be developed from a single pit on the Fort Yates Flats to supply the aggregate and silty clay raw materials needed for Standing Rock earthen/adobe construction.

Larger tonnages of clay/silt and sand and gravel are also estimated to underlie the Tribal Farming Areas as inferred mineral resources in the southern Fort Yates Flats area, but these materials may be permanently off-limits to development for adobe and construction materials. These Farm Unit resources are estimated to include 22 million tons of silty clay and 6.5 million tons of sand-and-gravel aggregate.

Fly-ash from coal-fired power plants throughout North and South Dakota represents a supplemental material that could be added as filler and/or for its pozzolanic effect to strengthen the adobe block.

Mud-Brick-Adobe, Pressed-Earth, and Rammed-Earth Construction Are Feasible

Testing was confined to mud-bricks to allow direct comparison with equivalent mud-bricks from southwestern sources. Earthen mixes for pressed-block and rammed-earth construction could be made from the same raw materials, but would require varying portions of the aggregates, clay binder, and fine-sand/silt filler, as well as water and stabilizers.

Pressed-block and rammed-earth construction also might be able to use some on-site earth materials, an advantage over mud-brick in raw-material transportation costs to the site. Such materials contribute neither aggregate strength nor binder effect but do reduce the volume of materials that must be hauled in.

Earthen Construction Can Meet Tribal Needs and Visions

Earthen construction produces very sturdy buildings, a definite need on the Standing Rock Reservation. Besides the energy efficiency, the exterior walls of the houses are solid and difficult to pierce, bullet-proof, and resistant to time-cracking and chinks that let the wind blow in. With exterior insulation, the interior walls can be left in their unfinished earthen state, which is generally more resistant to marking, piercing, or defacing than plaster or gypsum-wallboard walls.

Innovative architecture certainly can produce houses that are pleasant to live in rather than just to occupy. This would be a strong motivating factor in inspiring better homeowner care of the structure and its surroundings.

Sioux visions of housing designed and sited to some traditional or cultural criteria are possible also. If Feng Shui works well for 1.5 billion Chinese and Donald Trump, then Sioux geomantic concepts should certainly work as well locally. Circular floor plans and directional orientation of specific houses are important in Sioux logic. Building siting to take advantage of sheltering hills and trees, beautiful scenic views, and relationship to flowing or ponded water also can be very important. Patterns of grouped housing also may be more relevant to Sioux customs than laying out straight streets with houses in rows as in, for example, Lorrain, Ohio, or Aurora, Colorado. Tepee circles and such patterns were a well-defined Sioux housing concept before the 20th century.

Opening the concept of alternative architectural possibilities also empowers Sioux women to input their own ideas and preferences, if these are culturally or practically important to them. Certainly, Sioux women have been mostly left out of the loop of reservation house design during the past century.

A rammed-earth house was built in the town of Eagle Butte, South Dakota, on the Cheyenne River Sioux Reservation by the Habitat for Humanity in 1997. Constructed essentially to the same design as the small boxy frame houses around it, the structure will give researchers an opportunity to see how its durability and energy efficiency compare. The house has exterior-foam insulation over the rammed-earth walls and beneath a stucco exterior, the optimum way to insulate an earthen house in a very cold climate.

EMPOWERING SIOUX HOUSING DIVERSITY THROUGH EARTHEN CONSTRUCTION

Balancing Future Housing Needs with Alternatives

Expanding Tribal population will continue to put pressure for more housing construction on the Standing Rock Reservation. And more schools, administrative buildings, and commercial structures must follow to service the community overall. Budget and planning pressures will push to solve these needs by waves of new frame-building construction to satisfy short-term demands.

What is needed to find a long-term solution are longer-term planning, more innovative architecture design, and diversity in construction types to provide more durable and energy-efficient houses and buildings. Conquering the extreme cold and winds of the Dakota winters demands answers beyond an approach geared to Oklahoma or other warmer regions.

Probable Impact of Future High Energy Costs

Time is bringing another factor into the future picture as well. The world "energy crunch" in 1973 precipitated by an OPEC oil embargo brought a sharp jolt in world and national supply and demand of energy. Certainly the energy-affluent trends of the 1950s and 1960s came to a grinding halt in 1973. World oil availability and production leveled off for several years before resuming a more modest growth rate. A comprehensive study by Edwards (1997) of probable energy supplies ahead in the 21st century forecast that world petroleum supply will peak out by year 2020. Other studies reported more recently (Campbell and Laherrere, 1998; Kerr, 1998) are less optimistic and predicted the peak of world oil production would more likely be by 2010.

Consensus of the world's leading energy experts is that, within a generation ahead, the world is going to enter a domain that is characterized by petroleum scarcity. This trend will not be catastrophic, but certainly the energy-supply balance will shift more to coal, natural gas, nuclear, solar, and other sources. Cheap natural gas and petroleum will become memories, not everyday realities, and prices for all forms of energy will

rise. The impact on low-income families and communities will be especially tough. Where will Standing Rock stand in future energy supply?

Building sturdy, energy-efficient houses and other structures today is the solution to the energy problems of tomorrow. Standing Rock does not need to face a future built on "stick"-housing construction alone.

Taking a Hard Look at the Economics

Performed on a conventional contracting basis, earthen construction is in fact no cheaper than conventional frame construction. A concrete foundation should still be poured, and the walls require about the same labor costs. The finishing costs of house construction (that is, the wiring, plumbing, flooring, roofing, windows, etc.) remain essentially the same. So the initial cost of a contractor-built earthen house will be roughly equivalent to that of a frame or concrete-block structure. Two exceptions to this are construction using (1) strictly local earthen raw materials, and (2) self or volunteer labor. Many rural adobe homes in New Mexico were built by owners or as community efforts to provide effective long-term housing for low-income families.

The real savings in earthen-building construction lies in its greater energy efficiency. Utilizing the effect of earthen mass-heat supplemented by conventional insulation, both winter heating costs and summer cooling costs can be significantly lowered. In areas where extreme heat or cold occur, the heating and cooling costs can be a major part of an occupant's budget. Beyond these savings, the advantages of (1) greater building durability (earthen houses can last decades or centuries), and (2) greater resistance to wall-insulation failure from aging and the effects of prolonged high wind would make a significant long-term difference.

The New Mexico experience, both in traditional Indian and in contemporary urban sectors, has been that earthen construction has provided more stable, durable, low-cost housing and building for communities. This is echoed by earthen construction projects in other southwest U.S. states, Australia, and similar localities throughout the world where wood construction materials are scarce. One might note that the richer and the poorer people of New Mexico live in adobe homes—the first group out of choice, the second group out of necessity. It works for both.

The Standing Rock Sioux Making It Work

Nearly a century of government-built frame housing, mobile homes, and general poverty have given the Sioux people a lowered personal image of what they can expect in housing, whether from their own initiative or from government sources. The local construction industry has gone compliantly along with this logic, building frame housing, which is used for the lower-income population in the Dakotas in general.

Many Sioux, both male and female, express interest in the incorporation of Sioux housing traditions of the past into future earthen construction. In particular, this could include directional house alignment, circular-flow house layouts, circular arrangements of houses in the community, greater adaptation to passive-solar heating, and other factors. Certainly, both architectural creativity and budget constraints define the bounds here.

And what about the Sioux tradition of women's involvement in home design and construction? Conversations with Sioux women and showing them illustrations of adobe residences in New Mexico and elsewhere brought out great interest. It could probably be summarized in one woman's response: "Now that's a home I could really live in!" They are as fascinated with adobe-type architecture and good home design as any other American women, regardless of ethnic, racial, or social backgrounds.

Earthen housing and building construction does not answer all of Standing Rock's future needs alone; however, it does provide an alternative that strengthens building diversity on the Reservation. Certainly, a mix of earthen, frame, and, yes, even mobile homes, may be a better answer to bringing the tribe longer-lasting, more flexible, and more energy efficient long-term housing. More innovative architecture is also an answer to better housing for the Sioux people, not continued construction of rows of stick-houses on the windy plain.

What will finally make this project go? Three factors are relevant: (1) the coming impact of high-cost/scarce energy resources in the next decade; (2) the rising cost of competing building materials; and (3) the need for more fuel-efficient and durable buildings.

The Standing Rock people have their own earthen/adobe raw materials. They could mobilize their own labor resources. They have the power to solve their future housing needs with their own initiative.

ACKNOWLEDGMENTS

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Update on By-Product Resources in Virginia

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ABSTRACT.—By-products from mining and processing plants and coal-fired power plants are being utilized more as valuable resources in Virginia. Mining-related by-products are divided into two categories: those generated from mineral extraction and beneficiation, and those generated from mineral processing or from industrial plants. Materials from both categories are produced in Virginia, where by-products have been exploited for various uses in the past and/or present. These materials include coal-combustion products (fly ash and bottom ash), lime-kiln dust, flue-gas-desulfurization residue, rock fines, magnetite, Cold Spring clay (kaolin), Austinville tailings, soapstone rock, and calcium-carbonate paste. Some of these by-products have never been utilized, although several ideas have been investigated over the years.

INTRODUCTION

Several determining factors in utilization of by-products include the location of the material with respect to potential markets, chemical suitability of prospective material, and consistent quality and quantity. Some additional considerations include production rates, processing and handling costs, availability of competing materials, seasonal adjustments, and the experience of design engineers, purchasing agents, contractors, legislators, regulators, and other professionals. Following are some of the major mine, processing, and industrial-plant by-products, listed alphabetically, in Virginia. Their location, present use, and some potential uses are discussed (Fig. 1).

AUSTINVILLE TAILINGS

A tailings pile of approximately 6 million tons of carbonate material covering about 52 acres remained on the site of the former New Jersey Zinc Co. property at Austinville in Wythe County when the company ceased operations at the end of 1981 (Fig. 2). These tailings were the result of New Jersey Zinc Co. processing lead and zinc ore for about 250 years at this site. Independent chemical analyses from borings in the tailings pile in the early 1980s indicated 27% CaO, 20% MgO, <4% Fe_2O_3, and just over 1% SiO_2.

In October 1982, Austinville Limestone Co., Inc., a subsidiary of James River Limestone Co., began marketing the tailings for use as agricultural lime. The company has been marketing the tailings since late 1982, and they had sold about 1.5 million tons by 1997. They expect at least another 30 years of reserves remain on site. Austinville Limestone also opened a quarry just north of the tailings pile in 1984 to produce aggregate.

CALCIUM-CARBONATE-PRECIPITATE PASTE

Until August 1996, Cyprus Foote Mineral obtained lithium carbonate from brines in Nevada and also imported some lithium carbonate from Chile into the port of Charleston, South Carolina, from where it was trucked in bulk bags to the plant at Sunbright, Scott County. Calcium hydroxide, obtained from an in-state producer, was mixed with the lithium carbonate to produce lithium hydroxide powder, used in many multi-purpose-grease applications. A by-product was calcium-carbonate-precipitate paste (half silt and half clay), which contains 43–50% $CaCO_3$, 3–6% $Ca(OH)_2$, 40–48% H_2O, and some lithium. This material was disposed of in an on-site inactive, slope-entry, underground limestone mine at the rate of 225 tons per week (Fig. 3). Because of its lithium content, the material may not have a use as a fertilizer; however, there may be some potential to utilize it to neutralize and stabilize coal refuse in the Southwest Virginia coalfields. Although production at the plant has ceased and a new plant is now operational in Silver Peak, Nevada, the by-product calcium-carbonate paste remains on the site.

COLD SPRING CLAY DEPOSIT

The Cold Spring clay deposit, located near Big Levels in Augusta County, was last operated in 1951. White kaolinitic clay was first mined at this site in 1912 for use as a paper filler. By the late 1940s, the better quality clay had been mined, and production was only for oil paints and for camouflage paint for wartime use. Over the years, as much as 175,000 tons of material may have been produced. An old chemical analysis of the material indicates ≥39% Al_2O_3. A sample collected in 1988 was analyzed by X-ray fluorescence

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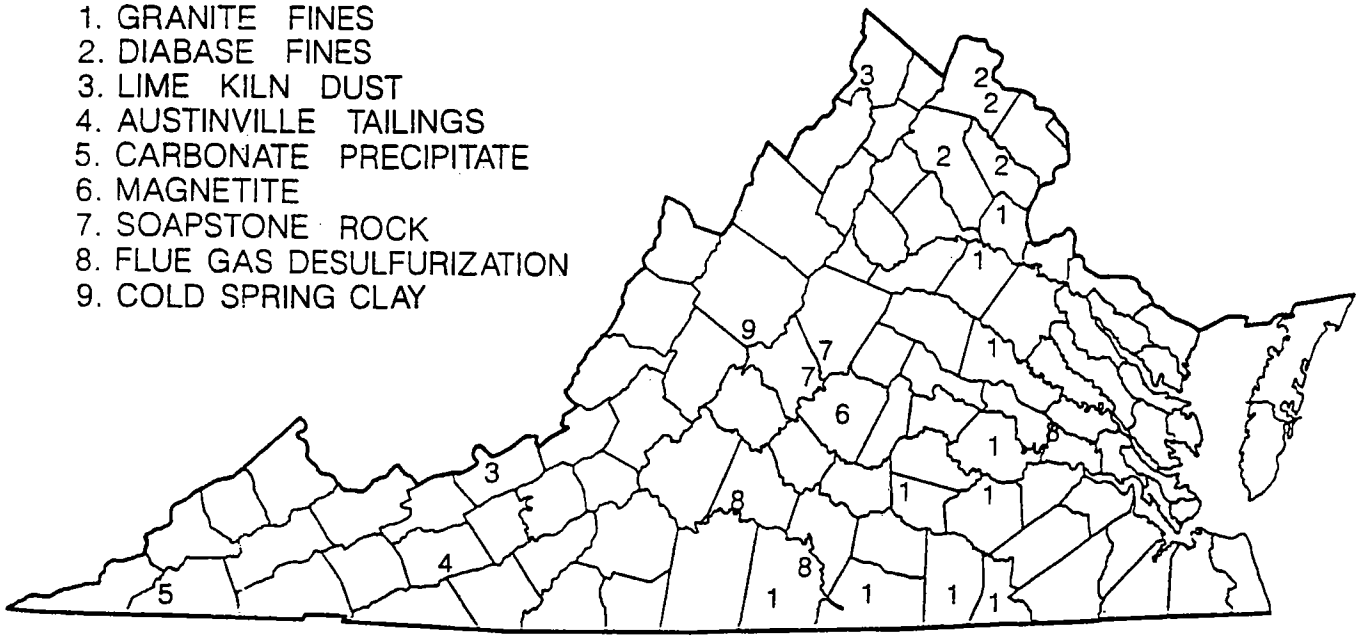


Figure 1. By-product-resource sites in Virginia.



Figure 2. Tailings at former New Jersey Zinc Co. site, Austinville, Wythe County (circa 1981).

(XRF), at the Division of Mineral Resources laboratory, and indicated 28.9% Al_2O_3 (Sweet and Giannini, 1990).

Today, the site contains large spoil piles of kaolinitic material mixed with occasional bits of bauxite. The spoil piles can be seen from Interstate 81, 4 mi away. In the early to mid-1980s, a company utilized some of this by-product material as a component in a filler-extender for use in a rug-backing product and also for use in the manufacture of white cement (Sweet, 1994).

FLUE-GAS DESULFURIZATION (FGD)

Flue-gas desulfurization (FGD) is a scrubber system, where wet or dry finely ground limestone is injected above the combustion zone and captures the sulfur from the burning coal. With the removal of sulfur, a FGD product is collected at the base of the boiler. The Environmental Protection Agency (EPA) has concluded that a flue-gas desulfurization residue in the form of "synthetic gypsum" does not exhibit hazardous characteristics. There are about 12.3 million tons of FGD material produced each year in the United States, according to the American Coal Ash Association (ACAA), a trade group made up of coal-burning electric utilities, coal-ash marketers, coal companies, and suppliers of ash-related equipment (ACAA, 1997).

Presently, the major use (815,000 short tons) of FGD

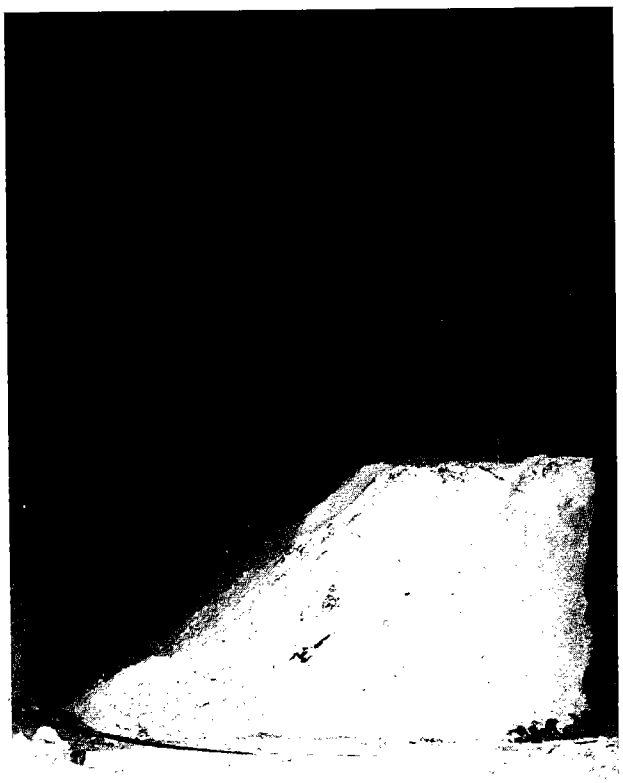


Figure 3. Calcium-carbonate-precipitate paste, inactive underground limestone mine, Cyprus Foote Mineral, Sunbright, Scott County.



Figure 4. Plant of ReUse Technology, Inc., where BUCKSHOT™ is produced from FGD residue, Rocky Mount, North Carolina.

is in wallboard. An important consideration with the use of gypsum in wallboard is the percentage of chloride present, as it may cause deterioration of nails and screws that secure the wallboard. Other uses, in descending tonnage, follow: (1) for agriculture, as "land plaster" to improve soil conditions for the peanut industry; (2) rolled in balls, as a crushed-stone substitute for roadbase and subbase material; (3) for water stabilization; and (4) as a retarder in cement.

ReUse Technology, Inc., R. T. Soil Sciences Division, at their location in Rocky Mount, North Carolina, has patented BUCKSHOT™, which is a pelletized FGD residue that makes a spreadable calcium- and sulfur-rich soil amendment (GYP SYN™) or "land plaster" that enhances the production of peanuts, sweet potatoes, Christmas trees, ornamental shrubs, and grasses. The company began investigating the use of FGD residue for production of "land plaster" after discovering that more than 200,000 acres of Virginia Style Peanuts were harvested annually in North Carolina and southern Virginia. The FGD residue that the company obtains from the local Cogentrix Energy, Inc., power plant (Battleboro), and also from LG Electric power plant in Altavista, Virginia, is a fine powder consisting of calcium sulfite, calcium hydroxide, calcium sulfate, and fly ash. The FGD residue is transported to the Rocky Mount plant in bulk tankers; the residue is fed in precise amounts along with wetting ingredients into a pin mixer for agglomeration. The BB-size granules are dried to a moisture content below 20%, screened, and stockpiled (Fig. 4). The product is shipped by truck in bags mainly to retail outlets and also in one-ton bulk bags and in bulk to market. The use of the high-intensity, pin-type mixers allows for agglomeration with the least amount of wetting, where other types of agglomeration devices on this material were proven uneconomical. The major calcium- and sulfur-supplement product (GYP SYN™) supplies the essential nutrients of calcium (20%) and sulfur (8%) to the peanut plants without changing the pH of the soil. Successful field testing has given ReUse product acceptance into the marketplace, and BUCKSHOT™ is currently registered in North Carolina as a by-product "land plaster" and as a registered fertilizer in Virginia. The company also is currently investigating FGD residue from power plants in the Richmond, Virginia, area for suitable material to make BUCKSHOT™.

ReUse Technology, Inc., utilizes a large amount of FGD residue to produce their product; the patented process generates a pelletized product that has excellent spreading and distribution characteristics and turns a potential disposal cost into a revenue-producing product. The cost for power plants to place FGD in landfills is $6 to $10 per ton, and estimates for the cost of disposing of this material in the future could range from $20 to $25 per ton (Sweet, 1994).

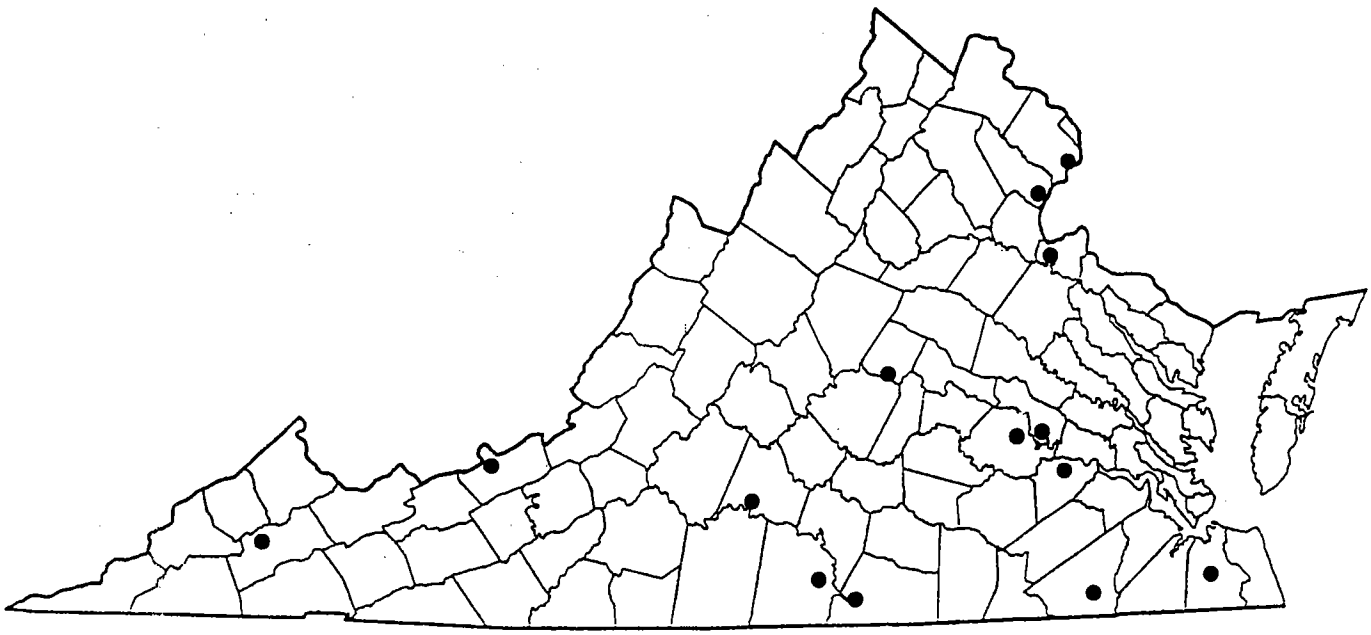


Figure 5. Location of coal-fired power plants in Virginia.

FLY ASH

Fly ash is a finely divided residue that results from the combustion of pulverized coal that is blown into a burning chamber. Heavier ash particles (slag or bottom ash) fall to the bottom of the boiler, whereas the lighter fly ash remains suspended in the exhaust gases; fly-ash particles are removed by a bag house, electrostatic precipitator, or other method.

The American Coal Ash Association (ACAA) promotes the use of coal combustion by-products in applications that are commercially effective, technically proven, and environmentally sound (Industry Newswatch, 1994). The ACAA reported that the total production of all coal combustion products in 1996 in the United States was 101,838,447 short tons (ACAA, 1997). This figure includes fly ash, bottom ash, boiler slag, and FGD material. The total of fly ash (dry and ponded) was 59.4 million tons; about 16.2 million tons were utilized primarily in flowable fill, structural fill, waste stabilization, and mining applications. Bottom ash is utilized in all these applications as well as for snow and ice control, blasting grit, and roofing granules. Almost 91% of boiler slag is used for blasting grit and roofing granules, and more than half of FGD by-product is utilized in wallboard (ACAA, 1997). All of these uses are described in detail in the publication by the Office of Technology Applications (1995).

Coal-fired power plants in Virginia produced about 2 million tons of coal combustion products (ash) in 1996 (Fig. 5). ReUse Technology, Inc., R. T. Construction Sciences Division, located in Chester, Virginia, has several products that they are marketing. Their Xtra Fill™ is a blend of fly ash, a cementitious binder (lime-kiln dust), and water that is combined in a pug mill; the amount of water added is controlled depending on the application. Cognetrix Energy, Inc., which operates power plants in nearby Richmond and Hopewell, daily truck fly ash to ReUse's plant site. The lime-kiln dust is obtained from Chemstone Corp. in Strasburg, Virginia.

An example of the use of Xtra Fill™ is the construction site of the Target Department Store on Midlothian Turnpike and Branchway Road near Midlothian, Virginia. The 25-acre Target site was very wet, and grade design required an average of 6 ft of fill in January 1997. Local stone contained too much moisture. Xtra Fill™ (about 2–5 in.) was disced into a wet, silty clay subsoil; the excess moisture was absorbed by the product, and then the site was stabilized with additional Xtra Fill™. A total of 250,000 yd^3 of the product was utilized. The material was so effective that only 5 additional work days were lost above the 15 days of rainfall.

Another ReUse site is the structural fill for the Warwick Road site in Richmond, where the Virginia Department of Transportation widened and regraded the road. The structural fill contains about 200,000 yd^3 of Xtra Fill™, up to 40-ft thick (Fig. 6). A construction site on Midlothian Turnpike, Chesterfield Marketplace, was a large, low, wet area that required a structural fill or a subbase material—a thin layer to the south and about 4 ft toward the north—to level the area. A total of about 80,000 yd^3 of fly ash was used (Fig. 7).

ReUse Technology, Inc., also obtains fly ash from the wet and dry ponds of the Chesterfield plant of Virginia Power. They operate a pug mill on site at the dry pond, which is part of what is called "Walden Pond." There they produce structural-fill material (Xtra Fill™) in their on-site pug mill, and they truck fly ash from there to their plant to produce EZ Fill™ (Fig. 8). EZ Fill™ is another product produced by ReUse Technology, Inc., by mixing fly ash with cement and water; this flowable fill is delivered in a cement truck. The product is a cost-

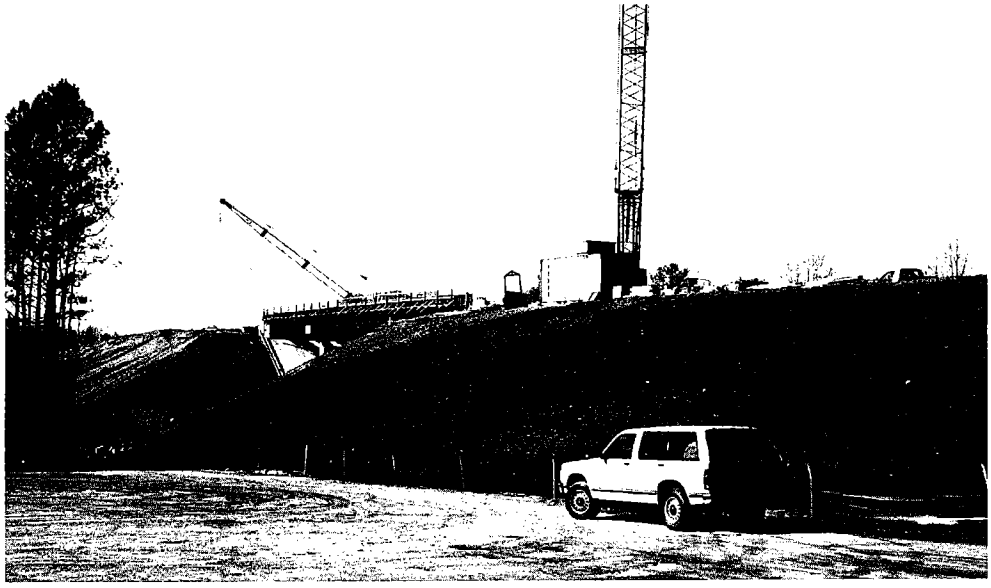


Figure 6. Grassed-over structural fill of Xtra Fill™fly ash, Warwick Road, City of Richmond.



Figure 7. Four feet of fly ash, utilized as a structural fill for subbase material, Chesterfield Marketplace, Chesterfield County.



Figure 8. Dry pond of fly ash, with pug mill, Chesterfield plant of Virginia Power, Chesterfield County.

effective construction backfill that is delivered in a slurry state and hardens to provide superior load-bearing characteristics. An example would be a private residence where the site soil is a plastic clay with shrink/swell potential. Ordinarily, a contractor would undercut and backfill with crushed stone or concrete. In using crushed stone, voids in the stone accumulate water. Softening the underlying dirt was a concern as well as the additional weight with concrete. Instead, 60 yd^3 of EZ Fill™ (flowable fill) was used, and the foundation was ready for pouring concrete in three hours. The cost was about half that of using concrete.

Agglite Corp., on site at the Chesapeake plant of Virginia Power, mixes bottom ash with portland cement, surfactant foam, a dry catalyst, and accelerators (Sweet, 1994). These ingredients combined with water are mixed with a screw auger, and the material is then pelletized. It is a cold-bonded process, with no external heat. Only the heat of hydration released by the combination of bottom ash and cement is utilized. The "manufactured aggregate" is spherical and light (58 lbs/ft^3) and has physical properties necessary to meet the three basic ASTM specifications for lightweight aggregate. The lightweight aggregate is stored in on-site silos. Markets for this product are for use in manufacturing concrete cinder block in Virginia and North Carolina. This company also has a small plant at the Chesterfield plant of Virginia Power, where they process the bottom ash to produce a lightweight material that is also used in concrete cinder block. The material is marketed to Tarmac in the City of Richmond and to a block company in Charlottesville. Bottom ash from the Cogentrix Energy, Inc., in Richmond is marketed to the block plant of Betco in Manassas, Virginia.

Fly ash from the Chesapeake plant also is used by Agglite Corp. as a compacted sand substitute as well as a flowable fill. The flowable-fill material is a combination of fly ash and cement, which are mixed with water in a concrete truck and then applied on-site just like concrete. A large quantity of flowable fill (~9,000 yd^3) was used as a base material under concrete slabs for vertical support beams at Harbor Park in Norfolk.

Presently, Virginia Power burns only coal at its Yorktown facility, and, in the early 1990s, was storing both bottom ash and fly ash on a 45-acre site about 2 mi south of the power plant. The ash was transported by truck, compacted, and stored in 3-acre "cells" that are underlain by a 5-ft layer of bentonite clay. Each cell contains about 90,000 yd^3 of ash. After the ash is dumped and rolled, it sets up hard, and, as the cell is filled, it is covered with a 2-ft layer of soil and is planted with grass. The final product is essentially a 20-ft high, long, flat plateau. Approximate cost of preparing a cell to store the ash was half a million dollars (L. Johnson, 1993, personal communication). By the end of 1997, four cells were complete and a fifth cell was being "mined" and utilized in the local area of York County. The fly ash is mainly used for structural fill, where the material (ash) is mixed in a pug mill with lime-kiln dust; some also is mixed with cement and water in a concrete truck to produce a flowable fill. ReUse Technology, Inc., Chester, Virginia, is the main company that presently is using all the ash produced by the Yorktown plant (B. Easley, 1998, personal communication).

Other potential uses of fly ash include the filling of borrow pits and for reclaiming surface coal mines. Borrow pits, in the Coastal Plain province of Virginia, can be lined with clay, filled with ash, brought back to their original contour level, covered with soil, and seeded. Buchanan (1993) noted that consideration was being given to utilizing fly ash in reclaiming surface coal mines. The Virginia Department of Environmental Quality (Waste Management) began formulating regulations that would ban fly ash or allow only a percentage to be returned to the Southwest Virginia coalfields, according to the volume of coal mined in the county. In 1995, new state guidelines were passed by the Virginia General Assembly that allowed by-product fly ash to be placed only on permitted land sites and only for helpful reasons.

Another potential use of fly ash was initiated in the Chesapeake Bay area of eastern Virginia in late 1994. This study involved the combining of fly ash, bottom ash, and portland cement into pellets (ping-pong-ball to grapefruit size) and their subsequent use as an environmentally acceptable substitute for natural shell in oyster-reef restoration (Industry Insight, 1994). The results of the laboratory study indicated that the pellets, which are made from a mixture of about 88% fly and bottom ash and 12% Type II portland cement, are environmentally safe and facilitate the settlement, attachment, and growth of oysters (Andrews and others, 1997). When a large volume of pellets (barge full) were produced, quality control of the pellet size became a problem, and the stack of pellets did not provide the interstitial space necessary for oyster habitat. Presently, the accessibility of ash, the cost of portland cement, and the necessary quality control are concerns; future studies should focus on making fly-ash-pellet reefs more economically feasible by reducing the cost of production through substitution of alternate stabilizers for the portland cement.

In late 1996, Michigan Technological University's Institute of Materials Processing developed a new carbon-recovery technology that would transform coal ash, by removing the carbon, into a useful mineral filler that can be recycled into concrete and other products (Industry Newswatch, 1996). This is important because the Clean Air Act Amendments of 1991 required coal-burning facilities to reduce carbon dioxide and other air emissions, which, in turn, led to increased levels of carbon in the ash and made it unsuitable for cement and concrete manufacturers. Mineral Resources Technologies (MRT) in Georgia is attempting to transform coal ash into a higher value mineral-filler product that can be recycled into concrete and other products. Their plans are to commercialize the technology by developing and operating facilities across the county. At the present time, this technology is not being used in Virginia (D. Bendein, 1998, personal communication).

LIME-KILN DUST

Lime-kiln dust is a by-product of calcining lime in a rotary kiln. The gases and dust are directed to a baghouse, where the dust is collected and the gases are vented into the atmosphere. The dust-particulate material consists of 15–18% CaO, and 70–75% $CaCO_3$, which makes the dust highly alkaline (up to 12.4 pH), and the remainder is fly ash, which is high in SiO_2 and Al_2O_3. When 2% by weight of lime-kiln dust is added to acidic coal refuse generated at coal-preparation plants, there is an increase in pH and alkalinity, bacterial growth is inhibited and the formation of acid water is drastically reduced (Rich and Hutchison, 1990).

Lime-kiln dust is trucked from APG Lime Corp. in Giles County, Virginia, to a preparation plant in Nicholas County, West Virginia, and loaded into a dust bin. From the bin, the lime kiln dust is metered onto the coal refuse belt by means of a variable-rate screw conveyor. The treated coal refuse is trucked to mined-out areas, where a cell (disposal site) is created. The dust not only neutralizes the coal refuse but also stabilizes the material, allowing dozers to easily push it up into piles. In a matter of a couple of days, the refuse will firm up enough to drive trucks on it. Some of the economic effects of utilizing lime-kiln dust here includes requiring less equipment to maintain the refuse cell, elimination of rock bridges to support trucks while moving coal refuse around, and the extended life of the cell (Sweet, 1994).

In Virginia, lime-kiln dust is trucked from Chemstone Corp., near Strasburg, to Chester, where it is utilized by ReUse Technology, Inc., R. T. Construction Sciences Division, to stabilize fly ash in structural fills and embankments in the area. Some of the benefits are that the material (fly ash and lime-kiln dust) is available in bulk quantities and is cost effective. Its low weight is ideal for placement over low bearing strength underlying soils; its high shear strength (compared to its unit weight) make it ideal for placement under building foundations; and its ease of handling and compaction reduce construction time and equipment costs.

There is also considerable interest in using lime-kiln dust at sulfide-metal-mining operations to neutralize tailings, waste rock, etc. On a trial basis, lime-kiln dust has been utilized on tailings embankments at Kennecott's Ridgeway Gold Mine in Ridgeway, South Carolina. In Virginia, it may have a potential around some of the former sulfide-metal-mining areas in Carroll or Louisa Counties.

MAGNETITE-COATED PYRITE

Kyanite Mining Corp. in Buckingham County quarries a kyanite-bearing quartzite, which contains some pyrite. After the material is crushed in a jaw crusher and a rod mill, froth flotation is used to remove the kyanite. It is then dewatered and dried. The high temperature of the drier converts the sulfides to oxides. Pyrite (FeS_2, ferric sulfide) is converted to magnetite (Fe_3O_4, ferrous oxide). The material is removed with magnetic separators and stockpiled (Fig. 9). The material was tested for use as the iron ingredient at a plant producing portland cement; it was discovered that, because the magnetite was not "through the body," it was introducing sulfur to the cement product. Presently, the material is being marketed for use in synthetic heating briquettes (used in gas-fired grills), for use in exothermic compositions, and as a brick colorant. In briquettes, the magnetite fines (>75%) are mixed with



Figure 9. Stockpile of by-product magnetite at Kyanite Mining Corp., Buckingham County.

some charcoal and a binder, and then the material is extruded. The extruded briquettes are shaped irregularly before being emplaced. For brick colorant, the magnetite fines are actually included in the mix to produce a black to bluish-black cast to the product.

Potential uses are still being investigated as an ingredient in cement, as a heavy media for cleaning coal, and in other uses where the magnetic properties can be utilized.

ROCK FINES

Processing of rock materials, by crushing and screening to meet specifications for clean, uniformly sized aggregate, generates 5–15% dust-size fines (–200 mesh) as a by-product. These fines (classifier tailings), which must be handled and discarded, presently are calculated as a part of the production cost, which must be handled and disposed. Fines are produced in both dry and wet processes, which are determined by the types of stone marketed. Wet-processed fines are generally collected in settling ponds (pond screenings). Major uses of dry and wet fines has been for general fill and reclamation.

Stokowski (1993) notes a long list of potential products from pond screenings that include agricultural, ceramic, chemical, cleanser, construction, industrial-mineral, precious-metal, mineral-coating, filler, pigment, pollution-control, and safety products. Numerous articles have suggested the value of powdered rock in replenishing essential minerals, improving existing soils, and creating new topsoil. Successful crop production has been carried on for years in regions of naturally fertile soils where geological processes provide a continuous supply of nutrients. The processes include a complex geochemical balance of all 92 elements present in minerals (Leonardos and others, 1987). Able (1992) noted the benefits of adding rock dust to soils. Rock dust can help (1) improve the soil quality; (2) reduce the need of soluble chemical fertilizers; (3) improve resistance of plants to insects, disease, and fungus; (4) improve the nutrient density and flavor of food and feed; (5) regenerate damaged forest ecosystems; and (6) preserve air and water quality. As for application rates of rock dust for remineralization of soil, the consensus of opinion through numerous articles indicates the standard is about 10 tons per acre. As much as 20 tons per acre is recommended for very poor, depleted soils (Able, 1992).

In 1996, more than 40 million tons of aggregate were produced from basalt, diabase, granite, and greenstone (metabasalt) in the Commonwealth of Virginia. Using even a median figure of 10% fines, this equals about 4 million tons of fines (rock dust) produced in one year.

Diabase

More than 11.2 million tons of diabase for aggregate were produced during 1996; all production was from northern Virginia. A large amount of fines resulted from these operations, especially from the production of "stone sand," mainly for use in asphalt. Minus 200-mesh materials are the fines by-product that are looking for a market; some are used as an extender in asphalt and in roadbase material.

During the early 1990s, one quarry supplied more than 150,000 yd^3 of diabase fines for use as bedding around concrete pipes for a municipal-water-supply project in northern Virginia. Luck Stone Corp. has installed a gravitational inertial classifier at their Leesburg plant, where they quarry and crush diabase. The classifier is a series of screens and fans in their sand plant, where the "stone sand" is produced in a dry process that requires less energy. Primary customers for the stone sand are asphalt companies, which require <5% passing 200 mesh. The company presently produces the product with <3% passing 200 mesh. Up to 50% of their –200 mesh fines is being marketed as a flowable stone fill (FSF), which is being utilized as a dry backfill around underground pipes and wiring. Very fine material is marketed as mineral filler in stone mastic asphalt (SMA), which gives the product various degrees of consistency required. Based on success at this plant, the company has installed the gravitational-inertial-classifier system at three of their other plants in Virginia.

Vulcan Materials Co. utilizes much of their diabase fines at the Manassas Quarry to produce a Super Top Soil™ (STS), which they describe as a manufactured organic-rich topsoil designed to optimize plant-growing conditions, by blending sand, silt, and clay constituents (rock fines) with specialty-designed organic compost. One of their components (–400 mesh) is a 100% natural rock dust soil amendment material itself (Mineral Rite™). The Mineral Rite™ adds potassium, depleted soil minerals, and secondary- and micro-nutrient materials (including S, Ca, Mg, Cu, Zn, Cl, Fe, and Co) and increases catonic-exchange capacity (the soil's ability to retain minerals and prevent leaching and runoff). This product combined with a finer clay material (–600 mesh), coarser sand, and compost allows for better root penetration. It is weed free, optimizes permeability, pH, water-holding capacity, porosity, organic content, and texture, is easily spreadable, and is mineral fortified.

Uses for remineralization are being investigated by several companies; however, it seems that the most marketable products include mixing the fines in a topsoil product or with other ingredients to make a soil amendment. Other possibilities are as a filler in charcoal briquettes and as an ingredient in the manufacture of clay pigeons.

Granite

Many of the granite quarries in the southern Piedmont province produce "stone sand" utilizing a wet process. Their resulting fines from these operations presently are stored in settling ponds on the property.

Potassium, one of the three main plant nutrients in fertilizer, is present in potassium silicates (orthoclase feldspar), which are common in igneous and metamorphic rocks. When these rocks weather, potassium is released not only from orthoclase feldspar but also from

minerals such as sylvite, which contains about 63% K_2O, and kainite, which contains about 19% K_2O. Some whole-rock chemical analyses for granitic materials in Brunswick and Nottoway Counties in the southern Piedmont province of Virginia indicate that they contain up to 4.5% K_2O (Alex Glover, 1995, personal communication). Granite fines may be suitable as a low-grade fertilizer or as a soil remineralization ingredient. This material needs to be dry in order to marketed; thus, one of the main problems is that the fines are produced wet because of the more economical milling process and would have to be dried before they could be sent to market.

Another potential market brought on by the environmental concerns is the use of fines for remineralization of golf courses, which would lead to the reduced use of chemical fertilizers. The Mineral Rite™ that Vulcan Materials Co. is presently evaluating is available from quarries in granite/diabase rocks that offer minerals necessary for remineralization. Additional benefits offered by this 100% natural, nonpolluting, soil amendment includes soil conditioning by improving the soil texture, structure, and porosity.

Other uses for the granite fines have been at farms for use in "loafing" pens for dairy cows, in horse arenas, and on farm roads. Other investigated uses are as a binder with charcoal in making charcoal briquettes. The specifications required for this use are that the fines be dry, are a suitable color, and be restricted in size to no larger than a buckwheat grain.

Another use of the granite fines has been as a base material in landfills, which are normally lined with clay. However, in a landfill in Chesterfield County, the clay is covered with a 1- to 2-ft layer of granite fines (acting as a bed), then a plastic liner is added and covered by another clay layer. This landfill is adjacent to a granite quarry, which allows for an accessible source of granite fines.

Slate

LeSueur-Richmond Slate Corp. produces almost 200,000 short tons of slate annually, which mainly is sold as roofing slate. In the production of roofing slate, ≥80% of the slate is unfit for roofing shingles and is utilized for floor tile, various pieces of architectural slate, and then for flagging. The rejected material from manufacturing these products is sent to the aggregate plant, and local road aggregate is produced. The aggregate material ranges in size from ⅜ in. to fines, some of which is put to use around the plant as landcover or "hole filler" and is also sold for this same end use. Some fines can be put back in with the aggregate for crusher run, some can also be used as a filler in asphalt for paving.

SOAPSTONE ROCK

Soapstone has been quarried in central Virginia since the 1880s by many companies. During the processing of soapstone for laboratory tops, sills, stoves, etc., thousands of tons of waste soapstone blocks were piled up around the inactive quarries near Alberene, Albemarle County, and at the plant site at Schuyler, Nelson County (Fig. 10).

In the early 1980s, several Lynchburg businessmen had the idea of utilizing this by-product-soapstone rock by crushing to 1-in. size and producing heat-retaining terrazzo panels with epoxy or high-temperature cement. These decorative panels could be used in various ways in the house. This proposed operation never came to pass. During the early part of the 20th century, the waste soapstone was pulverized into dust for various uses of its talc properties.



Figure 10. Inactive, water-filled, soapstone quarry with dumps of blocks, south of Alberene, Albemarle County.

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Coastal Plain Mineral Resources of Georgia: Environments of Deposition

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ABSTRACT.—Georgia's Coastal Plain contains important sediment-hosted deposits of kaolin, bauxite, heavy minerals, sand and gravel, silica sand, carbonate rocks, and fuller's earth. Genesis, location, size, and quality of these deposits are related to terrestrial, marginal-marine, and shallow-marine depositional environments that evolved during development of the southeastern North American continental margin. From the Cretaceous to Eocene, kaolin and aluminous sediments, which contained mica and feldspar, were deposited in marshes, ponds, and bays located in deltas or behind barrier islands or spits. In the Cretaceous sediments, subsequent, intensive, in situ chemical weathering converted mica and feldspar to kaolin. Kaolin eroded from deeply weathered granitic rocks in the Georgia Piedmont was deposited in Paleocene to Eocene sediments. Subaerial exposure during the Paleocene and Eocene desilicated kaolin sediments to form bauxite. Sand and gravel, silica sand, and heavy-mineral deposits are found in Cretaceous to Eocene fluvial and shoreline sediments, some of which are associated with the kaolin and bauxite deposits. Source areas, intensive chemical weathering in the source areas, transportation by the major river systems, and deposition of these clastic sediments in similar or nearby depositional environments are common elements in the genesis of these resources. Eocene fuller's-earth deposits are opaline claystones in near-shore to shelf-marine sediments, which overlie the kaolin-bearing strata. These claystones consist of montmorillonite and opal/cristobalite derived from alteration of diatom frustules. Favorable ocean currents provided nutrients for extensive planktonic growth. Oligocene and Miocene carbonate rocks were deposited principally in shallow-marine embayments. Miocene fuller's-earth deposits in south-central Georgia and adjacent parts of Florida contain palygorskite that formed through alteration of montmorillonite/bentonite clays. Deposition and subsequent alteration occurred in shallow, brackish-water lagoons under relatively high temperature and subtropical conditions. Middle and late Miocene phosphorites were deposited on a shallow carbonate-shelf platform and were concentrated proximal to anticlinal highs. Numerous marine transgressions and regressions since the beginning of the Pleistocene resulted in shoreline detrital deposits containing aggregate sand, silica sand, and heavy minerals on the Coastal Plain and on the Continental Shelf. Major river systems transported sand and heavy minerals from source areas in the Piedmont and Upper Coastal Plain. Deltaic deposits of heavy minerals were redistributed and concentrated by longshore currents, shoreline processes, and aeolian processes. River-terrace sediments, correlative with the Pleistocene shoreline deposits, contain sand-and-gravel and silica-sand deposits. Aeolian dune sands are associated with both Pleistocene fluvial and shoreline detrital deposits.

INTRODUCTION

Many of the world's largest cities are located on coastal plains and are strongly dependent on nearby sources for aggregate and construction materials. Commodities such as kaolin and heavy minerals, which have high unit values and may be used on a global basis, also are found in coastal-plain sediments. Industrial-mineral deposits in coastal-plain sediments are amenable to low-cost, bulk-extraction techniques, because the deposits are commonly large, near the surface, and occur in nonlithified or poorly lithified sediments. Some commodities, such as heavy minerals, have undergone several stages of sedimentary fractionation, including weathering and concentration, that have increased the value of these resources. Railroads and seaports are generally readily accessible and provide cheap transportation.

Cocker, M. D., 1999, Coastal Plain mineral resources of Georgia: environments of deposition, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 219–228.

Georgia's Coastal Plain province comprises 60% of Georgia's landmass and contains important deposits of kaolin, bauxite, fuller's earth, heavy minerals, sand and gravel, silica sand, carbonate rocks, phosphorites, and peat. These deposits range in age from Cretaceous to Holocene. Genesis, location, size, shape, and quality of these deposits are related to terrestrial, marginal-marine, and shallow-marine depositional environments that evolved during development of the southeastern North American continental margin. This paper discusses these relations in the context of our current understanding of the Coastal Plain. The mineral resources are discussed in approximate order of current importance.

GENERAL GEOLOGY OF THE GEORGIA COASTAL PLAIN

The southeastern United States Coastal Plain extends from the southern edge of the Piedmont southeast to the Atlantic Ocean and south through Florida to the Gulf of Mexico. In Georgia, the Coastal Plain includes those exposed Cretaceous and younger sediments that generally extend southward from the Fall Line. Erosional inliers or remnants are found scattered across the southern Piedmont and include the Warm Springs bauxite district. The approximate northernmost extent of the Cretaceous or younger shoreline (Salvador, 1991) is shown in Figure 1. Sedimentary units dip gently, on the order of 5 to 10 m/km, to the southeast. Georgia's Coastal Plain is stratigraphically diverse, because it has served as a connection between the Gulf of Mexico and the Atlantic Ocean. From the Cretaceous to the Holocene, numerous sea-level transgressive and regressive events are recorded in fluvial-to-marginal and shallow-marine sediments in updip (to the north) and downdip (to the south) directions. Significant facies changes also are found along strike from the Chattahoochee River on the Alabama-Georgia border to the Savannah River on the Georgia–South Carolina border (Huddlestun and Hetrick, 1991; Reinhardt, 1982; Reinhardt and Donovan, 1986; Reinhardt and others, 1980). Depositional environments generally become more marine to the south from the Fall Line and southwest toward the Gulf of Mexico. Faunal and facies changes associated with the various depositional environments and major water bodies complicate stratigraphic correlations in the Georgia Coastal Plain.

Recently, detailed stratigraphic studies and mapping redefined much of the Cretaceous through Holocene stratigraphy (Frazier, 1982; Gibson, 1982; Hetrick, 1990, 1992, 1996; Hetrick and Friddell, 1990; Huddlestun, 1988, 1993; Huddlestun and Hetrick, 1986, 1991; Huddlestun and Summerour, 1996; Reinhardt, 1982; Reinhardt and Donovan, 1986; Reinhardt and others, 1980). Because of the stratigraphic complexities, only a highly generalized summary of the Coastal Plain stratigraphy pertinent to this paper's subject is shown in Table 1. A summary of the Late Cretaceous through Miocene stratigraphy is discussed by Cocker (1998), and more details are provided by the authors cited above.

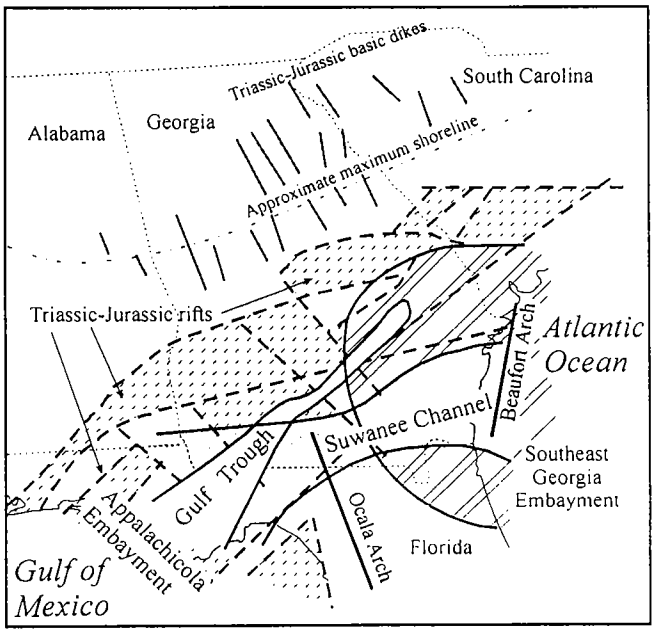


Figure 1. Major structural features in the subsurface of the Georgia Coastal Plain. Rift structure modified from Salvador (1991). Tertiary structures modified from Huddlestun (1988, 1993).

Development of Georgia's Coastal Plain began with Triassic-Jurassic rifting that is related to initial breakup of Pangea and consequent development of the Atlantic Ocean and Gulf of Mexico. Large, rift-related grabens extend across southern Georgia (Fig. 1), with the South Georgia Rift as the largest and most influential on Coastal Plain stratigraphy (Huddlestun, 1993). Subsidence along the South Georgia Rift during the Late Cretaceous permitted large-scale communication that persisted on an intermittent basis into the Miocene between the Gulf of Mexico and the Atlantic Ocean. The Appalachicola basin in western Florida and southwestern Georgia formed in the latter part of the Jurassic and may be related to the earlier rifting (Huddlestun, 1993).

The Appalachicola Embayment, Suwanee Channel, Gulf Trough, and Southeast Georgia Embayment (Fig. 1) are subsidence structures related to the Mesozoic rifting. From the Cretaceous into the Eocene, the Suwanee Current flowed from the Gulf of Mexico through the Appalachicola Embayment and Suwanee Channel to the Atlantic Ocean (Huddlestun, 1988, 1993). The Suwanee Channel eventually filled with sediment, and, from the Oligocene into the Miocene, the Suwanee Current shifted northward to the Gulf Trough. Eventually, the Gulf Trough became filled with siliciclastic sediment from the Georgia Piedmont and ceased to exist. During the Miocene, the Southeast Georgia Embayment subsided and was a depocenter principally for Miocene sediments.

Late Cretaceous and early Tertiary faulting is recorded in the Warm Springs bauxite district (White,

Table 1.—Rock Units, Environments of Deposition, and Industrial-Mineral Resources in the Georgia Coastal Plain

Series or system	Group	Rock unit	Depositional environment	Industrial-mineral resource
Holocene and Pleistocene		Satilla Formation, alluvial and aeolian deposits	Marginal marine (beach and barrier island), alluvial, and aeolian	Sand and gravel, sand, and heavy minerals
Pliocene				None identified
Miocene	Hawthorne	Hawthorne Group	Topographic/structural highs peripheral to marine basin	Phosphorite
		Meigs Member of Coosawatchie Formation Dogtown Member of Torreya Formation	Brackish lagoons in regressive marine sequence	Fuller's earth (attapulgite)
Oligocene			Continental shelf and bioclastic reefs	Limestone
Eocene	Barnwell	Twiggs Clay Member of Dry Branch Formation	Transgressive, shallow marine	Fuller's earth (opaline claystone/ montmorillonite), heavy minerals ?
	Ocala	Tivola Limestone	Marine continental shelf	Limestone
	Claiborne	Huber Formation	Deltaic, marginal marine (beach and barrier island), lagoonal,and near-shore marine	Kaolin, construction sand, heavy minerals
Paleocene	Oconee	Nanafalia Formation	Fluvial, deltaic, marginal marine (beach and barrier island), lagoonal, and near-shore marine	Kaolin, bauxite, heavy minerals ?
Cretaceous	Oconee	Buffalo Creek Member of Gaillard Formation Providence Sand Ripley Formation Cusseta Sand Blufftown Formation Eutaw Formation Tuscaloosa Formation	Fluvial, deltaic, marginal marine (beach and barrier island), near-shore marine	Kaolin, construction sand, bauxite, heavy minerals

Note: Stratigraphic units from Huddlestun and Hetrick (1986, 1991), Huddlestun (1988, 1993), and Huddlestun and Summerour (1996).

1965), Andersonville bauxite district (Cofer and Frederiksen, 1982), Irwinton kaolin district (Pickering and Hurst, 1989), and Augusta area (Prowell, 1988). Faulting is parallel to subparallel to the earlier Mesozoic rifting and may represent extensional reactivation of older compressional faults (Prowell, 1988). Late Oligocene and Early Miocene faulting is parallel and oblique to the Gulf Trough trend (Gelbaum and Howell, 1982). Thicker Ocala Limestone in the Gulf Trough area suggests that faulting may be at least Late Eocene (Gelbaum and Howell, 1982). Locally, these smaller scale faults appear to have controlled deposition of the kaolin-bearing strata in the Andersonville district (Cofer and Frederiksen, 1982) and perhaps in the Irwinton district (Pickering and Hurst, 1989). This faulting preserved the kaolin beds in these districts from erosion. Faulting in the Warm Springs district appears to post-date deposition of Late Cretaceous(?) kaolinitic and siliciclastic sediments but was prior to alteration of the kaolinitic beds to bauxite.

Cretaceous through Eocene clastic sediments (Table 1) near the Fall Line were deposited in fluvial, deltaic, lagoonal, marginal-marine, and near-shore environments. Sediments are generally more marine downdip to the south and southeast and along strike to the southwest. Repeated marine transgressions and regressions resulted in numerous fining-upward clastic sequences. Eocene, Oligocene, and Miocene carbonate sediments were deposited on a shallow shelf or carbonate banks (e.g., Florida Bank) in the central, southwestern, and southern parts of the Coastal Plain. Clastic sediments were derived from the Piedmont and spread southward, eventually filling the channels and embayments in this part of the Coastal Plain.

Pliocene, Pleistocene, and Holocene clastic sediments in southeastern Georgia were deposited in marginal-marine and near-shore environments during repeated marine transgressions and regressions. Seven major paleo-shoreline sequences (i.e., Wicomico, Penholoway, Talbot, Pamlico, Princess Anne, and Silver Bluff) were formed almost parallel to Georgia's present shoreline. These shoreline sequences consist of barrier-island and lagoonal salt-marsh facies. Barrier-island facies include dune, littoral, and offshore-channel deposits. Lagoonal salt-marsh facies include estuary and tidal channel sediments. These shoreline deposits are derived from reworking of deltaic clastic sediments that were transported from the Piedmont and Upper Coastal Plain by the principal river systems. Longshore currents, tidal, wave, and wind activity reworked and redistributed these sediments to form spits and barrier islands.

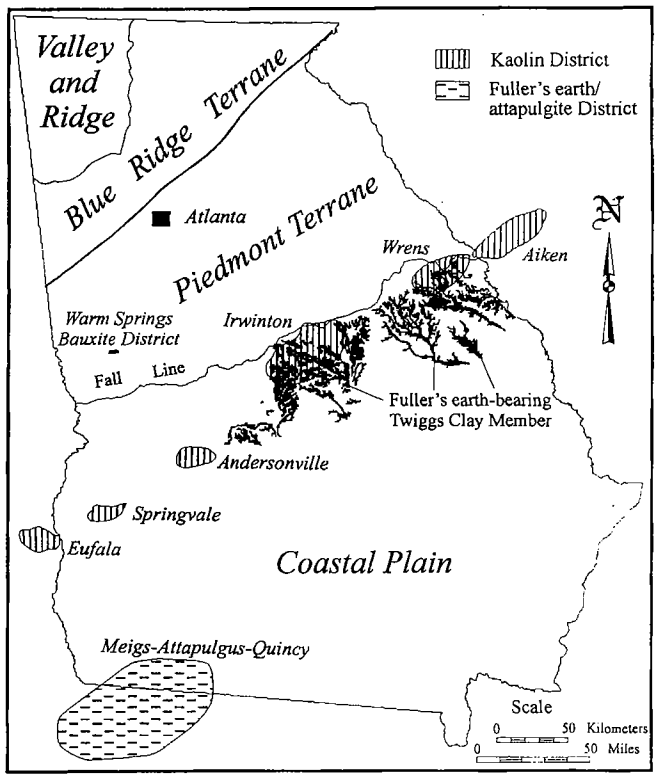


Figure 2. Cretaceous to Eocene kaolin districts, Warm Springs bauxite district, Eocene-age fuller's-earth–bearing Twiggs Clay Member of the Dry Branch Formation, and Miocene Meigs-Attapulgus-Quincy fuller's-earth- (attapulgite) district. Bauxite is locally an important component of the kaolin districts, particularly in the Eufala, Springvale, and Andersonville districts.

KAOLIN AND BAUXITE DEPOSITS

A string of kaolin-producing districts extends for 480 km from Aiken, South Carolina, to Eufala, Alabama (Fig. 2), and accounts for approximately 90% of U.S. kaolin production. Environmental and geological conditions from at least the Late Cretaceous through the Eocene favored formation of kaolin and bauxite in the southeastern United States. These conditions include: (1) source regions in the Georgia Piedmont with deeply saprolitized granitic rocks that probably included granites, granitic gneisses, and gneissic granites; (2) subtropical to tropical climate that fostered intensive chemical weathering in both the source regions and depositional sites, and that mineralogically enriched the kaolinitic sediments and locally favored bauxite formation; (3) low relief in the source and depositional areas favored chemical weathering rather than erosion; (4) major river systems that transported kaolin and kaolinitic detritus to depositional sites; (5) multiple episodes of fluvial sorting of eroded saprolitic materials, concentrated aluminous sediments, and kaolin; and (6) preservation of kaolin and bauxite concentrations through numerous transgressive and regressive depositional events.

Cretaceous kaolin deposits are found as irregularly shaped masses, tabular lenses, and discontinuous layers in the Buffalo Creek Formation (Table 1). This unit consists of siliciclastic sediments deposited in fluvial, marginal-marine, and shallow-shelf environments (Pickering and Hurst, 1989). Depositional environments in the kaolin districts of central and eastern Georgia are dominantly fluvial-deltaic. The size, shape, and quality of the kaolin deposits reflect the changing flow and depositional sites in a fluvial-deltaic system. Depositional environments grade from fluvial and marginal marine toward the open shelf downdip and to the west. Cretaceous kaolins are generally soft, and microtextures suggest that kaolin in these deposits have undergone in situ crystallization during diagenesis and weathering of feldspathic, micaceous sediments (Pickering and Hurst, 1989).

Tertiary kaolin deposits in central and eastern Georgia (Fig. 3) are found as bedded units in the Paleocene-Eocene Huber Formation (Table 1) (Austin, 1991; Buie, 1978; Hurst and Pickering, 1991; Patterson and Buie, 1974). In the Andersonville, Springvale and Eufala districts (Fig. 2), kaolin deposits are found within the Upper Paleocene Nanafalia Formation (Cofer and Frederiksen, 1982). Tertiary kaolins are generally hard, and microtextures suggest that these kaolins were deposited in a shallow-marine or lagoonal environment under brackish to salt-water, reducing conditions (Pickering and Hurst, 1989). These kaolins were

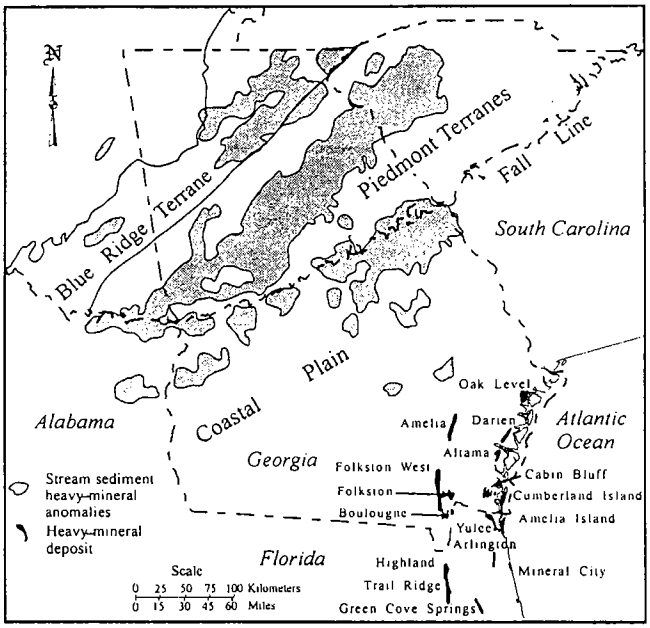


Figure 3. Stream-sediment heavy-mineral anomalies in the Upper Coastal Plain, Piedmont, and Blue Ridge terranes, and Pleistocene and Holocene heavy-mineral deposits. Heavy-mineral deposits at Amelia, Altama, Arlington, Boulougne, Cabin Bluff, Cumberland Island, Darien, Folkston, Folkston West, Green Cove Springs, Highland, Mineral City, Trail Ridge, and Yulee are associated with Pleistocene and Holocene marginal-marine (beach and barrier island) and aeolian environments (Pirkle and others, 1991).

apparently well-sorted kaolinitic detritus that was concentrated and deposited in a low-energy environment.

Desilication of kaolin and kaolinitic sediments during subaerial exposure of the southeastern kaolin deposits produced bauxite and bauxitic sediments. The Andersonville, Springvale, Eufala, and Warm Springs districts (Fig. 2) contain larger quantities of bauxite than the other southeastern kaolin districts. Bauxite formation occurred during the Paleocene and Eocene during extensive periods of subaerial weathering (Cofer and Frederiksen, 1982). Resubmergence permitted resilication of some of the bauxite deposits to form kaolin. The ages of the sediments and bauxite are uncertain in the Warm Springs district, which is a downfaulted inlier of Coastal Plain sediments within the Georgia Piedmont (White, 1965).

FULLER'S EARTH

In Georgia, fuller's-earth deposits are found in Eocene and Miocene sediments (Fig. 2, Table 1). Early Miocene depositional environments were more favorable for producing large, mineralogically uniform fuller's-earth deposits than were Eocene environments. In central Georgia, the lower to middle Eocene Twiggs Clay Member of the Dry Branch Formation contains opaline claystones that consist of opal (alpha cristobalite), montmorillonite, and quartz, with subordinate amounts of illite (Carver, 1972). The Twiggs Clay and Irwinton Sand Members are regarded as a series of regressive clastic sediments. Abundant siliceous radiolaria, diatom, and sponge microfossils, and montmorillonite indicate that the Twiggs Clay was deposited on an inner marine shelf at a depth of a few feet to 200 ft (Schmidt and Wise, 1982). Ocean currents supplied nutrients that favored extensive planktonic growth at that time (Wise and others, 1974). The association of opal claystones with clinoptilolite and phillipsite in South Carolina and with clinoptilolite and heulandite in Alabama may indicate a volcanic-ash input that supplied silica for the siliceous microfossils. The relative abundances of opal and montmorillonite as well as degree of porosity determine the absorption capacity of water and ethylene glycol for these fuller's earths (Carver, 1972). Most of the Eocene fuller's-earth deposits are rather limited in their economic development, perhaps because of the variable mineralogy. These fuller's-earth clays are used with Tivola Limestone in the production of portland cement and as absorbents.

In southern Georgia and north-central Florida, fuller's-earth deposits are found in sediments of the Miocene Hawthorne Group on the southeastern side of the Gulf Trough (Figs. 2, 3). Commercial deposits are found in the Dogtown Clay and Meigs Members of the Torreya Formation, which is at or near the surface only in southwestern Georgia and adjacent parts of Florida. Montmorillonite was deposited initially in restricted lagoonal environments that developed during several Early Miocene regressive sea-level events (Weaver and Beck, 1982). Montmorillonite was altered to palygorskite in the shallow, brackish-water lagoons by reaction with relatively high concentrations of silica and magnesium. The source of the silica may be upwelling, cold ocean water. Widespread dolomitization of Miocene sediments indicates that magnesium-bearing solutions were also abundant. High temperatures and subtropical conditions favored alteration of the montmorillonite to palygorskite. Palygorskite deposits in the younger Meigs Member may be detrital and perhaps derived from the older authigenic clay deposits (Weaver and Beck, 1982). Shorter palygorskite fibers in the Meigs Member may indicate that the Meigs Member palygorskite was derived from the Dogtown Member.

HEAVY MINERALS

Concentrations of heavy minerals are found in Cretaceous to Eocene clastic sediments near the Fall Line and Pleistocene to Holocene clastic sediments in southeastern Georgia, adjacent parts of northeastern Florida, and offshore Georgia. Stream-sediment geochemistry suggests that rock units (Table 1) in the Upper Coastal Plain of Georgia (Fig. 3) that are geochemically most favorable for heavy-mineral deposits (i.e., those that contain higher mean concentrations of the rare-earth elements, Hf, Th, U, and Ti, with low Fe/Ti ratios) include the Tuscaloosa Formation, undifferentiated Cretaceous and Tertiary strata, the Twiggs

Clay, and the Irwintown Sand (Cocker, 1998). Heavy minerals are commonly concentrated near the base of the Paleocene to Eocene Huber Formation (one of the undifferentiated Cretaceous and Tertiary strata), where that unit overlaps Cretaceous strata (Pickering and Hurst, 1989). Cretaceous to Eocene clastic sediments that are enriched in heavy minerals may represent barrier-island systems and beach deposits. Geological and climatic conditions from the Late Cretaceous through the Eocene that favored formation of kaolin and bauxite deposits also were favorable for heavy-mineral placer deposits. These conditions include: (1) source regions with preconcentrated heavy minerals in Paleozoic paleoplacer deposits; (2) subtropical to tropical climate that fostered intensive chemical weathering in both the source regions and depositional sites and that mineralogically enriched the economic heavy minerals; (3) low relief in the source and depositional areas favored chemical weathering rather than erosion; (4) major river systems that transported detritus to depositional sites; and (5) preservation of placer concentrations through numerous transgressive and regressive depositional events.

