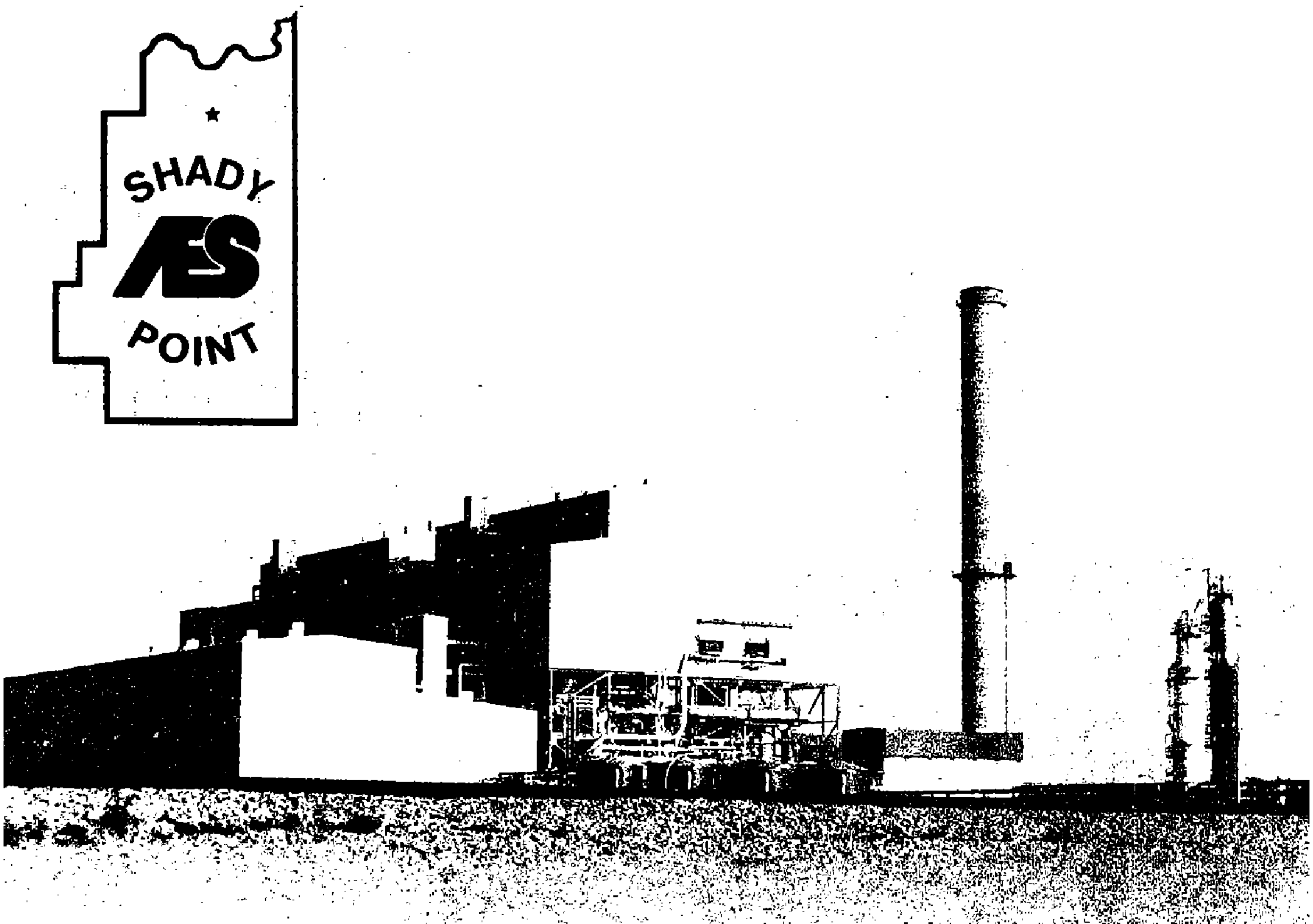
OKLAHOMA GEOLOGY



Vol. 54, No. 5
October 1994

Oklahoma Geological Survey

On The Cover —

Oklahoma's Newest Large Electric Power Plant

Applied Energy Services (AES) Shady Point cogeneration facility is Oklahoma's newest, large, coal-fired electric power plant. Rated at 320 megawatts (320,000 kilowatts), AES Shady Point went on-line January 15, 1991, serving Oklahoma Gas and Electric Co.'s power grid in eastern Oklahoma and in part of western Arkansas. The plant is located on a 393-acre hill adjacent to the Poteau River, 3 mi south of Spiro, Le Flore County, Oklahoma. It employs about 100 people and cost investors about $500 million to complete since the groundbreaking ceremony, September 3, 1987. The plant is unique because it (1) is the first circulating-fluidized-bed (CFB) coal combustion power plant in Oklahoma, (2) burns about one million tons of bituminous coal and about 300,000 tons of limestone that are mined in Oklahoma annually, and (3) is a cogeneration plant. The writer believes it is the largest coal-burning cogeneration plant in the world.

