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DISPOSAL OF INDUSTRIAL WASTES IN OKLAHOMA

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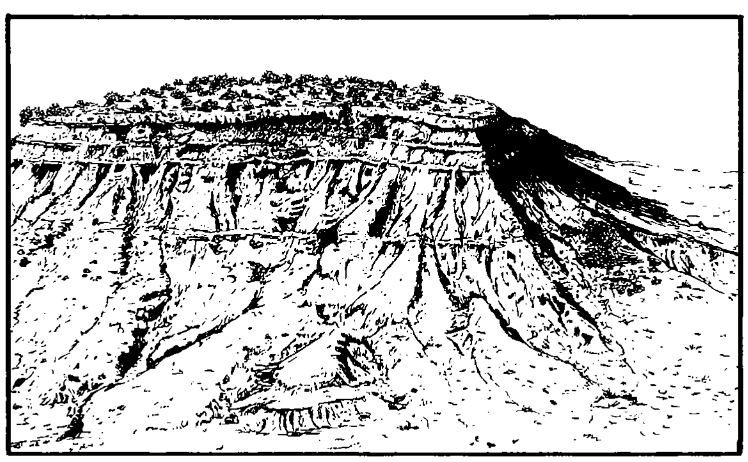

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The University of Oklahoma
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Title Page Illustration

Aerial view of a bluff composed of the Flowerpot Shale, capped by gypsum of the basal Blaine Formation, both of Permian age. The Flowerpot Shale is considered to be suitable locally for geologic containment of industrial wastes at or near the land's surface. Here, in this exposure near Mangum, in southwestern Oklahoma, the Flowerpot is 200 feet thick. Ink drawing by Roy D. Davis.

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DISPOSAL OF INDUSTRIAL WASTES IN OKLAHOMA

Abstract—A reconnaissance-level evaluation of the surface and subsurface geology of Oklahoma was conducted in order to identify those rock units that might be favorable for the disposal of industrial wastes. The data and interpretations presented should be of assistance in regional planning and in preliminary selection of potential disposal units, but additional detailed studies must be conducted to verify the waste-containment capability of a disposal unit at any particular site.

For surface disposal, the geologic setting, thickness, physical properties, and mineralogy were evaluated for each of the major geologic formations that crop out in the State. Geologic, mineralogic, and engineering data were used to classify the geologic formations in Oklahoma into three categories or zones: (1) generally favorable, (2) less favorable, and (3) least favorable for surface disposal of industrial wastes. Favorable units recommended for detailed study are shales, clays, and other low-permeability rocks that are more than 50 feet thick, whereas the least favorable category includes limestone, gypsum, permeable sandstone, alluvium, terrace deposits, and granite. The intermediate category embraces those rock units that locally contain thick shales or other low-permeability rocks that might be suitable for waste disposal. The foregoing information is displayed on a 1:750,000-scale base map of Oklahoma (pl. 1).

Rock types that are most desirable for subsurface waste disposal in Oklahoma are porous and permeable sedimentary rocks, such as sandstone, limestone, and dolomite, although fractured shale or mined caverns in shale and salt may also be suitable. Thick sequences of sedimentary rock make up most geologic provinces in the State, and it appears that most areas are underlain by potential host rocks that locally can contain industrial wastes safely. Major sandstone units that are capable locally of accepting liquid wastes include the Simpson Group, the Springer Formation, Pennsylvanian sandstones, granite wash, and Permian sandstones; major carbonate units include the Arbuckle Group, the Hunton Group, Mississippian limestones, the Brown dolomite, and Permian dolomites. Where used for waste disposal, these host rocks typically have porosities ranging from 5 to 20 percent and permeabilities ranging from 20 to 2,000 millidarcies.

PART I.—INTRODUCTION

KENNETH S. JOHNSON,[1] KENNETH V. LUZA,[1] AND JOHN F. ROBERTS[2]

In recent years, considerable attention has focused on the problem of disposal of industrial wastes in Oklahoma. Industrial wastes, such as spent acids, caustic solutions, poisons, flammable liquids, explosives, liquids containing heavy-metal ions, and other material, were disposed of in the past without sufficient assurance that they would be permanently isolated from fresh-water resources and the biosphere (the zone of living organisms). To properly regulate industrial-waste disposal in the future, the State of Oklahoma passed the Oklahoma Controlled Industrial Waste Disposal Act in 1976, modified in 1978, and the Oklahoma State Department of Health has established rules and regulations for carrying out the management and disposal of industrial wastes (Oklahoma State Department of Health, 1979).

To facilitate future selection of possible waste-disposal sites, the Oklahoma Geological Survey, in cooperation with the Oklahoma Department of Economic and Community Affairs, has conducted an evaluation of the surface and subsurface geology of the State in order to identify those rock units that appear generally favorable for the containment of wastes. This is a reconnaissance study, and it does not establish the suitability or unsuitability of any particular rock unit or any specific site for disposal of industrial wastes. The suitability of a rock unit for waste disposal at a particular site can only be established by detailed on-site investigations. Furthermore, this study addresses the disposal of controlled industrial wastes only and does not consider the disposal of radioactive wastes.

Waste disposal at the surface and in the subsurface is discussed separately in Parts II and III of this report, because of basic differences in the geologic criteria for emplace-

[1]Geologists, Oklahoma Geological Survey.
[2]Geologist, Oklahoma Geological Survey, deceased.

ment and containment of wastes in the two environments. Rock units most favorable for surface disposal are impermeable sedimentary rocks, such as shale and clay, that can be excavated and that can prevent loss or migration of wastes from the disposal pit. Rock types that are most desirable for subsurface waste disposal are porous and permeable sedimentary rocks, such as sandstone, limestone, and dolomite, that can accept injected liquid wastes. These porous and permeable subsurface units should be enveloped by impermeable strata to assure containment. Fractured shale or mined caverns in shale and salt may also be suitable locally for subsurface disposal.

Of primary concern in selecting a rock unit and site for waste disposal is the need for assurance that the waste will be isolated from fresh-water zones and the biosphere for as long as the waste is hazardous to man and his environment. This concern can be addressed by a thorough study of the geology and hydrology of a proposed site and its surrounding area. Such a study of the State and all the potential disposal sites within the State is beyond the scope of this report, but a brief summary of the State's geologic framework and hydrology is appropriate.

At many times in the past, parts of Oklahoma and surrounding states were covered by shallow seas, and thick layers of marine mud, sand, and lime were deposited. Other sands and muds were laid down at the same time as alluvial and deltaic deposits on land areas near the ancient seas. After burial beneath later sediments, these muds, sands, and lime layers were changed to shale, sandstone, and limestone, respectively, by compaction and the cementing together of the granular material. Rocks that now crop out are exposed by uplift of the earth's crust beneath parts of Oklahoma and by erosion of the sedimentary rocks that previously covered them. Uplift was accomplished either by gentle arching of broad areas or by the formation of mountains, where rocks were intensely folded and faulted and thrust upward.

The three principal mountain belts of Oklahoma—the Ouachita, Arbuckle, and Wichita—occur in the southern third of the State (fig. 1) and were formed by folding, faulting, and uplift during the Pennsylvanian Period of geologic time. North of the mountain uplifts are two deep basins (Anadarko and Arkoma), and north of these basins lie the relatively undisturbed shelf areas of northern Oklahoma.

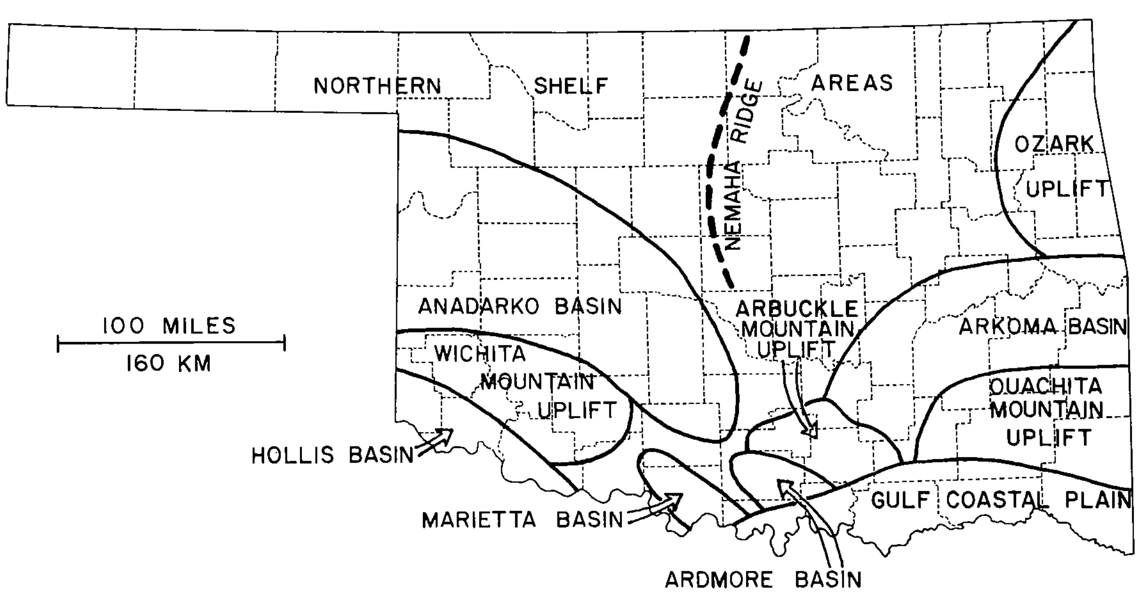


Figure 1. Map showing major geological provinces of Oklahoma.

The present distribution of rock units in Oklahoma is shown in geologic maps and cross sections (fig. 2). Although most of these rocks are of sedimentary origin, and range in age from Late Cambrian through Quaternary, the oldest are igneous rocks, or those that solidified from a molten state (chiefly granites, rhyolites, and gabbros), which crop out in the Arbuckle and Wichita Mountains. These and similar igneous and metamorphic rocks of Precambrian and Cambrian age underlie all of the State and are the floor or "basement" upon which all younger sedimentary rocks rest.

Sedimentary rocks in Oklahoma are as thick as 10,000 to 40,000 feet in the deep sedimentary basins, and they thin to 1,000 to 10,000 feet farther north in the northern shelf areas (fig. 2). In general, the strata are flat lying or gently dipping, except near the

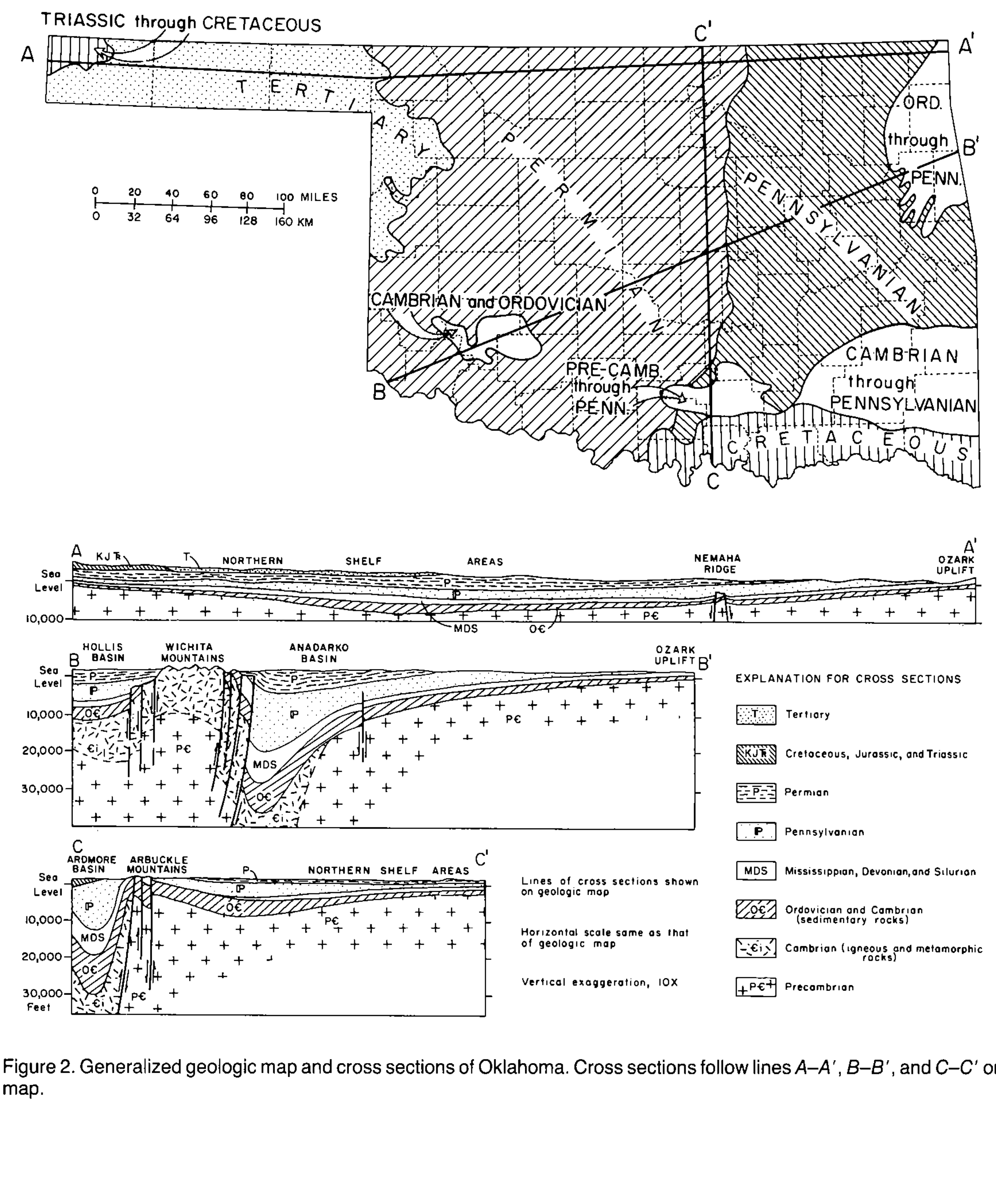


Figure 2. Generalized geologic map and cross sections of Oklahoma. Cross sections follow lines *A–A′*, *B–B′*, and *C–C′* on map.

mountain uplifts. These sedimentary rocks also contain the State's major ground-water aquifers (see fig. 6), which are chiefly sandstones, limestones, sands, gravels, and gypsum beds.

Most of the data used in preparing this report have come from published and unpublished reports of the Oklahoma Geological Survey, the Oklahoma Water Resources Board, the U.S. Geological Survey, the Oklahoma State Department of Health, the Oklahoma Department of Transportation, the Oklahoma Corporation Commission, the Oklahoma Department of Economic and Community Affairs, and other agencies and firms involved in testing earth materials or involved in waste disposal. We gratefully acknowledge the assistance and cooperation of each. Special thanks are due Ed Janesic of the Oklahoma Department of Economic and Community Affairs and H. A. Caves of the Oklahoma State Department of Health for their continued support and advice in carrying out this project. Assistance in compiling data was provided by Bill Fishman, Marty Reis, and Ernie Schmuckli. Cartographic work was done by Roy Davis, Bridget Houston, and Joe Zovak. Pete Eidson collected and analyzed shale samples for their clay-mineral content.

The manuscript was reviewed by R. H. Arndt, W. B. Creath, R. O. Fay, W. E. Harrison, R. B. Morton, and staff members of the Oklahoma State Department of Health and the Oklahoma Water Resources Board. We are grateful for their assistance. Recommendations made by each have been incorporated in the report.

Preparation of this study was financed in part by the Economic Development Administration, U.S. Department of Commerce, under grant no. 08-06-01879-40 (in the amount of $14,698), and in part by the Oklahoma Department of Economic and Community Affairs and by the Oklahoma Geological Survey. Statements, findings, conclusions, recommendations, and other data in this report are solely those of the authors and do not necessarily reflect the views of contributing agencies or the reviewers.

PART II.—SURFACE DISPOSAL OF INDUSTRIAL WASTES IN OKLAHOMA

KENNETH S. JOHNSON[1] AND KENNETH V. LUZA[1]

INTRODUCTION

Solid and liquid industrial wastes have been disposed of in some areas of Oklahoma by surface burial in soil or rock units. Waste products, such as acids, caustic solutions, flammable liquids, explosives, liquids containing heavy-metal ions, and other materials, have been placed in excavated pits and then buried beneath soil or rock. At present, Oklahoma has only two operating industrial-waste surface-disposal sites; one is near Criner, in McClain County, and the other is in northwest Major County. A third facility has been proposed for near Red Rock in Noble County.

In this statewide reconnaissance-level study, we have examined and evaluated the geologic parameters related to industrial-waste disposal at the surface, and we herein identify those bedrock units that appear generally to be most suitable for containment of waste. Data presented on potential host rocks for surface disposal include thickness, bedding-plane attitudes, and character. The character of a potential host rock includes its physical, mineralogic, and lithologic properties. Physical parameters are grain size, permeability, plasticity, and shrink-swell potential, whereas the mineralogic data of chief importance concern the identity of the major clay minerals. The lithologic properties used to evaluate bedrock units include the presence or absence of fractures, faults, joints, cavities, caverns, and thin layers or lenses of permeable rock.

In Oklahoma, shales and clays are generally the most desirable rock units for geological containment of industrial wastes at the surface. Most shales and clays, when wet, have more soil-like rather than rock-like properties, and they consist chiefly of clay minerals, such as illite, montmorillonite, chlorite, and kaolinite, that generally have the ability to adsorb metal ions as well as to retard the lateral and vertical migration of fluids. Several of the more comprehensive and (or) detailed studies of clays and shales in Oklahoma are those by Sheerar (1932), Weaver (1958), Everett (1962), Wong (1964, 1969), Cassidy (1966), Nalewaik (1968), Bucke (1969), Wu (1969), Bellis (1972), Laguros (1972), and Bellis and Rowland (1976).

Many other outcropping rock types in Oklahoma generally are not well suited for surface disposal of wastes. Rocks such as limestone and gypsum are quite susceptible to dissolution and commonly are cavernous, which makes long-term containment unlikely. Granite and metamorphic rocks generally are intensely fractured, which might permit the downward and lateral migration of fluids, and many sandstone units have a fairly high porosity and permeability that could permit the infiltration and migration of fluids.

Other factors that need to be assessed in selecting a disposal site include climatology, hydrology, and demography.

Climatological information, including annual and monthly precipitation records, evaporation data, and wind-direction information, needs to be incorporated into the disposal-site selection process. Evaporation and precipitation data are particularly important in determining the potential for solar evaporation of residual water that may occur with various industrial wastes. The prevailing wind speeds and directions are important parameters for assessing the dispersion of possible atmospheric releases from a storage facility.

The climate of Oklahoma varies considerably from east to west. Southeastern Oklahoma has a moist, humid climate, with annual precipitation locally averaging as high as 56 inches (fig. 3). Precipitation decreases westward across the State to the Panhandle, where average annual precipitation is 16 to 20 inches. Average annual lake evaporation ranges from a high of about 64 inches in the southwest part of the State to a low of 46 inches in the northeast (fig. 4). Data

[1]Geologists, Oklahoma Geological Survey.

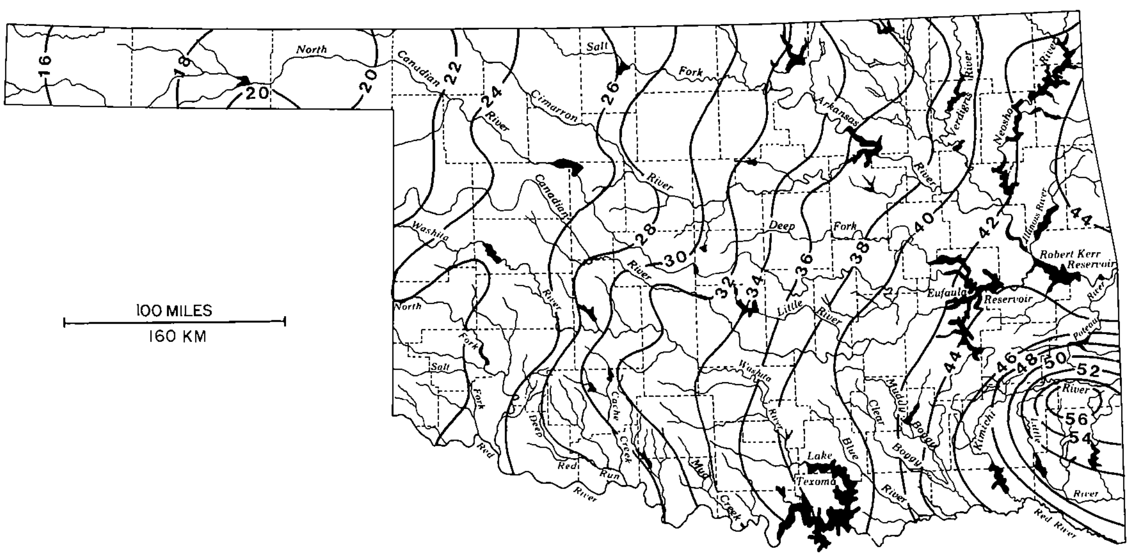


Figure 3. Map showing average annual precipitation, in inches, for Oklahoma during period 1931–60 (Oklahoma Water Resources Board, 1973).

in figures 3 and 4 show that annual evaporation exceeds annual precipitation in all parts of the State, except in the southeast in all or parts of Le Flore, Latimer, Pushmataha, and McCurtain Counties.

Records of atmospheric conditions and precipitation information are reported by the National Weather Service and the National Oceanic and Atmospheric Administration (U.S. Department of Commerce). Additional information can be obtained from local as well as regional weather stations, the Soil Conservation Service (U.S. Department of Agriculture), and the Water Resources Division of the U.S. Geological Survey (U.S. Department of the Interior).

Hydrologic information is most critical to evaluation of a potential waste-disposal site. The surface-water regime, which includes precipitation, evaporation, runoff, streams, rivers, lakes, and flood-prone areas, is important in assuring that a proposed site will not be inundated by floodwaters or be breached by erosion during or after its operation. In addition, the ground-water regime and the proximity of a proposed site to freshwater aquifers must be evaluated fully to assure that important water supplies will not be contaminated.

Surface water results chiefly from precipitation that falls on the land surface and runs off to form streams and rivers. Runoff ranges from about 0.2 inch a year in the Panhandle to nearly 20 inches in southeastern Oklahoma (fig. 5). The entire State is drained by the Arkansas and Red Rivers and their tributaries. Each year approximately 13 million acre-feet of water flows into the State through these streams, 22 million acre-feet is added by runoff from precipitation, and 35 million acre-feet flows out (Johnson and others, 1972, p. 8). Most streams have erratic flows, and many smaller ones go dry, or nearly so, each year. Consequently, reservoirs, lakes, and ponds have been constructed throughout the State to provide a dependable supply of water as well as for other purposes.

The State contains approximately 1,800 lakes with an area of 10 acres or more and an estimated 190,000 farm ponds with an area of less than 10 acres. The capacity of the 21 largest reservoirs is nearly 11 million acre-feet. The largest reservoirs are Lake Texoma, with a capacity of about 3 million acre-feet, and Eufaula Reservoir, with a capacity of about 2.4 million acre-feet. Reservoirs and lakes provide for flood control, generation of electricity, recreation, and water supply. About 80 percent of all water used by cities and industries is taken from surface-water sources (Johnson and others, 1972, p. 8).

The location and characteristics of

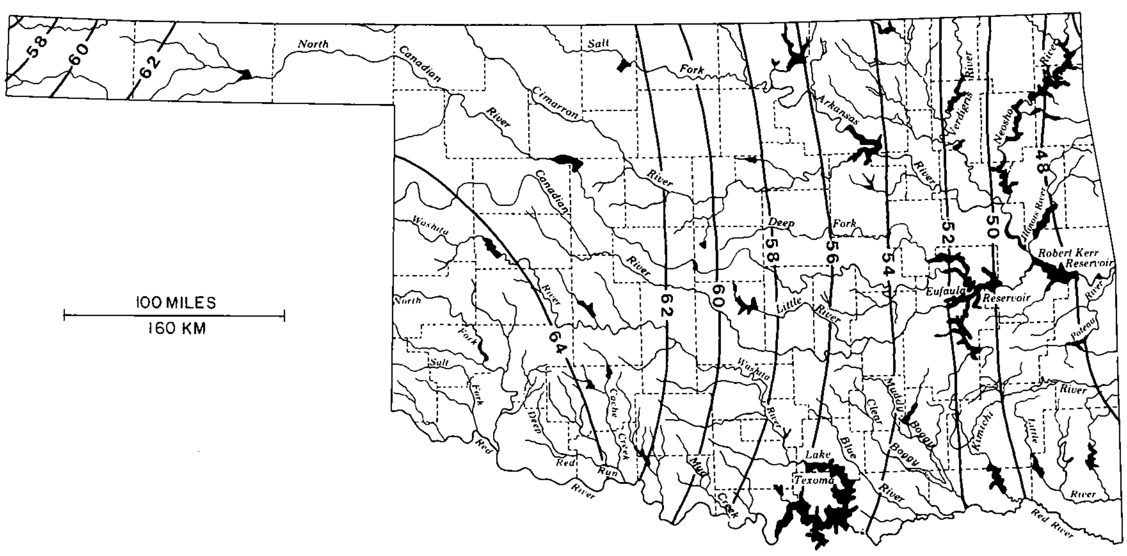


Figure 4. Map showing average annual lake evaporation, in inches, for Oklahoma during period 1946–55 (Oklahoma Water Resources Board, 1973).

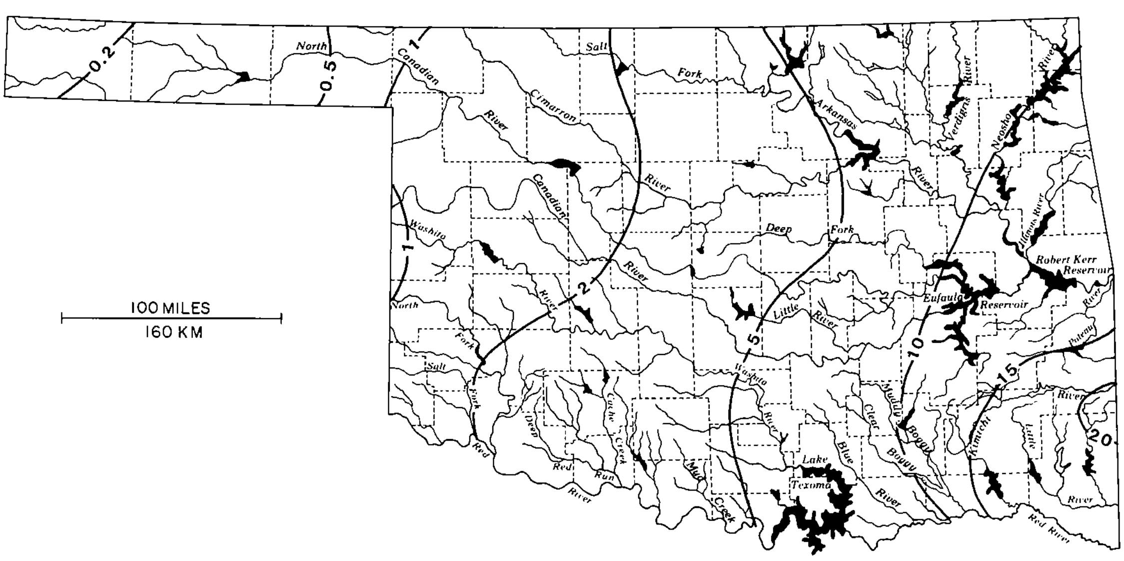


Figure 5. Map showing average annual runoff, in inches, for Oklahoma during period 1931–60 (Oklahoma Water Resources Board, 1973).

ground-water sources is an important element in judging the suitability of a region or a site for waste disposal. The recharge areas for aquifers should be avoided in order to prevent possible contamination of ground-water supplies. Oklahoma's major ground-water aquifers are stream deposits (alluvium, terrace deposits, and the Ogallala Formation), limestone, sandstone, and gypsum (fig. 6). The areas not underlain by aquifers consist mainly of shales, siltstones, and some sandstones that yield, in some cases, only enough water for household use (Johnson and others, 1972, p. 8).

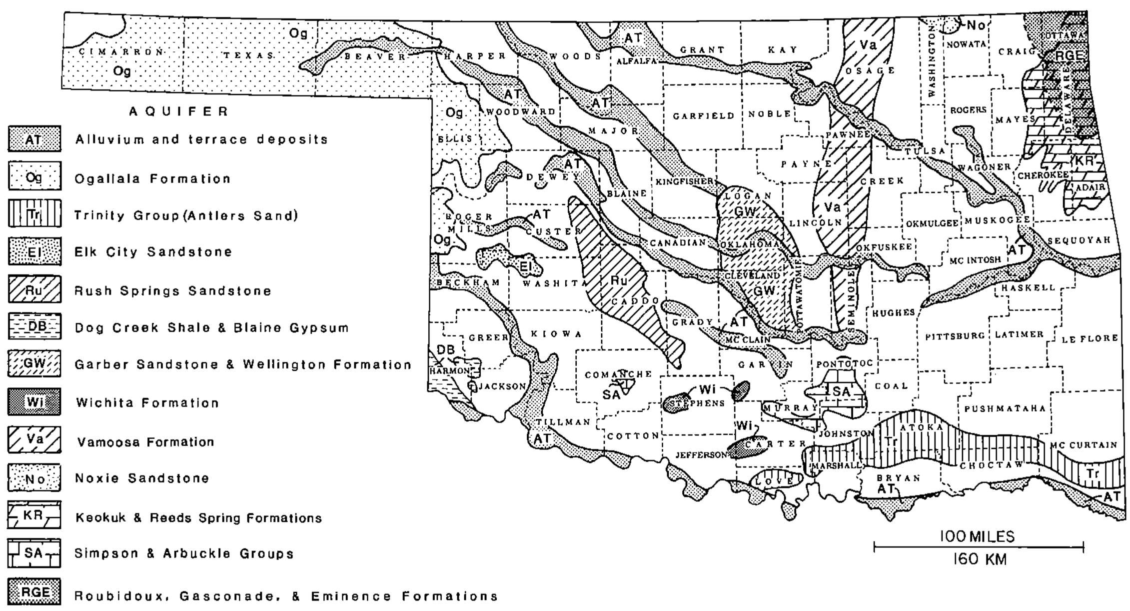


Figure 6. Map showing major sources of ground water in Oklahoma (modified from Johnson and others, 1972, p. 8).

Additional hydrologic information can be obtained from the Oklahoma Water Resources Board (Oklahoma City), the Water Resources Division of the U.S. Geological Survey (U.S. Department of the Interior), the U.S. Bureau of Reclamation (U.S. Department of the Interior), and the U.S. Army Corps of Engineers.

Population density, which is a measure of the average number of persons per square mile, can play an important role in the selection of a site for industrial-waste disposal. Five categories are used in figure 7 to portray population densities for the State of Oklahoma. Only two counties, Oklahoma and Tulsa, have population densities of 500 or more persons per square mile; 12 counties have densities greater than 50; and 14 counties have fewer than 10 persons per square mile.

Oklahoma is divided into 11 substate planning districts for planning and administrative purposes (fig. 8). Each district is intended to contain a group of people with similar attitudes and to consist of an area with similarities in natural and man-made resources, technology, and institutions. Many of the planning districts share the same geologic and tectonic settings, and the outcropping rock units favorable for waste disposal typically are widespread in one district but can extend across parts of two or more planning districts. Therefore, in the discussion that follows, we have grouped together those planning districts with similar geologic units in order to minimize repetition and to simplify the discussion of individual bedrock units. Planning districts discussed together include districts 1 and 2; 3 and 4; 5 and 6; 7, 8, and 9; and 10 and 11.