In southeastern Georgia and Florida (Fig. 3), the heavy-mineral deposits at Trail Ridge, Highland, Yulee, Cabin Bluff, Folkston, Boulougne, Green Cove Springs, and Altama are associated with major shoreline sequences. These detrital deposits were formed either during a major transgressive event or during a regressive phase of a transgressive-regressive event (Force, 1991; Pirkle and others, 1991). Heavy minerals that have been transported by the major river systems from the Georgia Piedmont or from Cretaceous and Lower Tertiary deposits in the Upper Coastal Plain (Table 1) were deposited in deltaic and near-shore-marine deposits. Longshore currents, wave and tidal action, and aeolian processes transported and concentrated the heavy minerals into beach and dune deposits (Cocker, 1993a,b; Force, 1991; Pirkle and others, 1991). Transportation and concentration of heavy minerals continues in the present shoreline environment (Bonn and Simonson, 1991; Cocker and Shapiro, 1994). In addition, heavy minerals were concentrated during periods of lower sea level in the Quaternary along the Atlantic continental shelf from Georgia and up to New England (Grosz, 1987, 1993; Grosz and others, 1986).

SAND AND GRAVEL AND SILICA SAND

Sand and gravel for aggregate, construction sand, and silica-sand deposits are found in unconsolidated Cretaceous and Tertiary clastic sandy units particularly near the Fall Line, in Pleistocene and Holocene beach sediments in southeastern Georgia, and in Quaternary-age river sediments such as point bars, river terraces, and aeolian dunes (Fig. 4, Table 1). Numerous sand deposits have been mined in unconsolidated Cretaceous and Tertiary clastic sediments, particularly from the Cretaceous Gaillard Formation. These sediments represent fluvial, deltaic, and marginal-marine depositional environments. Pleistocene and Holocene beach sediments located in southeastern Georgia were deposited during marine transgressive-regressive events. Quaternary alluvial deposits are predominantly sand with minor clay. Locally, river terrace deposits may be gravel-rich; their composition appears dependent on local sources (Huddlestun, 1988). River-terrace deposits have been linked tentatively to the Pleistocene sea-level changes. Larger, river-terrace deposits are located adjacent to the major rivers (i.e., Chattahoochee, Flint, Ocmulgee, Oconee, Altamaha, Ogeechee, and Savannah Rivers). In point-bar and flood-plain deposits the sand is clean, loose, and well-sorted, with sizes ranging from fine to coarse (Huddlestun, 1988). Aeolian dune deposits (Fig. 4) have been recognized on the eastern side of several smaller river systems (i.e., Ohoopee and Little Ocmulgee Rivers) in eastern Georgia and on the eastern side of the Flint River near Albany in western Georgia. These aeolian deposits may have formed by reworking of alluvial sand deposits during a dry and windy period in the Quaternary when river flow was lower. Sand in these deposits is well to moderately well sorted and fine- to medium-grained (Huddlestun, 1988).

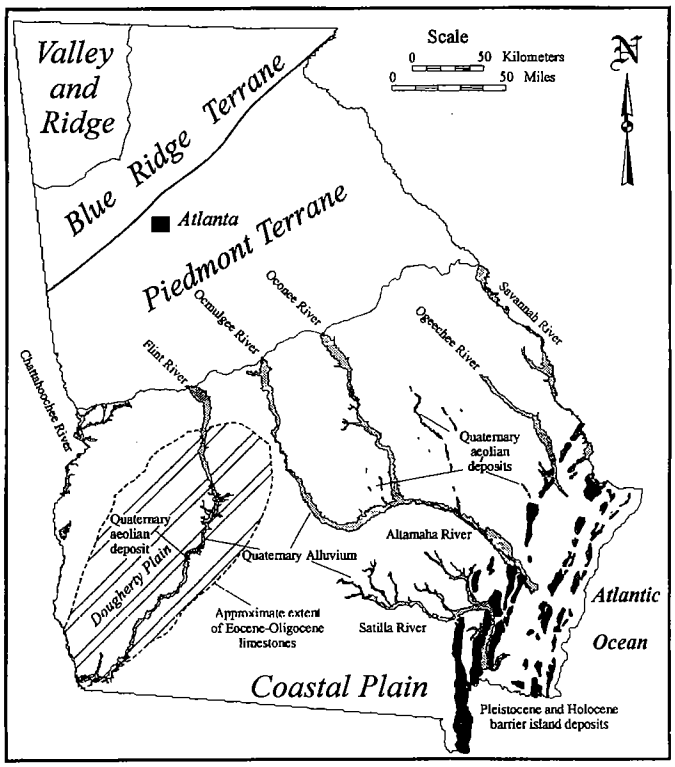


Figure 4. Eocene and Oligocene limestones, Quaternary alluvium and aeolian sand-and-gravel deposits, and Pleistocene to Holocene sand deposits. Alluvium and aeolian deposits are associated with the major river systems. Pleistocene to Holocene sand deposits are associated with barrier-island sequences.

Size fractions, mineralogical composition, impurities (e.g., clay beds) and size of these deposits vary with each type of deposit. Commercial viability of each deposit will depend on those factors as well as intended

uses and distance to markets. These deposits have been sources for glass sand, construction aggregate, and fill material. Friddell (1990), Friddell and Brackman (1990), and Brackman (1993) analyzed many of these deposits for their aggregate potential. Their analyses were based on sieve fractions and estimates of the size of each deposit that was sampled.

LIMESTONES

The Upper Eocene Tivola Limestone of the Ocala Group, and the Oligocene Bridgeboro and Suwannee Limestones (Table 1) are exposed primarily in the Dougherty Plain of southwestern Georgia (Fig. 4). Of lesser importance are carbonates of the Lower Paleocene Clayton Formation which are found in the Fall Line Hills northwest of the Dougherty Plain. Primary uses for Coastal Plain limestones include portland cement, aggregate, and agricultural lime.

The Tivola Limestone in central Georgia is a bioclastic limestone formed on a shallow-water shelf (Manker and Carter, 1989). It is the source of lime for portland cement at the Clinchfield quarry in Houston County.

The Bridgeboro Limestone is found on both flanks of the Gulf Trough and is thought to represent a shelf-edge buildup or reef. It is distinguished from the adjacent and superjacent limestone formations by the presence of common to abundant rhodoliths (Huddlestun, 1993). Formation of the rhodoliths may be associated with strong currents on the flanks of the Gulf Trough, and deposition was in moderately deep water under relatively high-energy conditions (Huddlestun, 1993). The Bridgeboro quarry is developed in 21 m of limestone that is dominated by a densely packed mass of algal rhodoliths (Manker and Carter, 1989; Carter and others, 1995). The principal use of the Bridgeboro Limestone is for aggregate. Other carbonate units (mudstones, wackestones, and packstones), which are present in the subsurface and are contemporaneous with the Bridgeboro Limestone, are thought to represent open-shelf, quiet-water deposits that developed shoreward from the Bridgeboro Limestone.

The Suwannee Limestone is a granular, relatively pure limestone that formed over much of southeastern Georgia. As the Suwanee Channel filled with sediment, the Florida Bank extended northward. The Florida Bank is considered to be an equivalent of the modern Bahama Banks (Huddlestun, 1993).

PHOSPHORITES

Major phosphorite deposits have been mined in North Carolina and Florida, with 95% of the U.S. production from these areas. Although no phosphorite has been mined in Georgia, important deposits are found in the Middle Miocene Hawthorne Formation and the Upper Miocene Duplin Marl within the Southeast Georgia Embayment (Figs. 1,5). Within these units, higher phosphorite concentrations are found adjacent to the Ocala and Carolina platform highs. Maximum concentrations (≥4.1% P_2O_5) are associated with anti-

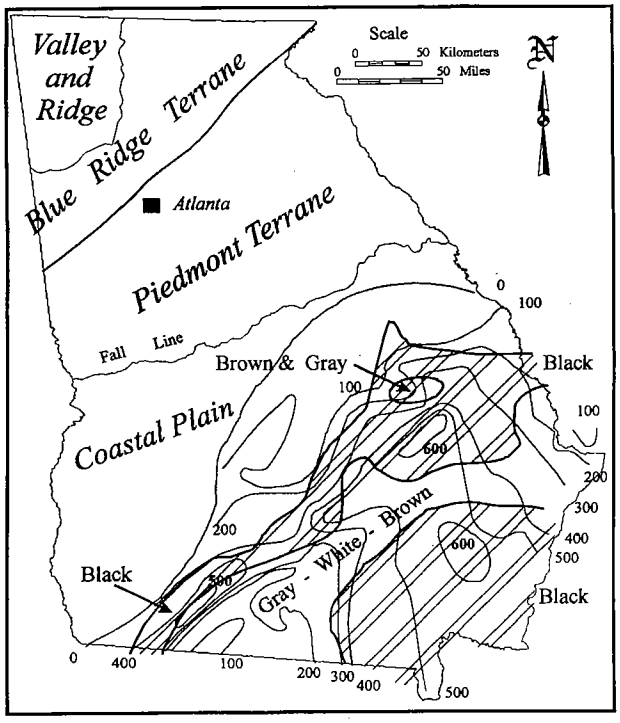


Figure 5. Relation of phosphorite color in Miocene sediments (Husted, 1970) to thickness (in feet) of Miocene to Holocene sediments (Herrick and Vorhis, 1963). Lighter colored phosphorites are found on and proximal to topographic highs where these sediments are thinner and reflect oxidizing conditions. Darker colored phosphorites reflect higher iron and organic contents found in deeper parts of the Miocene basins.

clinal structures (i.e., the Central Georgia Uplift in south-central Georgia, the Peninsular Arch in Florida, and the Beaufort Arch in eastern Georgia near Savannah). Potentially economic concentrations of phosphorite are found in Chatham (6–25% P_2O_5 in the Duplin Marl), Atkinson, Berrien, Clinch, Echols, Lanier, and Lowndes Counties (Husted, 1970). An increase in grain size, lighter color (gray to brown), and lower iron and carbon content of phosphorites near and on the anticlinal highs (Fig. 5) indicate a shallow, high-energy, oxidizing environment. Higher concentrations of phosphorite in these shallower areas may be caused by warming of upwelling, cold, nutrient-laden, ocean water, higher pH, increased salinity, lessened pressure, low rate of sedimentation, and biogenic activity. Black, finer grained phosphorites are found on both sides of the anticlinal high and contain exceptionally higher concentrations of carbon and iron.

Phosphorite genesis is related to five major Miocene sea-level transgressions within the Southeast Georgia Embayment. Major phosphorite enrichment zones are in basal sediments above the unconformities representing erosion during lower sea-level stands (Mannheim, 1992). These sea-level changes may be associated with major glaciation and deglaciation (Riggs and Belknap, 1988). Upwelling of cold, nutrient-rich, deeper

waters into the Southeast Georgia Embayment increased organic productivity and created conditions critical for phosphorite formation. Smaller scale structural or topographic features noted above determined the amount and types of phosphorite and associated sediment composition by controlling oceanic boundary currents.

PEAT

Peat deposits in Georgia are found in large coastal freshwater swamps (e.g., Okeefenokee swamp), intertidal salt marshes, Carolina bays, and small freshwater wetlands (Forston, 1961). Carolina bays are elliptical depressions that may be aeolian in origin, but that origin is controversial. All of these deposits are located on Pleistocene fluvial terraces, and they are believed to have formed during the Pleistocene or later (Huddlestun, 1988). Peat is presently mined only for agricultural soil improvement, but estimates of fuel-grade peat resources in Georgia are 800 million dry tons (Forston, 1961).

SUMMARY

Georgia's Coastal Plain contains a wealth of industrial-mineral resources that include world-class deposits of kaolin, bauxite, palygorskite, heavy minerals, and phosphorites, as well as locally important deposits of sand and gravel, industrial sand, glass sand, aggregate (crushed limestone), limestone, and peat. Factors that influenced the genesis, location, size, and quality of these deposits are related to: (1) depositional environments that evolved during development of the southeastern North American continental margin; (2) climatic conditions that favored intensive chemical weathering; (3) source areas with mineralogical or chemically favorable source materials; and (4) transportation of materials to depositional sites. Numerous marine transgressions and regressions from the Jurassic to the Holocene favored a variety of depositional environments and repetition of these environments. Chemical and physical reworking of earlier deposits is evident for some mineral resources (e.g., kaolin, bauxite, heavy minerals, palygorskite). Cretaceous to Early Eocene depositional environments are fluvial, deltaic, lagoonal, marginal marine, and near-shore marine. Cretaceous to Lower Eocene mineral resources include kaolin, sand, sand and gravel, bauxite, heavy minerals, and fuller's earth (opaline claystone). Middle Eocene to Miocene depositional environments are dominantly lagoonal, nearshore marine, and shallow continental shelf. Mineral resources formed during this period include limestone, fuller's earth (palygorskite), and phosphorite. Pleistocene and Holocene depositional environments are fluvial, aeolian, deltaic, lagoonal, and marginal marine. Mineral resources include heavy minerals, sand, and sand and gravel. Access to cheap transportation, industrial and urban centers, and amenability to low-cost production enhance the viability of Coastal Plain industrial-mineral resources.

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Nonmetallic Mineral Resources of Wisconsin

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ABSTRACT.—Construction aggregate is the most important nonmetallic-mineral commodity in quantity and value that is produced in Wisconsin. Crushed stone is produced from the Precambrian crystalline rocks and the Ordovician and Silurian carbonates, and sand and gravel is extracted from Quaternary glacial deposits. Dimension stone is quarried from both the Precambrian crystalline rocks and Paleozoic carbonate rocks. Other nonmetallic minerals include industrial sand, lime, roofing granules, terrazzo aggregate, and peat.

INTRODUCTION

The varied bedrock geology and the extensive glacial deposits of Wisconsin contain a wide variety of mineral resources. Historically, Wisconsin has been known for metals—lead and zinc from the Upper Mississippi Valley District, Lake Superior-type iron ores, and, more recently, copper and zinc from volcanogenic massive-sulfide deposits in the Precambrian. Wisconsin has no coal or oil and gas, but it has a long history as a producer of other nonmetallic minerals. Building stone was quarried and used by the earliest settlers. In the late 19th and early 20th century, Wisconsin had an extensive brick industry. During this period, more than 20 quarries produced dimension granite for building, paving blocks, and monument use, and Wisconsin exported brownstone from several quarries in the Keweenawan sandstones along the Lake Superior shore and in the Apostle Islands. Also at this time, the silica-sand industry began in response to the growing need for molding sand in the foundry industry.

Today, no metal mines are active in Wisconsin, although one massive sulfide (zinc-copper) deposit is in the process of seeking permits to open. With an annual value of around $250 million, crushed stone and sand and gravel for use as construction aggregates are the leading mineral commodities in quantity and value that currently are produced in Wisconsin. Other nonmetallic-mineral products currently produced in Wisconsin include dimension stone, industrial sand, lime, and peat.

GEOLOGIC SETTING

The geologic structure of Wisconsin is basically a broad arch of Precambrian rocks that extends southward from the Canadian Shield. This arch is surrounded on three sides by the major Paleozoic sedimentary basin in Michigan, Illinois, and Iowa. The Precambrian rocks of northern Wisconsin range in age from Archean to middle Proterozoic. The youngest Precambrian rocks belong to the 1,000 Ma Keweenawan Series of the Midcontinent Rift. These include metabasalts and related volcanic and intrusive rocks and a thick sequence of red sandstones exposed along the southern shore of Lake Superior (Fig. 1). To the south of the Keweenawan, a broad area of metamorphic and plutonic rocks represents remnants of the rifted southern margin of the Archean Superior Craton, and the volcanic arc that was accreted during the Penokean Orogeny at around 1,850 Ma (Greenberg and Brown, 1983). The Penokean volcanic terrane contains at least 15 known volcanogenic massive-sulfide deposits as well as abundant granite resources. The quartzites of the Baraboo Interval were deposited after the Penokean deformation and before the emplacement of the Wolf River Batholith, a large anorogenic granitic complex dated at ≈1,500 Ma (Greenberg and Brown, 1984).

No rocks representing the interval from the Keweenawan to the Late Cambrian are preserved in Wisconsin. In the Late Cambrian, the region was submerged by advancing seas, in which were deposited a series of quartz sandstones during several depositional cycles (Ostrom, 1964). From the Early Ordovician through the earliest Devonian, the depositional environment was dominated by carbonates, with the exception of the St. Peter Sandstone and the Maquoketa Shale. No rocks representing the interval from Devonian to the beginning of the glacial period in Late Pliocene are preserved in Wisconsin, with the possible exception of isolated gravels in the unglaciated area of southwestern Wisconsin, which may be Cretaceous in age.

All of Wisconsin, with the exception of roughly the southwestern quarter (Fig. 1), was covered by continental glaciers during the several periods of glaciation that occurred from Late Pliocene to early Holocene (Clayton

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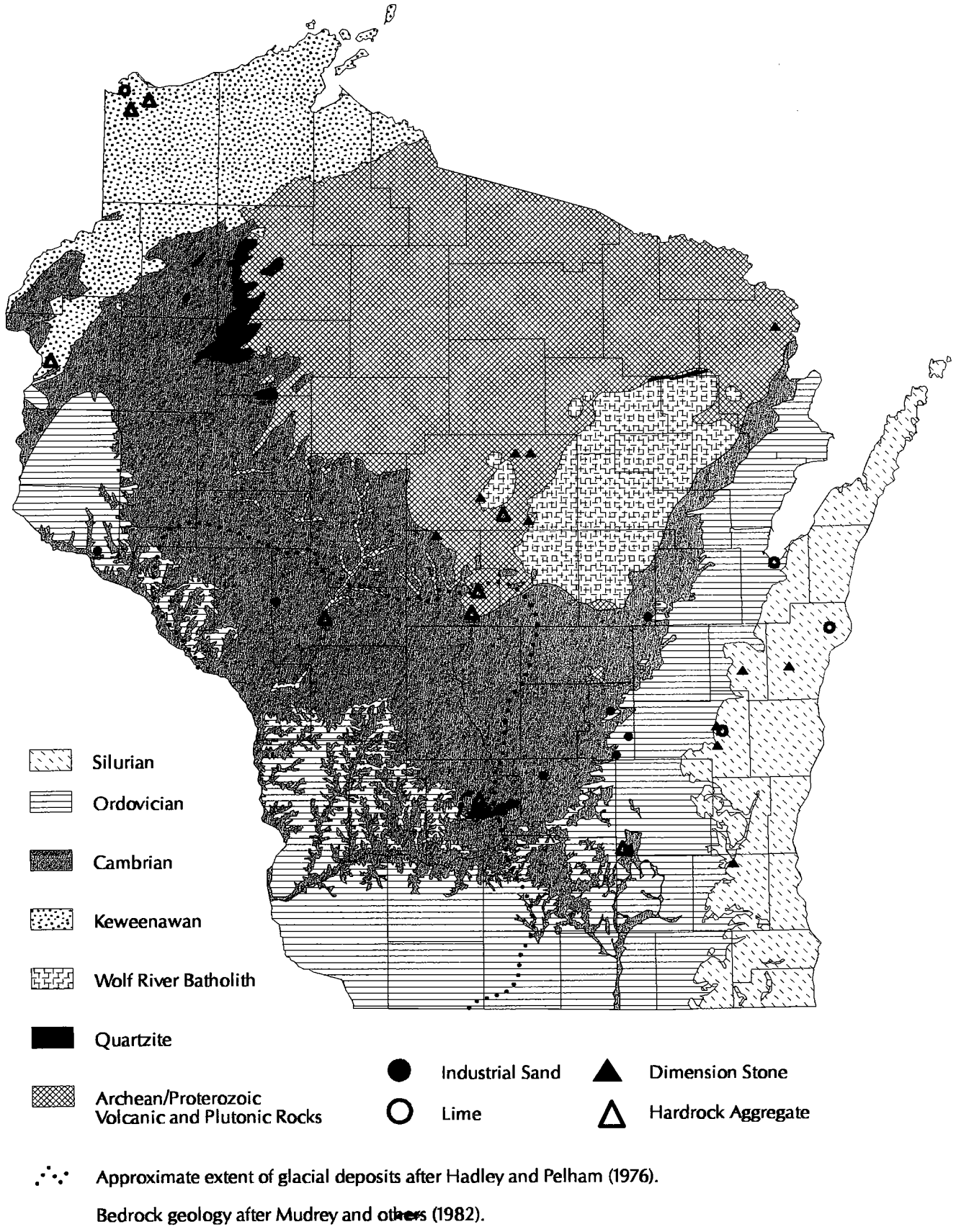


Figure 1. Map of Wisconsin showing generalized bedrock geology, limits of glaciation, and major nonmetallic-mineral-producing areas.

and others, 1992). Most of the surficial deposits and glacial landforms that dominate the topography of eastern and northern Wisconsin today resulted from the last period of glaciation, the Wisconsin glaciation, which lasted from approximately 25,000 to 9,500 years ago.

CRUSHED-STONE AGGREGATES

The Precambrian terrane of northern Wisconsin is a nearly limitless resource of high-quality crushed stone. Historically, the most important sources of crushed-stone aggregate have been metabasalt (traprock) of the Keweenawan and the Proterozoic quartzite exposed in the Baraboo area (Fig. 1). Both of these rocks are exceptionally hard and durable materials that have proven over many years to be excellent sources of railroad ballast and riprap. Increased demand for ballast and high-quality aggregate for asphalt paving has resulted in the opening of several quarries in granitic rocks in central Wisconsin. The Waterloo quartzite, a small inlier of Precambrian rocks in southeastern Wisconsin, has become an important source of ballast and aggregate as a by-product of quarrying riprap for breakwater construction on the Great Lakes.

Granitic rocks along the western margin of the Wolf River Batholith in Marathon and Portage Counties commonly become disaggregated by deep weathering. This material, which consists of feldspar and quartz grains, is technically called grus but is known locally as "rotten granite." It is easily quarried and has been used locally as road base and fill material for many years. Rotten granite is not suitable for concrete or asphalt aggregate, but, in recent years, it has become popular as a landscaping material and is now being shipped in large quantities to urban markets in southern Wisconsin and the Chicago area.

Most of the crushed stone aggregate produced in Wisconsin comes from the Paleozoic carbonate rocks. The Ordovician Prairie du Chien and Sinnipee Groups are the principal sources of aggregate in the unglaciated region of southwestern Wisconsin. Both are important in eastern Wisconsin as well, where, along with Silurian rocks, they are an important aggregate source for the Green Bay and Fox Valley urban corridor. The Silurian carbonates are the principal source of crushed stone for the Milwaukee and southeastern Wisconsin metropolitan region. Quarries developed in all three of the Paleozoic carbonate units produce quality stone that meets all state and local specifications for asphalt and concrete aggregate. The Sinnipee Group is the most variable of the three and may locally contain significant amounts of shale and shaly carbonate. Locating new quarry sites in the Sinnipee rocks requires careful evaluation and testing to avoid soundness problems. The Prairie du Chien and Silurian are less shaly than the Sinnipee, but they locally may contain beds with a high chert content.

The Paleozoic carbonates are in general an excellent aggregate resource and are widely utilized throughout their outcrop areas. The problem that threatens future supplies, particularly in southeastern Wisconsin, is not one of availability or quality but rather accessibility due to rapid suburban and rural residential development.

SAND AND GRAVEL

Sand and gravel are produced from the Quaternary glacial deposits that cover the eastern and northern areas of Wisconsin (Fig. 1). The best deposits generally are found in a variety of stagnant-ice and meltwater landforms, such as kames, eskers, and stream terraces, and in the extensive outwash deposits that formed in front of ice margins as the last glaciers retreated. The glacial gravels are generally of excellent quality, containing very few deleterious materials. Gravels from the Lake Michigan and Green Bay Lobes in eastern Wisconsin have a high carbonate content, which reflects the underlying Silurian and Ordovician rocks from which they were derived. Gravels in northern Wisconsin likewise consist predominantly of crystalline material derived from the Precambrian.

In the past, glacial sand-and-gravel deposits were mined and used directly with minimal processing. Today, most large producers must crush, screen, wash, and commonly blend material to meet gradation requirements. Sand and gravel are still the dominant source of aggregate in much of the state, particularly in the north. Production of crushed stone has surpassed sand and gravel in recent years, probably reflecting the demand for crushed material in modern asphalt mixes and the depletion of some of the larger sand-and-gravel deposits in the urban areas of southeast Wisconsin. Gravel, however, remains the preferred aggregate of the ready-mix-concrete industry, and pea gravel is in demand for roofing, seal-coat aggregate, and the manufacture of patio block and other ornamental concrete products.

The most extensive undeveloped gravel deposits left in Wisconsin are in the northern counties. This resource has long been recognized (Hadley and Pelham, 1976), but never was considered economic because of the great distance to urban markets. As with crushed stone, the difficulty of permitting new sites in southern Wisconsin and northern Illinois may make these resources economically attractive in the near future.

DIMENSION STONE

Various dimension-stone products are quarried from both the Precambrian crystalline rocks and the Paleozoic sedimentary rocks. One hundred years ago, more than 20 independent dimension-stone quarries were operating in the Precambrian rocks of northern Wisconsin. Products included monuments, granite building stone, paving blocks, and Lake Superior Sandstone (brownstone) from the Keweenawan (Buckley, 1898). Today, the Keweenawan sandstones are no longer quarried, and only two dimension-granite producers remain, operating five dimension-granite quarries. Four of the active quarries are in red granite of the Wausau area in central Wisconsin, and one is in gray granite in the Amberg area of northeast Wisconsin (Fig. 1). Monument granite is the principal product, but

but increasing amount of stone is being used for countertops, building stone, and paving tiles. A small amount of Wisconsin granite is made into surface plates for the machine-tool industry.

Ownership changes and consolidation of small operations have resulted in modernization and increased efficiency of quarrying operations. Antiquated quarry derricks have been replaced by ramp access, and heavy loaders are now used to transport large blocks from the quarry face to the slabbing saws. Different grades of stone now are quarried selectively. Stone with color variation or other slight imperfections that make it unacceptable for monument use is no longer waste but can be quarried expressly for use in countertops, building stone, floor tile, or crushed for terrazzo or aggregate. Modernization of the quarrying and finishing processes and expansion of product lines has revitalized the dimension-granite industry in Wisconsin after many years of steady decline.

In 1996, statistics compiled by the U.S. Geological Survey ranked Wisconsin second in the United States in production of dimension limestone. Building stone has been produced for many years from the Silurian in the Sussex-Lannon area of Waukesha County, the Byron area of Fond du Lac County, and quarries in Calumet and Manitowoc Counties (Fig. 1). Operators report that demand for structural and facing stone is strong, but the recent growth in total dimension-limestone production is due to a rapidly growing market for flagstone and stone for landscaping use.

Sandstone of the Keweenawan series was quarried extensively along the Lake Superior shore and shipped on the Great Lakes to many areas of the Midwest. This red to brown sandstone was easily worked into finely carved and ornamented building stone. It was popular in the late 19th century for public buildings but has not been quarried for many years. There has been recent interest in opening a new source of this stone for use in restoration work. A small amount of dimension sandstone is produced from silicified Cambrian sandstone by one operation in central Wisconsin. This deposit yields both thin slabs used as flagstone and more massive material that can be cut into building and facing stone. Because of its similar color and appearance, this stone is sometimes used in restoration work as a substitute for the Keweenawan sandstones.

Well-rounded glacial boulders are collected and split to make a popular dimension stone that looks like natural field stone. It is widely used for facing stone and for fireplace construction. Boulders of crystalline rock 8–12 in. in diameter are selected from coarse gravel deposits and split using a hydraulic splitter. Larger boulders, particularly those too large to easily crush, commonly are set aside and sold for landscaping use.

INDUSTRIAL SAND

The Upper Cambrian Wonewoc and Jordan Formations along with the Ordovician St. Peter Sandstone constitute a nearly inexhaustible resource of nearly pure quartz sand (Ostrom, 1971; Trainer, 1928). The Cambrian sandstones are exposed in a belt up to 75 mi wide across west-central Wisconsin (Fig. 1). These sandstones are in general poorly cemented and can be mined hydraulically. Most are sufficiently clean to require only minimal processing to remove clay and iron-oxide coatings.

Seven active sand mines produce a variety of industrial-sand products. Most sand produced in eastern Wisconsin comes from the Jordan or the St. Peter Formations and is used as foundry sand. Two operations in the Cambrian Wonewoc Formation (Galesville Member) in west-central Wisconsin produce filter sand, sand for sandblasting, hydrofrac sand for the drilling industry, and sand for the glass industry as well as foundry sand. An operation in the Jordan Formation in western Wisconsin produces exclusively hydrofrac sand from the only active underground mine in the state.

LIME

The Ordovician and Silurian carbonate rocks of Wisconsin are predominantly dolostones. Significant limestone is known only in the Sinnipee Group in extreme southwestern Wisconsin. The Silurian rocks are too magnesium-rich for portland-cement manufacture but are locally suitable for manufacture of lime for masonry and plaster and other industrial uses. At one time, Wisconsin had many small lime operations burning small quantities of lump lime in wood-fired shaft kilns. Today, three modern rotary-kiln plants in eastern Wisconsin produce a variety of lime products from the Silurian carbonates, although one manufacturer imports limestone to blend with local material. One lime plant in northwestern Wisconsin uses imported materials exclusively.

Wisconsin has more than 100 licensed producers of agricultural lime. Aglime is most commonly produced as a by-product in quarries where the primary product is aggregate. The best aglime, that with the highest calcium-carbonate content, comes from the Silurian carbonates. Rock from the Prairie du Chien and Sinnipee Groups are used for aglime locally in southern and western Wisconsin, although these rocks are commonly more dolomitic.

CLAYS AND SHALE

Wisconsin has no active industrial-clay or -shale production at present. Nearly a century ago, there was a growing brick and tile industry and considerable effort was made to find and evaluate clay resources throughout the state (Buckley, 1901; Ries, 1906). Clay deposits are found in a variety of environments, notably from glaciolacustrine deposits, residual soils, and weathered granite in the Precambrian, and the Ordovician Maquoketa Shale in eastern Wisconsin. Most brick-and-tile operations were small, using limited local clay deposits, and the industry died out in the 1970s. The last active brick producer in Wisconsin was located at Oakfield in Fond du Lac County, making brick from the Maquoketa Shale.

In the late 1970s, a study was made to evaluate a

clay deposit in western Wisconsin for suitability as a binder for taconite pellets (DasGupta and others, 1983), but the deposit was never developed. Today, the only clays mined in Wisconsin are used as impermeable-liner material in construction of landfills and reservoirs.

OTHER NONMETALLIC MINERALS

Other nonmetallic-mineral materials currently produced in Wisconsin include peat, roofing granules, and terrazzo aggregate. Several small operations mine peat from bogs in the glacial deposits of eastern Wisconsin. Most Wisconsin peat is used by the landscape and nursery industries. Two large operations in northern Wisconsin produce roofing granules. The rock mined and processed into granules is dense, fine-grained, felsic-to-intermediate metavolcanic rock of Proterozoic age. One specialized operation in central Wisconsin supplies aggregate for terrazzo, exposed-aggregate concrete products, and for the manufacture of artificial stone. This material is produced in a variety of colors and sizes from both imported stone and waste rock scavenged from the local dimension-granite quarries.

In the past, small amounts of talc, soapstone, and graphite were mined from small local deposits in the Precambrian rocks. Northern Wisconsin has not been explored fully for potential industrial-mineral resources. Occurrences of feldspar, anorthosite, and nepheline syenite as well as a variety of potential building and ornamental stones are associated with the Proterozoic granitic rocks, particularly the Wolf River Batholith.

FUTURE OUTLOOK

If the overall economy remains strong, the outlook for the nonmetallic-mineral industry in Wisconsin is good. The industrial-sand and -lime industries have remained stable in recent years and probably will continue to grow slowly. The dimension-stone industry has grown in response to increased demand for natural-stone countertops, tiles, flagstone, and landscape stone that have become popular in upscale housing construction. Growth of cities and suburban areas, particularly in southeastern Wisconsin and in the Fox River Valley of the northeast, is a source of both prosperity and concern for the aggregate industry. Many of the best resources of sand and gravel and crushed stone in these rapidly developing areas of the state are being sacrificed to other land uses. The future of the nonmetallic-mineral industry, and particularly of the aggregate industry in Wisconsin, depends on how soon we begin to incorporate mineral-resource information into the processes of regional and local land-use planning.

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An Overview of the Status of Industrial Minerals in the United States

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INTRODUCTION

The production and consumption of industrial minerals in the United States traditionally have played important roles in mining and in the supply of the bulk of basic raw materials to the economy. This diverse group of minerals extracted and consumed by a variety of industries accounts, on a weight and volume basis, for most mineral-based products consumed in our economy. Industrial minerals form the bulk of the basic raw-materials feedstock for most of the construction, agricultural, and inorganic-chemical-manufacturing sectors, and a good portion of the transportation, manufacturing, organic chemical, and service sectors of the U.S. economy.

In this presentation, I discuss current estimates of the amount and value of industrial minerals mined compared with all mining in 1997. I then present a summary of 1997 production of industrial minerals by several end-use industries. This is followed by a historical perspective of the consumption of industrial minerals as a subset of all basic materials, with special emphasis on the aggregates industry. The presentation concludes with a look at the geographic distribution of industrial mineral operations in the United States and some thoughts about the future.

DATA SOURCES

The U.S. Government has been gathering data on minerals, including industrial minerals, for more than 110 years. This has been one of the principal responsibilities of the U.S. Geological Survey (USGS) and the former U.S. Bureau of Mines (USBM). It is mostly from these data that the following observations and generalizations were derived.

Much of what is discussed here is from a perspective of weight. Data units for this study were, for the most part, in metric tons. Data on nonfuel minerals in this presentation have been gleaned from annual reports and Mineral Commodity Summaries. These reports were published by the USGS through 1923, by the USBM from 1923 to 1995, and by the USGS subsequently. Much of the interpretation of the historical data and trends for specific commodities was by the respective mineral-commodity specialists of the Industrial Minerals Section of the Minerals Information Team in the USGS. The credit belongs to them and their resources. For the most part, data for 1997 are preliminary estimates.

MONETARY VALUE

In 1997, the value of all mining and mineral-commodity extraction in the United States was approximately $60 billion (Fig. 1). One-third of this, $19.9 billion, was the value of 988 million metric tons of coal produced that year (Energy Information Administration, 1998). The remaining two-thirds, $39.5 billion, was the value of nonfuel minerals.

The value of industrial minerals amounted to $28 billion or 47% (Fig. 1) of all mineral extraction in the United States in 1997 (excluding oil, gas, and uranium). This was accounted for by over 6,400 companies producing from more than 11,000 mines, quarries, and processing facilities located in almost every county in the United States.

INDUSTRIAL MINERALS

Over the years, there have been several classification schemes for grouping industrial minerals. These schemes include criteria such as unit and place value, geologic characteristics, reactive versus nonreactive applications, and principal end-use. Because of a close association between the mineral resource and dominant end-uses, classification schemes based on end use have worked well for most of these minerals (Bates, 1983). For this presentation, industrial minerals will be grouped into the following categories: construction, agricultural, chemical, and other (Fig. 2). The last category is a combination of mineral commodities having multiple end-uses.

Construction

On the basis of tonnage and value, the rocks and minerals mined and consumed in the construction industries dwarf all other minerals, including metals and coal combined. Preliminary estimates indicate that, in 1997, more than 2.5 billion tons of industrial minerals and rocks, with a value of $19.5 billion, were mined and processed for the construction industry (Fig. 3). This is equivalent to almost 93% of the quantity and 70% of the value of all industrial minerals produced in the United States last year. On a weight basis, crushed stone accounted for 56% of the industrial minerals used

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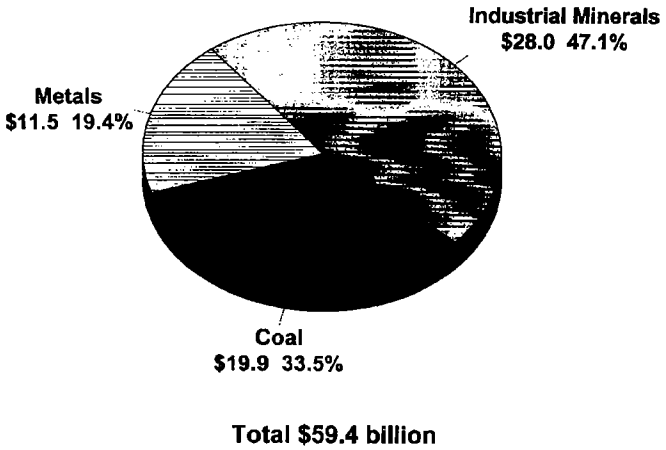


Figure 1. Mining value in the United States, 1997 ($ billion).

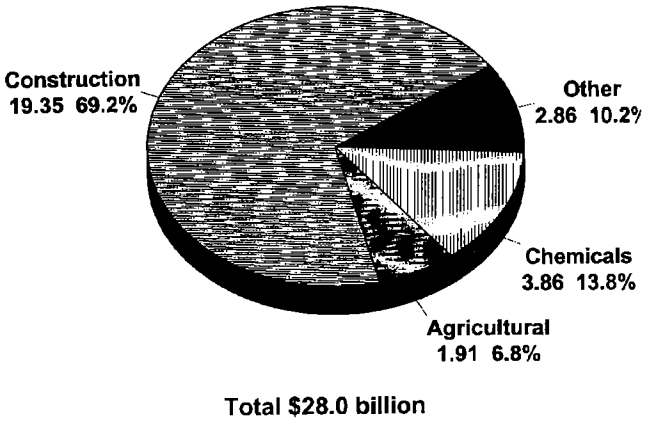


Figure 2. Value of industrial minerals production in the United States, 1997 ($ billion).

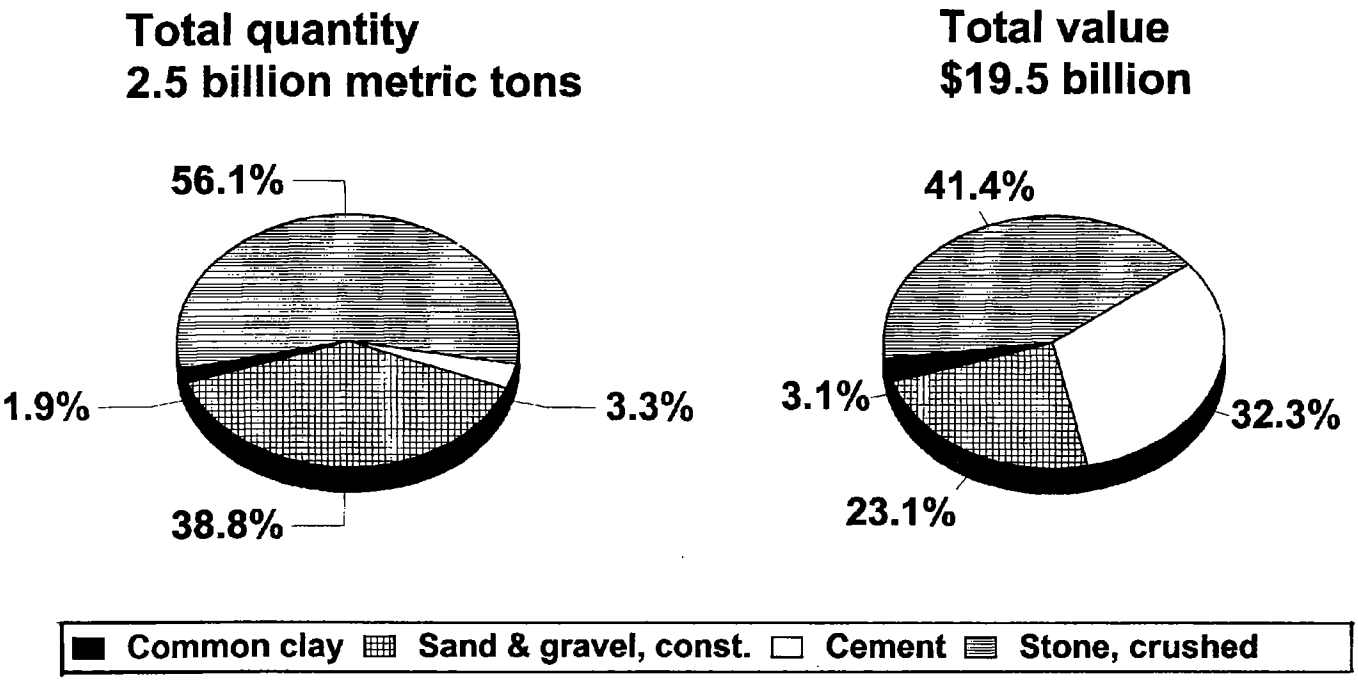


Figure 3. U.S. production of construction-mineral materials, 1997.

in construction; sand and gravel was 39%. Crushed stone was produced by 1,500 companies from over 3,600 quarries, and sand and gravel was produced by more than 3,800 companies from over 5,500 operations. Cement, gypsum, common clay, and other minerals including perlite and pumice make up the remaining 5.2% of tonnage of construction mineral commodities domestically produced in 1997.

The value of cement produced last year exceeded that of sand and gravel. Cement accounted for almost one-third of the value of industrial minerals used in the construction industry, an increase of 5% in 1997 over the previous year. This reflects the continuing economic health of the construction sector of the economy, especially for the aggregates and cement industries, which have enjoyed a steady annual growth since 1991. This trend is expected to continue for the next several years as work on roads and infrastructure receives financing from the new Surface Transportation Equity Act. Although aggregates and cement traditionally are obtained from local or regional sources, increasing quantities of both are now being imported or shipped greater distances to markets. This is reflected by an increased delivery price, especially in metropolitan areas. With increased demand for aggregates, cement, and other mineral commodities for infrastructure, transportation costs will more than likely become an ever-increasing portion of the delivered price.

A record high 18.4 million tons of gypsum was mined by 30 companies in 1997, reflecting a strong demand for wallboard and other gypsum products used in the construction industry. The production of commercial-

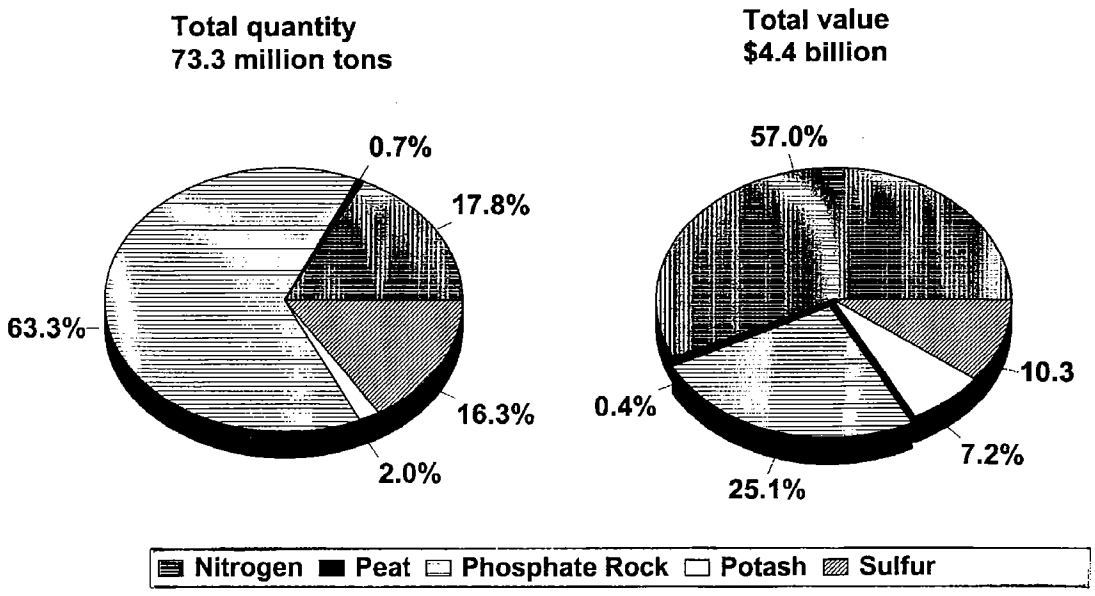


Figure 4. U.S. production of agricultural minerals, 1997.

grade synthetic gypsum, especially by retrofitted coal-burning utilities, also increased as new wallboard capacity has become increasingly dedicated to using this material. This important trend is expected to increase in the near future as gypsum companies implement plans to modernize and expand their wallboard production capacity.

Agricultural Minerals

More than 60 million tons of phosphate rock, potash, and sulfur, which had a value of nearly $1.9 billion, were mined and extracted by U.S. producers in 1997 (Fig. 4). When that figure is added to the 13 million tons of nitrogen contained in ammonia, which was essentially "mined" from the atmosphere, the tonnage and value of these commodities used principally as plant nutrients in agriculture and horticulture amount to over 73 million tons and $4.4 billion (Fig. 4). In 1997,

- 10 companies operated 17 phosphate-rock mines;
- six companies produced potash from five underground mines, two solution-mining facilities, and three plants based on subsurface and surface brines;
- elemental sulfur was recovered from natural gas, petroleum refineries, and coking plants by 58 companies at 138 operations and mined by the Frasch process at two mines by one company;
- by-product sulfuric acid was recovered by 10 companies operating 14 nonferrous smelters; and
- anhydrous ammonia was produced by 26 companies at 42 facilities.

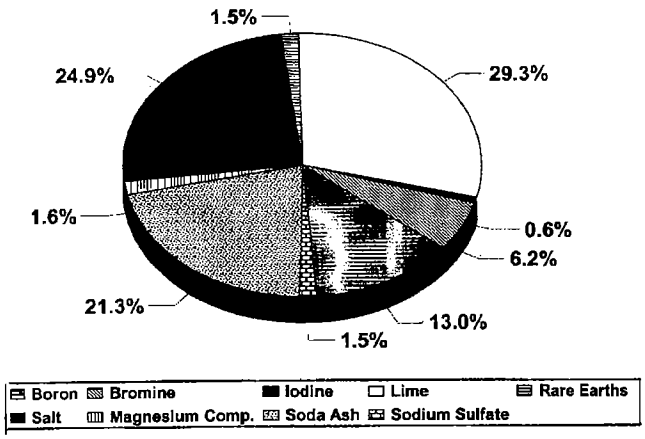
The basic inputs to the phosphate-fertilizer sector—phosphate rock, sulfur, and ammonia—were used to make the high-nutrient fertilizers, di- and monoammonium phosphates and super-triple phosphate. Sulfuric acid and phosphoric acid are chemical intermediates used in the production of these highly important chemical fertilizers. In addition, phosphoric acid may be used in liquid-fertilizer formulations. The phosphate sector has become more vertically integrated in recent years and has concentrated more on producing high-nutrient-analysis fertilizer materials. As a result, the exports of phosphate rock are waning, and phosphate fertilizer exports are at high levels. Although domestic demand for phosphate fertilizers is growing, the quantity exported exceeds domestic demand.

In the potash sector, domestic production has been static, and demand has increased over the past 5 years. Imports, primarily from Canada, account for about three-fourths of the U.S. consumption. World demand for fertilizer nutrients is expected to grow in the future, and this use will assist in increasing world food output. A variety of factors will affect the growth. These include cost and availability of fertilizer material, domestic and foreign government policies associated with farming practices and fertilizer subsidies, weather, population-growth rates, and others.

Chemical Minerals

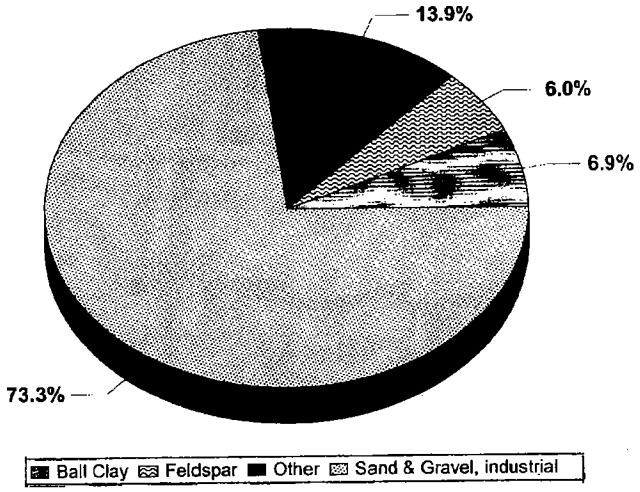
The combined value of minerals that are used extensively by the chemical industry and were produced by the United States in 1997 was an impressive $4 billion (Fig. 5). Lime was nearly $1.2 billion; salt was almost $1 billion; soda ash was more than $900 million; boron minerals were over $500 million; magnesium compounds were nearly $300 million; and bromine was almost $200 million. Iodine, sodium sulfate, and rare earths were each valued at less than $100 million in 1997.

The quantities of these minerals produced in the United States in 1997 (Fig. 5) ranged widely from over 41 million tons of common salt to slightly more than 1,300 tons for iodine. Production data for these commodities follow:



Total $4 billion

Figure 5. U.S. production of chemical minerals, 1997.



Total $689 million

Figure 6. U.S. production of glass, ceramics, and refractory minerals, 1997.

- lime approached 20 million tons produced from 107 plants;
- salt, 41 million tons by 27 companies operating 67 facilities;
- sodium sulfate, ≈10.7 million tons by 15 companies at 17 locations;
- magnesium compounds, ≈800,000 tons by 11 companies at 13 locations;
- soda ash, 580,000 tons (from natural and by-product sources) by six companies operating six plants; and
- bromine, boron, iodine, and rare earths, each produced at fewer than five locations by fewer than five companies.

Boron minerals alone constituted more than 1.1 million tons, and ≈20,000 tons of rare earths were produced.

A wide variety of factors will affect supply and demand for these mineral-based materials. Overall, consumption will be affected by the state of the national economy and should increase with it. Because soda ash and boron minerals have a high export component, production may decrease as a result of the current state of the economies in Asia.

Glass, Ceramics, and Refractory Minerals

Of those principal minerals having dominant use as basic raw materials for the glass, ceramics, and refractory manufacturing industries, industrial sand and gravel accounted for over 91% of the tonnage and almost 60% of their total value of production (Fig. 6). Eighty-two firms mined more than 28 million tons of industrial sand-and-gravel from 146 operations in 37 states in 1997, with a value of more than $500 million. The leading producing states, in descending order, were Illinois, Michigan, California, Texas, Wisconsin, North Carolina, and New Jersey. Their combined production represented 56% of the national total. About 76% of the total industrial sand and gravel was produced by 48 operations, each with an annual production of more than 200,000 tons. The 10 leading producers of industrial sand and gravel accounted for 71% of total domestic production from their 56 operations. Consolidation of the industry continued in 1997 partially in response to consolidation within the consuming industries themselves, such as the glass container industry. Not only has there been a decrease in the number of companies that control the glass container industry, but there has also been a trend toward larger and fewer glass plants (Glass, 1997).

Feldspar continued to be used in 1997 principally in glass manufacture to improve hardness, durability, and corrosion resistance, and in ceramics as a flux and for glazing. Twelve companies with 14 mine/plant operations accounted for the approximately 900,000 tons of domestic feldspar produced having a value of $42 million (6.1%, Fig. 6).

In 1997, 1.04 million tons of ball clay, valued at over $48 million, were produced from 32 quarries in five states. Tennessee accounted for two-thirds of the domestic production of ball clay followed by, in descending order, Kentucky, Texas, Mississippi, and Missouri. Since 1983, the production of ball clay has grown by 50% as its growth as a basic raw material in the manufacture of sanitaryware and tile closely followed that of the housing industry in the United States. The remaining minerals, fire clay, kyanite, mullite, and zirconium, used principally as raw materials for refractories, account for less than 2% of production of minerals in this category, and have 12% of the value. Demand for these minerals has been affected by the trend toward higher quality, longer life, and higher value refractories, and by changes being made in the steel, glass, and other industries in operation and lining design.

Other Industrial Minerals

The remaining group of industrial minerals covers a wide variety of end uses including pigments, coatings, fillers and extenders, absorbents, filtering agents,

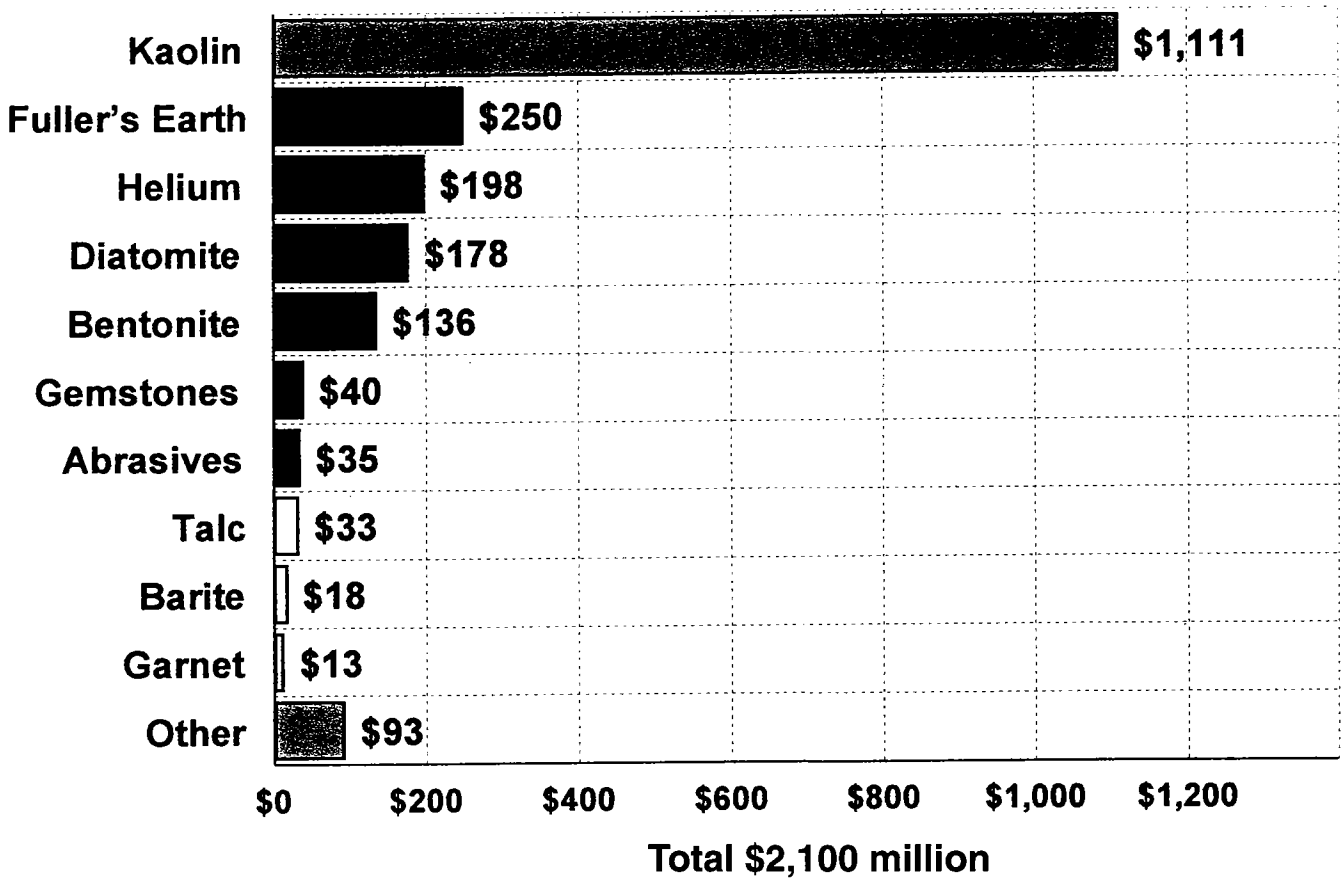


Figure 7. 1997 U.S. production of miscellaneous industrial minerals ($ million).

grinding-and-polishing materials, and cryogenics. Together, their value of production in 1997 was over $2 billion (Fig. 7). Kaolin accounts for over one-half of this value. In 1997, 9.4 million tons of kaolin were produced by 30 companies operating 120 quarries in 11 states. Eighty-nine percent of the tonnage and 94% of the total value of kaolin production came from kaolin mined and processed in Georgia. Although kaolin has a wide array of end-use applications, its principal use has been as a filler and coating in paper, which accounted for more than 56% of its use in the United States in 1997.

The movement by the paper industry from acid to alkali paper processing in the past decade has resulted in a noticeable displacement of kaolin by precipitated calcium carbonate as a filler in paper. However, paper coating and other markets for kaolin continued to sustain kaolin's positive growth in domestic and export demand.

The other clay minerals in this group, fuller's earth and bentonite, have both been enjoying steady growth in recent years, particularly in their use as pet-waste absorbents. For bentonite, its increase in iron-ore pelletizing and waterproofing and sealing applications also has contributed to its growth in consumption and production. Eighteen companies produced bentonite from 57 quarries in 10 states in 1997, while 17 companies produced fuller's earth in 12 states. Both mica (from 10 producers) and talc (from 17 domestic mines) have major uses as functional fillers in organic-compound formulations for both the paint and plastics industries. Diatomite, processed in 12 facilities in four states in 1997, has enjoyed steady growth over the past decade principally due to its increased use as a filler in the food and beverage industries.

IMPORT DEPENDENCE IN 1997

With a few exceptions, the United States has been either self-sufficient or a net exporter of industrial minerals (Table 1). For many industrial minerals, imports have been transborder shipments with Canada and Mexico for economic reasons based on transportation costs. Transborder imports to coastal cities have been increasing for many bulk commodities as overland access to domestic resources has become increasingly expensive. This trend is likely to increase because of uneconomic resources and depleted reserves. The United States is now totally dependent on imports for fluorspar, and significantly import-dependent for barite, dimension stone, heavy-mineral sands, iodine, potash, and peat. Other industrial minerals for which the United States is becoming increasingly import dependent include cement, perlite, and salt.

Table 1.—Industrial Minerals Import Dependence as a Percentage of Apparent Consumption

Commodity	Import dependence
Lime	1
Mica	3
Perlite	11
Sulfur	11
Rare earths	12
Sodium sulfate	12
Cement	14
Nitrogen, fixed	14
Salt	14
Pumice	21
Gypsum	30
Magnesium compounds	33
Asbestos	38
Diamonds, industrial	45
Peat	58
Stone, dimension	64
Iodine	65
Barite	71
Potash	76
Fluorspar	100
Graphite	100
Strontium	100

TRENDS

Another approach in looking at the status of industrial minerals in the United States is to examine the historical trend of production, consumption, and price, where possible, in the context of world production. Following are reviews of such historical data on specialty clays, barite, phosphate rock, and feldspar. Interpretations of shifts in trends and projections were made in consultation with USGS commodity specialists. The first example is a look at the relative trends in domestic production of specialty clays (Fig. 8). These include fire clay, kaolin, bentonite, fuller's earth, and ball clay.

Fire Clay

Fire clay generally is produced by small companies and traditionally was sold into refractories markets. Consequently, changes in the refractories industries had a large impact on fire-clay markets. Beginning in the early 1960s, the number of steel mills decreased, steel producers have replaced antiquated furnaces, and mini-mills have become widespread and profitable. More recently, customers have begun using more high-alumina and other more durable refractories to improve efficiency. As a result, firebrick sales plummeted dramatically, declining from over 8 million tons in 1965 to less than 650,000 tons in 1997. From a marketing standpoint, sales of fire clay for refractory applications have gone from 90% of the market in 1983 to

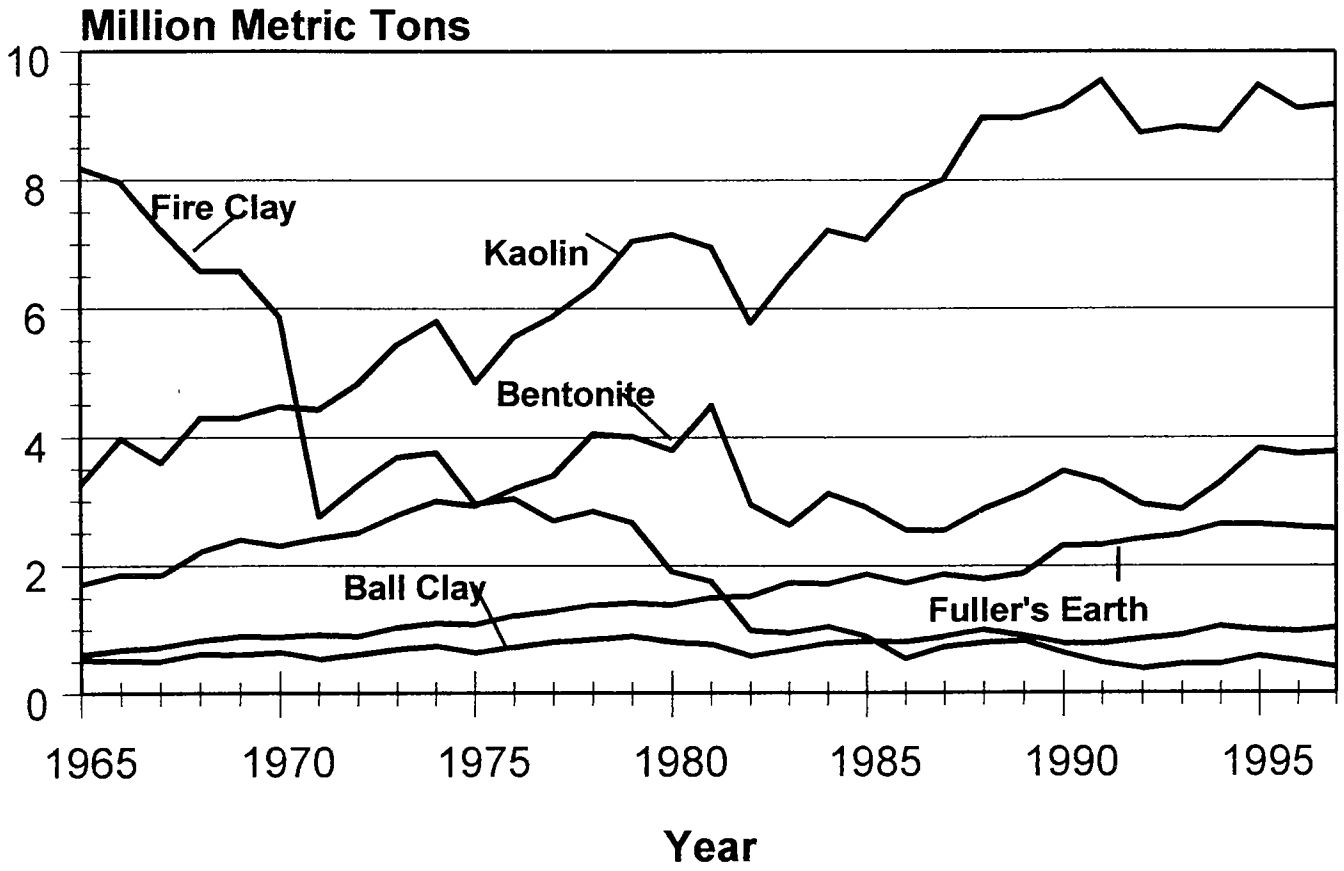


Figure 8. U.S. production of specialty clays, 1965–1997.

53% in 1997. A larger portion of the current production is being sold for end uśes such as brick manufacture, pottery, flowerpots, flue linings, and sewer pipe.

Kaolin

Production of kaolin grew almost steadily, principally in response to increased domestic and international demand for coating and filler grades of kaolin. These two markets alone accounted for about 72% of the 2.9-million-ton increase between 1983 and 1997. International sales of paper-coating grades of kaolin experienced the greatest growth of the end-use markets. Beginning in about 1992, the kaolin producers began to feel the impact of calcium carbonate substitution. Carbonate competition has been particularly strong in applications for paper-filler pigment, which have declined from 16% to 11% of total kaolin use in the five years since 1992. However, paper coating and other kaolin markets generally have continued to maintain their historic market share in tonnage sold. The paper-filler market has rebounded a bit since 1996 with further expansion of the paper market.

Bentonite

In the early 1960s, the principal uses for bentonite were in drilling muds, foundry sands, and pelletizing of iron ore. Increased drilling for oil in the late 1970s and early 1980s accounted for the growth in production until oil prices dropped, and consequently, oil drilling activities declined drastically around 1984. As sales for drilling-mud markets declined, those for pelletizing, foundry sand, and absorbents increased. By 1997, foundry-sand sales had overtaken drilling mud applications. In the last 10 years, sales for kitty-litter applications (clumping kitty litters) have grown rapidly. This application, which now accounts for about 16% of the total market, was practically nonexistent in 1965.

Fuller's Earth

Two markets dominate both the attapulgite- and montmorillonite-type fuller's-earth sales. These are absorbents and pesticide carriers. Production of attapulgite has been relatively flat over the 25-year period. There have been only minor fluctuations in sales. Montmorillonite-type fuller's earth has grown during that period. Again, the fluctuations in sales are attributed mainly to the eccentricities of the absorbent and pesticide markets. In general, though, the total fuller's-earth sales has grown at a fairly even pace. The largest change has been in the kitty-litter market, which has doubled since 1983. This market accounted for 87% of the 640,000-ton increase in consumption between 1983 and 1997.

Ball Clays

Domestic production of ball clay increased 3.5 times over this period, from 294 thousand tons in 1950 to 1.04 million tons in 1997. The principal uses for ball clay have been in the manufacture of pottery and stoneware as well as in sanitaryware and floor and wall tile. Sanitaryware and tile industries account for the biggest part of the increase in production of ball clay over this period representing over 51% of domestic consumption in 1997. Significant increases also were seen in export markets for ceramic-grade ball clays that year. Other markets that grew for ball clay include asphalt emulsions, pesticide carriers, and rubber fillers. The growth rate for domestic ball clay production has been between 2% and 3% per year, and this trend is expected to continue especially for domestic markets and for exports to Asia and South America for their sanitaryware markets.

Barite

Figure 9 provides a historical profile of the domestic production, consumption, and price, and the world production of barite from 1950 through 1997. For purposes of these discussions, it is reasonable to assume that world production of barite and other commodities is more or less equivalent to world consumption. The peaks and valleys of domestic and world consumption of barite reflect both economic as well as energy-crisis events. The rise in both domestic and world consumption of barite from the early 1970s through the early 1980s reflected the surge in petroleum exploration and the attendant increase in demand for barite in drilling muds. Domestic consumption began to exceed domestic production in the early 1950s and continued to do so throughout the remainder of the period, often times by a twofold amount. Throughout this period, drilling mud was the principal use of barite, as it continues to be today. Its use as a white pigment in paints and other products requiring light fastness and exterior durability has given way to titanium dioxide. The sharp rise and drop in price in the 1990s reflects the effect of railroad-tariff increases on the domestic price of barite and subsequent strategic moves by producers to ship crude barite to the Gulf market for processing, instead.