Cogeneration means that a plant's combustion by-products are used for another industry. In this case, food-grade CO_2 is produced from two towers for a food processing company. Cogeneration qualifies the plant for classification as a non-utility generating plant (NUG) under the regulations of the federal Clean Air Act Amendments, which are scheduled for enforcement beginning January 1, 1995, and under additional stricter regulations scheduled for the beginning of the 21st century.

AES Shady Point's use of state-of-the-art technology in its four boilers, in which coal and limestone are burned together, greatly reduces emissions of particulates, SO_2, NO_x, and metals and other trace elements from its 350-ft-high concrete stack. (When the writer visited and photographed the plant in October 1992, he observed no smoke or steam coming out of the stack.) Ash, composed of gypsum

(continued on p. 220)

OKLAHOMA GEOLOGICAL SURVEY

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OKLAHOMA GEOLOGY
Notes

VOL. 54, NO. 5

NATURAL GAS: OKLAHOMA'S UNDER-APPRECIATED ASSET

Charles J. Mankin[1]

The petroleum industry continues to be Oklahoma's largest economic activity. In spite of the collapse in world oil prices in 1986 that resulted in a 50% reduction in the gross value of the State's petroleum products, the value of crude oil and natural gas exceeded $5 billion in 1993 (Oklahoma Tax Commission, personal communication, 1994). Natural gas accounted for 70% of that total ($3.7 billion).

Natural gas has been produced in the region for almost 100 years, but most of the early production was in association with crude oil and was flared due to the lack of markets for the gas. No records on this early production were maintained. The earliest reliable records on natural gas production were compiled in the mid-1940s, and good data have been maintained since that time. Figure 1 depicts the production of natural gas in Oklahoma from 1947 through 1993. Production increased at a rather consistent rate of about 40 billion cubic feet (Bcf) per year to 1990 when the State produced 2.3 trillion cubic feet (Tcf). Since that time production has declined 300 Bcf in three years.

Oklahoma has the second largest natural-gas production among producing states. Figure 2 shows the relationship of Oklahoma's 1992 marketed production to that of the Federal Offshore

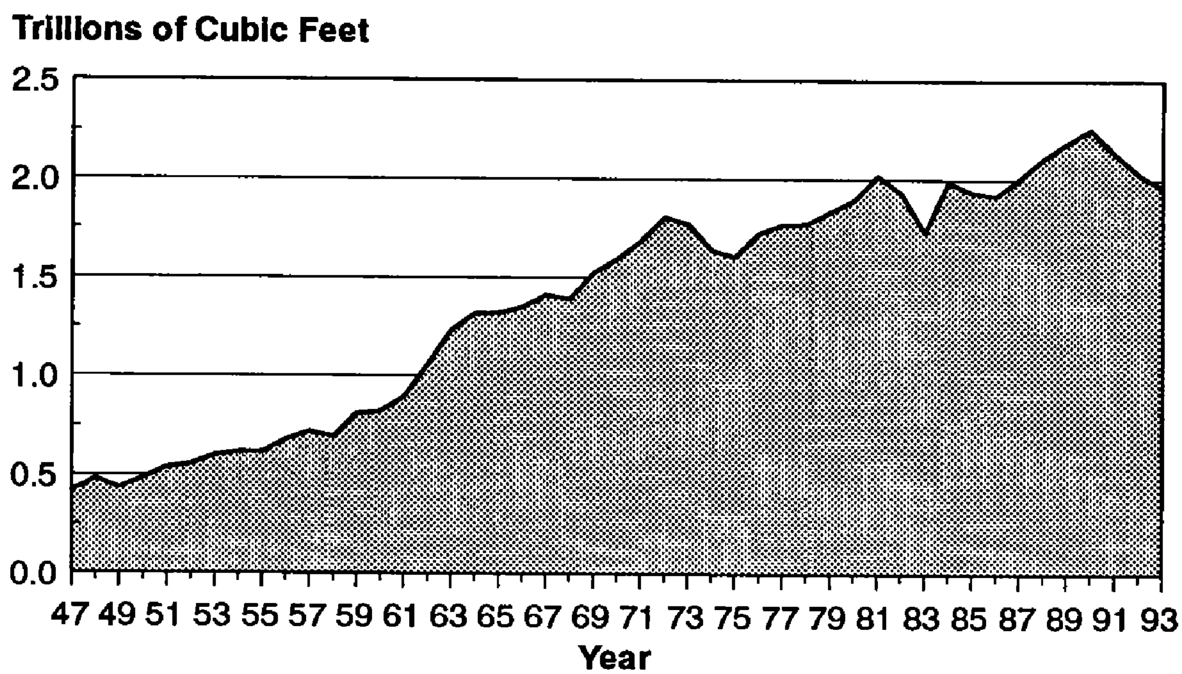

Figure 1. Production of natural gas in Oklahoma from 1947 through 1993. Production data prior to 1947 are not readily available and are unreliable. (Data from American Petroleum Institute, 1994.)