CLASSIFICATION OF ROCKS INTO ZONES 1, 2, AND 3

The geological rock units of the State are herein classified into three principal zones: Zone 1, generally favorable; Zone 2, less favorable; and Zone 3, least favorable for surface disposal of controlled industrial wastes.

The major criteria used in classifying a rock unit for Zone 1 are that the unit consist of low-permeability material and that it have sufficient vertical and lateral extent to assure long-term geologic containment of waste. Thick and widespread deposits of shale and clay best fulfill these general requirements in Oklahoma, and we arbitrarily have selected a minimum thickness of 50 feet as a criterion for identifying the most favorable rock units in the State. Although shales less than 50 feet thick may be suitable locally

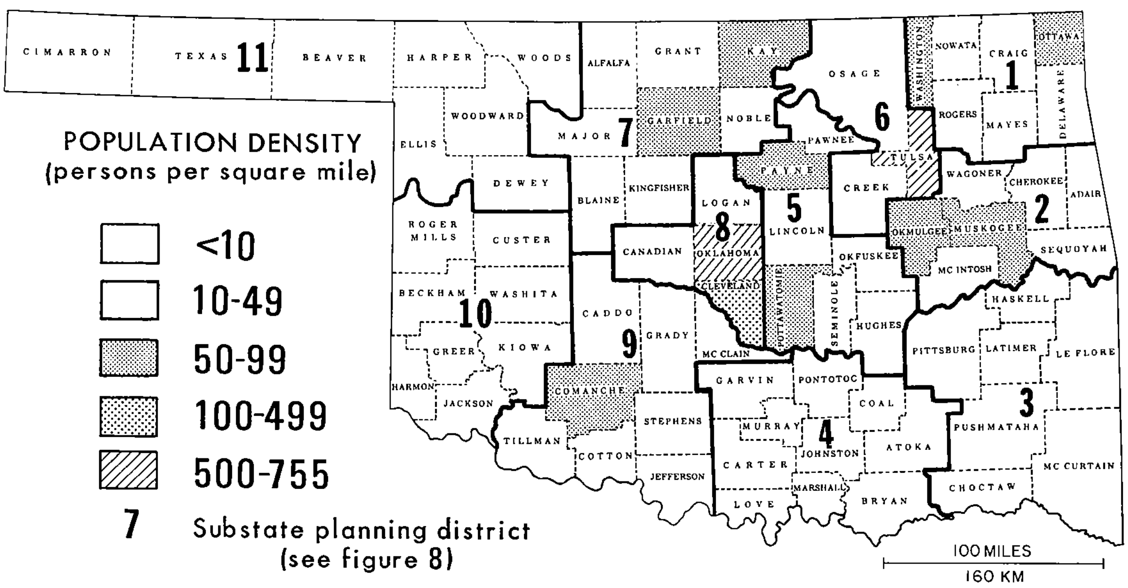


Figure 7. Map showing population density by county for Oklahoma; 1970 census figures (Oklahoma Office of Community Affairs and Planning, 1974; Shreiner and Chang, 1975).

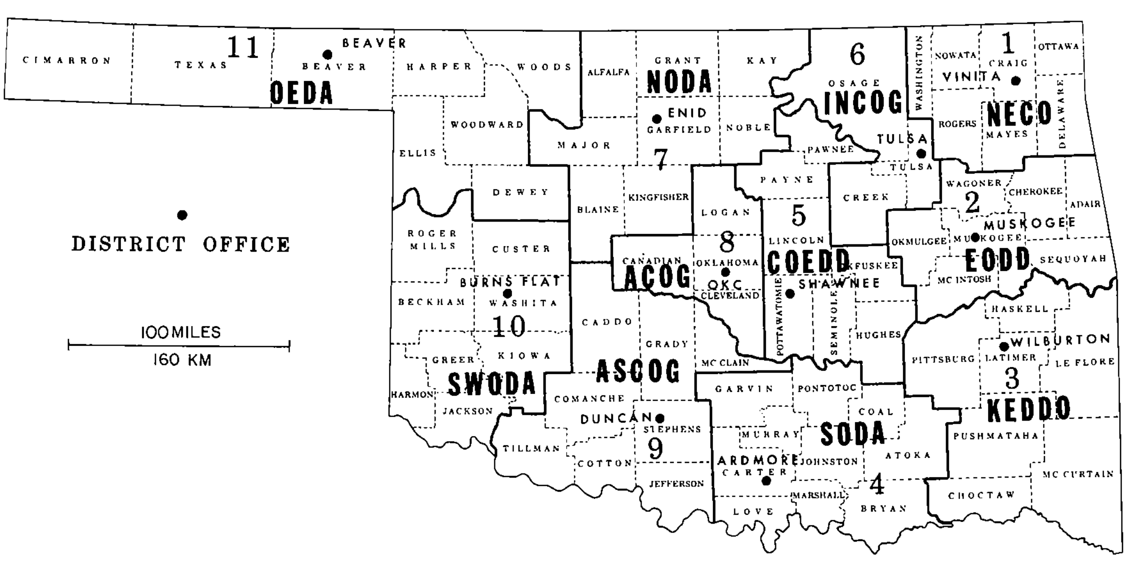


Figure 8. Map showing Oklahoma's 11 substate planning districts: *1*, Northeast Counties of Oklahoma Economic Development Association; *2*, Eastern Oklahoma Development District; *3*, Kiamichi Economic Development District of Oklahoma; *4*, Southern Oklahoma Development Association; *5*, Central Oklahoma Economic Development District; *6*, Indian Nations Council of Governments; *7*, Northern Oklahoma Development Association; *8*, Association of Central Oklahoma Governments; *9*, Association of South-Central Oklahoma Governments; *10*, Southwestern Oklahoma Development Association; *11*, Oklahoma Economic Development Association.

for waste containment, such shales are too numerous for us to characterize in this reconnaissance report and are too thin to be shown adequately on the accompanying maps (pl. 1, in pocket, and the planning-district maps in the text).

Zone 1, therefore, consists of the outcrop areas of those bedrock formations composed predominantly of shale or clay units at least 50 feet thick where such shale or clay units are at the land surface or are covered by no more than 10 to 20 feet of soil, alluvium, or other loose material that can be excavated easily. The shale and (or) clay materials typically have very low permeability coefficients, low to moderate plasticity, and low to moderate shrink-swell potentials. The dominant clay minerals are usually illite, kaolinite, and montmorillonite.

Zone 2 embraces areas that are less likely to contain bedrock units suitable for surface disposal of industrial wastes. This zone includes some outcrops of thick shale or clay, as in Zone 1, but the shales are relatively few and are interbedded with other rocks, such as sandstone, siltstone, and thin layers of limestone. Therefore, field studies are needed to identify those parts of a Zone 2 area that may be suitable locally for industrial-waste containment.

Zone 3 areas contain bedrock units least suitable for surface disposal of industrial wastes. There is little likelihood that thick shales or clays, such as those in Zone 1, are present in rock units placed in this category. The geologic units of this category consist mostly of porous and permeable rock units, such as (1) sand, silt, and gravel in alluvium and terrace deposits; (2) sand, sandstone, and limestone in the recharge areas of important ground-water aquifers; and (3) limestone, dolomite, and gypsum in areas of cavernous or karst features. Granite and other igneous rocks are also included in this zone.

Assignment of each of Oklahoma's bedrock units to one of these three zones is based upon previous field studies and upon review of published and unpublished geologic reports for all rock units in the State. Assignment of an area or a rock unit to a particular zone does not confirm or reject its suitability for waste containment, as that can be done only through detailed on-site exploration and testing of a prospective site. Furthermore, the assignment does not take into account any special engineering techniques, such as clay liners, that might assure long-term containment of waste in a somewhat permeable host rock.

The statewide distribution of geologic bedrock units according to this threefold zonal classification is presented on a map at a scale of 1:750,000, or 1 inch equals approximately 12 miles (pl. 1, in pocket). This map should be used as a preliminary guide to the geologic suitability of outcropping rocks for use as host rocks for the surface disposal of industrial wastes. Owing to the small scale of the map, many reservoirs, ponds, streams, and thin deposits of permeable surficial material have been mapped inadvertently as parts of Zones 1 and 2; these elements need to be taken into consideration during the site-selection process. The mapped boundaries between various zones have been compiled from the most recent geologic maps available, and it may be necessary for the user to refer to those detailed maps and reports that are cited in the references at the end of this report.

CLAY MINERALOGY AND SELECTED ENGINEERING PROPERTIES FOR ZONE 1

The evaluation of a prospective site for industrial-waste disposal must include the determination of some chemical and physical parameters, such as clay mineralogy and engineering properties, for the potential host rock. Clay mineralogy and selected engineering properties (plasticity index and shrink-swell potential) are described for each Zone 1 unit for the following reasons: (1) to assess the cation-exchange capacity, (2) to provide some insight into adsorption capacity, and (3) to use in making relative comparisons. The clay-mineral data and engineering-property values used in this report are only approximate and should be used only for comparisons relative to each geologic unit. The data presented for the various rock units in each planning district indicate average physical properties and should not serve as a substitute for detailed on-site investigations.

Clay Mineralogy

Materials that contain large amounts of clay and organic matter generally have higher cation-exchange capacities (CEC) than those that do not. CEC is a measure of the chemical reactivity of a material and generally is an indication of the effectiveness of the material in adsorbing contaminants such as heavy metals from waste water. Although CEC values of a rock generally increase with corresponding increases in clay content, the actual value depends largely on the type of clay mineral present. Expandable clays such as montmorillonite and vermiculite can adsorb 5 to 10 times more exchangeable cations than nonexpandable clays such as illite and kaolinite (U.S. Environmental Protection Agency, 1977). Griffin and others (1976, 1977) determined that montmorillonite has the greatest capability of attenuating (reducing the concentration of) chemical constituents of landfill leachates, with lesser capability exhibited by illite and kaolinite.

Some of the geologic materials that contain large quantities of clay minerals are shale, decomposed volcanic ash, and lake-bed deposits. Some stream deposits locally contain clay-rich layers, but their lateral extent is often limited. In Oklahoma, thick shale units, ranging in age from Mississippian to Cretaceous, contain significant quantities of clay minerals (table 1). The principal clay mineral is montmorillonite in the Cretaceous units (Eagle Ford and Bokchito Formations), with lesser amounts of illite and kaolinite. In the remaining geologic units (Permian through Mississippian), the principal clay mineral is generally illite, followed by lesser amounts of kaolinite, chlorite, vermiculite, montmorillonite, and mixed-layer clays such as illite-montmorillonite, illite-vermiculite, and illite-chlorite.

To supplement clay-mineralogy data available from previous studies, 17 geologic units at 32 localities were sampled for clay-mineral identification (fig. 9). Approximately 100 grams of material from each sample was placed in a 500-mL beaker, and distilled water, along with a dispersing agent, was added. An ultrasonic probe was placed in the beaker to aid in the dispersion process. Following dispersion, part of the sample was withdrawn and placed on a glass slide. Three X-ray-diffraction patterns—one for the sedimented slide, one for the sedimented slide treated with ethylene glycol, and one for a heat-treated glycolated slide—were obtained for each sample. These techniques were used to identify the clay minerals in each sample. A summary of the dominant clay minerals for each geologic unit sampled is presented in table 2. These mineralogical data, along with data obtained from published sources, are intended to provide only a general guide for the nature and distribution

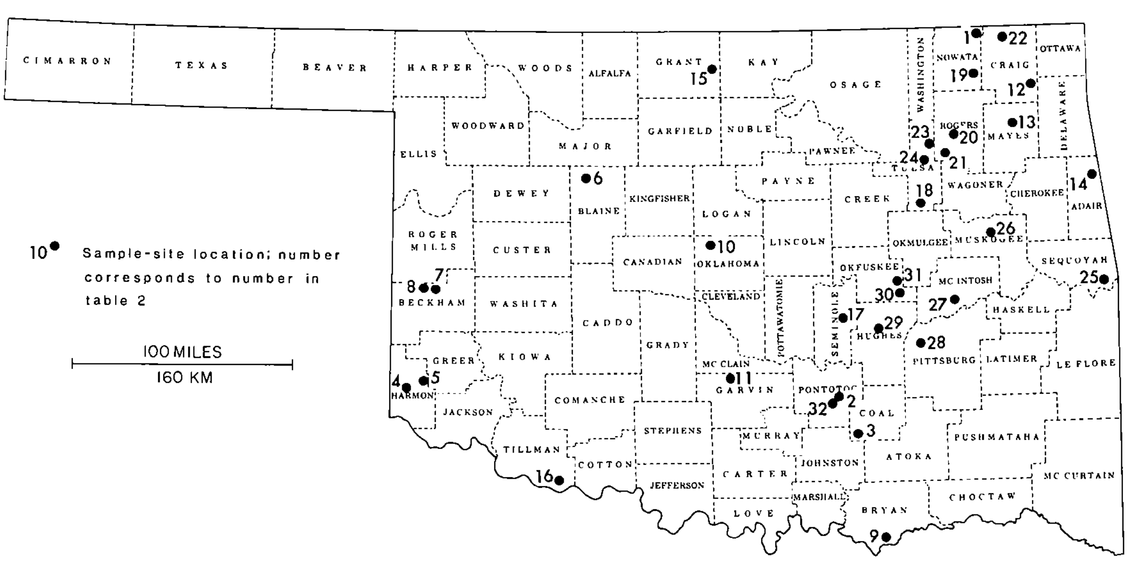


Figure 9. Map of Oklahoma showing localities from which 32 shale samples were collected for this investigation.

TABLE 1.—PRINCIPAL OKLAHOMA SHALE FORMATIONS AND THEIR DOMINANT CLAY MINERALS ARRANGED ACCORDING TO GEOLOGIC AGE

System	Formation	Dominant clay minerals	Information source(s)
Cretaceous	Eagle Ford	Montmorillonite, illite, kaolinite	8
	Bokchito	Montmorillonite, illite, kaolinite	7
Permian	Doxey	Illite, montmorillonite-chlorite, kaolinite, chlorite	8
	Dog Creek	Illite, kaolinite, chlorite-vermiculite, chlorite-montmorillonite	8
	Flowerpot	Illite, chlorite, kaolinite, montmorillonite	5, 7, 9, 15
	Bison	Illite, illite-chlorite	6
	Fairmont	Illite-chlorite-montmorillonite, illite, kaolinite, chlorite	8
	Garber	Illite, illite-chlorite-montmorillonite, kaolinite	8
	Wellington	Illite, kaolinite, chlorite, montmorillonite	7, 9
Pennsylvanian	Oscar	Illite, kaolinite, chlorite, illite-montmorillonite	1, 7, 9
	Vanoss	Kaolinite, illite, montmorillonite, illite-montmorillonite	4, 9, 10
	Hilltop	Kaolinite, illite, montmorillonite, chlorite	8
	Barnsdall	Illite, kaolinite, chlorite-vermiculite	1
	Chanute	Illite, kaolinite, vermiculite-chlorite	1
	Nellie Bly	Illite, kaolinite, vermiculite	1
	Coffeyville	Illite, chlorite, kaolinite, montmorillonite, vermiculite	2, 12
	Seminole	Illite, kaolinite, vermiculite, illite-vermiculite	12
	Holdenville	Illite-montmorillonite, illite, kaolinite	8
	Wewoka	Illite, illite-montmorillonite, kaolinite	8
	Wetumka	Illite-montmorillonite, illite, kaolinite	8
	Nowata	Illite, kaolinite, vermiculite, chlorite	8
	Bandera	Illite-vermiculite, illite	8
	Labette	Illite, illite-montmorillonite, illite-vermiculite, kaolinite	7, 8
	Senora	Illite, kaolinite	3, 7
	Stuart	Illite, illite-vermiculite, illite-montmorillonite, montmorillonite, kaolinite	8
	Boggy	Illite, kaolinite, montmorillonite, illite-montmorillonite	7
	Savanna	Illite, kaolinite, chlorite, vermiculite	8
	McAlester	Illite, kaolinite, illite-montmorillonite	7
	"Atoka"	Illite, chlorite, kaolinite, illite-montmorillonite, vermiculite	11, 14
	Johns Valley	Illite, chlorite, kaolinite	11
Mississippian	Stanley	Illite, chlorite, kaolinite	9, 11, 13
	Goddard	Kaolinite, montmorillonite, illite, illite-montmorillonite	7
	Fayetteville	Illite-chlorite-montmorillonite, illite, kaolinite, chlorite	8
	Delaware Creek	Illite-chlorite, illite-montmorillonite, illite, kaolinite, chlorite	8
Mississippian–Devonian	Woodford	Illite, illite-chlorite, chlorite	8

References

1. Bellis and Rowland (1976)
2. Bucke (1969)
3. Cassidy (1966)
4. Cullers and others (1975)
5. Everett (1962)
6. Ham and others (1959)
7. Laguros (1972)
8. Oklahoma Geological Survey (table 2, this report)
9. Shelton and Al-Shaieb (1976)
10. Thomas (1974)
11. Weaver (1958)
12. Wolfson (1963)
13. Wong (1964)
14. Wong (1969)
15. Wu (1969)

TABLE 2.—SUMMARY OF DOMINANT CLAY MINERALS FOR 32 SAMPLES FROM 17 GEOLOGIC UNITS
(Sample localities given in figure 9)

Location no.	Sample no.	County	Location	Geologic unit	Dominant clay minerals
1	NOW–1b	Nowata	SW¼ 36-29N-17E	Bandera	Illite-vermiculite, illite, kaolinite
2	PON–1	Pontotoc	SE¼ 35- 3N- 6E	Delaware Creek	Illite-montmorillonite, illite, kaolinite, chlorite
3	COA–1	Coal	SW¼ 11- 1S- 8E	Delaware Creek	Illite-chlorite, illite, chlorite, kaolinite
4	HRM–3	Harmon	SW¼ 33-3N-25W	Dog Creek	Illite, kaolinite, chlorite-vermiculite, illite-montmorillonite
5	HRM–4	Harmon	NW¼ 23- 4N-24W	Dog Creek	Illite, chlorite-montmorillonite, kaolinite, chlorite-vermiculite
6	BLA–2b	Blaine	SE¼ 21-18N-12W	Dog Creek	Illite, kaolinite, chlorite-vermiculite, chlorite-montmorillonite
7	BEC–2	Beckham	SE¼ 32-11N-23W	Doxey	Illite, chlorite-montmorillonite, kaolinite, chlorite-vermiculite, chlorite
8	BEC-4	Beckham	SE¼ 20-11N-24W	Doxey	Montmorillonite, illite, chlorite-montmorillonite, kaolinite, illite-chlorite
9	BRY-1	Bryan	NE¼ 6- 9S-10E	Eagle Ford	Montmorillonite, illite, kaolinite
10	OKL–1	Oklahoma	N½ 33-14N- 3W	Fairmont	Illite-chlorite-montmorillonite, kaolinite, illite, chlorite
11	GAR–1	Garvin	SW¼ 13- 4N- 3W	Fairmont	Illite-chlorite-montmorillonite, chlorite-vermiculite, illite, kaolinite
12	CRA–2	Craig	SW¼ 15-25N-21E	Fayetteville	Illite-chlorite-montmorillonite, illite, kaolinite
13	MAY-1	Mayes	SW¼ 6-22N-20E	Fayetteville	Illite-chlorite, illite, kaolinite, illite-montmorillonite, vermiculite
14	ADA–1	Adair	SE¼ 24-18N-25E	Fayetteville	Illite-chlorite, illite, kaolinite, chlorite
15	GRA–1	Grant	SE¼ 14-27N -3W	Garber	Illite, chlorite-montmorillonite, kaolinite
16	TIL–1	Tillman	NW¼ 4-4S-15W	Garber	Illite, illite-chlorite-montmorillonite, kaolinite, chlorite
17	SEM–1	Seminole	NW¼ 11- 8N- 7E	Hilltop	Kaolinite, illite, montmorillonite, chlorite
18	TUL–1	Tulsa	NW¼ 32-17N-13E	Holdenville	Illite-montmorillonite, illite, kaolinite
19	NOW–1	Nowata	SW¼ 17-26N-17E	Labette	Illite-montmorillonite, illite, kaolinite
20	ROG–1	Rogers	S½ 9-21N-15E	Labette	Illite, illite-montmorillonite, kaolinite
21	ROG–2	Rogers	SW¼ 19-20N-15E	Labette	Illite, illite-vermiculite, vermiculite, kaolinite
22	CRA–1	Craig	SW¼ 7-28N-19E	Labette	Illite, kaolinite, chlorite
23	TUL–ow	Tulsa	SW¼ 20-21N-14E	Nowata	Illite-vermiculite-montmorillonite, illite, vermiculite, kaolinite
24	TUL-2	Tulsa	SE¼ 36-20N-13E	Nowata	Illite, kaolinite, vermiculite, chlorite
25	SEQ-2	Sequoyah	22-11N-26E	Savanna	Illite, kaolinite, vermiculite
26	MUS–1	Muskogee	NW¼ 15-14N-18E	Savanna	Illite, kaolinite, chlorite, vermiculite, illite-chlorite
27	MCI-2	McIntosh	SW¼ 4- 9N-15E	Stuart	Illite-vermiculite, illite, kaolinite
28	PIT–1	Pittsburg	SE¼ 11- 6N-12E	Stuart	Illite, illite-montmorillonite, montmorillonite
29	HUG–2	Hughes	NE¼ 8- 7N-10E	Wetumka	Illite-montmorillonite, illite, kaolinite
30	OKF–2	Okfuskee	NW¼ 15-10N-11E	Wetumka	Illite-montmorillonite, illite, kaolinite
31	OKF–1	Okfuskee	SW¼ 11-11N-11E	Wewoka	Illite, illite-montmorillonite, kaolinite
32	PON-2b	Pontotoc	NW¼ 2- 2N- 6E	Woodford	Illite, illite-chlorite, chlorite

of clay minerals by geologic formation and not to serve as a substitute for detailed on-site investigations, because individual clay-mineral species, as well as concentrations, vary from site to site for each geologic unit.

Selected Engineering Properties

Thick shale units are ideally suited for surface containment of industrial wastes, because they normally have low permeability coefficients, 10^{-6} cm/sec or less. Since very few reported permeability-coefficient measurements are available for Oklahoma shale formations, no permeability data are reported here. However, there are indirect methods for assessing the relative permeability of a material as well as evaluating clay content and clay mineralogy for comparative purposes. One such technique utilizes a series of empirical tests to determine some physical properties of materials that have soil-like characteristics. The values derived from these empirical tests are known as Atterberg limits and indices (table 3). Each boundary or limit—shrinkage, plastic, and liquid—is defined by the water content for which the material is in a certain stage or state. The limits described are all expressed by their percentage of water content and normally are shown as a unitless number. The plasticity index (PI)—the difference between the liquid and plastic limits—represents the range in water content through which a material is in the plastic state. The plasticity index is inversely proportional to the ease with which water passes through a material. Therefore, a material with a high plasticity index will generally have a low permeability coefficient. The plasticity index also can be used to assess clay content. Generally, materials that have high plasticity indices also have high clay-mineral contents.

The plasticity index and shrinkage limit can be used to give some indication of the potential volume change that can be expected in a material (table 4). In general, a high plasticity index and a low shrinkage limit indicate a high shrink-swell potential. This is usually the case when clays of the montmorillonite family are present in significant enough quantities to cause large fluctuations between swelling and shrinking.

Plasticity-index and shrinkage-limit values were used to assess plasticity and

TABLE 3.—ATTERBERG LIMITS AND INDICES
(Modified from Sowers and Sowers, 1961)

Liquid state		
	Liquid limit (LL)	Plasticity index (PI) (PI = LL−PL)
Plastic state		
	Plastic limit (PL)	
Semi-solid state		
	Shrinkage limit (SL)	
Solid state		

TABLE 4.—SHRINK-SWELL POTENTIAL
(Modified from Sowers and Sowers, 1961)

Volume change	Shrinkage limit	Plasticity index
Probably high	0-10	>30
Probably moderate	10-12	15-30
Probably low	>12	0-15

TABLE 5.—PLASTICITY TERMINOLOGY IN RELATION TO PLASTICITY INDEX
(Modified from Sowers and Sowers, 1961)

Term	Plasticity index
Nonplastic	0-3
Slightly plastic	4-8
Medium plastic	9-30
Highly plastic	>30

shrink-swell potentials for the geologic rock units identified as generally favorable for the surface disposal of industrial wastes (tables 7, 9, 11, 13, 15). These parameters can be used to assess relative permeability and clay content and to provide a basis to make shale-formation comparisons for physical properties. There is considerable variation in properties from outcrop to outcrop. Therefore, descriptive terms, such as high, moderate, and low, were selected in order to incorporate a range of values that describe some of the physical characteristics of a shale formation (tables 4, 5).

Most of the engineering data were derived from laboratory tests conducted by the Oklahoma Highway Department, now the Oklahoma Department of Transportation (Hartronft and others, 1965, 1966, 1967, 1968, 1969, 1969a, 1969b, 1970).

DESCRIPTIONS OF ROCK UNITS IN ZONE 1

A total of 35 different formations in Oklahoma contain shale or clay units at least 50 feet thick that may be suitable locally for geologic containment of industrial wastes. All or part of each formation is classified as Zone 1, and the outcrop area of each Zone 1 unit is shown on plate 1 (pocket). The following descriptions of these units are generalized and apply to the statewide occurrences of the formations, but additional detailed data on each rock unit in specific areas can be obtained through the references cited for each formation.

1. "Atoka" Formation

The "Atoka" Formation (Lower Pennsylvanian) is a sequence of shale and interbedded sandstone 800 to more than 15,000 feet thick. Selected intervals, 50 to 500 feet thick, consist chiefly of brown to gray shale with minor amounts of interbedded sandstones; these intervals have been placed in Zone 1 in parts of districts 2, 3, and 4. These shales typically are not well exposed, except locally beneath small ridges capped by the interbedded sandstones. In most areas the shales have a thin to thick soil cover and form gently rolling to broad, flat plains. "Atoka" strata are gently to moderately folded, and in places they are faulted; dips range from low to high angle. Clay minerals in the shales are illite, chlorite, kaolinite, and mixed-layer illite-montmorillonite. Shales have a light to medium plasticity and a low to moderate shrink-swell potential.

References for the "Atoka" include Oakes and Knechtel (1948), Knechtel (1949), Weaver (1958), Wong (1969), Hartronft and others (1966, 1968, 1970), Marcher (1969), Hart (1974), Oakes (1977), and Marcher and Bergman (in preparation).

2. Bandera Formation

The Bandera Formation (Middle Pennsylvanian) is a gray to brown silty shale that is 50 to 120 feet thick and is classified as Zone 1 in the north part of district 1. It contains some thin beds of sandstone and has at times been mapped as part of the Oologah Formation. The Bandera shales form gently rolling plains with thin to thick soil cover. Strata are flat lying and lack structural disturbance. The clay mineralogy of shales in this unit is illite, kaolinite, and mixed-layer chlorite-vermiculite. The plasticity and shrink-swell potential are unknown.

Principal references are Cade (1952), Faucette (1954), Branson and others (1965), and Marcher and Bingham (1971).

3. Barnsdall Formation

The Barnsdall Formation (Middle Pennsylvanian) is chiefly red-brown shale in the upper part and sandstone in the lower part. The upper shales have been included in Zone 1 in small areas of districts 5 and 6, where they are 50 to 100 feet thick and contain thin sandstone interbeds. Farther south the Barnsdall is equivalent to part of the shales in the Hilltop Formation. Shales typically form gently rolling plains with thin to thick soil cover, but locally they are exposed beneath hills capped by the overlying Vamoosa Formation. The Barnsdall is flat lying and without structural disturbance. Clay minerals in the shale are illite, kaolinite, and mixed-layer chlorite-vermiculite. Shales have a medium plasticity and a low shrink-swell potential. Precautions should be taken to prevent an adverse impact on the Vamoosa fresh-water aquifer, which overlies the Barnsdall in part of northwest Okfuskee County.

Principal references include Ries (1954), Oakes and Jordan (1959), Hartronft and others (1965, 1967), Bingham and Moore (1975), and Bellis and Rowland (1976).

4. Bison Shale

The Bison Shale (Lower Permian) consists of 50 to 200 feet of red-brown blocky shale with thin interbeds of siltstone and sandstone. The unit is the upper part of the Hennessey Group. Outcrops classed as Zone 1 are present in parts of districts 4, 9, and 10. The shale is well exposed in the face of escarpments capped by the overlying Duncan Sandstone, and the soil cover ranges from thin to thick. The Bison Shale is flat lying and is structurally undisturbed. Clay minerals are chiefly illite, with lesser amounts of mixed-layer illite-chlorite. The shale has medium plasticity and a low shrink-swell potential. Special attention should be paid to the potential for damage to underlying aquifers in the Garber, Wellington, and Oscar in parts of districts 4 and 9.

Principal references include Hartronft and others (1968), Hart (1974), Carr and Bergman (1976), and Havens (1977).

5. Boggy Formation

The Boggy Formation (Middle Pennsylvanian) consists of 125 to nearly 3,000 feet of gray shale with interbedded sandstones and two thin coals. Individual shale units 50 to about 300 feet thick are classed as Zone 1 in widely scattered areas of districts 1, 2, 3, and 4. The shales generally are not well exposed, although locally they can be seen in the faces of escarpments capped by interbedded sandstones. Typically the shales form gently rolling and broad, flat plains and have a thin to thick soil cover. The strata are gently folded in most areas, and the dips are gentle to moderate. Clay minerals are chiefly illite, kaolinite, montmorillonite, and mixed-layer illite-montmorillonite. The plasticity of the shale is medium, and the shrink-swell potential is low to moderate.

Principal references for the Boggy Formation are Oakes and Knechtel (1948), Oakes and Koontz (1967), Hartronft and others (1965, 1968, 1970), Marcher (1969), Marcher and Bingham (1971), Laguros (1972), Hart (1974), and Oakes (1977).

6. Bokchito Formation

The Bokchito Formation (Lower Cretaceous) comprises several hundred feet of interbedded clays, sands, and limestones that crop out in the south part of districts 3 and 4. The formation contains two clay units, the Weno Clay Member (100 to 135 feet thick) and the Denton Clay Member (50 to 70 feet thick), which consist of blue-gray to brown-gray calcareous clay shale containing thin interbeds of sandstone, limestone, and gypsum. Clay shales in the Bokchito are poorly exposed and typically form grass-covered rolling plains with thin to thick soil cover. Strata are flat lying and are not structurally deformed. Clay minerals are montmorillonite, illite, and chlorite. Clay shales have medium to high plasticity and low to high shrink-swell potential. Special care must be taken to prevent adverse effects on thick sands of the Bokchito Formation or underlying units.

References to the Bokchito include Frederickson and others (1965), Hartronft and others (1966), Hart (1970), Laguros (1972), Hart (1974), Huffman and others (1975, 1978).

7. Chanute Formation

The Chanute Formation (Middle Pennsylvanian) contains 30 to 100 feet of gray shale in its upper part; this is classified as Zone 1 in the Creek County portion of district 6. The thick shale, which also contains thin interbeds of sandstone, is equivalent to part of the shales in the Hilltop Formation farther south. It typically forms gently rolling plains with a thin to thick soil cover. The strata are flat lying, although several faults cut the unit in central Creek County. Clay minerals are illite, kaolinite, and mixed-layer vermiculite-chlorite. The shale has medium plasticity and low to moderate shrink-swell potential.

References for the Chanute Formation include Oakes and Jordan (1959), Hartronft and others (1967), Bingham and Moore (1975), and Bellis and Rowland (1976).