Phosphate Rock

For many years, the United States has led the world both in the production and consumption of phosphate rock. Figure 10 gives an interesting profile of the domestic and world events of phosphate-rock production and consumption from 1950 through 1997. Until recently, the United States had been a major exporter of phosphate rock, supplying a significant portion of the world's needs. Florida has been the dominant producer of phosphate rock throughout this period. Other countries with large reserves—such as Morocco—have become major world producers. Throughout this period, the United States and the former Soviet Union were the main producers. The decrease in world production (consumption) of phosphate rock in the early 1990s was due principally to the socioeconomic restructuring of the former Soviet Union. The drop in both domestic production and consumption in the early 1980s reflects the effect of the U.S. Government's implementation of the "payment in kind" program to remove specific farm-commodity acreage, to tighten supplies, raise farm prices, and reduce costs for crop storage and farm

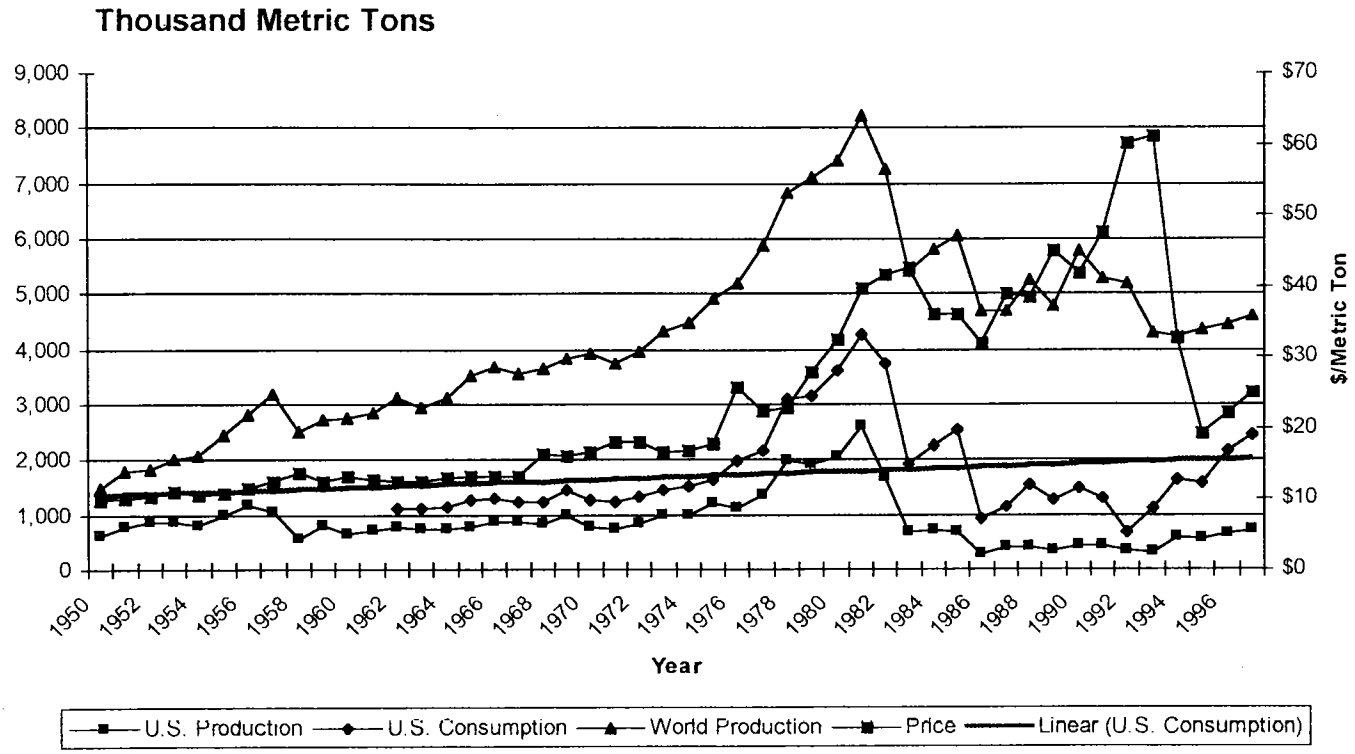


Figure 9. Barite production and average price, 1950–1997.

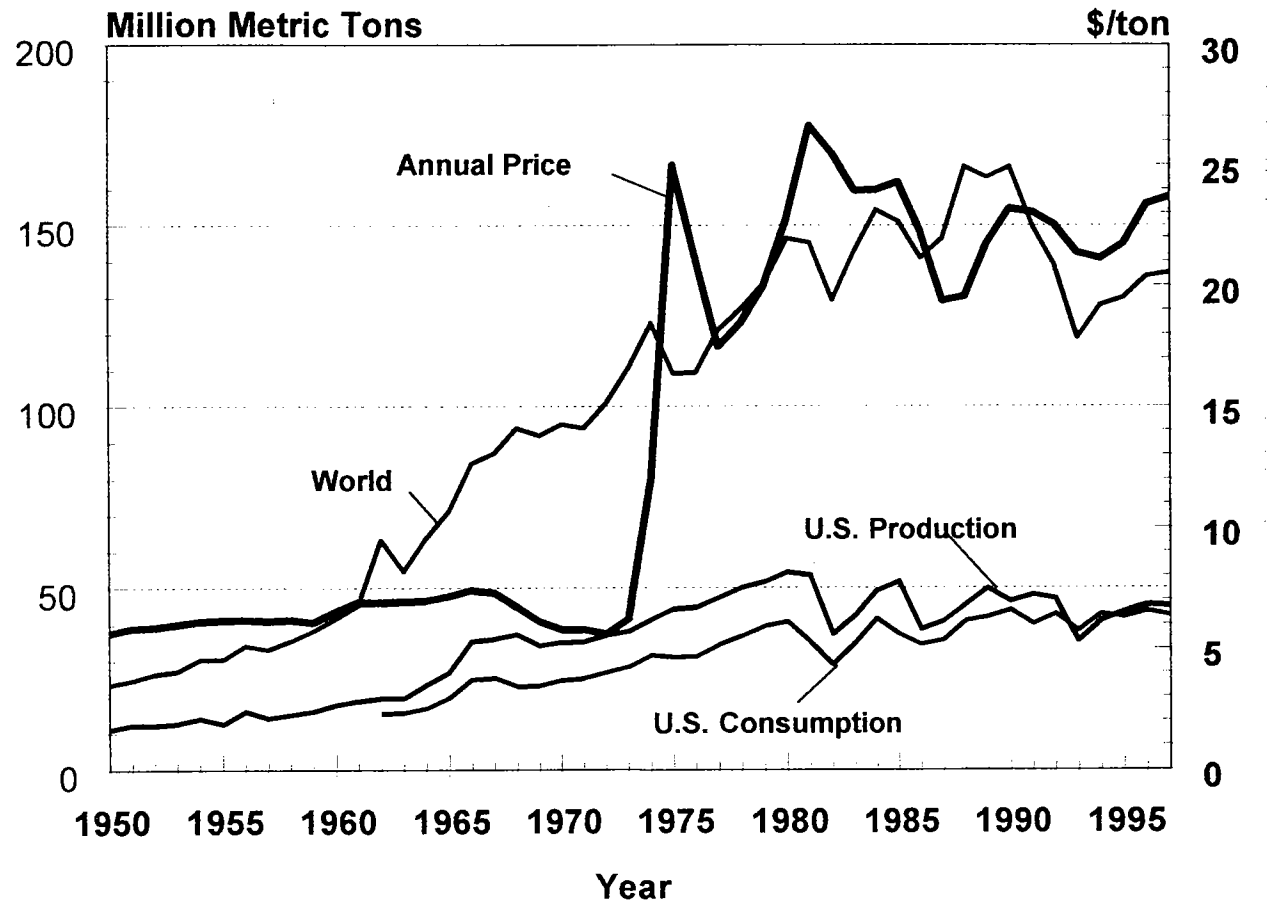


Figure 10. Phosphate-rock production, consumption, and annual price.

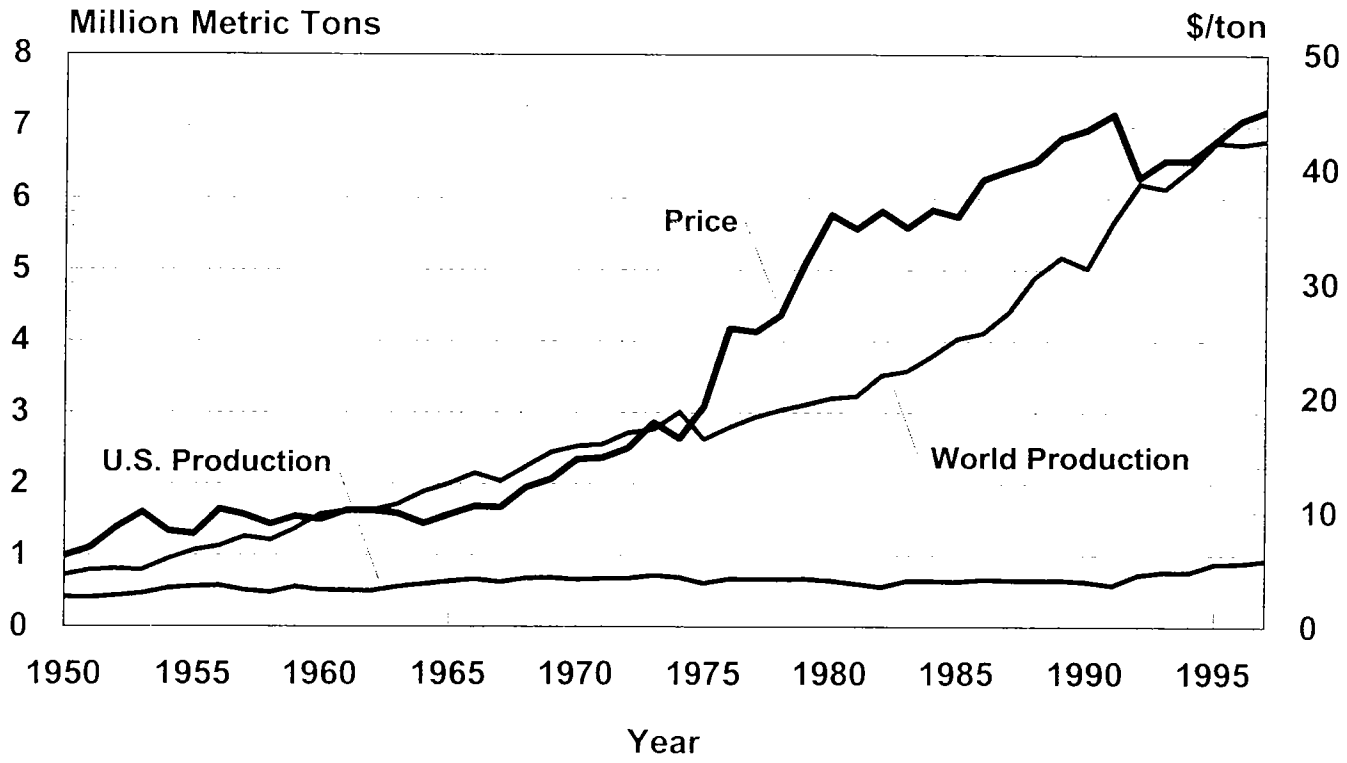


Figure 11. U.S./world production, U.S. consumption, and average price of feldspar.

loans. The sudden rise of the price of phosphate rock in 1973–75 coincides with the energy crisis of those years. It further reflects a perceived worldwide shortage that was projected to last and the efforts of the phosphate industry of Morocco to increase revenues. Mine and plant expansion in the United States and elsewhere quickly moved phosphate-rock availability to an oversupply situation, which resulted in a drop in prices in nominal and real terms. In 1997, the 46 million tons of phosphate rock produced in the United States came from 10 companies operating 17 mines. Florida continues to be the dominant domestic source of phosphate rock. Although imports of phosphate rock to that state may occur in the future, both the location of its existing fertilizer-processing facilities close to tidewater, and its proximity to sulfur supply should ensure that Florida will continue to be the principal source of domestic phosphate fertilizers well into the next century.

Feldspar

Feldspar has the ability to promote fusion and impart strength, hardness, and durability as a constituent in glass, pottery, and porcelain enamels, and is therefore a basic raw material for these industries. The amount and price per ton of this commodity from 1950 to 1997 are shown on Figure 11. In the early 1950s, the United States was the leading producer, exporter, and consumer of feldspar. North Carolina and California account for over two-thirds of domestic production of feldspar. The Spruce Pine and Bryson City districts were the principal sources of feldspar in North Carolina in the early part of this period (Castle and Gillson, 1960). North Carolina continues to provide the majority of domestic feldspar principally from the Spruce Pine district. Other important producing states are California, Virginia, and Georgia. In 1997, 930,000 metric tons of feldspar came from 12 companies operating 14 mines in the United States. More than 52% of that feldspar came from operations in North Carolina. Nepheline syenite, principally from Blue Mountain, Ontario, Canada, competes with feldspar in the glass and ceramics industries, but, because of the sensitivity to transport costs, the competition is limited geographically (Rogers and Neal, 1983). Throughout the period from 1950 to 1997, the quantity of domestic feldspar produced annually was virtually equivalent to domestic apparent consumption of feldspar. Over this period, world production of feldspar grew steadily at an average annual rate of 5%.

CONSUMPTION OF MATERIALS IN THE 20th CENTURY

Because of the diverse group of industries and almost infinite uses covered under the umbrella of industrial minerals, it is difficult to develop a common focus on their importance to the United States. One way is to look at industrial minerals in the context of all materials consumed over time and see some commonality in growth and behavior up to the present. By materials, I mean all physical raw materials except those used to produce energy. This includes "renewable materials" (animal-and-vegetable-derived materials other than

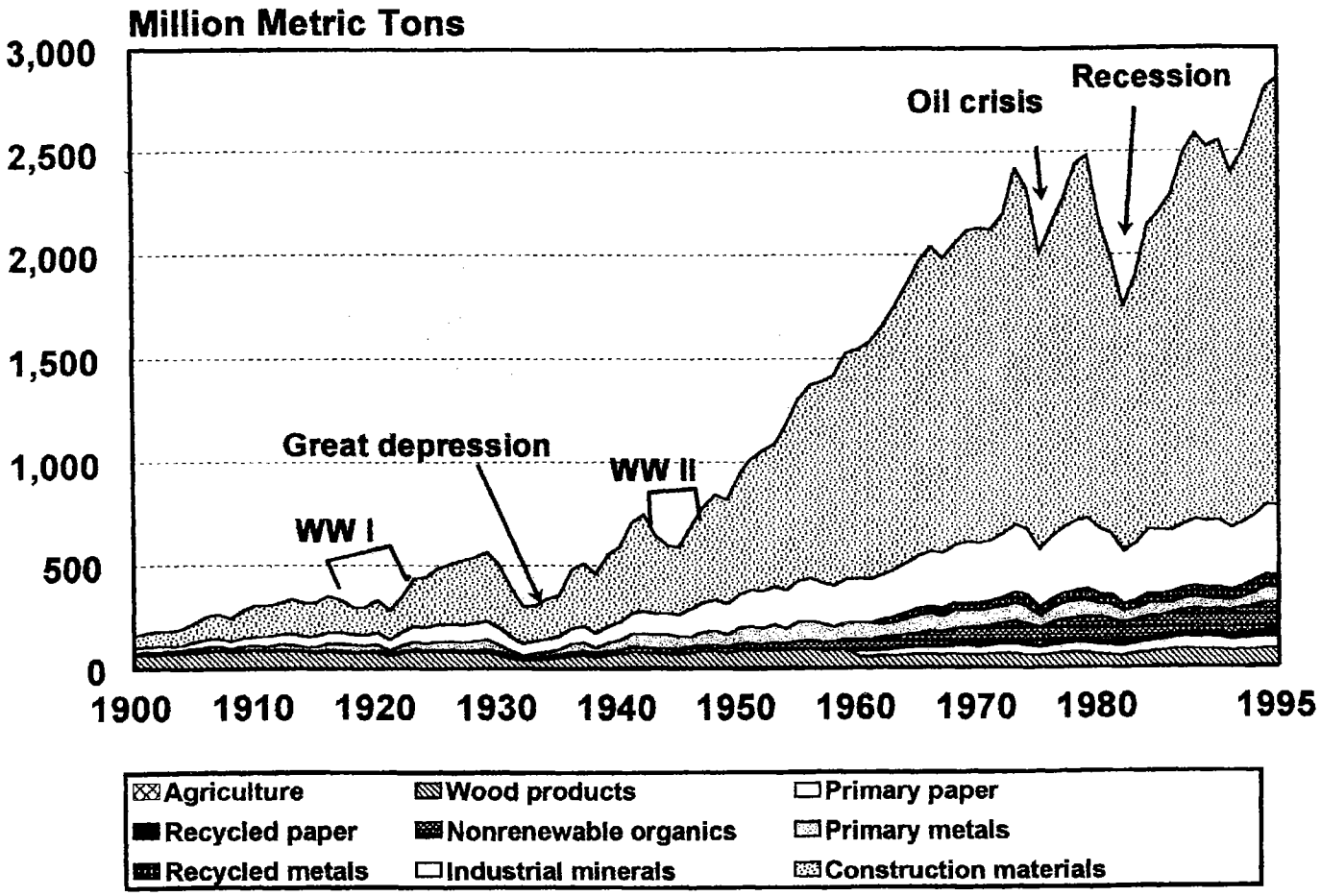


Figure 12. U.S. materials consumption, 1900–1995.

those used for food, such as timber, cotton, and leather), and "nonrenewable materials" (rocks, minerals, metals, and fossil-fuel derivatives not used for energy, such as motor oil, grease, solvents, monomers, and organic chemicals).

At the USGS, we have assembled data on consumption of minerals and other materials over the past century (Fig. 12). In looking at these components of material consumption, a number of interesting patterns were observed. The consumption profile of each of the groups of renewable and nonrenewable materials over this period of time reflects major economic and military events, including the depression of the 1930s, both World Wars, the post-WWII boom, the energy crunch of the 1970s, and the recession of the 1980s.

On a basis of weight or volume, industrial minerals dwarf all of the other categories of materials combined. This should not surprise us if we consider that stone and sand and gravel for building and construction have been the dominant materials used through the century, representing as much as three-quarters of annually consumed nonrenewable and renewable resources. However, over this period of time, the makeup of this construction material has changed significantly. With the increasing structural strength requirements of newer and taller buildings, the use of dimension stone for construction became more decorative than functional. The same rocks that were cut and carved were now becoming more useful when they were crushed, ground, and later pulverized.

By removing the construction-aggregates data, we get a better look at the other components of material over time (Fig. 13). The data on agriculture-derived materials—cotton, flaxseed, hemp, wool, leather, etc.—represent a relatively insignificant quantity on a weight basis. Consumption of forest products—that is, lumber for wood, plywood, and veneer—remained essentially unchanged throughout this period. Here, too, there has been a shift, as the laminated- and pressed-wood products are now dominant. Consumption of pulp for paper gradually increased over this same period. On a tonnage basis today, more timber is cut for paper than for wood products. What is most interesting is the emergence and growth of recycled metals and paper as significant components of material that we now consume.

Also notable is the gradual emergence in the early part of the century and the subsequent rapid growth of organic chemicals as a major component of materials consumed today. This reflects the limited use of petro-

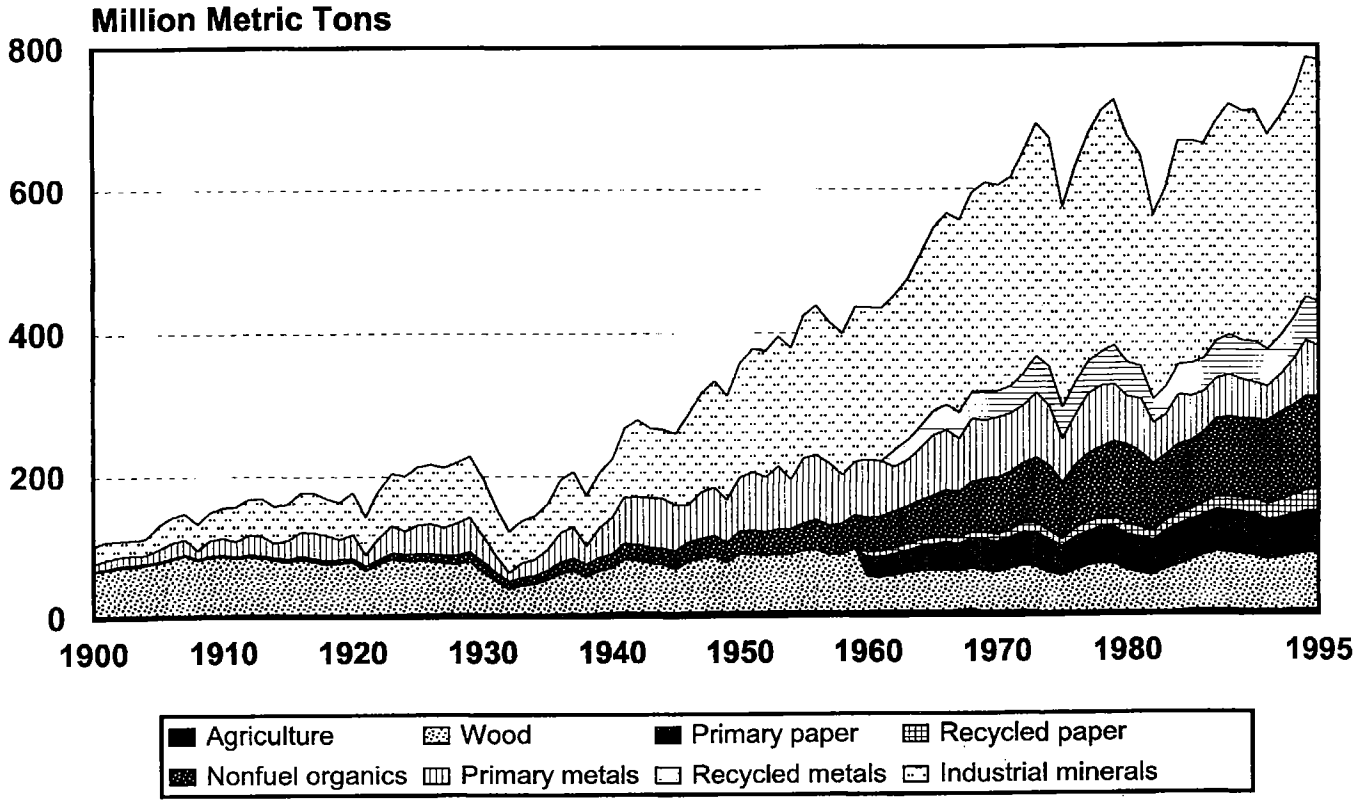


Figure 13. U.S. consumption of raw materials, 1900–1995.

leum- and coal-derived products in the early part of the century, principally as kerosene illuminate, mineral-oil lubricants, and asphalt for new roads for the emerging automobile. Applied chemical engineering in petroleum refining gave rise to catalytic distillation and a subsequent bounty of organic compounds, monomers, and synthetic materials, which, in the last half of this century, have been the basis of totally new material uses as well as lower cost or more economical substitutes for both renewable and nonrenewable resources.

The remaining industrial minerals (excluding sand and gravel and crushed stone) account for the next largest component of materials consumption, which is almost equivalent, on a weight basis, to all other materials combined. A closer examination of those industrial minerals (Fig. 14) reveals those most dominant, by weight, to be cement, clay minerals, gypsum, phosphate rock, industrial sands, salt, soda ash, and sulfur. At the beginning of the 20th century, apart from construction materials, the dominant nonmetallic minerals consumed were clay, phosphate rock, gypsum, sulfur, asbestos, and salt.

Other important minerals consumed included borax, bromine, barite, and abrasive minerals of all kinds. Several minerals, including chromite, rutile, ilmenite, uranium, vanadium, and cobalt were used principally for the manufacture of pigments. Consumption of salt grew from the time it was used almost exclusively as a principal meat preserver to today when it is a basic raw material for a wide array of sodium- and chlorine-chemical industries. Until about 1920, bentonite was a relatively unimportant mineral, with very few uses. Its principal uses were in the manufacture of medical dressings, packing and dressings for horse hoofs, and as an adulterant in drugs and candies. It went on to become a filler-retention additive for clays in papers, an enhancing extender in soaps, and a water softener. Today, its principal uses are for drilling muds, foundry sands, cementation of iron-ore pellets, pet litter, and as a general filler in plastics, rubber, and paints.

From the perspective of cumulative consumption since 1900, what is most important to note is that, for most of the industrial minerals as with other materials, more than half of what was consumed in the 20th century has been consumed within the last 20 to 25 years (Fig. 15). Over the past 95 years, an estimated 87 billion tons of industrial minerals and rocks was consumed in the United States. Seventy-two billion tons, or 82% of this, was stone and gravel. Of this, 47 billion tons, or 54%, was consumed in the past 25 years. For construction materials, this amounted to 42 billion tons; for phosphate rock, 890 million tons; for salt, 1 billion tons; for potash, 140 million tons; for sulfur, 300 million tons; for gypsum, over 0.5 billion tons; and for the remaining industrial minerals, over 2 billion tons.

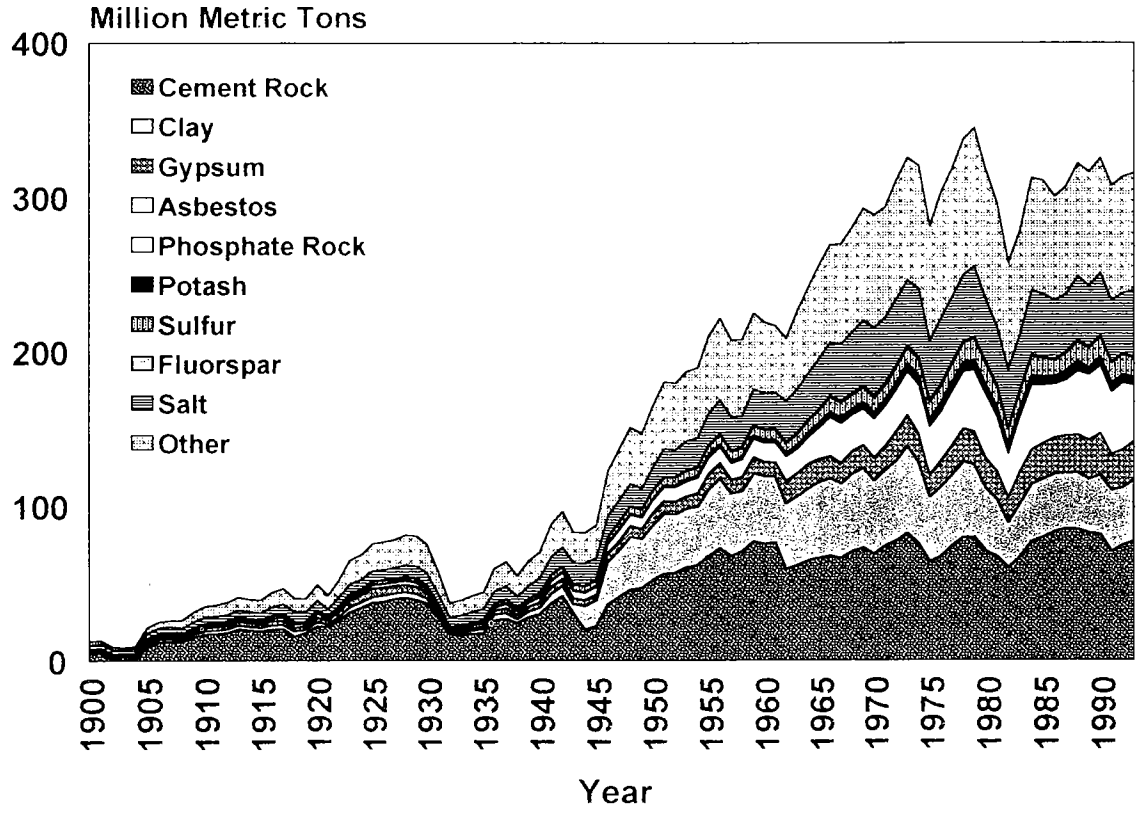


Figure 14. U.S. consumption of industrial minerals, 1900–1995.

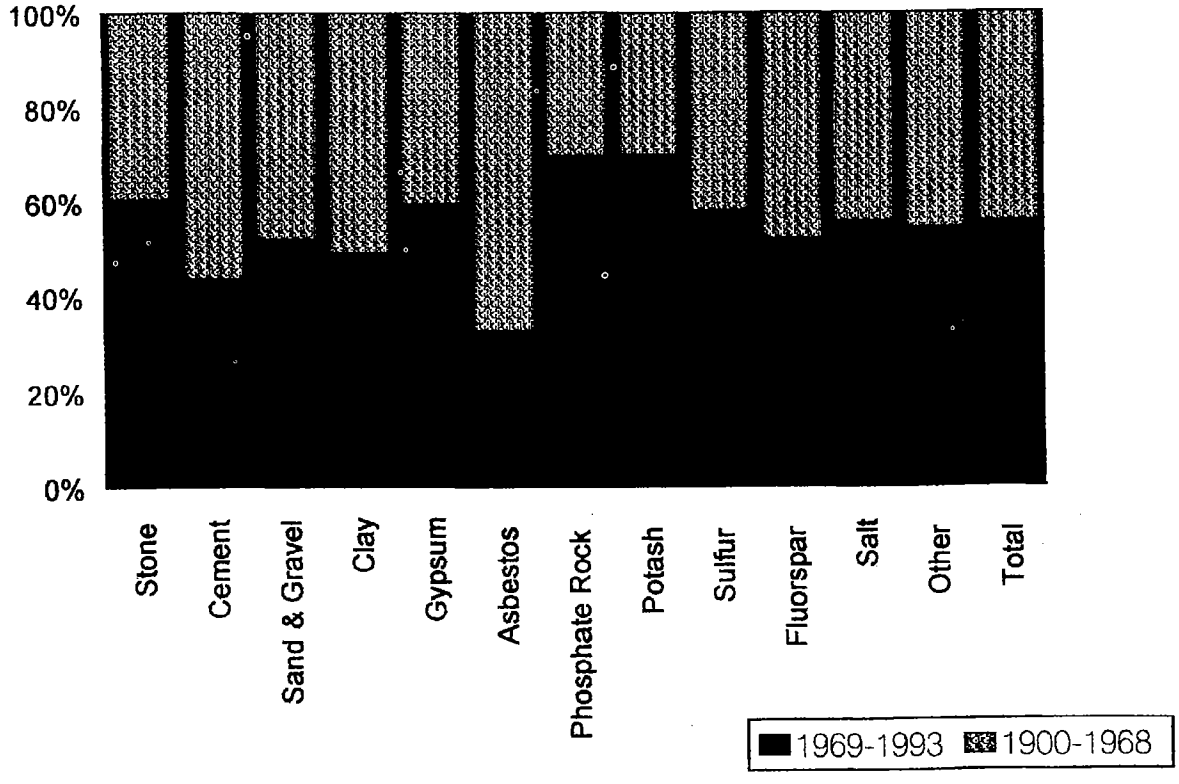


Figure 15. U.S. cumulative consumption since 1900.

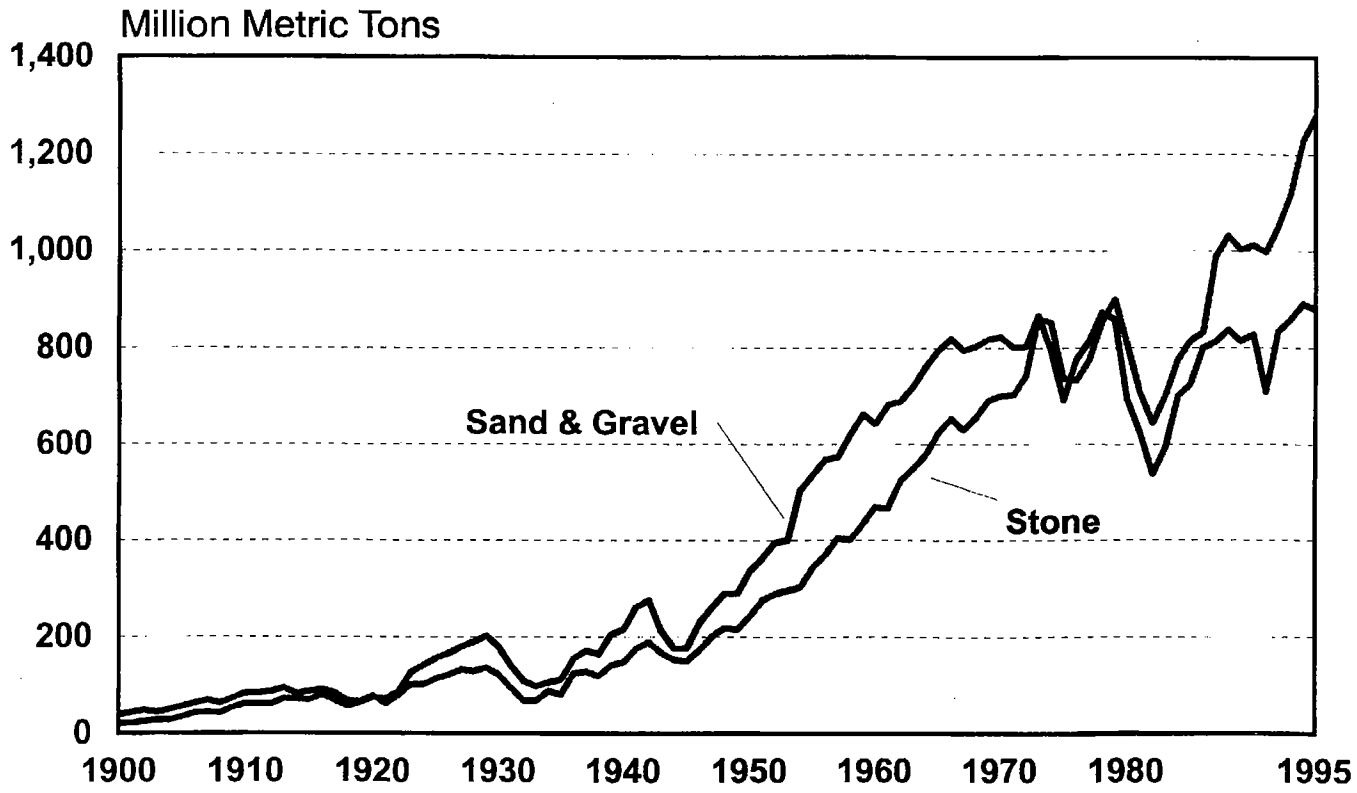


Figure 16. Aggregates production in the United States, 1900–1995.

HISTORICAL AND PROJECTED PRODUCTION OF AGGREGATES

Again, using data gathered by both the USGS and the former USBM on the production of stone and sand and gravel since the beginning of this century, we are able to generate a graphical profile of these industries over this time period (Fig. 16). In looking at this profile, we can see the exponential growth in production, with a 33- and 44-fold increase in stone and sand-and-gravel production, respectively, over this period. The peaks and valleys for both reflect economic and political events. Most important, we see the 20-year surge in production after World War II associated with building the country's major roads and freeways followed by the energy crisis of the early 1970s and the recession of the 1980s. Also interesting is the 1974 crossover in dominance of production from sand and gravel to crushed stone. To what extent this shift is due to depletion of and diminishing access to surficial sand-and-gravel resources needs to be better understood.

Again, it is very important to emphasize that over half of the sand and gravel and stone used this century was produced and consumed within the past 20 to 25 years.

As we peer into the next century, what might the future production of aggregates be over the next 25 years? Depending on how far one looks back, average annual growth rates have ranged from as high as 9% for crushed stone in 1950 to 3.1% over the past 5 years. Over the past 25 years, crushed-stone production has increased at an average annual rate of about 3.3%. On the other hand, sand-and-gravel production, which, up until 1974, exceeded that of crushed stone, has experienced a much slower growth rate. Average annual growth rate over the past 25 years has been less than 1%; the last 5 years averaging an annual growth rate of about 1.3% (Fig. 17). Using conservative assumptions, we then projected trends in production for sand and gravel and crushed stone from 1995 at average annual growth rates of 0.5% for sand and gravel and 1% for crushed stone to see where the domestic aggregate industry might be in the next 25 years. We assume, for this to be the case, a continual but normal growth in the construction sector of the economy and increasing demand for construction aggregate.

By the year 2025, assuming our projected annual growth rates, production of crushed stone in the United States will have increased by over 20% to approximately 1.6 billion tons, whereas production of sand and gravel would be approaching 1 billion tons per year. From a cumulative-production perspective, based upon the assumed 1% annual growth rate, the amount of crushed stone to be produced in the next 20 years will equal the quantity of all stone produced over this past century, approximately 36.5 billion tons. Combined with our projected cumulative production of sand and gravel, the amount of total aggregate to be mined in the

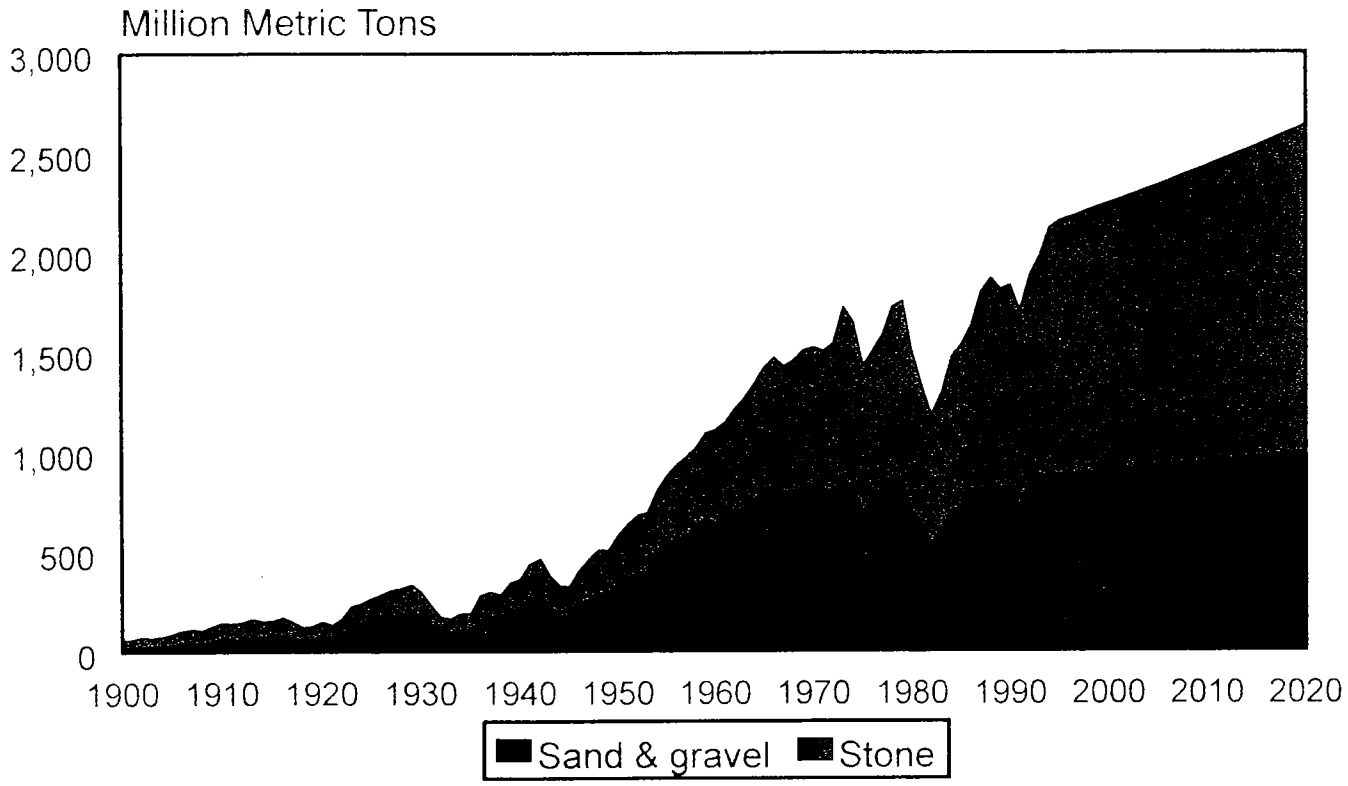


Figure 17. Aggregates production in the United States (1995–present, with projections to 2020). Projection based on growth rate of 1.0% for stone and 0.5% for sand and gravel.

next 25 years will be equivalent to almost all the mining that has occurred in this country for these materials in the past century.

Although these are simple projections and may not be a good forecast of the future, they do suggest a likelihood that vast quantities of stone and sand and gravel probably will be needed, and that much of this will have to come from resources yet to be delineated or defined. This is a critical issue especially in the coastal and near-coastal areas such as the Washington-Baltimore corridor, where urban sprawl and land development have rendered much of regional resources for future needs inaccessible. In fact, the trend for some bulk materials, for which the United States has been self-sufficient most of the past century, is toward an increasing dependency on imported material, especially in coastal and border regions of the country. This has been the case for gypsum, as eastern gypsum production gave way to cheaper imports from Canada, and western coastal cities have became increasingly more dependent on Mexican sources. One interesting aspect of this is the current growing supply of synthetic gypsum produced by flue-gas desulfurization (FGD) at coal-burning power plants. FGD gypsum is used primarily in the manufacture of wallboard in the midwest and eastern states; some FGD gypsum is displacing imported gypsum. Even crushed stone is now being imported in greater quantities to both eastern and western coastal borders.

SUMMARY

Geology dictates the location of mineral deposits. Unlike metal producers, which are located for the most part in the western states, producers of industrial minerals are widely distributed throughout the United States. Figure 18 shows the location of industrial-mineral operations that produced in 1997, exclusive of crushed stone, sand and gravel, and common clay. In 1997, the industrial-minerals industries—including aggregates and common clay—were represented by more than 6,400 companies producing almost $28 billion worth of basic raw materials from some 11,000 mines, quarries, and operations in the United States.

With few exceptions, domestic production of industrial minerals increased in 1997 over that of 1996. Many industrial minerals such as boron, bromine, cement, diatomite, feldspar, lime, phosphate rock, potash, soda ash, sulfur, and aggregates have enjoyed a steady growth in domestic production over several years.

Industrial minerals will continue to be the dominant raw-material resource for the construction, agricultural, and inorganic- and organic-chemical manufacturing, transportation, and service sectors of the economy in the foreseeable future. Most industrial minerals will come at least partly from domestic resources, some yet to be delineated.



Figure 18. Active industrial-mineral operations in the conterminous United States (1997) excluding crushed stone, sand and gravel, and common clay.

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Economic Evaluation of Industrial Minerals on Federal Lands

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ABSTRACT.—The methods of evaluation of industrial minerals occurring on Federal lands have different meanings if the evaluations are done by a company rather than a government agency. For example, when the Bureau of Land Management (BLM) conducts an examination of mining claims, this is commonly referred to as a "validity examination," whereas it is an "economic evaluation" when performed by a company. Not only is there a difference in nomenclature in these evaluations, but there is a general lack of expertise in the Federal government on industrial minerals in general. A *metallic mentality* still prevails in the U.S. Forest Service (USFS) and the BLM. Because of this, many validity exams on industrial-mineral deposits commonly just skim the surface concerning economics and marketability.

The BLM and USFS place a high amount of emphasis on past administrative case law pertaining to the validity of industrial minerals under the 1872 Mining Law and, rightly so, on marketability, which also is heavily addressed in case law. When the BLM considers marketability, only the marketability of a particular industrial mineral for only the primary use for which it was located is considered and any value-added markets cannot be included. The BLM defines marketability based only on the value of the mineral material in its in situ or raw state, rather than value-added through processing.

Another difference in the evaluation of industrial minerals by government and industry is the question of by-products. When a company evaluates a mineral material it looks at all the markets. The BLM looks only at that market for that locatable mineral for which the claim was located. In other words, sales from non-locatable by-products cannot be used to support marketability or the prudent-man rule (i.e., oversize silica sand from a glass-sand claim being sold for construction sand, road base, fill, etc.).

The question of reserves also can present conflicts. An industrial-mineral company will often try to identify all the reserves available for a possible future development. They must do this for financial backing and support from upper management. The BLM, however, will limit their validity examination only to those reserves that meet the prudent-man rule and marketability tests. The BLM will validate reserves sufficient to last 25–30 years, based on available market.

The development of industrial minerals on Federal lands is a difficult process, and, if the 1872 Mining Law is changed, it could become not only more challenging but also more costly. The industry must become more tolerant of the mineral specialists in the BLM and the USFS. On the other hand, the government mineral examiners must become more aware of the importance of industrial minerals in everyday living, and the economic evaluation of these materials.

INTRODUCTION

On October 1, 1994, Bruce Babbitt, Secretary of Interior, issued a moratorium blocking the issuance of any new patents on mining claims on public-domain lands. At that time, there were 553 applications for mineral patents, of which 221, or about 40%, were on industrial minerals.

In 1979, I was invited to be the keynote speaker at the Industrial Minerals Forum in Denver, Colorado. The title of my presentation was "Confusion, Mining Laws and the Industrial Minerals." After almost 20 years, there is still a lot of misunderstanding concerning the industrial minerals.

In the past, the management of industrial minerals on public-domain lands has been difficult due to the interpretation of the regulations pertaining to these materials, and also due to the lack of information on

Regis, A. J., 1999, Economic evaluation of industrial minerals on Federal lands, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 251–254.

the distribution, quality, and quantity of the nonmetallic resources on the public estate. With these two factors, the ability to manage and assess the priorities of the industrial minerals has been inadequate.

Probably the one regulation most responsible for the confusion in the legal disposition of the industrial minerals has been the Material Sales Act of 1955. This is apparent by the fact that nearly 75% of all the administrative decisions on minerals have been on industrial minerals. In fact, most of the landmark decisions through contest proceedings have been on these minerals. Decisions on quartzite, silica sand, zeolites, perlite, clays (including bentonite), building stone, limestone, etc., have involved questions concerning marketability, environment, locatability, chemistry, excess reserves, unique physical properties, and so on.

The concept of marketability as a natural supplement to the *prudent-man rule* was established in the Coleman (1968) decision. Kosanke (1973) established the fact that an environmental-impact statement (EIS) is not required in order to patent a mining claim on industrial minerals. The question of whether a mineral is locatable or leasable was partially resolved on zeolites in U.S. vs. Union Carbide in 1977. The definition of the term *exceptional nature* as used to define *common* versus *uncommon* varieties of industrial minerals was attempted in U.S. vs. McClarty (1974). Common versus uncommon was also the concern in the attempt to establish criteria for distinguishing locatable bentonite from common-variety bentonite based on chemical and physical properties. This resulted in a four-week hearing in Denver in 1978, which was the longest administrative hearing ever held on a mineral commodity. Excess reserves involving perlite was questioned in U.S. vs. Anderson in 1967.

Why all the confusion? The reason is that industrial minerals can come under all three of the mining laws we currently have: *locatable* (1872 Mining Law), *leasable* (1920 Leasing Act), and *salable* (1955 Minerals Materials Act).

The thought that a particular mineral commodity could be classified as either locatable (placer or lode), leasable, or salable, or as a common variety, which is widespread in occurrence, versus an uncommon variety, which possesses exceptional properties, is not only confusing, but also raises all sorts of speculations as to the disposition of these mineral materials. It also influences the economic evaluation of these materials on Federal lands.

The methods of evaluation of industrial minerals on Federal lands take on different meanings if the evaluations are done by a company rather than a government agency. For example, when the BLM conducts an examination of mining claims, this commonly is referred to as a *validity examination*, whereas it is called an *economic evaluation* when conducted by a company. Not only is there a difference in the terminology used in these evaluations, but a general lack of expertise in the Federal government on industrial minerals. A *metallic mentality* still prevails and, because of this, many validity exams on industrial mineral deposits often just skim the surface when evaluating economics and marketability. This is especially evident in the mineral inventories conducted on proposed wilderness areas. Precious and base metals are the priority minerals, and industrial-mineral commodities commonly are either not considered or the expertise is not available.

The BLM field examination represents a mineral-property evaluation or feasibility study of a mining claim. Commonly, the mineral examiner enters into this work with a scarcity of information regarding the marketability of the industrial mineral in question—generally through no fault of his or her own. Claimants and industry must understand that the government agency is not responsible for proving the validity of their mining claims—they are! The claimant is responsible for providing to the mineral examiner all reserve, marketability, and productivity data. In addition, the government agency may ask for drilling to validate a claim and/or to prove quality of the mineral commodity. If the claimant does not provide these data on request of the examiner, the government agency will determine validity based on the data at hand.

It is important that the claimant understands that the government is not required to make an exhaustive study of the deposit. The law requires only that the mineral examiner verifies and samples the discovery. It is up to the claimant to prove marketability and the prudent-man rule. In fact, an Interior Board of Land Appeals (IBLA) decision found that the testimony or presentation by a non-BLM expert on reserves, sampling, testing, marketability, etc., would have more creditability in determining validity of an industrial-mineral mining claim than the mineral-examiner's findings.

The BLM and USFS mineral examiners will not accept geological inference to support validity or the existence of a discovery on a mining claim. For example, the IBLA held that 23 drill holes over a 640-acre tract was not adequate to establish reliable geological inference. The BLM would like to see at least one or two drill holes per 20-acre claim. The BLM will also frown on geological mapping or geochemical testing to form an assumption of mineralization. These techniques invite further exploration, but they are not sufficient to show discovery or validity under the 1872 Mining Law.

MARKETABILITY

As we all know, marketability is the driving force behind industrial-mineral development. NO MARKET—NO DEPOSIT.

The BLM and USFS place a high amount of emphasis on past administrative case law as it pertains to the validity of industrial minerals under the 1872 Mining Law. Marketability is probably the most important ingredient to validity. When BLM personnel consider marketability, they mean the marketability of a particular industrial mineral for that primary use for which it was located and cannot include any value-added markets. The BLM defines marketability as being based on the value of the mineral material in the

ground rather than on value-added products through enhanced processing.

The question of marketability of industrial minerals on mining claims has gone all the way to the Supreme Court in U.S. vs. Coleman (1968). The Supreme Court pointed out that the marketability test is essential for revealing the claimant's true intention or good faith. A discovery or validation cannot be based on speculation or future economic changes or untested technological advances. Again, it is up to the claimant to prove marketability and supply sound market information to the government mineral examiner. The claimant must show through pricing and cost factors that there is reasonable chance of success for development. The IBLA held that a demand for the product must be demonstrated at the time of the validity examination. Lack of activity on a mining claim indicates lack of market creditability.

The existence of local or regional markets by themselves is not sufficient to establish marketability. The claimant must show that he or she can enter the marketplace by providing a better quality material or be able to market the same mineral at a lower cost and still show a profit (prudent-man rule).

Another important consideration of marketability by the government is the question of closed or captive markets versus open markets. The marketability test is not met unless the claimant can show that "willing customers" exist to whom the mineral could be sold at a profit.

VALUE-ADDED MARKETABILITY

The BLM and USFS do not accept or recognize the term *value added* when it evaluates a mining claim on an industrial mineral. They prefer to refer to value added as "extended beneficiation or manufacturing."

It has been upheld in numerous IBLA decisions that the value of an industrial mineral as it relates to the validity of a claim is the value of the mineral after its extraction from the mine but before any additional beneficiation that would significantly raise the value. In other words, the value must be based on the mineral in its raw state, which undergoes only that processing necessary for its primary market. The government reasoning is that the intrinsic value of the mineral is its value for the primary market upon which the marketability study was based and that any additional value for a by-product market only reflects the skill and ingenuity of the claimant.

COMMINGLED UNCOMMON-VARIETY BY-PRODUCTS

Another difference in the evaluation of industrial minerals by government and industry is the question of by-products. When a company evaluates a mineral deposit, they look at all the markets available. The BLM looks only at that market for that locatable mineral on which the claim is located. In other words, sales from nonlocatable by-products cannot be used to support marketability or the prudent-man rule. For example, the claimant cannot sell the oversize silica sand from a glass-sand claim for construction sand, road base, or fill. These are markets served by common-variety sand and gravel.

The IBLA has consistently held that, for a mining claim to be valid, the mining operation must be profitable for uncommon-variety minerals or locatable industrial minerals under the mining law.

The profit must come from sales on the mineral for which the mining claim was located and cannot be subsidized from sales of the common-variety material. In fact, if a claimant sells the locatable mineral for common-variety uses, this is considered as an act of trespass on Federal lands.

Another quirk of this philosophy is when a company gives away overburden in exchange for stripping costs. This is called "bootstrapping." The mining costs also cannot be reduced by the sale of the common-variety material commingled with the locatable mineral. Such a practice allows the locatable mineral to "ride piggyback" on the sale of the common-variety mineral. A mineral examiner disregards all income or cost savings from these practices, even if the commingled material can be sold at a profit. Many claimants have argued that the common-variety material on their claims meet ASTM standards, therefore it is unique. If it is being sold for common-variety markets such as aggregate or construction sand, regardless of the quality, it is not permitted.

EXCESS RESERVES

In most of the western states, on Federal lands, large claim groups cover industrial minerals. It is not unusual for the claims to cover far more reserves than the market could ever absorb.

The question of excess reserves can also cause conflicts. Most industrial-mineral mining companies commonly will make an effort to identify all the reserves available for a future development. Financial backing and upper-management support depend on a large reserve base. The BLM, however, will limit their validity examinations only to those reserves that meet the prudent-man and marketability tests. The BLM generally will validate claims with reserves sufficient to last 25–30 years, based on an available market.

The BLM defines *excess reserves* as those reserves covered by mining claims, the tonnage of which exceeds what the claimant can reasonably produce in the foreseeable future at the present or projected rate of production. Furthermore, each claim must be evaluated individually for reserve tonnage to satisfy a market. If the market can be satisfied from one claim, then the value of the other claims come into question.

The IBLA has recognized that mining claimants do have the right to hold "reasonable reserves" without development. The government will agree to this if the reserves are not in excess of 30 years. However, those mining claims holding "reasonable reserves" must still meet the same standards of validity as the other mining claims being mined and having a showing of marketability.

CONCLUSIONS

The development of an industrial-mineral venture on mining claims is a difficult process but not an impossible one. If the 1872 Mining Law is changed, it could become not only more challenging but also more costly. If you are going to apply for a patent, you had better have a market proven and adequate test work done to prove marketability and unique properties. Be willing to share all your market data and quality-control work with the mineral examiner. It will make his or her job easier and make the claimant look like a serious contender for development.

FEDERAL ACTS AND COURT DECISIONS CITED

This section is included to provide information about access to the pertinent Federal acts, statutes, agency determinations, and court decisions regarding mineral leasing on public lands and to provide an explanation of abbreviations used in the following list of Federal acts, agency actions, and court decisions, which may not be familiar to the reader.

The Acts of Congress (e.g., Act of July 23, 1955; 69 Stat. 367, the Mineral Materials Act) are U.S. Statutes-at-Large and can be found in a series of volumes that contain all the Acts of Congress in chronological order, arranged by their date of approval. If an act is amended, which is normally the case (and especially for the Mining Act of 1872), these amendments are published in the *Federal Register*. The current acts and laws with amendments also can be found in the United States Code (*USC*), such as *30 USC 22* (see list below), where *30* is the title number and *22* is the section number. Title number 30 (Mineral Lands and Mining) contains most of the Federal mining laws in effect, which makes it an essential reference concerning up-to-date laws and regulations pertaining to mining laws.

Citations to the U.S. Statutes-at-Large, such as *69 Stat. 367*, refers to the volume number (*69*), abbreviation for U.S. Statutes-at-Large (*Stat.*) and page number (*367*).

Interior Department decisions can be rendered by the Interior Board of Land Appeals (*IBLA*); by the Department of the Interior itself (*ID*–Interior Decision), and, most important of all, by the U.S. Supreme Court (*US*–abbreviation for U.S. Reports). All Supreme Court decisions are published in the *Supreme Court Reporter* and in the *U.S. Reports*. Thus, *390 US 602 (1968)*, refers to volume number (*390*), page number (*602*), and the year the decision was issued (*1968*). Interior Department decisions and opinion can be found in the sixth edition of the book *Mineral Law* by T. S. Maley (1996). This book is probably the best reference for mining case law because most Department of Interior land decisions are unpublished.

The Federal acts, agency decisions, and court decisions cited in this paper are listed alphabetically and chronologically below.

Act of May 10, 1872; *17 Stat. 91* (Mining Law of 1872).

Act of February 25, 1920; *41 Stat. 437* (Mineral Leasing Act of 1920).

Act of July 23, 1955; *69 Stat. 367* (Mineral Material Sales Act of 1955).

U.S. vs. Anderson, *74 ID 292, 303 (1967)*.

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U.S. vs. Kosanke Sand Corp, *12 IBLA 282 (1973)*.

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Advances in Topographic Mapping of Industrial Minerals

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ABSTRACT.—This paper is a case study using new laser-terrain-mapping technology by EagleScan, Inc., for creating topographic maps. Holnam, Inc., has used this technology to create maps and volumetric calculations of several mines in the United States. The information is superior to conventional methods through accuracy, manpower, time, and cost. Holnam, Inc., was the first cement manufacturer to use the Digital Airborne Topographic Imaging System (DATIS™).

The technology uses the DATIS™ to produce high-resolution terrain maps and volumetric assessments of any area. DATIS™ is a mapping instrument that integrates (1) a Light Detection and Ranging (LIDAR) instrument to measure terrain elevation using laser light, (2) a large-format digital camera, (3) a relative position Global Positioning System (GPS) to measure aircraft position, and (4) an Inertial Measurement Unit (IMU) to measure aircraft attitude. The DATIS™ can measure up to 220,000 elevation samples per mi^2. The system continually collects data on the aircraft's position and measures the time for each laser pulse transmission to return from the ground, giving each sample a GPS reference. The system can operate at night, in overcast sky, and during high-wind conditions and can measure terrain below vegetation cover, unlike standard aerial photography used for traditional surveying and mapping. Surveyed ground-control panels are no longer necessary with this new technology, and only one ground GPS base station located within 60 mi from the aircraft position is required.

A computer elevation-point data file is created with the x, y, z coordinates of each laser elevation sample. With this file, CAD engineering programs can create topographic maps that rival products using conventional aerial mapping techniques. Volumetric measurements of stockpiles and pits are also available due to the high density of points collected from an area.

This new technology radically changes the turnaround time for map users, giving a product in the format used by today's cartographers. The time line from flight to maps is measured in days instead of weeks.

INTRODUCTION

This paper discusses topographic mapping from its earliest beginnings to the present. Topographic maps will be defined as large-scale maps—ones that set out to convey the shape and pattern of landscape in a manner that lies within direct experience. Topographic maps are quite distinctive from small-scale maps that show features of whole provinces, nations, and continents.

The distinction between large- and small-scale maps is generally lost to modern man due to the great variety of maps available. However, the distinction was great and fundamental to the ancients. It wasn't until the second century in Europe that the concept of "chorographic maps" were created, and used for Roman taxation (Harvey, 1980). The Romans created topographic maps using pictorial elements where scale submitted to perspective. Ample medieval maps exist today as definitive examples of the fine art of perspective mapping on a large scale.

In the Middle East, topographic mapping has existed since 2100 B.C. These early maps have survived as stone carvings or clay tablets. They show the great leap into abstract thinking by depicting maps drawn to scale. The earliest European map showing scale was in 1421. It is a map of Venice that is pictorial in view but with a scale bar at the bottom, in paces. Interestingly, Egyptians, with their great knowledge in geometry, left not a trace of topographic mapping, not even of the Great Pyramids.

Topographic mapping continued as pictorial representations into the 18th century. During that great span of time, man discovered the world, created conti-

Newman, T. E., 1999, Advances in topographic mapping of industrial minerals, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 255–262.



Figure 1. Example of early bathometric contouring. From Topographic Map of Tarragonia, Spain (Anonymous, 1851).

nental trade, and developed modern warfare. It was not the military that drove the advancement of mapping but rather ocean navigation. The creation of ocean trade and profits brought modern mapping and with it contour lines (Anonymous, 1851).

In 1730, marine cartographers first developed contour lines to show the depth of water (Fig. 1). In 1791, contours were introduced for land maps as a way to show relief or height by the French engineer, J. L. Dupain-Triel. However, the use of contour lines in topographic mapping spread slowly. This new technology did not give as striking an impression of relief as did pictorial methods. Also, the creation of contour lines required tremendous amounts of time in the field gathering data, and, as now, time was money.

Filling the gap between pictorial topographic maps and contoured maps was "hachuring" (Fig. 2). It was fast and surprisingly accurate for its intended purpose (Osborn, 1919). Hachuring is the use of small lines or shading to show the exact shape of mountains or valleys from a vertical viewpoint. The first European map was made in 1718 by the Germans and depicted by hachuring the mountainous regions in southern Germany. The American "Everest" of hachuring is John Wesley Powell's maps of the first scientific journeys through the western U.S. and down the Grand Canyon. Today, hachuring is still in use in conjunction with contour lines of elevation. The Swiss use it for the higher and steeper mountains on their topographic maps.

Modern topographic maps using contour lines that gave precise heights and shapes began in the 19th century (Muehrcke, 1978). The United States advanced the science with the creation of government agencies such as the U.S. Geological Survey and the U.S. Coastal and Geodetic Survey. Contour topographic maps were reserved for special, important locations where time and money were not the principal concerns. The high cost of creating contour topographic maps continued until the marriage of photography and airplanes.

AERIAL PHOTOGRAMMETRY

The use of photography in airplanes came naturally. Early photographs were oblique depictions of the countryside. The science of aerial photography was not advanced until the 1920s. Aerial photogrammetry is now a precise term meaning a vertical record of ground details as determined by focal length of the camera lens, the flying height at time of exposure, and the creation of mosaics from multiple overlapping frames.

Aerial photography, when used in topographic mapping, makes use of a parallax difference of the same

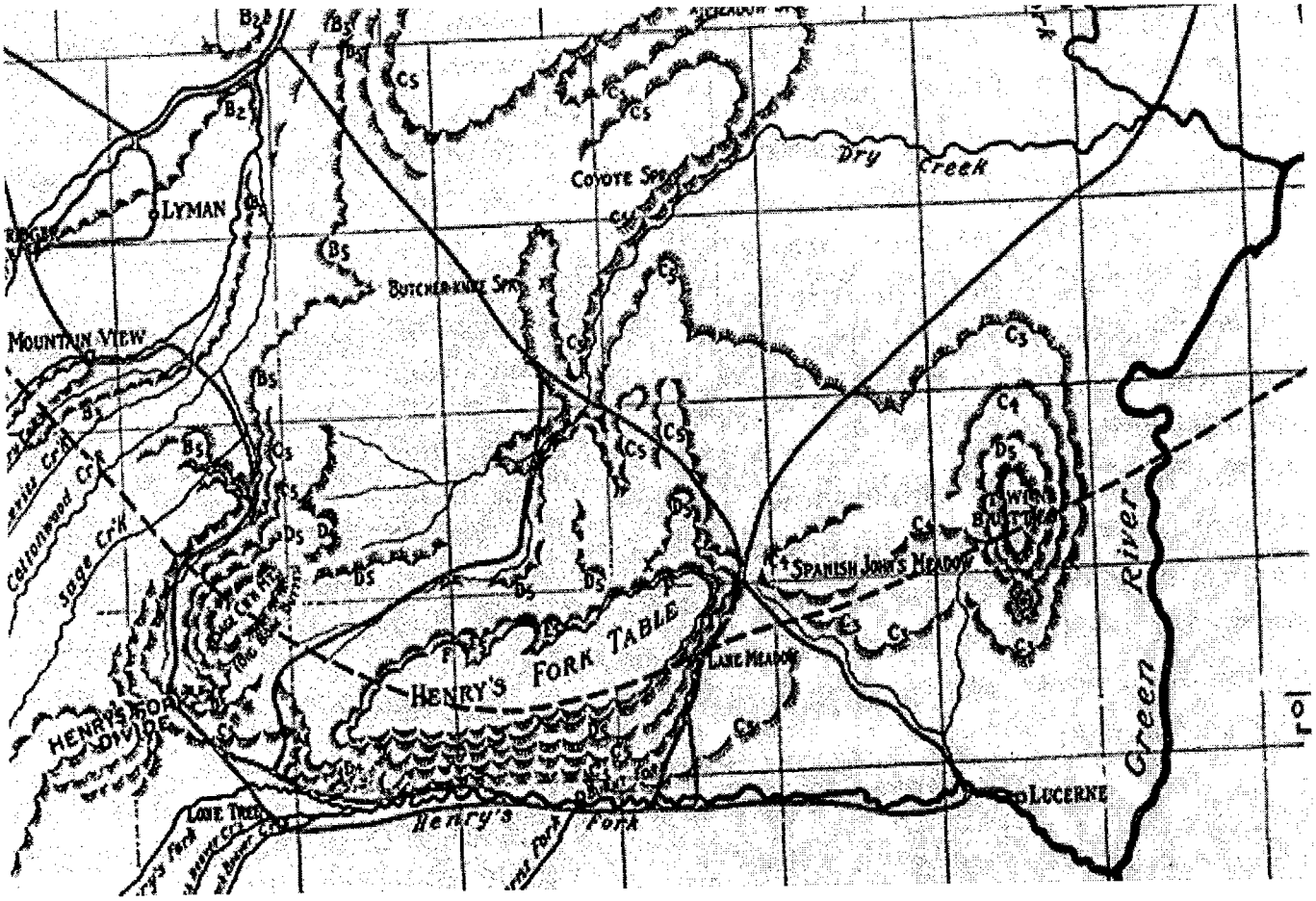


Figure 2. Example of hachuring technique before contouring.

object in two photographs. The parallax difference is what creates a stereoscopic image when viewing two photographs through map-making instruments or a stereoscope. Viewing the photographs creates an artificial focal point that represents an exact elevation. Changing the distance between the photographs and the lens can change the focal point and create a new elevation. In this way the map maker can trace the photograph's exact lines of elevation (focus point) by moving the photographs with special cranks and knobs. The elevations are scribed onto special templates for print processing (Ray, 1960).

Aerial photography depends on ground control in order to determine what base elevation is in the photographs. Ground control means that a survey crew has positioned precise location points on the ground before any photographs are taken. The ground-control points are surveyed into known geographic points by conventional survey. Then, each point is targeted with a wide fabric panel for identification in the photographs. The cartographer uses these panels to find the points to calibrate the contour lines that are created from the photographs.

There are instruments today that will perform the focal scribing and digitize the information into a map. This has greatly increased the speed of map making by adapting modern computer technology to an established process. The aerial photogrammetry system is still in use. Excellent maps are created but at a cost of manpower and time.

The next generation of topographic mapping consists of GPS satellites, aerial-scanning lasers, and computer software.

GLOBAL POSITIONING SYSTEMS

A Global Positioning System (GPS) is a constellation of 24 active satellites orbiting Earth at high altitude. GPS is based on satellite ranging (Hurn, 1989). Each satellite constantly transmits time by means of correlating four atomic clocks. To find an exact point in three dimensions, the satellites act as precise reference points in space in millisecond intervals. By knowing both exactly where the satellites are in space and exactly how far they are from a point, the position of that point can be calculated. The data are presented as latitude and longitude but can be converted into any datum, such as UTM or State Plane Coordinates.

To find a point on Earth requires a GPS receiver. The receiver collects the data from the active satellites and performs the calculations. To do a three-dimensional calculation requires that at least four satellites

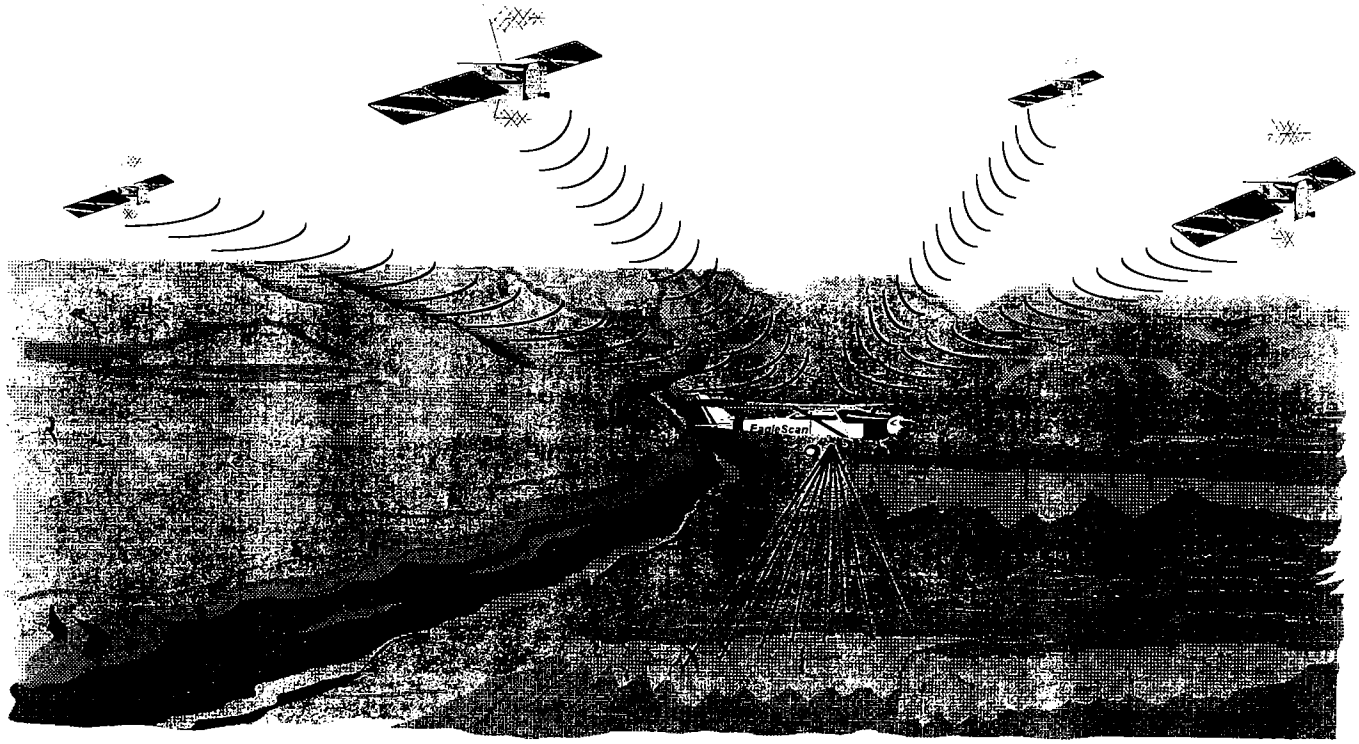


Figure 3. DATIS™ using GPS, laser scanning, and inertial measurement systems.

of the 24 be available. Each satellite is broadcasting precise time codes to be used in conjunction with other satellites. Spatial trigonometry is used to create a mathematical sphere around each satellite. The intersection of all four "spheres" is the location of the point. The fourth sphere gives the receiver information to correct its internal clock time and to heighten elevation accuracy.