[1]Director, Oklahoma Geological Survey.

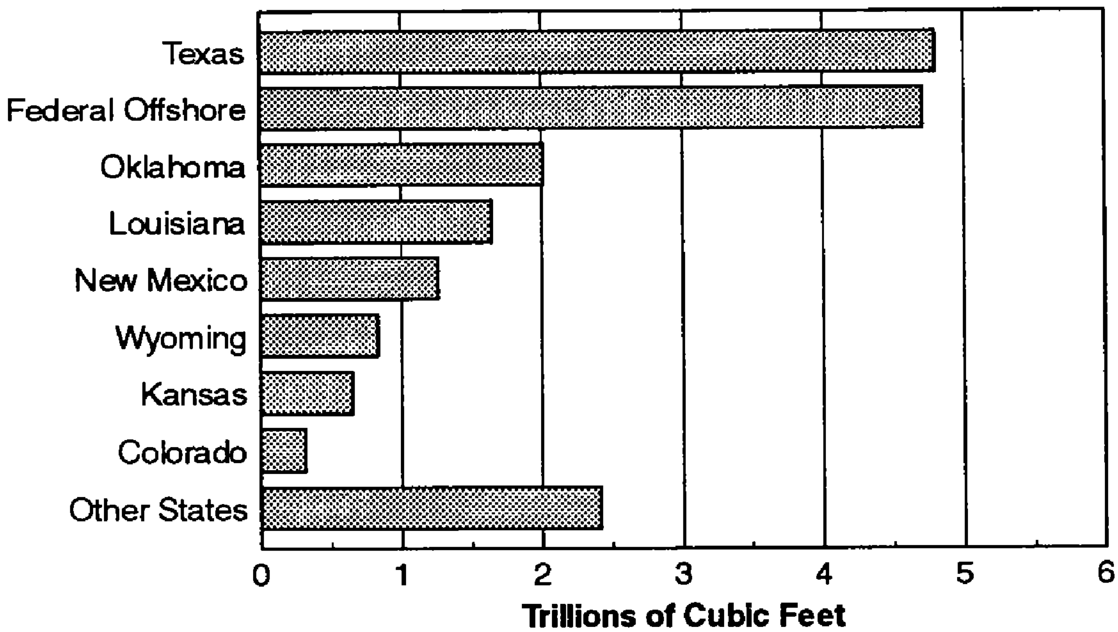

Figure 2. Production of natural gas from the Federal Offshore and the seven largest-production states for 1992. Data separating Federal Offshore production from that of Texas and Louisiana are not yet available for 1993. (Data from Energy Information Administration, 1993a.)

and the other six states with large gas production. The Federal Offshore and the seven largest-production states account for 87% of total U.S. marketed production, and Texas and the Federal Offshore account for about one-half of the U.S. total. Information separating the Federal Offshore production from the state totals for Louisiana and Texas is not readily available for 1993, but the individual totals are expected to be comparable to those of 1992. The state rankings and relative amounts of production will not change.

The growth in Oklahoma's natural gas production led to a corresponding increase in the share of the U.S. market. Figure 3 shows the growth in the State's share of the U.S. natural gas market, which rose from 7.25% in 1970 to 12.3% in 1989. Since that time, Oklahoma's share of the market has fallen, to 10.3% in 1993.

The declines in production and market share are matters of concern. First, it should be noted that all but 10 of the State's 67 natural-gas-producing counties have either flat or declining production and none of the increases in production among the 10 counties were significant. Second, the seasonal fluctuation in demand also has disappeared. Figure 4 shows the monthly production of natural gas for the years 1983 and 1993. In 1983, the seasonal demand clearly was evident and production declined during the summer months. In 1993, the production profile was essentially flat, which indicates that demand equals or exceeds supply. The decline in market share (Fig. 3) also suggests that demand exceeds supply. During this period of decline in market share for Oklahoma, U.S. production increased by 1.1 Tcf while the State's production declined by 300 Bcf.