8. Coffeyville Formation

The Coffeyville Formation (Middle Pennsylvanian) comprises 50 to 470 feet of blue-gray shale interbedded with sandstone, conglomerate, and locally a thin coal bed. Thick shale units, principally in the lower or upper part of the formation, are locally 50 to 150 feet thick and have been placed in Zone 1 in districts 1, 2, 5, and 6. These shales commonly form gently rolling to broad, flat plains with a thin to thick soil cover. Shales are locally exposed in the face of sandstone-capped escarpments, but generally they are not well exposed. The shale units are flat lying in all areas, although they are cut by faults in parts of Seminole County. Clay minerals in the Coffeyville Formation are illite, chlorite, kaolinite, montmorillonite, and mixed-layer illite-vermiculite. The plasticity of the shales is medium, and the shrink-swell potential is low to moderate. Shales of the Coffeyville have been mined in open pits for making brick and tile at Sapulpa (Sapulpa Brick and Tile Corp.) and Tulsa (Acme Brick Co.), and they also are the raw material used by Frankoma Pottery, Inc., just northeast of Sapulpa.

Principal references include Oakes (1940, 1963), Tanner (1956), Wolfson (1963), Hartronft and others (1965, 1967, 1968), Bucke (1969), Marcher and Bingham (1971), Bennison and others (1972), Hart (1974), Bingham and Moore (1975), Bellis and Rowland (1976), and Bingham and Bergman (in preparation).

9. Delaware Creek Shale

The Delaware Creek Shale (Mississippian) consists of 160 to 750 feet of dark-gray to black calcareous shale with thin interbeds of sandstone. It is classified as Zone 1 only in the Arbuckle Mountain area in district 4. The unit is gently to steeply dipping and locally is folded, faulted, and highly jointed, owing to mountain-building forces that acted on it and the nearby Goddard and Woodford Shales. A thin to moderately thick soil covers the shale in most areas, and the terrain is gently rolling to broad, flat plains. The principal clay minerals are illite, chlorite, and kaolinite. The plasticity of this shale is medium, and the shrink-swell potential ranges from low to high. Special care should be taken in evaluating the potential for high permeabilities along joints and fractures in the shale.

Principal references are Ham and others (1954), Hartronft and others (1966, 1968), Hart (1974), and Shelton and Al-Shaieb (1976).

10. Dog Creek Shale

The Dog Creek Shale (Upper Permian) comprises 100 to 200 feet of red-brown blocky shale with thinly interbedded siltstone, sandstone, gypsum, and dolomite. The formation is classified as Zone 1 in districts 7, 8, and 9, whereas elsewhere it contains thick gypsum beds or is closely associated with the thick gypsum beds of the underlying Blaine Formation. Much of the outcrop area is gently rolling plains with thin to thick soil cover, although the upper part of the shale is well exposed locally in the faces of moderate escarpments capped by the overlying sandstones of the Marlow Formation. The Dog Creek Shale is flat lying where classed as Zone 1 and is not known to be folded, faulted, or otherwise disturbed. Clay minerals are illite, kaolinite, mixed-layer chlorite-vermiculite, and mixed-layer chlorite-montmorillonite. The plasticity of the shale is medium, and the shrink-swell potential is low to medium. Special attention should be paid to the relation of the shale to thick underlying gypsum beds in Blaine County and nearby parts of Canadian County.

References for the Dog Creek Shale include Davis (1955), Armstrong (1958), Stevenson (1958), Howery (1960), Trapnell (1961), Fay (1962, 1964), Tanaka and Davis (1963), Hartronft and others (1967, 1969), Hart (1974), Bingham and Moore (1975), and Carr and Bergman (1976).

11. Doxey Shale

The Doxey Shale (Upper Permian) contains 150 to 200 feet of red-brown blocky shale with some thin interbeds of sandstone and siltstone. The unit is present in district 10 and in a small area of district 11. Shale is well exposed at many places in small escarpments capped by thin siltstone beds, and where soil is developed on the bedrock it commonly is thin. The Doxey Shale is flat lying in parts of its outcrop area, but locally it is steeply dipping, folded, faulted, and jointed where large blocks of the unit have collapsed owing to dissolution of salt deposits 500 to 1,000 feet below the surface. The dominant clay minerals that occur in the Doxey Shale are illite, mixed-layer montmorillonite-chlorite, kaolinite, and chlorite. The plasticity of the shale is slight, and the shrink-swell potential is probably low. Special attention must be paid to the possibility of higher than normal permeabilities along the faults, joints, and other fractures in the collapse areas and to the proximity of the overlying fresh-water aquifer in the Elk City Sandstone.

Principal references include Lovett (1960), Meinert (1961), Alexander (1965), Bowers (1967), Smith (1964), Hartronft and others (1969), Richardson (1970), Carr and Bergman (1976), Moussavi-Harami (1977), and Fay and Hart (1978).

12. Eagle Ford Formation

The Eagle Ford Formation (Upper Cretaceous) comprises 50 feet of dark-gray clay present only in the southeast part of district 4, in Bryan County. The unit is flat lying, is poorly exposed, and forms gently rolling, grass-covered plains with a thin to thick soil cover. Clay minerals are montmorillonite, illite, and kaolinite. The unit has medium plasticity and moderate to high shrink-swell potential. Special studies should be undertaken to assure no adverse effects on sands and conglomerates in the underlying Woodbine Formation where they might serve as aquifers.

Principal references are Hartronft and others (1966) and Hart (1974).

13. Fairmont Shale

The Fairmont Shale (Lower Permian) consists of 40 to 80 feet of red-brown shale interbedded with thin layers of siltstone and sandstone. The formation is in the lower part of the Hennessey Group and crops out in districts 4, 7, 8, and 9. Soil covering the bedrock shale ranges from thin to thick, and the unit typically forms gently rolling plains with some broad, flat prairies. The Fairmont is flat lying in all areas. The principal clay minerals are mixed-layer illite-chlorite-montmorillonite, illite, kaolinite, and chlorite. The shale has slight to medium plasticity and a low to medium shrink-swell potential. Of special importance in evaluating the Fairmont Shale is its stratigraphic position directly above sandstone of the Garber Formation, which is a major fresh-water aquifer serving a large part of central Oklahoma. Any plan for using the Fairmont must assure that there would be no adverse impact on the Garber aquifer.

References include Hartronft and others (1967, 1968), Wood and Burton (1968), Hart (1974), Bingham and Moore (1975), and Bingham and Bergman (in preparation).

14. Fayetteville Formation

The Fayetteville Formation (Mississippian) contains 30 to 100 feet of gray to black fissile shale and thin-bedded limestone in district 1. It is poorly exposed, but its outcrop area extends around the west side of the Ozark Plateau. Fayetteville shales form gently rolling to broad, flat plains, and they have a thin to thick soil cover. Strata are generally flat lying, although they are faulted at several places in the district. The principal clay minerals are mixed-layer illite-chlorite-montmorillonite, illite, kaolinite, and chlorite. The plasticity of the shale is slight to medium, and the shrink-swell potential is probably low. Special attention must be paid to the proximity of Fayetteville shales to limestones of the underlying formations. Some of these limestones are fractured and cavernous, and they constitute important fresh-water aquifers for the region. The Fayetteville shales are being mined in an open pit east of Pryor by Oklahoma Cement Co.

Principal references include Reed and others (1955), Huffman (1958), Branson and others (1965), Hartronft and others (1965), and Marcher and Bingham (1971).

15. Flowerpot Shale

The Flowerpot Shale (Upper Permian) consists of 100 to 400 feet of red-brown blocky shale containing thin interbeds of siltstone, sandstone, gypsum, and dolomite. It is present in parts of districts 7, 8, 10, and 11. The upper part of the shale is well exposed at many places in the faces of high escarpments capped by the overlying Blaine gypsum beds, and the deeply dissected shale commonly forms a badlands topography with little or no soil cover. The lower part of the formation typically forms flat to gently rolling plains with thin to thick soil cover. Strata in the Flowerpot are flat lying to gently dipping, with maximum dips of 2° to 4° in a narrow band along the Kiowa-Washita County line. Salt beds are present at shallow depth within the Flowerpot locally along the Cimarron River and in north Harmon County along the Elm Fork of the Red River, and ground water has formed small underground caverns by dissolution of the salt. Illite is the chief clay mineral in the shale, although lesser amounts of kaolinite, chlorite, and montmorillonite are also reported. The plasticity of the shale is medium, and the shrink-swell potential is low. Special studies may be needed where this unit contains caverns in subsurface salt deposits near the several natural salt plains, and where the overlying thick gypsum beds of the Blaine Formation are locally cavernous.

Major references are Scott and Ham (1957), Myers (1959), Jeary (1961), Hamilton (1961), Fay (1962, 1964, 1965), Hartronft and others (1967, 1969, 1969a), Wu (1969), Laguros (1972), Carr and Bergman (1976), Havens (1977), and Morton (in preparation).

16. Garber Formation

The Garber Formation (Lower Permian) is as thick as 600 feet in the north part of district 7, where it consists of red-brown shale interbedded with thin layers of siltstone and sandstone. Zone 1 outcrops are limited to the area north of the Salt Fork of the Arkansas River in district 7 and a small area in the south part of district 9. The shale is not generally well exposed but is covered by a thin to thick soil and forms gently rolling to broad, flat plains. The strata are flat lying and lack faults, folds, or other structural irregularities. Clay minerals in the Garber consist of illite, mixed-layer illite-chlorite-montmorillonite, and kaolinite. The plasticity of the shale is slight, and the shrink-swell potential is low. Special precaution must be taken to avoid contamination of the Garber Formation in central Oklahoma, where it is a major fresh-water aquifer classed as Zone 3, or in other areas where sandstone is an important component of the Garber.

References for Zone 1 portions of the Garber Formation include Hartronft and others (1967) and Bingham and Bergman (in preparation).

17. Goddard Shale

The Goddard Shale (Mississippian) consists of 240 to 3,600 feet of gray shale containing thin layers and nodules of limonite as well as thin to thick beds of sandstone. It is exposed in district 4 around the Arbuckle Mountains and the Ardmore Basin. Bedrock, which forms gently rolling plains, is poorly exposed and commonly has thin to moderate soil cover. In the Arbuckle region the unit is gently to steeply dipping and locally is folded, faulted, and highly jointed: it is closely associated with the Delaware Creek and Woodford Shales. Kaolinite, montmorillonite, and illite are the dominant clay minerals in the shale. Plasticity of the shale is medium, and the shrink-swell potential ranges from low to high. The possibility of high permeability owing to joints and fractures must be evaluated for this unit.

References for the Goddard include Ham and others (1954), Hartronft and others (1969a), Laguros (1972), and Hart (1974).

18. Hilltop Formation

The Hilltop Formation (Middle Pennsylvanian) is placed in Zone 1 within district 3. The formation consists of 50 to 200 feet of gray to brown shale with thin sandstone and limestone interbeds in a band extending across Seminole County. Equivalent shale strata farther north are placed in the Barnsdall and Chanute Formations. The Hilltop shale is locally exposed in the faces of escarpments capped by the overlying Vamoosa Formation, but in much of the area it is covered by thin to thick soil. Away from the escarpments the shale forms gently rolling plains. The Hilltop Formation is flat lying and is structurally undisturbed. Clay minerals are kaolinite, illite, montmorillonite, and chlorite. The plasticity of the shale is medium, and the shrink-swell potential is low. Special care should be taken to avoid contamination of the sandstones and conglomerates of the overlying Vamoosa Formation, a major fresh-water aquifer in central Oklahoma.

References for the Hilltop Formation include Tanner (1956), Hartronft and others (1968), and Bingham and Moore (1975).

19. Holdenville Shale

The Holdenville Shale (Middle Pennsylvanian) comprises 100 to 280 feet of brown and gray shale interbedded with thin beds of sandstone and limestone. Individual shale units 50 to 100 feet thick in the upper and lower parts of the formation are classified as Zone 1 in districts 2, 5, and 6. These thick shales typically form gently rolling plains with thin to thick soil cover. They are not well exposed, but locally they can be seen in escarpment faces. Strata are flat lying but are faulted in parts of Okfuskee County. The principal clay minerals of the Holdenville Shale are mixed-layer illite-montmorillonite, illite, and kaolinite. The shales have medium plasticity and low shrink-swell potential.

References dealing with these shales include Ries (1954), Oakes (1963), Hartronft and others (1965, 1968), Marcher (1969), Bennison and others (1972), and Bingham and Moore (1975).

20. Johns Valley Formation

The Johns Valley Formation (Lower Pennsylvanian) consists of 425 to 900 feet of dark-gray shale with thin to thick interbeds of sandstone. The unit is classified as Zone 1 only in western Pushmataha County, in district 3. It is moderately to steeply dipping and was broadly folded during formation of the Ouachita Mountains. Bedrock is poorly exposed, and at most places the gently rolling plains are mantled by thin to thick soil cover. Clay minerals in the Johns Valley are illite, chlorite, and kaolinite. The shales have medium plasticity and low shrink-swell potential.

References include Weaver (1958), Cline (1960), Hartronft and others (1966), and Marcher and Bergman (in preparation).

21. Labette Formation

The Labette Formation (Middle Pennsylvanian) consists of 120 to 240 feet of gray shale with thin interbeds of sandstone and limestone. The entire formation is considered Zone 1 in districts 1 and 6. Shales of the Labette form gently rolling to broad, flat plains with thin to thick soil cover. The upper part of the formation is well exposed locally in the face of the escarpment capped by the overlying Oologah Limestone. Strata are flat lying in all areas, but they are faulted in southeast Nowata County. Illite, mixed-layer illite-montmorillonite, mixed-layer illite-vermiculite, and kaolinite are the principal clay minerals in the Labette shales. The shales have a low to medium plasticity and probably have a low shrink-swell potential. The Labette shales are mined in open pits operated by Chandler Materials Co. near Catoosa (for manufacture of lightweight aggregate) and by Martin Marietta Cement Co. at Tulsa (for manufacture of cement).

References for the Labette Formation include Cade (1952), Tillman (1952), Faucette (1954), Gruman (1954), Sparks (1955), Branson and others (1965), Hartronft and others (1965), Marcher and Bingham (1971), and Bennison and others (1972).

22. McAlester Formation

The McAlester Formation (Middle Pennsylvanian) consists mainly of thick gray shales interbedded with thin to thick sandstones and several important coal beds. The total thickness of the formation is 1,000 to 2,800 feet in most areas but is only 200 to 600 feet in the northeast part of the State. Individual shale intervals and interbedded thin sandstones considered to be Zone 1 are 50 to more than 500 feet thick; they are located in districts 1, 2, 3, and 4. The shales form gently rolling to broad, flat plains and typically have thin to thick soil cover. Strata are locally faulted, are gently to moderately folded, and dip at angles ranging from gentle to steep. Clay minerals in the shales are illite, kaolinite, and mixed-layer illite-montmorillonite. The plasticity of the shales is slight to medium, and the shrink-swell potential is low to moderate.

Principal references are Oakes and Knechtel (1948), Knechtel (1949), Stringer (1959), Branson and others (1965), Hartronft and others (1965, 1968, 1970), Oakes and Koontz (1967), Marcher (1969), Marcher and Bingham (1971), Laguros (1972), Hart (1974), Oakes (1977), and Marcher and Bergman (in preparation).

23. Nellie Bly Formation

The Nellie Bly Formation (Middle Pennsylvanian) is made up chiefly of shale with interbedded sandstones and limestones. The formation is 250 to 550 feet thick, but only selected shale intervals 50 to 150 feet thick are herein classified as Zone 1 in the south half of district 6. Thick shales are gray to brown in color and contain thin sandstone layers. They form gently rolling to broad, flat plains with thin to thick soil cover. The shales are flat lying and are not structurally disturbed. Clay minerals are illite, kaolinite, and minor amounts of vermiculite. The plasticity of the shale is medium, and the shrink-swell potential is low.

References for Zone 1 areas of the Nellie Bly include Oakes and Jordan (1959), Hartronft and others (1965, 1967), Bennison and others (1972), Bingham and Moore (1975), Bellis and Rowland (1976), and Bingham and Bergman (in preparation).

24. Nowata Formation

The Nowata Formation (Middle Pennsylvanian) comprises 150 to about 500 feet of gray shale with some thin interbeds of sandstone and limestone. Almost the entire formation is placed in Zone 1 in parts of districts 1 and 6. The shales form gently rolling to broad, flat plains with thin to thick soil cover. Strata are flat lying and are without structural disturbance. The principal clay minerals are illite, kaolinite, vermiculite, and chlorite. Shales have a low to medium plasticity and probably have a low shrink-swell potential.

Principal references to the Nowata Formation include Faucette (1954), Sparks (1955), Hartronft and others (1965), Marcher and Bingham (1971), Laguros (1972), and Bennison and others (1972).

25. Oscar Group

The Oscar Group (Upper Pennsylvanian or Lower Permian) is a thick sequence of interbedded shales, sandstones, and limestones with two thick shales that are herein placed in Zone 1. The two shales are referred to as the Gage Shale, with outcrops in district 6 and 7, and the Eskridge Shale, in district 6. These shales are typically 50 to 70 feet thick and consist of maroon-colored shale with thin interbeds of limestone and sandstone. Bedrock is not well exposed, and there is a thin to moderate soil cover in most of the area. The shales make up a gently rolling terrain with several small benches formed by the thin limestones. Strata are not faulted or folded and are essentially flat lying. Illite, chlorite, and kaolinite are the chief clay minerals in the shales, although montmorillonite is also important in some localities. The shales have medium plasticity and low to medium shrink-swell potential. It should be noted that the Oscar Group is classed as Zone 1 only in the area north of the Salt Fork of the Arkansas River and a small area in district 9; elsewhere it is considered Zone 2 or Zone 3.

References for the Zone 1 portions of the Oscar Group include Taylor (1953), Vosburg (1954), Hruby (1955), Noll (1955), Fisher (1956), Hartronft and others (1967, 1969a), Shelton and Al-Shaieb (1976), Havens (1977), and Bingham and Bergman (in preparation).

26. Savanna Formation

The Savanna Formation (Middle Pennsylvanian) consists of interbedded sandstone and shale ranging from 100 to 2,500 feet thick. Selected intervals, and locally the entire formation, are made up predominantly of gray shale with thin to moderately thick sandstone interbeds: these intervals are 50 to 300 feet thick and are placed in Zone 1 in districts 1, 2, 3, and 4. Several thin but important coal beds occur in the Savanna Formation. The shale intervals form gently rolling to broad, flat plains with thin to thick soil cover. Strata are gently folded in most areas, and dips are gentle to moderate. Illite, kaolinite, chlorite, and vermiculite are the principal clay minerals in the Savanna shales. These shales have medium plasticity and low shrink-swell potential.

Principal references to the Savanna Formation are Oakes and Knechtel (1948), Knechtel (1949), Stringer (1959), Branson and others (1965), Hartronft and others (1965, 1966, 1968, 1970), Oakes and Koontz (1967), Marcher (1969), Marcher and Bingham (1971), Laguros (1972), Hart (1974), Oakes (1977), and Marcher and Bergman (in preparation).

27. Seminole Formation

The Seminole Formation (Middle Pennsylvanian) comprises 100 to 475 feet of gray and brown shale interbedded with sandstone, conglomerate, and one important coal in the north. Thick shales classified as Zone 1 are in the lower, middle, and upper parts of the formation in districts 1, 5, and 6. These shale units range from 50 to 150 feet thick and contain some thin interbeds of sandstone. They typically form gently rolling and broad, flat plains with thin to thick soil cover. Shale is locally exposed in the faces of hills capped by sandstone beds, but otherwise it is rarely seen. Strata are flat lying in all areas, but several faults cut the shales in district 5. Clay minerals are illite, kaolinite, vermiculite, and mixed-layer illite-vermiculite. Shales have slight to medium plasticity and low shrink-swell potential. Shale is worked in an open pit at Tulsa by Acme Brick Co. for the manufacture of brick.

Reports dealing with Zone 1 shales of the Seminole Formation include those by Weaver (1954), Ries (1954), Wolfson (1963), Hartronft and others (1965, 1967, 1968), Marcher and Bingham (1971), Bennison and others (1972), and Bingham and Moore (1975).

28. Senora Formation

The Senora Formation (Middle Pennsylvanian) is composed of 150 to 1,000 feet of gray shale with interbedded sandstones and about seven thin coals that have been mined locally. Individual shale units within the Senora are 50 to 150 feet thick, and they are classified as Zone 1 in parts of districts 1, 2, and 5. Generally the shales are not well exposed, but locally they can be seen below some of the sandstone-capped escarpments. The shales form gently rolling to broad, flat plains with a thin to thick soil cover. Strata are typically flat lying and are faulted at a few localities in eastern Hughes County. Clay minerals are mainly illite and kaolinite. The shales have a slight to medium plasticity and a low shrink-swell potential.

Principal references include Tillman (1952), Gruman (1954), Weaver (1954), Oakes (1963, 1977), Cassidy (1966), Oakes and Koontz (1967), Hartronft and others (1965, 1968, 1970), Marcher (1969), Marcher and Bingham (1971), Laguros (1972), Hart (1974), and Bingham and Moore (1975).

29. Stanley Shale

The Stanley Shale (Mississippian) is gray to dark-gray siliceous shale containing thin to thick interbeds of sandstone. The total thickness of the formation is as much as 11,000 feet. The unit crops out in many of the long and narrow valleys in the Ouachita Mountain region of districts 3 and 4. Strata in the Stanley are highly deformed in most areas, owing to formation of the Ouachita Mountains: dips are moderate to steep, and the rock commonly is tightly folded and is highly fractured, jointed, and faulted. Bedrock is poorly exposed in most areas, and the gently rolling or broad, flat plains have a thin to thick soil cover. Clay minerals in the shale include illite, chlorite, kaolinite, and montmorillonite. The plasticity ranges from slight to medium, and the shrink-swell potential is low. Special care must be taken in assessing the possibility of high permeability, owing to the common occurrence of joints and fractures.

Principal references include Bokman (1953), Cline (1960), Seely (1963), Hart (1963), Fellows (1964), Hartronft and others (1966), Laguros (1972), Shelton and Al-Shaieb (1976), and Marcher and Bergman (in preparation).

30. Stuart Shale

The Stuart Shale (Middle Pennsylvanian) is made up of gray to dark-gray shale with some thin sandstone beds. The formation ranges from 80 to 300 feet in thickness. Locally the entire formation is classified as Zone 1 in district 2, whereas in parts of district 3 only the lower part is placed in Zone 1. The Stuart Shale is not well exposed, and it commonly forms gently rolling to broad, flat plains with thin to thick soil cover. The unit is flat lying to gently dipping and lacks significant structural features. Clay minerals consist of illite, mixed-layer illite-vermiculite, mixed-layer illite-montmorillonite, and kaolinite. The shales have medium plasticity and low shrink-swell potential.

Major references for the Stuart include Weaver (1954), Wong (1964), Oakes and Koontz (1967), Marcher (1969), Hartronft and others (1970), and Hart (1974).

31. Vanoss Group

The Vanoss Group (Upper Pennsylvanian or Lower Permian) is a thick sequence of shales interbedded with thinner units of sandstone and limestone. Five of the thick shales are herein placed in Zone 1 in the north part of district 5: the Johnson and Roca Shales crop out in Payne and Pawnee Counties north of the Cimarron River, whereas the Johnson, Hughes Creek, Admire, and Pony Creek Shales are considered Zone 1 in Lincoln and southeast Payne Counties. These five shales are typically 50 to 100 feet thick and consist of gray or red-brown shale with interbedded sandstone and limestone. Shales form gently rolling plains with several benches capped by the thin sandstones or limestones. Soil cover is thin to moderately thick in most of the area, and the shales are exposed locally in escarpments. Strata are flat lying and have not been faulted. Principal clay minerals are kaolinite, illite, montmorillonite, mixed-layer illite-montmorillonite, and chlorite. The shales have medium to high plasticity and low to high shrink-swell potential. Parts of the Vanoss Group are classed as Zone 1 only north of Deep Fork; farther south the Vanoss contains much sandstone and conglomerate and is considered Zone 3.

Principal references include Nakayama (1955), Fenoglio (1957), Greig (1959), West (1955), Hartronft and others (1965), Thomas (1974), Bingham and Moore (1975), Bellis and Rowland (1976), Shelton and Al-Shaieb (1976), and Bingham and Bergman (in preparation).

32. Wellington Formation

The Wellington Formation (Lower Permian) is estimated to consist of 800 feet of shale in the north part of district 7 and to contain 50 to 100 feet of shale in several small areas of district 9. The shale is red brown and is interbedded with thin layers of siltstone, sandstone, and dolomite. It forms gently rolling and broad, flat plains in the Zone 1 areas and is commonly mantled by a thin to thick soil cover. Strata are flat lying and structurally undisturbed. Clay minerals of the Wellington shales are illite, kaolinite, chlorite, and montmorillonite. The plasticity of the shales is medium, and the shrink-swell potential is low to medium. In central Oklahoma the Wellington is a major fresh-water aquifer classified as Zone 3, and care must be taken to avoid endangering this aquifer.

References for Zone 1 portions of the Wellington are Hartronft and others (1967, 1969a), Laguros (1972), Shelton and Al-Shaieb (1976), and Bingham and Bergman (in preparation).

33. Wetumka Shale

The Wetumka Shale (Middle Pennsylvanian) comprises 100 to 250 feet of gray silty shale with some thin interbeds of siltstone and sandstone. The unit is present in districts 2, 4, and 5. It is poorly exposed and typically forms gently rolling plains with a thin to thick soil cover. Strata are flat lying in all areas, although they are faulted at a few localities. The principal clay minerals are mixed-layer illite-montmorillonite, illite, and kaolinite. The shale has medium plasticity and low shrink-swell potential.

References for the Wetumka are Weaver (1954), Ries (1954), Oakes (1963), Hartronft and others (1968, 1970), Lowe (1968), Marcher (1969), Hart (1974), and Bingham and Moore (1975).

34. Wewoka Formation

The Wewoka Formation (Middle Pennsylvanian) consists of 400 to 750 feet of interbedded sandstone and gray shale. Individual shale units containing thin sandstones within the Wewoka are locally 50 to 200 feet thick and are classed as Zone 1 in districts 2, 5, and 6. Shales typically form gently rolling to broad, flat plains and have a thin to thick soil cover. They are not well exposed, except locally in the faces of escarpments capped by sandstone interbeds. Strata in the thick shales are commonly flat lying and are not structurally disturbed. Clay minerals are illite, mixed-layer illite-montmorillonite, and kaolinite. The shales have a medium plasticity and a low shrink-swell potential.

References for thick shales of the Wewoka include Weaver (1954), Ries (1954), Oakes (1963), Hartronft and others (1965, 1968, 1970), Marcher (1969), Bennison and others (1972), and Bingham and Moore (1975).

35. Woodford Shale

The Woodford Shale (Upper Devonian and Lower Mississippian) is made up of 160 to 560 feet of dark-gray to black shale containing chert in the form of thin beds and nodules. It is exposed only in the Arbuckle

Mountain area in district 4. The unit is gently to steeply dipping and locally is folded, faulted, and highly jointed as the result of mountain-building processes. The Woodford is closely associated with the Delaware Creek and Goddard Shales. Bedrock is exposed only locally, and at most places it forms gently rolling terrain with thin to moderate soil cover. Clay minerals of the Woodford Shale are illite, mixed-layer illite-chlorite, and chlorite. Shales in the unit have medium plasticity and low shrink-swell potential. In evaluating this unit, special attention must be paid to the complex structure, to the potential for high permeability from joints and fractures, and to the proximity of underlying limestones and dolomites.

Principal references are Ham and others (1954), Hartronft and others (1968), Lowe (1968), and Hart (1974).

DISCUSSION OF SUBSTATE PLANNING DISTRICTS

Outcrops of rock units classified as Zone 1 are widely distributed in almost all parts of Oklahoma, and they occur in parts of each of the State's substate planning districts. In the following sections of the report we discuss the general character of outcropping rocks in each district and identify the various Zone 1, Zone 2, and Zone 3 rock units that occur in each district. The following text, as well as the accompanying maps and tables, emphasizes the distribution of Zone 1 units in the districts, and we refer the reader to the generalized description (presented in the preceding chapter) of those Zone 1 units that are of special interest to him or her. A brief description of the Zone 2 and Zone 3 units in each district is also given to provide a fuller understanding of the outcropping rock units.

Districts 1 and 2

District 1 is composed of Craig, Delaware, Mayes, Nowata, Ottawa, Rogers, and Washington Counties. District 2 consists of Adair, Cherokee, McIntosh, Muskogee, Okmulgee, Sequoyah, and Wagoner Counties. Ottawa, Washington, Muskogee, and Okmulgee Counties have population densities of 50–99 persons per square mile, and the remaining counties have population densities of 10–49 persons per square mile (fig. 7, table 6).

An urban county is considered to be one where more than half the population lives in towns or cities of 2,500 or more persons; by this criterion, Ottawa, Washington, Muskogee, and Okmulgee Counties would be considered urban counties. Counties that have fewer than 50 percent of their population living in incorporated cities or towns include Sequoyah, Wagoner, Cherokee, Adair, Delaware, Craig, and Rogers Counties. Nowata, Mayes, and Okmulgee Counties have 50 to 75 percent of their population living in incorporated cities or towns.

The landscape in districts 1 and 2 ranges from rugged hills and mountains to rolling hills and broad, flat plains. Rock units at the land surface are predominantly sedimentary and include sandstone, shale, limestone, chert, and coal; a small exposure of granite at Spavinaw represents the only outcrop of igneous rocks in both districts. The southeast part of district 1 and most of the east half of district 2 make up typically rugged and deeply dissected uplands formed on thick limestone and chert formations at the southwest end of the Ozark Mountains. Farther west in both districts the terrain consists of moderately high to high sandstone-capped ridges that rise above broad shale plains.

The average precipitation each year is moderate to high, ranging from about 36–38 inches in the west to 42–44 inches in the east (fig. 3). Vegetation in the Ozark region is mainly forests, with oak and hickory dominant, whereas vegetation elsewhere in both districts consists mainly of post oak-blackjack forest on the uplands and grasslands on the broad plains areas. Soils covering the bedrock range from thin to thick in both districts, and those overlying the shale units commonly are moderate to thick.

The outcrop areas of part or all of 15 different rock units in districts 1 and 2 are classified as Zone 1. Large parts of both districts are also classified as Zones 2 and 3.

Zone 1 Rock Units

Fifteen formations contain moderately thick to thick shale units that we consider Zone 1: "Atoka" Formation, Bandera Formation, Boggy Formation, Coffeyville Formation, Fayetteville Formation, Holdenville

TABLE 6.—POPULATION DENSITY AND LAND AREA FOR SUBSTATE PLANNING DISTRICTS 1 AND 2, OKLAHOMA, 1970

		Land area (square miles)		Population (per square mile)
District 1				
Craig Co.		764		19.3
Delaware Co.		707		25.1
Mayes Co.		648		36.0
Nowata Co.		537		18.2
Ottawa Co.		464		64.2
Rogers Co.		685		41.5
Washington Co.		424		99.7
	Total	4,229	Average	39.3
District 2				
Adair Co.		570		26.6
Cherokee Co.		756		30.7
McIntosh Co.		608		20.5
Muskogee Co.		818		72.8
Okmulgee Co.		700		50.5
Sequoyah Co.		696		33.6
Wagoner Co.		563		39.4
Woodward Co.		1,251		12.4
	Total	4,711	Average	40.6

Source: Shreiner and Chang (1975).

Shale, Labette Formation, McAlester Formation, Nowata Formation, Savanna Formation, Seminole Formation, Senora Formation, Stuart Shale, Wetumka Formation, and Wewoka Formation. All these units are Pennsylvanian in age except the Fayetteville, which is Mississippian.

All these shale units appear to be generally favorable locally for use in disposal of industrial waste, and they are widely distributed in all parts of the districts except the Ozarks region in the east (fig. 10). General characteristics of each Zone 1 formation are presented in the preceding chapter, and we have summarized those data here in table 7.