Inherent and planned errors are incorporated into GPS. The major unplanned errors are ionospheric and atmospheric delays in receiving satellite signals. There are errors from signals bouncing off objects that lengthen the transmission time and ellipsoid errors in the satellites' orbits that change the transmission time. Such unplanned errors can be corrected in advanced GPS receivers. The planned errors are installed by the U.S. military and take sophisticated mathematics to correct.

The U.S. Department of Defense (DOD) maintains the GPS system. It is a tactical system designed to protect the United States; civilian use is a bonus. The DOD purposely degrades the satellite signal by inputting an error into the signal. The error is called Selective Availability or S/A. S/A alters the timing signal from each satellite by means of a logarithmic equation that constantly fools all receivers to think that the point is moving. Fortunately, however, the error-causing logarithmic equation is the same in all satellites, and this provides an opportunity to systematically correct for the error.

The S/A can be corrected with Differential GPS (Hurn, 1989). Differential GPS is the use of two GPS receivers, one at the point the surveyors want to know and another ground receiver at a *known, stationary* location. The GPS receiver at the known ground location is recording the same signals as the surveyor's receiver. But, because it is stationary and at a known location (benchmark), the S/A error can be subtracted electronically from the data. The S/A error signals of the surveyor's receiver are subtracted electronically using the ground receiver's data. Differential GPS gives subcentimeter accuracy by using this kind of post-processing of the GPS data.

AERIAL SCANNING

The basic technique of scanning Earth via aircraft has been around since the 1920s. Essentially, an aircraft has a hole or port constructed into its belly. The port is used to insert cameras as the aircraft flies a path, and photographs are taken that will produce an overlapping mosaic of images. The precise position of the aircraft was not as important as were previously established ground-control points. The ground-control points had be set before the flight and are the topographic targets for photographic survey control. Each control point had precise elevation and coordinates.

It is important to get overlapping aerial coverage because of all the costs involved. Today, autopilot software guides the plane via ground-based navigation signals that give accuracies within hundreds of meters. The standard technique is to get coverage outside the target areas just to insure that the target was covered.

The advancement of GPS navigation has added to the accuracy of flight paths. The pilot inputs Differential GPS flight-path instructions into the autopilot and gets precise three-dimensional orientation within meters. The reliability of GPS navigation is so good that the U.S. Federal Aviation Administration will use Differential GPS as the standard navigation aid for all aircraft.

Digital Airborne Topographic Imaging System (DATIS™)

The DATIS™ process was developed by EagleScan, Inc., Boulder, Colorado (Edie, 1998), and it directly measures the earth's surface to provide topographic and geographic information (Fig. 3). DATIS™ consists of a package of instruments attached to the photo port in a fixed-wing aircraft. The package consists of a highly accurate scanning laser coupled with a GPS recorder and a flight-inertial-measurement unit (Fig. 4). Also coupled with the system is a high-resolution digital camera. All of the data from the instrument package is stored in an onboard computer for post-processing.

The DATIS™ scanning laser works by "firing" more than 4,000 pulses per second onto a precision scanning mirror. The mirror deflects each pulse toward the ground in a sweeping motion resembling scanned point lines. The laser pulses strike the earth and are reflected back to a receiver. Each laser pulse is recorded from the time it left the laser, the precise angle of the scanning mirror, and the time the pulse returned to the receiver. With this information, the computer can calculate the angle and distance to the ground from the aircraft.

With Differential GPS, the elevation of each laser point and the latitude and longitude of the aircraft are recorded four times a second into the same computer used to process the laser data. The aircraft's Differential GPS data are further post-processed against a ground GPS unit that records data at the same time as the flight. This eliminates the government S/A interference.

The aircraft's altitude and attitude (pitch and yaw) are measured with an Internal Measurement Unit (IMU). This information is combined with the position of the laser's scanning mirror to give the exact angle that the laser pulse left the aircraft. The IMU data are recorded into the same computer as the laser pulses and Differential GPS.

DATIS™ works by flying a precise flight path controlled by Differential GPS to within a few meters of accuracy. The precise flight lines ensure that only the areas needing coverage are flown.

All data are post-processed to create a dense (300,000 points/mi^2), accurate Digital Elevation Model (DEM). Each laser-generated point becomes an elevation and coordinate point with accuracies of 15 cm in elevation and 20 cm horizontally (Fig. 5). The high density of points makes features such as trees, buildings, and utility corridors easy to detect. Because DATIS™ directly measures elevation points, no film development, scanning, or stereo plotting is required.

A high-resolution digital camera is also attached to the DATIS™ platform. The camera can be used for conventional image creation (Fig. 6) or combined with DATIS™ elevation data to be draped into three-dimensional images (Fig. 7).

DATIS™ can be successfully taken when flying with overcast conditions, in high winds or even at night. The data collection is restricted *only* by cloud cover below the aircraft.

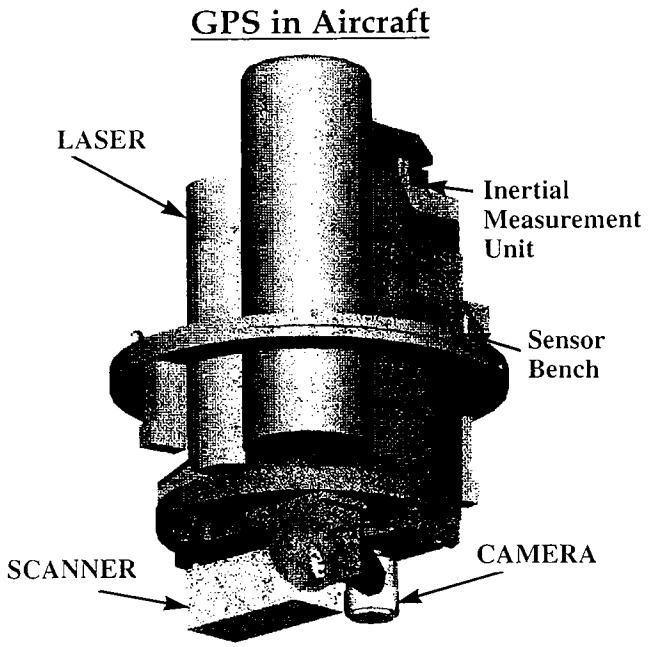


Figure 4. DATIS™ inside aircraft.

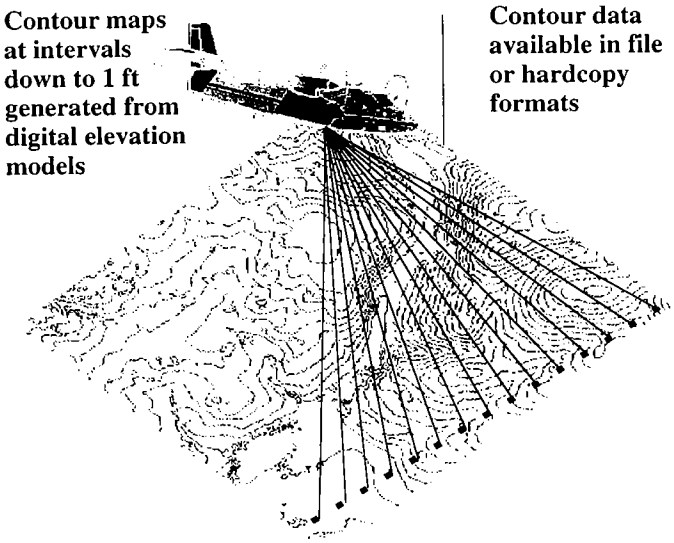


Figure 5. DATIS™ contour maps.

COMPUTER SOFTWARE

Computers and their software have revolutionized the world, including topographic contour mapping. The DATIS™ system's Digital Elevation Models are essentially computer files containing thousands to millions of individual data points tied into x (latitude), y (longitude), and z (elevation) coordinates. The computer positions each point into a virtual three-dimensional surface. The more accurate the data points and the greater the number of sample points, the more accurate the DEM.

Computer software will take a DEM and create contour lines around each "elevation" point creating a topographic map without intermediate "adjusted" contour intervals. The DEM also contains elevation points of structures, such as buildings and renders them into symbols that are acceptable to today's mapping customers. EagleScan has developed customized software that can also remove buildings and trees if necessary.

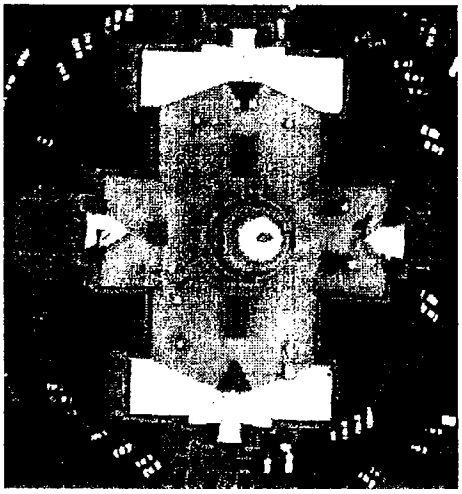
CASE STUDY

During April of 1997, Holnam, Inc., a cement manufacturer, contracted with EagleScan, Inc., to create a new topographic map for its Devil's Slide, Utah, plant and quarry (Fig. 8). The previous mapping had to be done by conventional aerial-photographic techniques (Fig. 9). Holnam, Inc., was the first cement manufacturer to use DATIS™.

The DATIS™ survey required only one day to collect the data for a new topographic contour map. The project consisted of using EagleScan's twin-engine aircraft as the instrument platform. On the ground, post-processing of Differential GPS was accomplished using a U.S. Geological Survey "brass cap" (benchmark) located at the Ogden/Hinckley Airport, Utah, as the survey control point.

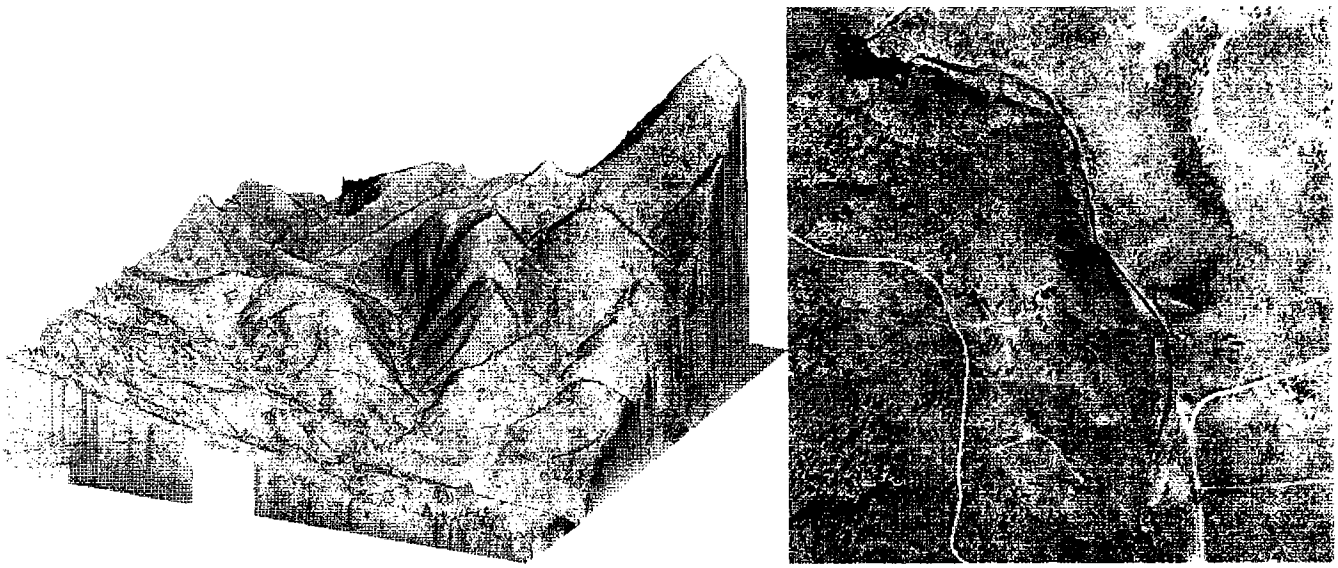
While the aircraft GPS was collecting data, the ground GPS was recording the same information for post-processing. The aircraft flew six survey flight lines to get the spatial coverage of the plant and quarry. The flight line widths were 2,600 ft (800 m). The flights were at 11,500 ft

* **Images Collected Using DATIS Digital Imager**
  - ★ **2024 x 2044 Pixels**
  - ★ **8 Bits Dynamic Range**
* **One Foot Resolution**
* **Digital Image Available as Georeferenced, Orthorectified and/or Mosaicked**



Colorado State Capitol

Figure 6. DATIS™ high-resolution image.



Digital Terrain Model Digital Image

Figure 7. Three-dimensional models can be created from DEMs.

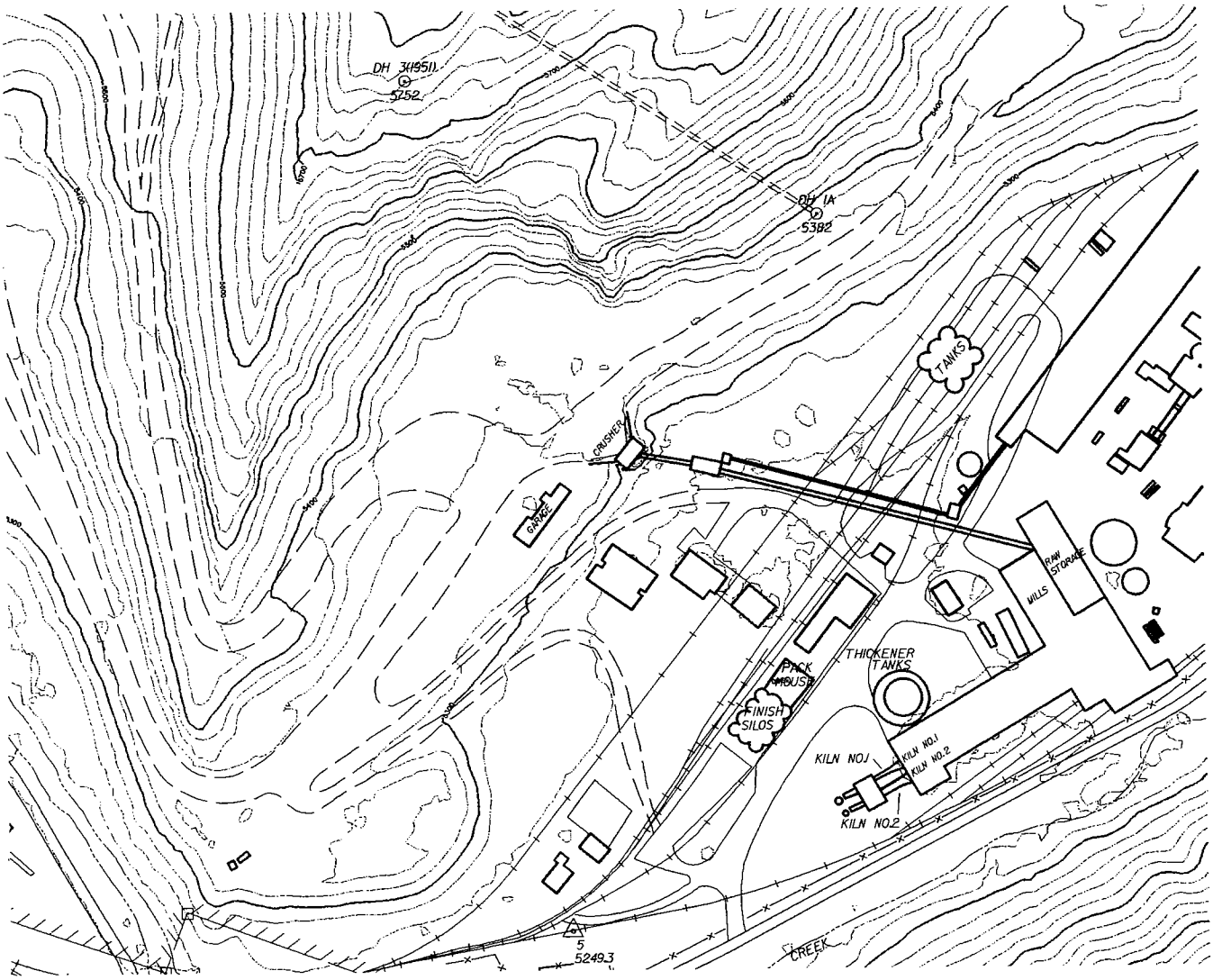


Figure 8. Devil's Slide, Utah, DATIS™ scan.

(3,540 m) above sea level and required course corrections to avoid clouds.

More than 400,000 data points were collected during the flight. Each data point represented a distinct latitude, longitude, and elevation location. Once the aircraft was on the ground, post-computer processing confirmed good data. The on-site data clarification ensures that the information is reliable before the aircraft leaves the area.

Creation of the topographic contour map required two days of work in the office. The work consisted of software converting the data points into contour lines. Extraneous data such as trees, people, moving autos, and equipment had to be removed. The contour intervals were accurate to one-foot spacing, but Holnam, Inc., created contour intervals at 5 ft for its internal use.

The advantages of the DATIS™ system over aerial photogrammetry were time and labor. Cost of the DATIS™ map was comparable to conventional methods but with the advantage of having the map in a computer software format. The computer data could be manipulated into an infinite variety of products. The added benefit was a topographic map with directly measured contour lines that can be used in cross sections and volumetric calculations.

ACKNOWLEDGMENTS

Special recognition to David Box, Verlin Fisher, Chandler Smith, Rob Eadie, Joyce Herbst, and Jamie Young at EagleScan, Inc., for their generous help in creating this paper. Also, I want to thank Roy Stienmier, Chief Geologist, and John Olivas, CAD Draftsman, Holnam, Inc., for their cooperation.

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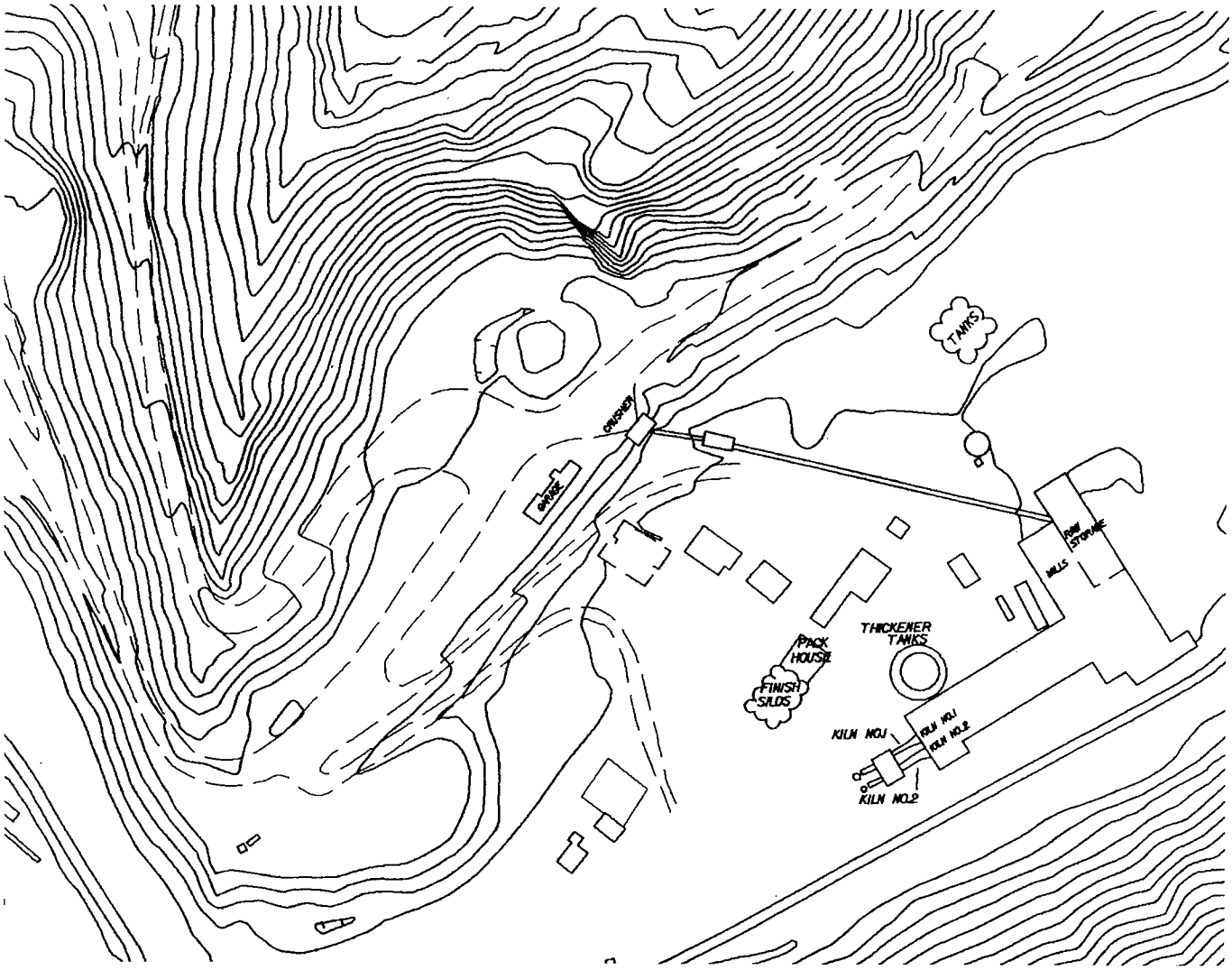


Figure 9. Devil's Slide, Utah, traditional method.

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Design Approaches in Quarrying and Pit-Mining Reclamation

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ABSTRACT.—Reclaimed mine sites have been evaluated so that the public, industry, and land planners may recognize there are innovative designs available for consideration and use. People tend to see cropland, range, and road cuts as a necessary part of their everyday life, not as disturbed areas despite their high visibility. Mining also generates a disturbed landscape, unfortunately one that many consider waste until reclaimed by human beings. The development of mining provides an economic base and use of a natural resource to improve the quality of human life. Equally important is a sensitivity to the geologic origin and natural pattern of the land. Wisely shaping our environment requires a design plan and product that responds to a site's physiography, ecology, function, artistic form, and public perception.

An examination of selected sites for their landscape design suggested nine approaches for mining reclamation. The oldest design approach around is nature itself. Humans may sometimes do more damage going into an area in the attempt to repair it. Given enough geologic time, a small-site area, and stable adjacent ecosystems, disturbed areas recover without mankind's input. Visual screens and buffer zones conceal the facility in a camouflage approach. Typically, earth berms, fences, and plantings are used to disguise the mining facility. Restoration approaches the best land use as restoring to its original condition. Rehabilitation targets social or economic benefits by reusing the site for public amenities, most often in urban centers with large populations. A mitigation approach attempts to protect the environment and return mined areas to use with scientific input.

The reuse of cement, building rubble, and macadam meets only about 10% of the demand for aggregate. Recognizing the limited supply of mineral resources and encouraging recycling efforts are steps in a renewable resource approach. An educative design approach effectively communicates mining information through outreach, land stewardship, and community service. Mine sites used for art show a celebration of beauty and experience—abstract geology. The last design approach combines art and science in a human-nature ecosystem termed integration.

With environmental concerns, an operating or reclaimed mine site can no longer be considered isolated from its surroundings. Site analysis of mine works needs to go beyond site-specific information and relate to the regional context of the greater landscape. Understanding design approach can turn undesirable features (mines and pits) into something perceived as desirable by the public.

INTRODUCTION

In the past, human beings viewed the landscape as wild and fearful—something to be tamed and controlled. If scientists, engineers, and designers become familiar with the term "landscape" more fully, as something involving the interaction of people and place, they might see their work as mutually beneficial.

A study of landfill and sewage treatment by Engler (1995) discussed eight different approaches to designing waste landscapes. Mining generates a disturbed landscape that many consider waste until reclaimed by nature or human beings. The language appears adaptable to reclaimed mine sites with minor reinterpretation of her terminology (see Table 1). One approach Engler did not mention is the oldest one around—nature itself.

DESIGN APPROACHES FOR RECLAIMING MINE SITES

Although a combination of the eight approaches given by Engler (1995) is most commonly applied, it is still useful to examine the specific categories with examples.

Arbogast, B. F., 1999, Design approaches in quarrying and pit-mining reclamation, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 263–271.

Table 1.—Design Approaches to Reclaiming Mine Sites

Engler's list	Author's list	Description
	Natural	Allow nature to reclaim site with no, or minimal, human influence
Camouflage	Camouflage	Conceal a mining facility with visual screens and buffers
Restoration	Restoration	Return land to its approximate original condition
Recycling	Rehabilitation	Use site for public amenities
Mitigation	Mitigation	Repair mined-out site that has experienced extensive damage from human or natural causes
Sustainable	Renewable	Use site to recycle man-made resource or natural resources
Educative	Education	Communicate resource information through outreach
Celebrative	Art	Treat site as work of beauty and unique experience
Integrative	Integration	Combination of approaches integrating art and science

Natural

Wait long enough and no matter the disturbance, nature works to regenerate with or without the benefit of man—thus, the adage "time heals all wounds." A conscious natural design approach may be one of hands off. Some areas devastated from fire, landslide, volcanic eruption, or quarrying manage to recover well without human intervention. Alaska's moist climate, dense vegetation, and remoteness are suited for some abandoned pits to be passively reclaimed by nature. Heavy equipment brought in to recontour these old sites may do far more damage to the existing ground cover and surface soil than the benefit gained. Long-term natural recovery may or may not bring about the specific changes people find desirable. How many people living near Appalachian mining sites want to wait 30 years for hardwood seedlings to sprout? Studying nature's ability to heal is one way scientists and designers can learn new techniques for reclamation taking maximum advantage of natural geological and biological processes.

Near Fort Collins, Colorado, a sand and gravel pit was used to test natural seedfall for restoration of cottonwood (*Populus* sp.) and willow (*Salix* sp.). The WREN pit (Fig. 1), a cooperative study project, was conducted by Western Mobile Corp., Colorado State University, and the U.S. Geological Survey. Controlled flooding was used to "simulate historic spring flooding conditions along the Poudre River" to establish vegetation (Gladwin and Roelle, 1997). With additional timed floodings, clearing of undesirable exotic saltcedar seedlings (*Tamarix chinensis*) was successful. The pit is an example of semi-native riparian vegetation being used to reclaim a site with little human involvement and cost.

Camouflage

Camouflage uses visual screens and buffer zones to conceal the mining facility. Typically, an immediate response by the industry is to utilize fences, earth berms, and plantings (small-scale features) to disguise the activity from residential areas. The design solution is commonly associated just with the site perimeter as shown in Figure 2. Wide buffer zones are frequently abandoned in the interest of cost. Camouflage commonly makes use of linear, uniform rows of quick-growing plant species for wind breaks and disguise, and does not necessarily reflect a long-term planning scheme. A longer term approach could involve using quick-growing plants as part of a matrix containing the slower-growing native species matched to grow in the overburden and spoil material. Another consideration should be the profound effect vegetation has on water control (infiltration and erosion).

Austin (1995) calls using landscape skills "merely to provide a cosmetic touch to an otherwise ravaged landscape, an exercise akin to putting lipstick on a pig." This may have been true in the past when reclamation took a backseat to exploration, but there are instances where a minimal approach is justified. A mining site within an urban corridor may require a different design approach from one in a wilderness area. The National Park Service has elected to close roads and add visual screens to designated sites if an environmental-impact assessment determines it appropriate. Today, progressive aggregate companies recognize the value of including landscape architects early in the planning stage.

Restoration and Reclamation

Restoration involves returning the land exactly to its original condition. Mining, thus, is considered a temporary activity that leaves a disturbed area in a status that requires a return to its pre-mining biological conditions. Restoration is seldom possible because we currently do not have the level of information and skill required to return ecosystems exactly to their original structure. Furthermore, complete biological restoration is seldom possible because many native organisms do not return or fill the exact same ecological niche. Instead the new land is environmentally unstable, and exotic species are ready to invade disturbed sites. A more realistic approach is to approximate the new habitat as close as possible to its original function and recapture the landscape character (Fig. 3).

As a reaction to landscape scars caused by coal mining, reclamation came to be defined legally as "back to approximate original contour." The recommendation of the Secretary of the Interior for reclamation was to correct damage to the lands and waters of the vicinity and leave the area in a usable condition (Simpson, 1985). Scientific data and budget constraints were not dealt with by public servants in reacting to the destruc-



Figure 1. Photograph of WREN pit near Fort Collins, Colorado.

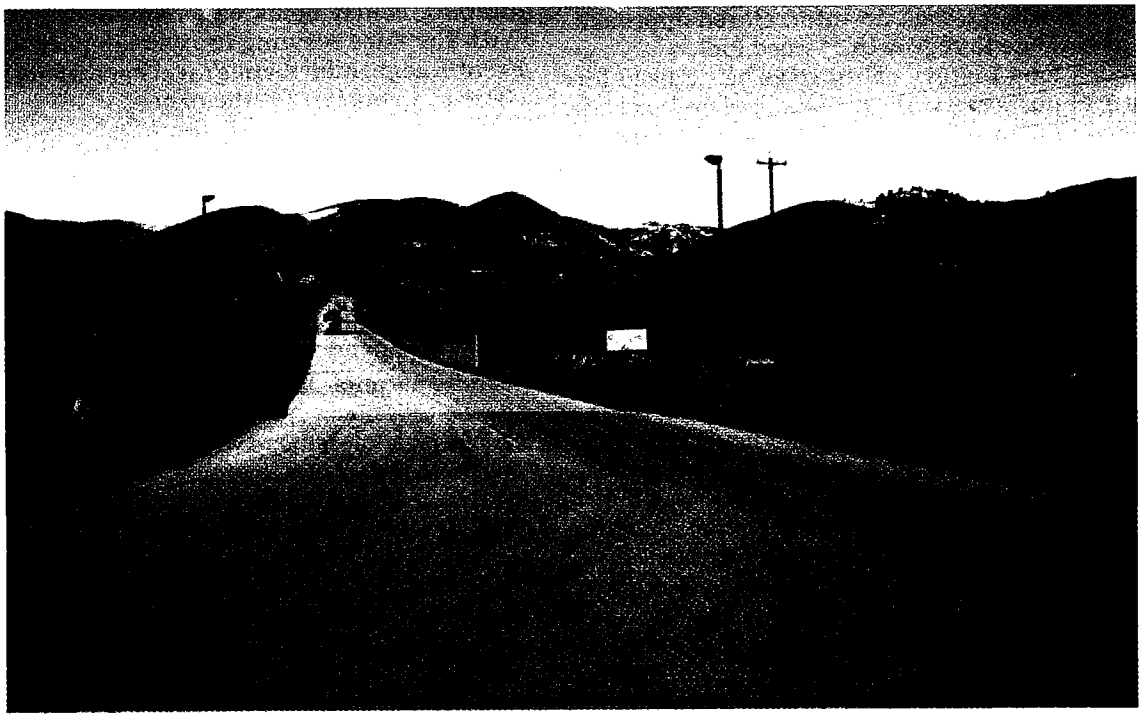


Figure 2. View of vehicular entrance to a working mine site.

tive practices of coal mining. In the 1970s, lawmakers reasoned that the best land use was to restore it to its original condition. Does that mean the way the land looked before European settlers arrived, before Indians set wild fires to the Great Plains, or prior to the last ice age? In attempting to reshape the land back to its pre-mining form, billions of dollars are required to move millions of cubic yards of earth to fill thousands of acres for aesthetic purposes and it would still not meet "original condition."

Pit sites above the water table return to pre-mining condition more successfully than pits below the water

table, especially for agricultural use. Cherries, corn, alfalfa, and apples are harvested on a former mined-out gravel pit in Ontario, Canada (Kuennen, 1983). A growing number of people are demanding that land reclamation be measured by how well the landscape functions, not by how well the landscape resembles the pre-mining form.

Rehabilitation

A rehabilitative approach targets social or economic benefits by reusing the site for public amenities, most often in urban centers. The city of Hagen, Germany, has a city hall located on the site of an inactive quarry (Dietrich, 1990). Many of the natural rock outcroppings remain, and, in places, form parts of the interior and exterior of the building. Golf courses have been built over abandoned quarries from New York to Florida, and from California to Texas. Construction of townhouses, shopping centers, or industrial parks are other examples of a rehabilitative approach.

Near Mombassa, on the coast of Kenya, an abandoned quarry illustrates a more comprehensive rehabilitation plan. Once barren land, with almost no underground water, is covered now with grass and trees. Rene Haller, a Swiss agronomist, introduced agriforestry, animal farming (including cattle, sheep, oryx, tilapia, and crocodiles), and tourism to the wasted landscape at low cost (Myers, 1990). Rather than introducing monocultures, he took an interrelated approach from farm garbage to regrowth of wood fuel.

There is a long history of quarries being used for horticultural purposes from gardens and orchards to parks. Beginning in 1904, Butchart Gardens in British Columbia, Canada, reclaimed 50 acres of an exhausted limestone quarry to a premier botanical garden (Fig. 4). Opened to the public in the 1940s, the site hosts more than a million visitors each year. This grand, artificial landscape is only one in a long line of quarries reclaimed as gardens, aesthetically pleasing to the public as cultural art, but ecologically not a copy of nature.

Mitigation

Some mined areas have undergone major changes, either human or natural, after mining ceased. A mitigation approach attempts to protect the environment and return these mined areas to beneficial use with scientific input. Environmental data utilized in mitigation planning include geomorphic setting, watershed, viewshed, hydrology, soil/waste characterization, climate, vegetation, wildlife habitat, and historic use. Illegal dumping can seriously degrade a mined-out site. Dumping of contaminated debris from the U.S. Department of Defense and Atomic Energy Commission into the Weldon Spring Quarry (30 mi west of St. Louis, Missouri; Fig. 5) went on for nearly 30 years (U.S. Department of Energy, 1996). Groundwater contamination was spreading toward well fields that supplied homes and industries throughout the area. A quarry cleanup of the bulk waste began in 1989 under the auspices of the Environmental Protection Agency (EPA) Superfund Program and the State of Missouri. High-quality clay soil is required to construct the permanent disposal facility and make it impervious to water. Nearly 2 million cubic yards of clay will be excavated from more than 200 acres of land in the nearby Weldon Spring Conservation Area. In this case, the cleanup of one mine site requires the construction of another.

Nature can also degrade mined lands. Over a 35-year period, Cooley Gravel Co. extracted more than 26 million tons of aggregate from a site along the South Platte River, Colorado. Floods in 1965 and 1973 breached levees and changed river channels and caused catastrophic impact on the land. Cooley reclaimed the land and donated 425 acres to the City of Littleton. Today, together with adjacent land dedicated by Littleton, South Platte Park is one of the largest wildlife parks within city limits in the United States. Cooley worked closely with a number of government agencies including the South Suburban Park and Recreation District, Army Corps of Engineers, and Soil Conservation District. The design made use of native-seed mixes, and incorporated trails, fishing along the South Platte River, and educational tours at the Carson Nature Center.

Efforts to mitigate the biological impact of mining include industry, state, and federal agencies. States check for endangered or threatened species within an area requesting mining permit approval. The U.S. Fish and Wildlife Service has proposed the Preble's meadow jumping mouse be listed as an endangered species. With the mice residing in riparian pockets along the Front Range, mined-out gravel operations could be reclaimed as habitat for the mouse.

Renewable Resources

Mined-out land can be a source of renewable resources or a place to process renewable resources. Renewable-resource use is complex and implies environmental sensitivity, biological controls, and results in a reduction in resource/energy inputs. Essentially, the reclaimed landscape minimizes inputs and ecologically harmful outputs. The reclamation of gravel-mining pits at a custom-home development called The Farm (Boulder Valley, Colorado) to wetlands is an example. One of the most dramatic effects that man has had on the ecosystem relates to loss of wetlands. During the period 1780 to 1980, Colorado lost about half of its wetlands (Dahl, 1990). The Farm design incorporates oxbow lakes and more than 39,000 plants native to prairie wetlands in a hundred-acre site (Leccese, 1996). One important aspect of this project is the operators' recognition of their impact upon natural riparian ecosystems and the renewal of water resources.

For some experts, a sustainable relationship with the earth will only come about by controlling growth, reducing our consumption of goods, and preserving diverse landscapes. Recognizing the limited supply of mineral resources and encouraging recycling efforts are beneficial steps. England and Wales have established planning guidelines that include reducing the proportion of stone removed from land, from the current 83% to 68%, by 2006 (Richardson, 1995). A tremendous



Figure 3. View of tallgrass prairie on gravel resource in Minnesota. Photo courtesy of Richard Hamilton Smith.

amount of construction material is wasted landfill and is an underutilized resource. The current reuse of concrete, building rubble, and macadam meets only about 10% of the demand for aggregate. Unfortunately, recycling programs do not play a significant role in reducing consumption. Some mined-out areas are contributing to the reuse effort by serving as locations for recycling of concrete, macadam, glass, and other resources (Fig. 6).

Education

In the educative approach, mining information is communicated effectively through outreach, so that citizens can make informed choices about future land use. Europeans tend to be ahead of the United States in this regard, perhaps, due in part to their limited available land. They also focus on aesthetics as much as the functional after-use. For example, scientists in the United Kingdom have understood the importance of gravel pits for bird habitat since the 1930s and 1940s.

In the United States, The National Stone Association (NSA) and American Association of Landscape Architects (ASLA) jointly sponsor an Annual Landscape Architecture Student Competition, aimed at giving aggregate operators new ideas on reclamation and beautification. Judged on creativity, practicality, and design, winners earn cash prizes and an opportunity for feedback from the producers. These tantalizing projects have been going on for 22 years. One such example is shown in Figure 7. Unfortunately, the NSA does not keep historic records of the winning entries other than names.

Another example of educational outreach is in



Figure 4. The Butchart Gardens, British Columbia, is an example of reclamation from quarries being used for horticultural purposes. Photo courtesy of Butchart Gardens, Ltd.



Figure 5. The visual effect of dumping operations at Weldon Spring Quarry, Missouri. Photo courtesy of Morrison Knudsen Corp.

Albuquerque, New Mexico, where Western Mobile replaced the grass lawn at its corporate headquarters with a xeriscape garden. The ground cover, parking lot, pavement, signage, and building make use of aggregate and together with the garden help educate and promote their products. The garden requires about 10–20% of the water needed previously and is open to the public.

Art

An artistic approach is one where the site is celebrated as a work of beauty and unique experiences. Engler (1995) categorized the approach as celebrative; people become fully aware of the connection between the production of an item and their everyday lives. One pioneer in the earthworks-as-art movement was Robert Smithson. Smithson made field trips to abandoned quarries and experimented with the sculptural qualities of earth, calling such projects "abstract geology" (Bourdon, 1995). He proposed, "Art can become a resource that mediates between the ecologist and the industrialist" (Holt, 1979). Sites examined include Smithson's Broken Circle, Parc des Buttes-Chaumont, Aexoni Quarry, and Untitled (Johnson Pit #30).

The public Parc des Buttes-Chaumont in Paris (ca. 1864–1869) was built upon old quarried limestone and gypsum pits, abandoned gallows, a sanitary sewage dump, and a mass grave. After the reclamation, Parisians could stroll "aimlessly while observing the city's changing physical and social structure" and appreciate "artistic urban accomplishments" (Meyer, 1991, p. 19). Views of the built environment were important with walking being the primary recreation.

A sculpted quarry at Aexoni, Greece, celebrates music and dance while acknowledging the natural landscape. The quarry expresses the Greek philosophy of the unity of all things. While providing a stage for performing arts and exhibitions, the sculptured quarry illustrates both the artistic and *rehabilitative* approaches. Regional plant species were planted and sculptural forms relate to adjacent rock formations (Golanda, 1994). There, the floor plane and backdrop of the stage design were presented by Nella Golanda as an impression of excavation—a cave.

Robert Smithson utilized a sand pit and body of water in 1971 to create a more open sculptural form. Titled Broken Circle (Fig. 8), the project, a circular jetty and canal, was planned in the Netherlands as part of an international art exhibition. About 140 ft in diameter, the symmetrical landform suggests yin and yang, inviting human passage. The earthwork also evokes images of dikes and polders that are the backbone of Dutch landscape. Smithson was aware of the constant changes in nature and believed it could interact and enhance art on disturbed land.

Another site-specific earthwork is Untitled (Johnson Pit #30) by Robert Morris, a minimalist sculptor. Sponsored by the King County Arts Commission, Washington, Morris formed an earth sculpture from an abandoned four-acre gravel pit in 1979. It stimulates a strip mine with concentric terraces (Morris even cut down fir trees that had been growing on the pit rim). Residents complained the site was simply being exploited once more; however, Morris replied (King County Arts Commission, 1979, p. 16):

> The selling point was, is, that the art was going to cost less than restoring the site to it "natural condi-



Figure 6. Stockpile of mixed-color glass for recycling in a self-compacting flowable structural fill macadam. Photo courtesy of Western Mobile.



Figure 7. NSA/ASLA Student Competition First Place: Linda Attaway, Mary Dewing, University of Colorado at Denver. From Thompson, 1991, p. 79.

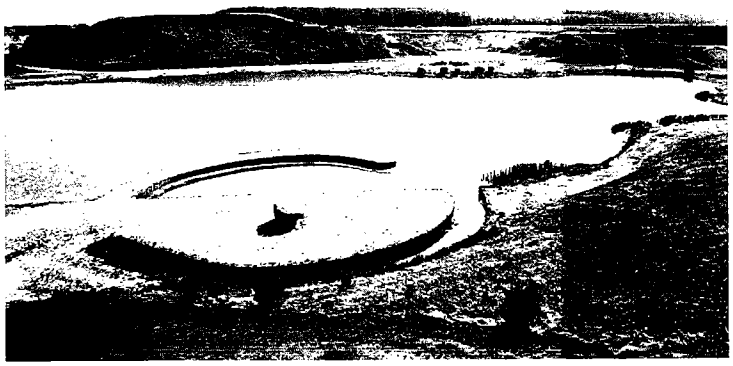


Figure 8. Broken Circle. Photograph by Pieter Boersma. From Bourdon, 1995, p. 214.



Figure 9. Earthen water strider sculpture from Effigy Tumuli, 1983–85. Photo courtesy of Department of Natural Resources, Buffalo Rock State Park, Illinois.

> tion." What are the implications of that kind of thinking . . . that art should be cheaper than nature? . . . The most significant implication of art as land reclamation is that it can and should be used to wipe away technological guilt. . . . Will it be a little easier in the future to rip up the landscape for one last shovelful of non-renewable energy source if an artist can be found (cheap, mind you) to transform the devastation into an inspiring and modern work of art? . . . It would seem that artists participating in art as land reclamation will be forced to make moral as well as aesthetic choices.

Integration

The combination of art and science in a "human-nature ecosystem where work and leisure coexist" is an integrated approach (Engler, 1995). Combining art with science is ridiculed by professionals on both sides. Scientists complain that artists are imprecise, touchy-feely, subjective, and that designers do not make use of scientific information. Artists retort that scientists are narrow minded, too specialized, and out-of-touch with aesthetics. The public often considers both groups elitist and isolated from the community they are supposed to serve. There is a common ground where all sides need to meet, understand the other's limitations, and take mining reclamation to the next level.

Three representatives of the integrated approach are the Clay County Beach Ridges Forum, Quarry Cove, and Effigy Tumuli.

A portion of Minnesota has native tallgrass prairie over gravel resources. By addressing potential resource problems in both the macro and micro landscape before serious conflict arises, the Clay County Beach Ridges Forum enabled people (landowners, gravel producers, conservationists, government agencies) to understand their common interests were stronger than their different viewpoints. Selected viewpoints expressed in the report (Clay County Beach Ridges Forum, 1997) include:

- Maximize utilization of aggregate resources (the concept being to minimize land surface disturbance by exhausting the resource on an approved site by mining deeper and using aggregate resources of the highest quality when feasible).
- Promote aggregate recycling (including a public information fact sheet).
- Consider aggregate resources in future land use decisions throughout the county.
- Provide incentives through the permitting process to avoid native prairie (one suggestion is to expedite the permitting process for proposals sited outside of prairie).
- Minimize development of new haul roads across prairie.
- Use prairie grasses and forbs for gravel pit reclamation whenever possible.

On the Oregon coast is Quarry Cove, the first quarry converted into a man-made tidal zone fed and nourished by wave action (Thompson, 1996). Developed by the Bureau of Land Management, the site is wheelchair accessible, provides a variety of wildlife habitats, and is expected to have species diversity comparable to a natural tidal pool within 5 to 10 years. Graduate students in marine biology are conducting research, and visitors can view nature taking its course as marine life invades the area. The cove is an exciting example of an exhausted site becoming a "natural" biological laboratory with community outreach.

On a larger architectural scale is a design by sculptor Michael Heizer. In Illinois, on land disturbed by coal mining, the reclamation plan celebrates the region's history of Indian burial mounds with earth shapes or tumuli; water strider, frog, turtle, snake, and catfish (Massie, 1985). Located on a sandstone bluff above the Illinois River, the 150-acre outdoor project was a cooperative team effort by Ottawa Silica Co., a nonprofit organization, and state and federal governments (Illinois Department of Conservation, 1997). The artist minimized expensive earth moving by studying existing mine site topography for hidden forms. Named Effigy Tumuli, the project (Fig. 9) includes the treatment of millions of gallons of acid water, neutralizing acid spoil, and seeding with wildflower and grass. Although this instance concerns a coal mine, pit and quarry reclamation can be tailored to include landform sculptures as demonstrated under the Art section. Interestingly, Heizer was more interested in this project from a standpoint of "I don't support reclamation art sculpture projects. This is strictly art. I love mining sites. My whole family has been in the mining business" (Bourdon, 1995, p. 226). Yet, the design addresses environmental concerns for toxic waste while creating a public recreational facility.

CONCLUSIONS

A failure to perceive the real demand for raw materials in an ever-growing society hinders decisions on how to manage resources and create meaningful landscapes. The public needs to understand the economic value of the aggregate industry, and the industry needs to recognize the ecological, cultural, and aesthetic value of an area. Optimists believe that new technologies, substitutes, and more efficient recycling will allow continued supplies of new mineral resources for society. On-site recycling for construction materials offers potential lower costs and environmental sensitivity for a natural resource. Pessimists think that we must reduce the demand for minerals by population control and *per capita* consumption.

Planners are using landscape architects to help "enhance the native character of the created or restored site, fitting the built landscape into the natural design of the surrounding area" (Manci, 1989, p. 18). By discovering the true landscape and understanding it, when mining occurs, we can concentrate on designing and planning the site with information on ecology and development, research and technology, culture and nature, and science and art. The data may not tell us what choices to make, but it can help with wise options. Whether a geologist, biologist, landscape architect, or city planner, we all experience change in our environ-

ment. Wetlands can be viewed as a hydrologic disturbance just as it is a man-made disturbance. Even though the industry's bottom line may involve profit and meeting legal requirements, most operators would agree good public relations and aesthetics are an important part of business.

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Use of Limestone Resources in Flue-Gas Desulfurization Power Plants in the Ohio River Valley

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ABSTRACT.—In 1994, more than 41 of the approximately 160 coal-fired, electrical-power plants within the six-state Ohio River Valley region used flue-gas desulfurization (FGD) units to desulfurize their emissions, an approximately 100% increase over the number of plants using FGD units in 1989. This increase represents a trend that may continue with greater efforts to meet Federal Clean Air Act standards. Abundant limestone resources exist in the Ohio River Valley and are accessed by approximately 975 quarries. However, only 35 of these are believed to have supplied limestone for FGD electrical generating facilities. The locations of these limestone suppliers do not show a simple spatial correlation with FGD facilities, and the closest quarries are not being used in most cases. Thus, reduction in transportation costs may be possible in some cases. Most waste generated by FGD electrical-generating plants is not recycled. However, many FGD sites are relatively close to gypsum wallboard producers that may be able to process some of their waste.

INTRODUCTION

Approximately one-third of the nation's coal-burning electric-power plants that use flue-gas desulfurization (FGD) units to remove SO_2 emissions are located in the six-state region (Illinois, Indiana, Kentucky, Ohio, Pennsylvania, and West Virginia) that borders the Ohio River. In 1989, 29 of the more than 160 coal-fired electric-power plants within this region used FGD units to desulfurize their emissions. By 1994, the number of FGD plants had increased to 40. This trend toward increasing numbers of FGD units probably will continue with greater efforts to meet the standards of the Federal Clean Air Act as amended in 1990. It will result in an increased demand for limestone and the disposition of increased amounts of waste.

Some of the issues associated with this increase are highlighted by the generalized reactions by which limestone ($CaCO_3$), as a sorbent, removes SO_2 emissions (equation 1).

$$CaCO_3 + SO_2 + \tfrac{1}{2}H_2O \rightarrow CaCO_3 \cdot \tfrac{1}{2}H_2O + CO_2$$

$$CaSO_3 \cdot \tfrac{1}{2}H_2O + \tfrac{1}{2}O_2 + \tfrac{3}{2}H_2O \rightarrow CaSO_4 \cdot 2H_2O \quad (1)$$

In practice, this reaction means that the burning of every 100 truckloads of coal (sulfur content of 3.5%) requires 10 truckloads of limestone to neutralize SO_2 emissions. In turn, this reaction generates 20 carloads of gypsum sludge and approximately 10 carloads of coal ash. Increasingly, it is necessary to understand the use and disposition of materials on both sides of this reaction, and it is the goal of this paper to address issues associated with limestone availability, transport, use in FGD power plants, and the subsequent distribution of derived waste products.

LIMESTONE AND DOLOMITE RESOURCES AND SUPPLY

In 1989, FGD units within the Ohio River Valley consumed more than 2,736,000 tons of limestone. By 1994, consumption of stone exceeded 3,301,000 tons. Most of this material was derived from relatively local sources, and such sources will probably meet most future increases in demand.

The distribution of the resources that supply most of this area's limestone is shown in Figure 1; those are subdivided by amounts of $CaCO_3$. As indicated by equation 1, limestone with the highest $CaCO_3$ content should neutralize the most SO_2 and, therefore, perform better in FGD units. In practice, numerous other factors affect the reactivity of limestone, and many studies show that $CaCO_3$ content is a relatively poor predictor of stone performance in a FGD unit (e.g., Miller and others, 1996). However, $CaCO_3$ is relatively easy to measure and consequently provides the only currently available regional indicator of stone quality in this area.

Foose, M. P.; and Barsotti, A. F., 1999, Use of limestone resources in flue-gas desulfurization power plants in the Ohio River Valley, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 273–278.

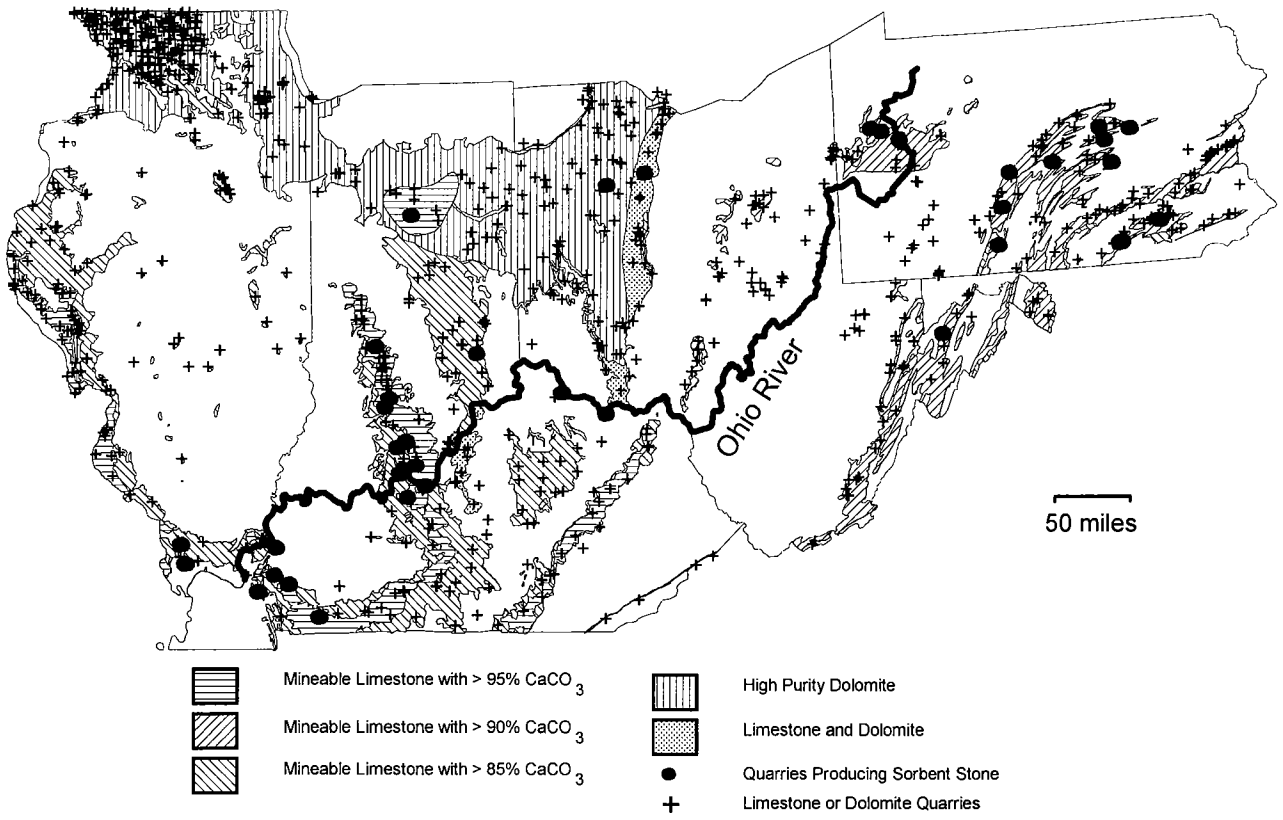


Figure 1. Generalized distribution of minable limestone resources in the Ohio River Valley subdivided by $CaCO_3$ content. Also shown are location of limestone or dolomite quarries (crosses) and quarries that are known to have supplied stone to FGD utilities (dots). The geology was compiled by the State Geological Surveys of Illinois, Indiana, Kentucky, Ohio, Pennsylvania, and West Virginia (Stith and others, 1997).

Figure 1 can be used to make two points. First, limestone resources in the Ohio River Valley area are not evenly distributed. One result is that transportation of stone will be a more important and costly issue in some parts than in others. Second, higher-quality limestone (higher $CaCO_3$ content) will be less available than lower-quality material. The latter point is illustrated further by using the areal extent of limestone outcroppings as a proxy for the amount of available resources (Fig. 2).

Figure 1 also shows the location of the approximately 975 limestone or dolomite quarries. This compilation of quarry sites was made from diverse sources that include Shaffer (1984), Samson and Masters (1992), Barnes (1997), and Weisgargber (1997), and also includes internally acquired U.S. Geological Survey (USGS) data and data provided directly by cooperating state geological surveys. It does not, however, represent an exhaustive survey of all quarry sites. Nevertheless, the distribution patterns defined by the quarries should be substantially correct, and these patterns do show that quarries are localized in specific areas and within specific rock units. Most striking is the high concentration of quarries around the Chicago urban area (northwest part of the map.)

TRANSPORT OF MATERIAL TO FGD UNITS

Of the nearly 1,000 quarries in this region, only 35 are known to produce stone for FGD power plants (Figs. 1, 3). Thus, the stone requirements for FGD plants currently are being supplied by a relatively small number of quarries. Also plotted on Figure 3 is the location of the region's 160 coal-fired electric gener-

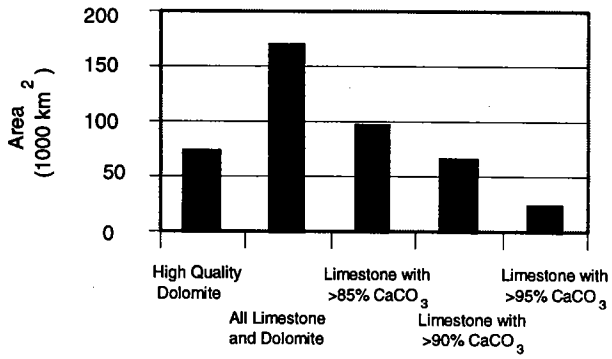


Figure 2. Areal extent of minable limestone in the Ohio River Valley. A significant decrease in areal extent of resources occurs with increasing $CaCO_3$ content.

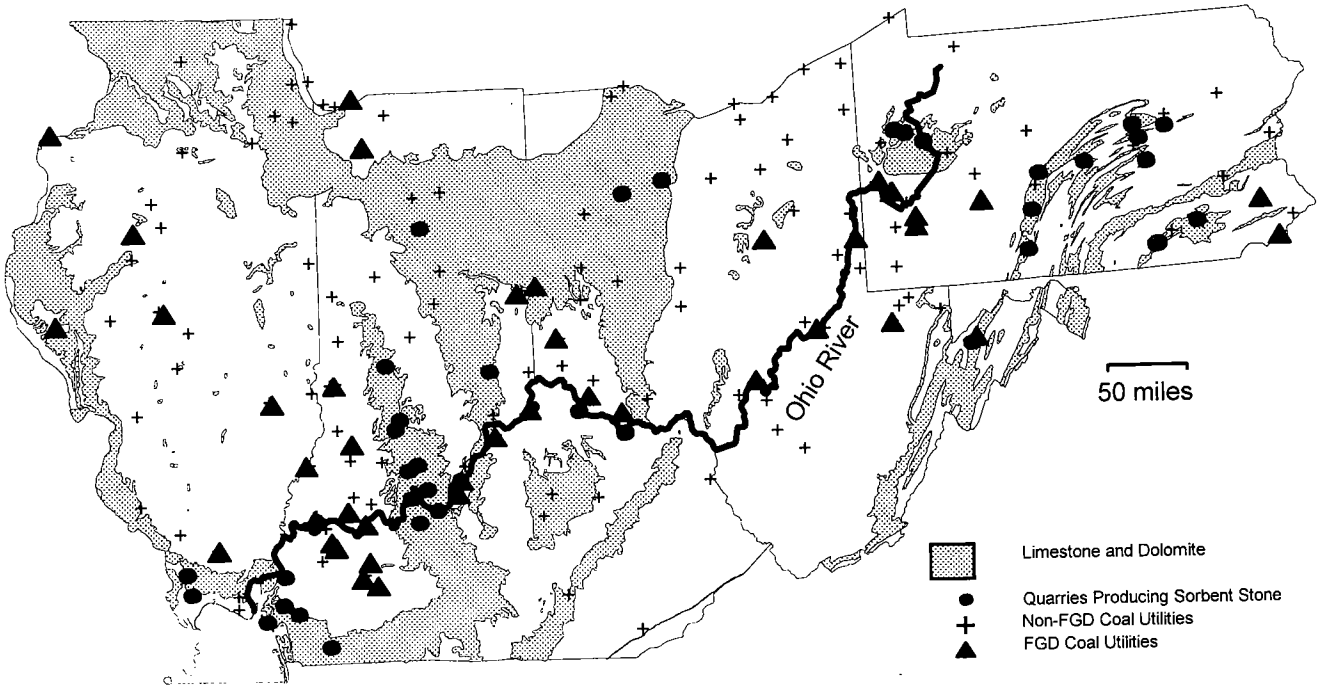


Figure 3. Distribution of coal-burning electric utilities and quarries that produce stone for FGD power-generating utilities.

ating facilities plants and the 40 plants that use FGD. The majority (27 of 40) of these FGD plants are sited within 50 mi of the Ohio River. Of the approximately 1,000 quarries shown, 21 are within 10 miles of a FGD unit, whereas 474 are within 50 miles. Notably, these FGD plants show no clear spatial association with the location of quarries that supply stone to FGD power plants (Fig. 3). Further, Figure 4 shows that few of these quarries are located within 40 mi of a FGD power plant. These relations suggest that, in some cases, closer suppliers of stone might exist.

In an effort to more clearly document the spatial association of quarries and FGD power plants, a survey of the sources of limestone used by FGD plants was made. Response to the survey was limited, and the results were combined with information compiled by Dever (1995) to show the link between some FGD plants and sources of limestone (Fig. 5). When barge and/or rail transport are used, limestone may be moved large distances. In one case, combined barge and rail transport of stone exceeded 550 mi. However, when truck transport is used, transport distances seldom exceed 130 mi.

GENERATION AND DISPOSITION OF WASTE

In 1989, the FGD units in the Ohio River Valley consumed more than 2,736,000 tons of sorbent and produced more than 5.62 million tons of waste. By 1994, these amounts had increased to more than 3,301,000 tons of sorbent and more than 6.4 million tons of waste. The largest increases in limestone use were in FGD plants located near the Ohio River (Fig. 6). Equation 1 shows that a result of increased limestone consumption is the increased generation of gypsum waste, and Figure 7 shows the pattern of increased waste generation between 1989 to 1994. This trend of increasing waste production probably will continue with ongoing efforts to meet increasingly stringent air-quality standards. A result is that disposition of waste will become an increasingly costly issue.

Most of this waste is not recycled (Barsotti and Kalyoncu, 1995). In 1994, only Pennsylvania and Illinois recycled significant amounts of the gypsum generated by FGD electric plants (Fig. 8). Most other waste was discarded in ponds or landfills. Cost to the utility and its customers for such disposition can be substantial, and in some cases exceeds $50 per ton.

An alternative to this form of disposal may be to use

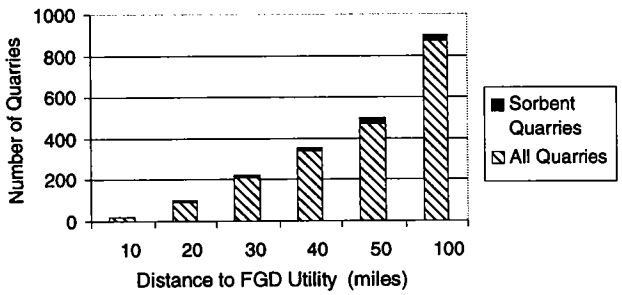


Figure 4. Distance of quarries from FGD utilities. Most quarries that provide stone to FGD utilities are more than 40 mi from a FGD plant.

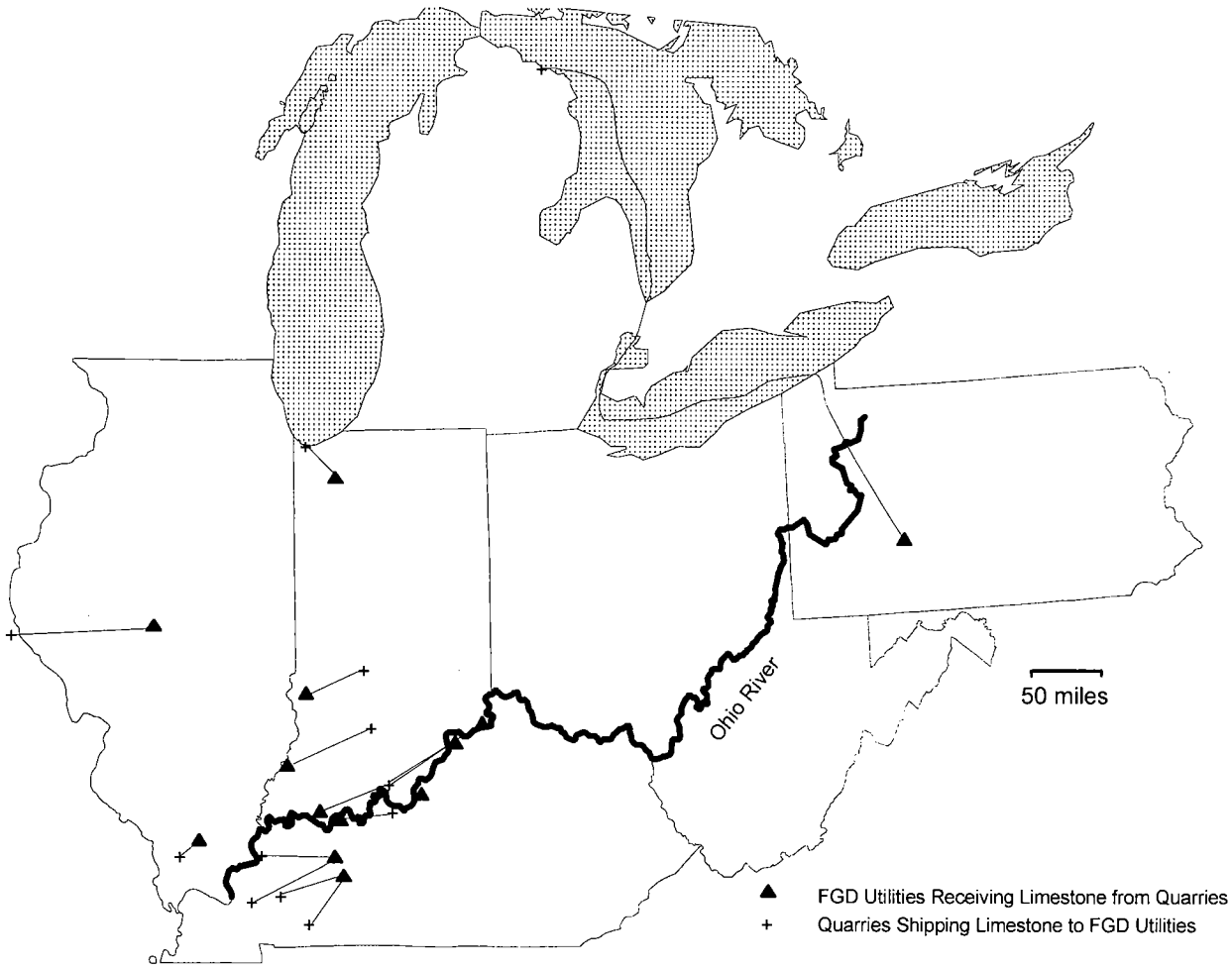


Figure 5. Transport distance of limestone to some FGD units.

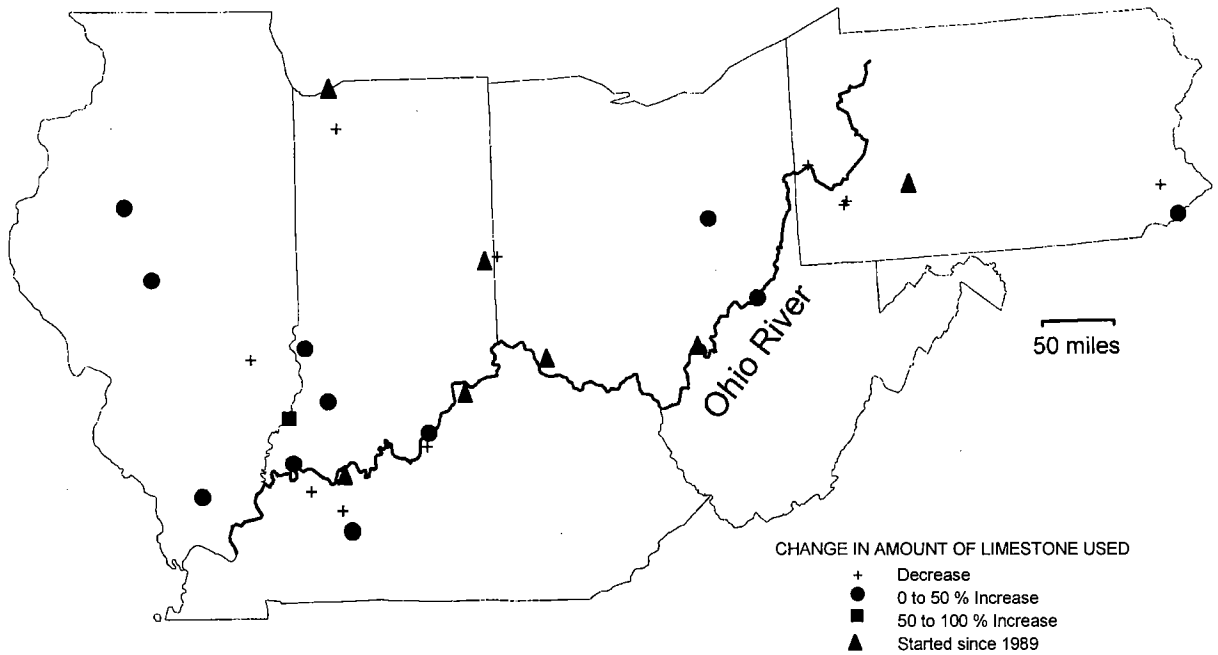


Figure 6. Changes in amount of limestone used in FGD utilities within the Ohio River Valley. Symbols show increase or decrease in limestone use between 1989 and 1994. (Data from U.S. Department of Energy/Energy Information Agency Form 767.)