Further evidence for a decline in productive capacity in Oklahoma can be obtained by examining the change in proven reserves of natural gas in the

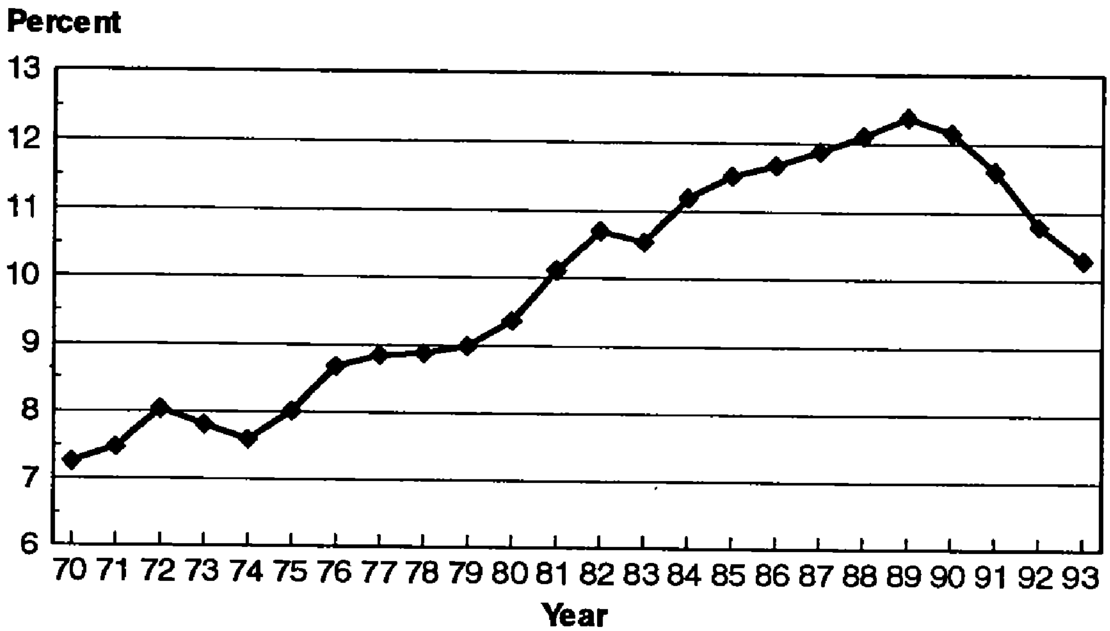

Figure 3. Oklahoma's share of U.S. natural-gas market from 1970 through 1993. (Data obtained from the Natural Resources Information System [1994] data system for Oklahoma production and from Energy Information Administration [1993a] for U.S. production.)

State. From 1987 through 1992, proven reserves declined by 2.8 Tcf (Fig. 5). While proven reserves alone cannot be correlated directly to declining productive capacity, the reserves-to-production ratio is a good indicator. Figure 6 is a graphic representation of the reserves-to-production ratio for Oklahoma, the Federal Offshore, and the other major gas-producing states. Note that the reserves-to-production ratio for Oklahoma, at 6.9:1, is similar to those of the Federal Offshore, Louisiana, and Texas. This correlation is contrary to what is expected. Low reserves-to-production ratios commonly correlate with reservoirs that have active water drives, similar to those in the Federal Offshore, Southern Louisiana, and the Gulf Coast of Texas, where production rates are enhanced by this additional reservoir energy. This leads to more rapid depletion of reservoirs, and thus to lower reserve-to-production ratios. In contrast, most of Oklahoma's natural gas reservoirs are expansion drives similar to those of New Mexico, Kansas, and Colorado. Expansion drive reservoirs produce lower volumes of natural gas as the reservoir pressure declines, thus leading to longer reservoir life and commonly to larger reserve-to-production ratios. The extensive development in Oklahoma of pipelines that provide market access and the small number of unitized fields may account for the more rapid depletion of reserves.

A conclusion that can be drawn from this analysis is that Oklahoma's natural gas production will continue to decline until the rate of exploration and development is able to arrest the decline in reserves. The present drilling rate in the State is not sufficient to achieve that objective. Hopefully, the tax incentives passed during the last legislative session will contribute to an expansion of drilling in the State. Among those incentives is a reduction in gross production tax for production from any well that is drilled to a depth of at least 15,000 ft (Mankin, 1994). A revision of that incentive to wells drilled to depths of at least 12,000 ft should have a substantially greater ef-