District 1 contains Zone 1 units in a series of long and narrow bands (fig. 10) that make up the gently rolling plains between ridges of sandstone and limestone. The Fayetteville shales crop out along the flanks of the Ozarks in the east, whereas the Bandera, Boggy, Coffeyville, Labette, McAlester, Nowata, Savanna, Seminole, and Senora shales make up subparallel belts of Zone 1 rock units farther west.

In district 2 the shales are widely distributed in the west and extreme southeast. The Coffeyville, Holdenville, Senora, Stuart, Wewoka, and Wetumka shales form subparallel bands in the far west, similar to those of district 1, but elsewhere the "Atoka," Boggy, McAlester, and Savanna have irregular outcrop patterns.

Zone 2 Rock Units

Rock units classified as Zone 2 within districts 1 and 2 (pl. 1, in pocket) are thick Pennsylvanian sequences of interbedded shale, sandstone, and siltstone. Some of these shales are locally more than 50 feet thick, and they also may be suitable in some areas for disposal of industrial waste. In both districts, the Zone 2 units are chiefly parts of the

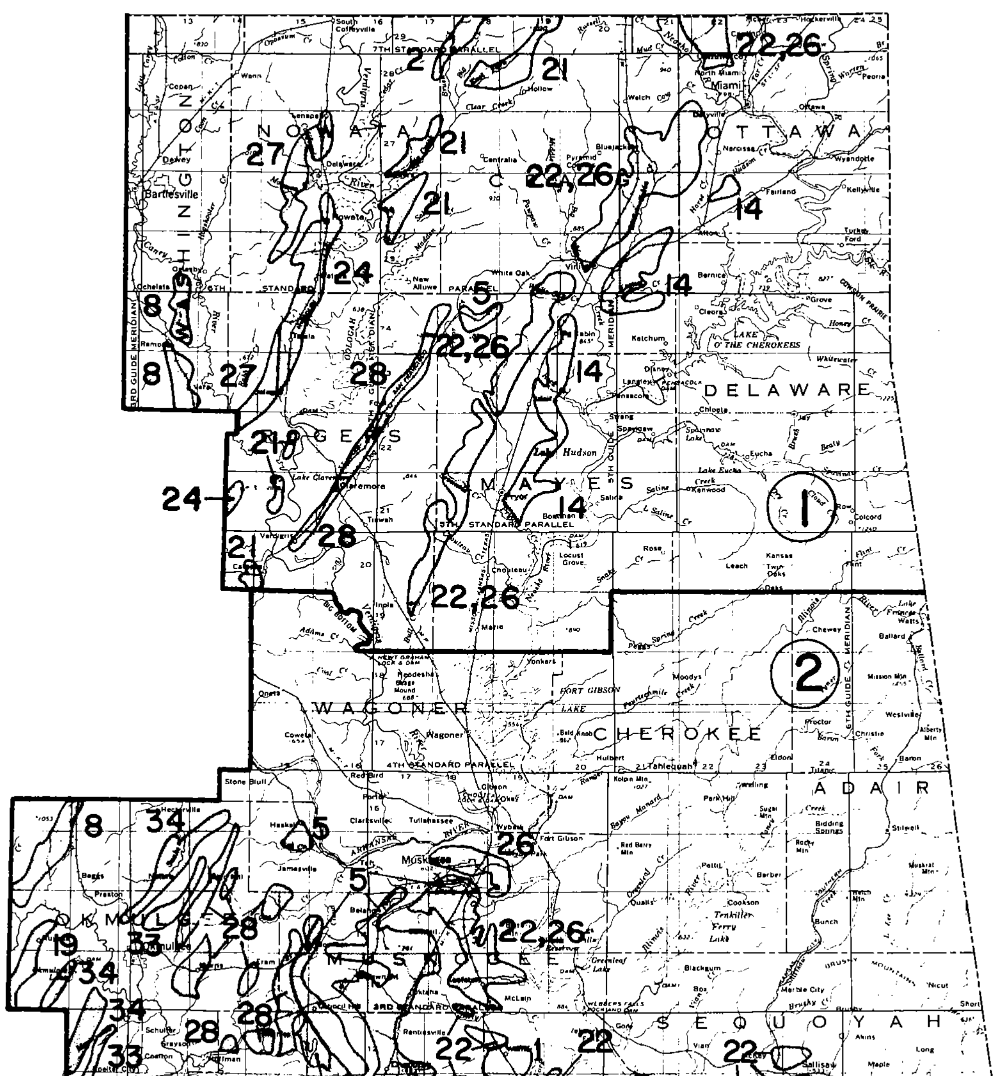
TABLE 7.—PHYSICAL CHARACTERISTICS OF ZONE 1 GEOLOGIC UNITS IN DISTRICTS 1 AND 2

Geologic unit	Portion of unit	Lithology	Thickness (in feet)	Structure	Clay mineralogy*	Plasticity	Shrink-swell potential	Additional comments
1. "Atoka" Formation	Selected shale intervals	Shale, brown to gray, with interbeds of sandstone	50-500, for shale intervals	Gentle to moderate folds, some faults, gentle to moderate dips	Illite, chlorite, kaolinite, and mixed-layer illite-montmorillonite	Slight to medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover.
2. Bandera Formation	Entire	Shale, gray to brown, with thin interbeds of sandstone	50-120	Flat-lying	Mixed-layer illite-vermiculite, illite, kaolinite	Unknown	Unknown	Gently rolling plains with thin to thick soil cover.
5. Boggy Formation	Selected shale intervals	Shale, gray, with interbeds of sandstone and siltstone	50-300, for shale intervals	Gently folded, locally faulted, gentle to moderate dips	Illite, kaolinite, montmorillonite, and mixed-layer illite-montmorillonite	Medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover.
8. Coffeyville Formation	Selected shale intervals	Shale, blue-gray, with interbeds of sandstone	50-150	Flat-lying	Illite, kaolinite, vermiculite, and montmorillonite	Medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover.
14. Fayetteville Formation	Entire	Shale, gray to black, with thin interbeds of limestone	30-100	Flat-lying with several faults	Mixed-layer illite-chlorite, illite, kaolinite, mixed-layer illite-montmorillonite	Slight to medium	Probably low	Gently rolling and broad, flat plains with thin to thick soil cover; overlies thick limestone units.
19. Holdenville Shale	Upper	Shale, brown and gray, with thin interbeds of sandstone and limestone	50-100	Flat-lying, with some faults	Mixed-layer illite-montmorillonite, illite, kaolinite	Medium	Low	Gently rolling and broad, flat plains with thin to thick soil cover.
21. Labette Formation	Entire	Shale, gray, with thin interbeds of sandstone	120-240	Flat-lying	Mixed-layer illite-montmorillonite, illite, mixed-layer illite-vermiculite, kaolinite	Low to medium	Probably low	Gently rolling and broad, flat plains with thin to thick soil cover; exposed in escarpments capped by overlying limestone; open-pit mining of shale.

TABLE 7.—*Continued*

Geologic unit	Portion of unit	Lithology	Thickness (in feet)	Structure	Clay mineralogy*	Plasticity	Shrink-swell potential	Additional comments
22. McAlester Formation	Selected shale intervals	Shale, gray, with interbeds of sandstone	50-500, for shale intervals	Flat-lying to moderate dips, moderate folds and some faults in district 2	Illite, kaolinite, mixed-layer illite-montmorillonite	Slight to medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover.
24. Nowata Formation	Entire	Shale, gray, with thin interbeds of sandstone and limestone	150-500	Flat-lying	Illite, kaolinite, vermiculite, chlorite	Low to medium	Probably low	Gently rolling to broad, flat plains with thin to thick soil cover.
26. Savanna Formation	Selected shale intervals	Shale, gray to black, with interbeds of sandstone	50-300, for shale intervals	Flat-lying, with a few faults	Illite, kaolinite, vermiculite, chlorite	Medium	Low	Gently rolling to broad, flat plains with thin to thick soil cover.
27. Seminole Formation	Selected shale intervals	Shale, gray and brown, with interbeds of sandstone	50-100, for shale intervals	Flat-lying	Illite, kaolinite, vermiculite, and mixed-layer illite-vermiculite	Slight to medium	Low	Gently rolling to broad, flat plains with thin to thick soil cover; open-pit mining of shale.
28. Senora Formation	Selected shale intervals	Shale, gray, with interbeds of sandstone	50-150, for shale intervals	Flat-lying, with a few faults	Illite and kaolinite	Slight to medium	Low	Gently rolling to broad, flat plains with thin to thick soil cover.
30. Stuart Shale	Entire	Shale, gray and tan, with thin interbeds of sandstone	80-300	Flat-lying to gentle dips	Mixed-layer illite-vermiculite, illite, kaolinite	Medium	Low	Gently rolling plains with thin to thick soil cover.
33. Wetumka Formation	Entire	Shale, gray, with thin interbeds of sandstone	100-250	Flat-lying	Mixed-layer illite-montmorillonite, illite, kaolinite	Medium	Low	Gently rolling plains with thin to thick soil cover.
34. Wewoka Formation	Selected shale intervals	Shale, gray, with thin interbeds of sandstone	50-200, for shale intervals	Flat-lying	Illite, mixed-layer illite-montmorillonite, kaolinite	Medium	Low	Gently rolling to broad, flat plains with thin to thick soil cover.

* May incorporate clay-mineralogy data from other planning districts.



1	Atoka Formation	24	Nowata Formation
2	Bandera Formation	26	Savanna Formation
5	Boggy Formation	27	Seminole Formation
8	Coffeyville Formation	28	Senora Formation
14	Fayetteville Formation	30	Stuart Shale
19	Holdenville Shale	33	Wetumka Formation
21	Labette Formation	34	Wewoka Formation
22	McAlester Formation		

Figure 10. Map showing distribution of Zone 1 bedrock formations in planning districts 1 and 2.

same formations placed in Zone 1, but here they contain more sandstone interbeds and are not mapped separately as Zone 1. Among the Zone 2 units covering especially large areas are the "Atoka," Boggy, Coffeyville, McAlester, Savanna, Seminole, and Senora formations.

Zone 3 Rock Units

Areas classified as Zone 3 (pl. 1, in pocket) consist mainly of the recharge areas of fresh-water aquifers that supply municipal, irrigation, and domestic water. These aquifers include (1) Mississippian limestones and cherts, such as the Keokuk and Reeds Spring ("Boone") formations, in the Ozark Mountain region of the east; (2) the Pennsylvanian Noxie Sandstone Member at the base of the Chanute Formation in the northwest corner of district 1; and (3) Quaternary sand, silt, clay, and gravel in alluvium and terrace deposits.

Districts 3 and 4

District 3 is composed of Choctaw, Haskell, Latimer, Le Flore, McCurtain, Pittsburg, and Pushmataha Counties. District 4 consists of Atoka, Bryan, Carter, Coal, Garvin, Johnston, Love, Marshall, Murray, and Pontotoc Counties. Pushmataha County alone has a population density of 0 to 9, and the remaining 16 counties have population densities of 10 to 49 (fig. 7, table 8).

An urban county is considered to be one where more than half the population lives in towns or cities with 2,500 or more persons, and only Pittsburg, Pontotoc, and Carter Counties are considered urban counties.

TABLE 8.—POPULATION DENSITY AND LAND AREA FOR SUBSTATE PLANNING DISTRICTS 3 AND 4, OKLAHOMA, 1970

		Land area (square miles)		Population (per square mile)
District 3				
Choctaw Co.		778		19.5
Haskell Co.		602		15.9
Latimer Co.		737		11.7
Le Flore Co.		1,560		20.6
McCurtain Co.		1,800		15.9
Pittsburg Co.		1,241		30.2
Pushmataha Co.		1,420		6.6
	Total	8,138	Average	17.4
District 4				
Atoka Co.		991		11.1
Bryan Co.		889		28.7
Carter Co.		830		45.0
Coal Co.		526		10.5
Garvin Co.		814		30.6
Johnston Co.		638		12.3
Love Co.		513		11.0
Marshall Co.		366		21.0
Murray Co.		423		25.2
Pontotoc Co.		714		39.0
	Total	6,704	Average	24.5

Source: Shreiner and Chang (1975).

These counties contain the three largest metropolitan centers in districts 3 and 4: McAlester, Ada, and Ardmore. Counties that have fewer than 50 percent of their population living in incorporated cities or towns are Haskell, Latimer, Pushmataha, McCurtain, Atoka, and Love. The remaining counties have between 50 and 75 percent of the population living in incorporated cities or towns. No county in either planning district has more than 75 percent of its population living in incorporated cities and towns.

The terrain in districts 3 and 4 is highly variable, ranging from broad, flat plains to rugged mountain areas. Most of the surface units are sedimentary rocks, including sandstone, shale, limestone, dolomite, chert, and coal, although granite and other igneous rocks crop out in Johnston County in the eastern part of the Arbuckle Mountains. Gently rolling plains characterize much of the south part of districts 3 and 4 as well as the west and north parts of district 4. The remainder of the region typically is made up of high ridges and mountains that rise 300 to 2,000 feet above nearby broad valleys or wide, gently rolling plains.

The annual precipitation is moderate to high and ranges from about 34 inches in the west to 44–56 inches in the east (fig. 3). The vegetation consists chiefly of forests, with pine and oak dominating in the Ouachita Mountains and nearby areas and post oak-blackjack in most other areas. Soils on the bedrock range from thin to thick in both districts, with soils on the shale units commonly being moderate to thick.

Parts or all of 15 rock units are considered Zone 1 in widely scattered areas of districts 3 and 4. Substantial areas of both districts are also classified as Zones 2 and 3.

Zone 1 Rock Units

Fifteen formations contain moderately thick to thick shales that are herein classified as Zone 1: "Atoka" Formation, Bison Shale, Boggy Formation, Bokchito Formation, Delaware Creek Shale, Eagle Ford Formation, Fairmont Shale, Goddard Shale, Johns Valley Formation, McAlester Formation, Savanna Formation, Stanley Shale, Stuart Shale, Wetumka Formation, and Woodford Shale. Geologic age assignments are as follows: the Woodford is Devonian and Mississippian; the Delaware Creek, Goddard, and Stanley are Mississippian; the Bison and Fairmont are Permian; the Oscar is either Late Pennsylvanian or Early Permian; the Bokchito and Eagle Ford are Cretaceous; and the remaining seven formations are Pennsylvanian.

Each of these formations appears locally to be generally favorable for disposal of industrial waste, and Zone 1 units are widely distributed in all areas except for the southeast part of district 3 (figs. 11, 12). A generalized description of each formation is presented in the previous chapter, and the data are summarized here in table 9.

District 3 contains a series of long and narrow belts of Zone 1 rock units that typically form valleys and broad, rolling plains. The Johns Valley and Stanley formations crop out within the Ouachita Mountain province, in the central part of the district, whereas the "Atoka," Boggy, McAlester, Savanna, and Stuart formations crop out farther north in the Arkoma Basin portion of the district. Shales of the Bokchito Formation are limited to the southwest.

Zone 1 units in district 4 are widely distributed and have irregular outcrops. The "Atoka," Boggy, McAlester, Stanley, and Wetumka formations are present in the northeast, in the Arkoma Basin and Ouachita Mountains. Zone 1 outcrops in the central part of the district around the Arbuckle Mountains are the Delaware Creek, Goddard, and Woodford formations. The Bokchito shales extend in a discontinuous belt across the south, and the Eagle Ford is limited to southern Bryan County in the southeast. Garvin County in the northwest contains the only outcrops of the Bison and Fairmont Shales.

Zone 2 Rock Units

Thick units of interbedded sandstone, siltstone, and shale are present in the areas classified as Zone 2 in districts 3 and 4, and some of the shales in these units may be suitable locally for waste disposal. Much of the central part of district 3 consists of outcrops of the Stanley and Jackfork formations, whereas the Zone 2 areas farther north and in the northeast part of district 4 embrace parts of the "Atoka," Boggy, McAlester, and Savanna formations as well as many other

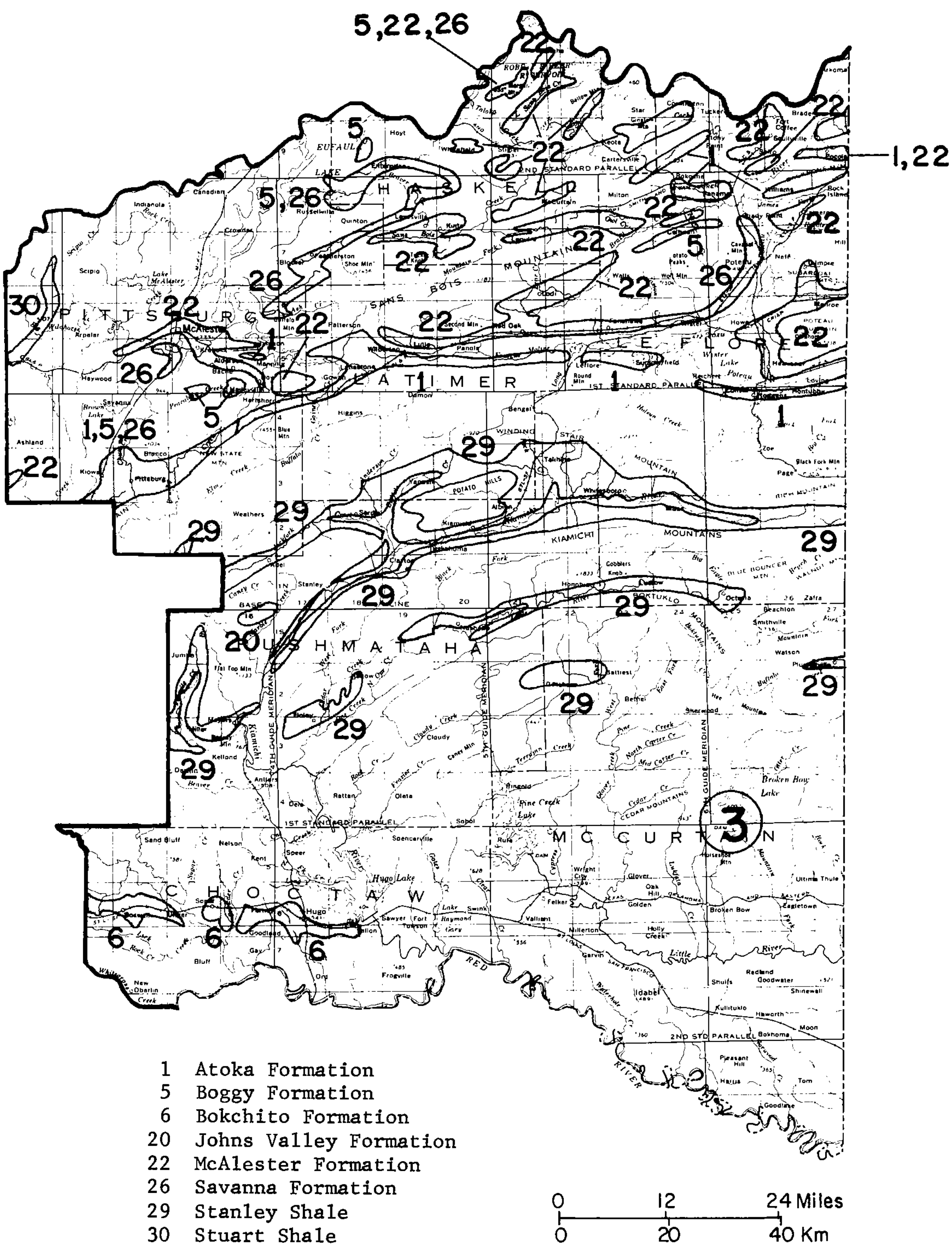


Figure 11. Map showing distribution of Zone 1 bedrock formations in planning district 3.

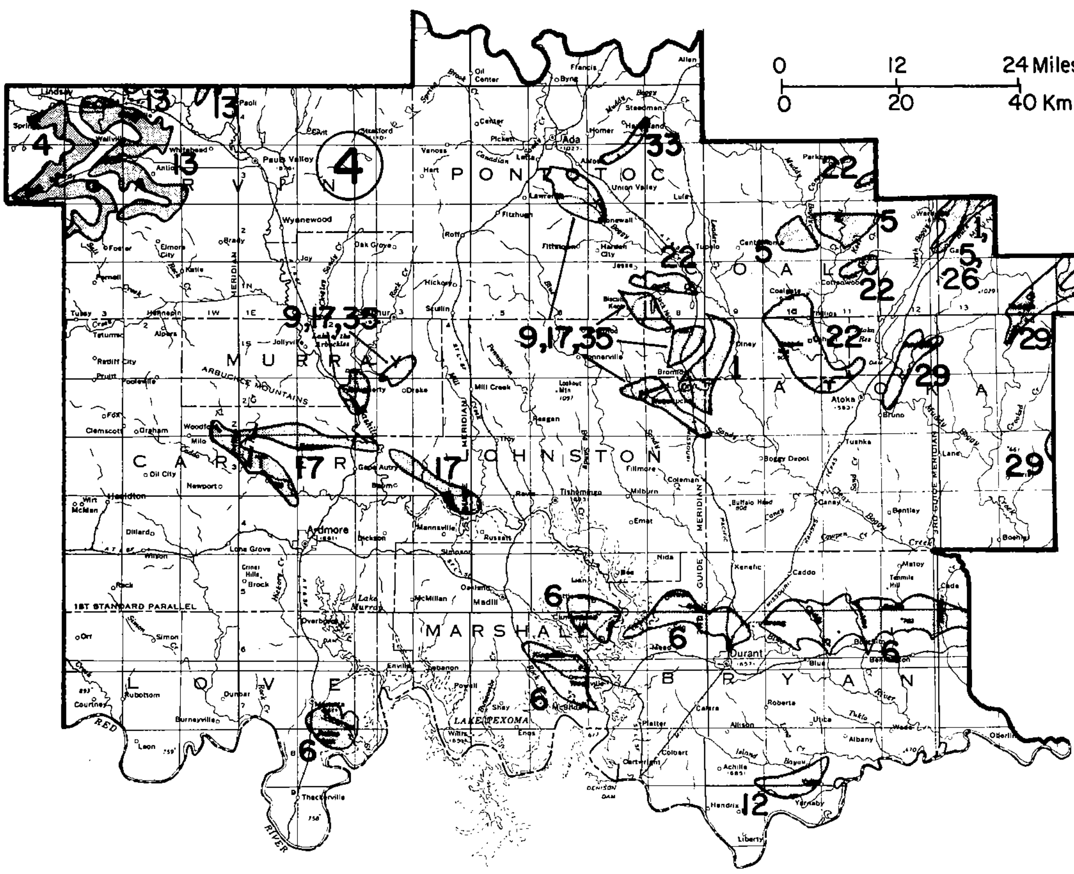
TABLE 9.—PHYSICAL CHARACTERISTICS OF ZONE 1 GEOLOGIC UNITS IN DISTRICTS 3 AND 4

Geologic unit	Portion of unit	Lithology	Thickness (in feet)	Structure	Clay mineralogy*	Plasticity	Shrink-swell potential	Additional comments
1. "Atoka" Formation	Selected shale intervals	Shale, brown to gray, with interbedded sandstones	50-500, for shale intervals	Gentle to moderate folds, some faults, gentle to steep dips.	Illite, chlorite, kaolinite, and mixed-layer illite-montmorillonite	Medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover.
4. Bison Shale	Entire	Shale, red-brown, with thin interbeds of siltstone and sandstone	50-100	Flat-lying	Illite and mixed-layer illite-chlorite	Medium	Low	Gently rolling and broad, flat plains with thin to thick soil cover.
5. Boggy Formation	Selected shale intervals	Shale, gray, with interbedded sandstones	50-300, for shale intervals	Gently folded, with gentle to moderate dips	Illite, kaolinite, montmorillonite, and mixed-layer illite-montmorillonite	Medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover.
6. Bokchito Formation	Selected clay intervals	Clay shale, gray to black, with thin interbeds of sandstone	50-135, for clay intervals	Flat-lying	Montmorillonite, illite, and kaolinite	Medium to high	Low to high	Gently rolling plains with thin to thick soil cover.
9. Delaware Creek Shale	Entire	Shale, dark-gray to black, with thin sandstone interbeds	160-750	Gentle to steep dips, locally folded, faulted, and jointed	Mixed-layer illite-chlorite, mixed-layer illite-montmorillonite, illite, kaolinite, chlorite	Medium	Low to high	Gently rolling plains with thin to moderate soil cover.
12. Eagle Ford Formation	Entire	Clay shale, dark-gray	50	Flat-lying	Montmorillonite, illite, and kaolinite	Medium	Moderate to high	Gently rolling plains with thin to thick soil cover.
13. Fairmont Shale	Entire	Shale, red-brown, with thin interbeds of siltstone	40-80	Flat-lying	Mixed-layer illite-chlorite-montmorillonite, mixed-layer chlorite-vermiculite, illite, kaol[illegible]	Slight to medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover.

TABLE 9.—*Continued*

Geologic unit	Portion of unit	Lithology	Thickness (in feet)	Structure	Clay mineralogy*	Plasticity	Shrink-swell potential	Additional comments
17. Goddard Shale	Entire	Shale, gray, with interbeds of sandstone and limestone	240-3,600	Gentle to steep dips, locally folded, faulted, and jointed	Kaolinite, montmorillonite, and illite	Medium	Low to high	Gently rolling plains with thin to moderate soil cover.
20. Johns Valley Formation	Entire	Shale, dark-gray, with interbeds of sandstone	425-900	Folded, with moderate to steep dips	Illite, chlorite, and kaolinite	Medium	Low	Gently rolling plains with thin to thick soil cover.
22. McAlester Formation	Selected shale intervals	Shale, gray, with interbeds of sandstone	50-500, for shale intervals	Gentle to moderate folds, some faults, gentle to steep dips	Illite, kaolinite, mixed-layer illite-montmorillonite	Slight to medium	Low to moderate	Gently rolling to broad flat plains with thin to thick soil cover.
26. Savanna Formation	Selected shale intervals	Shale, gray, with interbeds of sandstone	50-300, for selected shale intervals	Gently folded, with gentle to moderate dips	Illite, kaolinite, chlorite, vermiculite	Medium	Low	Gently rolling and broad, flat plains with thin to thick soil cover.
29. Stanley Formation	Entire	Shale, gray to dark-gray, with interbeds of sandstone	About 10,000	Jointed, faulted, tightly folded, with moderate to steep dips	Illite, chlorite, kaolinite, and montmorillonite	Slight to medium	Low	Gently rolling and broad, flat plains with thin to thick soil cover; long and narrow valleys in Ouachita Mountains.
30. Stuart Shale	Lower	Shale, gray, with thin sandstone interbeds	80-300	Flat-lying to gently dipping	Illite, mixed-layer illite-montmorillonite, montmorillonite	Medium	Low	Gently rolling plains with thin to thick soil cover.
33. Wetumka Formation	Entire	Shale, gray, with thin interbeds of siltstone and sandstone	100-250	Flat-lying	Mixed-layer illite-montmorillonite, illite, kaolinite	Medium	Low	Gently rolling plains with thin to thick soil cover.
35. Woodford Shale	Entire	Shale, dark gray to black, with layers and nodules of chert	160-560	Gentle to steep dips, locally folded, faulted, and jointed	Illite, mixed-layer illite-chlorite, chlorite	Medium	Low	Gently rolling plains with thin to thick soil cover.

* May incorporate clay-mineralogy data from other planning districts.



1 Atoka Formation
4 Bison Shale
5 Boggy Formation
6 Bokchito Formation
9 Delaware Creek Shale
12 Eagle Ford Formation
13 Fairmont Shale
17 Goddard Shale
22 McAlester Formation
26 Savanna Formation
29 Stanley Shale
33 Wetumka Formation
35 Woodford Shale

Figure 12. Map showing distribution of Zone 1 bedrock formations in planning district 4.

Pennsylvanian units. Zone 2 units around Ardmore are Pennsylvanian shales and sandstones, and those extending across the south part of both districts are the Cretaceous Caddo and Kiamichi Formations.

Zone 3 Rock Units.

Formations classified as Zone 3 are mainly fresh-water aquifers supplying municipal, irrigation, and domestic water. These aquifers include (1) Cretaceous sandstones and limestones, such as the Antlers, Goodland, and Woodbine Formations in the coastal-plain area of the south; (2) the thick sequence of Cambrian through Devonian limestones, dolomites, and sandstones of the Arbuckle Mountains; (3) Pennsylvanian and Permian sandstones and conglomerates of the Vamoosa, Ada, Vanoss, Oscar, Wellington, and Garber units in the northwest part of district 4; and (4) Quaternary sand, silt, clay, and gravel in alluvium and terrace deposits. Also included in Zone 3 are the granites and other igneous rocks in Johnston County.

Districts 5 and 6

The counties in district 5 consist of Hughes, Lincoln, Okfuskee, Pawnee, Pottawatomie, and Seminole Counties. Creek, Osage, and Tulsa Counties make up district 6. Tulsa County has a population density of 500 to 755 persons per square mile, and Payne and Pawnee Counties have population densities of 50 to 99 persons per square mile. The remaining counties have population densities of 10 to 49 persons per square mile (fig. 7, table 10).

An urban county is considered to be one where more than half the population lives in towns or cities with 2,500 or more persons, and Tulsa, Creek, Payne, Pottawatomie, and Seminole Counties are considered urban counties. Only Okfuskee County has fewer than 50 percent of its population living in incorporated cities or towns. Osage, Pawnee, Creek, Lincoln, Pottawatomie, Seminole, and Hughes Counties have 50 to 75 percent of their population in cities or towns. Seventy-five percent or more of the population in Tulsa and Payne Counties is concentrated in incorporated cities or towns.

Districts 5 and 6 are characterized by a gently rolling terrain developed on sedimentary rock units consisting mainly of sandstone, shale, and thin beds of limestone. A series of moderately high sandstone-capped ridges rises above the broad shale plains in parts of the east half of both districts.

Precipitation is moderate and ranges from 32–36 inches per year in the west to 36–42 inches per year in the east (fig. 3). Vegetation in most of the region is dominated by post oak-blackjack, although grasslands occur in northwest Osage County, in the north part of district 5, and in other scattered areas in both districts. Soils that overlie the bedrock range from thin to thick in the region.

Outcrop areas of parts or all of 14 different rock units are considered Zone 1 within districts 5 and 6. Large parts of both districts are also placed in Zones 2 and 3.

Zone 1 Rock Units

Fourteen rock units with moderately thick to thick shale units are classified as Zone 1. These units are as follows: Barnsdall

TABLE 10.—POPULATION DENSITY AND LAND AREA FOR SUBSTATE PLANNING DISTRICTS 5 AND 6, OKLAHOMA, 1970

		Land area (square miles)		Population (per square mile)
District 5				
Hughes Co.		807		16.4
Lincoln Co.		973		20.0
Okfuskee Co.		637		16.8
Pawnee Co.		561		20.2
Payne Co.		694		73.0
Pottawatomie Co.		794		54.3
Seminole Co.		630		39.9
	Total	5,096	Average	34.1
District 6				
Creek Co.		936		48.6
Osage Co.		2,272		13.1
Tulsa Co.		573		701.0
	Total	3,781	Average	126.4

Source: Shreiner and Chang (1975).