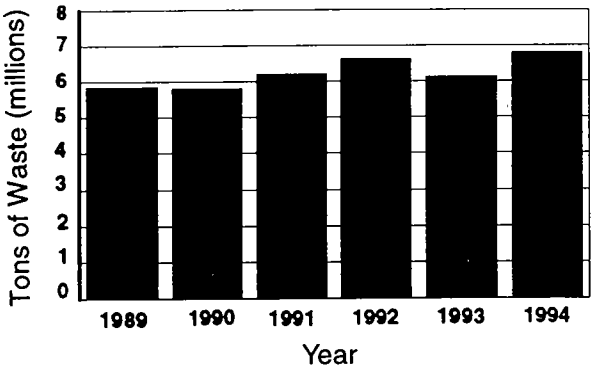


Figure 7. Tons of waste generated by FGD utilities in the Ohio River Valley from 1989 to 1994. (Data from U.S. Department of Energy/Energy Information Agency Form 767.)

FGD waste in the manufacture of gypsum wallboard. Although, some gypsum wallboard operations are using FGD by-products, sales of FGD-produced gypsum are not yet common. However, a number of wallboard operations are relatively close to FGD electric plants. Figure 9 shows that 3 gypsum operations are within 25 miles of a FGD plant, 7 are within 50 miles, and 24 are within 100 miles.

CONCLUSIONS

Implementation of the Clean Air Act Amendments by the 101st Congress in 1990 mandated reductions in SO_2 and caused an increase in numbers of FGD units in the Ohio River Valley. Implementation of Phase II of this act on January 1, 2000, will result in further efforts to clean emissions from coal-fired electric plants. Further, complicating industry's response to these regulations is the movement toward increased deregulation of electric-generating facilities. The specific response of each utility to these diverse pressures is unclear, but certainly any information that promotes increased efficiency of resource acquisition and the disposition of by-product material will be of benefit.

This survey has attempted to relate the distribution of limestone resources, the location of sites where these resources can be accessed, aspects of the transportation of limestone to electric-generating plants, and the final disposition of limestone-derived waste. This examination of diverse aspects of material use is an attempt by the USGS to better understand the mineral life cycle of different commodities. It is felt that this approach ultimately will facilitate the use of these materials in ways that both makes the most economic sense and induces the least environmental impact.

In the Ohio River Valley, increased use of limestone by FGD utilities is expected. Although the resources are large, their uneven distribution will affect resource availability. The quarries that access the limestone resources are also not evenly distributed, and the transportation patterns from quarry to FGD plants show that the closest quarries generally are not being utilized. This suggests that reductions in transportation costs and transportation-related impacts may be achievable locally. Finally, the disposition of waste through recycling may be a viable option for FGD electric generating facilities that are located near gypsum operations that can process their waste.

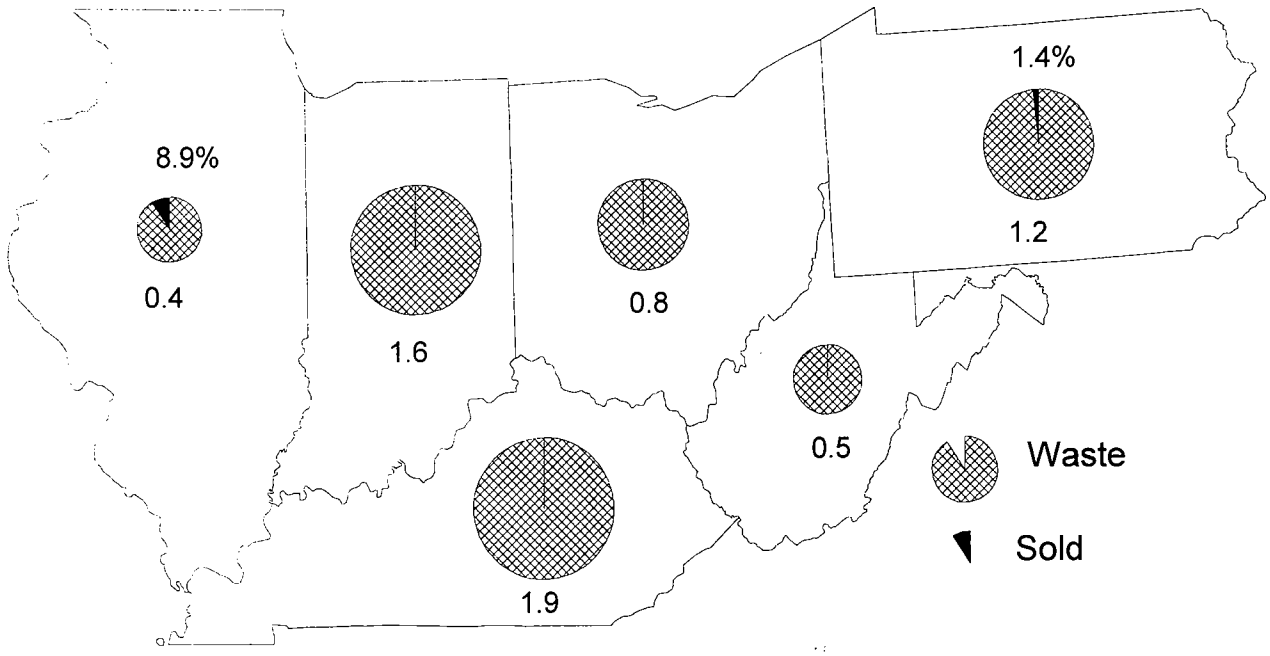


Figure 8. Amount of waste generated and sold by FGD utilities in the Ohio River Valley. Data are for 1994. Lower number shows approximate tons of waste produced in millions; upper number (where present) shows percentage of waste that was sold. (Data from U.S. Department of Energy/Energy Information Agency Form 767, 1994.)

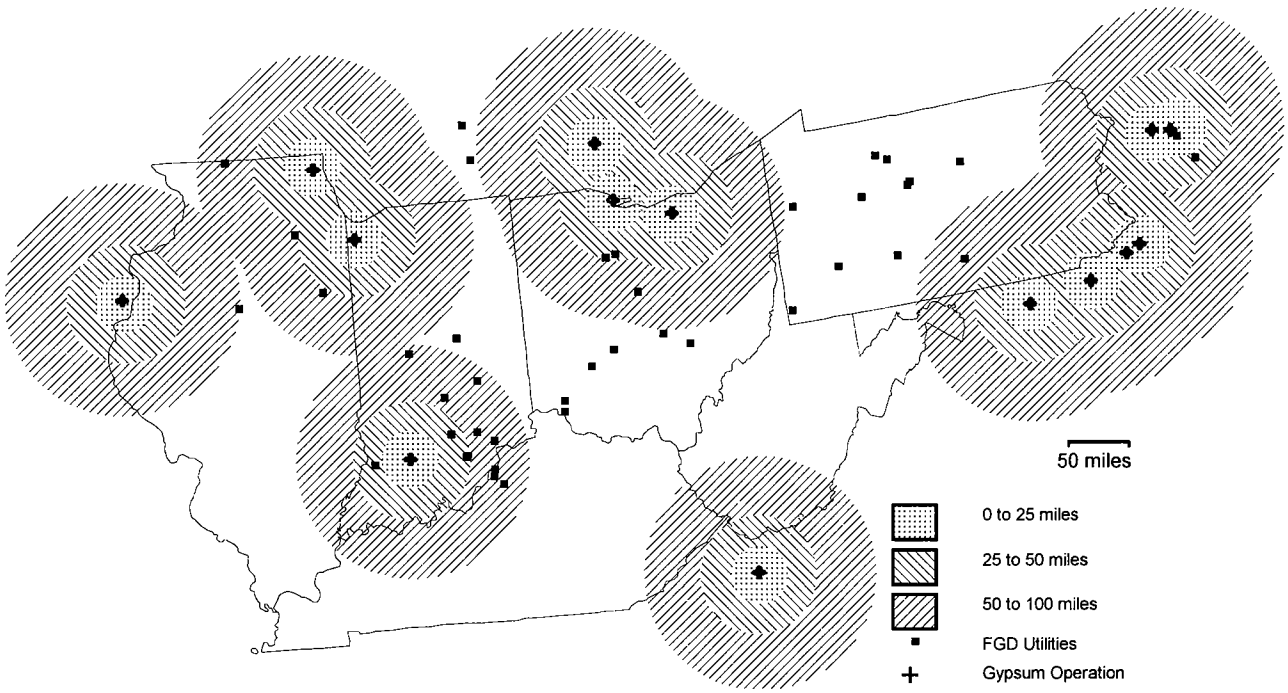


Figure 9. Location of FGD utilities and gypsum wallboard operations in the Ohio River Valley.

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Scenic Mines, Spectacular Geology, and Scenery Observed on Forum Field Trips

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The 34th Forum on the Geology of Industrial Minerals gave members a chance to see the geology of various stone and ore deposits displayed graphically in quarry walls and also provided an opportunity to hear and see first-rate papers and posters on the geology of industrial minerals. Also, some field trips passed through areas of spectacular scenery. As a bonus, participants saw scenic mines, some of which are "pretty as a picture." Watercolor paintings prove it.

At the Oklahoma Forum, the writer displayed a number of paintings of mines and other landscapes seen during previous Forum trips. These paintings and this brief article are part of a crusade to prove that some mines and geologic vistas are scenic wonders and belong in our visual heritage. It is a plea to save some of our best geologic exposures for future geologists, tourists, and artists.

The first field trip of the 1998 Forum stopped at the Meridan Aggregates Co. quarry in the Arbuckle Mountains of southern Oklahoma, where diabase dikes cut the Precambrian Troy Granite; the pit face contains an unusual criss-cross display of intersecting dikes (Fig. 1). Another subject suitable for watercolors is the red iron oxide (hematite) that colors the overburden and stains the surface of the snow-white silica sand in the U.S. Silica Co. quarry, also in the Arbuckle Mountains. The dark brownish-red Quaternary soils and overburden and the green trees provide striking contrast with the white and partly stained Ordovician Oil Creek Sandstone, making this a scenic mine. The trip to the Arbuckle Mountains took participants through green pastures containing many small man-made lakes filled by recent rains. Among the trees and along the roads was an abundance of wild flowers. This was truly spectacular prairie-state scenery.

The two-day post-meeting field trip to northwest Oklahoma featured pure white gypsum, less-pure gray gypsum, and salt (halite), all of Permian age. The white gypsum, exposed in the floor of a pit worked by U.S. Gypsum Co. at Southard, lacks the red and brown pigments (iron stain) that enhance a colorful painting. The gray gypsum, which is used for base material and surface material in construction of unpaved roads, is colorful, and the Western Materials Co. mine has picture possibilities. Some western scenery, such as the small red-walled canyon rimmed by white gypsum beds and partly covered by green grass and trees, should yield an Oklahoma watercolor masterpiece (Fig. 2). In addition to showing outcrops of several gypsum beds, and quarries where the gypsum is mined, the Forum showed what it is like *inside* a gypsum bed; photographs taken inside the cave at Alabaster Caverns State Park indicate that the cavern has definite picture possibilities. Although Oklahoma is not internationally noted for its *haute cuisine*, those attending the 1998 forum (to use a term from neighboring Arkansas) "ate high on the hog."

The 1997 forum in Quebec City featured the old Quebec City itself. There it was possible to "play hooky," skip a couple of papers, and walk through the old city. Dining in Quebec City was exotic and *tres cher*. The field trips also provided beautiful scenery. A silica quarry beyond Lac Saint-Jean was a scenic mine, with remnants of a seven-meter snow, white rock, and green trees (Fig. 3). Paintings of other vistas in Quebec, which include Mont Saint-Hilaire, Saguenay Fjord, a river swollen with snow melt, and Artist's Alley, were sold at auction during the 1998 Forum, with all proceeds going to the Robert L. Bates Scholarship Fund to help bring industrial-minerals students to future

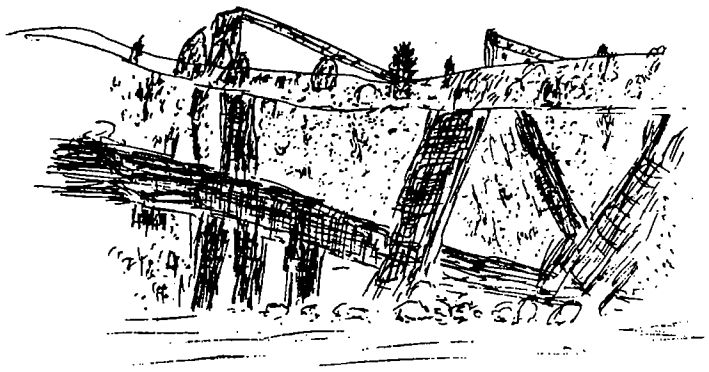


Figure 1. Crossed dikes. Meridan Aggregate Co. quarry, where intersecting diabase dikes cut the Precambrian Troy Granite in the Arbuckle Mountains of southern Oklahoma.

Clarke, O. M., Jr., 1999, Scenic mines, spectacular geology, and scenery observed on forum field trips, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 279–280.

forums. The sale included some of the better paintings from previous forums.

Future forums also will bring us to very interesting and scenic places. The 1999 forum will be in Utah, a western state well known for its scenery (Fig. 4); and the 2000 forum in Bath, England, promises to be one of the best sessions, with field trips into Cornwall, the ancestral home of our Cousin Jacks (Fig. 5). We wonder if anyone there serves the ancient traditional "pasty" prepared for Cousin Jack lunches.

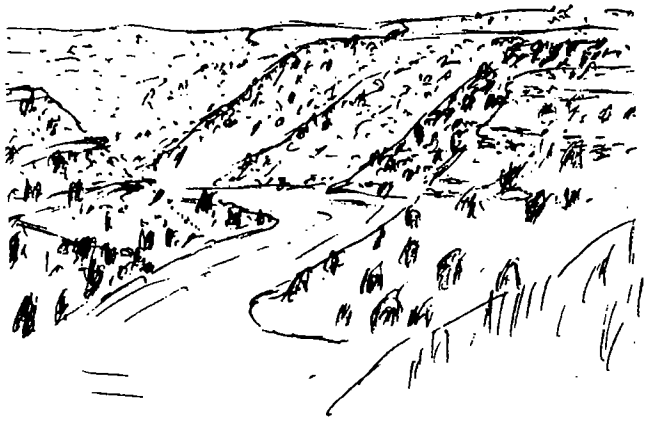


Figure 2. Scenic vista in northwest Oklahoma. View of Salt Creek Canyon, adjacent to U.S. Gypsum Co. quarry at Southard, Oklahoma. The small canyon exposes three white gypsum beds of the Blaine Formation that overlie the striking red beds of the Flowerpot Shale (all strata are Permian in age). The little canyon is an especially good subject for painting in the spring, when the grass is green, when a salt crust forms along the creek, and a trickle of water flows in the gulch.

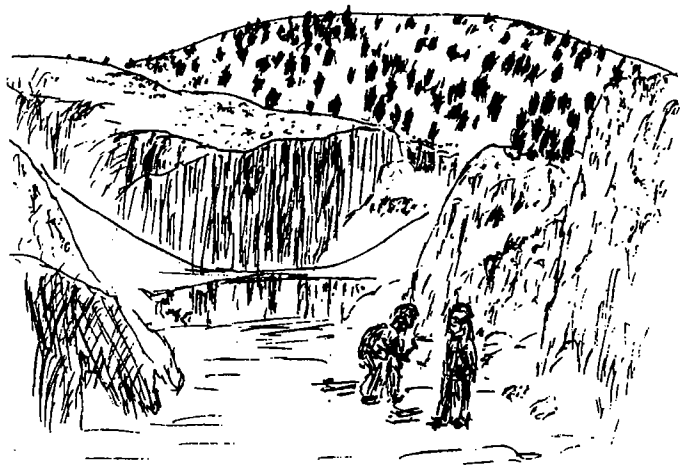


Figure 3. Scenic mine in Quebec. The silica quarry is east of Lac Saint-Jean; snow, dark-green trees, and white and tan silica make the quarry a scenic mine. Two geologists collecting a specimen form the center of interest.

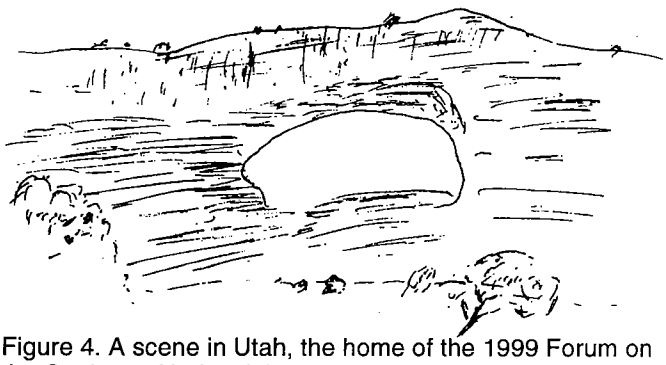


Figure 4. A scene in Utah, the home of the 1999 Forum on the Geology of Industrial Minerals. The scene shows one of the beautiful arches that characterize Arches National Monument in eastern Utah.

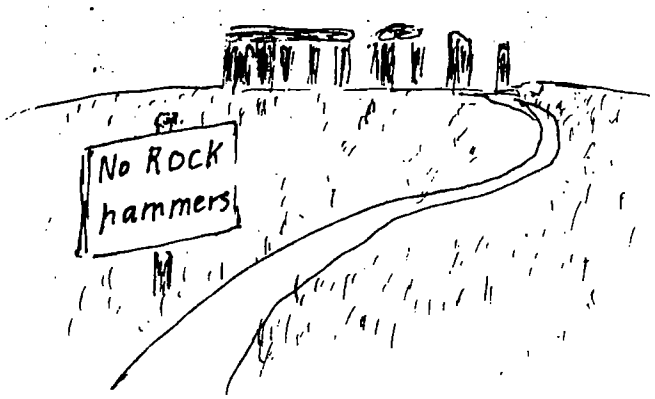


Figure 5. "Outcrops" in southwestern England, the home of the 2000 Forum on the Geology of Industrial Minerals. Stonehenge is a monument to the dedication and tenacity of early-day industrial-minerals geologists in serving their fellow Druids (and Gods). Ancient geologists certainly were involved in stone selection, quarrying, transportation, erection, and EIS-preparation for this phenomenal collection of stones. This is a probable field-trip stop for the 2000 forum.

What Geologists (and Perhaps Others) Should Know About Marketing Industrial Minerals, Rocks, and Materials

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ABSTRACT.—Marketing is the linchpin of the industrial-mineral (IM) industry. Without markets and consumers for IM products, all other associated IM activities are superfluous. The simple existence of an IM deposit does not mean that it can be exploited. A dynamic interaction between exploration (geology), mining, processing, transport, marketing, sales, and consumers is required for profits. Geology dictates the existence of a deposit, but markets dictate its development, and transportation provides the connection. This is true to such an extent that marketing commonly is called the exploration phase of IMs.

Marketing is strategic and includes long-range market-development and planning activities, whereas selling is tactical and more focused on day-to-day consumer interactions. Each will help the other when properly done. Many producers of IMs have failed because of inadequate marketing skill, information, and practice. Over many years at the Montana Bureau of Mines, the many developers seeking technical assistance to find an IM deposit, but who had no marketing plan, always failed. In contrast, the few who sought assistance first on marketing, with the IM deposit to be found later, always succeeded (Richard Berg, personal communication, 1998).

Marketing has many facets helped by geologists who must be aware of what marketing is attempting to do. A geologist needs to understand many aspects of IMs: location (deposits, plants, consumers), processing (specifications), transportation (truck, rail, barge, ship), competition (local, regional, national, international), substitutes, pricing, and new developments and market forces of all kinds. Some needed skills are not taught formally to geologists, so well-rounded self-education and on-the-job training are the way a geologist normally enters into IM marketing.

The IM geologist generally is associated with marketing either by helping to prepare a market study or by acting on the results of one. Preparing a market study is a two-part process. The first part is relatively simple but requires a time-consuming collation of data into an IM survey (mostly past- and present-oriented). The more difficult and much more important second part entails expanding the IM survey into a market evaluation (mainly future-oriented) that emphasizes forecasting, timing, location, and specific products. A market evaluation generally boils down to formulating the right questions to ask of the right persons. One very good question to ask is, "What could be the market for *this specific IM*?" while thinking for yourself without excessive recourse to gossip, rumors, promoters, developers, or (at times) IM experts.

The evaluation must prove that market potential exists and suggests a marketing plan. Effective marketing is an ongoing process, with the initial marketing plan modified over time, using wide and continuous input to avoid tunnel vision.

Industrial-mineral markets are based either on commodity (lower-priced, basic-processing) minerals or specialty (higher-priced, value-added) minerals. IM marketing methods are either product-driven (commodity minerals), a more traditional approach, or market-driven (specialty minerals), but these are neither mutually exclusive nor is one always better than the other. Focusing too much on specialty minerals can lead to problems. A blend of commodity products with specialty products commonly lowers risk and enhances long-term profits. The highest profits occur in specialty minerals at the cost of higher risk and complexity and require intelligent marketing, versatile technical services, and creative research and development.

Industrial minerals are best served by an industrial-marketing approach rather than a consumer approach. Modern industrial marketing emphasizes the consumer using the "marketing concept." The marketing concept focuses all management and operational activities on total consumer management and satisfaction similar to the total quality management approaches to excellence.

Barker, J. M.; Austin, G. S.; and Santini, Ken, 1999, What geologists (and perhaps others) should know about marketing industrial minerals, rocks, and materials, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 281–295.

INTRODUCTION

In the industrial-mineral (IM) industry, a precise interaction between exploration (geology), mining, processing, transport, marketing, sales, and consumers (Fig. 1) is required to generate profits. Marketing is the linchpin in this sequence and marketing is the point at which an IM operation comes in contact with the outside world. Without markets for IM products, all other associated IM activities are wasted (Farr, 1981). The old saying "Nothing happens until someone sells something" is still true (McVey, 1976). The simple existence of an IM deposit does not mean that it can be exploited at a profit, and many producers have failed because of inadequate marketing skill, information, and practice (DuCharme, 1967; McCabe and McCabe, 1998). It is best not to view IM marketing as a lesser function than the "more important" production of IMs (Farr, 1981).

Numerous deposits exist for most IMs, but their reputation for abundance must be tempered because not all are commercial (Harben, 1983). In practice, exploration (geology) is commonly less emphasized than marketing for IMs (Holmes and Santini, 1985). Geology dictates the existence of a deposit, but market location/price/specifications dictate its development (McVey, 1980a), and transportation connects the deposit to the market (Fig. 1). This is true to such an extent that marketing commonly is called the exploration phase of industrial minerals (McVey, 1980b, 1985; Holmes and Santini, 1985; Bristow, 1992). Specifications determine the salability of a product to the extent that material even slightly out of specification may be unsalable at any price.

The geologist should be associated with marketing, either by helping to prepare a market evaluation or by acting on the results of one for market development. Marketing has many other facets that can be helped by geologists, but they must be aware of what marketing is attempting to do in order to help. Many factors must be considered in the dynamic IM marketplace (McVey, 1980b). These include: by-products and co-products (McVey, 1983b), place value, production, price, bulk/volume, specifications, sample evaluation, properties and uniformity, testing, substitution, marketing and management styles, main sales basis, time to first sale, rate of market growth or change, and the need for in-house laboratories and research and development (R&D) (Table 1).

Geologists commonly contribute to a market evaluation as discussed in Part I below. They are much less likely to participate in the actual marketing process whereby new or existing markets are developed, as discussed in Part II below. Experienced IM geologists who are serious consultants (defined as geologists still consulting after turning down the first permanent job offered following their layoff) commonly help with market development when proposing strategies based on a market evaluation. A few IM geologists actually work in marketing groups.

Marketing tends to emphasize strategic aspects of market development and long-range planning, whereas "sales" is more focused on action and day-to-day interactions with consumers. Time is critical because marketing is not a short-term business function. This is one of the main differences between IM marketing over time and a sale, which occurs in the very short term. Each will help the other when properly done. It has been said that marketing is good sales but sales is not marketing (Smith, 1991). Marketing does not end with the signing of a contract, and efforts to insure that the consumer receives proper quality and service should continue. This vigilance will ensure that shipments continue and that the product will have a long life in the marketplace (McVey, 1981). Industrial minerals are best served by an industrial-marketing approach using the "marketing concept" rather than a product or consumer approach.

This paper is organized into two main parts: Part I: IM Market Evaluation, and Part II: IM Market Development Using the "Marketing Concept."

Table 1.—General Comparison of Marketing Factors Between Metallic- and Industrial-Mineral Commodities

Factor	Metals	Industrial minerals
Total value	low (one-third)	high (two-thirds)
Unit value	higher	lower
Market type	undifferentiated	differentiated
Place value	low	higher
Specifications	few	many
Buyer loyalty	lower (price)	higher (performance)
Branding	less common	more common
Marketing	less needed	more needed

Note: Some overlap occurs depending on the industrial minerals compared.

BASIC CONCEPTS

Useful Definitions

Place value is the value of an IM deposit based on its location relative to consumers. It is the result of a complex interaction among production cost, transportation cost, competition, substitutes, and consumer needs. High place value means location is critical for these IMs because they cannot be transported far. Aspects of central-place market theory are useful in place value when amended to suit the IM situation (Fakundiny, 1980). At some distance from the central marketplace (the consumer), transportation costs reach their economical limit (farthest mine location) at the zero-demand distance. Higher-value industrial minerals have longer zero-demand distances than common, lower-value ones. Place value is also important for other ele-

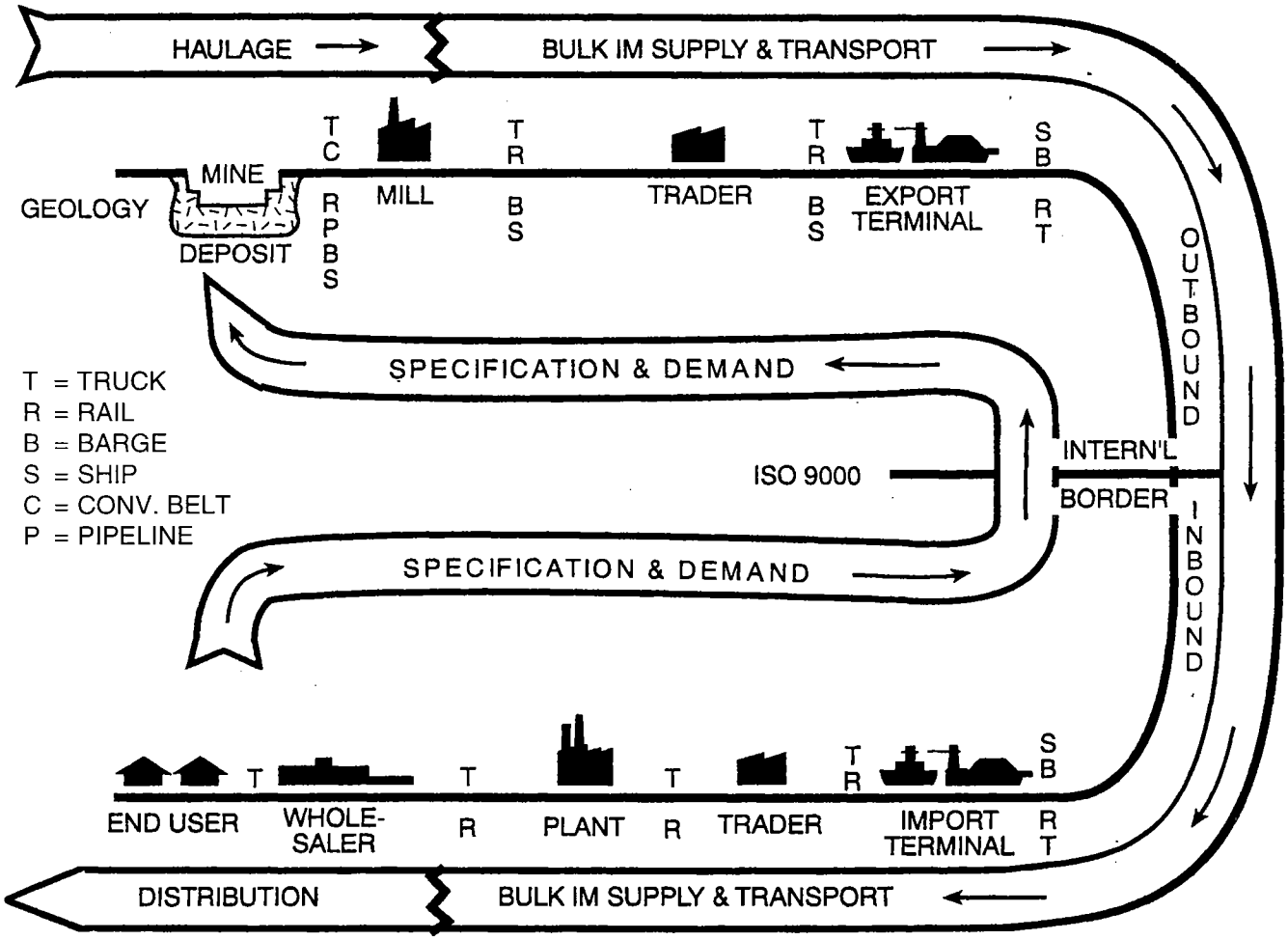


Figure 1. Flow diagram of industrial-mineral products and information. The outer "U" is the transportation flow. Transportation types are rated as major (above line) or minor (below line) for each link from mine to consumer (end user). The inner "U" is the feedback from end users that controls the flow of IMs. Trader represents traders, merchants, distributors, and agents. After Barker (1997).

ments of IM production such as plants (Keating and Williams, 1997), which may be near deposit, port, or consumer or may be located based on taxes, etc.

Value / volume generally are considered together to highlight the high place value and low profit margins on high-volume/low-value commodities (Bates, 1969, table 2.2; Harben, 1983). This is contrasted to the low place value associated with low-volume/high-value specialty minerals that typically are valuable enough to be transported as far as needed.

Differentiation is the perception by consumers that an IM product from one producer differs significantly from a supposedly identical product from another producer. Minerals can be differentiated in two main ways: either enhance sales/service activities or modify physical/chemical parameters. Commodities tend to be undifferentiated. For example, gravel from one producer may be as acceptable as that from another as long as specifications are met. In contrast, IM products with special capabilities, perhaps one-of-a-kind, will be purchased only from one producer who is highly differentiated from other producers generally by offering products tailored specifically for a consumer's plant.

Commodity minerals are IMs that are characterized by large volume, lower value, relatively simple processing, and high place value. These are both widely distributed and used. Thus, substitution is easy.

Specialty minerals are IMs that are characterized by smaller volume, higher value, and value added generally by more complex processing, and are commonly unique and utilized by a few or one consumer. Thus, substitution is difficult.

Industrial marketing and *industrial buying* are the purchase or resale of goods (tangible products) and services (intangible products) between industrial, institutional, and governmental consumers rather than by individuals. The purchases generally are made for further processing, use in operations, or resale, rather than for final consumption (Hisrich, 1990).

Consumer marketing and *consumer buying* emphasize products and services purchased for individual use

Table 2.—Market Characteristics of Commodity and Specialty Minerals

Market characteristics	Commodity minerals	Specialty minerals
Place value	high (transport sensitive)	low (transport insensitive)
Volume/bulk; value	large/high; low	small/low; high
Specifications	industry standard	end-user customized
Sample evaluation	short	long
Properties & uniformity	general	highly controlled
Testing	standard	specific or customized
Substitution	easy	hard
Marketing & management style	business	technical
Main sales basis	price (undifferentiated mineral)	performance (differentiated mineral)
Time to first sale	short	medium to long
Rate of market change	slow to moderate	rapid to moderate
Need for in-house labs and R&D	low	high

Sources: Larson (1990, 1992), Fallon (1984), and McVey (1983a).

and satisfaction. The consumer market has a large number of buyers and sellers. A wide variety of heterogeneous products are offered, and individual purchases are small and dispersed over a wide geographic area (Hisrich, 1990).

The *marketing concept* is the process of maximizing profits by achieving the complete satisfaction of the target consumer. The consumer is the dominant focal point of the producer whose marketing is geared to making products consumers want rather than making the consumer want their products.

Metals versus Industrial Minerals

Industrial-mineral marketing differs substantially from metal marketing (Table 1). In the United States, the total value of IMs ($27 billion) is slightly more than twice that of the metals ($12 billion), although metals are traditionally, popularly, and erroneously viewed as "the" mining industry (U.S. Geological Survey, 1998).

Metals are largely undifferentiated, with price being the main arbiter in an exchange; thus buyer loyalty is lower. Almost all metals are commodities that have relatively few specifications compared with the myriad associated with many IMs (Fallon, 1983a). The use of metals typically is based on rarely changed specifications, without the lengthy bench-scale to pilot-plant to carload testing so common to IMs. Industrial-mineral utilization is based on specifications under use (McVey, 1983a) with a continuing trend toward higher quality, tighter specifications, and consistency (McVey, 1985). The high buyer loyalty and other factors inherent in IMs yield more stable mineral production contrasted to the boom-or-bust cyclicity (Ganetsos and others, 1992) of metals (Holmes and Santini, 1985).

Gold is a classic example of an undifferentiated commodity. It has few specifications and is exchanged solely by price (except for collectible nuggets). Most buyers neither know nor care where or by whom the gold was mined and processed. Gold is not branded, and little marketing, other than calling a broker, is needed. Brands are more common among IMs than metals. Gold is valuable enough that the buyer will come to the mine or mill. Thus, place value and transport is not a factor. Overall, less marketing is expended on metal marketing than on IMs where establishing differentiation commonly is paramount.

Commodity versus Specialty Industrial Minerals

Industrial-mineral markets are based either on commodity (lower value and basic-processing) minerals or specialty (higher value, value-added) minerals. Typical characteristics (exceptions always exist) are listed in Table 2. Fallon (1981) places the major division on the volume (high for a commodity) and ease of significant substitution (high for a commodity). Many IM producers are content to mine, process, and ship their products to consumers. By restricting themselves to this basic process of supplying raw materials, they miss opportunities to add value by physical and chemical transformations (Olmstead, 1984). These value-adding transformations may be relatively simple, or they may be very complex, involving coupling agents, surface treatments, controlled grinding and sizing or shaping, calcining or expanding/exfoliating, coating, coloring, blending or compounding, purification, irradiation, encapsulation, and others. Value may be added either during the IM-production process or in an end use (Fallon, 1983a). The situation in which a new product will compete with that of one of your consumers must be gauged carefully (Fallon, 1983a).

Marketing methods are either product-driven (generally commodity minerals), emphasizing volume and market share, or market-driven (normally specialty

Table 3.—Risk and Profit Potential Comparison between Commodity and Specialty Minerals

Type	Value	Risk
Commodity alone	low	moderate
Specialty alone	high	high
Commodity + specialty	moderate	least

Table 4.—Comparison of Relative Efforts Needed in Some Major Areas between Commodity and Specialty Minerals

Major IM area	Commodity mineral	Specialty mineral
Marketing needed	less	more
Technical support	less	more
Research & development	less	more

minerals), emphasizing the consumer interaction. These are neither mutually exclusive nor is one always better than the other (Larson, 1990, 1992). Mining companies exist to acquire reserves, which are then extracted and sold, so its entire focus is commonly on the product (Olmstead, 1984) and this focus is difficult to break. Consumers are expected to buy what is produced rather than what they want when the focus is on the market. Marketing and sales literature should be benefit-oriented, not feature-oriented (McCabe and McCabe, 1998).

Industrial-mineral mining companies that use traders (Koeten, 1977; Sykes, 1992) or other outside marketing groups (McVey, 1983a) are further insulated from consumers. The technical needs of value-added products may also be a barrier. Detecting market needs and developing product variants require a team with technical skills and a large investment in research facilities (Olmstead, 1984). When a company begins to ask consumers what products and services best meet their needs, they are becoming market-driven. Consumer needs commonly involve adding value. Thus, the mining company benefits, as do their consumers, who receive exactly what they need.

Focusing too much on specialty minerals can lead to problems (Fallon, 1984). For example, commodity coproducts, if not marketed, may be a source of significant loss of revenue to the specialty-mineral producer (McVey, 1983b) and even become a cost during disposal. Olmstead (1984) listed the following potential problems: (1) competing with your consumers; (2) lack of in-house expertise or facilities; and (3) difficulty in changing company culture that causes delays or resistance to using the needed time, money, and management for a value-added, consumer-centric specialty mineral business. Be wary of going so much by the numbers in an attempt to move into specialty minerals that "unprofitable products," which were acceptable before, are eliminated prematurely (Fallon, 1983a).

A blend of commodity products with specialty products commonly lowers risk and enhances long-term profits (Table 3). Many outside forces can erode demand or prices for an IM commodity. Creation of specialty minerals by maximizing value-added helps maintain or increase demand and increases profits per unit of sales (Olmstead, 1984). The highest profits occur in specialty minerals at the cost of higher risk and complexity (Table 4), requiring intelligent marketing, versatile technical services, and creative R&D (Fallon, 1981).

THE OKLAHOMA FORUM SURVEY

We suspected that perceptions of the relative importance of the five IM segments by geologists would be influenced strongly by their background. An informal survey of participants was obtained at the 34th Forum on the Geology of Industrial Minerals in Norman, Oklahoma, to gauge these perceptions. The poll results are shown in Table 5.

The geocentric importance ranking derives from the idea that a typical geologist not familiar with IMs would be very familiar with geology, somewhat familiar with mining, less so with processing, and might not pay much attention after that. Our own rankings varied over time, with Table 5 showing the one given in our presentation at the 34th Forum. About 25% of the participants responded to a survey handed out before our talk, and their combined ranking is shown in Table 5. This result caused us to rethink our ranking; marketing remains number 1 (because you need a consumer first), but transport drops to number 3, and exploration and geology is elevated to number 2. After finding a market, the next problem is to find a deposit that will meet (perhaps with beneficiation) the consumer's specifications (as recognized by Veesaert, 1979). Only then can the effects of transportation cost be assessed and followed by determining the relative importance of mining or processing. Whereas processing ranked number 4 to mining as number 5, the difference in score was less than 2%, reflecting the commodity/company specific nature of their importance. Overall, transport is probably more important than some respondents realize because it is commonly more than half of the delivered cost of an IM (McVey, 1985).

The survey also asked whether a respondent's organization was oriented toward commodity or specialty minerals or both. The results were relatively balanced between commodity minerals (35%), specialty minerals (42%), and both (23%). Industrial minerals listed as commodity minerals were gypsum, aggregate, common clay, cement, limestone, and industrial gases (CO_2 and He). Specialty minerals were used as fillers and extenders, pigments, roofing granules, building stone/tile, specialty clays, and silica/industrial sand. Specialty

Table 5.—Results of the Informal IM Survey Taken at the 34th Industrial Minerals Forum

IM segments	Geocentric importance[a]	Author importance[a]	Survey importance[a]	Survey raw score[b]
Marketing	5	1	1	73
Transport	4	2	3	132
Processing	3	4	4	142
Mining	2	5	5	144
Exploration (Geology)	1	3	2	114

[a]Rank of 1 (highly important) to 5 (least important).
[b]Total of rankings by respondents at Forum are added (1 = 1 point, 2 = 2, 3 = 3, 4 = 4, 5 = 5); the lower the scores, the more important for the respondents.

minerals also include olivine, burnt lime/lime, phosphate, and quartzite. Companies with both commodity and specialty minerals produced aggregate, gypsum, mica, feldspar, kaolin, clay, barite, talc, high-purity quartz, silica sand, soda ash, limestone, refractories, lime, and marble/dimension stone.

PART I: IM-MARKET EVALUATION

General

Market studies are applied research that is far less a science than an art (Veesaert, 1979). They are used in several situations: market entry (basic exploration), market acquisition (nonproducing or operating property), and market expansion (expansion of existing property or new product) (McVey, 1979). Market studies for commodity minerals commonly are worked back from delivered price (Berson, 1990). In contrast, market studies for specialty minerals are worked back from detailed specifications. The main problem is deciding on a budget. The budgets for IM market studies are normally remarkably small, considering the cost and risk of the proposed project (McVey, 1979). It is not unusual for a market study to be done after the decision to go ahead has been made.

Making a market study is a two-part process (McVey, 1976). The first part is relatively simple but requires a time-consuming collation of data and rarely basic financial analysis into a IM survey (mostly past- and present-oriented). Data needed are generally both internal (producer-oriented) and external (target-oriented) and may be gathered by an in-house market-research group or consultants or both (McVey, 1979). Sources (Gorin, 1993) are all levels of government, trade and other associations, media, trade journals, universities, annual reports, required filings to the Securities and Exchange Commission (10K, 20K, etc.), and consultants or commercial data services. Several types of reports are available (Peter Harben, personal communication, 1998). Multi-client reports (the Roskill approach; $1,000–$1,500) are useful but may be 1–3 years old. The subscribed reports (the Kline approach; $1,000–$30,000) cover commodities in great detail by region (i.e., Europe and Asia). The key points about these sources are that the data already are collated and available, but they may have been gathered for a different purpose or are intended for a wide audience. Although useful, these reports may not focus as much as is needed by individual firms.

The more difficult and much more important second part of the market-study process entails expanding the IM survey into a market evaluation, which is mainly future-oriented (Veesaert, 1979), that emphasizes forecasting, timing, location, and precise cost-benefits of specific products (McVey, 1980a, 1983a; Fallon, 1983b,c). New data that are specific to the problem at hand are gathered to enhance the data from the IM survey. The overall document can be quite detailed and lengthy (see Appendix 1, a particularly detailed example). Forecasting demand can be tricky for IMs, with greatest accuracy for products used in consumer nondurable goods, which are little affected by swings in the business cycle (Kline, 1977). Forecasting is more difficult for consumer durable goods, even more difficult for capital goods, and most difficult for materials used in construction (building starts or government projects) or agriculture (crop cycle). The data gathered in a market evaluation are very time sensitive. A common mistake is to avoid making a decision long enough that the market evaluation is essentially invalid (Fallon, 1983c) but is used nonetheless.

Market evaluation requires a personal approach entailing telephone/fax surveys, mail surveys, on-site visits, networking, focus groups, and so forth. Mainly individual consultants or small groups of associates do a market evaluation. It is a client-specific, highly detailed report based on a jointly developed scope of work that states the reason for the study (due diligence, introduce new product, capture market share, and so forth). The client develops the questions perhaps with the help of a consultant who then gets the answers and makes recommendations. The inherent risk in a venture can be minimized by careful market evaluation, but the possibility of gain or loss still exists. Most of the risk for IMs is in the marketing area and more so for specialty minerals (Fallon, 1981).

The market evaluation must prove that market potential exists and suggest a plan of action based on a strategy. The market evaluation does not sell a product, it simply shows that sales potential exists (DuCharme, 1967). Effective marketing is an ongoing process, with the initial plan derived from the market evaluation modified over time based on wide and continuous input to avoid tunnel vision (Fallon, 1983a).

Telephone Surveys

Telephone or personal interviews are the primary means of developing focused data in most IM studies. Advantages (Hisrich, 1990) are: (1) questions can be adapted; (2) some response is almost always gained, contrasted to mail, fax, and e-mail; (3) misunderstandings are immediately eliminated; (4) respondent reactions are available; (5) more accurate and in-depth data commonly are gained; (6) some verification of data can be attained by observation and additional questioning; and (7) the interviewer learns throughout so the process can be fine-tuned while in progress. Limitations are: (1) interviewer bias, (2) leading questions, (3) desire of respondent to please interviewer, (4) data recording errors, (5) using data from uninformed but loquacious respondents, (6) difficulty in keeping respondent interested during difficult questions or rankings, and (7) high cost.

A sample interview form is shown in Appendix 2. It is important that the tougher questions be placed last, in order to get as much data as possible before an abrupt end to the conversation. The most difficult to obtain is price. Most firms are reluctant to discuss price during initial conversations, although there are occasional exceptions.

A market evaluation generally boils down to formulating the right questions to ask of the right person (McVey, 1976). The person responsible for purchasing IM products will have many possible titles, depending on the company. These might be a purchasing manager or agent, purchasing manager for raw materials, raw-materials buyer, corporate buyer, and others. Some companies purchase IMs from a raw-material distributor rather than buying from a producer. It is very beneficial also to interview distributors because they inform you about the sources—both from whom they buy from and to whom they sell. After making contact with the person responsible for purchasing IMs, identify yourself and explain the purpose of the interview. The majority of people interviewed are cooperative. As professionals, they are interested in alternate sources of supply. However, a telephone survey may require a few calls to make contact (messages are infrequently answered). Persistence is commonly a key trait when conducting surveys.

One very good question to ask is, "What could be the market for *this specific IM*?" while thinking for yourself without recourse to gossip, rumors, promoters, developers, or (at times) experts (Fallon, 1983a). Key questions involve the inclination of a consumer to consider new or alternative sources or products and what they are now paying (at least approximately).

PART II: IM-MARKET DEVELOPMENT USING THE "MARKETING CONCEPT"

Some IM geologists occasionally move into marketing, but all should understand the basic principles and goals of the marketing effort. To be effective in marketing, a geologist needs to understand many aspects of the IMs: (1) location (deposits, plants, and consumers); (2) processing (specifications); (3) transportation (truck, rail, barge, and ship); (4) competition (local, regional, national, and international); (5) substitutes and new developments; and (6) market forces of all kinds. Some of the needed skills are not taught formally to geologists; thus, self-education and on-the-job training are the way geologists normally enter into IM marketing. An outline of a marketing organization is presented in Appendix 3. The following brief overview of market development via the "marketing concept" is based heavily on Hisrich (1990), Webster (1991), Peter (1992), Chisnall (1995), and De Bonis and Peterson (1997). Marketing in general and aggregates in particular are detailed in Smith (1991). Sandhusen (1997) is the main source of the international IM marketing discussion.

IM marketing is best examined as industrial, business, or supplier marketing (called marketing hereafter), rather than consumer marketing. Marketing has been defined in many ways, both simple and complex. For our purposes, the following definition is useful: *marketing* is the process by which an organization produces and distributes industrial minerals, rocks and materials, or services (hereafter collectively called IMs) priced to satisfy target consumers and to yield a desired profit in a continually evolving environment. As with any definition of a complex issue, this definition leaves out considerable detail. Seven general aspects are apparent from this definition. These are: (1) the marketing process occurs over time (strategic or middle-to-long term); (2) production (exploration, mining, and processing); (3) delivery (logistics and transportation); (4) products (new or existing materials or services, research, and promotion); (5) correct pricing, timing, and specifications (end-user satisfaction); (6) profit (producer satisfaction); and (7) constant change (modern economic conditions). Thus, marketing is the whole business as viewed by the consumer (Webster, 1991). The heart of the marketing concept is the satisfaction of the target consumer. Attainment of this satisfaction is the single most important factor governing the strategy and direction of many modern firms.

Industrial organizations are being forced to adopt a consumer focus and become market driven using a long-range strategic emphasis involving all levels of the firm. This focus, called the "marketing concept," was originally popular in the 1950s and has seen resurgence since the mid-1980s in response to competitive pressures and rapid change. It is similar in many ways to the move to total quality management (TQM) and ISO 9000 (Holmes, 1996) in the 1990s. Managing for profit, not just market share and sales volume, demands careful market segmentation, by end-use or products (Fallon, 1983a), and targeting in consumer focus. Consumers feel many of the same pressures in

their business, so they are changing in similar ways. Sales are the residue of marketing strategy. Profit is the reward from a satisfied consumer.

Industrial marketing is the exchange of goods (tangible products) and services (intangible products) with industrial, institutional, and governmental consumers. The distinguishing feature of industrial marketing is the consumer's use of purchased goods and services in production of their own goods and services. If this consumer sells to another, who will use the purchased goods and services in production of their own goods and services, a series of value-added steps occurs. Given that all industrial concerns depend on other industrial concerns for goods and services, the chain is virtually endless. These chains lead to a high degree of buyer/seller interdependence after the sale. These industrial-marketing transaction chains are estimated to be at least twice the dollar value of consumer purchases.

Industrial consumers are generally relatively few in number for any given supplier so the value of each sale is larger. Industrial buying is a complex process by many people interacting in a formal organization. This buying may take a long time and be more highly structured (rational) although an emotional element still exists. Demand for IM products generally is derived from the demand for consumer products or services. To further complicate matters for the producer, they need to understand their own business, their consumer's business (Fallon, 1984), and their consumer's consumer's business, not to mention your and their competitor's business (Farr, 1981). This is why a long-term approach generally succeeds and a short-term one generally fails. The marketing concept as applied to industrial marketing is actually closer and more involved with the consumer than is consumer marketing, contrary to what these titles imply.

Unlike consumer marketing, where useful changes can be made in the marketing department alone, industrial marketing generally involves substantive company-wide changes involving many layers of management. These changes may involve capital outlays (new mine, mill, or equipment) or changes in engineering, research, or other major processes. This interdependence between functional groups in a market-oriented IM firm must be recognized and utilized. Interdependence exists between the producer and its consumers, who need constant supply and specifications, technical assistance, and a whole array of other services to handle change in their industry. Use of technical people in marketing can be very beneficial because they can more easily solve consumer problems (Anonymous, 1997).

The major barrier to true adherence to the marketing concept in a firm is technical product complexity. Management in these situations is generally from the engineering or research side, so technical issues may override consumer needs. A tendency arises to favor the product more than the consumer. In the worst case, management tries to change the consumer to fit the product instead of the needed reverse of fitting the product to the consumer. The R&D effort commonly is focused on one aspect of the company, normally processing for IM firms, and less so on end-use technology (Fallon, 1983b). The R&D effort must also be market oriented and continue through development to selling. The product in an IM firm should always be regarded as a variable, not a constant. In fact, the "product" is not always physical in an IM firm—it is commonly an array of economic, technical, logistics, service, or personal relationships between producer and consumer. IM marketing entails the technical/commercial balancing of the product line with market requirements (Fallon, 1981).

Production includes most of the traditional view that a geologist has of the IM industry. These elements are basically a reaction to end-user specifications or price sensitivity and thus can be controlled or altered, commonly with considerable geological input, as described above. A real problem can present itself under the marketing concept relative to production and processing (standard order versus accommodation order) in particular (David Holmes, personal communication, 1998). Most IM producers have a standard product line that processing personnel are oriented toward producing. Accommodating orders with varying specifications from customers, while increasing customer satisfaction, are more costly, less efficient and somewhat disruptive to processing because it deviates from the standard product line. At some point, an IM producer must consider an order as a special or custom order for toll processing and charge accordingly (do a little value-added processing). The decision commonly is based on such factors as customer history, size and frequency of accommodation orders, goodwill, and others. The management of accommodation orders and special orders is a tricky proposition under the marketing concept.

Distribution, as logistics (Coyle and others, 1992) and transportation (Barker, 1997), is typically the largest cost involved in the delivered price of an IM product. Distribution encompasses logistics channels (retailers, wholesalers, and representatives) and physical distribution (packaging, inventory, warehousing, and transportation).

Products are tangible (minerals, rocks, and materials) and intangible (service). Industrial marketing emphasizes the technical service so common in the IM industry. Existing products must be promoted (publicity, advertising, and selling) and new products developed (research). Product mix includes quality, assortment, breadth and depth of line, warranty, guarantee, service, and packaging.

Price involves the consumer, the producer, and competitors in a complex interaction driven primarily by the consumer. The price is set to keep a consumer while thwarting competitors and yielding a profit. Profit must be acceptable while none of the above aspects are ignored. However, in general, neither lowest price nor product feature and benefits are enough—both the supplier and consumer must know that the price is more than justified by the value derived from the product (Conger, 1995).

The business environment consists of a complex set

of external factors (Hisrich, 1990) that constantly evolve while impacting all IM operations and activities into the future (Murray, 1981). Some typical external factors include cultural and social, economic and business, political and legal, and geological factors. Cultural and social marketing factors include lifestyle, quality of life, consumerism, ecology, and social responsibility. Economic and business marketing factors include supply and demand, markets, business cycles, competition, energy, technology, labor, and infrastructure. Political and legal marketing factors include regulation, legislation, demographics, trademarks, brands, packaging, and promotion. Geological marketing factors include deposit location, distribution, tonnage, and grade.

OVERVIEW OF INTERNATIONAL IM MARKETING

Growth in international trade increased from $200 billion in 1975 to $4 trillion in 1995. This very significant growth was due largely to relative world peace, new technology (paradoxically, often related to war), and international trading agreements (Sandhusen, 1997). Benefits of international trade include exploitation of comparative advantage, larger markets contrasted to only domestic ones, access to more world-class deposits (McCarl, 1990; Rivington, 1977), leveraging of company strengths over many more consumers, competitive edge over noninternational competitors, tax advantages, prolonged product life, and increased (often greatly) profits.

All the advantages of international marketing are not gained without difficulties (Farr, 1981). The difficulties in entering foreign markets are political and legal, economic and demographic, social and cultural, technological and environmental, and operational (management and control).

Many approaches and combinations of approaches exist for entry and growth in risky international markets. This growth generally follows a cautious staged approach to minimize risk and cost while maintaining control and flexibility. Three stages are typical: *international → multinational → global.* The international stage typically emphasizes exports to one or a few countries (Canada is the most frequent initial choice for U.S. firms) often using distributors or traders (Osterchrist, 1977; Sykes, 1992). The multinational stage emphasizes joint venture and direct ownership in several nations. The global phase emphasizes wide-ranging, integrated operations in many nations worldwide.

Some major trends are increased cooperation among nations (i.e., European Union and NAFTA), freer flow of technology, growth of emerging nations, concurrent reductions in differences among nations, and more aggressive industrial policies by governments (perhaps a subtle reversing of trade agreements).

The move into international markets requires much of the same information and approaches as domestic marketing. To be sure, some additional factors are important—especially risk—but use of the general marketing principles and the marketing concept in particular will be fruitful.

SUMMARY

Metals and IMs require markedly different approaches to marketing. Marketing dominates IMs, with geology second in importance and transportation third. IM marketing is mainly exchange of goods and services between industrial concerns or institutional or governmental entities rather than exchanges with individual consumers.

Marketing (strategic) and sales (tactical) differ in their basic approaches and focus but are interrelated. Geologists typically are involved with preparation of market studies and market evaluations leading to acquisitions or marketing plans. IM market evaluation essentially is asking the right questions of the right person rather than relying on government statistics alone.

Modern IM marketing is moving toward the marketing concept by emphasizing consumer satisfaction. Higher profits are generated by supplying products that consumers want rather than supplying a product and using marketing to make consumers want to buy it.

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APPENDIX 1

Outline of a Professionally Prepared Major-Market Study Done In-House for a Major IM Firm

Data and projections were developed to some degree for all categories and the final document was quite lengthy. A market study of this scope is unusual and most would not be this extensive. This outline is useful to see the wide range of possible topics.

MARKET

Total market (all products)

- Segmented by end use, geography, product, or grade
- Segments classified as supplied or not supplied
- Size of each segment
- Segment totals (annual tons consumed and total dollars) for last 5 years and for next 5 years
- Growth rates for each segment and the total growth for the past 5 and next 5 years

Emerging and potential new markets

CONSUMERS

Major consumers (all products)

- Grouped by market segment, supplied and not supplied
- Annual purchases (tons and dollars) for the past 5 years and for the next 5 years
- Comparison of the mix of supplied consumers with that for the total market (size of consumer, distribution between segments, growth in annual purchases)

Analysis (all products)

- Importance of product in consumer process and as percent of final product
- What consumer values in the product
- Needs satisfied and unsatisfied by product, including emerging or future needs
- Consumer perception of product quality, service, and price
- Repeat sales as percent of total sales
- Developments that could impact consumer demand for product
- Strength of the markets into which the consumer sells products
- Strength of supplied consumers versus strength of their competitors
- Which consumers are important to our competitors
- Cyclical/seasonal aspects market segments

COMPETITORS

Market share

- Share of total industry sales (tons and dollars) for each important competitor in each supplied market segment plus the total market for the past 5 years and for the next 5 years
- Level of competitor satisfaction with their current market position
- Competitor segmentation of the market and their definition of the business
- Current strategies and future goals of important competitors
- Strategic moves made by competitors during the past year
- Strategic shifts expected from competitors during the next 1 to 2 years

Competitor profiles

- Integration (vertical and horizontal)
- Financial strength
- Profitability
- Reputation
- Product quality and ISO 9000 status
- Product line and differentiation
- Marketing and sales
- Pricing
- Technical service
- Distribution
- Technology
- Reserve position
- Mining practices
- Production facilities
- Production capacity
- Management and labor force
- New product research

Competitive analysis (must be candid)

- **Industry forces and trends**
  - Define major forces driving competition in the industry, market or market segment supplied (threat of potential entrants, barriers to entry, concentration ratios, bargaining power of consumers, threat of substitute products)
  - Position relative to major forces and trends compared to competitor positions
- **Keys to success**
  - Define most important factors that will drive success over the next 5 years (factors differ from segment to segment)
  - Rank versus major competitors to evaluate relative strengths and weaknesses
- **Competitor cost position analysis**
  - Estimated unit costs of important competitors at each stage of their operation
  - Current cost advantages and disadvantages relative to competitors
  - Time over which cost advantages can be sustained
  - Operational components or stages having the greatest cost impact
  - Alternate options for each component or stage, option costs and their potential impact on total costs
  - Potential cost advantages and disadvantages relative to competitors

- **Strategy formulation**
  - Areas of greatest competitor capability and greatest competitor vulnerability
  - Sources of greatest leverage
  - Use of market evaluations
  - Areas where competitive advantages can actually be achieved (to focus limited resources)

TECHNOLOGY

Technology analysis

- Differences in technologies employed and their maturity and limits
- Position relative to competitors in terms of these technology limits
- Importance of these technologies in current market segments (they should rank high among key success factors)
- Competitive/alternative technologies for each consumer group or application
- Opportunities to improve existing technology base or to adopt alternative technology that builds a competitive advantage that has strategic business potential

POLICY AND ECONOMIC ENVIRONMENT

Developments and long-term trends

- Key elements of the domestic (and international) economic environment, including 5-year forecasts of various economic indicators
- Expected policies and legislative or regulatory actions of foreign national or federal, state, and local governments
- Changing concerns and attitudes of society as a whole
- Other external factors that are largely beyond the control of management

Impact analysis

- Evaluate impacts of these events and trends (internal)
- Evaluate impacts of these events and trends on consumers, suppliers, and competitors (external)

RESOURCES

Goals

- Analyze capabilities, strengths, and weaknesses compared to competitors
- Find areas where a competitive advantage can be exploited

Work force (human resources)

- Promotion and succession
- Compensation and incentives
- Hiring (workforce growth)
- Training and quality (ISO 9000 needs)
- Benefits
- Review of above

Production

- Costs of materials, energy, labor, maintenance, mining, processing, etc.
- Productivity
- Labor organization
- Engineering and technical skills
- Mining and processing equipment, types and age, automation, product yield from crude ore, etc.
- Product quality and consistency (quality assurance; ISO 9000)

Transportation and logistics

- Truck, rail, barge, or ship
- Packaging
- Warehousing
- Inventory management
- Effectiveness of distribution channels
- Downstream integration

Marketing

- Specialty versus commodity markets supplied and not supplied
- Sales force compensation, organization, and effectiveness
- Extent and quality of market research carried out, and use of information developed

Research

- Current level of new value-added specialty product research and progress
- List of present and desired new specialty product research in order of priority
- Estimated annual budget requirements for new product research
- Estimated minimum capital cost for developing new products by category
- Estimated time frame for developing new products by category

Management

- Market and technical awareness
- Hiring and motivational skills
- Risk aversion
- Business or technical orientation
- Success (failures) relative to competitor management
- Is success attributed to good management or to a strong market and industry
- Ability to anticipate changes in the marketplace and environment and to take advantage of them
- Tendency toward problem solving versus problem prevention—smooth, integrated work environment versus repetitive crises and emergencies
- Success (failures) of strategies used to increase market share and profitability
- Record of meeting goals

APPENDIX 2

Record of Phone/Fax Interview Form

This form has been used in surveys and can be expanded or amended as needed.

Respondent: _____ **Company:** _____

Title: _____ **Phone:** _____

Address: _____ **Fax:** _____

_____ **E-mail:** _____

Annual volume (TPY): _____

Bulk, bag, or packaged: _____

Rail, truck, or water delivery: _____

Present supplier(s) and supplier location(s): _____

Product quality specifications: _____

Demand forecast: _____

Interest level for new supplier: _____

Delivered price now paid: _____

Other comments: _____

APPENDIX 3

Outline of a Successful Marketing Operation that Focused on the Consumer and Strove to be the Low-Priced Supplier

(Modified from Smith, 1991)

PEOPLE

Hire qualified staff
Train and support them
Commit to organizational total quality management (TQM)
Commit to total customer marketing concept (TCM)

ANALYSIS

Market evaluation using reliable data
Analyze competition (products and firms) and consumers
Market (segments, consumers, products, and location)
Forecast supply and demand

TOOLS

Advertising
Direct sales contact
Direct mail and advertising
Seminars
Participation in professional groups
Trade publications and shows
Technical publications
Industry association resource groups

PLAN

Objectives (TQM, TCM)
Strategy for success
Markets, segmentation, and priorities
Product positioning
Pricing policy
Promotional programs
Distribution of promotional materials
Forecast revenues and profitability
Measurement/tracking to monitor the plan

Niche Marketing of Industrial Minerals: An Oklahoma Company's 22-Year History

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McCabe Industrial Minerals, Inc.
Tulsa, Oklahoma

INTRODUCTION

The principals of McCabe Industrial Minerals, Inc., have been involved in the mining, processing, and marketing of nonmetallic minerals for more than 40 years. In addition to marketing nonmetallic minerals produced by other companies, McCabe Minerals owns and operates three plants that produce headlap-roofing granules, with 25 employees and annual sales approaching $6 million. During its 22 years of operation, the company has developed many different markets, and a list of factors that is used in making our marketing and feasibility studies. These criteria (Table 1) are used extensively by the company in all of its projects, and we present this and other data about the company in this brief report.

HISTORY OF THE COMPANY

A brief outline of the history of McCabe Industrial Minerals follows:

I. McCabe Industrial Minerals, Inc. (Formerly McCabe-Woody & Co.).
   A. Founders:
      1. Henry F. McCabe (experience):
         a. Heart of Texas Sand Co., Brady, Texas (1959–67)
         b. Delta Mining, Mill Creek, Oklahoma (1967–76)
      2. A. H. Woody (experience):
         a. Heart of Texas Sand Co., Brady, Texas (1961–65)
         b. Featherlite Corp.—Light-weight aggregate
   B. McCabe-Woody & Co. was founded in 1976, and Piedmont Mining Corp., a wholly-owned subsidiary, was established concurrently in Kingsport, Tennessee, to produce chemical-grade dolomite:
      1. We had a market-niche goal, to produce a glass-flux stone to serve a glass-manufacturing plant in east Tennessee, as well as chemical-grade dolomite for feed and fertilizer
      2. Plant constructed in 1977
      3. Plant sold to the glass company in 1980

II. Concurrent with Piedmont: McCabe-Woody Co. was incorporated in June 1977. Also, we entered a new market niche in 1978: oil-well-drilling and -cementing industry, based on our associations and previous experiences in this market with Heart of Texas Sand Co.
   A. Provided cement additive for Dowell. A plant was constructed to serve this specific market niche, based on using ground coal as the additive
   B. A lost-circulation-product plant was built to produce material for drilling-fluid companies, using an Amoco-licensed blend of various products
   C. Provided an asphalt-based–drilling lubricant, packaged and marketed under agreement from Sun Oil Co.

III. A new focus on non-cyclical market niches was developed as a result of the downturn in oil-well–drilling industry in 1984. The company surveyed several opportunities and made decisions based on its associations, previous contacts, and marketing expertise. Various markets were pursued as the company was growing to serve these market niches.
   A. Residential-roofing-market niche:
      1. This niche was chosen because of the steady nature of the business: 1–3% growth in annual demand
      2. The market for roofing is driven by the fact that 75% of annual business consists of replacement of roofing, due to wear out, storm damage, and customer desire
      3. Market study for headlap-granules plant was made in 1983:
         a. Headlap vs. colored granules:
            (1). Headlap plant has a lower capital investment
            (2). Raw material is readily available; coal slag is preferred
            (3). Plant site is close to the market to gain freight savings, which could result in a higher selling price and a competitive price when delivered to the customer

McCabe, H. F.; and McCabe, V. L., 1999, Niche marketing of industrial minerals: an Oklahoma company's 22-year history, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 297–299.

Table 1.—Factors to Consider When Selecting an Industrial Mineral Operation

- Industrial mineral needed
- Location of mineral deposit
- Assay of material
- Processing cost
- Potential market volume
- Transportation of finished product: by rail or truck
- Competition
- Marketable differences
- Nonsalable waste
- Raw-material availability
- Cost of raw material
- Capital equipment and construction cost
- Environmental and safety considerations
- Operations manager
- Availability of labor
- Purchase commitments from customers
- Equipment selection and plant design (material testing)
- Caliber of miner or operator (raw-material supplier)
- How it is to be financed (adequate working capital)
- Quality control and on-time delivery
- Market variety and number of separate products available on site

b. Plant site was chosen in Kansas to serve Texas, Arkansas, Missouri, Kansas, and Oklahoma roofing plants in 1984:
   (1). Raw material: coal slag from Empire District Electric, Asbury, Missouri
   (2). Plant site is on Burlington Northern Railroad
   (3). Rail rates lower than competition
   (4). Started shipments in October 1984

B. Other nonmetallic-mineral resales, purchased from existing producers during the company's 22 years of operation (not currently active):
   1. Calcitic limestone: glass-flux stone for glass containers (1981)
   2. Specialty sands: for oil-well fracturing and water filtration (1978)
   3. Pebble lime: for paper manufacturing (1980)

C. New market niches entered, based on broadening the company activities:
   1. Barium sulfate for automotive acoustic applications and used as a functional filler in under-dash, interior parts, and carpet backing:
      a. Entered market by processing waste by-product from a fluorspar (fluorite, CaF_2) operation in southern Illinois
      b. The volume of sales increased beyond the available supply of waste, resulting in a need to obtain long-term source from a basic producer of barite
      c. Began selling products under an exclusive marketing agreement with Baroid Drilling Fluids (1986)
      d. Sales currently continue to increase and represent over half the company's annual sales

IV. Roofing niche began demanding new headlap materials, due to a decline in the supply of traditional materials (coal slag), which caused the company to begin evaluating the use of an alternate material:
   A. A study was conducted of natural materials that meet the criteria for processing into roofing granules. The asphalt-shingle industry needs materials that meet the following criteria:
      1. *Low translucency*—measure of the amount of ultraviolet light that passes through the granule and deteriorates the asphalt substrate
      2. *Chemical and physical weatherability*—the ability to resist exposure to the elements in the atmosphere and to temperature changes
      3. *Particle shape*—it is desirable to have equidimensional fracture, so that crushing results in particles that are somewhat cubic in shape
      4. *Color*—uniformly dark gray to black
      5. *Bulk density*—similar or equal to the colored surface granules, with a target minimum of 80 lbs/ft^3
      6. *Gradation*—percentage of the various fractions of the product that fall into a specific product-distribution curve
   B. Based on this study, subsequent plant trials, and customer approvals, a plant was constructed in 1993 using rhyolite from the Arbuckle Mountains, Oklahoma, as feedstock:
      1. Markets to be served are roofing plants in Oklahoma and north Texas
      2. Raw material secured from a rhyolite quarry which produces railroad ballast and construction aggregates
      3. Rhyolite meets all of the criteria for a natural-mineral headlap for asphalt shingles; it is the fine-grained, volcanic equivalent of a granite and consists primarily of alkaline feldspars and quartz
      4. Following extensive customer trials and plant testing, a plant was constructed in 1993 and began shipments in the same year

V. The company grows horizontally by expanding the roofing niche:
   A. Surveyed the electric-generation industry and located an additional source of coal slag near Lincoln, Nebraska, in 1996
   B. Secured a long-term supply agreement with a Texas roofing-manufacturing plant
   C. Secured a long-term, exclusive purchase of the coal slag in 1997
   D. Conducted plant trials and customer trials in 1997
   E. The plant was constructed in 1997, and began operation in the fourth quarter of 1997

SUMMARY

McCabe Industrial Minerals, Inc., a privately held Oklahoma company, continues to grow in sales and assets through its efforts in niche marketing of industrial minerals. The company believes that this focus, along with its current goals and objectives, will ensure the company's continued success well into the new millennium. More information on the company is available via telephone (918/252-5090) or by e-mail: <mccabe@iamerica.net>.