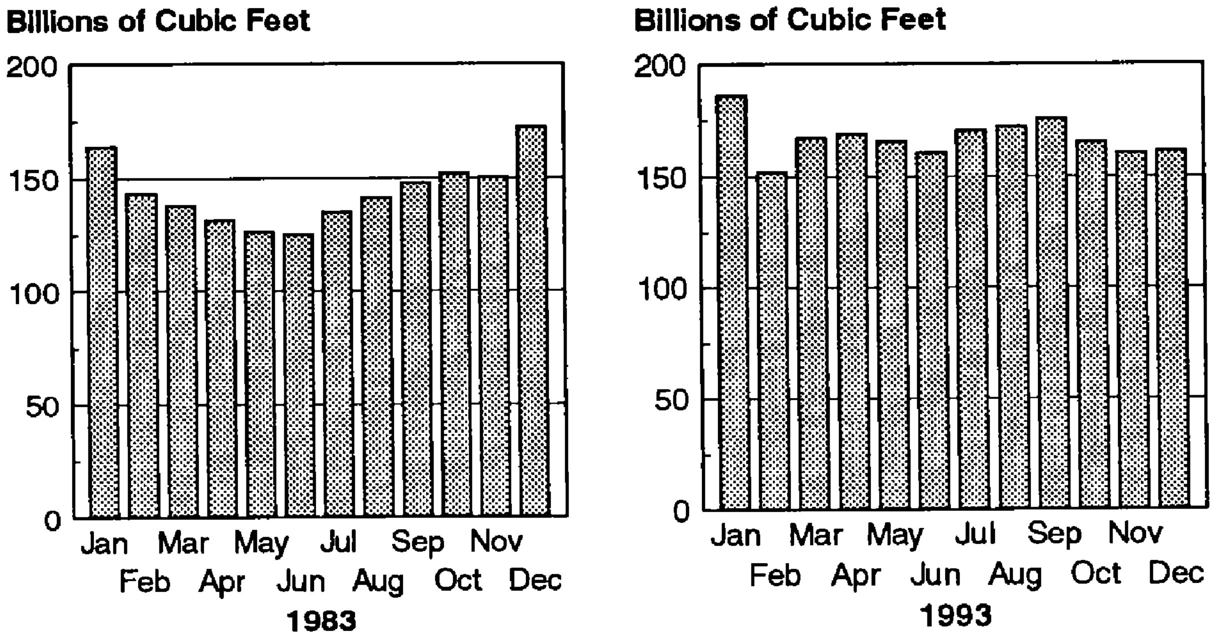

Figure 4. Monthly natural gas production in Oklahoma for the years 1983 and 1993. (Data from the Natural Resources Information System [1994] data system.)

fect because of the attractive targets for exploration at that depth in the Anadarko basin.

While these concerns about declining production and market share are important, they can be addressed. Increased exploration and development will lead to a reversal of these trends. Incentives such as those enacted by the last legislature will contribute, but are not sufficient. Increases in price for natural gas will be required if the deep potential of the Anadarko and Arkoma basins is to be realized. Such increases are likely and may occur much sooner than some experts have forecast. As evidence for this view, it should be noted that natural gas reserves both nationwide and in the major producing states have declined continuously since the mid-1970s. There have been increases to the proven reserves for the lower 48 states only three times in the past 16 years, and each of those was small. Thus, the reserve-to-production ratio for the lower 48 states is at a modern low of 8.6:1. For Texas and the Federal Offshore, the combined ratio is 6.8:1. Given that the average depletion rate for reservoirs in the Gulf of Mexico and the Texas Gulf Coast is about six years, these ratios give little evidence of excess capacity. Because Texas and the Federal Offshore provide about one-half of the current natural gas supply, declines in these areas will have obvious market consequences.

The argument has been made that imports, especially from Canada, will restrain price increases for natural gas. Increases in Canadian natural gas imports have been occurring and may well continue to increase, but not at the current rate. Since 1986, Canadian imports have increased by 1.6 Tcf, or about 230 Bcf per year (Energy Information Administration, 1994). That volume is roughly equal to the annual production of natural gas from Louisiana. In 1993, annual imports from Canada were 2.27 Tcf or 11% of U.S. demand. From 1986 through 1992, U.S. demand has grown by 1.4 Tcf per year, or 200 Bcf less than the annual increase in Cana-