TABLE 11.—PHYSICAL CHARACTERISTICS OF ZONE 1 GEOLOGIC UNITS IN DISTRICTS 5 AND 6

Geologic unit	Portion of unit	Lithology	Thickness (in feet)	Structure	Clay mineralogy*	Plasticity	Shrink-swell potential	Additional comments
3. Barnsdall Formation	Upper	Shale, red-brown, with thin interbeds of sandstone	50-100	Flat-lying	Illite, kaolinite, and mixed-layer chlorite-vermiculite	Medium	Low	Gently rolling plains with thin to thick soil cover; locally overlain by Vamoosa fresh-water aquifer.
7. Chanute Formation	Upper	Shale, gray, with thin interbeds of sandstone	30-100	Flat-lying	Illite, kaolinite, mixed-layer vermiculite-chlorite	Medium	Low to moderate	Gently rolling plains with thin to thick soil cover.
8. Coffeyville Formation	Selected shale intervals	Shale, blue-gray, with interbedded sandstone and conglomerate	50-150, for shale intervals	Flat-lying, with some faults in Seminole County	Illite, chlorite and kaolinite	Medium	Low to moderate	Gently rolling to broad, flat plains with thin to thick soil cover; open-pit mining of shale.
18. Hilltop Formation	Entire	Shale, gray and brown, with thin interbeds of sandstone and limestone	50-200	Flat-lying	Kaolinite, mixed-layer illite-montmorillonite, chlorite	Medium	Low	Gently rolling plains with thin to thick soil cover; overlain by Vamoosa fresh-water aquifer; open-pit mining of shale.
19. Holdenville Shale	Upper	Shale, brown and gray, with thin interbeds of sandstone and limestone	50-100	Flat-lying, with some faults	Mixed-layer illite-montmorillonite, illite, kaolinite	Medium	Low	Gently rolling plains with thin to thick soil cover.
21. Labette Formation	Entire	Shale, gray, with thin interbeds of sandstone and limestone	120-240	Flat-lying	Illite, mixed-layer illite-montmorillonite, mixed-layer illite-vermiculite, kaolinite	Low to medium	Probably low	Gently rolling to broad, flat plains with thin to thick soil cover; exposed in escarpments capped by overlying limestone; open-pit mining of shale.
23. Nellie Bly Formation	Lower and middle	Shale, gray to brown, with thin interbeds of sandstone	50-150	Flat-lying	Illite, kaolinite, vermiculite	Medium	Low	Gently rolling to broad, flat plains with thin to thick soil cover.

TABLE 11.—*Continued*

Geologic unit	Portion of unit	Lithology	Thickness (in feet)	Structure	Clay mineralogy*	Plasticity	Shrink-swell potential	Additional comments
24. Nowata Formation	Entire	Shale, gray, with thin interbeds of sandstone and limestone	150-500	Flat-lying	Illite, kaolinite, vermiculite, chlorite	Medium	Low	Gently rolling to broad, flat plains with thin to thick soil cover.
25. Oscar Group	Selected shale intervals	Shale, red-brown, with thin interbeds of siltstone and sandstone	50-100	Flat-lying	Illite, kaolinite, chlorite, and illite-montmorillonite	Medium	Low	Gently rolling plains with thin to moderate soil cover.
27. Seminole Formation	Selected shale intervals	Shale, gray and brown, with interbeds of sandstone and conglomerate	50-100, for shale intervals	Flat-lying, with a few faults	Illite, kaolinite, vermiculite, and mixed-layer illite-vermiculite	Slight to medium	Low	Gently rolling to broad, flat plains with thin to thick soil cover; open-pit mining of shale.
28. Senora Formation	Upper	Shale, gray, with interbeds of sandstone	50-150	Flat-lying	Illite, kaolinite	Medium	Low	Gently rolling plains with thin to thick soil cover.
31. Vanoss Group	Selected shale intervals	Shale, gray and red, with interbeds of sandstone and limestone	50-100, for shale intervals	Flat-lying	Kaolinite, illite, montmorillonite, mixed-layer illite-montmorillonite	Medium to high	Low to high	Gently rolling plains with thin to moderate soil cover; Zone 1 units only north of Deep Fork.
33. Wetumka Formation	Entire	Shale, gray, with thin interbeds of siltstone and sandstone	100-200	Flat-lying	Mixed-layer illite-montmorillonite, illite, kaolinite	Medium	Low	Gently rolling plains with thin to thick soil cover.
34. Wewoka Formation	Selected shale intervals	Shale, gray, with interbeds of sandstone	50-150, for shale intervals	Flat-lying	Illite, mixed-layer illite-montmorillonite, kaolinite	Medium	Low	Gently rolling to broad, flat plains with thin to thick soil cover.

*May incorporate clay-mineralogy data from other planning districts.

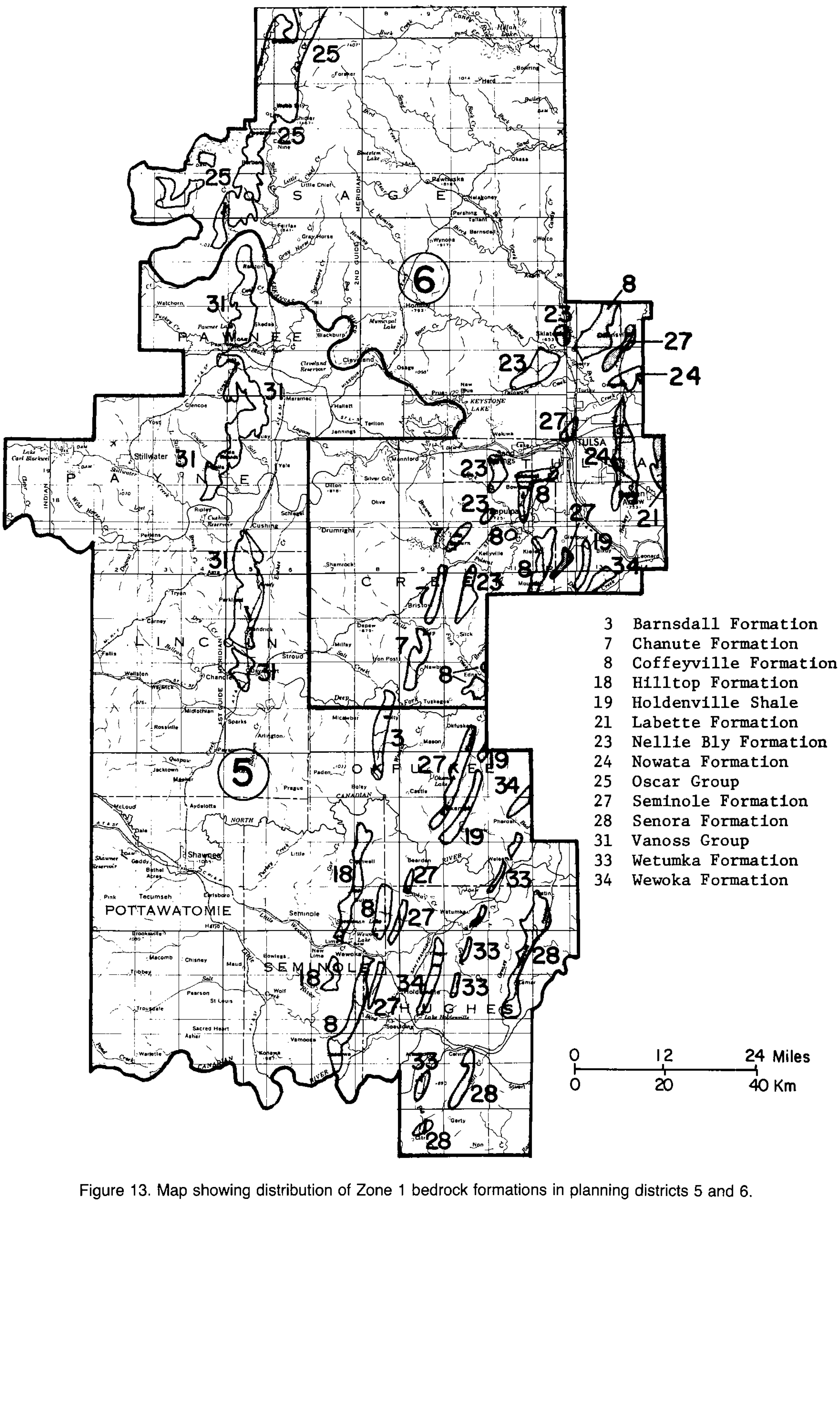


Figure 13. Map showing distribution of Zone 1 bedrock formations in planning districts 5 and 6.

Formation, Chanute Formation, Coffeyville Formation, Hilltop Formation, Holdenville Shale, Labette Formation, Nellie Bly Formation, Nowata Formation, Oscar Group, Seminole Formation, Senora Formation, Vanoss Group, Wetumka Formation, and Wewoka Formation. All these units are of Pennsylvanian age, although the Oscar Group also has been considered of Early Permian age.

The thick shale units in each of these formations appear locally to be suitable for use as host rocks for disposal of industrial waste. They are classified as Zone 1 in widely scattered areas embracing all but the southwest part of district 5 and the northeast part of district 6 (fig. 13). Each Zone 1 unit is described in the previous chapter of this report, and the descriptions are summarized here in table 11.

A series of long and narrow subparallel bands of Zone 1 rock units extends across the south and east parts of both districts (fig. 13). These bands embrace all the Zone 1 units except the Oscar and Vanoss Groups, which make up the outcrop belts that extend across the north and west portions of both districts.

Zone 2 Rock Units

Rock units herein considered parts of Zone 2 are Pennsylvanian in age and consist of thick sequences of interbedded sandstone, shale, siltstone, and limestone. Locally some of these shales may be more than 50 feet thick and may also be suitable for waste disposal. Zone 2 areas in the north half of both districts are those parts of the Oscar and Vanoss Groups not mapped separately as Zone 1. The Zone 2 areas elsewhere consist mainly of parts of the Senora, Wewoka, Coffeyville, Nellie Bly, and other formations that also are not mapped separately as Zone 1.

Zone 3 Rock Units

Strata classified as Zone 3 in both districts are mainly fresh-water aquifers that supply municipal, irrigation, and domestic water. These aquifers include (1) Pennsylvanian and Permian sandstones and conglomerates of the Vamoosa, Ada, Vanoss, Oscar, and Wellington units south of the Cimarron River in district 5; (2) Pennsylvanian sandstones of the Vamoosa Formation, extending northward in a belt across district 6; and (3) Quaternary sand, silt, clay, and gravel in alluvium and terrace deposits.

Districts 7, 8, and 9

The counties in district 7 consist of Alfalfa, Blaine, Garfield, Grant, Kay, Kingfisher, Major, and Noble Counties. Canadian, Cleveland, Logan, and Oklahoma Counties make up district 8. Caddo, Comanche, Cotton, Grady, Jefferson, McClain, Stephens, and Tillman Counties make up district 9. Oklahoma County has a population density of 100 to 499 persons per square mile. Counties that have population densities of 50 to 99 persons per square mile include Comanche, Kay, and Garfield. Except for Alfalfa, Grant, Jefferson, and Major Counties, whose population densities are fewer than 10 persons per square mile, the remaining counties have population densities of 10 to 49 persons per square mile (fig. 7, table 12).

An urban county is considered to be a county where more than half the population lives in towns or cities with populations greater than 2,500 or more persons, and Kay, Garfield, Noble, Canadian, Oklahoma, Cleveland, Comanche, and Stephens Counties are considered urban counties. No counties in these three planning districts have fewer than 50 percent of their population living in incorporated cities and towns. Grant, Alfalfa, Major, Noble, Blaine, Kingfisher, Logan, Caddo, Grady, McClain, Stephens, Cotton, and Jefferson Counties have between 50 and 75 percent of their population living in cities or towns. Kay, Garfield, Canadian, Oklahoma, Cleveland, Comanche, and Tillman Counties have more than 75 percent of their population living in incorporated cities and towns.

The topography of the districts is characterized by gently rolling to broad, flat plains developed on sedimentary units consisting chiefly of sandstone, shale, gypsum, limestone, and unconsolidated sand and gravel. In the south, granite and other igneous rocks of the Wichita Mountains locally dominate the landscape. Precipitation is low to moderate, ranging from 25–28 inches per year in the west to 32–36 inches in the east (fig. 3). The vegetation includes grassland prairies in the west and north and post oak-blackjack woodlands on sandstone

TABLE 12.—POPULATION DENSITY AND LAND AREA FOR SUBSTATE PLANNING DISTRICTS 7, 8, AND 9, OKLAHOMA, 1970

		Land area (square miles)		Population (per square mile)
District 7				
Alfalfa Co.		868		8.3
Blaine Co.		917		12.9
Garfield Co.		1,054		52.5
Grant Co.		1,007		7.1
Kay Co.		950		51.4
Kingfisher Co.		904		14.2
Major Co.		963		7.8
Noble Co.		743		13.5
	Total	7,406	Average	21.7
District 8				
Canadian Co.		897		35.9
Cleveland Co.		527		155.3
Logan Co.		751		26.2
Oklahoma Co.		700		752.6
	Total	2,875	Average	229.8
District 9				
Caddo Co.		1,272		22.7
Comanche Co.		1,084		99.8
Cotton Co.		651		10.5
Grady Co.		1,096		26.8
Jefferson Co.		780		9.1
McClain Co.		573		24.7
Stephens Co.		891		40.3
Tillman Co.		901		14.3
	Total	7,248	Average	33.6

Source: Shreiner and Chang (1975).

units chiefly in the east and south. Soil covering the bedrock units ranges from thin to thick in the districts; shales are fairly well exposed in much of the west half of the districts but are generally covered by moderate to thick soils in the east.

Seven rock units classified as Zone 1 are widely distributed within districts 7, 8, and 9. Several other units are considered Zone 2, and large parts of the region are considered Zone 3.

Zone 1 Rock Units

Seven moderately thick to thick red shales are considered Zone 1 in the three-district region. These shales make up all or parts of the following rock units: Bison Shale, Dog Creek Shale, Fairmont Shale, Flowerpot Shale, Garber Formation, Oscar Group, and Wellington Formation. All units are of Permian age except the Oscar Group, which has been variously placed in the Late Pennsylva-

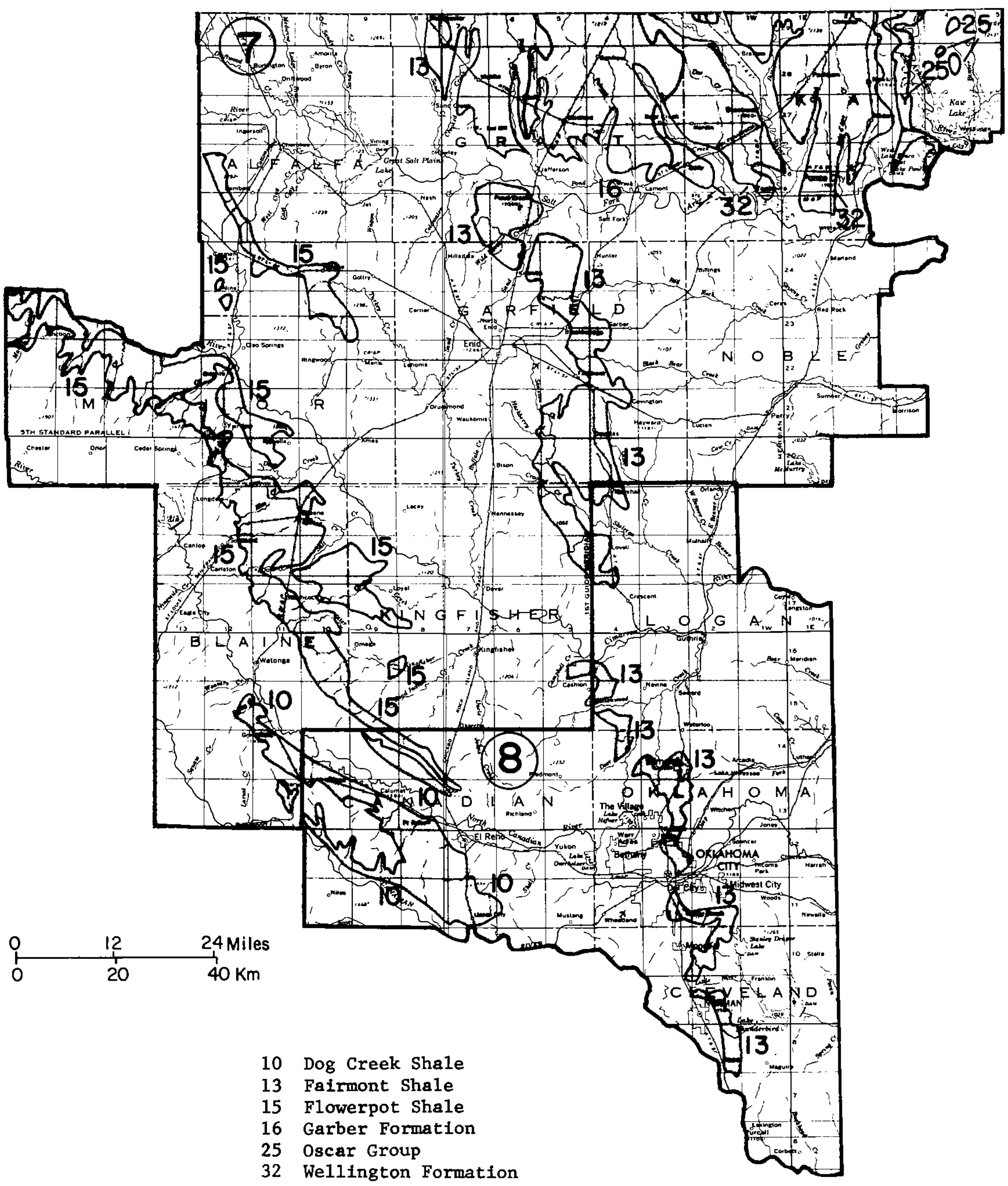


Figure 14. Map showing distribution of Zone 1 bedrock formations in planning districts 7 and 8.

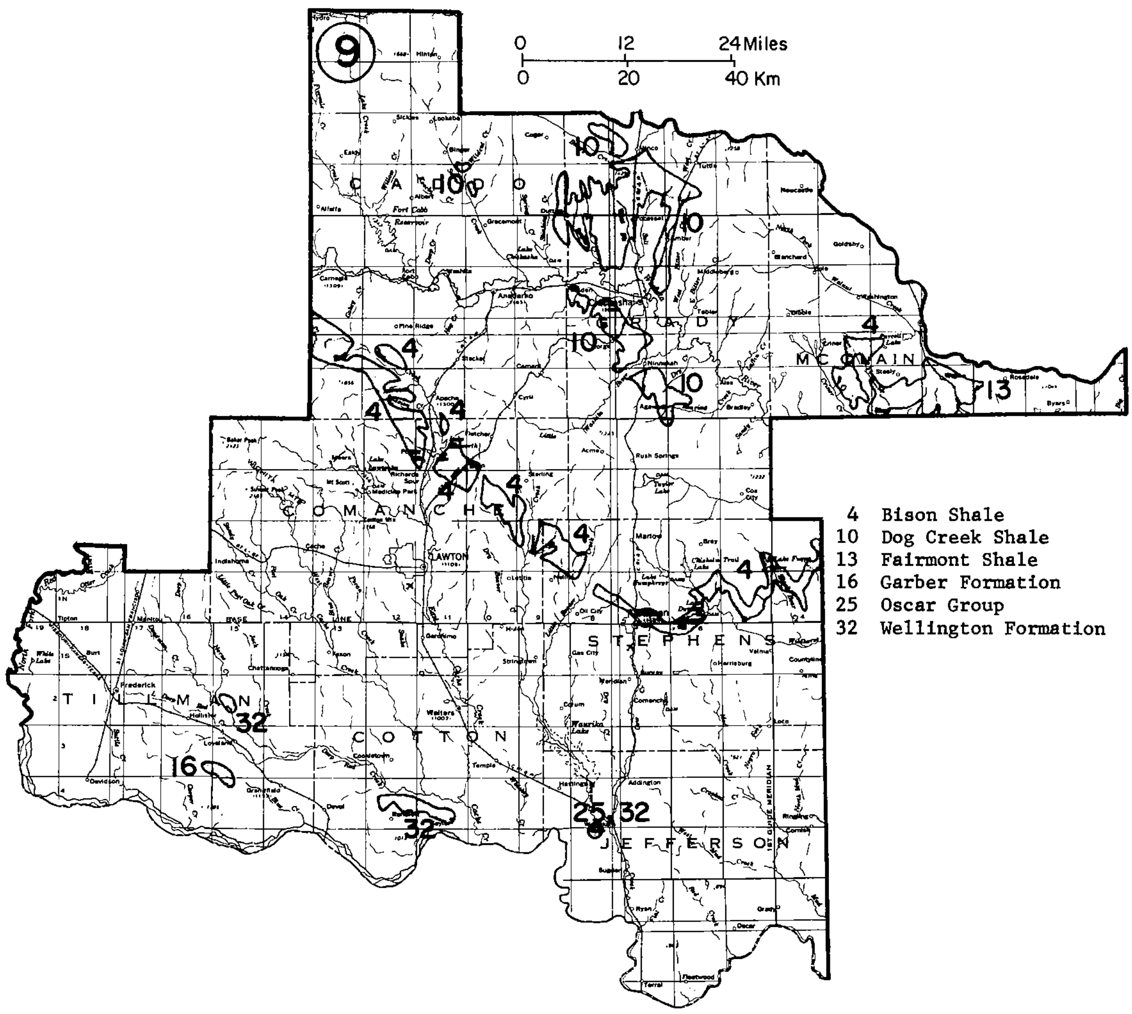


Figure 15. Map showing distribution of Zone 1 bedrock formations in planning district 9.

nian (Gearyan Series) and Early Permian.

All seven rock units classed as Zone 1 appear to be generally favorable for development of waste-disposal sites, and these units are widely distributed in all parts of districts 7, 8, and 9 except for the south part of district 9 (figs. 14, 15). Descriptions of the seven formations are given in the preceding chapter, and data on all of them are summarized here in table 13.

District 7 has several Zone 1 units north of the Salt Fork of the Arkansas River: the Garber and Wellington Formations are mostly shale in this area, and the Oscar Group contains one shale formation in the extreme northeast (figs. 14, 15). The Fairmont Shale extends south of the river across the central part of the district. In the west are outcrops of the Flowerpot Shale, whereas in the far south are outcrops of the Dog Creek Shale.

District 8 embraces a discontinuous belt of Fairmont Shale in the central part, and in the west are a large area of Dog Creek Shale and a narrow band of Flowerpot Shale. In

TABLE 13.—PHYSICAL CHARACTERISTICS OF ZONE 1 GEOLOGIC UNITS IN DISTRICTS 7, 8, AND 9

Geologic unit	Portion of unit	Lithology	Thickness (in feet)	Structure	Clay mineralogy*	Plasticity	Shrink-swell potential	Additional comments
4. Bison Shale	Entire	Shale, red-brown, with thin interbeds of siltstone and sandstone	50-100	Flat-lying	Illite and mixed-layer illite-chlorite	Medium	Low	Gently rolling and broad, flat plains with thin to thick soil cover; well exposed in escarpments capped by overlying sandstone.
10. Dog Creek Shale	Entire	Shale, red-brown, with thin interbeds of siltstone, sandstone, gypsum, and dolomite	100-200	Flat-lying	Illite, kaolinite, mixed-layer chlorite-vermiculite, mixed-layer chlorite-montmorillonite	Medium	Low to moderate	Gently rolling plains with thin to thick soil cover; exposed in escarpments capped by overlying sandstone; locally overlies thick gypsum beds of Blaine Formation.
13. Fairmont Shale	Entire	Shale, red-brown, with thin interbeds of sandstone	40-80	Flat-lying	Mixed-layer illite-chlorite-montmorillonite, kaolinite, illite, chlorite	Slight to medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover; locally overlies major fresh-water aquifer (Garber).
15. Flowerpot Shale	Entire	Shale, red-brown, with thin interbeds of siltstone, sandstone, gypsum, and dolomite	100-400	Flat-lying	Illite, with lesser amounts of kaolinite and montmorillonite	Slight to medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover; well exposed in escarpments capped by overlying gypsum beds.
16. Garber Formation	Entire	Shale, red-brown, with thin interbeds of siltstone and sandstone	600 (estimated)	Flat-lying	Illite, mixed-layer illite-chlorite-montmorillonite, kaolinite	Slight	Low	Gently rolling and broad, flat plains with thin to thick soil cover; unit classified as Zone 1 only north of Salt Fork of Arkansas River and in extreme south.
25. Oscar Group	Selected shale intervals	Shale, red-brown, with thin interbeds of siltstone and sandstone	50-100, for shale intervals	Flat-lying	Illite, chlorite, kaolinite	Medium	Low to moderate	Gently rolling plains with thin to moderate soil cover; unit classified as Zone 1 only in small areas of extreme north and south.
32. Wellington Formation	Entire	Shale, red-brown, with thin interbeds of siltstone, sandstone, and dolomite	800 (estimated)	Flat-lying	Illite, kaolinite, chlorite, montmorillonite	Medium	Low to moderate	Gently rolling and broad, flat plains with thin to thick soil cover; unit classified as Zone 1 only north of Salt Fork of Arkansas River and in extreme south.

* May incorporate clay-mineralogy data from other planning districts.

district 9, the Dog Creek crops out in the north, and the Bison Shale forms a discontinuous band across the center. Small areas of exposure include the Fairmont in the northeast and the Wellington, upper Garber, and Oscar in the south.

Zone 2 Rock Units

Thick units of interbedded sandstone, siltstone, and shale make up the areas shown as Zone 2 in the region. Some of the shales may locally be more than 50 feet thick and may be acceptable as host rocks for disposal of industrial waste. The large Zone 2 area in the east half of district 7 and the north part of district 8 consists of the Garber, Wellington, and Oscar units, where they are transitional between the thick shales to the north and the major sandstone aquifers to the south. A similar transition is found in the Garber, Wellington, and Oscar where they are classed as Zone 2 in the south half of district 9.

The remaining Zone 2 units are the Chickasha, Duncan, Salt Plains, and Kingman formations in districts 7 and 8 and in the north half of district 9. Also included in Zone 2 are those parts of the Hennessey Group not separately mapped as Zone 1. The Cedar Hills Formation is considered Zone 2 in Blaine and Kingfisher Counties.

Zone 3 Rock Units

Strata classified as Zone 3 in all three districts are mainly fresh-water aquifers for municipal, irrigation, and domestic water use. These aquifers include (1) Permian sandstones and siltstones of the Garber-Wellington Formation and Rush Springs Sandstone, and (2) Quaternary alluvium and terrace deposits composed of mixtures of sand, silt, clay, and gravel. Granite and limestone outcrops in the Wichita Mountain area, in the western part of district 9, are also included within this categoy.

Districts 10 and 11

District 10 is composed of Beckham, Custer, Greer, Harmon, Jackson, Kiowa, Roger Mills, and Washita Counties. Beaver, Cimarron, Dewey, Ellis, Harper, Texas, Woods, and Woodward Counties make up district 11. Woodward, Custer, Beckham, Washita, Greer, Kiowa, and Jackson Counties have population densities of 10 to 49 persons per square mile. The remaining counties have population densities of fewer than 10 persons per square mile (fig. 7, table 14).

An urban county is considered to be one where more than half the population lives in towns or cities with 2,500 or more persons, and Woods, Woodward, Custer, Beckham, Greer, Harmon, and Jackson Counties are considered urban counties. Beaver and Roger Mills Counties have fewer than 50 percent of their population living in incorporated cities and towns. Cimarron, Harper, Ellis, Woodward, Dewey, Washita, and Harmon Counties have between 50 and 75 percent of their population living in incorporated cities or towns, whereas 75 percent or more of the population in Texas, Woods, Custer, Beckham, Greer, Kiowa, and Jackson Counties is concentrated in incorporated cities or towns.

The terrain typically consists of gently rolling to broad, flat plains developed on sedimentary units composed chiefly of sandstone, shale, gypsum, and unconsolidated sand and gravel. Precipitation is low, ranging from 16 to 25 inches per year (fig. 3), and the region is predominantly grasslands. Soil cover above bedrock units is generally thin, and in many areas the shales are well exposed in deeply dissected badlands.

The outcrop areas of three rock units are classified as Zone 1 within districts 10 and 11. A few other areas are classified as Zone 2, but most of the region is considered Zone 3.

Zone 1 Rock Units

Three thick red shales of Permian age are classified as Zone 1 in districts 10 and 11: Bison Shale, Doxey Shale, and Flowerpot Shale. General characteristics of these formations are described in the preceding chapter, and those data are summarized here in table 15. All three of the units appear to be generally favorable for use in disposal of industrial waste, and Zone 1 materials are present in all areas except the southern and Panhandle parts of district 11.

District 10 contains substantial outcrops of the Bison Shale and Flowerpot Shale in the south and a large area of Doxey Shale in the north (figs. 16, 17). District 11, on the other

TABLE 14.—POPULATION DENSITY AND LAND AREA FOR SUBSTATE PLANNING DISTRICTS 10 AND 11, OKLAHOMA, 1970

		Land area (square miles)		Population (per square mile)
District 10				
Beckham Co.		907		17.4
Custer Co.		980		23.1
Greer Co.		633		12.6
Harmon Co.		545		9.4
Jackson Co.		810		38.2
Kiowa Co.		1,027		12.2
Roger Mills Co.		1,140		3.9
Washita Co.		1,009		12.0
	Total	7,051	Average	15.8
District 11				
Beaver Co.		1,790		3.5
Cimarron Co.		1,843		2.2
Dewey Co.		1,018		5.6
Ellis Co.		1,242		4.1
Harper Co.		1,041		4.9
Texas Co.		2,062		7.9
Woods Co.		1,298		9.2
Woodward Co.		1,251		12.4
	Total	11,545	Average	6.1

Source: Shreiner and Chang (1975).

hand, has extensive outcrops of the Flowerpot Shale along the Cimarron River and in Woods County in the northeast, and a small outcrop of the Doxey Shale in the extreme south.

Zone 2 Rock Units

Included within Zone 2 are thick units of sandstone, siltstone, and shale wherein some of the shales may exceed 50 feet in thickness and may locally be suitable for waste disposal. The lower parts of the Hennessey Group and the Duncan Sandstone make up the Zone 2 area in the southeast part of district 10, whereas the Cloud Chief Formation makes up the Zone 2 area in all other parts of district 10 and the east three-fourths of district 11. In the west part of district 11, in Cimarron County, the Zone 2 area consists of outcrops of Triassic, Jurassic, and Cretaceous shale, sandstone, marl, and limestone.

Zone 3 Rock Units

Rock units classified as Zone 3 within districts 10 and 11 are chiefly fresh-water aquifers supplying municipal, irrigation, and domestic water. Aquifers include (1) Permian sandstones, such as the Marlow and Rush Springs Formations; (2) Permian gypsums, such as the Blaine-Dog Creek formations and the lower part of the Cloud Chief Formation; (3) Tertiary sand, silt, clay, and gravel of the Ogallala Formation; and (4) Quaternary sand, silt, clay, and gravel in alluvium and terrace deposits. Outcrops of granite and limestone in the Wichita Mountain area (southeast part of district 10) are also included in the Zone 3 classification.