Transloading: A Case Study of the Tucker Hill Perlite Project and Its Transloading Terminal

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ABSTRACT.—The cost of transportation of industrial minerals frequently is higher than the cost of the product. When a mine, industrial-mineral plant, or customer is served by a single railroad, because of the lack of competition, that railroad may increase rates and/or reduce service so that the economics of that mine, plant, or customer are affected adversely.

Transloading of industrial minerals from rail-to-truck or truck-to-rail to improve economics and sales of product is not a new concept. However, transloading to create competition and reduce freight costs or to improve service is a relatively new concept brought on by the recent mergers of many of the main-line railroads, both in the eastern and western United States. For example, in 1998, with completion of the Burlington Northern/Santa Fe (BNSF) and the Union Pacific/Southern Pacific mergers (UPSP), the western United States has only two main-line railroads.

The industrial-mineral producer, to reduce the cost of transportation or increase the level of service, must evaluate potential transloading opportunities in light of higher prices and reduced service brought on by reduced railroad competition.

This paper discusses industrial-mineral transloading and examines the case history of the Tucker Hill perlite project in southern Oregon. The Tucker Hill project is a classic study of industrial-minerals transloading where the project would have failed without the transloading.

INTRODUCTION

The cost of transportation of industrial minerals commonly is higher than the cost of the product. Anything that causes higher transportation rates or reduced transportation service can seriously impact the economics or reliability of industrial-mineral production. Recent developments within the U.S. railroad industry have reduced or eliminated competition to many industrial-mineral producers. These developments have increased transportation rates, reduced levels of service, or both. When a mine, industrial-mineral plant, or customer is served by a single railroad, that single railroad, having no competition, tends to increase rates and/or lower service so that the economics of that mine, plant, or customer can be affected adversely, or so that the level of rail service precludes satisfactory performance by the industrial-mineral producer.

Transloading of industrial minerals from rail-to-truck or truck-to-rail to improve economics and sales of product is not a new concept. The transloading of industrial minerals from rail-to-truck from mines served by rail to customers not served by rail, or from truck-to-rail from mines not served by rail to customers served by rail, is a well-established technique for extending market areas by utilizing lower-cost rail transportation to augment higher-cost truck transportation. There are many examples in the soda ash, industrial silica sand, construction aggregates, and portland cement businesses, where transloading has enabled producers to enter markets in which, without transloading, they would have little chance to complete.

However, transloading to create competition between railroad companies is a new concept. When both the mine and the customer are rail served, a need for transloading is not obvious. However, if a producer or customer can create competition between rail carriers, or between rail and truck, that competition will serve to reduce freight rates and/or improve service.

The conflict created between the need to maximize railroad profits and the needs of the industrial-mineral producer or consumer seems to surface at three points.

1. *A railroad will increase rates to match those charged by the competition in an effort to improve revenues.* If no alternative rail competition exists, railroads can increase rates to approximately those charged by the trucking industry. Truck transportation

Speltz, C. N., 1999, Transloading: a case study of the Tucker Hill perlite project and its transloading terminal, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 301–307.

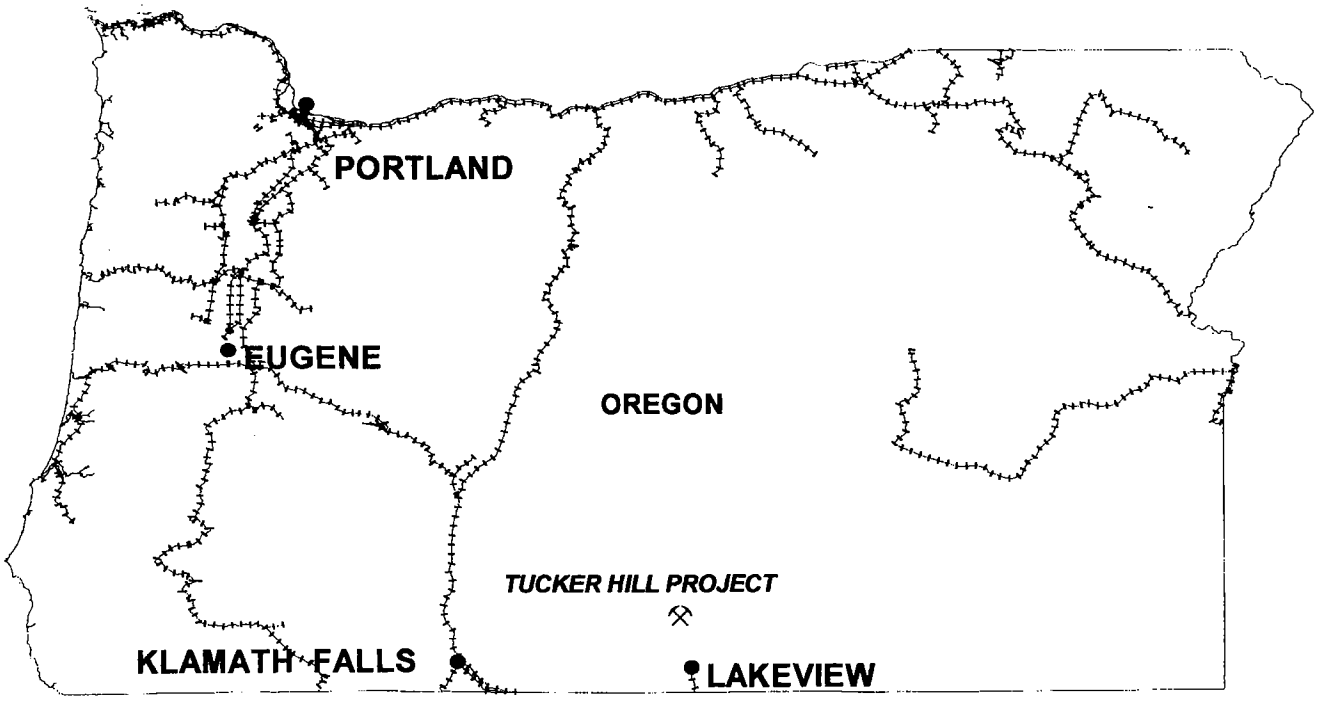


Figure 1. The Tucker Hill perlite project.

can range from 6½¢ to 20¢ per ton mile, depending on gross weight levels, type of equipment required, haul distance, and individual state laws. Rail tariffs generally range between 2¢ and 11¢ per ton mile. A range of between 4¢ and 9¢ per ton mile is an inviting target to any railroad trying to improve profitability.

2. *A railroad will defend existing business in an effort to protect existing revenues.* If a railroad has a revenue-generating business, it will try to prevent competition from reducing that revenue. For example, if a new mine were opened on the same railroad half the distance to the customer from an existing mine, the new freight rate would not be one-half the old rate.

3. *A railroad will curtail service to reduce expenses.* Reducing service is the easiest way to reduce expenses. Labor is one of the highest-cost items for a railroad, followed closely by the cost of equipment. Anything that a railroad can do to reduce labor or transfer the cost of equipment to the customer will reduce expenses. A car shortage inducing the customer to lease or purchase rail cars will reduce the railroad's equipment costs. Labor costs can be reduced by reducing switching from daily to less-frequently than daily.

However, the very things that make railroads less competitive also lay the seeds for competition by transloading terminals. Reduced competition leads to escalating railroad freight rates, route abandonments, or the creation of a "short line," any of which can serve as the catalyst to consider transloading. As competition is reduced, prices generally increase. At some price or level of service, a transloading terminal on an alternative railroad becomes an attractive proposition.

Transportation cost is not the only factor leading to consideration of transloading; abandonment of trackage creates an obvious need for transloading. If a producer or consumer loses rail service because of abandonment, a transloading terminal must be installed at the nearest available railhead if rail service is necessary. For example, the abandonment of the Tennessee Pass route in central Colorado by the UPSP Railroad, will leave ASARCO (a base-metal producer at Leadville) and Calco (a lime producer at Salida) without any rail service. If they wish to ship by rail, they must construct a transloading terminal at Cañon City, the nearest railhead to their operations.

Creation of short-line railroads, in lieu of abandonment, leads to consideration of transloading even though the mine or customer still has rail service. When trackage is taken over by a short-line railroad, the cost of operating that trackage is almost always higher than when it was operated as part of a "class A" railroad.

Short-line railroads are created, in lieu of abandonment, on trackage that serves existing customers, but does not produce sufficient revenue to justify continued operation by a class A railroad. Unless the class A railroad subsidizes the short-line railroad, the cost of operating, and the price of transportation almost always will be higher than before the short line was created.

In considering a transloading terminal, the rationale behind a railroad's actions must be understood. Railroads do not arbitrarily raise prices, abandon trackage, or create short lines. At the heart of all such actions lies the railroad's own self-interest. In order to survive, railroads must generate profit. There is a constant demand



Figure 2. Potential market access on the Southern Pacific Railroad.

to improve profitability by maximizing revenues and minimizing operational costs.

WHAT HAPPENED TO RAILROAD COMPETITION?

Railroad competition has been reduced by two relatively recent events—the Stagger's Act of 1980 and railroad mergers.

First, passage of the Stagger's Act in 1980 provided limited deregulation of railroad freight rates, and authorized railroads to increase or lower freight rates in response to market conditions. The Staggers Act was passed to create competition in the unit-train coal business and to lower freight rates to electric utilities. It did! Predicated on the success of the Stagger's Act, eventually all railroad tariffs were deregulated. Prior to 1980, railroads were locked into an inflexible, regulated tariff system. Competition did not exist. Freight rates could neither be increased nor decreased without regulatory approval of the Interstate Commerce Commission. The regulatory system allowed railroads to charge monopolistic freight rates even though they were not monopolies. Even after total deregulation, the only constraint to railroad tariffs was truck transportation, but where competition was weak, or nonexistent, rail rates increased. Truck transportation is not creditable competition to railroads except on short hauls of ≈200 mi.

Second, the merger of class A railroads, both in the eastern and western United States, has eliminated competition. As the number of railroads decrease, rail transportation cost has increased; rail abandonments have accelerated, and short-line railroads have been created to serve trackage not deemed profitable by the class A railroads. With completion of the Burlington Northern/Santa Fe (BNSF) and the Union Pacific/Southern Pacific (UPSP) mergers in 1997, the western United States has only two class A railroads; hundreds of miles of track have been abandoned, and dozens of short-line railroads have been created.

The industrial-mineral producer, to reduce the cost of transportation or to increase the level of service, must determine if transloading opportunities exist, must evaluate those opportunities, and, in most cases, must build and operate the transloading terminal before the competing railroad will respond. Railroads do not respond to threats; they will respond only after losing the business. Then, they frequently will do whatever is necessary to regain the lost traffic.

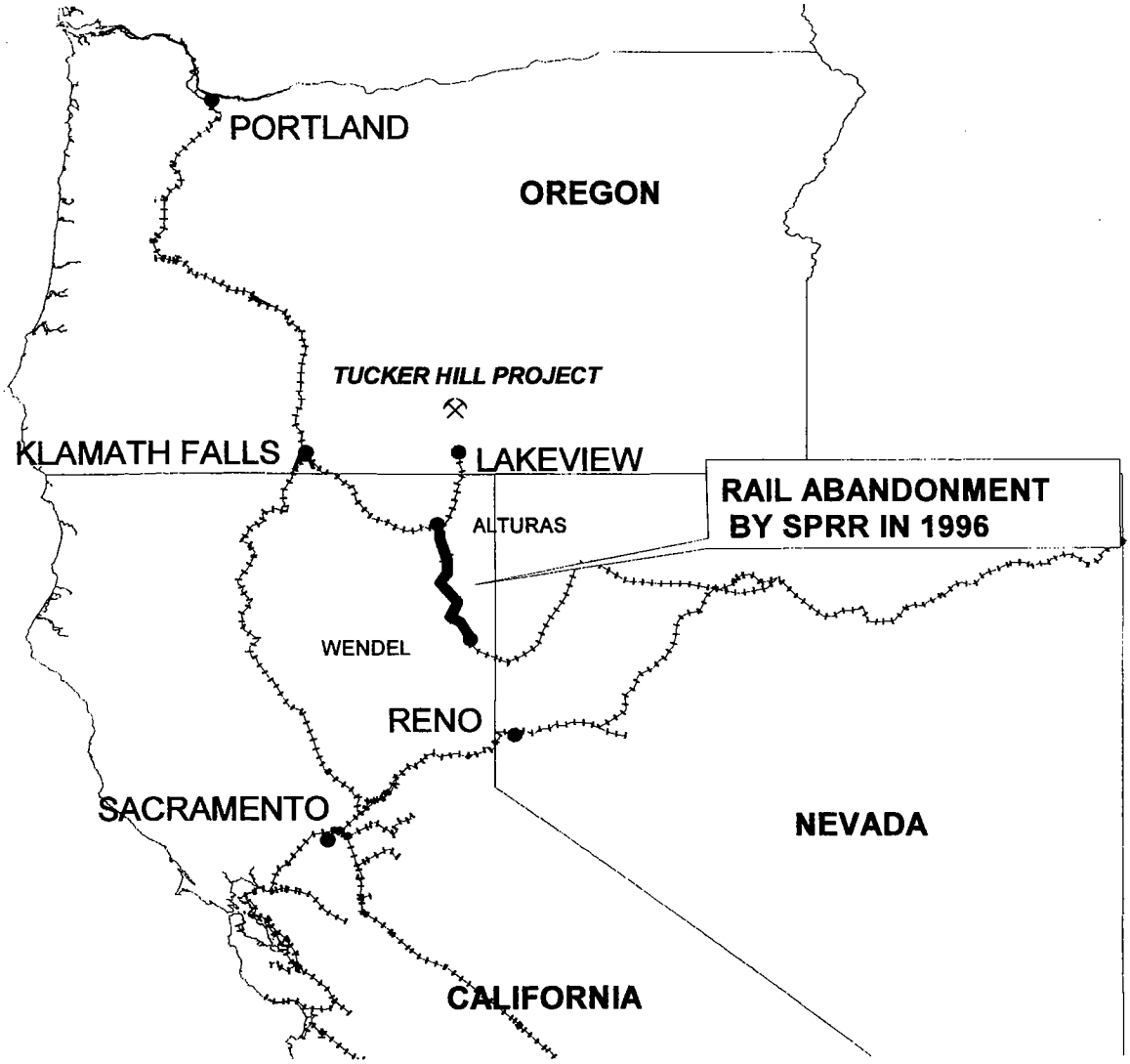


Figure 3. Proposed rail abandonment by the Southern Pacific Railroad.

THE TUCKER HILL PERLITE MINE

The Tucker Hill perlite deposit has been known for as long as perlite has been an industrial mineral. The deposit is on Bureau of Land Management land and was claimed in 1983. It was evaluated and rejected by a number of potential operators. Looming large amongst the reasons for rejection was the location of the deposit and its disproportional high cost of transportation to the market. Although the perlite was refuted to be of exceptional quality, the cost of transportation to potential customers seemed to be an insurmountable obstacle.

The Tucker Hill deposit is in southeastern Oregon (Fig. 1) about 18 mi north of Lakeview, the intended railhead. The perlite processing plant was to be built in Lakeview on the Great Western Railroad (GWRR), a short line resulting from a SP abandonment.

In 1995, the Atlas Mining Co., operating as Atlas Perlite Co., acquired the claims and proceeded to develop the property. The project looked as though it had excellent access to the marketplace (Fig. 2) because the GWRR interchanged with the SP at Alturas, California, 55 mi south of Lakeview. This interchange, in turn, provided excellent access to the north into Oregon and Washington, to the south into California, and to the eastern markets via Denver.

However, a problem arose. In 1996, the SP Railroad decided to terminate usage, and apply for abandonment (Fig. 3), of 85.5 mi of track from Alturas to Wendel, California. The SP had limited local traffic since 1995 and did not intend to use the trackage proposed for abandonment, regardless of whether the abandonment was permitted or not. Unfortunately for the Tucker Hill project, the route between Alturas and Wendel, California, was the only direct route to eastern markets. The alternative route (Fig. 4) proposed by the SP Railroad added an additional 200 mi to the direct route by going west to Klamath Falls, Oregon, south to Roseville, California, and then east. This abandon-

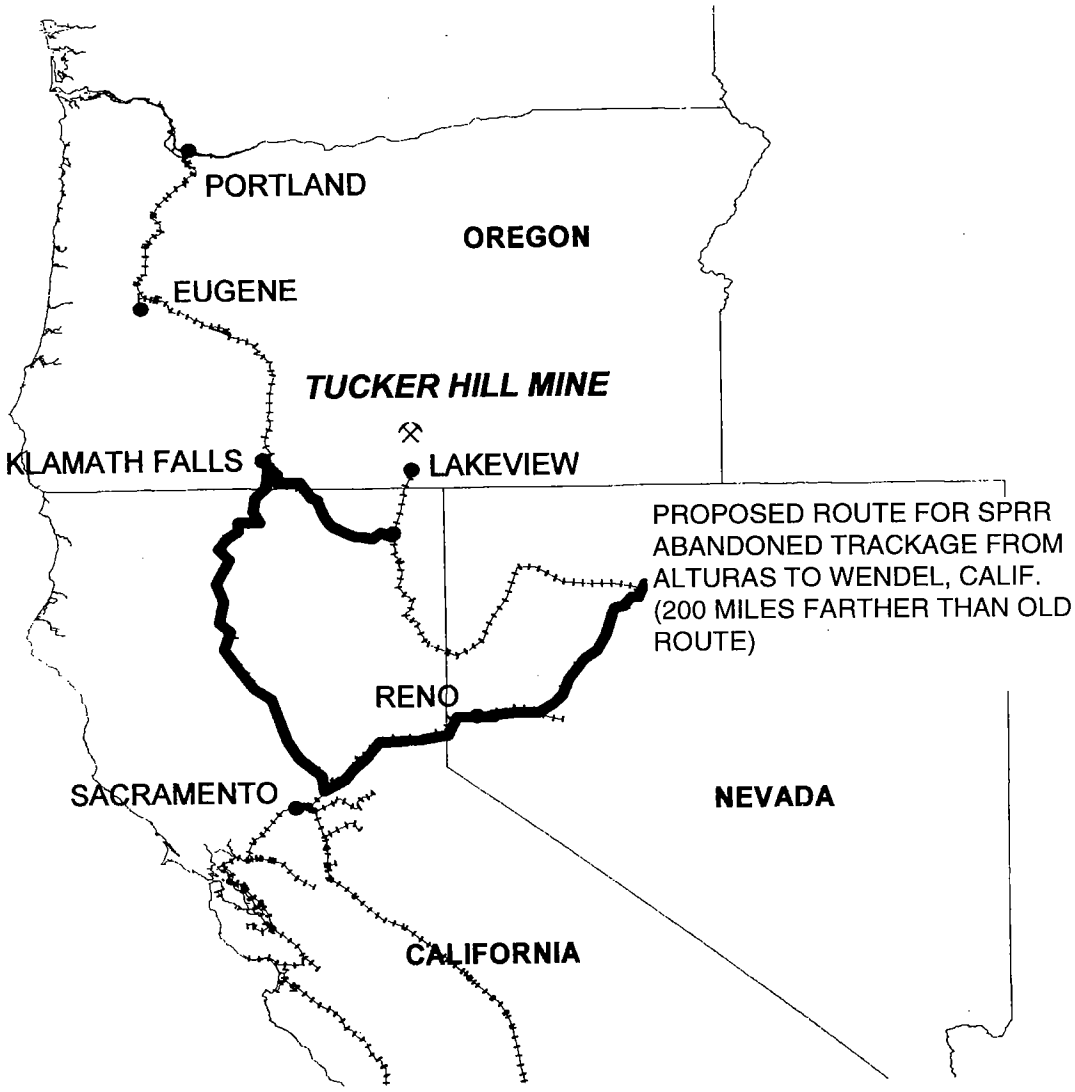


Figure 4. Proposed alternate route by the Southern Pacific Railroad .

ment, for all practical purposes, precluded any possibility of shipping Tucker Hill perlite to eastern customers because the new freight rate was simply noncompetitive. Furthermore, perlite mines in Antonito, Colorado, and Socorro, New Mexico, were substantially closer to the eastern markets than was Lakeview, Oregon.

Having lost any possibility of marketing perlite to the east, it became increasingly obvious that the viability of the Tucker Hill project depended on finding one large customer in the west to provide a base load for the project. That one customer was the ceiling tile plant of Armstrong World Industries at St. Helens, Oregon, 12 mi northwest of Portland, Oregon. Armstrong previously had tested the perlite and found it superior to its existing supply. Atlas Mining Co., operating as Atlas Perlite, decided that the Tucker Hill deposit could be placed in operation only if Armstrong could be secured as a customer.

Armstrong was encouraging, thinking that it could get a better quality perlite from the Tucker Hill project at a lower price and could improve substantially its rail service from the SP Railroad because Lakeview is considerably closer to St. Helens than was its existing supplier at Antonito, Colorado. Armstrong was, at that time, buying perlite from Antonito, Colorado (Fig. 5), a SP origin, 2,180 mi from Portland, Oregon. The Burlington Northern (BN) would switch the cars the final 12 mi from Portland to St. Helens. The SP was charging $31 per ton to deliver perlite from Antonito to Portland, and the BN was charging $6 per ton from Portland to St. Helens, for a total of $37 per ton. However, because of the distance and the number of times that the shipments were re-routed, rail service from Antonito was unreliable.

Armstrong occasionally had run out of raw perlite and would truck material from Antonito. Alternatively, rail cars, which were released from Antonito daily, would be bunched upon delivery and would incur de-

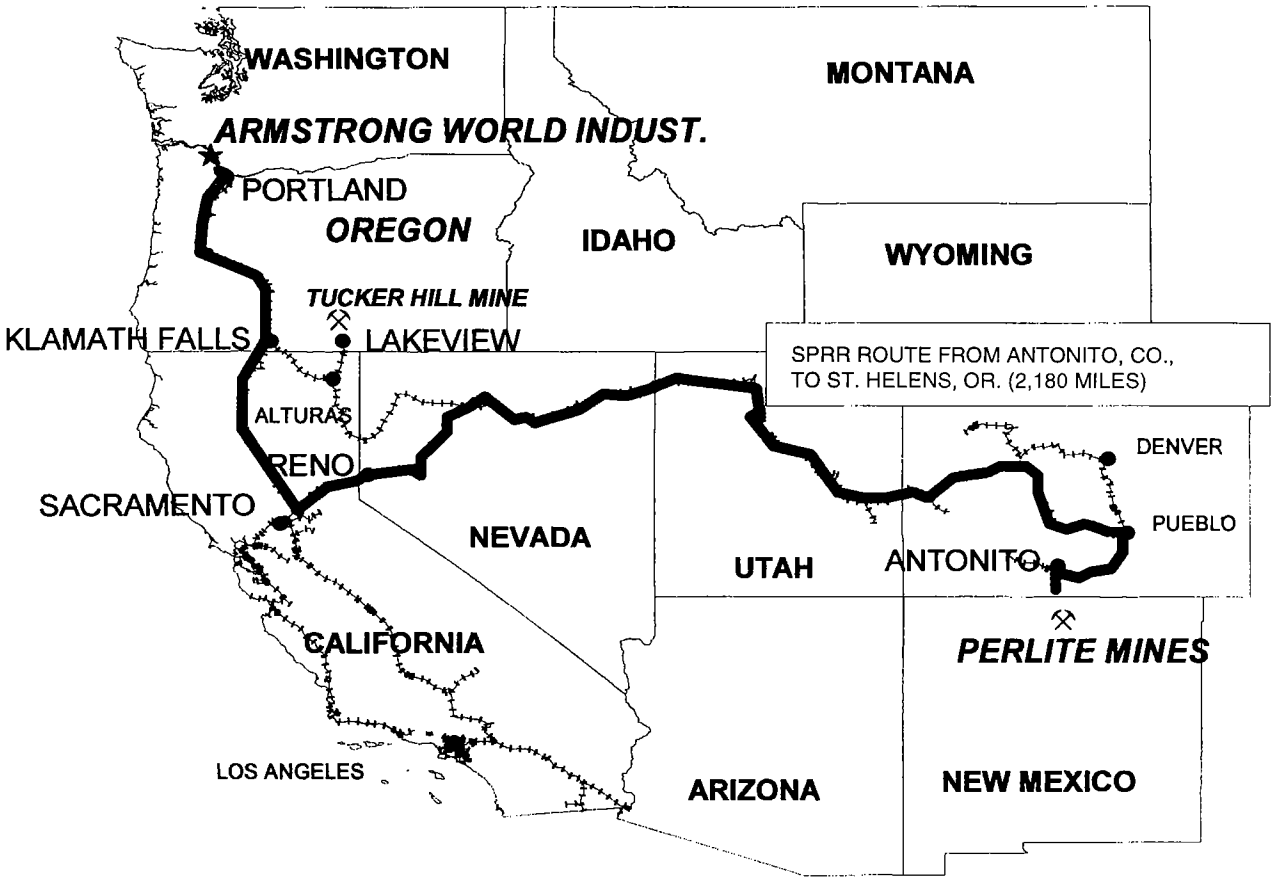


Figure 5. Existing Southern Pacific Railroad route from Antonito, Colorado, to St. Helens, Oregon.

murrage charges. Armstrong would go without a rail delivery for two weeks only to have 12 railcars delivered all at once. Armstrong neither had the trackage, the equipment, nor the storage to handle 12 cars. Hence, in 1995, Armstrong incurred a $30,000 demurrage bill. Armstrong expressed a strong desire to buy from Atlas if the delivery problems could be solved and the delivered price of perlite was attractive.

The SP Railroad quoted $27 per ton from Lakeview to St. Helens (482 mi at $0.056 per ton mi) versus the existing rate of $37 per ton for 2,180 mi at $0.017 per ton mi. The delivery distance declined by almost 80%, whereas the freight rate was reduced by only one-third. Clearly, the SP Railroad was attempting to protect its revenues from Antonito.

The SP received $31 per ton for delivering perlite from Antonito ($37 per ton total less $6 per ton for the BN switch). If the Tucker Hill project were placed in production, the SP would receive only $16 per ton ($27 per ton total, less $6 per ton for the BN switch, and less $5 per ton for the GWRR from Lakeview to Alturas). Successful development of the Tucker Hill project would not be in the best interests of the SP.

The SP informed Atlas that, at $27 per ton, they would provide only one switch per week. Switching once a week meant that if any cars missed the local train from Klamath Falls to Lakeview, those cars would have to be held in Klamath Falls awaiting the next weekly switch. It also meant that if any cars missed the local train, the processing plant would not have sufficient cars to load its weekly requirements.

Armstrong refused to buy perlite from the Tucker Hill project under those delivery conditions. They were told to either arrange more frequent switching service with the SP or to find additional railcars to insure continuous service. But, how many cars would be necessary? There was no answer! The SP would not estimate cycle time from Lakeview to St. Helens and back to Lakeview. Furthermore, the SP would not supply extra cars to make up any shortages incurred. The BN refused to provide extra cars on the basis that they received only $6 per ton for the switch from Portland to St. Helens.

Direct truck delivery was impractical as the road distance was 524 mi one-way. The roads were load restricted in the spring when the frost was coming out of the ground; the mountain passes frequently were blocked by snow in the winter; and Armstrong required four hours to unload a truck.

The BN suggested that the SP load extra cars, store the extras in Klamath Falls, and release them singularly, as required by the customer. The SP was unable to supply extra cars and was unwilling to take responsibility for metering the cars to the customer.

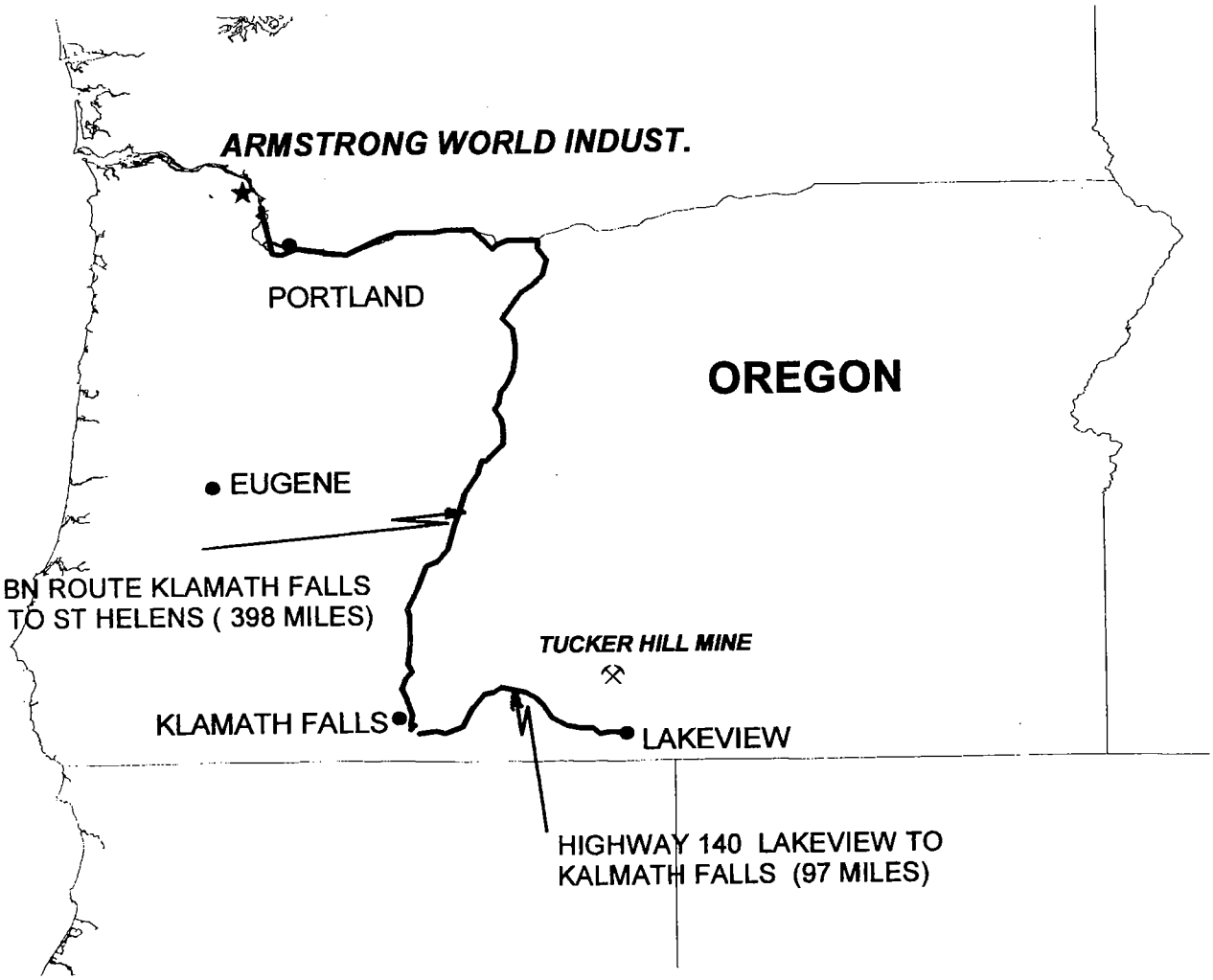


Figure 6. Rail and truck route used in transloading.

At this point, Armstrong notified Atlas that if the Tucker Hill project was going to depend on the SP Railroad, Armstrong would not use perlite from the Tucker Hill project. Confronted with an impossible situation, Atlas evaluated the possibility of transloading perlite in Klamath Falls for direct loading on the BN.

Atlas purchased an unused grain elevator in Henley, Oregon (Fig. 6), a few miles south of Klamath Falls and 97 mi from the perlite mill at Lakeview. The elevator was on the BN Railroad. The elevator was converted to handle perlite rather than wheat. Furthermore, the elevator provided up to 600 tons of live storage as a surge between the mill and the customer.

The BN posted a rail rate of $12 per ton from Klamath Falls directly to Armstrong at St. Helens; local truckers charged $11 per ton to deliver perlite from Lakeview to Klamath Falls. Total operating costs for the elevator were about $2 per ton. Thus, the overall price for transloading was $25 per ton, exclusive of capital and renovation costs for the Henley elevator. Because the transload terminal proved possible, the mine was opened. Armstrong World Industries got a reliable supply of perlite 414 mi away on the BN Railroad, rather than 2,200 mi away.

Innovative thinking put the Tucker Hill perlite mine in production. The transloading terminal in Klamath Falls did not reduce transportation expense, but it did alleviate the impossible delivery situation faced by Atlas Mining. The SP Railroad posted high freight rates in order to protect an existing, high-revenue delivery and refused to provide service sufficiently high to enable the mine to meet the customer's requirements.

Industrial Minerals of Saskatchewan

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INTRODUCTION

Industrial-mineral production contributes on the order of CDN$1.5 billion per year to the economy of Saskatchewan, Canada. Potash is the primary industrial mineral produced in the province, followed by aggregate, sodium sulphate, salt, potassium sulphate, peat, clays, silica sand, calcium-chloride brine, and "clinker." Potentially economic deposits of kaolin, diamond, and building stone are under evaluation. All of the major deposits of commodities discussed here are located south of lat 56°30'N. Most of the locations are presented on Figure 1.

POTASH

Saskatchewan supplies approximately 30% of the world's demand for potash. Eight conventional underground mines and two solution mines produced an all-time high of more than 13 million metric tonnes of potash (KCl) (8 million tonnes K_2O equivalent) in 1997, valued at over CDN$1.4 billion. All of the mines exploit the middle Devonian Prairie Evaporite. The four potash-bearing members of the Prairie Evaporite underlie much of southern Saskatchewan and extend southward into North Dakota and Montana and eastward into Manitoba (Fig. 2). Halite and anhydrite separate the potassic members. The evaporite beds locally are interrupted by solution structures (anomalous ground). Some of the structures may be related to deep-seated tectonic features.

Potash resources generally are accepted as being extremely large. Barry (1981) calculated reserves for single- and double-level conventional mining as 10.5 and 14.0 billion tonnes K_2O equivalent, respectively. However, the influence of solution structures on recoverable reserves, particularly in the region where the ore is at a conventional mining depth of 1,100 m or less, makes any attempt at precise estimates difficult. Deeper resources recoverable by solution mining are estimated to be at least 42 billion tonnes K_2O equivalent.

AGGREGATE

Production of about 11 million metric tonnes of sand and gravel was reported in 1997. This material was derived from Pleistocene glacial and glaciofluvial deposits and Tertiary fluvial deposits.

SODIUM SULPHATE

Saskatchewan is also one of the world's leading producers of natural sodium sulphate. The deposits occupy closed basins or depressions in southern Saskatchewan that resulted from various glacial and proglacial processes (Last and Slezak, 1987). The most abundant mineral salts are mirabilite ($Na_2SO_4 \cdot 10H_2O$), thenardite (Na_2SO_4), bloedite ($Na2Mg(SO_4)_2 \cdot 4H_2O$), as well as magnesian sulphates such as epsomite and kieserite.

Figure 3 illustrates the general morphology of the deposits and mining methods. Typical crystal bed thickness is 1–5 m but exceeds 30 m in a few locations. Natural sodium sulphate deposits generally are interlayered with impurities of silt, clay, and biogenic material.

Currently four operations produce about 320,000 metric tonnes per year, about 90% of which is detergent grade (~99.5% Na_2SO_4), and the balance is salt cake (~97% Na_2SO_4). The value of production in 1997 was approximately CDN$30 million. Two operations further combine sodium sulphate with potash to produce potassium sulphate.

The origin of the ions in these basins is not yet fully understood. Saline springs near many of the basins are presumed to have a genetic relationship to the sodium-sulphate deposits. Potential mechanisms for the springs include: shallow (meteoritic) ground water; deep (connate) ground water, possibly modified during ascent; and surface leaching of the surrounding terrain.

Tomkins (1954) identified 21 Saskatchewan deposits, each containing between 500,000 tons and 9 million tons of anhydrous sodium sulphate equivalent. Twenty-four others were listed as containing between 100,000 and 500,000 tons each.

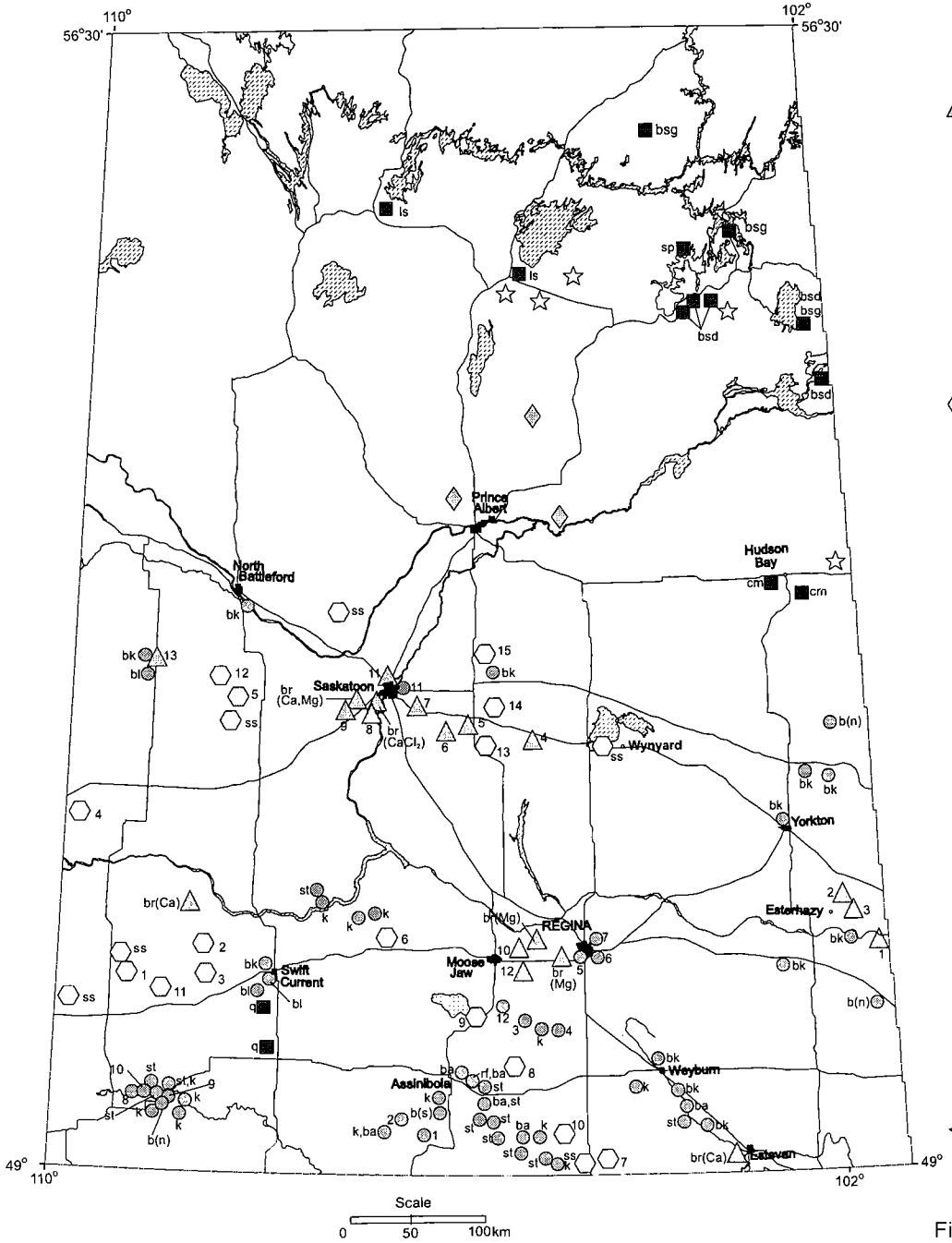
SALT

Salt is produced as a by-product at four potash mines and by two stand-alone solution mines. Table salt, livestock blocks, road de-icing salt, water-softener salt, and a variety of sodium-based chemicals are produced.

PEAT

At present, Saskatchewan peat production is limited to a single operator that produces horticultural peat

Kelley, L. I., 1999, Industrial minerals of Saskatchewan, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 309–312.



Legend

△ POTASH, SALT, AND BRINE
1. Potash Corp. of Sask., Rocanville potash mine
2. IMC-Kalium, K1 potash mine
3. IMC-Kalium, K2 potash mine
4. Potash Corp. of Sask., Lanigan potash mine
5. IMC-Kalium, Colonsay potash mine
6. Potash Corp. of Sask., Allan potash mine
7. Potash Corp. of Sask., Patience Lake potash solution mine
8. Potash Corp. of Sask., Cory potash mine (by-product $CaCl_2$ brine)
9. Agrium Ltd., Vanscoy potash mine
10. IMC-Kalium, Belle Plaine potash solution mine
11. Sterling Pulp Chemicals (brine)
12. Canadian Salt Co. Ltd., salt plant (waste salt from 10)
13. Sifto Canada Inc., salt plant (brine)

other brine occurrences: br; (Mg), magnesium; (Ca), calcium; ($CaCl_2$), calcium chloride

⬡ SODIUM SULPHATE
1. Sask. Minerals, Ingebright Lake sodium sulphate plant
2. SOTEC Products Ltd., Snakehole Lake sodium sulphate plant (idle)
3. SOTEC Products Ltd., Verlo Lake sodium sulphate quarry (idle)
4. Potassium Sulphate Company Alsask Inc., Alsask Lake potassium sulphate plant
5. Millar Western Industries, Whiteshore Lake sodium sulphate plant
6. Sask. Minerals, Chaplin sodium sulphate plant
7. Sask. Minerals, Sybouts East sodium sulphate plant (closed)
8. Ormiston Mining and Smelting Co. Ltd., Horseshoe sodium sulphate plant
9. Sask. Minerals, Frederick Lake sodium sulphate plant (closed)
10. Ceylon Lake, sodium sulphate deposit
11. Vincent Lake, sodium sulphate deposit
12. Aroma Lake, sodium sulphate deposit
13. Little Manitou Lake, sodium sulphate deposit
14. Berry Lake, sodium sulphate deposit
15. Muskiki Lake, sodium sulphate deposit

other occurrences ss

■ BUILDING MATERIALS
cm, calcareous shale (cement rock); q, quartzite gravels;
bsd, dolomite and dolomite marble building stone;bsg, granitic building stone; ls, limestone

◎ CLAY RESOURCES
1. Estevan Brick Ltd., Div. IXL Industries Ltd., clay quarry (st, bk)
2. Estevan Brick Ltd., Div. IXL Industries Ltd., clay quarry (rf, ba, k)
3. A.P. Green Refractories (Canada) Ltd., clay plant (closed) IXL Industries Ltd., clay quarry (rf, bk)
4. Canadian Clay Products Ltd., swelling bentonite quarry
5. IXL Industries Ltd., Western Clay Products Div., clay products plant
6. Cindercrete Products Ltd., expanded clay aggregate
7. Inland Cement Ltd., expanded clay aggregate
8. IXL Industries Ltd., clay quarry (st)
9. IXL Industries Ltd., clay quarry (st)
10. Plainsman Clay Ltd., clay quarry (st)
11. Cindercrete Products Ltd., expanded clay aggregate
12. A. P. Green Refractories (Canada) Ltd., Clay quarry (closed)

other occurrences b(s), swelling bentonite; b(n), non-swelling bentonite; bk, brick clay; ba, ball clay; bl, bloating clay; rf, refractory clay; k, kaolin; st, stoneware

◇ DIAMONDIFEROUS KIMBERLITE CLUSTERS

☆ SILICA SAND

Figure 1. Industrial minerals of Saskatchewan, south of lat 56°30´N.

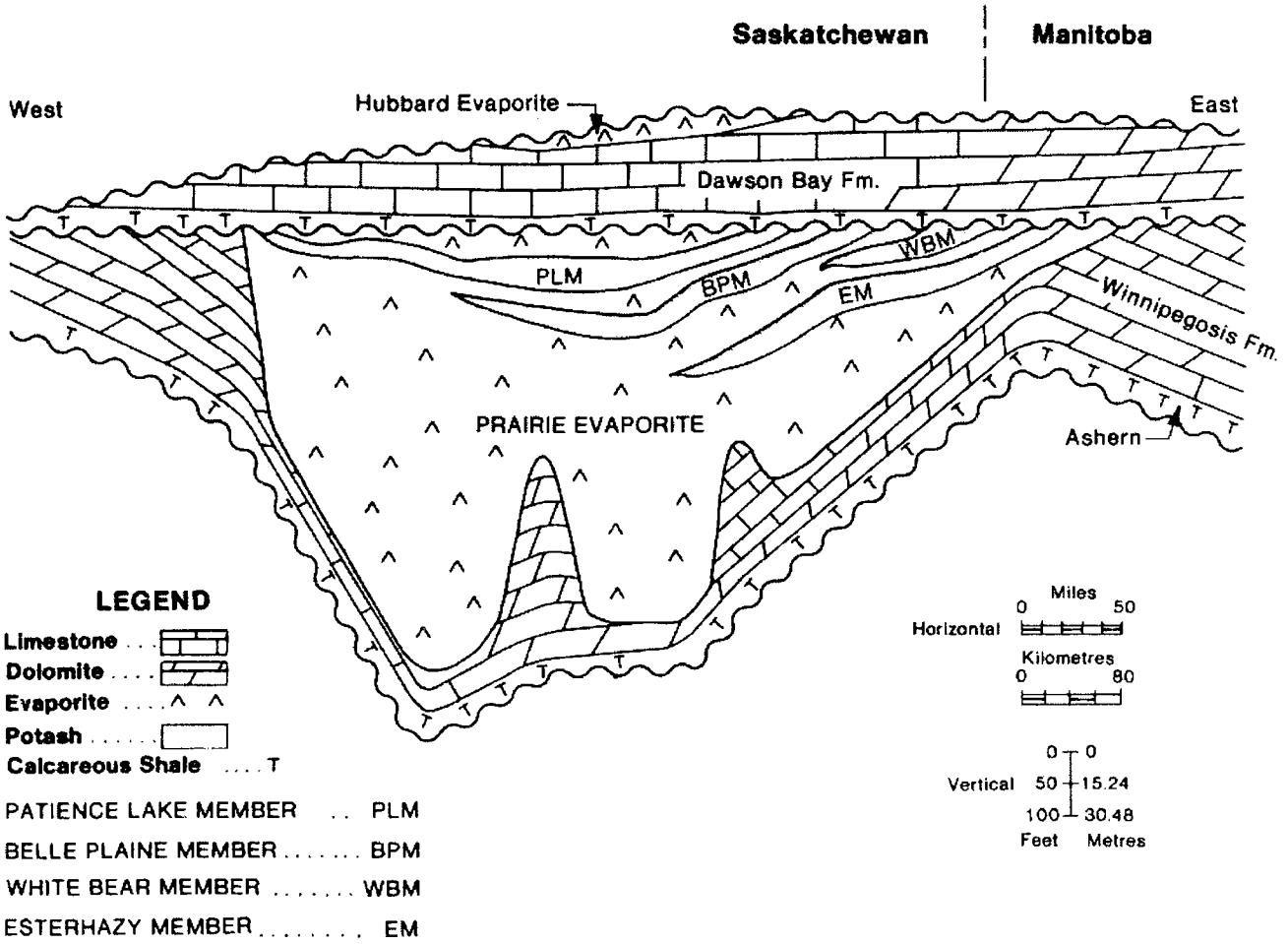


Figure 2. Schematic east-west cross section through the Prairie Evaporite. From Fuzesy (1982).

near Carrot River. Troyer (1985) completed the most recent investigation of Saskatchewan peatlands. He identified fuel peat in the La Ronge, Pinehouse, Buffalo Narrows, and Beauval areas that contained approximately 4,600–4,900 BTU/lb.

STRUCTURAL CLAY

Canada's only bentonite producer exploits several seams in the Cretaceous Bearpaw Formation in southern Saskatchewan. Brick production in the province ceased in 1996, but clay for brick-making, porcelain, and general pottery uses is still quarried from several locations in south-central and southwestern Saskatchewan.

SILICA SAND

High purity (>95% SiO_2) silica sand is quarried from the Ordovician Winnipeg Formation for use as smelter flux and from the Cretaceous Mannville Group for golf-course-bunker sand. Several exploration programs are currently evaluating the Winnipeg sands for hydrofracturing propping media and as feed for high-purity silica specialty applications.

BRINE

Calcium chloride-saturated brine infiltrates one of the potash mines. It is recovered and distributed by a chemical re-seller for use in road-dust suppression and as tractor-tire ballast (SG (≈1.3). Analysis of Paleozoic formation brines indicates considerable potential for development of a multielement brine-based chemical industry. Kreis and Gent (1992) compiled analyses including iodine concentrations in excess of 500 mg/l and bromine concentrations in excess of 20,000 mg/l. The Saskatchewan Geological Survey is a partner with the University of Saskatchewan and the University of Alberta in enhancing the brine database by systematic analysis of formation waters from petroleum wells. Results of this work may support the resource potential of the brines.

CLINKER

"Clinker" is used to describe materials that have been thermally indurated by in situ coal-seam combustion to a degree up to and including fusion. Clinker deposits are found in the Paleocene Ravenscrag Formation in southern Saskatchewan, where mudstones have

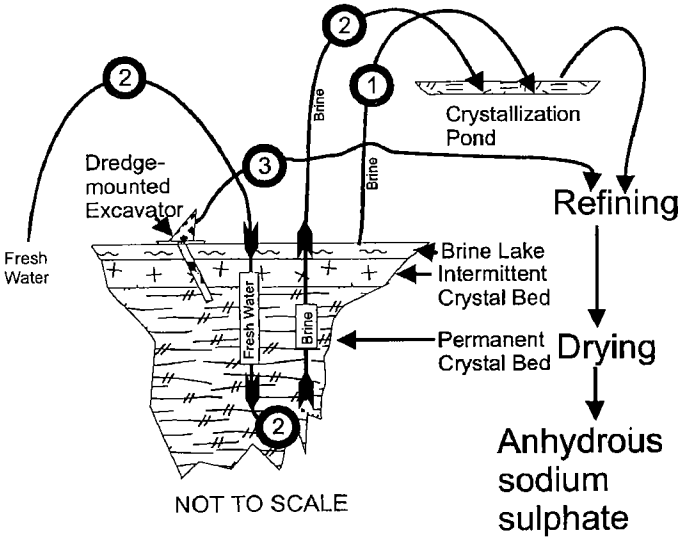


Figure 3. Schematic cross section of idealized Saskatchewan sodium-sulphate deposit. Mining methods illustrated are: (1) Evaporative concentration of lake brine in crystallization pond, followed by precipitation of crystals of Glauber's salt (mirabilite) as the water cools in autumn. (2) Solution mining of thick crystal beds. The brine return is treated as in (1). (3) Dredging of lake-bottom crystal beds.

been altered by the combustion of lignite. The clinker is quarried for use as decorative coloured blocks and aggregate in landscaping applications. It also has been used as a replacement for the crushed-brick product used to improve drainage and control mud on baseball infields (Guliov, 1995). Clinker is also a potential source of road metal.

KAOLIN

The Upper Cretaceous Whitemud Formation represents a very large kaolin resource in south-central Saskatchewan. A reserve of 200 million tonnes has been drill-tested near the village of Wood Mountain. Bench- and pilot-scale testing has produced the following: low-brightness, calcined coating-grade kaolin; non-calcined low-brightness filler; high-brightness calcined filler; and medium-brightness delaminated kaolin. The western Canada kaolin market is currently on the order of 50,000 tonnes per year, but two lightweight-coated-paper plants currently being permitted in Alberta could increase that figure by five times or more in the next few years. At the time of writing, two companies were exploring the kaolin potential of the Whitemud Formation.

DIAMOND

In the Fort-à-la-Corne and Candle Lake areas of central Saskatchewan, more than 70 kimberlite bodies have been drill-tested. Most of the kimberlites are diamondiferous, and gem-quality stones have been reported. Evaluation of these deposits, which are typically overlain by 100 m of glacial drift and poorly consolidated Cretaceous clastic rocks, is ongoing.

A major exploration effort began in late 1997 in south-central Saskatchewan, stimulated by a Saskatchewan Geological Survey sampling program that identified several diamond-indicator mineral anomalies.

STONE

A mottled buff and tan Ordovician dolomite, which is not metamorphosed but meets ASTM specifications for marble, has been quarried for several ashlar-block-construction projects in the last 10 years. Other very attractive stones have been identified, including a green granite and an injection gneiss reminiscent of "Verde Antique."

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The Application of Airborne Electromagnetics and Ground Geophysics to the Detection of Buried Gravel Deposits

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ABSTRACT.—Sand-and-gravel aggregates have become the number-one, nonmetallic-mineral resource in the world. Surficial aggregate deposits of economic size are becoming increasingly rare in most parts of Canada. In southern Saskatchewan, this is especially true, and detection and delineation of intertill sand-and-gravel deposits with airborne electromagnetic (EM) surveys have proven very successful. Airborne and ground geophysical surveys detect such deposits by their resistivity contrast relative to the surrounding clay-rich soils. Dighem helicopter-borne electromagnetic surveys map soil variations over a large area quickly and cost effectively, greatly reducing the cost of detecting and mapping deposits compared with traditional methods (air-photo interpretation, ground EM, and drilling).

The multiple-frequency EM system used by Dighem can map variations both horizontally and vertically. Magnetic data collected simultaneously are useful in mapping bedrock geology. Both resistivity and bedrock maps aid in the important task of reducing drilling costs and person-hours in the field.

The results of the survey are presented as maps of ground resistivity, which are relatively easy to interpret. These maps are produced in the field at the time of the survey, making quick follow-up of the survey possible.

Airborne EM surveys can map the extent and depth of aggregate deposits more effectively than is practical from the ground. Since aggregate deposits can vary tremendously in a very short distance (<300 m) large-area EM maps can show both local area variability and also help develop intertill trends.

A test survey for the Saskatchewan Highways and Transportation Department over a 3-km by 5-km area mapped all the known deposits as well as some unknown deposits, subsequently proven by drilling. The test-survey data show that the method not only detected the deposits, but also gave an estimate of the shape (volume) of each of the deposits. Comparison of the data to drill sections shows excellent correlation.

Theoretical modelling demonstrates that the multifrequency system can discriminate sand and gravel from bedrock ridges.

Since the successful test work, about 725 km^2 of ground have been surveyed, resulting in the discovery of four new deposits, which can be used immediately, resulting in significant savings for the Saskatchewan government and taxpayer.

INTRODUCTION

Sand-and-gravel aggregates have become the number one nonmetallic-mineral resource in the world (Derry, 1980; Jenson and Bateman, 1981). In total tonnes produced it far exceeds iron ore, salt, or coal. Production in the United States is about a billion tonnes annually (Barsotti, 1999, this publication); in Canada, more than 200 million tonnes (Giancola, 1997). Because of the high volume of material, and an average cost of $1.00 to $2.50 per tonne at the pit, transportation costs are a major factor in the purchase of aggregate. This makes it essential that sand and gravel be found as close as possible to the site where it will be used. Deposits near major urban areas are exhausted in some cases, forcing producers to resort to

Hodges, Greg; and Latoski, Michael, 1999, The application of airborne electromagnetics and ground geophysics to the detection of buried gravel deposits, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 313–318.

long haul distances or expensive crushed rock. The ability to locate sand and gravel hidden beneath other sediment layers can extend the reserves and reduce the cost of locating deposits.

In this paper, we would like to show some new techniques, particularly airborne electromagnetic surveys, that have been used successfully to detect buried sand-and-gravel deposits in Saskatchewan in 1997.

BACKGROUND

Geology

Sand-and-gravel deposits generally occur as sedimentary beds or pockets, commonly interbedded with other sedimentary layers. They are formed from fluvioglacial deposits, stream channel and floodplain deposits, on the margins of current or ancient sea and lake beds, or as desert sand dunes (Jenson and Bateman, 1981). Sand-and-gravel deposits in Saskatchewan mostly originate from fluvioglacial deposition—from meltwater deposits on, under, and marginal to the continental glaciers (Giancola, 1997).

Methods for Finding Sand and Gravel

Traditional methods of locating aggregate deposits include (1) prospecting—or going out and looking around, (2) air-photo interpretation, (3) satellite-image interpretation, and (4) drilling or trenching. Prospecting is obviously slow. Air-photo interpretation is relatively low cost, but can be successful only where there are indications on the surface of the presence of the aggregate. It cannot help with intertill deposits. Satellite-image interpretation suffers from the same problems. In either case, heavy forest cover or swamp also can mask the deposits. Interpretation of geomorphology can aid this search.

Drilling and trenching can penetrate the overlying sedimentary layers, but these methods are slow, comparatively expensive, and sample only a single point. These methods also damage the surface, which increases the cost and slows down or prohibits exploration because of land-access and permitting problems. Wildcat drilling without previous indications of the existence of the deposit is much too expensive.

Examination of existing drill information, such as water-well drill logs, works in areas where this information is available. It can be time-consuming and requires an advanced knowledge of the geomorphology. The coverage and detail can be sparse.

Ground geophysical methods also are used to detect sand and gravel. Portable electromagnetic (EM) systems such as the Geonics™ EM31 are popular and can penetrate conductive clay layers to a depth of a few metres. They do minimal crop damage and no land damage. They are limited, however, to the distance they can be carried in a day (5–10 km). They can be mounted on a vehicle, but this approach reintroduces the problems of drills—damage to the land, and access and permitting.

The smaller ground EM units such as the EM31 are limited in their depth penetration and generally do not provide a multilayer section. Larger units can see to economic depths, and some can detect at different depths; however, as the unit becomes larger, the cost goes up and often the production slows down.

Ground-penetrating radar also is used to detect aggregate deposits and provides high-resolution images of the subsurface. However, the instruments provide very limited penetration in the high-clay tills, which commonly may cover sand-and-gravel deposits in Saskatchewan. Radar can be portable or truck mounted, with the same benefits and limitations as a ground EM system.

Helicopter EM surveys lack the high resolution of ground EM systems for small targets but cover a lot of ground quickly, are multifrequency/multidepth, and do not require ground access. They are unaffected by tree cover or swamp. Typical production is about 65 km^2 a day, at 200-m line spacing.

THE DIGHEM^V HEM SYSTEM

The Dighem^V HEM system is a frequency-domain electromagnetic system with five transmitter/receiver coil pairs in a bird slung below the helicopter at a ground clearance of about 30 m. The standard system has a frequency range from about 380 Hz up to 56,000 Hz, with coils oriented in both coplanar configuration for best sensitivity resistivity mapping and vertical-coaxial coils for sensitivity to vertical conductors.

Currently, a new system designed for this type of resistivity mapping work is being built, which will employ five coplanar coil pairs with a frequency range up to over 100,000 Hz.

The transmitted field energises the ground below, inducing electric currents, which change depending on the resistivity of the ground. Variations in the soil and rock conductivity, which generally are calculated as the apparent resistivity, change the strength and phase relationship of the returned secondary field measured with the receiver.

Electromagnetic Surveys for Sand and Gravel

The depth of exploration depends on several factors: the frequency of the EM signal, the sensitivity of the receiver, and the resistivity of the ground. The penetration increases as the EM frequency decreases. By employing five different frequencies, the Dighem^V system is able to sample the ground at different depths, building a three-dimensional picture of the distribution of resistivity in the ground. For example, in ground of 10 ohm-m resistivity, the spread of frequencies will roughly sample between surface and 60 m deep. Sensitivity is controlled by the quality of the electronics, and by the ability to see the weak secondary field through the powerful primary field. Dighem accomplishes this by moving the receivers as far as practical from the transmitters, 8 m. Increasing resistivity allows the EM fields to penetrate deeper into the earth, increasing the depth of exploration.

Sand-and-gravel deposits are generally more resis-

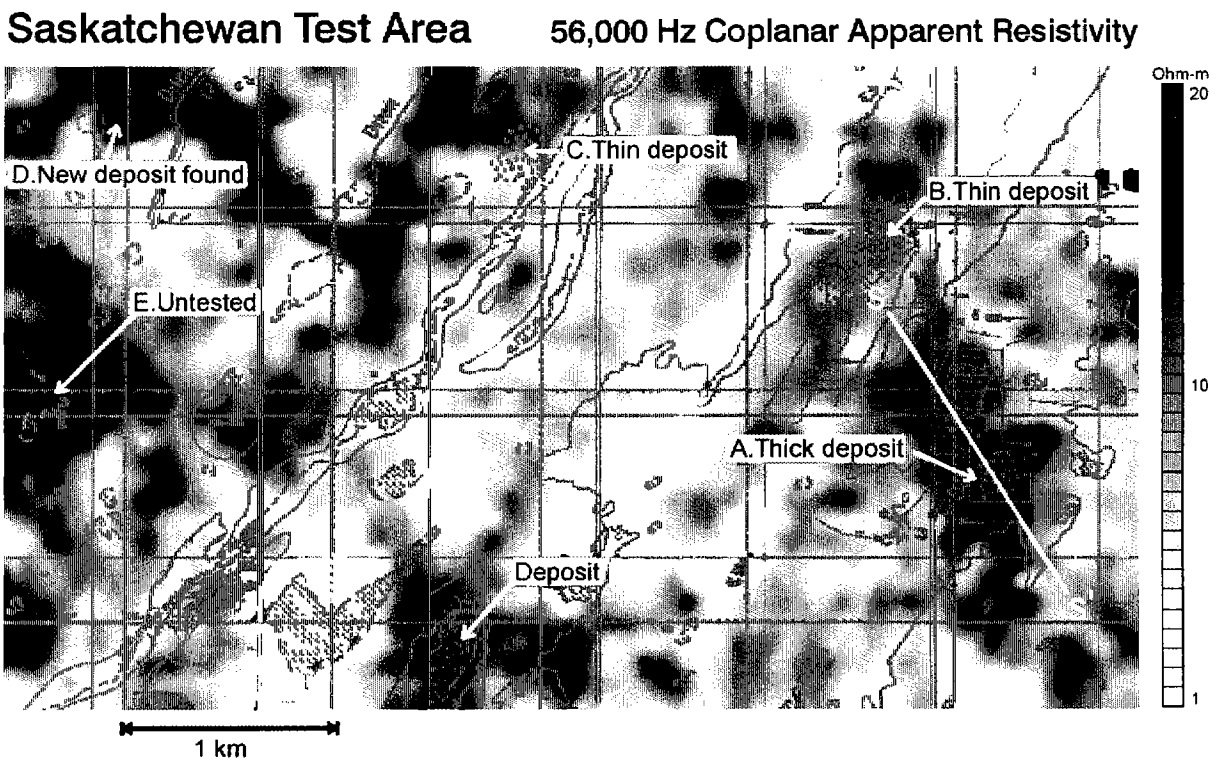


Figure 1. Saskatchewan Dighem^V test survey, 56,000-Hz coplanar apparent resistivity.

tive than the surrounding glacial tills or lake sediments, which generally are high in clay minerals. The strength of the anomaly from the aggregates depends on several factors: the clay content of the aggregate, the thickness of the deposit, the porosity and hence water content of the sands, and the salinity of the water. Additional clay in the sand will make it less resistive, and thus more like the surrounding clay-rich tills. The thicker deposits occupy a larger percentage of the volume of ground that the system samples, and so provide a better measure of the real resistivity of the deposit and a better contrast to the surrounding tills. Increased water content, commonly due to increased porosity relative to the clays, can make a clean deposit less resistive. Saline water can make a sand lens highly conductive.

The shape of the anomaly on the map can be used to define the shape and extent of the deposit.

The relationship of EM response to water content and salinity has been used many times to map groundwater resources, for detection of freshwater and for salinity mapping.

The system is positioned by real-time differential GPS, and magnetic data and a video of the ground track are collected with the EM. The magnetic data can help interpret the changes in bedrock, as well as cultural interference. The ground-track video helps to verify position and to identify surficial features and culture. A 60-Hz detector will identify artificial power sources—power lines and buildings.

TEST SURVEY

The test area flown for the Saskatchewan government was 3 km by 5 km (Fig. 1) and is covered by interlayered sand and glacial till. There were six drilled areas before the survey was conducted. All of the previously known gravel deposits were detected and mapped by the HEM survey, and some new deposits were detected as well. In this location, the depth to bedrock is >150 m; thus, bedrock does not affect the data. The background clay and till resistivity is in the range of 1–10 ohm-m.

Results

Anomaly A

The previously known deposit at locality A (Fig. 1) appears as a strong anomaly of 30 ohm-m, indicating that it is thick and large. The data show that the strongest part of the anomaly—hence, the best part of the deposit—is between the two groups of holes drilled on this test area. This is just north of the arrow from locality A. The drilled holes (round gray dots) cover most of the anomalous zone, which extends a few hundred metres west of the north end of the drilled areas and south 700 m. The resistivity highs are weaker to the south, suggesting either that the deposit is thinner or that it has a higher clay content.

The drill results for this deposit show an average depth to the top of 1.5 m to 2 m. A few holes in the centre of the deposit that were drilled beyond 4 m showed

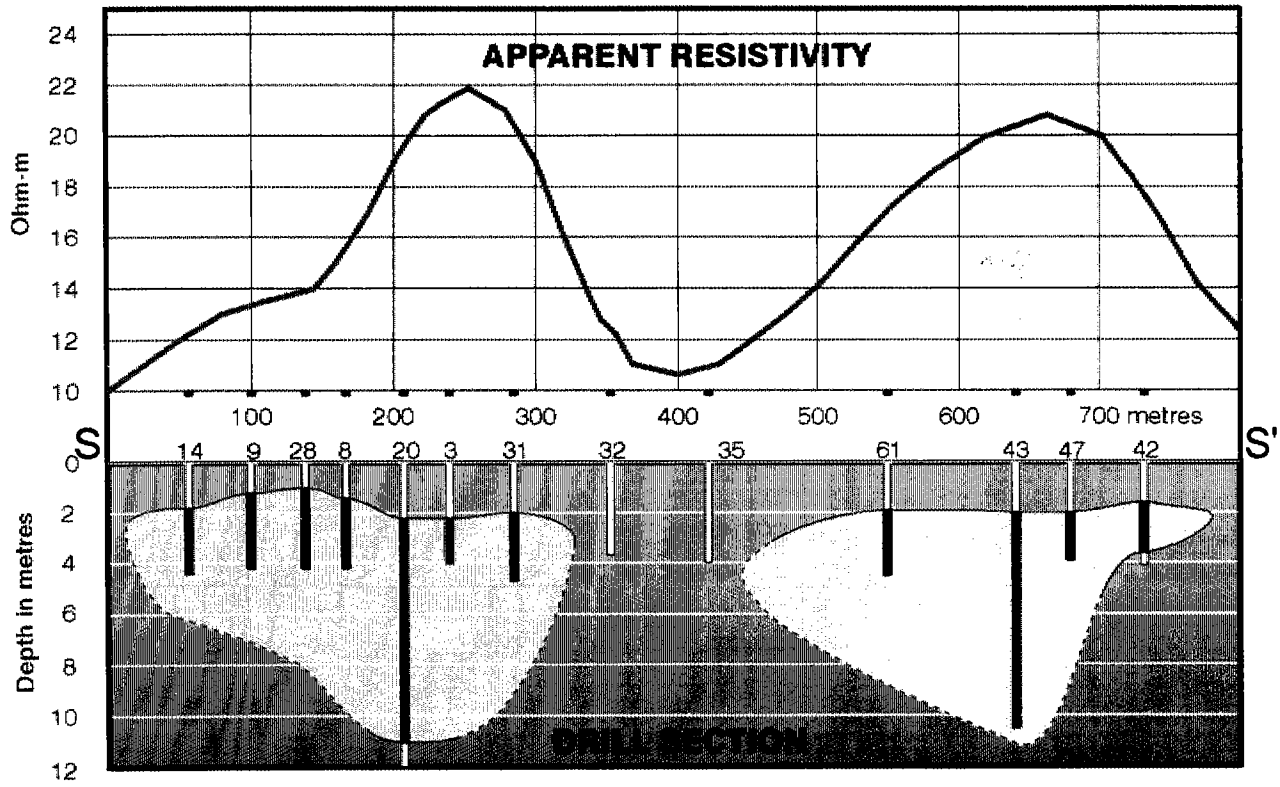


Figure 2. Drill section and resistivity profile through test survey (Fig. 1), S to S´.

a depth of 10 m or more to the bottom. A section cutting south-southeast through the long axis of the deposit at locality A (Fig. 2) shows the drilled depth to gravel (if any) for all the drill holes along that section, compared with a profile of the apparent resistivity. Although many of the drill holes stop at 4 m, whether or not in gravel, the two deep holes (20 and 43) show that it is a thick deposit. Along with the two holes that hit no gravel at all (32 and 35), the data show that a good correlation exists between the thickness and extent of the gravel beds and the resistivity. Note that the drill section has considerable vertical exaggeration.