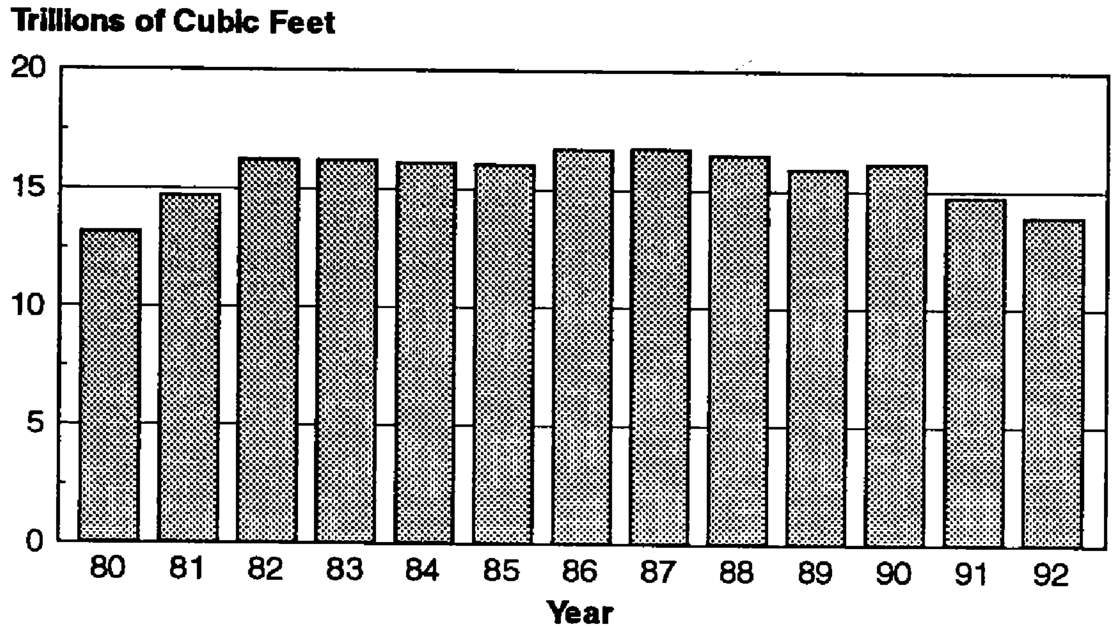

Figure 5. Proven reserves of natural gas in Oklahoma for 1980 through 1992. (Data from Energy Information Administration, 1993b.)

dian imports during that time. So the total displacement of domestically produced natural gas has been about 30 Bcf per year. Because of spot shortages in the Canadian system last winter, the growth in exports to the U.S. is likely to be constrained.

In 1993, U.S. demand for natural gas increased by more than 500 Bcf, and through the first six months of 1994 it increased at an annual rate of more than 300 Bcf (Energy Information Administration, 1994). The U.S. market now is growing faster than the historical growth in Canadian imports, and thus price constraints from such imports should not be a factor.

This analysis prompts one observation with which most should agree: the infamous "gas bubble" is now a part of history. Supply and demand for natural gas are in closer balance than at any time in more than a decade. On a national basis, there is little evidence for the traditional summer/winter fluctuation in demand.

Since prices for natural gas have been lower than expected during recent months, an argument can be made that the preceding analysis is faulty. However, it should be noted that this analysis looks at the broader market picture, not at the apparent short-term capacity that is reflected by the natural-gas commodities market. The commodities market does not reflect the changes that can occur over a period of six months to a year and is, thus, a very poor measure of natural gas supply. Shortages in supply cannot be rectified in days or weeks, but current low prices can have an adverse effect on exploration and development decisions that will affect the supply two to five years hence.

Some of the additional factors that need to be considered in looking toward the next five years or so are changing demand patterns for natural gas and the related future sources of supply. While most of the changing demand patterns have been the subject of many analyses, one factor has not received much attention. At present, there is a large but difficult to quantify amount of fuel-switching capability in the domestic industrial and electric-utility market.

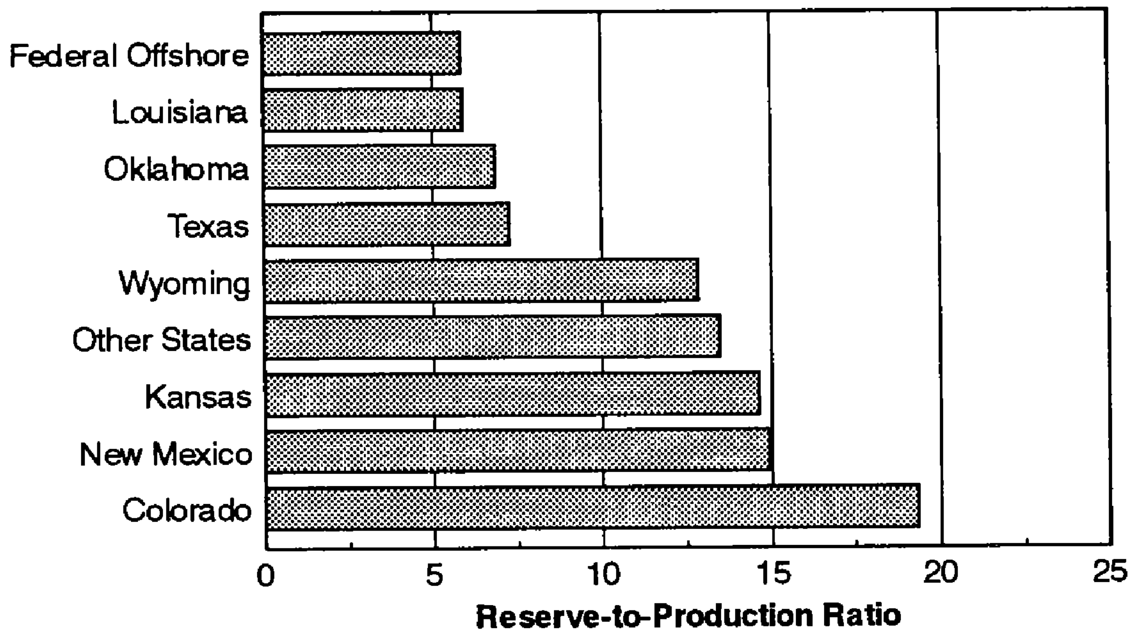

Figure 6. Ratio of natural gas reserves to production for the Federal Offshore, each of the major producing states, and an average for all other producing states. (Data from Energy Information Administration, 1993b.)