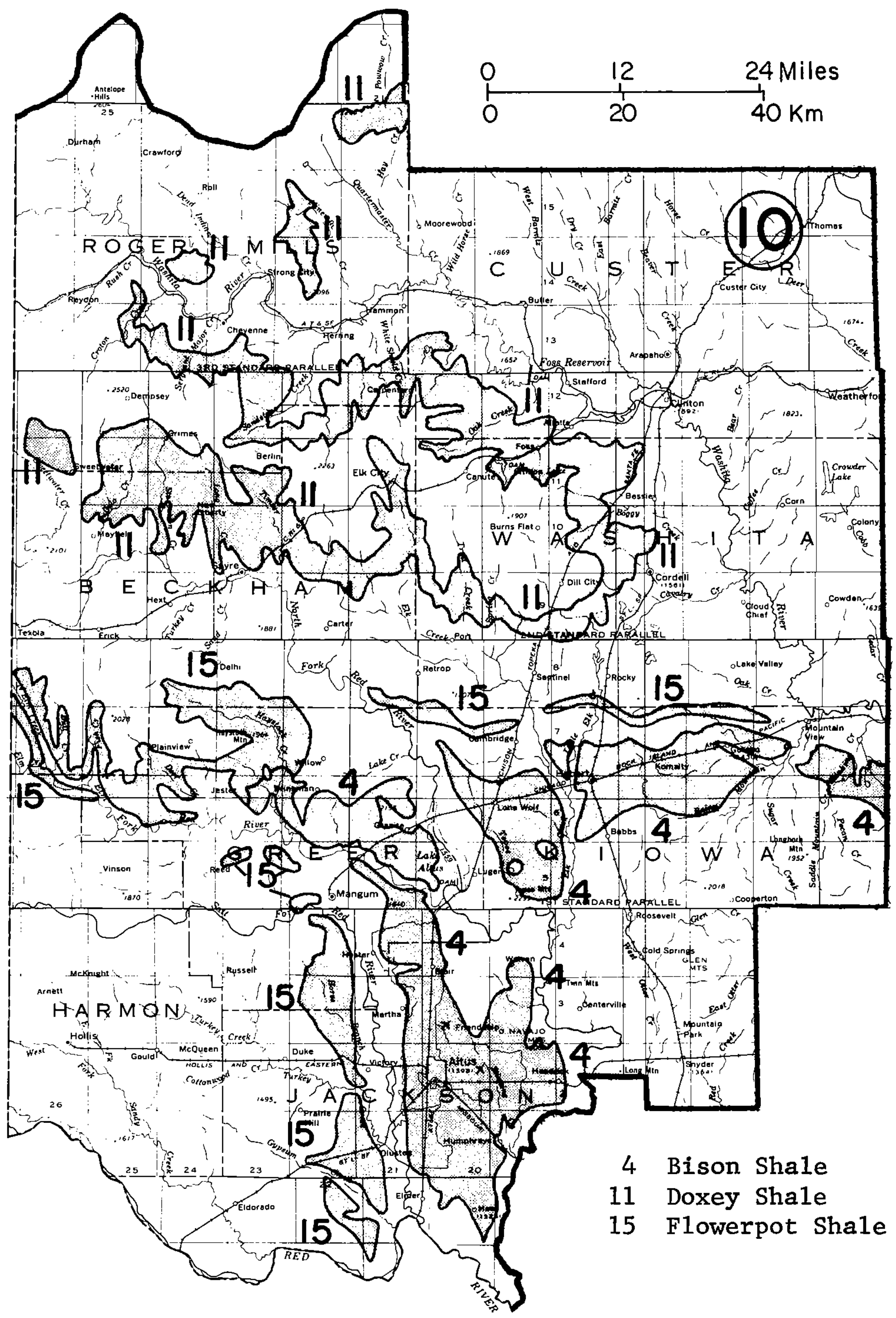


Figure 16. Map showing distribution of Zone 1 bedrock formations in planning district 10.

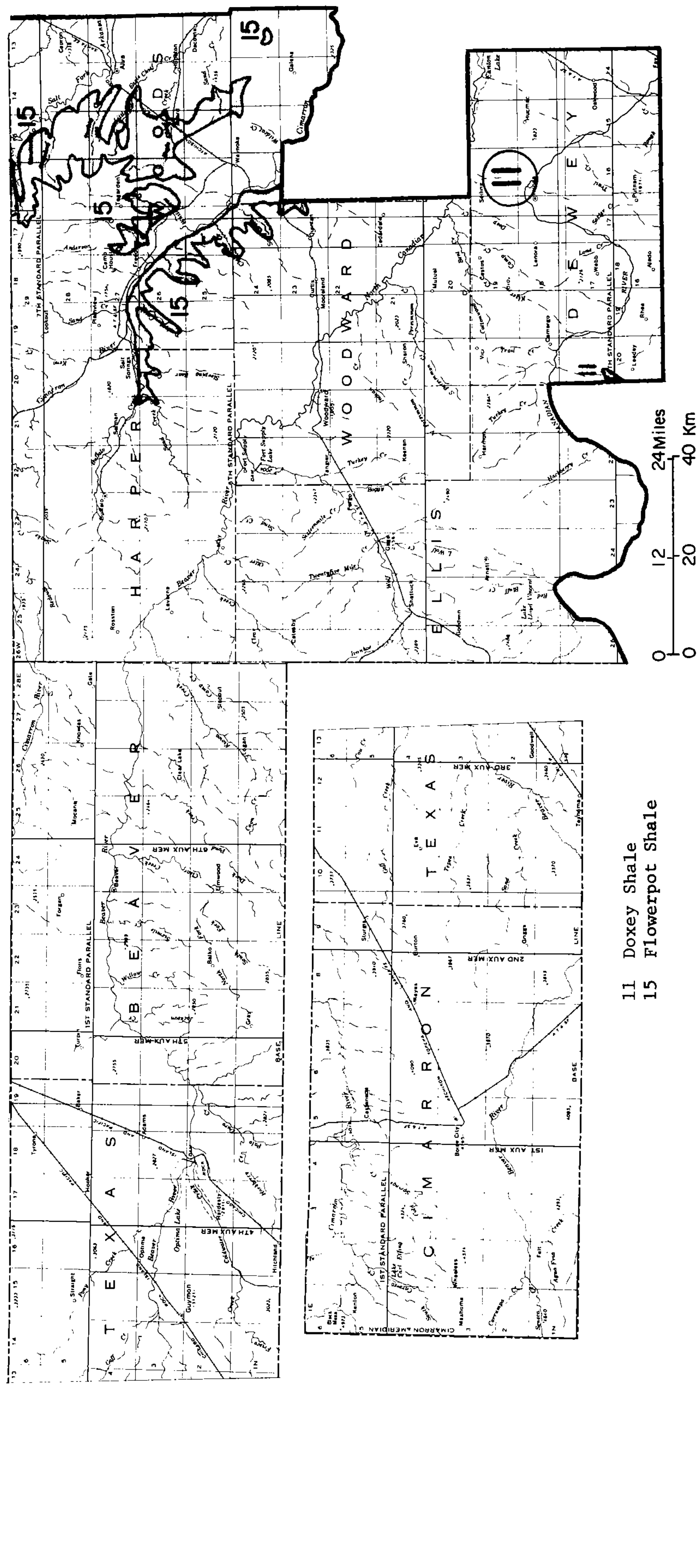


Figure 17. Map showing distribution of Zone 1 bedrock formations in planning district 11.

TABLE 15.—PHYSICAL CHARACTERISTICS OF ZONE 1 GEOLOGIC UNITS IN DISTRICTS 10 AND 11

Geologic Unit	Portion of unit	Lithology	Thickness (in feet)	Structure	Clay mineralogy*	Plasticity	Shrink-swell potential	Additional comments
4. Bison Shale	Entire	Shale, red-brown, with thin interbeds of siltstone and sandstone	100-200	Flat-lying	Illite and mixed-layer illite-chlorite	Slight to medium	Low	Gently rolling plains and broad, flat plains with thin to thick soil cover; well exposed in escarpments capped by overlying sandstone beds.
11. Doxey Shale	Entire	Shale, red-brown, with thin interbeds of siltstone and sandstone	150-200	Flat-lying; locally with steep dips, folds, and faults in areas of collapse blocks	Illite, mixed-layer montmorillonite-chlorite, kaolinite, chlorite	Slight	Probably low	Gently rolling hills with thin soil or no soil in most places.
15. Flowerpot Shale	Entire	Shale, red-brown, with thin interbeds of siltstone, sandstone, gypsum, and dolomite	100-250	Flat-lying to gently dipping	Illite, with lesser amounts of kaolinite and montmorillonite	Medium	Low	Gently rolling plains and broad, flat plains with thin to thick soil cover; well exposed in escarpments capped by overlying gypsum beds; contains cavernous salt locally along Cimarron River and Elm Fork of Red River.

*May incorporate clay-mineralogy data from other planning districts.

PART III.—SUBSURFACE DISPOSAL OF INDUSTRIAL WASTES IN OKLAHOMA

KENNETH S. JOHNSON[1] AND JOHN F. ROBERTS[2]

INTRODUCTION

The subsurface disposal of liquid industrial wastes has been carried out for many years in Oklahoma. Waste products, such as spent acids, caustic solutions, solvents, salt water, and other chemicals, are injected into underground "reservoirs" (porous and permeable rock units that can hold fluids) that are deep below the land surface and are removed from fresh-water aquifers and the biosphere. The purpose of this study is to assist industry and government in identifying the more promising reservoir rocks in various parts of the State and also to discuss a number of the factors that are important in evaluating the suitability of a potential disposal site. The data and interpretations we present must be used only for regional planning and as a guide to those rock units that might be acceptable locally. We do not confirm or reject the suitability of any rock unit in any part of the State, as this can be done only through detailed studies of a proposed site.

Subsurface isolation of wastes from fresh-water zones and the biosphere can be largely assured by injecting the wastes in reservoir rock units that are bounded by unfractured shales or other impermeable rocks. If adequate safeguards are not taken, liquid wastes or leachate might migrate laterally through the reservoir or vertically through permeable zones or improperly sealed boreholes and thus contaminate fresh groundwater or surface-water supplies. Furthermore, the condition of the land surface and shallow subsurface should be considered by trying to avoid areas that are flood prone or are underlain by major fresh-water aquifers, and by favoring areas with low-permeability surface soils, such as clays.

Rock types that commonly possess the properties needed for the injection of liquid wastes are certain sedimentary rocks, such as porous and permeable sandstones, limestones, and dolomites. Major sandstone reservoirs that are locally capable of accepting liquid wastes in Oklahoma include the Simpson Group, the Springer Formation, Pennsylvanian sandstones, granite wash, and Permian sandstones; major limestone and dolomite reservoirs include the Arbuckle Group, the Hunton Group, Mississippian limestones, the Brown dolomite, and Permian dolomites. Where used for waste disposal, these reservoirs typically have porosities ranging from 5 to 20 percent and permeabilities ranging from 20 to 2,000 millidarcies. Other rock units that may be capable of containing industrial wastes locally in fractures or mined caverns are Permian salt beds and the numerous shale units described in Part II.

In discussing the potential for subsurface disposal of waste in Oklahoma, we herein subdivide the State into seven major geologic regions (see fig. 26), each of which has undergone a different geologic history and each of which contains a thick suite of sedimentary rocks with similar reservoir potential. General data that we present on potential reservoirs in each of the seven regions include lithology, porosity, permeability, thickness, lateral extent, and depth. Also needed for full evaluation of any potential disposal site are data concerning structure, geologic framework, confining rocks, hydrology, fresh-water aquifers, compatibility of waste with the reservoir, mineral resources, and the presence of boreholes or other excavations. Principal nongeological factors that need to be assessed include population density, transportation facilities, possible atmospheric degradation (odors, fumes, etc.), and the assured safety of fresh-water streams and lakes.

At present, Oklahoma has 15 wells for injection of industrial wastes at 10 sites in Mayes, Oklahoma, Rogers, Stephens, Tulsa, and Woodward Counties (table 16, fig. 18). Reservoirs used for waste disposal are lime-

[1]Geologist, Oklahoma Geological Survey.
[2]Geologist, Oklahoma Geological Survey, deceased.

stones, dolomites, sandstones, and hydraulically fractured shales that range from 358 to 7,350 feet below the surface. Throughout the United States, at least several hundred industrial-waste-disposal wells are now in operation, and several tens of thousands of other wells are used for disposal of salt water produced along with oil and (or) natural gas.

A study by Reeder (1971) on "The Feasibility of Underground Liquid Waste Disposal in Northeastern Oklahoma" is the only recent comprehensive report covering a large part of the State. However, a number of other reports have been prepared on the problems of industrial-waste disposal elsewhere in the United States, and the reader is referred to the following publications for additional information. Several symposia released by The American Association of Petroleum Geologists include the work edited by Young and Galley (1965), Galley (1968), Cook (1972), and Braunstein (1973). Also, a comprehensive discussion of the principles and implementation of liquid-waste disposal is given in the report by Rudd (1972), and a discussion of the problems of waste injection was presented by Piper (1969).

There are a number of valuable sources of data on subsurface geology and reservoir rocks of Oklahoma that would be useful in studying the feasibility of a waste-disposal facility. Cramer and others (1963) prepared a report on oil and gas fields of Oklahoma, and this work was later supplemented by Berg and others (1974). The Oklahoma City Geological Society has published a great number of regional and field studies in the *Shale Shaker*, and the Tulsa Geological Society has published similar data in its *Digest*. The American Association of Petroleum Geologists has published many reports on reservoir rocks of Oklahoma in its monthly *Bulletin* and in several of its Memoirs on oil fields in the United States. Additional detailed data can be found in the large number of master's and doctoral theses done for the departments of geology,

TABLE 16.—LOCATION AND CHARACTERISTICS OF INDUSTRIAL WASTE-DISPOSAL WELLS IN OKLAHOMA

Company	Well name or number	Location	County (Nearby city)	Starting date	Total depth (feet)	Disposal zone: Depth range (feet)	Disposal zone: Geologic age
1. Agrico Chemical Co.	—	NW NW sec. 9, T 20 N, R 15 E	Rogers (Catoosa)	Dec. 1977	2,600 (est.)	1,450–T.D.	Cambrian-Ordovician
2. American Airlines, Inc.	—	NW SE sec. 13, T 20 N, R 13 E	Tulsa (Tulsa)	Jan. 1960	3,036	1,807–3,036	Ordovician
3. Amoco Production Co.	Iodine plant injection wells (6 wells)	Secs. 3, 9, 10, T 24 N, R 20 W	Woodward (Woodward)	June 1976	7,600 (avg.)	7,250–7,350 (avg. of 6 wells)	Pennsylvanian
*4. Beard Oil Co.	1 Berkenbile	SW NW sec. 29, T 18 N, R 6 W	Kingfisher (Dover)	Jan. 1969	7,173	7,079–7,173	Mississippian
5. N-Ren Corp., Cherokee Nitrogen Division	1	SE NW sec. 3 T 20 N, R 19 E	Mayes (Pryor)	June 1968	912	395–912	Ordovician
6. Halliburton Services	MRD 16	NE SE sec. 7, T 1 S, R 7 W	Stephens (Duncan)	Sept. 1970	1,238	1,216—1,238	Permian or Pennsylvanian
7. W. J. Lamberton		NW SW sec. 15, T 19 N, R 12 E	Tulsa (Tulsa)	Mar. 1974	3,364	2,093–3,360	Ordovician
8. Macklanburg-Duncan Co.	1	NW SW sec. 15, T 23 N, R 3 W	Oklahoma (Okla. City)	Mar. 1976	9,848	6,700–6,800	Ordovician
9. Nipak, Inc.	1	NW NE sec. 33, T 21 N, R 19 E	Mayes (Pryor)	June 1955	820	358–820	Ordovician
10. Nipak, Inc.	2	SE NW sec. 33, T 21 N, R 19 E	Mayes (Pryor)	Oct. 1966	815	398–815	Ordovician
*11. Ozark-Mahoning Co.	1	SE SE sec. 8, T 19 N, R 12 E	Tulsa (Tulsa)	Application pending	3,300	2,100–3,300	Cambrian-Ordovician
12. Rockwell International Co.	—	SW NE sec. 24, T 20 N, R 13 E	Tulsa (Tulsa)	Feb. 1968	3,100	1,800-3,100	Cambrian-Ordovician
*13. U.S. Pollution Control, Inc.	—	NE SW sec. 1, T 18 N, R 12 E	Tulsa (Tulsa)	Aug. 1971	3,359	2,027–3,359	Cambrian-Ordovician

*These wells were not operational late in 1978 and early in 1979.

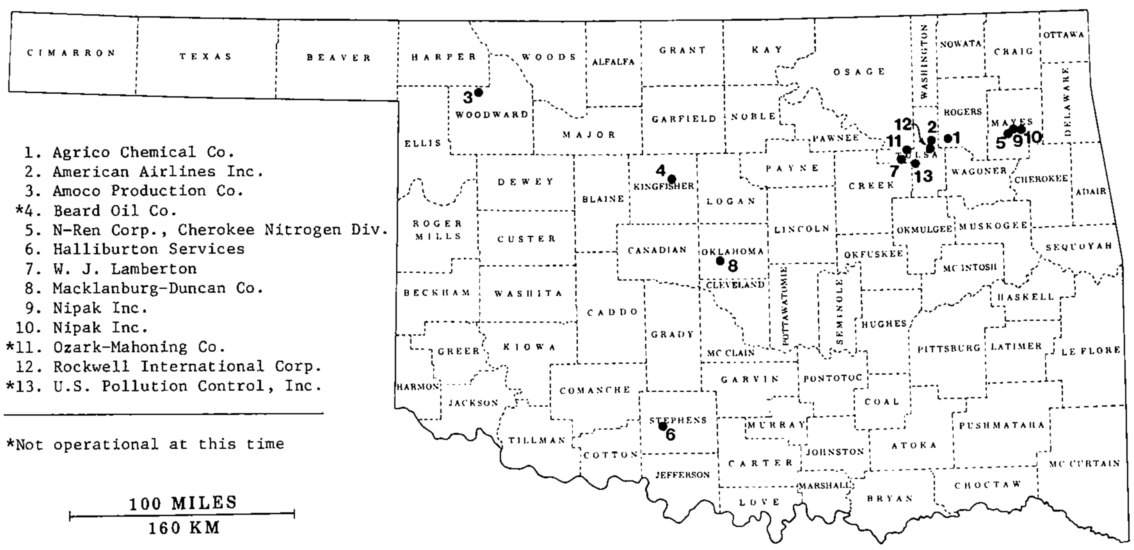


Figure 18. Map of Oklahoma showing locations of facilities for subsurface disposal of industrial waste as of January 1, 1979. See table 16 for descriptions of wells.

Formation	Disposal zone: Rock type	Porosity (%)	Permeability (md)	Injection rate, avg. (gpd)	Injection pressure at surface (psi)	Injected wastes
Arbuckle Group	Limestone	20	—	450,000	400	Fluids consisting chiefly of nitrates and ammonia.
Arbuckle Group	Limestone and dolomite	20	—	550,000	450	Organic solvents, acids, caustics, detergents, paint remover, and metal solutions.
Morrow	Sandstone, fine-grained, well-sorted	16	100	—	—	Process water, salt water, cooling water, and boiler blowdown.
Meramec ("Miss. Lime")	Limestone and dolomite	3	5-200	25,000	450-750	Originally solvents, acids, caustics, and salt water; only oil-field brines during 1974-78.
Arbuckle Group	Dolomite	10	—	75,000	450	Cooling water, condensate and process water from production of ammonia fertilizer.
—	Shale	Induced fracture	—	—	2,800	Cement slurry from lab mixing tests.
Arbuckle Group	Limestone and sandstone	11	—	—	—	Acids, aromatic compounds, and herbicide rinse waters.
Bromide ("Wilcox" # 2)	Sandstone	Up to 30	900-2,000	200,000	—	Acids, caustics, process waters, and rinse waters from aluminum, steel, and plastic fabrication.
Arbuckle Group	Dolomite	—	—	60,000	130	Urea, ammonia, and traces of chromates in process waters, cooling waters, and boiler blowdown.
Arbuckle Group	Dolomite	—	—	400,000	380	Urea, ammonia, and traces of chromates in process water, cooling waters, and boiler blowdown.
Arbuckle Group	Limestone and sandstone	—	—	—	—	Acids returned from refineries.
Arbuckle Group	Dolomite and limestone	5 to 8	—	40,000	240	Acids, solvents, paint, and process waters from aircraft assembly.
Arbuckle Group	Limestone and dolomite	2 to 11	200-2,000	2,000	—	Acids, caustics, solvents, paint thinner, nitrates, chromates, and oil.

geological engineering, and petroleum engineering at The University of Oklahoma, Oklahoma State University, and The University of Tulsa. The Oklahoma Geological Survey has released Bulletins and Circulars dealing with the subsurface and petroleum geology of a number of counties and has also compiled a series of index maps showing those parts of the State for which subsurface geologic mapping has been done and where the maps have been published.

CHARACTERISTICS IMPORTANT IN SITE EVALUATION

The main goal in selection of a subsurface disposal site is that the waste be emplaced in such a manner that it is isolated from fresh-water supplies and the biosphere during its hazardous life. In general, the best reservoir conditions are met where a permeable rock unit is surrounded by thick impervious layers, far removed from any fresh water. Geologic characteristics of each potential waste-disposal site in Oklahoma are different, and thus each site must be selected on its own merits and considered unique. Although a rigid set of site-selection criteria cannot be formulated, there are a number of geologic characteristics that must be evaluated in making such a selection.

Structure and Geologic Framework

The geology and geologic history of the region surrounding a potential site must be known in order to understand the processes that have acted on the site in the past and that will affect containment of waste in the future. Normally, the optimum conditions for subsurface disposal are met where sedimentary rock layers are flat-lying, or nearly so, and where they have not been faulted, tightly folded, or otherwise deformed. Faults and joints generally are not desirable in a reservoir rock because these fractures might be pathways for the escape of liquids from the disposal zone; but some fractured shale units appear to be suitable in certain circumstances. Rocks with steep dips or tight folds have been subjected to deformation that may have produced complex geologic structures that are poorly understood.

Lithology

The lithology or physical character of the proposed reservoir is critical to its acceptability as a waste-disposal zone. Important lithologic characteristics of a reservoir are mineral components, grain size, cement, porosity, permeability, and the uniformity of these parameters throughout the disposal zone. Porous and permeable sandstones or limestones that are moderately deep to deep below the land surface generally are best capable to serve as reservoirs for liquid wastes. Injection of wastes into low-permeability rocks, such as shale and siltstone and the various igneous and metamorphic rocks of Oklahoma, generally is not practical because of their low permeability; however, liquid wastes can be injected into some of these rocks locally if they are naturally fractured or can be hydraulically fractured. Wastes also may be disposed of in mined-out caverns created in such low-permeability rocks or in salt.

Thickness and Extent

A potential reservoir obviously must have sufficient vertical and lateral extent to contain the injected waste. The thickness of the disposal zone can range from 10 feet to several hundreds of feet, and its upper and lower boundaries must be established. The lateral dimension of the disposal zone may be large, but if not, the limits should be known as precisely as possible in order to design the facility properly.

Impermeable Confining Rock

Impermeable layers of rock above and below the disposal reservoir are needed to isolate the waste from the biosphere and fresh water for as long as the waste material remains hazardous. Thick beds of shale generally would be most desirable, although thin shales and other types of rocks with low permeability might also inhibit ground-water circulation and prevent migration of injected wastes. Moreover, the confining beds should be free of fractures.

Depth

A reservoir should be deep enough below the present land surface to ensure that its contained waste will not enter fresh-water systems or be exposed to the biosphere in hazardous concentrations. It is not possible to express, in feet, the minimum depth for suitable disposal zones throughout Oklahoma, because each region and each site have a unique set of geologic and hydrologic characteristics that must be individually analyzed to determine the optimum depth for safe waste disposal. Certainly in all areas of the State a disposal zone must be below the zone of fresh ground water, at depths where the formation waters are saline and where these saline waters will not migrate laterally or upward to the biosphere: such depths may range from a minimum of several hundreds of feet in some areas to several thousands of feet in many parts of the State.

Porosity and Permeability

Porosity is the ratio of the volume of pores or holes in a rock to the total volume of the rock, usually expressed as a percentage. Permeability of a rock, on the other hand, is a measure of its capacity for transmitting a fluid through the pores and their interconnections and is commonly expressed in millidarcies (md). Porosity or void space may be intergranular or in vugs and small cavities, and in places may be increased by natural or artificially created fractures. Sandstone reservoirs in Oklahoma typically have porosities of 10 to 20 percent and permeabilities of 20 to 1,000 md: limestone or dolomite reservoirs typically have porosities of 5 to 20 percent and permeabilities of 50 to 2,000 md. A rock such as shale may have a moderate porosity (20 to 30 percent), but it almost totally lacks the interconnections between pores and thus has very low permeability (less than 0.1 md) and is not a suitable reservoir unless fracturing has occurred.

Compatibility

The suitability of a prospective reservoir depends also upon the chemical compatibility of the wastes with the mineral and fluid components of the host rock. Chemical reactions could produce precipitates that would plug pore spaces in the rock and thus reduce the permeability and storage capacity. Clay minerals between larger grains may swell owing to injection of certain wastes and thus reduce pore space. On the other hand, the chemical reactions might increase the porosity and permeability by dissolving certain minerals and thereby open new passages that were not anticipated in the original design. Such channeling might enable toxic materials to escape. Therefore, the mineral and fluid content of the reservoir must be analyzed carefully, and laboratory studies of the interaction between this content and the waste must be carried out before injection is started. Problems of incompatibility might be minimized or overcome by treatment of the waste before injection.

Hydrology

Special attention must be paid to the hydrology of a prospective disposal site because of the importance of keeping injected fluids from escaping from the disposal zone and contaminating fresh-water aquifers or reaching the biosphere. The depth and thickness of fresh-water zones at a site must be established, and adequate measures must be taken to ensure their protection. Low-salinity ground waters in various parts of Oklahoma may have some value in the future, and thus consideration should be given to protecting potential water supplies with as much as 10,000 mg/L of total dissolved solids. In some cases, water with concentrations considerably higher than 10,000 mg/L should be protected, depending on the particular chemical constituents present and the expected or most likely future use of the water. An understanding of the nature and flow characteristics of fluids in and near the proposed disposal zone will enable better prediction of possible long-term migration or flushing of waste from the immediate vicinity of the injection site.

Some of the specific measures that need to be addressed to protect water supplies include well design, suitability of surface soils to contain accidental spills, and avoiding areas prone to surface flooding. Well-design and casing programs should assure that injected waste will not escape from the borehole or reservoir and come in contact with fresh-water zones. It would be preferable to locate such disposal systems away from areas underlain by major fresh-water aquifers (see fig. 6) and thus minimize this potential problem. Surface soils and shallow bedrock at a site should have a sufficiently low permeability to prevent downward migration of wastes that might accidentally be released from the surface storage and handling facilities. Also, inasmuch as lagoons or tanks are normally a necessary part of injection-well systems, it would be advisable not to have such facilities located within the flood plains of streams and rivers where they might be breached by floodwaters.

Mineral Resources

Important mineral deposits, such as oil, natural gas, mineral-laden brines, and salt, may be present at or near a potential disposal site. Such minerals can occur above, below, or even within the disposal zone, and if they do exist it may be necessary to consider the present or future needs for extracting mineral resources at that site as well as the possible legal ramifications. Once a site is used for disposal of wastes, it may be difficult to safely conduct additional exploration or development of minerals within or below the disposal zone during the hazardous life of the wastes. In general, therefore, a region or a site should be viewed more favorably for waste disposal if it has little or no potential for discovery and production of scarce or valuable mineral resources.

Boreholes and Other Excavations

It is necessary to determine the location and characteristics of all preexisting boreholes, mine shafts, solution cavities, and other man-made excavations in the vicinity of a proposed disposal site. All such artificial openings, particularly those that come near or penetrate the disposal zone, are potential avenues for vertical migration of fluids from the disposal zone to shallow, lower pressure zones or to the biosphere and the fresh-water zone. Areas of extensive early-day drilling are perhaps more risky than areas drilled recently, because they are more likely to contain boreholes that have been drilled and forgotten or that have been improperly plugged. It is essential that all potential migration paths be plugged and sealed effectively.

Geography

A number of geographic elements must also be assessed in selecting a waste-disposal site. Such factors as population, land use, land ownership, transportation facilities, and proximity to industries generating wastes can be critical in site selection.

ROCK TYPES SUITABLE FOR WASTE DISPOSAL

In general, underground disposal of industrial wastes requires a reservoir or host rock with sufficient porosity or void space to accommodate the waste, and with enough permeability to allow waste to infiltrate the available voids. Porous and permeable sandstones, limestones, and dolomites are most commonly used for waste disposal, although fractured shales or mined caverns in shales and salt may also be suitable. Liquid and gaseous wastes can be accommodated in all these rock types, whereas solid wastes are best disposed of in mined-out caverns in shale or salt (or in surface facilities, as described in Part II of this report).

Sandstone

Sandstone is a sedimentary rock consisting of small sand-sized mineral grains that are held together by a cementing material: it is the consolidated or cemented equivalent of sand. Quartz, a mineral that is inert to most industrial wastes, is the dominant sand particle in most sands or sandstones. Quartz typically makes up 70 to 95 percent of the sand grains. The most common secondary mineral grains are feldspars, which typically are almost as inert as quartz. Spaces between the sand grains may be partly filled with clay minerals or a mineral cement (calcite, $CaCO_3$, is most common), or these pore spaces may contain water, oil, gas, or air that can be displaced by injected liquid wastes.

The thickness, lateral extent, and character of most sandstones are variable. Some sandstones are extensive and are thick "blanket" deposits with uniform grain size, such as those of the Simpson Group, whereas others are lenses or channel-like deposits that have irregular boundaries and may underlie only small areas. Impermeable boundaries for a suitable reservoir sandstone may be layers of shale or silt that are interbedded with the sandstone, or they may be parts of the same reservoir sandstone that are "tight" because the pores are filled with finer grained clays or with mineral cement. Sandstones typically are tight and are not good host rocks at depths greater than 15,000 to 18,000 feet below the surface, inasmuch as the pore spaces are sharply reduced in size owing to excessive compaction and recrystallization of minerals that partly fill the pore spaces.

The character of material in the space between sand grains is critical to the performance of a proposed waste-disposal system. Some mineral cements, such as calcite and dolomite, are soluble in acids, and thus the porosity and permeability of such calcitic or dolomitic sandstones can be increased by injection of acidic wastes. Certain clay minerals between sand grains expand upon exposure to certain liquids and thus decrease the rock's porosity and permeability.

Limestone and Dolomite

Limestone and dolomite (dolostone, in some reports) are sedimentary rocks consisting chiefly of the minerals calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), respectively. These two minerals commonly coexist in the same rock, as dolomitic limestone or limy dolomite. Collectively, limestone and dolomite are referred to as carbonate rocks. Commonly 5 to 15 percent of carbonate rocks are made up of noncarbonate minerals such as quartz or clay minerals, and some of these rocks may react adversely with injected waste. Some carbonate-rock units, such as the Arbuckle Group and the Mississippi lime, are several hundred to several thousand feet thick over large areas of the State, whereas other carbonates are lenses less than 10 feet thick in an area of several thousand square feet.

The porosity and permeability patterns within carbonate rocks are more complex than those in sandstones. Some carbonates consist mostly of fossil fragments or other granular material, and they have intergranular porosity similar to that of sandstones. In other carbonate rocks, porosity has been naturally induced through chemical alteration or through dissolution of carbonates and other soluble minerals by weakly acidic water permeating the formation. Pores in carbonate rocks may be microscopic in size, or they may be cavernous openings several feet across. Carbonates are brittle rocks that commonly contain fractures caused by structural deformation after burial. Such fractures may be quite small, but they can contribute significantly to the porosity and permeability of the rock.

Inasmuch as carbonate rocks consist almost entirely of acid-soluble minerals, the porosity and permeability of these rocks will almost always be increased by injection of acidic wastes. However, the chemical constituents of the rocks may react with other types of injected wastes in such a way as to decrease the porosity and permeability.

Containment, not ease of injection, is of paramount importance in considering carbonate rocks as possible disposal zones. A major drawback to the use of carbonates for waste disposal is their unpredictability with respect to the development of porosity and permeability features, especially channels. Therefore, a detailed knowledge of the geologic occurrence and history of prospective carbonate-rock disposal zones must be gained.

Shale

Shale is a sedimentary rock formed by the consolidation of layers of clay or mud. Shales have a wide range of mineral and chemical composition, but they consist chiefly of clay minerals (illite, chlorite, kaolinite, and montmorillonite) and quartz. The minute mineral grains commonly are cemented by calcite ($CaCO_3$) or silica (SiO_2). Although shales can have moderate porosity, permeability is low.