This example also demonstrates how the airborne EM data and the drill information complement each other. Whereas the drill results are definitive about the depth, thickness, and grade of the deposit, they represent data at only one location, a few centimetres across. The HEM data are less definitive but cover a large area completely, quickly, and cheaply. Once a probable deposit has been found, drilling can be targeted on the best zones. Only a few drill holes are needed initially to give some ground truth to the resistivity data, allowing a more accurate quantitative assessment of the deposit depth, thickness, and total volume.

Anomaly B

The weaker anomaly over the known deposit at locality B (Fig. 1) is a thin deposit that is currently being exploited. This anomaly is not as strong as that at locality A. It is strongest at the north end—about 16 ohm-m, and extends north of the drilling shown on the map. Drill results here show an average depth to the top of the sand and gravel of about 1–1.5 m. Where the drill was pushed through the deposit, the depths to the bottom were about 8 m.

Anomaly C

The deposit at locality C (Fig. 1) is a very thin, small deposit. The anomaly is quite weak, only about 12 ohm-m. The drill results show that the depth to the top averages a metre or less. The thickness is typically 2–3 m, except at the very centre, where the apparent resistivity anomaly is strongest, and where the bottom is beyond the 4-m depth of the drill holes.

Anomaly D

A previously unknown deposit was detected at locality D (Fig. 1), which has been confirmed by drilling based on the Dighem^V resistivity survey. This arcuate anomaly extends outside the survey area at both of its northern ends, so that the full extent is not mapped. It is strongest and widest at the northwest end, where the resistivities rise to about 28 ohm-m. This suggests a thickness of 10 m or greater.

Anomaly E

The anomaly at locality E (Fig. 1) has not yet been tested, but appears to be a new deposit of significant

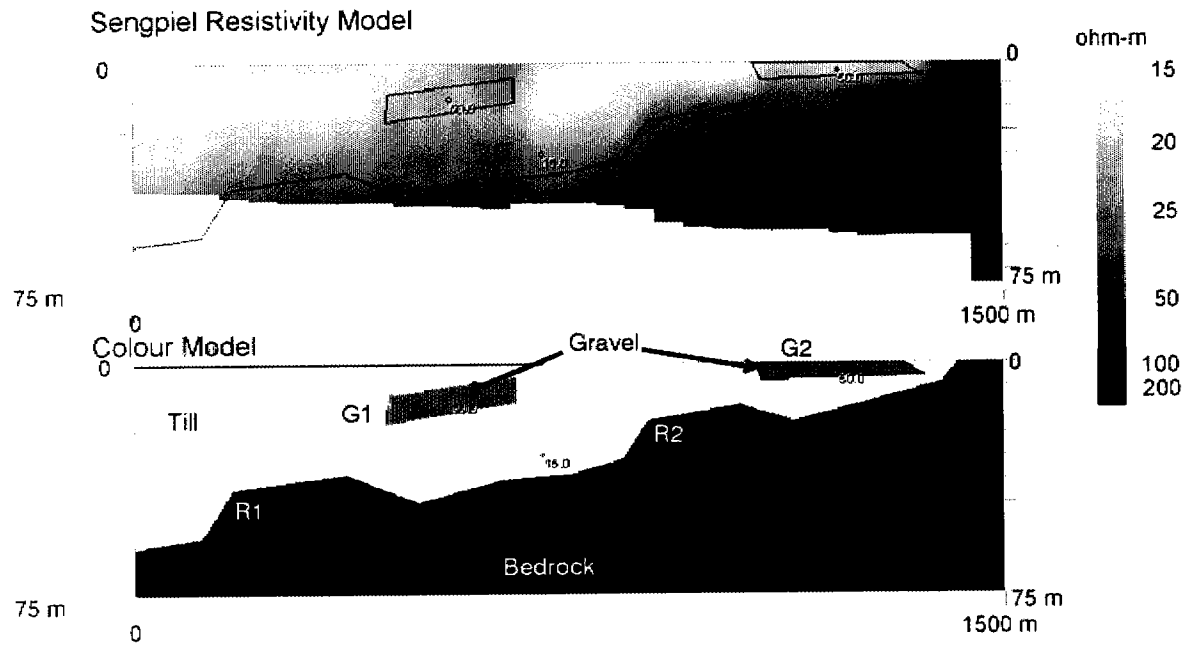


Figure 3. Resistivity-model section: gravel deposits and bedrock ridges.

thickness and size. This is the largest anomaly on the property (not the "strongest"); it covers a roughly semicircular area of 800 m by 1200 m and appears to extend off the edge of the survey area. Thus, its total extent is unknown. The highest resistivities are about 25 ohm-m; thus, the deposit appears to have both economic size and thickness.

The results from these test areas show an excellent correlation between the extents of the deposit and not only the location of the EM anomalies, but also the strength of the anomalies. Coverage of the area took about 2 hours, and colour maps of the apparent resistivity were completed the same day.

The 7,200-Hz resistivity data are generally more resistive than the 56,000-Hz data, and represent a deeper "sample" of the earth (8–15 m), so any anomalies may come from deposits too deep to be of interest. However, these anomalies will also represent thicker deposits, because the lower frequency samples a greater depth and is less sensitive to narrow zones.

Modelling

The depth to bedrock in this area is about 150 m (Saskatchewan Water Resources Map NTS 73A). Where the bedrock is shallow, it also can create a resistivity-high anomaly. These anomalies can be distinguished from the near-surface sand and gravel by the relative strengths of the anomalies on the shallow and deeper frequencies. The artificial model in Figure 3 shows a vertical resistivity section for a typical situation. The bedrock varies from deep to shallow across the section, with ridges at R1 and R2. There are also gravel lenses in the till at G1 and G2. The ridge R1 is mapped by the lowest frequency, but it is too deep to see on the highest frequency and would not concern us. Only the higher frequencies map deposits at economic depths. The high frequency resistivity over the ridge at R2 is comparable to the resistivity over the gravel deposits, but, by examining the next lower (deeper) frequency at the gravel anomalies, we can see that the resistivity maps the conductive till under the gravel. At the bedrock ridge, the resistivity of each lower frequency keeps getting higher, showing the interpreter that we are exploring deeper into the bedrock rather than a gravel lens.

CONCLUSIONS

The success of this test survey led to further production work, over nine areas for a total of 700 km^2 (273 mi^2). Several economic deposits have been located by the work, some of which would not have been located using air photos. It has been estimated that cost savings up to $750,000 already have been realized from the survey results, with a number of identified anomalies still to be followed up on the ground.

Along with the extensive gravel deposits, the Digham^V resistivity survey located shallow sources of fresh groundwater and areas of high clay soils. The ability to locate freshwater aquifers is crucial for farming as well as for environmental site studies.

ACKNOWLEDGMENTS

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Industrial Minerals in the Caribbean

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ABSTRACT.—The Caribbean islands, with their very diverse geology, are a source of several industrial minerals both for their own domestic consumption and for export. The geology of the Greater Antilles, which comprises Cuba, Hispaniola, Puerto Rico, and Jamaica has a Mesozoic or pre-Mesozoic basement overlain by sediments and volcanics, the latter being dominantly island arc in character. Later granitoid intrusions were emplaced. Obduction of ophiolites also occurred variously from the mid-Cretaceous to the Palaeogene. Thick accumulations of limestones surround the older strata, along with Neogene and younger sediments. The Lesser Antilles islands form an arcuate chain, mainly of volcanic rocks of calc-alkali or sub-alkaline affinity with some younger limestones and siliciclastic sediments. Trinidad and Tobago have closer similarities with the South American continent in their geology. Tobago has a metamorphic complex, juxtaposed with a volcanic-plutonic complex, and limestones. Trinidad has very thick Cretaceous to Recent exposed sedimentary sequence. The current exploitation of industrial minerals in the Caribbean is dominated by construction raw materials (mainly sand and gravel, limestone, and cement), although there is extraction of gypsum, silica sand, marble, clay (almost entirely for construction use), pumice, and natural asphalt. Salt is obtained from solar evaporation of seawater. Limestone of high purity and high brightness, gypsum, pumice, and high-density igneous rock have potential for further development of their markets, particularly exports. Potential new and undeveloped industrial-mineral resources include residual and sedimentary kaolin, bentonite, zeolites, magnesite, and talc. Cuba could be a source for many industrial minerals in the future.

INTRODUCTION

The Caribbean islands are mainly independent nations. Those of the Greater Antilles (Fig. 1) make up the larger islands and comprise Cuba, Hispaniola (Haiti and the Dominican Republic), Puerto Rico, and Jamaica. Smaller islands include the Cayman Islands and the numerous islands of the Bahamas and the Virgin Islands; but a major part of the Caribbean is the Lesser Antilles island-arc chain, which includes the independent St. Kitts and Nevis, Antigua and Barbuda, Dominica, St. Lucia, St. Vincent, and Grenada as well as the French-owned Antilles of Guadeloupe and Martinique, and the British Crown Colonies of Montserrat and Anguilla. To the west of the chain lies the isolated island of Barbados, and immediately adjacent to the South American continent is the twin island Republic of Trinidad and Tobago. There are very considerable differences in the wealth and economic activities of the islands as illustrated in the approximate income per capita data of Table 1. Apart from Puerto Rico, which has virtually no mineral exploitation and is heavily subsidised from the United States, the Greater Antilles are relatively poor nations. Haiti is one of the poorest countries in the world. The Lesser Antilles have a greater wealth mainly generated through tourism. Through its oil production and associated manufacturing activities, Trinidad and Tobago has an overall higher income than several of the smaller countries. Some islands such as the Caymans and Bahamas gain their increased wealth through tourism or as havens for tax exiles. The English-speaking Caribbean countries are economically joined together through CARICOM, which encourages inter-island trade and natural-resource utilisation, including minerals.

Scott, P. W.; and Jackson, T. A., 1999, Industrial minerals in the Caribbean, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 319–328.

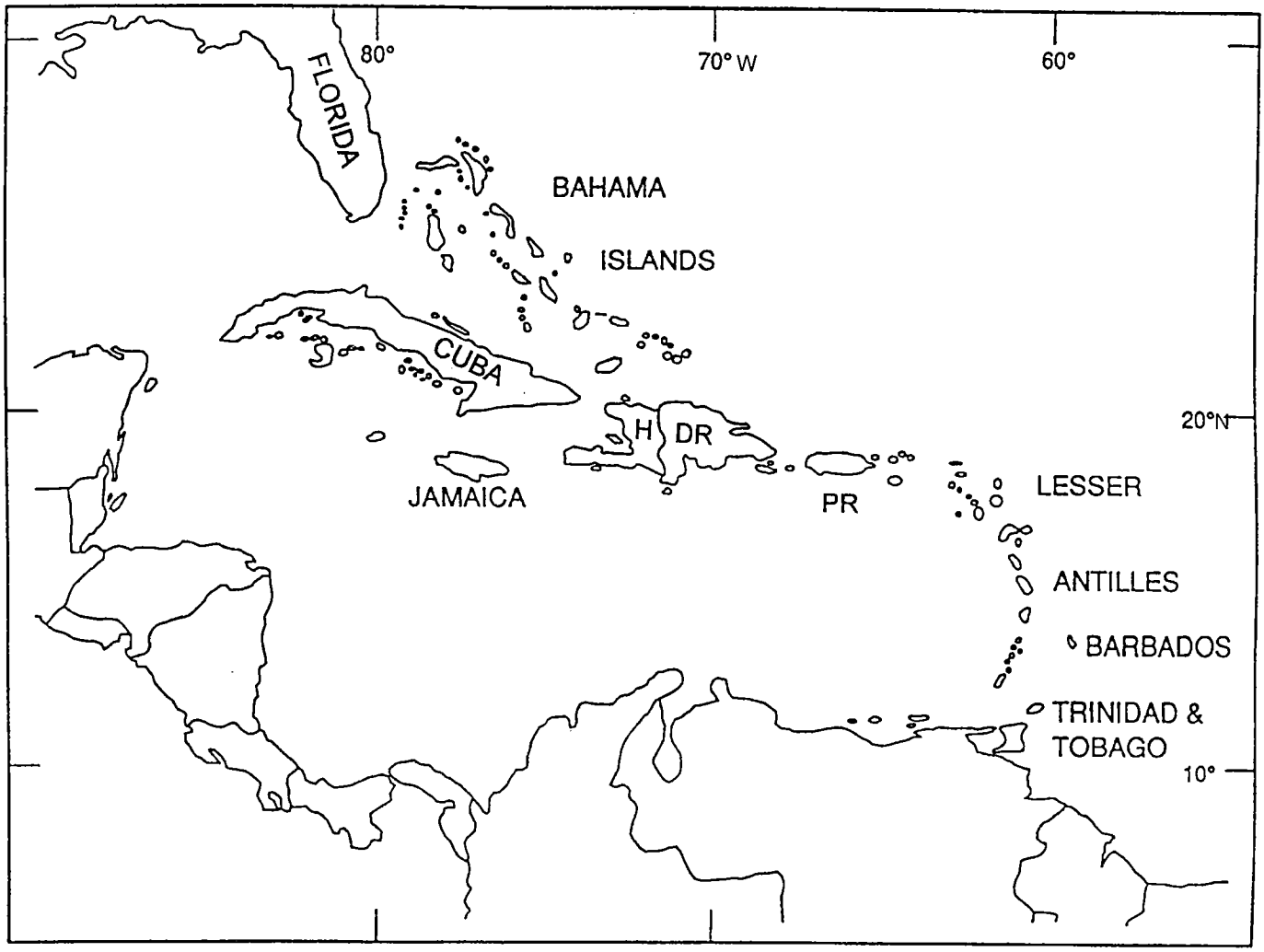


Figure 1. Map of the Caribbean showing the main islands: H, Haiti; DR, Dominican Republic; PR, Puerto Rico.

The purpose of this paper is to relate the industrial-mineral resources of the Caribbean islands to the geology, and to describe the current utilisation of the industrial minerals and the potential to supply new markets, including exports outside the Caribbean. The data have been obtained through literature searches; from the authors' visits to industrial-mineral operations on many of the islands; and through discussions with other academic, government, and independent personnel working on the islands. The data are accurate and up-to-date as far as possible, but for some islands and for Cuba in particular, much recent literature, maps, and other knowledge of the industrial-minerals resources are not readily available. The contents of the paper are inevitably somewhat biased toward the English-speaking, British Commonwealth parts of the Caribbean. The final part examines the geology of the Caribbean, especially Cuba; gives an indication of the industrial-mineral deposits; and suggests others that might occur and be worthy of exploitation. The islands on the northern margins of South America (e.g., Aruba, Bonaire, and Curacao) are excluded from this study, but it is known that Margarita Island, which is part of Venezuela, has deposits of magnesite (Abu-Jaber and Kimberley, 1992).

The geological setting of the major mineral resources of the Caribbean region, mostly metals and a few industrial minerals, are described in Kesler and others (1990). More detailed treatment of the industrial-mineral resources of the English-speaking Caribbean are found in Fenton and others (1984), Scott and Jackson (1994), and Drakapoulos (1996). Several descriptions of individual industrial-mineral deposits or resources in individual countries are found in Lyew-Ayee (1981), Drakapoulos (1991), and Lyew-Ayee (1997). Fenton (1981) describes the mineral resources of Jamaica, and Geddes (1985) and Henry (1997) give an overview of the industrial minerals. The development of industrial minerals in CARICOM countries is described in United Nations (1998). Tomblin and Tomblin (1985), Barker and Gordon (1987), and Marshall (1981, 1982) give details of the industrial-mineral resources of the Lesser Antilles, Barbados, and Trinidad and Tobago, respectively. A bibliography of published litera-

Table 1.—Approximate Income per Capita for Some Caribbean Islands

	$US
Greater Antilles	
Cuba	1,500
Haiti	200
Dominican Republic	1,500
Puerto Rico (U.S.)	10,700
Jamaica	1,300
Lesser Antilles	
Antigua	6,600
Martinique (France)	7,700
Dominica	2,700
St. Lucia	2,200
St. Vincent	1,800
Barbados	6,000
Grenada	2,400
St. Kitts and Nevis	3,100
Others	
Cayman Islands	29,300
Bahamas	11,600
Trinidad and Tobago	4,300

Note: Data from various statistical sources, dated 1995–96, and rounded to nearest $100.

ture and reports on the industrial rocks and minerals of Trinidad and Tobago is given in Salisbury (1992). Short descriptions of the industrial-mineral resources of Cuba are presented in Geologia y Mineria '98 (1998), including reference to a 1:500,000 map of the nonmetallic mineral resources of the country (Batista Gonzalez and others, 1998). Numerous other papers on individual industrial-mineral resources exist, and relevant ones are referenced in the text below.

GEOLOGY OF THE CARIBBEAN ISLANDS

The Greater Antilles islands of Cuba, Hispaniola, Puerto Rico, and Jamaica have a Mesozoic or pre-Mesozoic basement, mostly of deformed sedimentary and metamorphic strata of island-arc terrane, overlain by sediments and, rarely, younger volcanics. In Cuba, the older tectonic units throughout much of the island are composed of a complexly deformed orogen arising from the collision of a Cretaceous island arc with the Jurassic-Cretaceous sedimentary rocks of the Florida-Bahamas platform (Lewis and Draper, 1990; Draper and Barros, 1994). The different structural units contain a wide range of geosynclinal-type siliciclastic sediments, pelagic sediments, calc-alkali volcanics and quartz diorites, granodiorites and granites (Lidiak and Jolly, 1996), basic intrusives, and major units of limestones and dolomites. Metamorphic equivalents of some of these rocks are also represented as phyllites, schists, gneisses, migmatites, marbles, and calc-silicate rocks. They have both low temperature–high pressure (glaucophane-pumpellyite facies), and high temperature–medium pressure characteristics (garnet, mica, andalusite, kyanite, sillimanite, staurolite) in different parts of the island. Evaporites are common and commonly have diapiric structures. Oceanic crustal rocks were caught up in the collision and are now represented by major ophiolite units, containing significant serpentinised ultramafics and gabbros. In southeastern Cuba, the Sierra Maestra is characterised by a Cenozoic (Palaeocene to middle Eocene) volcanic-plutonic-arc complex. Middle Eocene to Recent, mainly undeformed post-orogenic sediments are siliciclastics and carbonates. They separate the older tectonic units. Figure 2 is a cross section through central Cuba, illustrat-

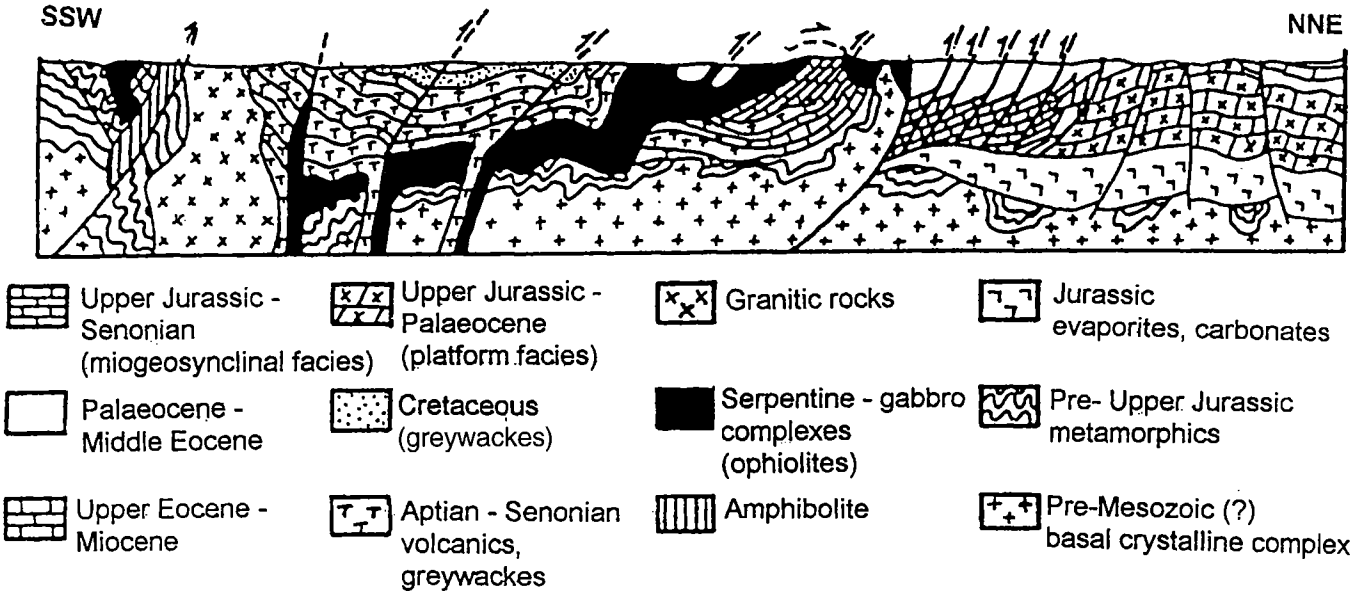


Figure 2. Sketch cross section of central Cuba illustrating the very varied geology of the island. Modified and simplified after Draper and Barros (1994). The section is approximately 75 km across.

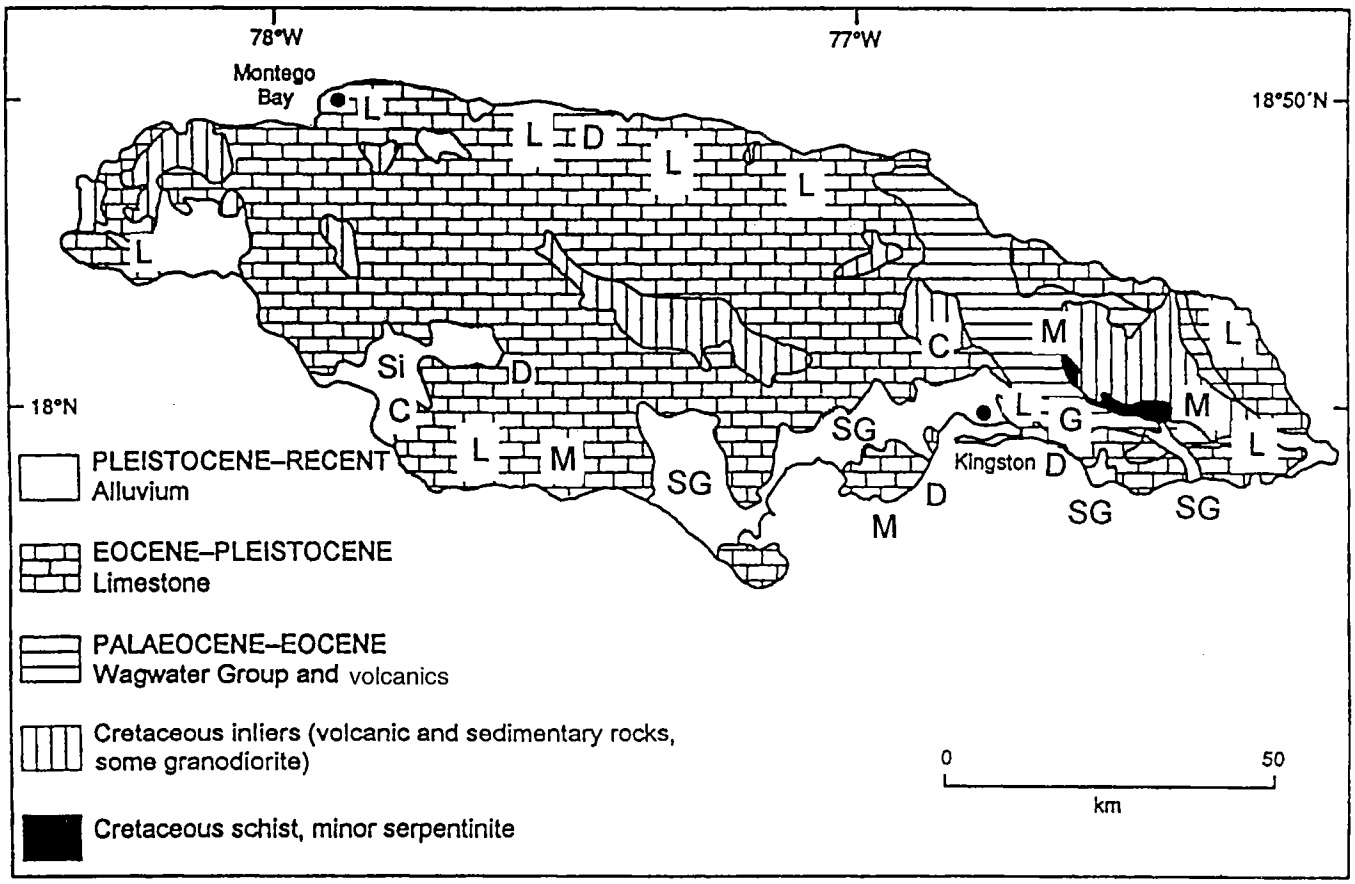


Figure 3. Simplified geological map of Jamaica showing locations of industrial mineral resources: L, limestone; D, dolomite; M, marble (including recrystallised limestone); G, gypsum; Si, silica sand; C, clay (kaolin); SG, sand and gravel.

ing the relationship between the different tectonic units.

Hispaniola contains a similar wide range of lithologies to Cuba, forming basement structural units of complex island-arc terranes separated by younger Neogene sediments. The older Cretaceous and pre-Cretaceous strata occur in belts of metamorphic rocks in the North Coast and Central mountainous parts of the island. They contain greenschists, greenstones, felsic metavolcanics, marbles, gabbros, and serpentinised peridotites of ophiolitic origin, along with other volcanics and volcaniclastics and late Cretaceous to early Tertiary granitoid plutons (Lewis and Draper, 1990; Draper and others, 1994). The southwest part of the island has a late Cretaceous oceanic plateau of basalts and intercalated sediments. Extensive pelagic limestones were deposited during the Eocene. Oligocene and younger Neogene and Recent sediments are of considerable thickness, sometimes many kilometres, and are siliciclastic, sometimes conglomeratic, and karstic and raised reef limestones. Puerto Rico and the adjacent Virgin Islands are similarly composed of a Mesozoic to Palaeogene deformed island-arc terrane separated by younger Tertiary (Oligocene-Miocene) limestones and Pliocene-Recent siliciclastic sediments. Lavas and volcaniclastic sediments intruded by granitoids occur in the central and eastern part of Puerto Rico. The southwest igneous zone of the island contains ophiolitic serpentinites, cherts, and amphibolite, along with lavas, volcaniclastic sediments, and limestones (Lewis and Draper, 1990).

The geology of Jamaica (Fig. 3; Robinson, 1994) is dominated by limestone of Tertiary age, separating older island-arc lavas, volcaniclastics, minor limestones, and granodiorites of Cretaceous age, some regionally metamorphosed strata, and a small disjointed ophiolite with serpentinised peridotites, gabbros, and basalts. The metamorphics and ophiolite occur only locally in the Blue Mountains. The older strata are exposed in erosional inliers throughout the island. A northwest-southeast–trending belt of thick (7 km) dominantly siliciclastic sediments, but also with some minor limestones and evaporites, and intercalated volcanics occurs as a fault-bounded half-graben structure. Pliocene, Pleistocene, and Recent limestones dominate the northern coastal part of the island, whereas the youngest sediments along the south coast are sand-and-gravel alluvium and minor associated clays.

The smaller islands of the Lesser Antilles form an arcuate chain extending southward to the South American continent. The chain splits into two in the

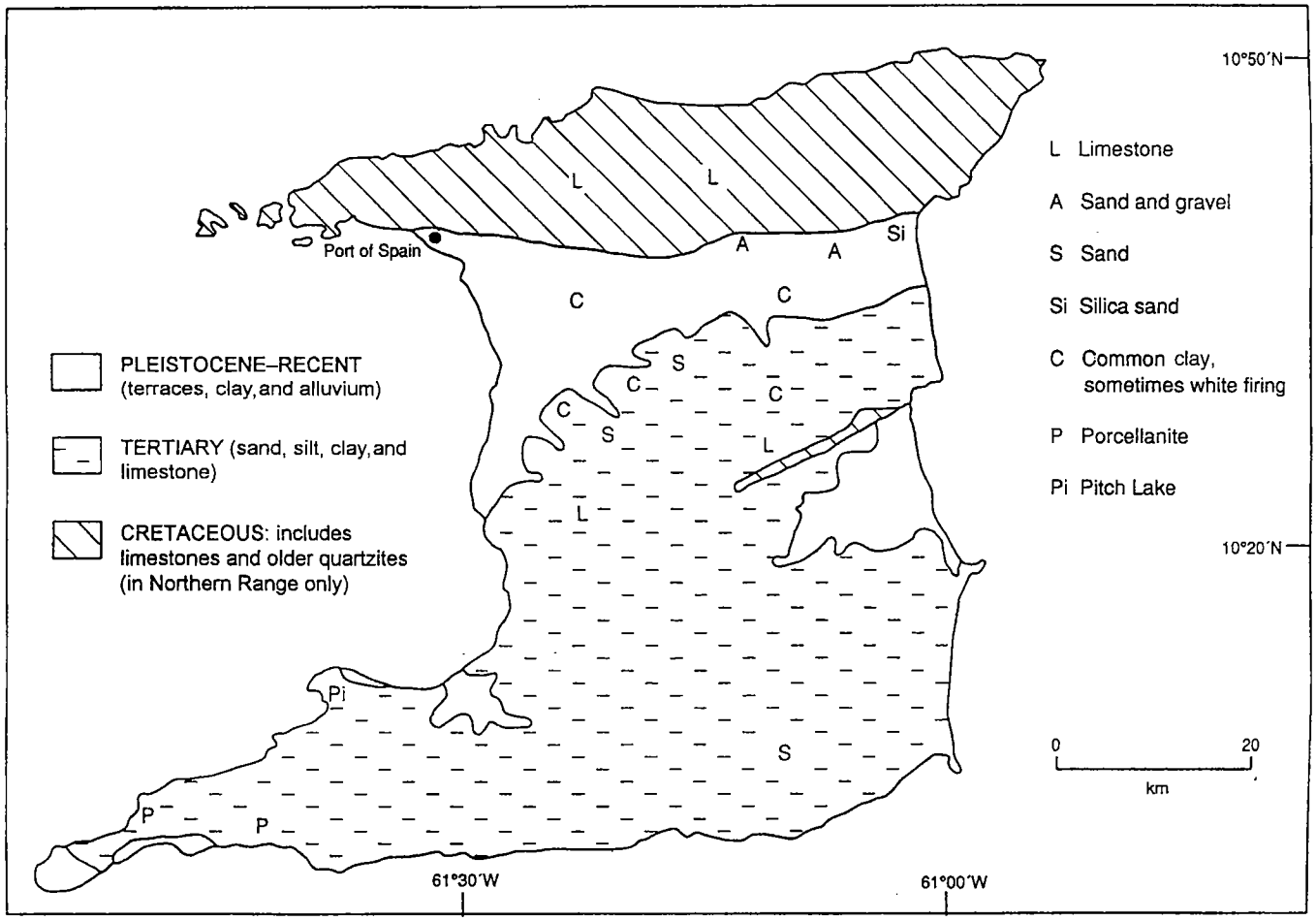


Figure 4. Simplified geological map of Trinidad showing location of industrial-mineral resources. After Scott and Jackson (1994).

northern part giving rise to the so-called Limestone and Volcanic Caribees. The Limestone Caribees includes the islands of Anguilla, St. Marten, Barbuda, Antigua, and the eastern part of Guadeloupe, the strata being dominated by Cenozoic limestones overlying older volcanics. The Volcanic Caribees includes Saba, St. Kitts, Nevis, Montserrat, the western part of Guadeloupe, Dominica, Martinique, St. Lucia, St. Vincent, the Grenadines, and Grenada. Igneous rocks are almost exclusively present (Wadge, 1994). The volcanics range through Mg-rich alkaline basalts to tholeiitic calc-alkaline basalts, andesites, dacites, and rhyolites. Air-fall and ash-flow pyroclastics are common, and there has been much reworking of the volcanic material into thick alluvial sediments both between separate volcanic episodes and after cessation of activity. Some islands (e.g., Montserrat) still have active volcanic centres. Barbados differs geologically from the other islands. It evolved as an accretionary prism and is the only exposure above sea level of the Barbados Ridge, which is east of and separate from the magmatic arc. The island is dominately made of Pleistocene coral reef deposits, but, beneath these and exposed over about a quarter of the island's area, are radiolarian marls, intercalated with ash bands of Eocene age, and a quartzose-sandstone- and mudstone-turbidite sequence (Scotland Formation). These older sediments have undergone polyphase deformation, but are essentially unmetamorphosed (Ladd and others, 1990).

Trinidad and Tobago have closer similarities with the geology of the northern margins of the South American continent than the rest of the Caribbean. In Tobago, basement strata of greenschist-facies metavolcanics, possibly of oceanic island-arc setting, mica schists, quartzites, and phyllites, together with minor graphitic schists and cherts, form the basement (Jackson and Donovan, 1994). These strata are in faulted contact with an ultramafic-gabbro-diorite intrusive suite (Frost and Snoke, 1989). A volcanic group of basalt and andesite flows, volcaniclastic breccias, and tuffs overlies the basement strata and is intruded by a suite of ultramafic gabbro-diorite intrusives. Neogene sandstones, conglomerates, and limestones complete the sequence. In Trinidad (Fig. 4; Donovan, 1994), a northern range of hills includes low-grade metamorphosed limestones, phyllites, and quartzites with minor volcanics. The remainder of the island contains a small amount of Upper Cretaceous siliciclastic sediments and limestones, but mainly is made of a thick sequence of

Tertiary and Quaternary sandstones, mudstones, clays, gravels, and some limestones that are deformed in series of thrust faults and fold belts, cut by a number of major strike-slip faults, and disrupted by mud diapirism in places.

CURRENT EXPLOITATION OF INDUSTRIAL MINERALS

The islands of the Greater Antilles have the most varied geology, and thus the presence of industrial minerals in suitable quantities for exploitation might be expected to be much greater compared with the smaller islands. This may be the case and is discussed below, but the extent of exploitation does not reflect this situation. For example, there appears to be virtually no extraction of industrial minerals in Puerto Rico other than of construction materials and cement manufacture, and some salt and lime production. In Cuba, there is extraction of chromite from ultramafic rocks, gypsum, and salt (British Geological Survey, 1995). Although not shown in international statistics, it is likely that industrial minerals other than construction materials, such as clay for ceramics and limestone for lime, are exploited in small amounts to supply the country's self-sustaining industries. In the Dominican Republic, limestone is exploited for cement and lime; and gypsum and salt are extracted. There is some nonmetallurgical use of the country's bauxite. Cement is produced in Haiti (22.3×10^3 tonnes in 1992–93), and there is further extraction of limestone and marble.

A summary of the mineral-based industries of Jamaica, Trinidad and Tobago, and the Lesser Antilles is given in Table 2. The sugar industry is included as it is important in several islands and consumes lime. Alumina production from bauxite is important in Jamaica, also using lime. Although Jamaica is a major producer and exporter of bauxite, it is high in Fe_2O_3, and has no uses other than for Bayer alumina and aluminum production. Many of the industries in Table 2 are at least partly supplied by local industrial minerals, and there is some interisland trade in industrial minerals. For examples, limestone from Barbados is exported for glass making in Trinidad; gypsum from Jamaica supplies the Trinidad cement industry; cement from Trinidad supplies much of the Lesser Antilles, as does lime from Jamaica and Barbados. Table 2 lists the current exploitation and uses of industrial minerals in these countries and Barbados, and the locations of industrial-mineral deposits in Jamaica and Trinidad are shown in Figures 3 and 4.

The use of industrial minerals is dominated by the construction industry, which in Jamaica and the Lesser Antilles has increased considerably in recent years with the expansion of tourism. Sand and gravel in Jamaica is exploited mainly from active river-channel deposits in the major rivers draining to the south coast. Their petrography is dominated by volcanic and volcaniclastic rocks and limestone in the centre part of the island and by volcanic and metamorphic rocks with minor plutonics (including gabbro and serpentinite) and limestone in the rivers draining the Blue Mountains in the east of the island. The silica-sand deposit in the west of Jamaica is Recent fine-grained alluvium, interbedded with clay (West-Thomas, 1989). The Tertiary limestones are the other major source of aggregate in Jamaica. In Trinidad, sand-and-gravel deposits are quartzite rich, forming as Pleistocene terraces on the lower lying areas immediately to the south of the Northern Range of mountains, which provided the source area. The silica sand, most likely, has a similar origin. Sand-and-gravel deposits in the Lesser Antilles are mostly reworked volcanics. Basaltic scoria provides a useful uniform-sized, dense, hard aggregate in some islands (Rajpaulsingh and Scott, 1997). Pumice is much used for concrete-block making where it is available,

Table 2.—Industrial Minerals in Jamaica, Trinidad, and the Lesser Antilles

(A) Existing Mineral-Based Industries

Jamaica:	Construction, cement, alumina, glass, ceramics (local craft pottery), (sugar)
Trinidad:	Petroleum/petrochemicals, construction, cement, steel, glass, ceramics (craft pottery, bricks and tiles)
Lesser Antilles:	Construction, (sugar)

(B) Current Exploitation of Industrial Minerals

Jamaica:	Sand and gravel (construction) Crushed rock (limestone) (construction) Limestone (cement, lime, export) Gypsum (cement, alabaster carvings, export) Silica sand (glass, abrasive, filtration) Marble (mainly recrystallised limestone) (dimension stone) Common clay (cement) Kaolin clay (minor use for artisan and craft pottery) [Bauxite (Bayer alumina and aluminum only)]
Trinidad and Tobago:	Sand and gravel (construction) Crushed rock (limestone, quartzite, porcellanite, volcanic rock in Tobago) (construction) Limestone (cement) Silica sand (glass) Common clay (bricks, tiles, artisan pottery when off-white or white firing) Natural asphalt (bitumen, construction)
Lesser Antilles:	Sand and gravel (construction) Crushed igneous rock (construction) Limestone (construction, lime) Scoria (construction) Pumice (construction, export) Common clay (bricks, tiles) Salt (food preservation and domestic)
Barbados:	Sand (construction) Limestone (construction, cement, lime) Clay (bricks, tiles, artisan pottery)

and it is exported. Sand from beaches, mostly but not exclusively volcanic in origin, has been used traditionally as a source of fine aggregate in the smaller islands. Extraction from this source has now mostly ceased, although older carbonate beach sand from behind the present beach is extracted in Antigua. Extraction of sand from beaches has created oversteepening and erosion in some of the smaller islands.

Cement production in Jamaica is based on the relatively pure limestone from the Tertiary Newport Formation calcined with shales from the Wagwater Group located some distance away (as far as 25 km) from the works. In Trinidad, the limestones of the Miocene Guaracara Formation, which have a variable purity, are blended to give the correct composition for the cement kiln. Unlike much of the Caribbean, Trinidad produces clay bricks and tiles from Pliocene red-firing clays. White-firing clays are used only in very small amounts by local potters for artisan and craft ware.

The gypsum in Jamaica is part of the Palaeogene Wagwater Group. It is much disjointed by faulting into several separate worked areas. It is associated with anhydrite, which occurs as cores to lenses of gypsum (Blackwood, 1997) and some limestone. The marble industry in Jamaica is mostly based on pale-grey to white recrystalised limestone of the Tertiary Newport Formation, although some true marbles of varying colours and textures are present and exploited in the Blue Mountains.

Porcellanite is a naturally burnt clay occurring mainly in the southwest of Trinidad. It is used as an aggregate (Mootoo and Suite, 1992), because other suitable hard rocks are lacking in that part of the country. In concrete mixes, it imparts some additional strength through its pozzolanic properties. The natural asphalt, found in the famous Pitch Lake in Trinidad, and other bituminous sands are used extensively on roads in the country. Bitumen is extracted from the Pitch Lake and is exported. Salt is obtained from solar evaporation of seawater in some of the islands of the Lesser Antilles and in the Bahamas (British Geological Survey, 1995).

In Barbados, limestone is mostly of high purity. It is used for dimension stone, as an aggregate, and, more recently, for cement production and for lime (Barker, 1997). Sand and clay are extracted from the Scotland Formation.

FUTURE POTENTIAL FOR INDUSTRIAL MINERALS IN THE CARIBBEAN

The two aspects to be considered here are, first, the development of markets for the known resources, and, second, the potential for finding new deposits of industrial minerals, both for indigenous manufacturing industries and for export. All of the industrial minerals currently exploited are low-value commodities, where transport is a significant proportion of the cost to the consumer. However, the Caribbean islands have an advantage over many inland continental areas in that all the existing and potential industrial-mineral resources are near a coastline. Sea transport by container or bulk carrier from the Caribbean is a relatively cheap way of taking raw materials to the eastern and southern seaboards of North America. If the industrial minerals can meet the required specifications in terms of quality and quantity, they should be able to compete with many other North American sources of similar minerals.

Table 3.—Industrial Minerals in the Caribbean with Potential for Market Development

Limestone	High-purity white limestone from Jamaica, Cuba, Haiti, Barbados
Gypsum	Jamaica, Cuba, Dominican Republic
Pumice	Dominica, St. Lucia, Martinique, Guadeloupe
Igneous rock	High-density basalts from Grenada, St. Vincent, St. Lucia, and other small islands

Four industrial minerals that are currently exploited and have potential for market development (Table 3) are limestone, gypsum, pumice, and high-density igneous rock. Much of the limestone in Jamaica, Haiti, and Barbados is pale grey to white in colour and of high purity and brightness. Measured properties of some in Jamaica and Haiti show >98% $CaCO_3$ and powder dry brightness >92% (Henry and others, 1991; Michel and others, 1991; Henry 1997). A substantial investment (Anonymous, 1998) currently is being made to develop a ground-calcium-carbonate plant in Jamaica to produce white-filler and glass-grade limestone products. Production of gypsum and exports from Jamaica have increased considerably in recent years (82,000–204,000 tonnes produced between 1990 and 1994; British Geological Survey, 1995); but, as the occurrence of gypsum is quite localised and disturbed by faulting, the total resource may not be extensive. However, the geology of Cuba indicates that substantial resources of gypsum could be present in that country. The same may be true for Hispaniola. The estimated rate of extraction of gypsum in Cuba in recent years is quite low (125,000 tonnes per annum, British Geological Survey, 1995). Pumice is available in large quantities in the Lesser Antilles islands where acid volcanism dominates, such as Dominica and St. Lucia. The French Antilles, Martinique, and Guadeloupe have exported significant amounts (250,000 tonnes) annually. Those islands where there are large volumes of fresh olivine and pyroxene phyric basalts at the surface, such as in Grenada and St. Vincent, have potential to provide high-density blocks of igneous rock for use as armour stone (e.g., Rajpaulsingh and Scott, 1997) for coastal protection in low-lying areas, such as the U.S. states bordering the Gulf of Mexico.

The available literature on the geology of the Caribbean islands can be used to indicate potential undeveloped resources of industrial minerals. Also, knowledge of the geological setting can be used in a predictive mode to suggest the presence of others. Industrial min-

Table 4.—Potential Undeveloped and Predicted Industrial Mineral Resources in Some Caribbean Islands

Cuba (Batista Gonzalez and others, 1998; Perez Nevot and others, 1998)

Silica sand and vein quartz (Leyva Rodriguez, 1998), bentonite (Rueda Lopez and others, 1998), limestone, dolomite, marble, phosphate, palygorskite, semi-precious stones (Coutin and Nagy, 1976), kaolin, magnesite (residual), zeolites (Borrero Guevara and others, 1998), pumice and pozzolan (Coutin and others, 1976; Coutin and Torres, 1998), feldspar (Coutin Correa and Pantaleon Vento, 1976), talc, asbestos (chrysotile and amphibole) (Coutin and others, 1998), barite, garnet, serpentine, olivine (Leyva Rodriguez and others, 1998), graphite, mica (Montejo Serrano and others, 1998), salt, wollastonite (Fattah, 1994), diatomite (Nagy and Coutin, 1976), andalusite (p), chromite (Gonzalez Ponton, 1998; Munoz Gomez, 1998), Fe and Mn oxide pigments (p)

Hispaniola (mainly Dominican Republic)

Kaolin (residual and sedimentary) (p), bentonite (p), chromite (p), magnesite (p), talc (p), alunite (p), limestone (Michel and others, 1991)

Puerto Rico (Cadilla, 1966)

Kaolin for ceramics (sedimentary and residual), bentonite, feldspar, quartz, mica, gypsum, bat guano (phosphate)

Jamaica (Drakapoulos, 1996)

Kaolin (residual and sedimentary) (Hill, 1978), dolomite, bentonite (p), heavy mineral sands (Geddes, 1981), marble (Busby, 1985)

Lesser Antilles (Tomblin and Tomblin, 1985; Fenton, 1991)

Bentonite (p), zeolites (p), sulphur, alunite (p), barite (Antigua)

Trinidad and Tobago

Kaolin (sedimentary)

Note: A reference following the country name refers to a publication with information on several industrial minerals. Where the reference follows a mineral name it refers specifically to that mineral. (p) refers to a prediction that the geological setting indicates the likely presence of the industrial mineral but no reference is found in the literature. A list of the Caribbean Geological Conferences up to and including the 11th, is given in Draper and Dengo (1990). Rocks used solely for low value construction uses are excluded.

erals in these categories are given in Table 4, along with the bibliographic sources of information, where appropriate. Many of these industrial minerals may be no more than "mineral occurrences" and some others may provide only minor amounts of mineral product for low-value uses. However, some appear to have real potential for development and are at least worthy of further investigations.

Deposits of residual kaolin worthy of exploitation, arising from the deep tropical weathering of granodiorites and related acid intrusions, may exist in Jamaica, Cuba, Dominican Republic, and Puerto Rico. In Jamaica, 4–6 m of intensive kaolinisation, giving a variable, but commonly white kaolin, occurs over the Above Rocks Granodiorite, to the northwest of Kingston, which is the largest intrusion in the country. However, because of the high rate of physical erosion, which gives a very rugged topography, the kaolin is restricted to the ridges of hills. In Cuba and the Dominican Republic, where the topography is generally less severe, more extensive deposits of residual kaolin might be present. Sedimentary kaolin derived mainly from weathered intermediate- and acid-plutonic rocks likely are to be found in inland drainage basins in Jamaica, Cuba, Hispaniola, and Puerto Rico.

There is presently no source of bentonite in the Caribbean region, and zeolite deposits are reported only from Cuba. This is surprising because of the abundance of volcanic ash and tuff. These make ideal source rocks for alteration to bentonite and zeolites, as in the Aegean Islands, Greece, which are of similar age and are host to substantial quantites of both minerals. The most likely places for bentonite to be found in commercial quantities are in Cuba, Dominican Republic, Jamaica, and the smaller islands, such as Martinique, St. Lucia, and St. Vincent, where hydrothermal alteration associated with the volcanism might have caused bentonitisation. Alunite might similarly be present, and alunite may also be associated with the epithermal gold mineralisation in the Dominican Republic.

The ultrabasic rocks in the ophiolite complexes of Cuba, Hispaniola, Puerto Rico, and Jamaica may be sources of magnesium-rich minerals such as magnesite and talc; however, a detailed study by the authors of the small area of serpentinised ultramafic rocks in Jamaica did not find any of these minerals. It is likely that Cuba with its very diverse geology, as illustrated in Figure 2, has the potential to be a source for several more industrial minerals in the future.

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Investment Opportunities in Industrial Minerals for Small- to Medium-Scale Operations in Chile

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ABSTRACT.—Because of the Chilean Ministry of Mining's interest in the development of industrial minerals, the Chilean Geological and Mining Service (Servicio Nacional de Geología y Minería, SERNAGEOMIN) has carried out a research program during the last two years to identify projects that represent interesting investment opportunities for small- to medium-scale operations in Chile.

Most important of these projects are: (1) Quebrada Lluta aluminum sulphate, for drinking- and industrial-water treatment, with a potential domestic and foreign market of almost 43,000 tonnes per year and investments of about US$1.8 million; (2) Quebrada Lluta–Quebrada Cardones pumice, for abrasives, filters, fillers, and lightweight aggregates, with a potential market of about 30,000 tonnes per year, and investments of US$2.0 million; (3) El Maule dolomite, for soil conditioner and iron smelting, with a total potential domestic market of some 60,000 tonnes per year, and estimated investments of US$2.0 million; (4) Las Escaleras bentonite, for animal feed, pelletising, and oil absorbents, with a potential market of almost 6,000 tonnes per year, and investments of about US$2.4 million; (5) Laraquete-Carampangue andalucite, for alumina refractories, with a future total domestic and foreign demand of about 15,000 tonnes per year, and estimated investments of US$2–2.5 million; (6) Río Lía garnet, for fillers and sand-blasting abrasives, whose domestic market represents 10,000 tonnes per year, with investments of US$2.3 million; and (7) Munilque pumice, for building bricks and panels, with a potential domestic market of 250,000 tonnes per year, and investments of US$1.4 million.

The development of these projects will represent an important increase and a significant diversification in Chilean industrial-minerals production.

INTRODUCTION

Due to the remarkable development of industrial-minerals-mining activity in Chile in the last 10 years, production and export volumes have grown 122% and 117%, respectively, between 1988 and 1997. The value of this production also has increased from less than 5% of the total income of Chilean mining activity to almost 10% in the same period.

Nevertheless, this panorama is related mainly to the industrial-mining activity in medium- to large-scale operations in Chile, represented by chemical/industrial and construction sectors. The former sector, comprising the producers of saline industrial minerals, accounts for more than 97% of industrial-minerals exports (Comisión Chilena del Cobre, 1997). The latter sector accounts mainly for limestone, clays, gypsum, and pumice used for cement products and wallboards manufacture. These are the main industrial minerals produced and consumed in Chile (Servicio Nacional de Geología y Minería, 1997).

On the other hand, mining activity of small- to medium-scale operations has grown at a very slow rate, due to more-or-less restricted domestic markets, related mainly to manufacturing and agribusiness sectors. Even though, these industrial activities, combined with the mining metallurgy and chemical sectors, demand the greatest variety and quality of industrial minerals, amounting to some 27 different minerals.

Consequently, the Chilean Ministry of Mining is interested in investigating deposits of domestic industrial minerals that are a suitable supply for the various industrial sectors, and encouraging the economic development of small- to medium-scale mining companies in the country. Therefore, the Industrial Minerals Section of the Chilean Geological and Mining Service, during 1996 and 1997, conducted a research program to iden-

Gajardo, Anibal, 1999, Investment opportunities in industrial minerals for small- to medium-scale operations in Chile, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 329–335.

tify different investment opportunities for this type of company (Gajardo, 1997). This program is based on projects done in 1993 (Gajardo and Gutiérrez, 1993) and in 1997 (Gajardo and Carrasco, 1997; Gajardo and others, 1997).

INVESTMENT OPPORTUNITIES

Definition of these investment opportunities is based on geological, technological, and economical information gathered during the program development. Nine projects whose required investments are less than US$3 million were identified (Figs. 1–3), with the seven most important projects described below. Projects are related to aluminum sulphate for drinking- and industrial-water treatment; pumice for abrasives, filters, fillers, and lightweight aggregates; dolomite for soil conditioner and iron smelting; calcium bentonite for animal feed, pelletising, and oil absorbents; andalusite for alumina refractories; garnet for sand-blasting abrasives and filtration; and pumice for building bricks and panels. Projects dealing with perlite for lightweight aggregates and combarbalite for refractory clays are not described.

Development of these projects requires private investment to determine the reserves, quality of the minerals, processing techniques, and detailed market demands. Once in production, they will supply domestic and foreign requirements for high- to medium-value industrial minerals.

Quebrada Lluta Aluminum Sulphate Project

Production of aluminum sulphate for drinking- and industrial-water treatment and for paper and pulp production is the main objective of this project. The project utilizes water-soluble alunogen deposits located some 44 mi east of Arica, I Región (Fig. 2; Table 1) and is based on regional, national, and foreign demand—the latter mainly from neighboring countries, due to location of the project area (Fig. 1). Domestic demand will represent some 25,000 tonnes per year, according to increasing paper and pulp production. Foreign demand, mainly from Bolivia, is expected to be around 18,000 tonnes per year (Gajardo, 1997; Gajardo and others, 1997).

The basic process consists of leaching, filtration, fractioned crystallization, and natural drying; the latter two steps utilize solar energy. Required investments are about US$1.8 million (Guarachi, 1995). Substitution of aluminum sulphate and alumina imports plus the creation of an industrial-mining activity in an economically depressed area are the main benefits of this project for the regional and national economies.

Quebrada Lluta–Quebrada Cardones Pumice Project

Production of abrasives, filters, and fillers is the main objective of this project. A second objective is the production of lightweight aggregates. It is based on large pumice deposits located in Quebrada Lluta–Quebrada Cardones, 19–63 mi east of Arica, I Región (Fig. 2; Table 1), and on a growing domestic and foreign market demand, especially from the United States. This demand is due to environmental regulations that will reduce U.S. domestic production, thus increasing the need for imports (Gajardo, 1997; Gajardo and others, 1997).

The U.S. demand is about 600,000 tonnes per year, and the average import is some 200,000 tonnes per year, with the main imports coming from Greece (85%), Ecuador (7%), and Turkey (6%). Average price is around US$25 per tonne (U.S. Geological Survey, 1997). Location of these Chilean pumice deposits close to the sea, and thus closer to the U.S. Pacific Coast, represents a great advantage over the other exporting countries, including Ecuador, whose deposits are located more than 150 mi from the seaport.

The basic process is grinding and classification, and total investments are: US$2.0 million for an abrasives, filler, and filter plant, with a production capacity of 5,000 tonnes per year; and US$1.3 million for a lightweight-aggregate plant, with a capacity of 1,500 tonnes per year (Corporación de Fomento de la Producción, 1995). Creation of an industrial-mining activity in the Arica area and additional production of a commodity exploited mainly for cement manufacture are the main benefits of this project.

El Maule Dolomite Project

Production of soil conditioner and flux for iron smelting is the objective of this project. The project is based on a known dolomite deposit, located some 67 mi southeast of Talca, VII Región (Fig. 3; Table 1), and on a domestic demand of some 8,000 tonnes per year for soil conditioner, and some 52,000 tonnes per year for iron smelting (Garjardo, 1997; Gajardo and Carrasco, 1997).

The basic process is crushing, grinding, and classification, and investment for producing soil conditioner has been estimated at less than US$2.0 million. An increase in regional production and an alternative mining activity are the main benefits of this project.

Las Escaleras Bentonite Project

Production of calcium bentonite for the agribusiness is the main objective of this project. The second objective is to supply bentonite for foundry molds and fishmeal pelletiser. The project is based on a deposit with about 600,000 tonnes of calcium bentonite and fuller's earth, located 29 mi east of Chillán, VIII Región (Fig. 3; Table 1). It is hoped to serve regional and national demands, both current and potential, for animal feed, pelletising, and oil absorbents. These demands could amount to some 6,000 tonnes per year, valued at US$100–300 per tonne (Gajardo and Gutiérrez, 1993; Gajardo, 1997).

The basic process is grinding and classification, and the total investment for a 25,000-tonne-per-year plant is US$2.4 million (Corporación de Fomento de la Producción, 1995). Access to developing national markets, creation of a new mining activity in the southern

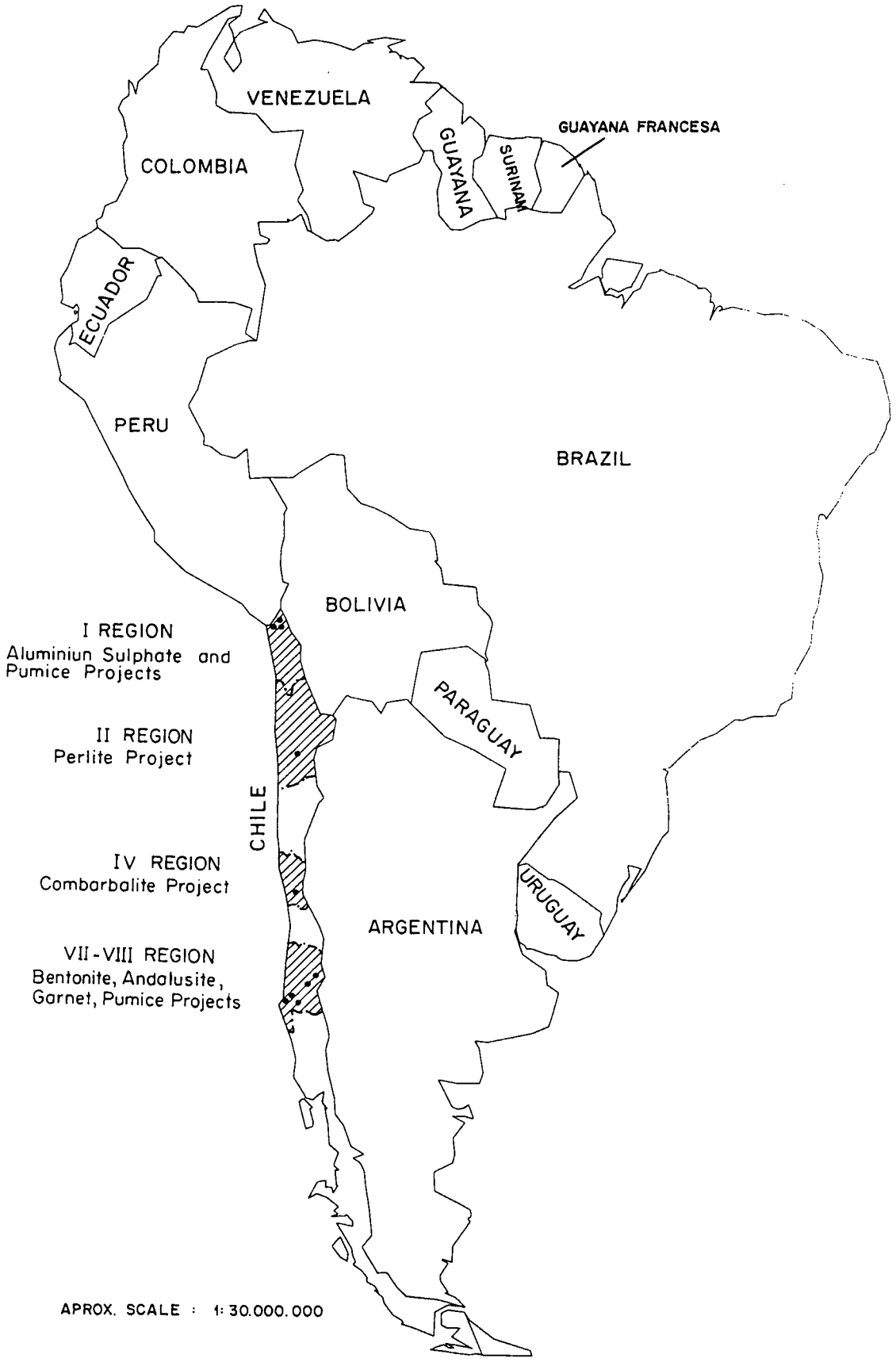


Figure 1. General location of investment-opportunity projects for industrial minerals in Chile.

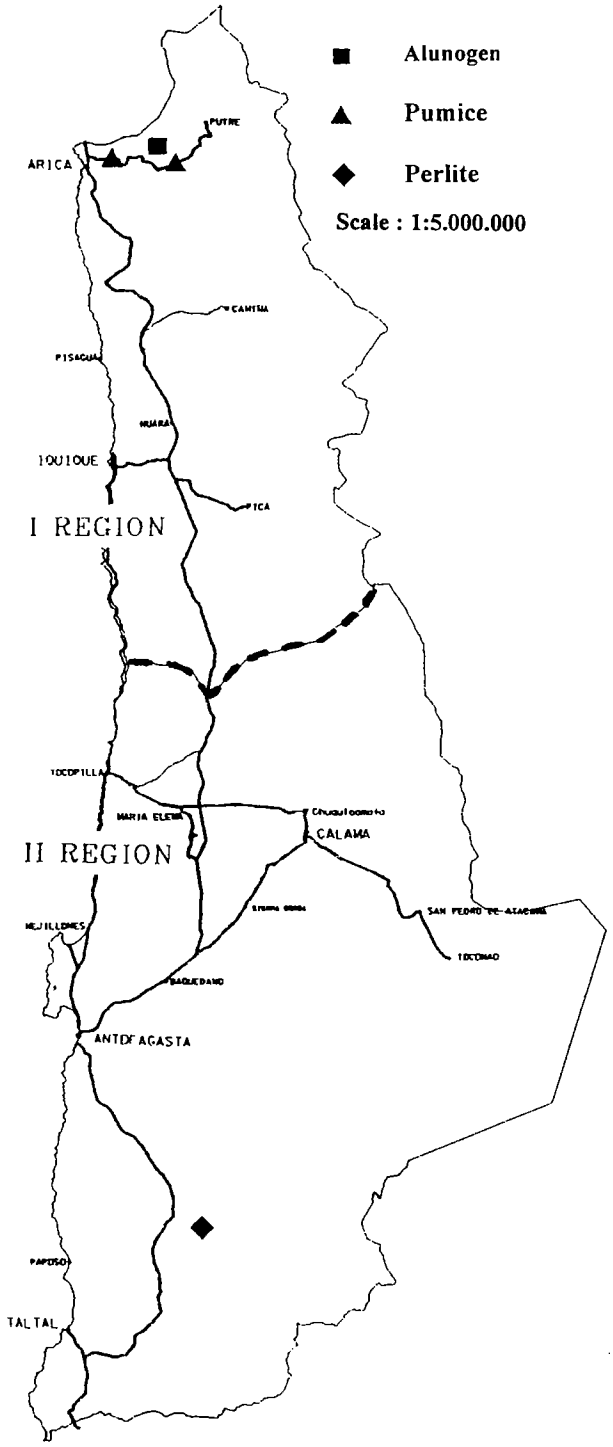


Figure 2. Maps showing selected industrial-mineral projects in I and II Regións of northern Chile.

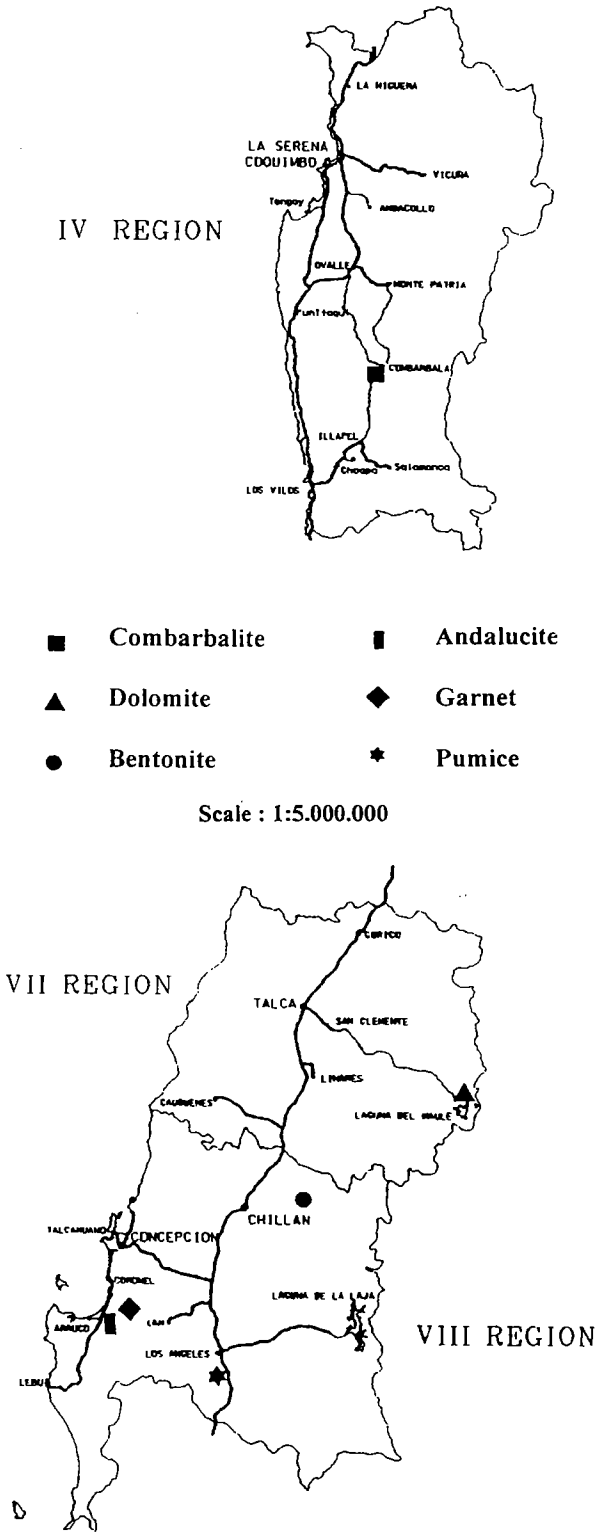


Figure 3. Map showing selected industrial-mineral projects in IV, VII, and VIII Regións of central Chile.