Much of that capability is between natural gas and heating oil. Heating oil is essentially a by-product of crude oil refining for transportation fuel. At present, heating-oil stocks are high because of the high demand for transportation fuel. While the demand for transportation fuel has grown very slowly during the past two decades, that rate of growth will increase much more rapidly in the future. Most of the past growth has been constrained by improving mileage efficiency of the U.S. automobile fleet, but that constraint now seems to have run its course. Thus, one would expect that heating-oil stocks would grow as well. However, current U.S. refining capacity is effectively saturated and there is little likelihood that new capacity will be developed. Thus, the growth in imports probably will be largely in refined products rather than crude oil. While heating oil could be imported, that would increase its cost and thus provide a wider price margin for natural gas.

The source of future supply also is an important consideration, especially for Oklahoma. During the next five or six years, most of the currently producing reservoirs in the Gulf of Mexico and many of those in the Gulf Coast will be depleted. While reservoirs in those areas will continue to be developed, it will take a significant exploration and development effort to succeed. Exploration opportunities exist in other parts of the lower 48 states, but significant constraints also are present. While most agree that there is a large undiscovered resource base of natural gas in the lower 48 states, substantial areas where such resources are expected to be found are either restricted to exploration or constrained in ways that make exploration uneconomical. Access to onshore public lands is becoming exceedingly difficult and expensive in terms of the time and effort required to obtain leases, permits to drill, and to develop gathering and transmission pipelines. Because of these constraints on exploration for new sup-

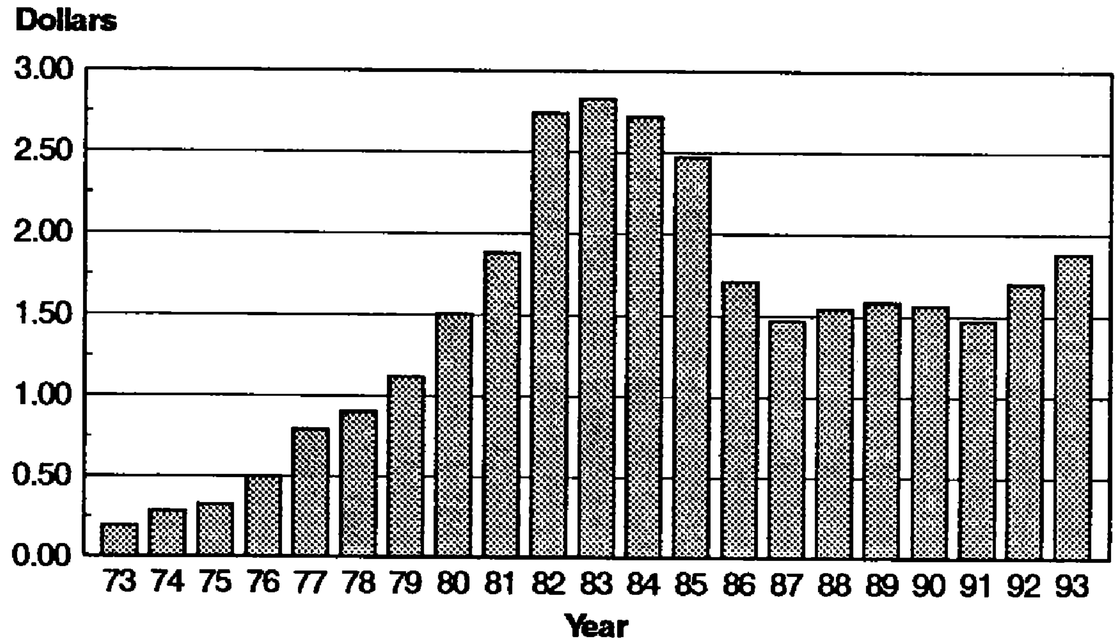

Figure 7. Average annual well-head price for Oklahoma natural gas. (Data from Energy Information Administration, 1993a.)

plies of natural gas, it may be unwise to count on development of new supplies from areas other than those where such activities are occurring at present. As a matter of good public policy, an examination of the status of public lands where natural gas resources are expected to be present should be a high priority.