Shale typically is unsuitable for liquid-waste disposal because of low permeability. However, shale can serve, under certain circumstances, as an effective host rock for waste if the shale is fractured, either naturally or artificially, or if an underground cavity is created by mining. Natural openings, such as fractures, joints, or partings parallel or at an angle to the bedding, can greatly increase the permeability of an otherwise "tight" rock. Hydraulic fracturing, which is the injection of water or other fluids into a borehole under high pressure, can prop open and widen a set of incipient fractures in a shale formation or it can induce fracturing in a competent rock. Liquid waste can be injected into such fractured rocks, and also it can be mixed with a cement grout which will help immobilize the waste within a nearly impermeable medium (Sun, 1973). Many of the clay minerals in shales have a high cation-exchange capacity (CEC) and thus could adsorb certain contaminants.

Underground cavities suitable for storage of petroleum products have been created in shales in Oklahoma using a conventional room-and-pillar mining method, and under certain circumstances this might be a practical means of disposing of liquid or solid wastes. Jordan (1959) described a 110,000-barrel underground propane-storage facility created by Sinclair (now Atlantic Richfield) west of Wewoka in Seminole County. A modified room-and-pillar mine, with tunnel-like rooms 15 to 28 feet high and 8 feet wide, was opened by the company about 300 feet below the surface in a thick shale at the top of the Nellie Bly Formation. Conoco created a similar facility at Ponca City for storage of 300,000 barrels of propane in low-permeability limestone about 350 to 400 feet below the surface (Jordan, 1961). Other storage caverns have been formed in shales 300 to 400 feet deep near Tulsa and Drumright.

Salt

Salt is a sedimentary rock consisting of intergrown crystals of the mineral halite (NaCl). In Oklahoma, rock salt occurs as widespread layers in three principal salt sequences, each 100 to 1,000 feet thick, that are restricted to Permian rocks in the western half of the State (Jordan and Vosburg, 1963). Individual salt beds are typically 5 to 30 feet thick and are interbedded chiefly with shale and (or) anhydrite.

Large underground openings suitable for disposing of industrial wastes are created in salt beds by conventional shaft-mining or solution-mining techniques. In fact, the favorability of salt as a host rock for waste isolation has spurred much research in recent years on the feasibility of burying solidified forms of radioactive wastes in underground salt deposits (Bradshaw and McClain, 1971; Angino, 1977; Johnson and Gonzales, 1978).

Bedded salt deposits more than 500 to 1,000 feet deep and distant from areas of present or ancient salt dissolution generally are suitable for injection of certain kinds of solid or liquid industrial wastes; their contact with ground water or the biosphere during the hazardous life of the waste would be extremely unlikely. Such salt deposits, especially the middle parts of thick salt sequences, have remained free of circulating waters in the past. Because of the rock's high plasticity, any fractures developed in the salt would seal or close rapidly. Possible interaction between the waste and salt must be understood in order to prevent uncontrolled dissolution of the salt and migration of contaminants beyond the intended waste-disposal zone. The underground mining of salt and tests on disposal of radioactive wastes in central Kansas were described by Empson and others (1966) and Bradshaw and McClain (1971). The storage of petroleum products in four solution caverns created in Oklahoma salt deposits was described by Jordan and Vosburg (1963).

CURRENT WASTE-DISPOSAL OPERATIONS

At the present time, 15 wells are disposing of controlled industrial wastes at 10 different localities in Oklahoma (table 16). Most of the wells are in northeast Oklahoma, but several are scattered in the central and northwest parts of the State (fig. 18). Two wells recently ceased operation, but it is possible that one or more may be reactivated; thus the data on these wells are presented in our table. Permitting and monitoring the operation of these and future disposal wells are carried out by the Oklahoma State Department of Health, under authority of the Oklahoma Solid Waste Management Act and the Oklahoma Controlled Industrial Waste Disposal Act of 1976. We are not including a detailed discussion of approximately 1,300 salt-water-disposal (SWD) wells that are disposing of oil-field brines within the State. These wells operate under licensing of the Oklahoma Corporation Commission.

Most of the waste-disposal systems are using reservoirs of Cambrian and Ordovician age (Arbuckle Group and Simpson Group). These limestones, dolomites, and sandstones have porosities that range generally from 5 to 20 percent and permeabilities that range from 200 to 2,000 md. Other disposal systems are using rocks of Mississippian, Pennsylvanian, and Permian age, and the reservoirs include sandstones, limestones, dolomites, and hydraulically fractured shales.

The depth of disposal zones ranges from 358 feet to as much as 7,350 feet in various wells in the State. Wells in the northeast, in Mayes, Rogers, and Tulsa Counties, are being used to inject liquids at shallow to moderate depths of 358 to 3,360 feet, whereas most of the wells in the central and northwest part of the State are using disposal zones 6,700 to 7,350 feet deep.

Wastes now being injected include a great variety of liquids. Acids, solvents, caustics, and salt water are being injected at most disposal sites. A number of wells are also injecting various process-, cooling-, and rinse-waters, as well as paints, paint thinner, and paint remover. Other materials being disposed of at one or several sites include urea, ammonia, detergents, metal-bearing solutions, and cement slurry.

Injection rates at each facility are variable, depending mainly upon the rate at which waste is delivered for disposal. Rates of injection range from 2,000 to 550,000 gallons per day (gpd), but most of the facilities operate at rates of 40,000 to 400,000 gpd.

Injection pressures at the surface range from 130 to as much as 750 pounds per square inch (psi), although most wells operate with known pressures of 380 to 450 psi. The extreme exception is 2,800 psi needed for injection of cement slurry into a hydraulically fractured shale in well 7.

Kerr-McGee Corp. received a construction permit in March 1979 for an injection well to be drilled to the Arbuckle Group at a 5,000-foot depth near Wynnewood (Garvin County). Additionally, applications are now being processed for four other wells to be completed in the Arbuckle: two wells are proposed for the Bartlesville area (Washington County), and two are proposed for the Catoosa area (Rogers County).

POTENTIAL RESERVOIRS FOR WASTE DISPOSAL

Oklahoma contains many rock units that are potential reservoirs for subsurface disposal of controlled industrial wastes. Deep sedimentary basins contain up to 30,000 to 40,000 feet of strata, and broad shelf areas adjacent to the basins are underlain by several thousand feet (up to 10,000 feet) of strata (fig. 19). Within these thick sequences of sedimentary rock are a number of beds of porous and permeable sandstone, limestone,

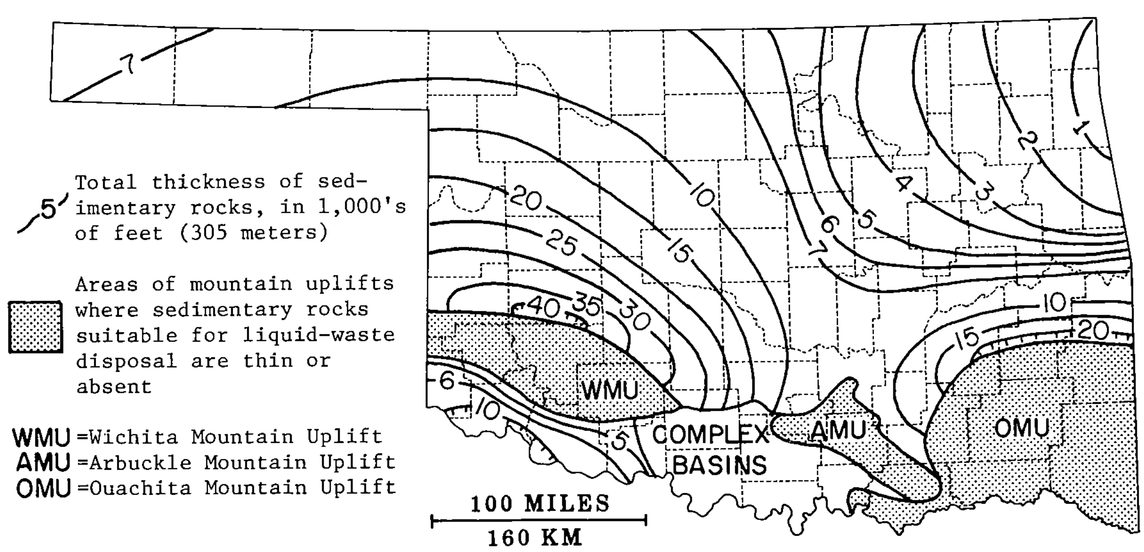


Figure 19. Generalized map showing total thickness of sedimentary rocks in Oklahoma. Sedimentary rocks overlie a basement of Precambrian and Cambrian igneous and metamorphic rocks (based on data in Jordan, 1967). Sedimentary rocks over Wichita Mountain Uplift are generally thin (200-2,000 feet thick); sedimentary rocks over Arbuckle Mountain Uplift include major fresh–water aquifers; sedimentary rocks in Ouachita Mountain Uplift are 20,000–30,000 feet thick but do not appear to contain porous and permeable reservoir rocks suitable for waste disposal.

and dolomite—at least to depths of about 15,000–18,000 feet. In addition, some of the thick shales can accept liquid wastes in natural or induced fractures; also, the shales and salt beds can host wastes in mined-out caverns.

Major geologic provinces of the State include the Ouachita, Arbuckle, and Wichita Mountain belts in the south, along with the large and deep Anadarko and Arkoma Basins just north of the mountain uplifts (see fig. 1). Another group of smaller deep basins—the Ardmore, Marietta, and Hollis—is present south of the Arbuckle and Wichita Mountains (fig. 1). To the north of the Anadarko and Arkoma Basins are the relatively undisturbed shelf areas and Ozark Uplift area of northern Oklahoma (fig. 1). The generalized stratigraphic chart (fig. 20) shows the relative positions and the names commonly used for rock formations or groups in the subsurface of Oklahoma. Brief discussions of the geologic history and the major rock types deposited during each geologic period are presented in Part I.

We have prepared a series of generalized maps (figs. 21–25) to show the distribution of each of the principal rock units in the State that is a potential reservoir over large areas and to show the depth below land surface to

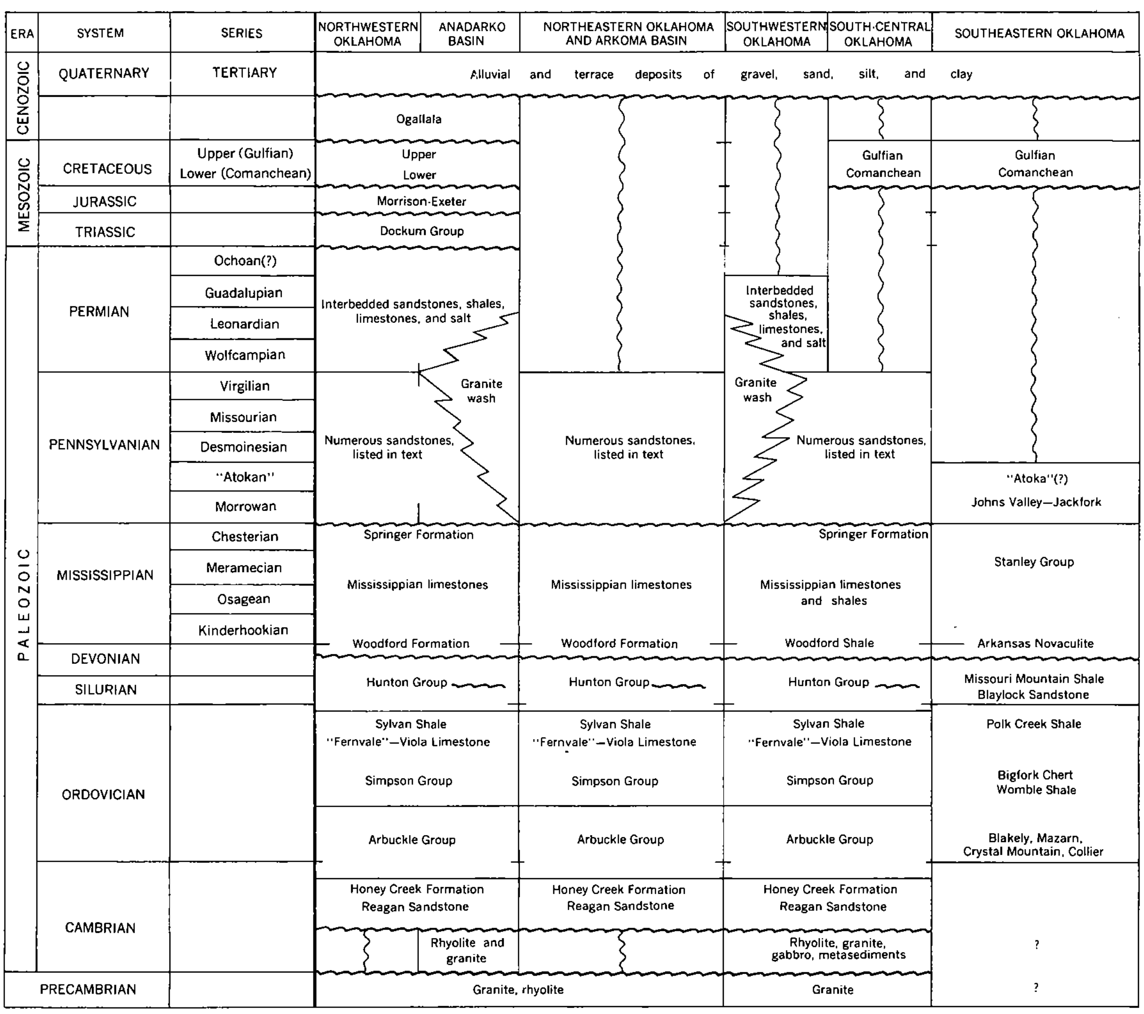


Figure 20. General stratigraphic succession in major regions of Oklahoma. Principal regional unconformities shown by horizontal wavy lines; absence of stratigraphic record (owing to nondeposition or erosion) shown by vertical wavy lines. Data from Miser and others (1954), Ham (1961), Jordan (1967), and R. O. Fay (Oklahoma Geological Survey, oral communication, 1979).

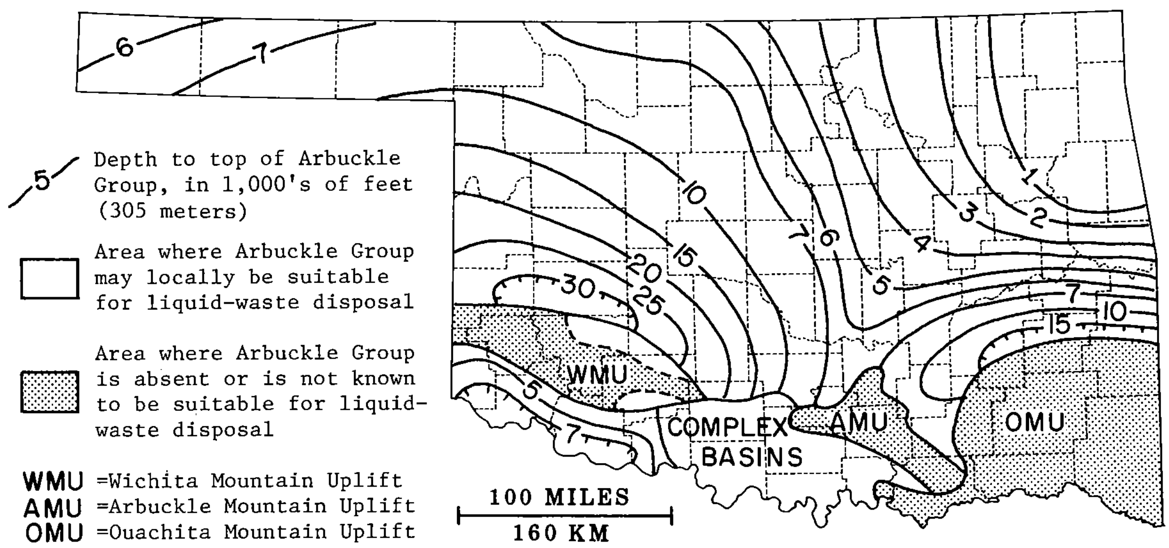


Figure 21. Generalized map showing depth to top of Arbuckle Group (Upper Cambrian and Lower Ordovician) in Oklahoma. Arbuckle Group consists chiefly of limestone and (or) dolomite, and its thickness ranges from several hundred to more than 6,000 feet.

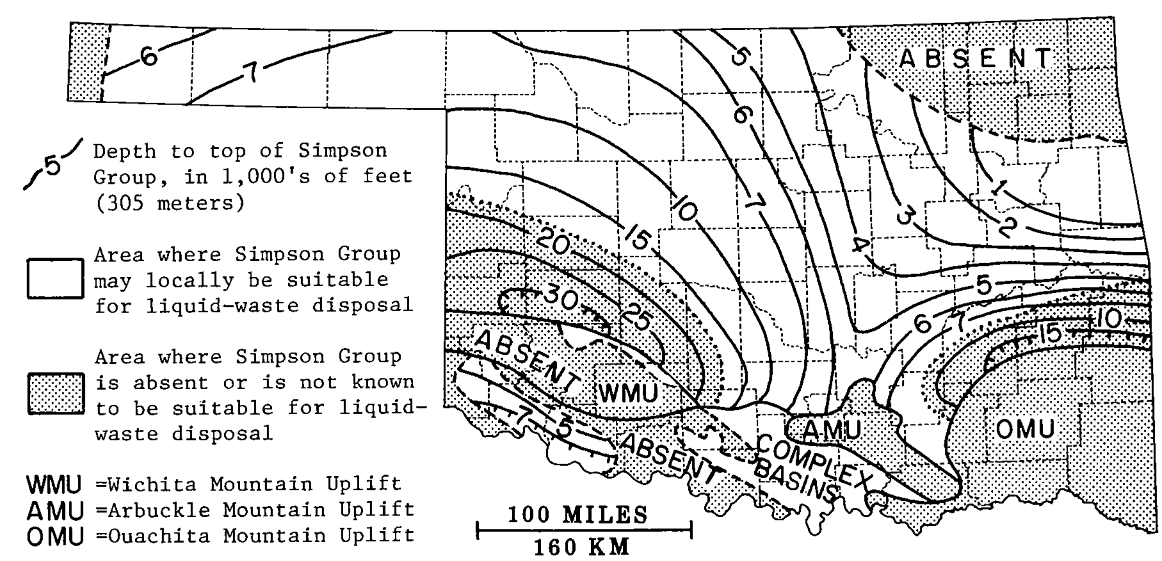


Figure 22. Generalized map showing depth to top of Simpson Group (Middle Ordovician) in Oklahoma. Simpson Group ranges in thickness from 100 to 2,000 feet and contains several widespread clean reservoir sandstones that are 20–100 feet thick. Dotted line shows those areas in deep Anadarko and Arkoma Basins where Simpson sandstones have low permeabilities.

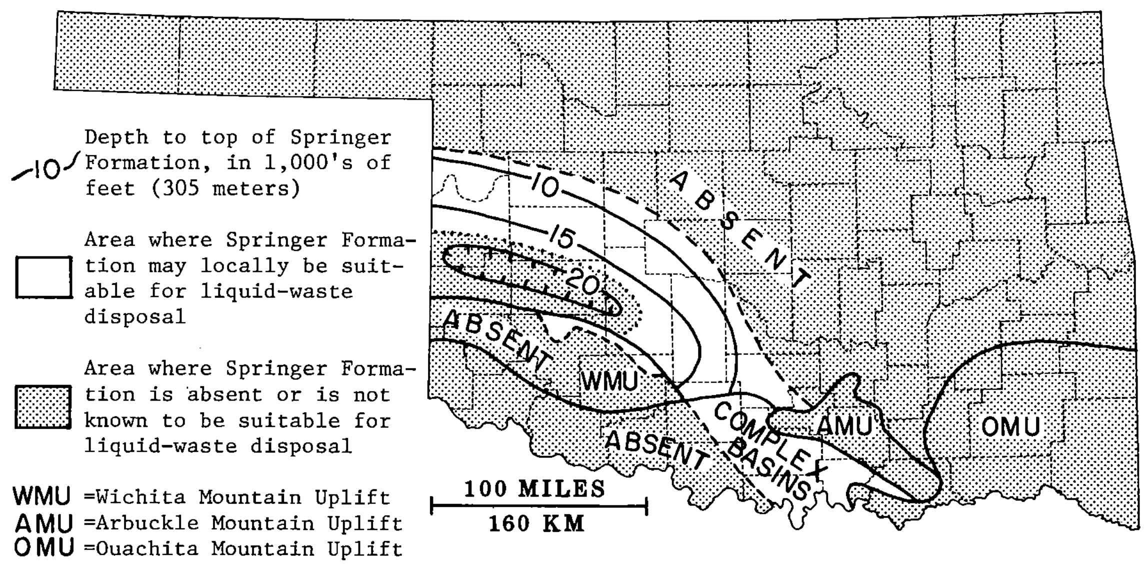


Figure 23. Generalized map showing depth to top of Springer Formation (Upper Mississippian) in Oklahoma. Springer Formation is mostly shale but contains several sandstones 20–100 feet thick. Dotted line shows area in deep Anadarko Basin where sandstones have low permeability. Area of few thin sandstones in western Arkoma Basin not shown.

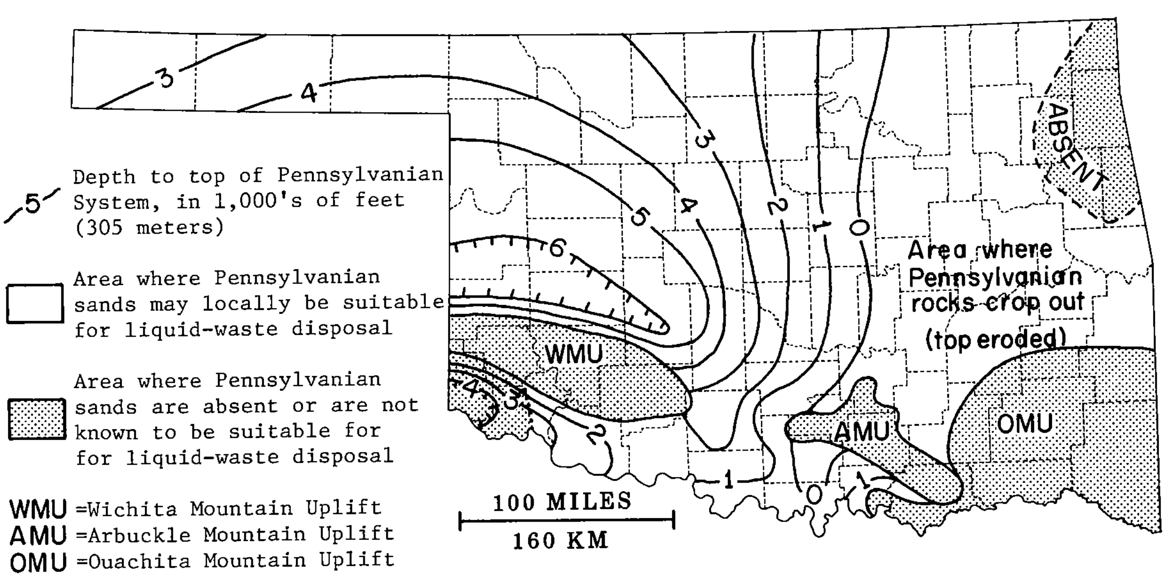


Figure 24. Generalized map showing depth to top of Pennsylvanian System in Oklahoma. Pennsylvanian rocks are generally 1,000–15,000 feet thick and consist mainly of shales that contain several suitable sandstone reservoirs at various depths (not necessarily at or near top of Pennsylvanian). Dotted line shows area in Hollis Basin where sandstones have low permeability.

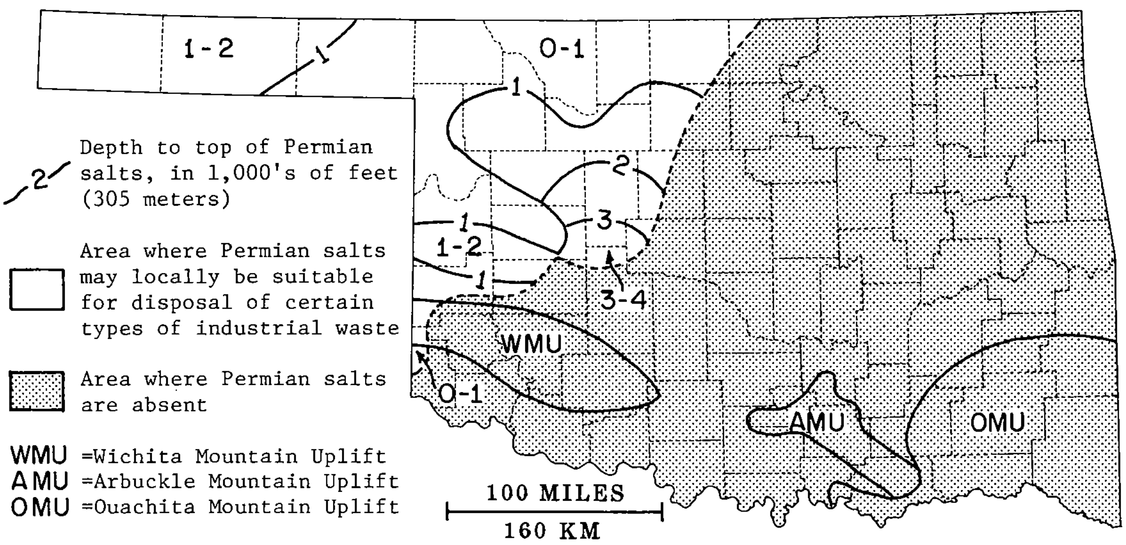


Figure 25. Generalized map showing depth to top of salt beds of Permian age in Oklahoma. Salt-bearing sequences are 100–1,000 feet thick, with individual beds of rock salt ranging from 5 to 30 feet thick.

the top of these rock units. A total of five major sandstone-bearing units are considered capable of accepting liquid wastes in some part of the State; these units include (1) the Simpson Group, (2) the Springer Formation, (3) Pennsylvanian sandstones, (4) granite wash, and (5) Permian sandstones. Five major carbonate-rock units locally suitable for waste disposal include (1) the Arbuckle Group, (2) the Hunton Group, (3) Mississippian limestones, (4) the Brown dolomite, and (5) Permian dolomites. These ten rock units, as well as the bedded salt deposits and the major shale units, are all Paleozoic strata (fig. 20). We do not feel that any of the Precambrian, Mesozoic, or Cenozoic rock units in Oklahoma is generally well suited for accepting industrial wastes, although one or several of them might be found locally acceptable as a result of detailed study.

Most data on the lithology, porosity, permeability, and other characteristics of the reservoir rocks are derived from oil- and gas-producing areas, where many test holes have been drilled and many detailed studies of the reservoirs have been made. Paradoxically, densely drilled oil and gas fields, for which there are so many data, generally should be avoided as disposal areas for industrial wastes, chiefly because of the large number of boreholes and the potential conflict with recovery of mineral resources. Boreholes are potential avenues for vertical migration of waste fluids from an intended disposal zone, and it may be difficult and quite expensive to locate and plug all such boreholes and effectively seal the reservoir. In considering waste disposal in an oil or gas field, one must assess the potential for petroleum production in both known and undiscovered reservoirs and weigh the relative value of these hydrocarbon resources against use of the site for waste disposal.

Many of the reservoirs we describe are now being used for disposal of oil-field brines. Salt-water-disposal (SWD) wells commonly are located within the petroleum fields, close to the wells that are producing brines along with oil and (or) gas. Data from these SWD wells are valuable in assessing the local potential use of a reservoir rock for waste disposal.

For purposes of discussing waste-disposal reservoirs, we subdivided the State into seven regions (fig. 26), each of which embraces one or more geologic provinces with a similar geologic history and similar reservoir potential (see also fig. 1). A descrip-

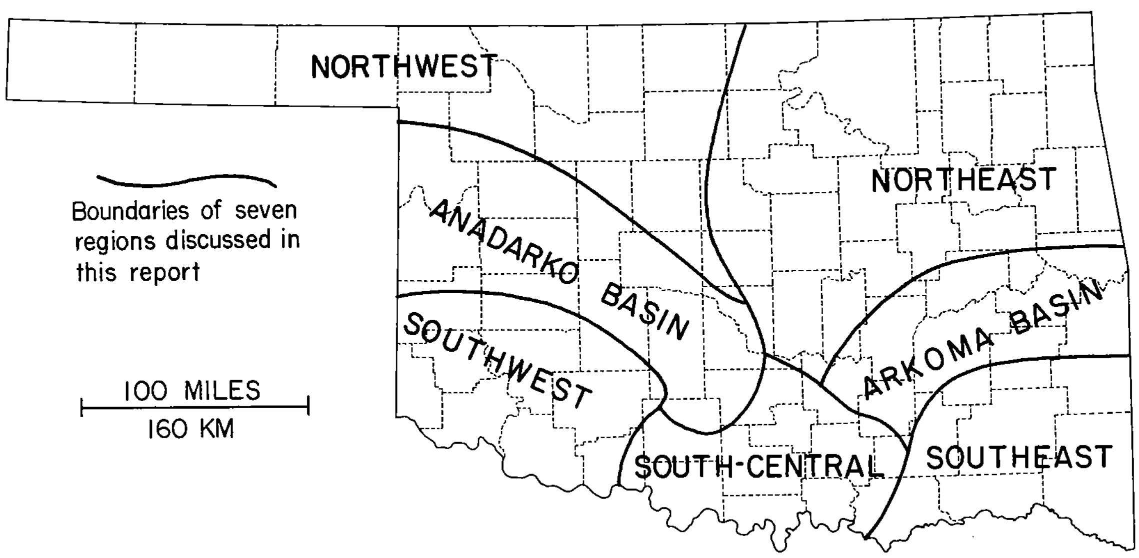


Figure 26. Map of Oklahoma showing seven regions into which State is divided for consideration of subsurface liquid-waste disposal. Regions approximate major geologic provinces (see fig. 1).

tion is given of the major reservoir rocks in each of these seven regions, and the reader is also referred to figures 21–25 for information on the statewide distribution and depth of reservoirs that may be of special interest.

Reservoir rocks that may be suitable for disposal of industrial wastes are present in six of the seven regions (fig. 27). Southeast Oklahoma alone appears to lack porous and permeable sandstone or carbonate rocks that can readily and safety contain waste; however, some potential exists for disposal in shale and other nonporous rocks where the rocks are fractured. In some areas, artificial fracturing may be necessary.

Northeast Oklahoma

For purposes of this report, northeast Oklahoma includes the Ozark Uplift as well as the broad shelf areas north of the Arkoma Basin and east of the Nemaha Ridge (figs. 1, 26). The thickness of sedimentary rocks overlying the basement complex in the region ranges from about 1,000 feet in the northeast to nearly 10,000 feet in the southwest (fig. 19). Within this sedimentary sequence are several carbonate, sandstone, and shale units that are suitable locally for waste disposal. In fact, 10 of the State's 13 operating industrial-waste-disposal facilities are located in northeast Oklahoma. An earlier study by Reeder (1971) provides data on disposal of liquid wastes in much of this region.

Rock units of principal interest for injection of liquid wastes include carbonates of the Arbuckle Group and sandstones of the Simpson Group and Pennsylvanian System. Shales at shallow to moderate depth in the region that may be suitable locally for accepting wastes in hydraulically induced fractures or mined-out caverns include the same units that crop out in the region (see Part II of this report) as well as the Woodford Shale. Four of the underground caverns for the storage of liquefied petroleum gas (LPG) in the State have been created in shales or tight limestones 300 to 400 feet deep in northeast Oklahoma (Jordan, 1959, 1961).

Principal references dealing with the subsurface geology of northeast Oklahoma include Oakes and Jordan (1959), Clare (1963), McCracken (1964), Berry (1965), Cole (1965, 1969), Strong and Huffman (1965), Busch (1971), Lalla (1975), and Pulling (1976).