Table 1.—Main Characteristics of Industrial-Minerals Deposits for Small- to Medium-Scale Operations in Chile

Project	Location	Geology, morphology	Chemical composition	Mineralogic composition	Physical properties	Estimated reserves	Current situation
Quebrada Lluta Alunogen	44 mi NE of Arica, I Región	Hydrothermal veins and irregular bodies	60% $Al_2(SO_4)_3 \times 18\ H_2O$ 6% $MgSO_4$	Alunogen (60%)	Not applicable	>1,000,000 tonnes	Shut down
Quebrada Lluta–Quebrada Cardones Pumice	19–63 mi E of Arica, I Región	Volcanic, irregular bodies	74% SiO_2 12% Al_2O_3 1.2% Fe_2O_3	Volcanic glass	Particle size = 25–33% between 0.5 and 2.0 mm	Tens of millions of tonnes	Prospect
El Maule Dolomite	67 mi NE of Talca, VII Región	Sedimentary, stratiform	16–20% MgO 5–7% SiO_2 3–11% Fe_2O_3	Not applicable	Not applicable	>1,000,000 tonnes	Shut down
Las Escaleras Bentonite	29 mi E of Chillán, VIII Región	Sedimentary, stratiform	56–61% SiO_2 19–20% Al_2O_3 1.5–3.5% CaO 0.05% Na_2O	Montmorillonite, volcanic glass	Particle size = 47–60% 2μ, 62–77% 45μ; Density = 0.8–0.95	>600,000 tonnes	Prospect
Laraquete-Carampangue Andalucite	38 mi S of Concepción, VIII Región	Sedimentary, placer --- Metamorphic, irregular body	39–41% SiO_2 48–51% Al_2O_3	Andalucite = 5–20%; also biotite, muscovite	PCE = 35 Particle size: 21–44% <1 mm	30,000 tonnes --- 1,000,000 tonnes	Prospect
Río Lía Garnet	32 mi S of Concepción, VIII Región	Sedimentary, placer	Not applicable	Almandine = 3–19%	Particle size = 95% between 0.5 and 2.0 mm; Hardness = 7.5 Mohs	>50,000 tonnes	Exploitation
Munilque Pumice	94 mi SE of Concepción, VIII Región	Volcanic, stratiform	67–75.7% SiO_2 13–14% Al_2O_3	Volcanic glass, feldspar	Particle size = 41–75% 20–40μ; 17–37% 6.3–20μ; Density = 1.3–1.4	2,500,000 tonnes	Prospect

Table 2.—Investment Opportunities for Small- to Medium-Scale Operations in Chile

Project	Objective	Foundation	Demand	Price	Basic processes	Total investment
Quebrada Lluta, Aluminum Sulphate, I Región	Aluminium sulphate production for drinking- and industrial-water clarification	• Alunogen (water soluble) deposits in Quebrada Lluta, 44 mi E of Arica • Intensive use of solar energy • Demand is for domestic and Bolivian markets	25,000 tonnes/year Chile; 18,000 tonnes/year Bolivia	Domestic = US$64–255/tonne Import = US$450–5,000/tonne	Leaching, filtration, fractioned crystalization, natural dry	US$1.8 M
Quebrada Lluta–Quebrada Cardones Pumice, I Región	Abrasives, filters, and fillers production	• Large pumice deposits in Quebrada Lluta–Quebrada Cardones, 19–63 mi E of Arica • Growing U.S.A. markets, because of environmental regulations	U.S.A. import demand is some 200,000 tonnes/year; 6–20% could be captured from Ecuador, Turkey, and Zaire	Domestic = US$90/tonne Import = US$130/tonne	Grinding, classification	US$2.0 M
El Maule Dolomite, VII Región	Soil conditioner and flux production	• Dolomite deposit of appropriate quality, some 67 mi E of Talca • Soil-conditioner in acid soils of southern Chile, and flux material for smelters	• Soil conditioner demand is some 8,000 tonnes/year • Smelter demand is some 52,000 tonnes/year	Soil-conditioner domestic price is about US$80–84/tonne; import price (Argentina) is US$43–44/tonne	Crushing, grinding, classification	US$2.0 M (estimated)
Las Escaleras Bentonite, VIII Región	Calcium bentonite production, mainly for animal feed	• Ca Bentonite deposit in Las Escaleras ranch, 29 mi E of Chillán • Interesting potential markets for animal feed, pelletising, and oil absorbent, mainly in southern Chile	6,000 tonnes/year	Domestic = US$150/tonne	Grinding, classification	US$2.4 M
Laraquete-Carampangue Andalucite, VIII Región	Andalucite production for refractory bricks	• Primary and secondary andalucite deposits with adequate quality, 38 mi S of Concepción • Interesting current and potential domestic and foreign refractory markets	5,000 tonnes/year in Chile; 10,000 tonnes/year in South America	Import = US$337/tonne	Grinding, flotation	US$2–2.5 M (estimated)
Rio Lía Garnet, VIII Región	Garnet production for abrasive sands	• Almandine deposits, 32 mi S of Concepción • Important markets for abrasive sands in VIII Region	10,000 tonnes/year	Import = US$846/tonne	Grinding, classification	US$2.3 M
Munilque Pumice, VIII Región	Construction bricks and panels production	• Pumice deposits in Munilque, some 94 mi E of Concepción • Growing demand in construction sector in southern Chile	250,000 tonnes/year	Domestic = US$0.12/brick	Crushing, grinding, classification	US$1.4 M

part of the country, and import substitution are the main objectives of this project.

Laraquete-Carampangue Andalusite Project

Production of andalusite for alumina refractories is the objective of this project. It is based on primary and alluvial deposits located some 38 mi south of Concepción city (Fig. 3; Table 1), and on regional and national demands, both current and potential. This demand will represent around 5,000–6,000 tonnes per year, valued at US$250–300 per tonne. Market projection to South American countries could represent about 14,000–15,000 tonnes per year (Gajardo and Gutiérrez, 1993; Gajardo, 1997).

The basic process consists of grinding and flotation, and investment has been estimated in US$2–2.5 million. Substitution of high-alumina clay, bauxite, and andalusite imports and the creation of an industrial-mining activity are the main benefits of this project for the Chilean economy.

Rio Lía Garnet Project

Production of garnet, for use as sand-blasting abrasives to treat metallic surfaces, is the main objective of this project. The second objective is to produce various grades of garnet for filtration and jewelry.

The project is based on almandine-bearing alluvial deposits, located some 32 mi south of Concepción city (Fig. 3; Table 1), in a region where there is potential demand from a variety of metal and mechanical industries. This future demand represents around 8,000–10,000 tonnes per year, valued at almost US$200 per tonne (Gajardo and Gutiérrez, 1993; Gajardo, 1997).

The basic process is grinding and classification, and total required investment for a 1,000-tonnes-per-year plant is some US$2.3 million (Corporación de Fomento de la Producción, 1995). The main benefits of this project are the creation of new mining and industrial activity in Chile, substitution for imports, and access to new markets.

Munilque Pumice Project

Production of lightweight-construction materials is the objective of this project. It is based on a volcanic deposit of pumice, located 90 mi southeast of Concepción (Fig. 3; Table 1). It is expected to meet future demand in the region for building bricks and panels, which will result from future building expansion in the southern part of Chile. Estimated pumice demand is 250,000 tonnes per year, and the estimated price of pumice bricks is US$0.125 per unit, which is only 50% of the price for clay bricks in the area (Gajardo and Gutiérrez, 1993; Gajardo, 1997).

The basic process is crushing, grinding, and classification, and the total investment for a 40,000 m^2 per year panel plant is about US$1.4 million (Corporación de Fomento de la Producción, 1995). Creation of a new industrial-mining activity in the country and securing a market share in a developing construction market with alternative low-price products are the main objectives of this project.

SUMMARY

There are many investment opportunities for small- to medium-scale industrial-minerals operations in Chile. Table 2 summarizes the information regarding the investment opportunities that has been described.

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Recent Data Regarding the Genesis and Formation of Sulfur Deposits around Isparta Region, Turkey

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ABSTRACT.—The study area is located in the Alpine-Himalayan zone in Turkey. Geologically, this is a very complicated region, and the rock units generally are divided into two groups as either allochthonous and autochthonous. Tectono-stratigraphically, the units are Paleozoic quartzite, black limestone, arkosic sandstone, interlaminated radiolarite and Triassic limestone, thick Jurassic limestone, detritic limestone with alternating Eocene *Nummulites* beds and cream-green marl, Miocene siltstone, and ophiolite. Trachyte, trachyandesite, feldspathoidal trachyandesite porphyry, tuff, and pumice formed by volcanism during the Plio-Quaternary also are present. Recent alluvium and slope detritus locally cover all the other rock units.

A number of sulfur outcrops occur in the area. Among them are outcrops at Keciborlu, Yelliyatak Hill, Buyuk, and Kucuk Kukurt Dere. The most important sulfur deposits are found in volcanic tuff and siltstone-marl, and they include highly organic material. Sulfur may accumulate around recent gas diffusions and also as massive formations. The information about local geology and sulfur isotopes shows that the sulfur originated from the crust and probably comes from organic-rich Paleozoic and Triassic units. The sulfur did not move between Triassic and Pliocene time. However, Plio-Quaternary volcanism did cause movement of the sulfur, and this was followed by formation of the secondary sulfur due to post-tectonic thermal activities and the mixing of other surface waters.

GEOLOGICAL SETTING

The Isparta fold of West Taurides, which is located in the Alpine-Himalayan belt, has been extremely affected by tectonic activity. The rocks in the study area are both allochthonous and autochthonous. It is necessary to consider the Korkuteli and Beysehir districts together when evaluating the study area. Therefore, the stratigraphic sequence is given for a large area.

Paleozoic rocks are exposed around the Karacahisar (Anamas Mount) region in the southern part of the area. Cambrian rocks consist of arkosic sandstone, quartzite, dolomite, lensoidal limestone, and diabase dikes or sills. Devonian strata are sandstone, and neritic and arkosic sandstone, from bottom to top. Permian and Early Triassic units include gray detritic and lensoidal limestones. Late Triassic rocks are conglomerate, black limestone, dolomite, dolomitic limestone, and marl. In contrast, chert, radiolarite, and limestone are present in the Egirdir, Isparta, and Burdur regions. Jurassic rocks are platform carbonates, and these extend up to the Upper Cretaceous (Maestrichtian). Lower and Middle Triassic gypsum and marl are exposed in Gulluk Mountains, located between Isparta and Burdur regions.

Paleocene beige and green marl-claystone and microbreccia units overlie the Jurassic rocks. Thick Eocene nummulitic limestones concordantly overlie the Paleocene rocks. As a result of tectonism during the Late Eocene, ophiolitic rocks were emplaced in the study area (Yalcýnkaya, 1985). This tectonic activity continued up to the Late Miocene.

A group of volcanic rocks—augite-trachyte, trachyandesite, feldspathoidal trachyandesite porphyry, andesite, tuff, and tuffite—formed during the Late Pliocene. Large sanidine crystals are present in calc-alkaline trachyandesites. Biotite and pyroxene phenocrysts and plagioclase minerals are present in other volcanic rocks as well. These volcanic rocks have been intruded into the entire stratigraphic sequence. The silica content of these volcanic rocks ranges from 52% to 68%. Extreme alteration is observed in zones with a high silica content. Chemical analyses of the volcanic rocks present in the Daridere location yielded 190 ppm molybdenum and 660 ppm copper. Alluvium and Recent sediments are present at the top of the sequence.

Kumral, Mustafa; and Gedikoglu, Atasever, 1999, Recent data regarding the genesis and formation of sulfur deposits around Isparta region, Turkey, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 337–340.

Arsenic and sulfur deposits are present within the West Taurides, although the study area is quite poor in terms of ore provinces. Although field surveys (Yalcýnkaya, 1985; Kumral and Gedikoglu, 1993) showed that the sulfur ores were formed by volcanism, recent isotopic investigations suggest contrary results concerning ore genesis.

Previous studies showed that these ores were formed due to alteration of volcanic rocks. However, in this study, sulfur-isotope investigations revealed that sulfur may have been derived from the organic materials. Thus, it will be necessary to reinvestigate the field data in view of the genesis of sulfur deposits. Examination of 50 petroleum and asphaltite remnants implies that there must have been a pre-Triassic petroleum province in the study area. The presence of Paleozoic reservoir rock, such as limestone-dolomite, sandstone, and conglomerate, and also of petroleum remnants identified during recent drill-hole investigations, confirm the possibility of petroleum-rich rocks in the past. However, strong tectonism decreases the possibility of economic oil occurrences.

The geology of the study area has been investigated in a very large scale because it is necessary to determine the presence of a particular petroleum reservoir similar in genesis (i.e., organic occurrences during the Early Triassic).

The similarity of sulfur isotope analyses to those that are organic in origin indicates that the sulfur occurrences had been formed previously by reduction of the organic units or bacterials and then transported by volcanic activity. The existence of small asphaltite and petroleum occurrences further confirms this hypothesis.

EVALUATION OF SULFUR ISOTOPES

Geochemical formulas and related information on sulfur isotopes are given in papers by Nielsen (1972, 1974a,b), Ohmoto (1972), and Saupe (1994) and are not repeated here. The data $\delta^{34}S$ of the volcanics, including native sulfur and pyrite from Isparta region, are given in Table 1.

The ratios of $^{34}S/^{32}S$ in the samples: $\delta^{34}S‰$ is calculated as given below:

$$\delta^{34}S‰ = ([R_{sample}/R_{standard}] - 1)10^3 \text{ and}$$

$R_{standard}$ (in Cañon Diablo meteorite, the ratio of $\delta^{34}S$) $= 0.0450045$

Thus,

$$^{34}R_{sample} = ([\delta^{34}S‰ \times R_{standard}] \times 10^{-3}) + R_{standard},$$

$$^{34}R_{sample} = ([\delta^{34}S‰ \times 0.0450045] \times 10^{-3}) + 0.0450045$$

DISTRIBUTION OF $\delta^{34}S‰$

The value of $\delta^{34}S‰$ of the Isparta samples compared with those belonging to various rocks or environments is given in Figure 1. This shows that there is a low possibility of a match of the Isparta samples with volcanic H_2S, S^0, sulfide, shale, sandstone, graywacke, reduction of bacteria, or volcanic H_2S or sulfate. Also, there is no relation between the sulfur data and mafic rocks, granitic rocks, or limestone.

Table 1.—The Data $\delta^{34}S$ of the Volcanics Including Native Sulfur and Pyrite from Isparta Region

Sample number	Sample name	Location	$\delta^{34}S$	R_{sample}
S1-1	Native sulfur	Degirmendere	−6.0	0.0447165
S1-2	Native sulfur	Degirmendere	−6.0	0.0447345
S2	Native sulfur	Uyuzpinar	−2.0	0.0449145
S3-1	Pyrite + Q + clay	Daridere	−4.3	0.0448110
S3-2	Pyrite + Q + clay	Daridere	−6.45	0.0447120

VARIATION INTERVAL OF $^{34}S‰$ VALUES

The notation $\Delta(\delta^{34}S)$ is used to show the change interval of $\delta^{34}S‰$ values. The recent $\delta^{34}S‰$ values changed from approximately −65 to +95; thus, the $\Delta(\delta^{34}S)$ value is about 160‰ for all sulfur compounds. The changes between −40 and +40 and $\Delta(\delta^{34}S)$ value ^{34}S is about 80‰ because the extreme values are rarely observed. In this case, $\Delta(\delta^{34}S) = 4.5$ is quite a narrow interval change for ^{34}S and ^{32}S isotopes which have the widest variation interval in nature. This fact indicates that sulfide occurrences are not subjected to effective geological deformations.

ISOTOPIC-FRACTIONATION CONSTANT (α)

The ratio of isotope couples of the same element of two different samples (α) is indicated as:

$$\alpha = R1/R2,$$

where R1 = heavy isotope/light isotope ratio in one compound, and R2 = heavy isotope/light isotope ratio in the other compound. Generally, R1 is used for heavy isotopes and R2 is used for light ones.

The relation between α and δ can be easily calculated. Considering the samples S2 and S1-1 which are native sulfur :

$$\alpha = 0.0449145/0.0447165 = 1.004428$$

When isotopic fractionation is stated as "permil";

$$(1000\ [\alpha - 1])$$

$$10^3 \ln \alpha \approx 4.428$$

The value of α can reach up to 1.086. This indicates that there is important isotopic fractionation among sulfide compounds in nature. However, α values in Isparta region are rather lower than in nature. This is ascribed to the following: (1) The reasons depending

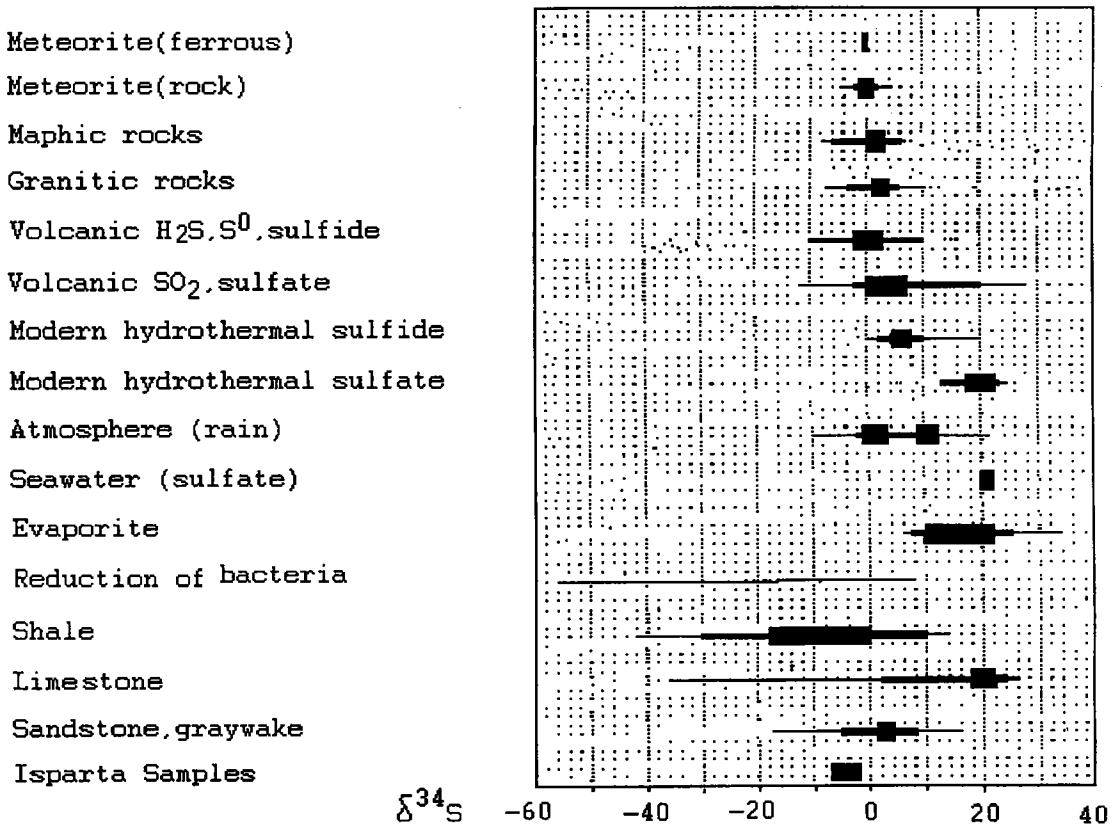


Figure 1. The distribution of the $\delta^{34}S$(‰) values in some environments.

upon the sulfur distribution are not present. These sulfur isotopess are generally in different phases and charges. (2) Fractionation mechanisms are not effective (solid-liquid variations, chemical reactions, isotopic-equilibrium reactions etc.).

SOLID-LIQUID VARIATIONS

The $^{34}S/^{32}S$ ratio decreases in recent compounds during the conversions among solid-liquid and liquid-gas phases but increases in partially converted compounds. In contrast, the $^{34}S/^{32}S$ ratio increases in recent compounds during the conversions among gas-liquid and liquid-solid phases but decreases in partially converted compounds.

1. If the assumption that Isparta sulfides originated from magma is accepted, then the $\delta^{34}S$ value, which is close to zero and positive, should have decreased and become negative. In this case, the idea of which sulfur derived from magma was converted into liquid and gas phases becomes more logical. The samples belong to solid phase although the cycle of liquid and gas in sulfur evolution is accepted. Therefore, $\delta^{34}S$ should increase (solid-liquid-solid). However, this hypothesis is invalid because isotopic fractionation is about 4.4, and there is no evidence concerning the existence of older magmatic sulfur in the solid phase.

2. If organic genesis is accepted, then $\delta^{34}S‰$ in higher negative values increased to lower negative values. In this case, the validity of the presence of organic sulfur that is in liquid or gas phase and its conversion into solid phase must be confirmed. The presence of organic rocks, asphaltite, and bituminous shale within the Isparta region confirms this hypothesis. Therefore, only one-way phase variation (liquid-solid) is valid in this evolution.

On the other hand, negative $\delta^{34}S‰$ values indicate a reducing environment because, although ^{32}S isotopes concentrate in reduced molecules, the ^{34}S isotopes concentrate in oxidized molecules. For example, the SO_4^{-2} anion has a higher $^{34}S/^{32}S$ ratio than that of native sulfur. If the second hypothesis is accepted, the following are consequences: (1) The sulfur is derived from reduction environment at the beginning. (2) The sulfur is probably in the form of liquid H_2S. (3) The $\delta^{34}S‰$ is lower than −6.5. (4) The sulfur is carried by means of volcanism. (5) The sulfur is also in H_2S form during transportation (because the Nielsen diagram refers to H_2S environment for the $\delta^{34}S$ values between −10 and 0 in a hydrothermal solution). (6) Sulfur passes into the stronger oxidation environment. $S^{-2} \rightarrow S^0$.

In an oxidation environment:

$$H_2S + ½O_2 \rightarrow S + H_2O$$

and $\delta^{34}S‰$ increases due to the conversions from liquid to solid and from reduction environment to oxidation environment ($< -6.5 \rightarrow > -6.5$).

THE ROLE OF HEAT IN SULFUR EVOLUTION

It is well known that high temperatures have an important role in the fractionation of sulfide compounds in Isparta region. It is not possible to use the sulfur-isotope thermometer because there is no sufficient sample and various compound samples. However, as a general rule, isotopic fractionation can occur at temperatures lower than 200°C. Higher temperatures have been effective in the evolution of sulfur because of low-grade fractionation. That these volcanic rocks originated from the hydrothermal solutions that were carrying the sulfur confirm these data.

CONCLUSIONS

Isotopic analyses of the sulfur occurrences of Isparta indicate the following four conclusions. (1) The sulfur in the study area is organic in origin, but the number of the samples is not sufficient to be definitive. More samples are required to reach a definitive conclusion. (2) Sulfur is probably in the form of liquid H_2S, derived from a reducing environment at the beginning, and, during transportation, $\delta^{34}S‰$ is approximately lower than –6.5. (3) Since the $\delta^{34}S$ values between –10 and 0 in hydrothermal solution refer to an H_2S environment in the Nielsen diagram, it is proposed that sulfur is in the form of H_2S and carried by means of volcanism. (4) Sulfur passes into the stronger oxidation environment. ($S^{-2} \rightarrow S^0$).

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Albite Occurrences and Their Economic Significance in the Muğla–Milas Region, Southwestern Anatolia, Turkey

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ABSTRACT.—Albite ($NaAlSi_3O_8$) is one of the important raw materials for the rapidly developing Turkish ceramic and glass industry. Prior to 1980, development of the ceramic industry in terms of raw material was dependent upon small-scale mining operations; in the last decade, these efforts have increased substantially.

The aim of this study is to investigate the geochemical properties and distribution of albite occurrences in the Kocayayla district, which is about 12 km northeast of the town of Milas, about 50 km west of the city of Muğla in southwestern Anatolia. Kocayayla is also well known for its famous ancient city, Labranda. The field area is located in the Menderes Massif, which was formed by major tectonic events during the Late Proterozoic and subsequent periods.

The target area was studied to prepare a detailed geological map (scale, 1:10,000), and to determine the formation of albite–mica-schist–quartzite borders in the host rock gneiss. To do this, systematic sampling of albite was done in the two main areas, the Sarikaya and Yumrutaş regions. In the study area, albite zones are scattered within an area of about 20 km^2, and they extend in a northeast-southwest direction; mica-schists and quartzite veins accompany these units.

Mineralogical observations show that quartz is the main mineral associated with albite. In the ceramic industry, the albite + quartz assemblage is well known and is classified as "standard" or "super type," depending upon the content of TiO_2 and Fe_2O_3. In this study, the Sarikaya albites (profile I) exhibit remarkably lower TiO_2 (0.15% on the average) values contrasted to that of Yumrutaş (profile II; 0.24% on the average), whereas Fe_2O_3 values vary slightly from 0.076% to 0.085% in both regions.

INTRODUCTION

Albite was discovered in the study area in the southwestern part of the Anatolia region of Turkey (Figs. 1,2) in 1981, and it has been exploited by open-pit–mining methods since 1988. The albite deposits are in a large area where the albite-gneiss contacts had not been clearly studied or mapped. The 20-km^2 target area was studied to prepare a detailed geological map at a scale of 1:10,000 by Budakoğlu (1989) and Alakbarzadeh (1989) (Fig. 3); the map includes contacts of the albite, mica-schist, and quartzite formations.

These deposits are commercially important because of their industrial qualities and the good transportation facilities. Exportation of this raw material from the studied area started in 1986, and 800,000 metric tons of albite were shipped to Italy and Spain in 1997.

GEOLOGIC SETTING

The Kocayayla albite is present in about 1,500 ha (hectares) of an area located northeast of Milas, within the Menderes Massif, which covers a large area of southwestern Anatolia (Figs. 2,3). The area is bounded by Tauros Mountain Belt on the south and by the Izmir-Ankara ophiolitic belt on the west (Fig. 2). The Menderes Massif extends about 200 km from Muğla to Simav, and its width is approximately 150 km from Denizli to Turgutlu.

The area had been investigated by different researchers with various geological points of view. Some of the early scientists (references are not included in this paper) were Naumann in 1896, Philippson in 1910, Penck in 1918, Salamon-Calvi in 1931, and Kober and Pajeras in 1940. Later work (which is referenced in this paper) was done by Blumental (1946). Between 1956 and 1959, Ketin interpreted the geology of the study,

Budakoğlu, Murat; and Suner, Fikret, 1999, Albite occurrences and their economic significance in the Muğla–Milas region, southwestern Anatolia, Turkey, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 341–345.

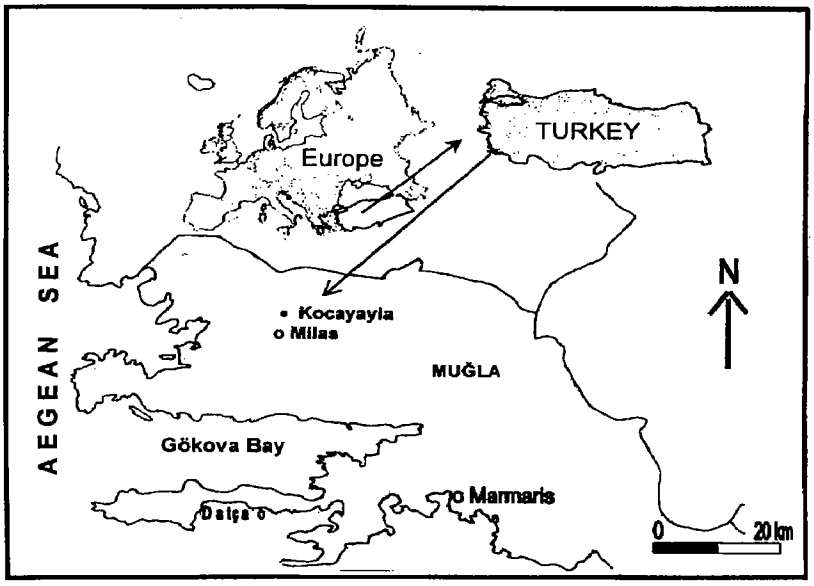


Figure 1. Map showing location of Europe and Turkey (above) and southwest Anatolia region (below).

using modern tectonic concepts for the first time, and this work was published in 1966. Wippern published a study of this region in 1964.

The Menderes Massif includes the following: (1) Precambrian gneiss; (2) Paleozoic mica-schist; (3) Permo-Carboniferous metaquartzite, black phyllite, and recrystallised limestone; (4) Mesozoic bauxite-bearing limestone; and (5) lower Eocene recrystallised pelagic limestone and flysch. Barrovian-type regional metamorphism has been reported by various scientists, including Asworth and Evirgen (1984), Okay (1985), and Satir and Friedrichsen (1986).

The Menderes Massif is a major tectono-stratigraphic unit, and many aspects of this feature are under intense study by earth scientists looking at a wide range of geological characteristics.

The first observation of albitisation in the area was pointed out by Nebert and

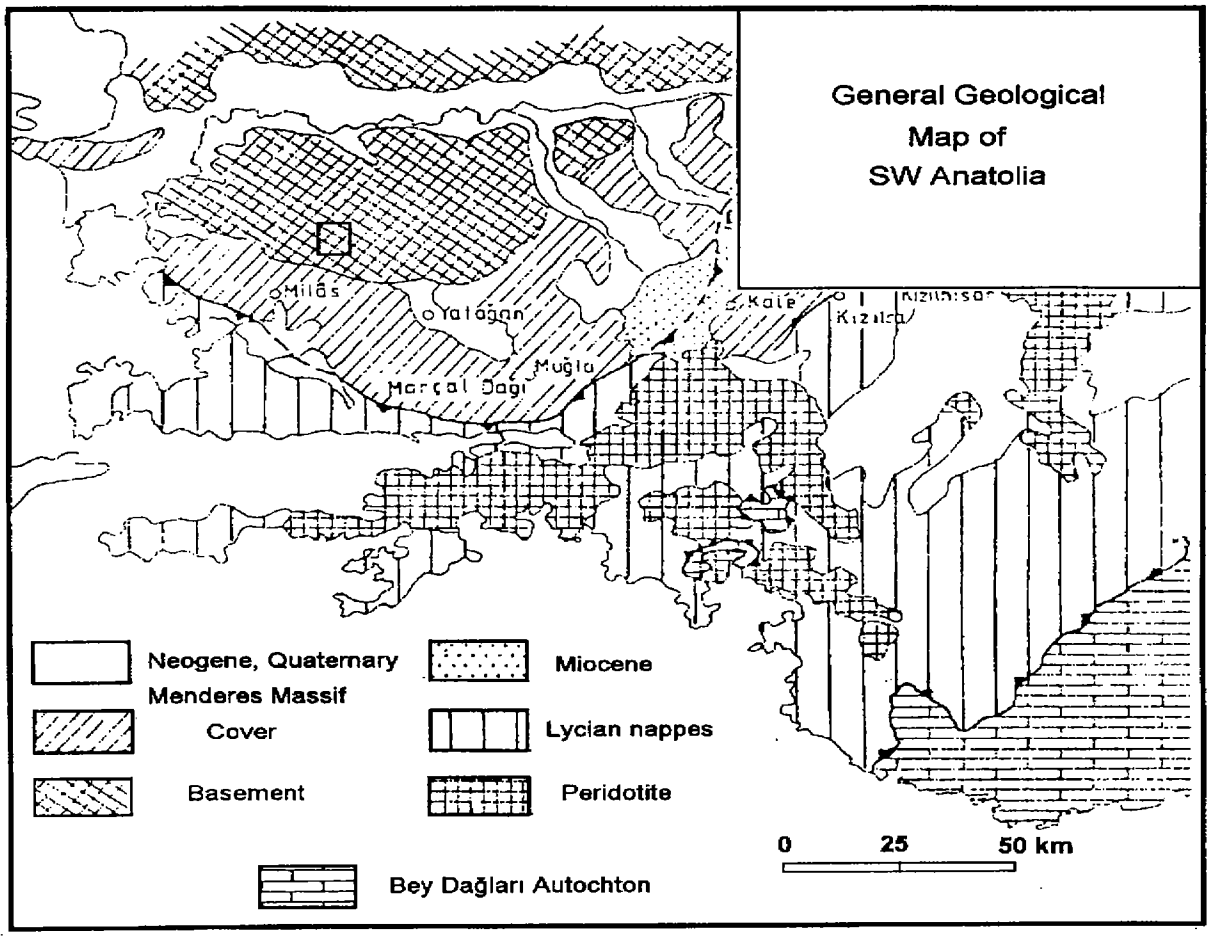


Figure 2. Simplified geological map of southwestern Anatolia (Okay, 1989), showing location of study area (box) northeast of Milas.

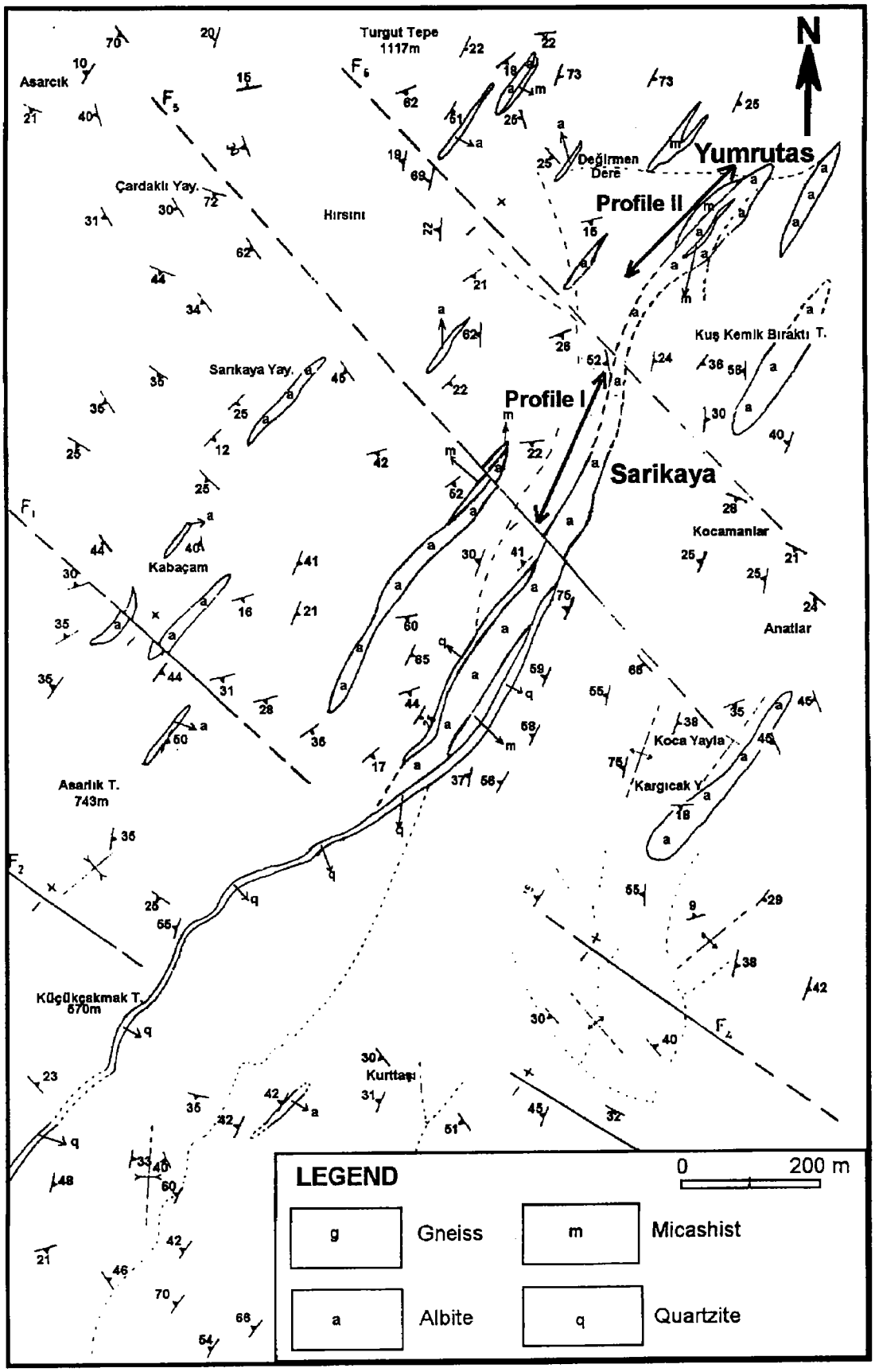


Figure 3. Geological map of the study area, showing albite outcrops and location of profiles I and II.

Ronner (1956). According to their studies, albite had formed in both silicates and carbonates from Na-rich solutions, which had originated in response to Alpine tectonics.

FIELD STUDIES AND PETROGRAPHIC DETERMINATIONS

Field studies reveal the presence of four rock types: albite, mica-schist, quartzite, and gneiss (Fig. 3). Albite zones have a length between 50 m and 1,500 m. The main direction is about northeast-southwest. Schistosity is common. Many normal faults are present and are remarkable in terms of pointing to albite occurrences. The albite is white and brittle. Mica and rutile are present in some samples, and quartz is very common in some albite seams.

Gneiss is the oldest rock in the area, and it is regarded as basement rock in the massif. Gneiss occurs as large, white to yellowish-white blocks. They have granoblastic texture, and paragenesis of quartz–potassium-feldspar–plagioclase–biotite–muscovite–apatite–tourmaline–zircon is observed.

Quartzite is another common rock in the area; it contains feldspar, magnetite, hematite, garnet, ilmenite, and calcite in minor amounts. Quartzites also have granoblastic texture and may be economically important. The gray mica-schist occurs with the albite zone. The observed paragenesis of the mica-schist is biotite–muscovite–quartz, and it exhibits lepidoblastic texture.

SAMPLE COLLECTION AND ANALYTICAL METHODS

Samples were collected from different albite zones to determine geochemical (Table 1) and mineralogical parameters. In addition, two adjacent horizontal profiles were chosen specially (Fig. 3) and sampled in detail within the albite units; these were analyzed for their TiO_2 and Fe_2O_3 contents (Table 2).

Four bulk samples, each less than 1 kg, were taken at intervals of about 10 cm in depth. At the laboratory the samples were dried at 40°C, disaggregated, and homogenized. We preferred to analyze the <125 mm fraction, and 0.1 gram of the sample was decomposed in a mixture of nitric acid (65%, 10 ml), sulfuric acid (95%, 0.2 ml), and hydrofluoric acid (38–40%, 35 ml) using a teflon pot. After evaporation, the residue was dissolved in 5 ml hydrochloric acid (37%) and 20 ml pure-water mixture. After filtration, the fluid was diluted to 100 ml. Ti, Fe, and Al were analyzed by colorimetric spectrometry; Ca and Mg were analyzed with AAS; Na and K were analyzed using flame photometry, and Si values were determined using carbonate-decaying methods (Table 1).

RESULTS

In this study, a geological map (scale, 1:10,000) was made, with special attention to the contacts between albite, quartzite, mica-schist, and gneiss. In the samples, which were taken from the Sarikaya and Yumrutaş regions, the contents of TiO_2 and Fe_2O_3 were determined in addition to whole-rock analyses for some samples. We found that the contents of TiO_2 and Fe_2O_3 are acceptable for ceramic and glass industries.

In the ceramic industry, the albite + quartz assemblage is a well-known paragenesis and classified as "standard" or "super type," depending upon the contents of TiO_2 and Fe_2O_3. In this study, chemical data show that the Sarikaya albites (profile I) are remarkably lower in TiO_2 (0.15%, on average) than the Yumrutaş albites (profile II; 0.24% TiO_2, on average); whereas Fe_2O_3 values vary slightly from 0.076% to 0.085% for both regions (Table 2).

Chemical properties of the albite are very important, and the results of our study show that the chemistry is quite favorable to commercial demand for this material. Although the results of XRD show that this albite contains some free silica (quartz), it does not seem to be a negative factor for ceramics and glass-production processes.

Table 1.—Geochemical Analyses of the Two Albite Occurrences

Percentage	Sarikaya Sample 1	Sarikaya Sample 2	Yumrutaş Sample 1	Yumrutaş Sample 2
SiO_2	72.05	71.9	72.14	72.25
Al_2O_3	13.45	13.68	13.54	13.49
Fe_2O_3	0.062	0.068	0.92	0.95
TiO_2	0.10	0.09	0.35	0.40
CaO	0.50	0.80	0.50	0.60
MgO	0.15	0.14	0.17	0.16
Na_2O	10.10	10.04	9.68	9.72
K_2O	0.25	0.34	0.19	0.21
Lg. loss	1.65	1.57	1.60	1.69

Table 2.—Horizontal Profiles Value for the TiO_2 and Fe_2O_3 Ratios

Profile I			Profile II		
Sample points	TiO_2 (%)	Fe_2O_3 (%)	Sample points	TiO_2 (%)	Fe_2O_3 (%)
1	0.14	0.085	1	0.32	0.087
2	0.17	0.075	2	0.35	0.092
3	0.09	0.070	3	0.40	0.095
4	0.10	0.062	4	0.38	0.080
5	0.09	0.077	5	0.31	0.085
6	0.09	0.068	6	0.34	0.075
7	0.22	0.083			
8	0.31	0.088			

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Formation of the Cryptocrystalline Magnesite Ores within the Yaylacik (Tavsanli–Turkey) Ophiolite Sequence and Its Industrial Use

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ABSTRACT.—This paper presents detailed information on the genesis, formation, and industrial utilization of Yaylacik magnesites. Tectonically, the study area is located within the Tavsanli Zone, immediately south of the Izmir–Ankara suture in western Turkey.

The geologic setting mainly comprises ophiolitic melangés basics, and ultrabasics associated with very rich magnesite deposits and lacustrine sediments. The ophiolitic unit tectonically overlies the schists and carbonate rocks. The presence of glaucophane and lawsonite indicates a low-temperature/high-pressure metamorphism. The ultrabasic rocks, which exhibit cumulate composition, have been mostly serpentinised and represent the oceanic floor of the Yaylacik ophiolite. Basic intrusives consist of dolerite and diabase, and they show the characteristics of within-plate dolerites.

The magnesite occurrences are commonly observed in block, stockwork, lens, and vein forms and were deposited within the serpentinites. In most magnesite samples, secondary quartz/chalcedony formations are observed as fracture fillings due to the highly effective tectonic movements. Field surveys and microscope studies reveal that magnesites had been formed by the metasomatic alteration of serpentinites.

Chemical analyses show that, although MgO content of the magnesites varies from 43.41% to 50.48%, Fe_2O_3 and CaO are lower than 1%. Silica contents are as high as 5.52% in a few samples. Although Yaylacik magnesites are not suitable for making basic refractory bricks, they are widely used as caustic-calcined magnesite in a variety of applications, including animal food, artificial fertilizer, chemical (acid neutralizer), medical and pharmaceutical, and water treatment.

INTRODUCTION

The process of magnesitation is still a subject of scientific argument, and it is explained by various theories based on experimental studies. According to the *descendant theory*, magnesite forms by the alteration of serpentinites and ultrabasic rocks through atmospheric effects. *The ascendant (hydrothermal) theory* is based on the alteration of serpentinite by means of CO_2-rich thermal solutions under high pressure.

Magnesite occurrences have been studied in terms of mineralogical and geological properties to reveal impurities that affect the quality of magnesite in various fields of industrial utilization. The largest reserves of cryptocrystalline magnesite in the world are in Turkey. Toward this aim, Yaylacik (Tavsanli–Kutahya) magnesites, which represent a good example of cryptocrystalline-magnesite deposits, have been studied extensively. Economic aspects of magnesites have been investigated by a number of researchers (Petrascheck, 1963; Arda and others, 1971). Okay (1981) studied the geology and blueschist metamorphism of the ophiolites in northwest Turkey (Tavsanli–Kutahya), and Goncuoglu and others (1992) investigated the stratigraphy of the Kutahya region.

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GEOLOGIC SETTING

The study area is located in the Anatolide–Tauride platform of western Turkey (Fig. 1) and mainly comprises Upper Cretaceous, Miocene, Pliocene, and Quaternary units. One Upper Cretaceous unit, named the

Elmas, Numan; Celenli, Ahmet; and Suner, Fikret, 1999, Formation of the cryptocrystalline magnesite ores within the Yaylacik (Tavsanli–Turkey) ophiolite sequence and its industrial use, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 347–351.

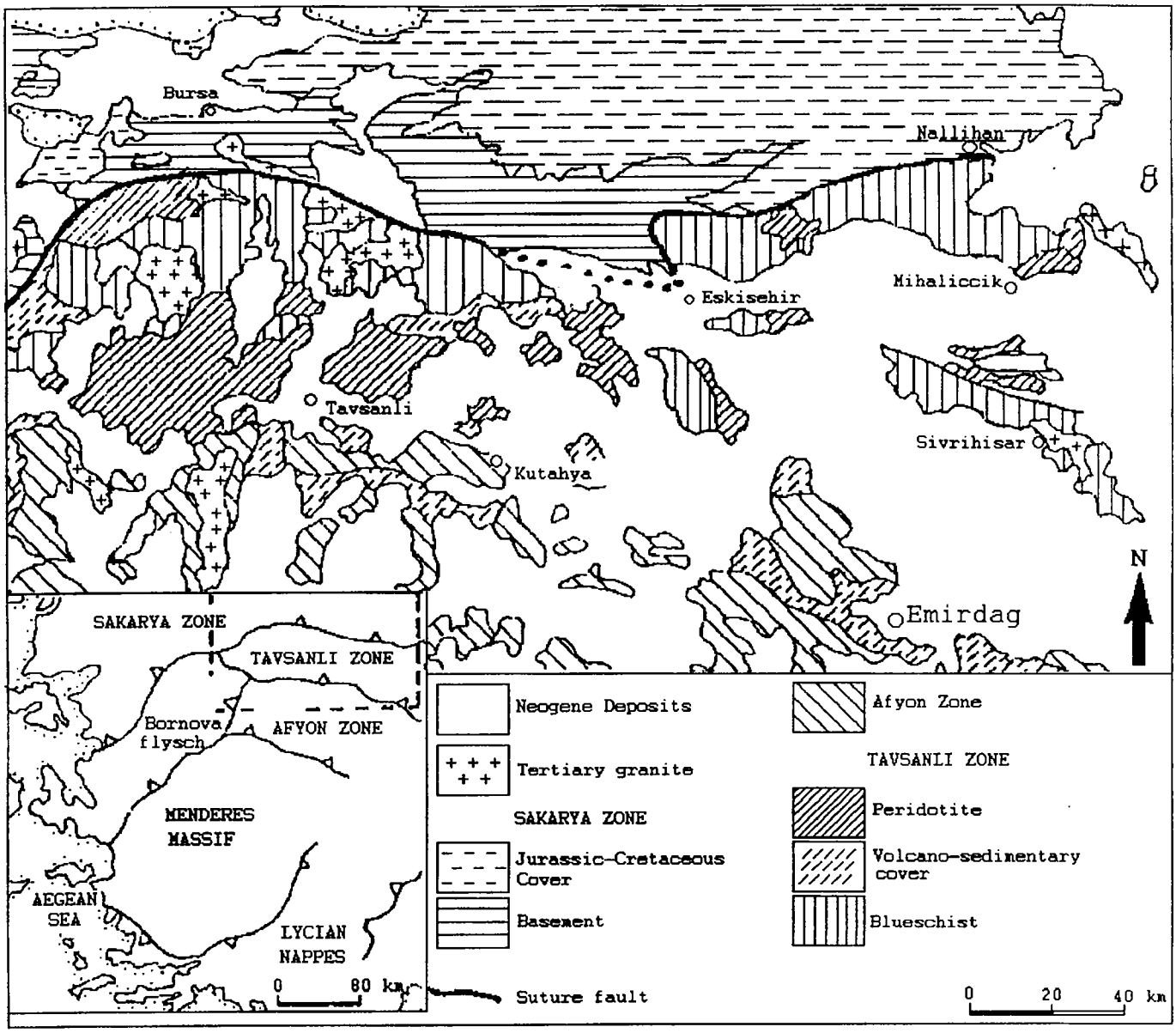


Figure 1. Generalized geological and tectonic map of the study area (Okay and others, 1998).

Arifler Formation, is a small melangé in the district. This unit, subjected to high tectonism, consists of marble, schist, diabase, mudstone, and limestone with tectonic contact. A second unit, known as the Yaylacik Formation, includes ultrabasic rocks such as peridotite (mostly harzburgite), serpentinite, pyroxenolite, massive dolerite, diabase, and microgabbro; it tectonically overlaps the metamorphics and Arifler melangé. The Miocene is represented by the Tuncbilek Formation, which discordantly overlaps the older formations and comprises lacustrine sediments such as marl, claystone, siltstone, limestone, tuff, and coal. Near the top, one of the Lower Pliocene units is the Saruhanlar Formation, which is an alluvial-lacustrine deposit and consists of alternating conglomerate-sandstone-tuff-tuffite and limestone. The top unit, the Cukurköy Formation, is similar to the Saruhanlar Formation, except that it also contains marl.

Formation of the Yaylacik Magnesites

The ophiolite sequence has tectonically overlapped the carbonate series, resulting in the formation of magnesite under the effect of high-pressure/low-temperature conditions. This compressional activity had caused an increase in temperature, up to 300–400°C, and in turn has caused release of CO_2. In the presence of hydrothermal solutions, due to metasomatic reactions, magnesite ($MgCO_3$) formed within the cavities and cracks under proper physicochemical conditions. Massive and lensoidal magnesites are present in the form of blocks, lenses, veins, and stockwork structures. Although massive magnesites have sharp contacts with

the host rocks, lensoidal types are located at shear zones and milonitized contacts. Magnesite + serpentine and magnesite + talc or magnesite + quartz/chalcedony paragenesis are common for massive magnesites, whereas lensoidal magnesites generally are attributed to magnesite + quartz/chalcedony, occasionally magnesite + serpentine, and rarely magnesite + talc paragenesis. Some metamorphic minerals (lawsonite + glaucophane + albite + quartz/chalcedony) also have formed because of the metamorphic conditions necessary for formation of magnesite. This paragenesis shows the high-pressure/low-temperature conditions (350–400°C, 7 kb). In addition, the identification of jadeite and the presence of talc minerals in shearing zones indicates high pressures.

Ultrabasic Rocks

Ultrabasic rocks generally are represented by peridotites (dunite and harzburgite), which are part of the ophiolite sequence. Most ultrabasics have become serpentinite, and rarely listwanite, in response to the metamorphic processes. Talc and quartz are other minerals that indicate the metamorphic conditions. Chrysotile and lizardite are commonly minerals compared with antigorite in serpentinites.

Eight samples were collected from the study area to determine the origin of the ultrabasic rocks. Chemical results of ultrabasics were plotted in the Fe_2O_3–MgO–($Na_2O + K_2O$) diagram (Fig. 2). As seen in the diagram, the ultrabasics indicate cumulate composition.

Basic Rocks

Basic intrusive rocks are dolerite and diabase, and they are present as massive blocks. Mineralogical studies show that plagioclase and pyroxene (augite) are the main minerals, with sphene, chlorite, actinolite, epidote, and zeolite as accompanying minerals. Sosurite, uralite, and albite transformations are commonly observed. Chemical data for eight samples were plotted in the Irvine and Baragar (1971) and Mullen (1983) diagrams (Figs. 3,4). Figure 3 indicates that the basic intrusives had been derived from tholeitic magma, except for sample 5. On the other hand, the Zr–Ti/100–Y*3 diagram (Fig. 4) shows that these samples formed in the "within-plate dolerites" (WPD) environment.

INDUSTRIAL USE

One of the main sources of commercial magnesia (MgO) is natural magnesite ($MgCO_3$). It is found in nature in two different physical forms, cryptocrystalline (gel) and large-crystal form. Large-crystal magnesites are not so preferred, due to their excessive iron content, whereas cryptocrystalline magnesite, generally found in smaller but purer deposits, is widely used

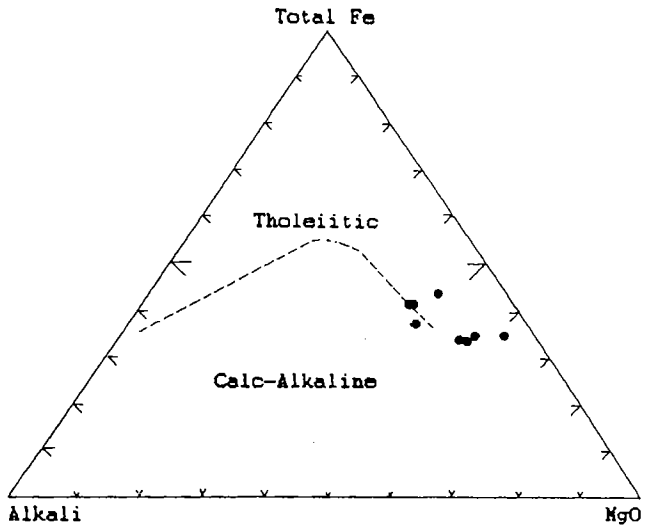


Figure 3. Irvine and Baragar (1971) triangular diagram for the Yaylacik basic intrusives.

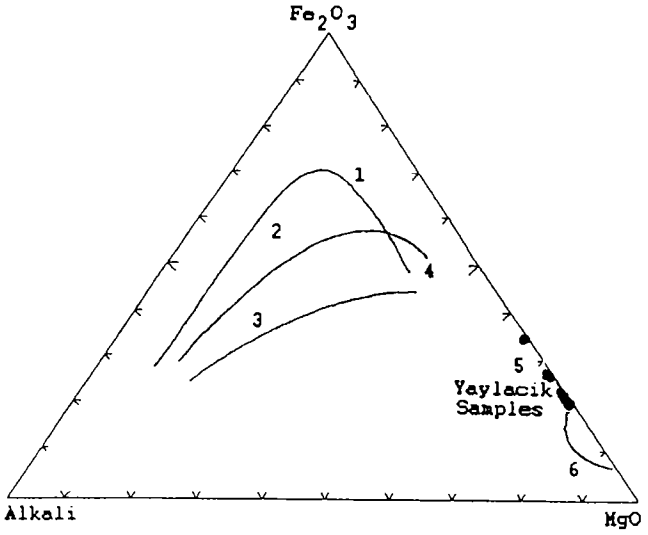


Figure 2. Fe_2O_3–MgO–alkali($Na_2O + K_2O$) triangular diagram of the ultrabasic rocks.

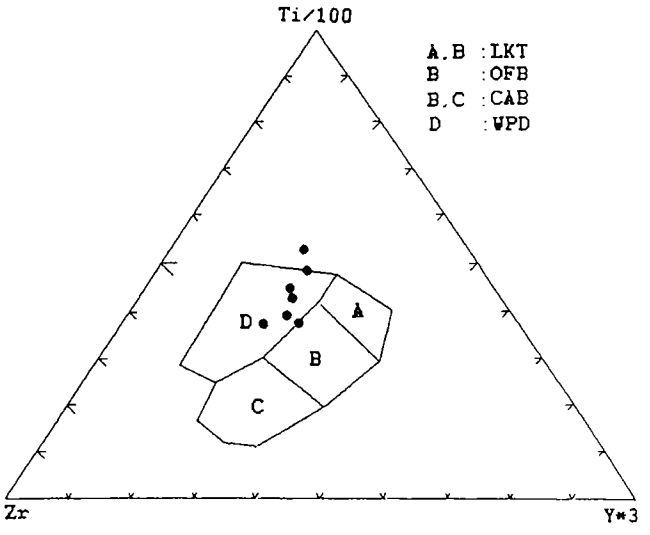


Figure 4. Zr–Ti/100–Y*3 triangular diagram (Mullen, 1983) of the Yaylacik basic rocks.

in many industries. There is a close relationship between the specifications and the price of magnesite and its products. For cryptocrystalline (gel) magnesite, the content of SiO_2 and CaO should not exceed 3%, and Fe_2O_3 should be lower than 1%. On the other hand, for large-crystal magnesite, these contents should be lower than 6%, 5%, and 11%, respectively. These chemical parameters are the determinative factors in price and sale. For example, excessive silica decreases the resistance against high temperatures. Moreover, magnesite brick containing high CaO is easily broken up. Therefore, a CaO/SiO_2 ratio of 2/1 is the best condition for magnesite in making brick.

To reduce the CaO content, crude ore is immersed into the pool so that external lime can be removed. Removal of silica, however, is not so easy. It is possible to remove silica by triage, if it is present in vein form. In this case, both ores are mixed to reduce the silica content. Fe_2O_3 generally is present as hematite in magnesite, but it is completely altered to magnetite (Fe_3O_4) after calcination and then can be removed easily by using a magnetic separator.

Magnesite is used for various purposes in industry. Magnesite is mostly calcined to produce caustic-calcined (at 800–1,000°C) magnesia and sintered (dead-burned) magnesia (>1,450°C). Sintered magnesite is consumed mainly in the iron and steel industry, in which magnesite is used as a refractory material in oven lining due to its high resistance against basic slags at high temperatures (>1,450°C). The use of calcined magnesite is very different. Generally, it is used many ways in the agriculture and construction sectors, such as in animal food, artificial fertilizer, rayon, stack-gas scrubbing, sorrel and oxisulfate cement, chemistry (acid neutralizer), medical and pharmaceutical, sugar and candy, pulp and fine paper, and as a water treater.

In the Kutahya region, magnesite deposits are mined by the Kutahya Magnesite Works Co. (KUMAS) and the Continental Mining Industry and Trade Co., Inc. (COMAG), with 350,000 tons of total annual production of magnesite; KUMAS produces 250,000 tons of sintered magnesia per year, whereas COMAG, which is the only producer of caustic-calcined magnesia in Turkey, produces 30,000 tons of calcined magnesia per year. Calcined magnesia is being exported to countries such as England, France, Germany, Holland, and the United States. The chemical character of Yaylacik magnesites is given in Table 1.

Table 1.—Chemical Content (%) of Yaylacik Magnesites

	SiO_2	CaO	Fe_2O_3	MgO	LOI
S1	1.05	0.26	0.65	48.48	49.56
S2	0.40	0.15	0.65	49.81	48.99
S3	1.63	1.24	0.24	46.00	50.38
S4	0.53	0.85	0.04	46.61	51.55
S5	5.03	0.63	0.02	46.21	47.64
S6	1.85	0.44	0.02	46.76	50.43
S7	5.52	0.52	0.84	45.87	46.82
S8	5.11	0.70	0.14	46.09	47.50
S9	0.13	1.58	0.02	46.07	51.83
S10	3.50	0.72	0.10	45.95	49.70
S11	2.50	0.45	0.11	48.44	48.45
S12	1.29	0.78	0.14	49.76	48.03
S13	1.16	0.95	0.09	49.88	47.93
S14	3.57	1.09	0.18	45.14	50.02
S15	2.82	0.75	0.09	46.84	49.50
S16	4.10	0.98	0.08	44.04	50.80
S17	1.51	0.91	0.18	49.08	48.32
S18	1.07	0.75	0.10	50.48	47.60
S19	1.35	1.10	0.10	43.41	51.04
S20	1.26	0.90	0.11	48.53	49.20

CONCLUSIONS

1. The study area had been highly affected by compressional tectonism in the Late Cretaceous.

2. The genesis and formation of the Yaylacik magnesites were studied using geological, mineralogical, and chemical methods. Field surveys indicate that the magnesites were formed by metasomatic alteration of serpentinites (ascendant model); the descendant hypothesis cannot be accepted for the Yaylacik magnesites because of the absence of hydromagnesite and brucite mineralization.

3. Some metamorphic minerals, such as talc, crysotile, and lizardite, proved that the study area has been affected by the Alpine orogenesis and blueschist metamorphism.

4. The chemical content of Yaylacik magnesites suggests that they are suitable for the production of calcined magnesia. However, Yaylacik magnesites have a high silica content in fracture zones, due to tectonism, and this has a negative effect on the quality of these magnesites during calcination.

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Nepheline Syenite Resources of Central Arkansas

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ABSTRACT.—Igneous rock exposures occupy only a minor portion of surface area (<18 mi^2) in Arkansas, and are divided into two major groups: nepheline syenite (7 mi^2) and syenite complexes (8 mi^2), with various dikes and sills representing the remaining surface exposures. The syenite complexes have been the sites of major vanadium and minor titanium production during the past 50 years. Nepheline syenite exposures were important in the early production of locally used building stone; however, aggregate and roofing granules have now become the principal market for the production of nepheline syenite in Arkansas.

Nepheline syenite intruded into a sequence of Paleozoic sedimentary rocks in Arkansas and is exposed in two areas: in Saline County near the town of Bauxite, and in Pulaski County at Granite Mountain, just southeast of Little Rock. Although the central Arkansas region had been investigated thoroughly for bauxite by the early 1950s, the nepheline syenite resources of the region have yet to be evaluated systematically by the state. Arkansas nepheline syenite was evaluated for its ceramic uses in 1952. Some recent industry interest has revolved around its potential use as a sand-blast abrasive. The largest exposed areas of nepheline syenite, located at Granite Mountain, currently are being mined by the Minnesota Mining & Manufacturing Company (3M) and McGeorge Contracting (Granite Mountain Quarry). 3M has been in operation since 1947 and mainly produces roofing granules. A fine powder produced by 3M during crushing that is marketed under the name Donnafill™ recently has seen use as filler in self-compacting confined construction and as an additive (frit) in common brick. Since the early 1960s, Granite Mountain Quarries has produced a variety of aggregates, ranging from riprap to industrial sand, and recently constructed a computerized hot-mix-asphalt production facility.

Approximately 4.5 million tons and 1.2 million tons of syenite were produced from Granite Mountain and 3M, respectively, during 1979. No production values are available after this date; however, combined production from both quarries is estimated to be at least 6 million tons annually.

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A Mineralogical, Stratigraphic, and Geochemical Profile of Trona Bed 17 in the Solvay Trona Mine near Green River, Wyoming

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ABSTRACT.—Trona, $Na_3(CO_3)(HCO_3) \cdot 2H_2O$, is mined in quantity from saline facies of the Eocene Green River Formation of southwestern Wyoming. The Green River deposits are the world's largest known resource of natural sodium carbonates. An estimated 127 billion tons of trona ore are known to occur in beds exceeding 4 ft in thickness (Wiig and others, 1995). Twenty-five trona beds, exceeding 3 ft in thickness, and covering at least 100 mi^2 have been identified. The beds are numbered sequentially in ascending stratigraphic order. Trona beds underlie more than 850 mi^2 (bed 17) and are up to 37 ft thick (bed 1) (Culbertson, 1966). Five underground mines, operating in beds 17, 19, 20, 24, and 25, process trona to produce soda ash (sodium carbonate). A total of 11,837,703 short tons of soda ash were produced from 17.1 million tons of trona ore in 1997 (Kostick and Clark, 1998).

A detailed study of trona bed 17, using techniques of petrography and X-ray diffraction, has been undertaken in the Solvay trona mine, near Green River, Wyoming. A continuous, vertical-channel sample was taken from near the production shaft for this study. At this location, bed 17 is 12.6 ft thick and includes several stratigraphic markers that are easily correlated throughout the mine and in surrounding drill cores. Bed 17 in this area averages 90% trona through its entire thickness (Wiig and others, 1995) and 95–100% trona in the lower two-thirds of the bed. Mineral impurities include water-insoluble dolomite, quartz, pyrite, clays, and other minerals and partially water-soluble northupite and shortite. Northupite, $Na_3Mg(CO_3)_2Cl$, contributes to chloride contamination in the soda-ash product and is concentrated in the upper one-third of bed 17, which is left behind as roof rock. Northupite has two modes of occurrence: (1) as bedded strata with dolomite, chert, clay, and shortite and (2) between primary trona crystals in trona spar.

Petrographic and mineralogic data indicate that this section of bed 17 was deposited subaqueously during its early and late history and may have undergone periods of deposition in a subaerial or marshy environment. Stratigraphic data indicate that trona accumulated at an annual rate of 2–4 in. per year.

During trona deposition, dolomite, $CaMg(CO_3)_2$, precipitated in parting layers when new water entered the lake, freshening supplies of calcium and magnesium. The lack of clay minerals in the trona facies suggests water input may be by means of springs, as opposed to overland flow. Clay occurrences in thicker dolomitic partings within the trona facies indicate periods of episodic overland flow, possibly resulting from storms in the surrounding basin.

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Flue Gas Desulfurization (FGD) Scrubber Stone in Indiana

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ABSTRACT.—Implementation of the Clean Air Act Amendments of 1990 is negatively affecting production of coal used for generating electric power in Indiana and elsewhere in the Midwest. Required reduction of sulfur compounds from gas streams, or flue gas desulfurization (FGD), as mandated by these laws has encouraged installation of wet limestone scrubbers at many generating plants. Increasingly stringent requirements that will begin in 2000 are expected to necessitate even more extensive use of such scrubbers. Indiana has large deposits of limestone—the major consumable alkaline raw material for scrubbers—that can meet an expected demand of several million tons per year. Limestones are not, however, all the same. Different limestone units behave quite differently when used as scrubbing agents under differing conditions in actual practice. Decisions about FGD scrubber details would be more meaningful if made with thorough knowledge of which rock units contain the most efficient FGD limestones and which sites of suitable stone are located nearest to power plants. Even though abundant carbonate rocks occur in Indiana, their suitability in scrubbing systems has received little attention, and few attempts have been made to match details of stone resources to the needs of various utility scrubbing systems. Optimization of the fit between geologic characteristics of the existing limestones and prospective scrubber systems should allow for greatly improved planning and operation of FGD systems with attendant lower overall costs.

Electric utilities have developed computer models to predict FGD system operations (i.e., the FGD-PRISM model of the Electric Power Research Institute). These models require geologic data such as reactivity that are commonly unavailable. We generated data needed for the model during a cooperative effort among the Indiana Department of Commerce, the Indiana Geological Survey (IGS), The Indianapolis Power & Light Company (IP&L), and the Indiana Mineral Aggregates Association. Our goal was to provide missing geologic details of Indiana scrubber-stone raw materials and apply them to the FGD-PRISM model to provide general guidance to determine which geologic units can provide stone for most efficient sulfur removal. Results of the model for selected limestones and parameters specific to one IP&L generating plant were calculated. Geologic data generated may be applied to other generating operations, and our examples should help other utilities optimize their FGD strategies.

Several hundred samples from more than 30 active quarries were collected and their physical properties determined. Grindability values ranged from 7.2 to 21.7 for 50 selected samples. Acid-insoluble residues of less than 1% to 13% were found. Dissolution rates as an index of reactivity varied over two orders of magnitude for the selected set of samples. These data plus chemical analyses and Ca/Mg ratios were entered into a generic scrubber model to determine rates of stone use and scrubber efficiency for various stone.

Removal of SO_2 was projected by this model to range from 89% to 98% with stone utilization rates from 91% to 93%. Excellent scrubber stone sources were found in Mississippian rocks in central and southern Indiana. Rocks of the Ste. Genevieve and Salem Limestones were especially efficient. Even small amounts of dolomite, clay minerals, and quartz diminished a stone's usefulness for FGD scrubbing.

Shaffer, N. R.; and Sadowski, Robert, 1999, Flue gas desulfurization (FGD) scrubber stone in Indiana, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 355.

A Rapid, Inexpensive, Nondestructive Technique to Assess Building-Stone Stains

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ABSTRACT.—Secondary minerals, amorphous materials, and biologic entities that form on building stone can cause aesthetically unflattering changes in color and may even result in stone decay. Techniques to determine causes of such changes generally have entailed destructive sampling and often required chemical, thin section, X-ray, or other relatively slow, expensive measurements. We have found that a rapid leach of in-place stone using small volumes (50–100 ml) of very pure distilled, deionized water provides recovery of sufficient dissolved material to help diagnose stone anomalies. Water is sprayed onto the stone and collected in a nonwetting plastic pan. Ion chromatograph analysis of waters thus collected from more than 160 sites showed wide variations in concentration of anions F, Cl, NO_3, and SO_4. Anion analyses were made in minutes for less than $20 per sample. Cations Ca, Mg, Fe, and Sr also were detected, and analyses might be used to determine mineral sources using equilibrium computer models. Solid particles filtered from the samples can be examined microscopically to provide further information about atmospheric agents affecting the stone. The collected water can even be evaporated to precipitate dissolved minerals.

Chloride values in samples rinsed from stone ran as high as up to 17,000 ppm, nitrate to 100 ppm, and sulfate to 1,000 ppm. Limited data also indicate that measurable amounts of fluoride were found in some of the rinse waters. Chlorides were most abundant in areas where the stone has become dimpled or spalled. Nitrates were generally higher near ground level, and sulfate tended to be more abundant in samples taken from higher sites or from sheltered sites. Dark-stained limestone tended to yield less soluble material than clean-looking stone. Leachable elements were higher in samples from urban areas. Most of our data are from limestone buildings, but the technique works on other types of dimension stone, man-made construction materials, and even natural outcrops of rocks. Longitudinal studies show that soluble materials vary through time and are affected by climate. This rapid, in situ leach technique, although still being perfected, shows great promise in the diagnosis of stone alteration and in the evaluation of stone treatments because it is completely nondestructive.

Shaffer, N. R.; and Branam, T. D., 1999, A rapid, inexpensive, nondestructive technique to assess building-stone stains, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 356.

Mining of Aggregates in Oklahoma

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ABSTRACT.—Before you begin mining aggregates in Oklahoma, you must first look at the market and ask these questions: (1) Is there a need for additional aggregate production? (2) Can we produce the aggregate efficiently enough to compete? (3) Is the deposit close enough to the market? If you can answer "yes" to each of these three questions, then you are ready to start the process for mining aggregates in Oklahoma.

The first consideration to be made is whether the aggregates produced will need to meet state specifications. If you do not want to meet state durability standards, there are numerous formations you can mine and produce aggregates. We will deal only with the formations that will meet state durability standards.

These formations are located in the southern half of Oklahoma and in the Tulsa area. Some of the formations that contain limestone, dolomite, and sandstone that will meet state durability tests are West Springs Creek, Kindblade, McKenzie Hill, Butterly-Royer, and Rush Springs Formations. Granite and rhyolite also are found in Oklahoma and can be used as construction aggregates.

Once an area has been identified as having durable material, and drilling has verified its properties, a permit must be secured from the Oklahoma Department of Mines, Oklahoma Department of Environmental Quality, and any other applicable agency before construction of a plant occurs.

There are many different brands of crushers available, but all work on one of two crushing principles—either compression breakage or impact breakage. Each type has its application in different industrial-mineral types and the desired end product. A typical small crushing plant would start with a jaw crusher for primary reduction, and then employ one standard cone and one shorthead cone for secondary reduction. One grizzly would be in the circuit with one finished-product screen and three to four finished-product stackers.

Natural sands and gravels are found in rivers and old river channels. These too need to be tested to see if spec product can be produced. All of our sand operations have very little gravel; thus, we do not process the gravel. The sand is processed through classifying tanks for gradation.

Lain, A. S., 1999, Mining of aggregates in Oklahoma, *in* Johnson, K. S. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, 1998: Oklahoma Geological Survey Circular 102, p. 357.

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