Arbuckle Group

The Arbuckle Group (Upper Cambrian and Lower Ordovician) is a reservoir-rock unit in northeast Oklahoma capable of accepting a wide variety of industrial wastes. The rock unit consists chiefly of limestone, dolomitic limestone, and dolomite, although it contains some thin beds of sandstone. Dolomite, which locally makes up as much as one-third of the total thickness, is irregularly interbedded with the limestone. Intergranular and vuggy porosity combine with extensive fractures in some areas to form reservoirs with porosities of 5 to 20 percent and permeabilities ranging from 100 to several thousand md.

The Arbuckle Group is typically 500 to 1,000 feet thick and is several hundred to several thousand feet below the surface in the northeast part of the region (fig. 21). The unit is progressively deeper and thicker to the south and southwest, and at Oklahoma City it is as much as 7,000 feet deep and 2,500 feet thick.

All nine of the industrial-waste-disposal wells in Tulsa, Rogers, and Mayes Counties (wells 1, 2, 5, 7, 9, 10, 11, 12, and 13 in table 16 and fig. 18) are injecting wastes into the Arbuckle Group at depths ranging from 800 to 3,300 feet. Wastes now being injected include acids, caustics, solvents, and metal solutions.

REGION	POTENTIAL RESERVOIRS
Northeast Oklahoma	Pennsylvanian sandstones Simpson Group Arbuckle Group (various shales)
Arkoma Basin	Pennsylvanian sandstones Simpson Group Arbuckle Group (various shales)
Southeast Oklahoma	(various shales and other fractured rocks)
South-Central Oklahoma	Pennsylvanian sandstones Springer Formation Simpson Group Arbuckle Group (various shales)
Northwest Oklahoma	Permian salts Permian dolomites Pennsylvanian sandstones Mississippian limestones Arbuckle Group (various shales)
Anadarko Basin	Permian salts Permian sandstones Pennsylvanian sandstones Springer Formation Mississippian limestones Hunton Group Simpson Group Arbuckle Group (various shales)
Southwest Oklahoma	Permian salts Brown Dolomite Granite wash Arbuckle Group (various shales)

Figure 27. Potential reservoirs for underground disposal of industrial wastes in seven regions of Oklahoma.

Simpson Group

The Simpson Group (Middle Ordovician) contains several widespread sandstones capable of accepting industrial wastes. Individual units, including the Bromide, Second Wilcox, Tulip Creek, McLish, Tyner, Burgen, and Oil Creek sandstones, are similar in being typically fine-grained, well-rounded, clean quartz sands (more than 95 percent quartz grains). At some localities the porosity ranges from 5 to more than 20 percent, and the permeability is several hundred to several thousand md.

The Simpson sandstones are not present in the extreme northeast part of the region, north of Claremore and east of Pawhuska (Huffman, 1959), but several units about 20 feet thick are present in the Tulsa area at depths of about 1,000 feet. South, southwest, and west of this area the sandstones are deeper and thicker, and in the Oklahoma City area they are about 6,500 feet deep (fig. 22) and have an aggregate sand thickness of several hundred feet.

The tenth of the injection wells in the region (well 8 in table 16 and fig. 18) is disposing of acids, caustics, and process waters in Simpson sandstones at a depth of 6,700 to 6,800 feet in Oklahoma City.

Pennsylvanian Sandstones

A large number of sandstones of Pennsylvanian age are good prospects for injection of industrial wastes. These rock units are commonly channel-like or discontinuous lenses that may be 20 to 100 feet thick, or more, in the middle and grade laterally into shale on the perimeter. Individual sandstones may be 6 to 10 miles long and 1 to 2 miles wide, or they may underlie an area only several hundred feet on a side.

The physical characteristics of Pennsylvanian sandstones are similar. The units are composed chiefly of fine-grained quartz sand, are cemented in part by calcite, and commonly range from mostly quartz grains in the middle to a mixture of quartz grains and shale or clay toward the sides. Porosities of reservoir rocks range from 10 to 20 percent and average about 15 percent. Permeabilities in the more promising areas range from 10 to 80 md and average about 30 md.

Following is a list of the principal Pennsylvanian sandstones that locally may be possibilities for disposal use (fig. 28). There is no area in which all these units are present in the subsurface, but one or several of them may be present and suitable for waste injection at all localities but the Ozark Uplift, from which the Pennsylvanian rocks have been eroded (fig. 24). The total thickness of the Pennsylvanian System ranges from a few hundred feet on the flanks of the Ozarks to more than 5,000 feet in the southwest part of the region.

Hogshooter	Missourian Series
Cleveland	
Prue	Desmoinesian Series
Calvin	
Skinner	
Allen	
Senora	
Red Fork	
Earlsboro	
Burbank	
Bartlesville	
Glenn	
Savanna	
Booch	

Figure 28. List of Pennsylvanian sandstones that may be suitable locally for liquid-waste injection in northeast Oklahoma.

Arkoma Basin

The Arkoma Basin is a major geologic province in east-central Oklahoma (fig. 26). It is both a depositional and a structural basin, for it contains 5,000 to 20,000 feet of sedimentary rocks preserved between the northeast shelf region and the Ouachita Mountain Uplift (fig. 19). Rocks within the Arkoma Basin are broadly folded and in places faulted.

In the Arkoma Basin, rock units most likely capable of accepting liquid industrial wastes are carbonates of the Arbuckle Group and sandstones of the Simpson Group and of the Pennsylvanian System. Wastes can also be disposed of at shallow to moderate depths in fractures or mined-out caverns in some of the same shale units that crop out in the region (see Part II of this report).

Principal references describing the subsurface geology of the Arkoma Basin include: Koontz (1967), Woncik (1968), Busch (1971), Lumsden and others (1971), and Anderson (1974).

Arbuckle Group

The Arbuckle Group (Upper Cambrian and Lower Ordovician) underlies all parts of the Arkoma Basin and locally is a suitable reservoir for injection of industrial wastes. The Arbuckle Group consists of limestone and dolomite that in some areas has a moderate amount of intergranular porosity and permeability, augmented by fracture porosity. The thickness of the Arbuckle Group ranges from about 2,000 feet in the north part of the basin to about 4,000 feet in the south. The depth to the top of the Arbuckle Group ranges from about 5,000 to 6,000 feet on the north flank to more than 15,000 feet in the south near the Ouachita Mountain front (fig. 21).

Simpson Group

In the western part of the Arkoma Basin (Hughes, Pontotoc, and Coal Counties) the sandstones of the Simpson Group (Middle Ordovician) locally may be able to accept injected industrial wastes. Potential reservoirs, including the Wilcox, McLish, and Oil Creek sandstones, are widespread, sheet-like units composed of fine to medium, well-rounded quartz grains that generally are loosely cemented and lack clay minerals. The porosity of the sandstones is as high as 20 percent locally, and permeability is as much as 1,000 md. Individual sandstones are as thick as 50 feet in the area and are about 5,000 to 7,000 feet below the surface (fig. 22). These sandstones are now used extensively as salt-water-disposal reservoirs.

Pennsylvanian Sandstones

Across the north half of the arcuate Arkoma Basin, a number of Pennsylvanian sandstones are prospects for injection of industrial wastes. Sandstone bodies are typically discontinuous, linear, and sinuous in plan view and do not occur as blanket sandstones with large areal extent. Individual sandstones are as thick as 50 feet in the middle and grade laterally to about 10 feet on the edges. They are enveloped by shales and other low-permeability sedimentary rocks.

Sandstones are mostly fine grained and consist chiefly of quartz. Calcite cement is common, and locally the sandstones are quite shaly. Reservoir porosity ranges from 8 to 20 percent, averaging about 15 percent, and permeability ranges from 5 to 80 md, averaging about 35 md.

The accompanying list (fig. 29) includes the best prospects for liquid-waste injection, and any one or several of these units may be suitable reservoirs in the north half of the basin. The Pennsylvanian System crops out throughout the Arkoma Basin (fig. 24), and the depth to the top of the potential reservoir units generally ranges from several hundred to 3,500 feet in the area.

Calvin Senora Stuart Savanna Hartshorne	Desmoinesian Series
Gilcrease Dutcher	Atokan Series
Cromwell Jefferson	Morrowan Series

Figure 29. List of Pennsylvanian sandstones in Arkoma Basin that may be suitable locally for liquid-waste injection.

Southeast Oklahoma

Southeast Oklahoma embraces the Ouachita Mountain uplift and the eastern two-thirds of the Gulf Coastal Plain (figs. 1, 26). Rocks of the Ouachita Mountains are sedimentary in origin, but they have been complexly folded and faulted and some of them have been mildly metamorphosed. Ouachita-type rocks extend southward and underlie the thin cover of unconsolidated sediments making up the Coastal Plain.

Although the region contains some 20,000 to 30,000 feet of sedimentary rock, there apparently are no porous and permeable sandstone or carbonate reservoirs suitable for waste disposal. Sandstones are fine grained and shaly and typically are well cemented and tight as a result of deep burial, deformation, and low-grade metamorphism. However, owing to deformation of the region, some of the shales (e.g., the Stanley Shale), cherts, and novaculites of the Ouachitas are fractured, and these units locally may be able to accept fluids injected under pressure. The shales also may be capable of safely retaining wastes placed in mined-out caverns.

Cretaceous-age sediments of the Coastal Plain thicken southward from 0 to nearly 2,000 feet along the Red River. They consist chiefly of unconsolidated sands that are important fresh-water aquifers, and thus they generally are not suitable reservoirs for industrial wastes.

Principal references to geology of the region include Cline (1960), Seely (1963), Hart (1963), Fellows (1964), Briggs (1973), and Fay and others (1976).

South-Central Oklahoma

The south-central Oklahoma region embraces a geologically complex group of basins along with adjacent mountain areas and sharp uplifts (figs. 1, 26). Major geologic features include the Ardmore and Marietta

Basins, the Arbuckle Mountains, and the Criner Uplift. The region also includes the west part of the Gulf Coastal Plain, where a thin sequence of Cretaceous strata overlies part of the deep-basin Paleozoic rocks. Owing to the complex folding and faulting in and around the basins, the depth to potential reservoir rocks changes greatly within short distances. As much as 20,000 to 30,000 feet of sedimentary rock is present in each of the basins.

Reservoirs with the highest potential for accepting industrial wastes are carbonate rocks of the Arbuckle Group and the sandstones of the Simpson Group, the Springer Formation, and the Pennsylvanian System. Many of these units are widely used for disposal of oil-field brines. Also, shale that crops out in the region (see Part II of this report) locally may be capable of receiving injected wastes in zones of fracture porosity or of containing waste in mined-out caverns at shallow to moderate depths.

Among the principal studies of subsurface geology in the region are Jacobsen (1959), Ham and others (1964), Westheimer (1965), Ham (1969), Fay and others (1976), and Huffman and others (1978).

Arbuckle Group

The Arbuckle Group (Upper Cambrian and Lower Ordovician) consists chiefly of limestone in the basins of south-central Oklahoma but is predominantly dolomite in much of the Arbuckle Mountain area. Locally in the basins the Arbuckle is expected to have sufficient intergranular porosity and permeability to act as a suitable reservoir for liquid wastes, particularly in those areas where the unit also has fracture porosity. The total thickness of the Arbuckle Group is as much as 6,000 feet in parts of the region, and depth to the Arbuckle ranges from a few hundred feet to more than 20,000 feet in the deep basins. The Arbuckle Group generally is not suitable for waste disposal on the Arbuckle Mountain Uplift (fig. 21), because the rock unit crops out extensively in the mountains and is a major fresh-water aquifer in the area.

Simpson Group

The Simpson Group (Middle Ordovician) consists of several widespread sandstone units that could be used for injecting industrial wastes in parts of south-central Oklahoma (fig. 22). These rock units, including the Bromide (First, Second, and Third), Tulip Creek, McLish, and Oil Creek sandstones, are all composed of fine to medium, well-rounded, clean quartz grains that are loosely cemented. Locally the porosity in these sandstones ranges from 10 to 25 percent, and the permeability ranges from 10 md to more than 400 md. The thickness of individual sandstones in the Simpson is 20 feet to as much as 100 feet, and depth to the Simpson Group ranges from a few hundred feet to more than 15,000 feet in the deep basins. Inasmuch as the Simpson sandstones are major fresh-water aquifers where they crop out and are at shallow depth, these reservoirs are not considered suitable for waste disposal over the Arbuckle Mountain Uplift or in the immediately surrounding area.

Springer Formation

The Springer Formation (Upper Mississippian) in the Ardmore Basin contains a number of sandstones capable of accepting injected industrial wastes. The sandstones are fairly uniform over large areas, and reservoir rocks have porosities that average about 17 percent and permeabilities that average about 70 md. The thickness of individual sandstone units ranges from 20 to as much as 100 feet, and their depth ranges from several hundred feet to more than 10,000 feet in the deep basins.

Named units that are potential reservoirs for industrial-waste injection include (in descending order) the Markham, Aldridge, Humphreys, Sims, and Goodwin sandstones. One or several of these units underlie most parts of the region (fig. 23).

Pennsylvanian Sandstones

Pennsylvanian sandstones in each of the basins of south-central Oklahoma locally may be capable of accepting injected industrial wastes. Individual sandstone bodies typically are many miles long and up to 2 or 3 miles wide, although in some areas some of them are discontinuous and lens-like. The thickness of the sandstone units generally ranges from 10 to 50 feet and averages about 30 feet.

Most of the sandstones consist of fine-grained, subangular to rounded quartz sand that is cemented in part by calcite. Some of the sandstones are shaly or clayey toward the edges of the deposits. Reservoir porosity ranges from 10 to 22 percent, averaging about 16 percent, and permeability ranges from 10 to 150 md, averaging about 35 md.

The Pennsylvanian sandstones shown on the accompanying list (fig. 30) are believed to be most acceptable for injection of

Hewitt (First, Second, Third, Fourth, and Fifth)	Missourian Series
Deese (First, Second, Third, Fourth, and Fifth)	Desmoinesian Series
Culbertson	
Fusulinid	
Tussy (First, Second, Third, Fourth, and Fifth)	
Carpenter	
Morris	

Figure 30. List of Pennsylvanian sandstones that may be suitable locally for liquid-waste injection in south-central Oklahoma.

wastes. One or two of these units are expected to be present in the subsurface in most parts of the region at depths that range from several hundred feet to more than 5,000 feet (fig. 24). Several closely associated sandstones are given numerical designations, and some sandstones are given different names in different basins.

Northwest Oklahoma

The northwest Oklahoma region consists of the northern shelf of the Anadarko Basin and the Oklahoma Panhandle (figs. 1, 26). The thickness of sedimentary rocks ranges from about 7,000 feet in the north part of the region to nearly 15,000 feet in the south, near the margin of the deep Anadarko Basin (fig. 19).

Reservoir rocks that locally are suitable for liquid-waste injection include carbonates of the Arbuckle Group, Mississippian limestones, Permian dolomites, and sandstones in the Pennsylvanian System. Liquid wastes currently are injected into Mississippian limestones and Pennsylvanian sandstones of the region. Beds of rock salt also may be suitable to retain wastes in solution-mined or dry-mined cavities. Outcropping shales of the region (see Part II of this report) may be able to retain waste in hydraulically induced fractures or in caverns mined at shallow to moderate depths in the shale.

Major references to the subsurface geology of the region include Jordan and others (1959), Bado and Jordan (1962), Thornton (1962), Jordan and Vosburg (1963), Barrett (1964), Berg (1969), Quackenbush (1969), Gatewood (1970), Benton (1972), Withrow (1972), Khaiwka (1973), and Harris (1975).

Arbuckle Group

The Arbuckle Group (Upper Cambrian and Lower Ordovician) underlies all parts of northwest Oklahoma and is believed to have the capacity for accepting injected liquid wastes in most areas. The total thickness of the Arbuckle Group here is typically 1,500 to 2,000 feet. The unit consists of both dolomite and limestone, and locally as much as 25 percent of its thickness is porous and permeable. The depth to the top of the Arbuckle is as little as 5,000 feet in the northeast and about 6,000 feet in the northwest; the depth increases southward into the Anadarko Basin and reaches about 12,000 feet at the south edge of the region (fig. 21).

Mississippian Limestones

In some parts of the region, limestones of Mississippian age have sufficient porosity and permeability to qualify for injection of liquid industrial wastes. The porosity and permeability result from a variety of processes in different areas: reef development, deposition of oolites, dolomitization, and fracture porosity. Suitable Mississippian reservoirs are locally as thick as 35 feet, although commonly they average about 20 feet. They occur at depths ranging from 4,000 feet in the northeast to 8,000 feet in the south part of the region.

Industrial wastes, including solvents, acids, and caustic solutions, are now being disposed of in one of the Mississippian limestones (Meramecian) at a depth of about 7,100 feet (well 4 in table 16 and fig. 18) near Dover in Kingfisher County.

Pennsylvanian Sandstones

Numerous Pennsylvanian sandstones capable of accepting liquid wastes are present over most of the region. The sandstones are commonly discontinuous lenses or channel-like bodies that are up to several miles wide and may be as much as 25 miles long. Sandstone bodies are typically 15 to 50 feet thick in the middle and grade laterally into thin sandstones and shales on the sides. Morrowan sandstones in the Panhandle and nearby counties are locally as thick as 150 feet.

Most Pennsylvanian sandstones consist of fine- to medium-grained quartz sands that locally are micaceous, shaly, and calcareous. The sand grains are subangular to rounded and generally are well sorted. Morrowan sandstones near the base of the Pennsylvanian are somewhat coarser grained and in part are conglomeratic.

Porosity of Pennsylvanian sandstone reservoirs typically ranges from 10 to 20 percent and averages about 15 percent. Permeability ranges from 1 to 140 md but most commonly is in the 50–100-md range.

The most important reservoir sandstones in the region are shown on the accompanying list (fig. 31). Not all of these units are present at any one locality in northwest Oklahoma, but one or more of them may be expected in most areas. The depth of these sandstones ranges from 2,000 to 3,000 feet in the north to more than 5,000 feet in the south part of the region (fig. 24).

Hoover, Elgin, Endicott, Tonkawa	Virgilian Series
Avant, Cottage Grove	Missourian Series
Oswego, Red Fork, Cherokee	Desmoinesian Series
Purdy, Kelly, Keyes	Morrowan Series

Figure 31. List of Pennsylvanian sandstones that may be suitable locally for liquid-waste injection in northwest Oklahoma.

Liquid wastes from an iodine plant are now being disposed of at a depth of 7,300 feet in basal Pennsylvanian (Morrowan) sandstones north of Woodward (well 3 in table 16 and fig. 18). Iodine-bearing brines are being produced from Morrow sandstones, and after extraction of iodine the stripped brine is reinjected into the same sandstones both for disposal purposes and to repressure the reservoir and thus drive more iodine-rich brine to the production wells.

Permian Dolomites

Several dolomite beds of Permian age locally may be targets for industrial-waste disposal in the Panhandle area, especially in Texas County. Individual units, including the Herington, Krider, and Winfield Dolomites, typically average about 15 feet in thickness and extend over large areas. Two or more dolomite beds are present at many locations, and the depth to the shallowest carbonate unit commonly is 1,500 to 3,000 feet below the surface. The dolomite beds typically are porous with rather low permeabilities.

Permian Salts

Rock salt (Lower and Upper Permian) underlies almost all the region. It occurs in three principal salt sequences, the Hutchinson salt, the Cimarron salt, and the Flowerpot salt, and is interbedded with shale and (or) anhydrite in all areas. Individual layers of rock salt are typically 5–30 feet thick. In many parts of the region the top of the salt beds is 500–1,000 feet below the surface (fig. 25), and locally some of the lower salt units are as much as 3,000 feet below the surface.

Three underground storage facilities have been created by dissolution of salt in parts of northwest Oklahoma (Jordan and Vosburg, 1963). Texaco, Inc., formed a 33,000-barrel cavern for storage of propane at a depth of about 900 feet in the Camrick district of southwest Beaver County. Warren Petroleum Corp. created several caverns, with a total capacity of 150,000 barrels, at a depth of 1,500 feet; the facility is for storage of liquefied petroleum gas at its Mocane plant in north-central Beaver County. Continental Oil Co. (Conoco) is storing 150,000 barrels of butane at a depth of 900 feet near Medford in central Grant County.

Anadarko Basin

The Anadarko Basin, one of the major geologic provinces in Oklahoma, is the dominant structure in the west half of the State (fig. 26). It is a depositional basin that has the form of a great asymmetrical syncline, with the steeper dips on the south side near the Wichita Mountain Uplift. The basin contains as much as 40,000 feet of sedimentary rocks along the axis in the south part of the basin; the strata thin northward to about 15,000 feet in the north part (fig. 19). Reservoir rocks in the Anadarko Basin that are discussed here do not include those on the south flank, as these rocks are closely associated with events in the Wichita Mountains and are discussed in the section on Southwest Oklahoma; nor do they include those on the northern shelf of the basin, as they are discussed in the section dealing with Northwest Oklahoma.

A number of carbonate and sandstone units appear capable of accepting liquid industrial wastes in various parts of the Anadarko Basin: carbonate rocks include the Arbuckle Group, the Hunton Group, and Mississippian limestones, whereas the sandstones include the Simpson Group, the Springer Formation, and units within the Pennsylvanian and Permian Systems. Wastes may be injected into caverns formed in bedded rock salt that underlies much of the region. They also may be placed in shallow shale deposits (see Part II of this report) that are hydraulically fractured or are excavated to form underground caverns. The State's only industrial-waste-disposal system based upon injection into hydraulically fractured shale is located at Duncan in Stephens County (well 6 in table 16 and fig. 18).

Among the principal references on subsurface geology of the region are the following: Slate (1962), Jordan and Vosburg (1963), Peace (1965), London (1975), and Amsden (1975).

Arbuckle Group

The Arbuckle Group (Upper Cambrian and Lower Ordovician) extends throughout the Anadarko Basin and is a potential carbonate reservoir for liquid-waste injection in much of the region. The unit is commonly dolomitic, and locally it is expected to have moderate intergranular porosity and permeability, augmented by fracture porosity. The depth to the top of the Arbuckle ranges from about 10,000 feet in the north part of the region to as much as 31,000 feet along the basin axis in central Washita County (fig. 21). Deep drilling near the axis has established that the Arbuckle Group has some porosity even at depths greater than 31,000 feet; the Lone Star Producing Co. 1 Bertha Rogers Unit yielded sulfur-bearing fluids from the upper Arbuckle 31,441 feet below the surface in west-central Washita County (Rowland, 1974).

Simpson Group

In the north and southeast parts of the region the Simpson Group (Middle Ordovician) contains several widespread sandstones that may be suitable for injection of liquid wastes. The Bromide, Tulip Creek, McLish, and Oil Creek sandstones are usually present at any given locality, and one or more of them commonly have sufficient porosity, permeability, and thickness to be acceptable waste-disposal reservoirs. Depths to Simpson Group reservoirs generally range from 10,000 to more than 15,000 feet in the north and southeast parts of the Anadarko Basin (fig. 22). At greater depths the Simpson sandstones have significantly lower permeability and typically are not suitable reservoirs.

Hunton Group

The Hunton Group (Ordovician, Silurian, and Devonian) apparently underlies all parts of the region, and locally it may be capable of accepting liquid wastes. Several zones within the Hunton are locally dolomitized and fractured and have a porosity range of 5 to 20 percent and a permeability range of 1 to 200 md. The thickness of the Hunton Group increases southward from several hundred feet in the north part of the region to approximately 1,000 feet in the deep part of the basin on the south. The top of the unit ranges from 7,000 feet in the north to 28,000 feet in the south. The Hunton has sufficient porosity and permeability to produce natural gas from a depth of 24,548 feet in northwest Beckham County, north of Mayfield.

Mississippian Limestones

In the north part of the region, some of the limestones in the upper part of the Mississippian System (Chesterian Series) are somewhat porous and permeable and are similar to those in northwest Oklahoma. Southward, the permeability is lost as limestone grades laterally into shale. Porous Mississippian limestones lie at depths ranging from 8,000 feet in the north to about 15,000 feet in the central part of the region.

Springer Formation

Southward from the north hinge of the Anadarko Basin, a southward-thickening wedge of sandstones and shales makes up the Springer Formation (Upper Mississippian): the sandstones locally may be suitable reservoirs for liquid wastes. The porosity of the sandstone reservoirs commonly ranges from 10 to 20 percent and averages about 14 percent; the permeability ranges from 1 to 100 md and averages about 40 md. Sandstone bodies are fairly uniform over large areas; they generally average 30 feet in thickness but locally are as thick as 100 feet. The depth to the top of the Springer ranges from about 8,000 feet in the north to nearly 20,000 feet in the central part of the region, where the sandstones grade southward into shale (fig. 23). At depths greater than about 15,000 feet, the sandstones in the Springer Formation have significantly lower permeability and typically are not suitable reservoir rocks. Named units in the southeast part of the basin include (in descending order) the Woods, Cunningham, Britt, Spiers, and Boatwright sandstones.

Pennsylvanian Sandstones

The numerous Pennsylvanian sandstone reservoirs described and listed in the chapter on Northwest Oklahoma (see fig. 31) are also generally present, and are prospective units for waste disposal, in the north part of this region. General properties of the sandstones are similar to those farther north, except that here they are typically 7,000 to more than 10,000 feet below the surface (fig. 24). In the south part of the region most of these sandstones grade laterally into shale, although locally they interfinger with some of the wedges of granite wash that thin northward from the Wichita Mountain Uplift.

In the southeast part of the region, another group of Pennsylvanian sandstones may be capable of accepting liquid wastes (fig. 32). These sandstones are typically 10 to 50 feet thick over fairly large areas and range in depth from about 3,000 to 15,000 feet below the surface.

Garner	
Rowe (several sands)	Virgilian Series
Niles	
Yule	
Wade	
Medrano	Missourian Series
Marchand	
Culp	

Figure 32. List of Pennsylvanian sandstones that may be suitable locally for liquid-waste injection in southeast part of Anadarko Basin.

Permian Sandstones

Several of the sandstones of Permian age may locally be suitable for industrial-waste disposal. The depth to these units ranges from several hundred feet to more than 3,000 feet, but at the shallower depths care must be taken to avoid contamination of ground-water supplies. Named units that may be suitable in the southeast part of the region include the Fortuna and several of the Noble-Olson sandstones.

Permian Salts

Beds of rock salt (Lower and Upper Permian) underlie the west half of the Anadarko

Basin and are present in the Hutchinson salt, the Cimarron salt, and the Beckham evaporites. Individual layers of rock salt, typically 5 to 30 feet thick, are interbedded chiefly with shale and (or) anhydrite in each of the three salt sequences. The depth to the top of the shallowest salt unit ranges from 600 to more than 3,000 feet in different parts of the region, and in places the lower salt beds are 3,500 feet below the surface (fig. 25).

A 15,000-barrel propane-storage cavern, created by Shell Oil Co. at a depth of 1,400 feet near Elk City in Beckham County (Jordan and Vosburg, 1963), is at the south edge of the region along the axis of the Anadarko Basin.

Southwest Oklahoma

For this report, southwest Oklahoma embraces the Wichita Mountain Uplift, as well as the Hollis Basin and the south flank of the Anadarko Basin where the depositional history is closely tied to geologic events in the Wichita Uplift (figs. 1, 26). Crystalline basement rocks crop out along the central part of the uplift, but elsewhere several hundred to several thousand feet of sedimentary rocks overlie the basement on the Wichita block. The thickness of sedimentary rocks is 5,000 to 12,000 feet in the Hollis Basin, south of the mountains, and reaches 30,000 to 40,000 feet along the axis of the Anadarko Basin, to the north (fig. 19). Owing to complex folding and faulting along the north and south boundaries of the Wichita Uplift, the depth to potential waste-disposal reservoirs in these areas varies greatly within short distances.

Rock units considered best suited for accepting liquid wastes include carbonates of the Arbuckle Group, the Brown dolomite, and sandstones and conglomerates in the series of granite-wash deposits. Thick salt deposits of the region could also accommodate industrial wastes in natural solution caverns or in mined caverns. Shales at shallow to moderate depths in the region (see Part II of this report) might be suitable locally for accepting wastes in hydraulically induced fractures or in mined-out caverns.

Principal studies of the subsurface geology of southwest Oklahoma include Sears (1951), Edwards (1959), McDaniel (1959), Bozovich (1963), Jordan and Vosburg (1963), Blazenko (1964), Ham and others (1964), Johnson (1967), and Harlton (1972).

Arbuckle Group

The Arbuckle Group (Upper Cambrian and Lower Ordovician) is a carbonate reservoir that may be suitable for liquid-waste injection in many parts of the Hollis Basin and locally on the north side of the Wichita Mountain Uplift, where the reservoir rock is preserved in down-faulted blocks. Elsewhere on the Wichita Uplift the Arbuckle is absent, owing to uplift and erosion during Pennsylvanian time.

In this region the Arbuckle is predominantly tan, sucrosic to coarse-crystalline, porous dolomite. Intergranular porosity of reservoir rocks is calculated between 4 and 12 percent, averages about 8 percent, and may be augmented by fracture porosity. Permeability of the unit averages about 100 md and locally may reach or exceed 500 md.

The thickness of the Arbuckle in southwest Oklahoma is estimated at 4,000–5,000 feet. Its depth is typically 5,000–8,000 feet below the surface in the Hollis Basin (fig. 21) and ranges from about 1,000 to more than 20,000 feet in the fault blocks on the north side of the Wichita Uplift. On the south flank of the Anadarko Basin the Arbuckle Group is locally more than 30,000 feet deep.

Granite Wash

The term granite wash has been used by petroleum geologists working in southwest Oklahoma to describe the thick series of granitic or arkosic conglomerates and sandstones interbedded with shales within and surrounding the Wichita Mountain Uplift. Granite wash is the debris weathered and eroded from the rising Wichita Mountain block during Pennsylvanian and Early Permian time; it was deposited in channels and sheetlike layers on the flanks of the mountains and in nearby parts of the Hollis and Anadarko Basins and locally is a suitable reservoir for liquid-waste disposal.

To the south, in parts of the Hollis Basin, the granite wash is locally porous and permeable. Individual beds in the north part of the basin are up to 50 feet thick and occur at depths ranging from 500 to 3,000 feet. These same conditions also exist west of the Wichita Mountains and beneath the broad plains that form valley-like areas between scattered outcrops of granite within the mountain area.

The principal deposits of granite wash are on the north flank of the Wichita Uplift and northward into the Anadarko Basin. The system of complex faults close to the mountains locally limits the lateral extent of individual layers of granite wash and causes their depth to range from 1,000 to more than 5,000 feet. Beyond this fault zone, however, granite-wash layers extend more than 20 miles northward across the Anadarko Basin, where they are as deep as 15,000 feet below the surface. The entire sequence of granite wash and interbedded shale is as thick as 10,000 feet near the axis of the basin. Individual beds range from 10 to 50 feet thick, although an aggregate thickness of as much as 240 feet of porous sandstones is present at some localities. The reservoir sandstones have highly variable porosity and permeability but average about 17 percent and 175 md, respectively.

Brown Dolomite

The Brown dolomite (Lower Permian) is a prospective reservoir for liquid-waste disposal west and northwest of the exposed Wichita Mountains, chiefly in Beckham and northern Greer Counties. The Brown dolomite is gray brown and fine to medium crystalline and contains both intergranular and vuggy porosity. Reservoir porosity ranges up to 20 percent but averages about 11 percent, whereas the permeability is as high as 50 md and probably averages about 10 md. The porous zone in the Brown dolomite averages about 25 feet in thickness and ranges in depth from 1,500 to about 3,000 feet.

Permian Salts

Layers of rock salt (Lower and Upper Permian), interbedded with shale and anhydrite, underlie the northwest part of the region. They occur in the Cimarron salt and also in the Beckham evaporites. Individual salt beds of both salt sequences are commonly 5 to 30 feet thick. The depth to the top of salt in the region ranges from about 800 to 1,000 feet over the Wichita Uplift and about 500 to 1,300 feet in parts of the Hollis and Anadarko Basins (fig. 25).

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