Fortunately, Oklahoma does not have such constraints. There are opportunities for the development of future supplies in many parts of the State. The economic incentives provided by the last Legislature hopefully will aid operators to generate the capital needed for an expanded exploration and development effort. Ready access to information and technical assistance also will be important since most exploration and development activity is expected to come from small companies and independent operators who now produce 80% of the natural gas in the State. The development of the Natural Resources Information System (NRIS) (1994) by the Oklahoma Geological Survey (OGS) in cooperation with Geological Information Systems (GIS) of the University of Oklahoma and the implementation of the Petroleum Technology Transfer Council (PTTC) program by the OGS, GIS, and the State's Marginal Well Commission should be helpful. (The PTTC program is a national effort, funded in part by the U.S. Department of Energy, to provide information and technical assistance to the domestic petroleum industry.)

While tax incentives and information and technical support will be helpful in increasing exploration activity, the primary driver for such effort is the price of the commodity. Figure 7 shows the average annual well-head price for natural gas for Oklahoma from 1973 through 1993. Following a peak in 1983 of $2.83 per Mcf for the average price of Oklahoma natural gas, the average price declined sharply to less than $1.50 per Mcf in 1987, and remained in that range through 1991. That was a decline of almost 50% in four years. From 1991 through 1993, the average price for Oklahoma natural gas has increased by 40¢ per Mcf. If the thesis of this article proves correct, that trend of increasing prices should continue.

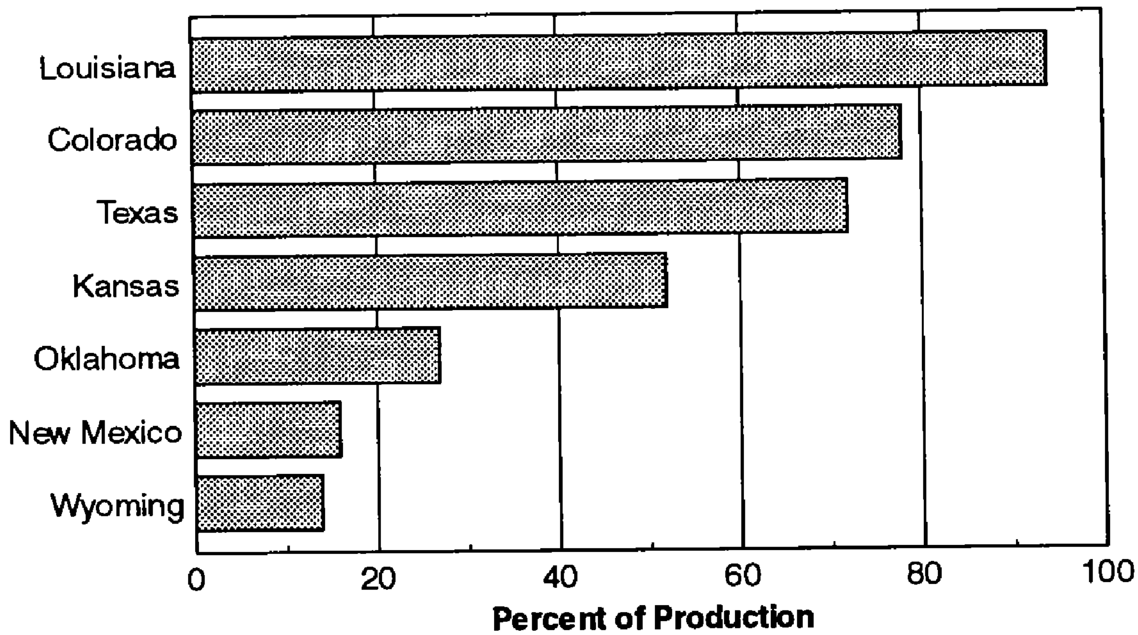

Figure 8. Consumption of natural gas as a percentage of production for each of the major producing states. (Data from Energy Information Administration, 1993a.)

A final observation regarding Oklahoma's future with respect to natural gas is the concern about its use. While the State is an important producer of natural gas and has the potential to develop substantial future supplies, it is losing much of the benefit from the resource that is realized by other states. Figure 8 shows the relationship of production to consumption of natural gas for each of the major producing states. Among the seven major producing states, only Wyoming and New Mexico use a smaller percentage of their production than does Oklahoma. While Louisiana consumes 94% of the natural gas produced in that state and Texas uses 72% of its production, Oklahoma consumes only 27% of its produced natural gas. The State thus loses much of the real value added in using natural gas to manufacture products and, in the process, to create jobs and produce revenue. An important goal for the State should be to attract natural-gas-using industries in order to realize the full value of this resource.

In summary, while problems still exist for the domestic natural gas industry, it seems apparent that brighter days are near at hand, especially for Oklahoma. That brighter future will be realized only with effective leadership in the State directed toward that end.

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NEW OGS *Publication*

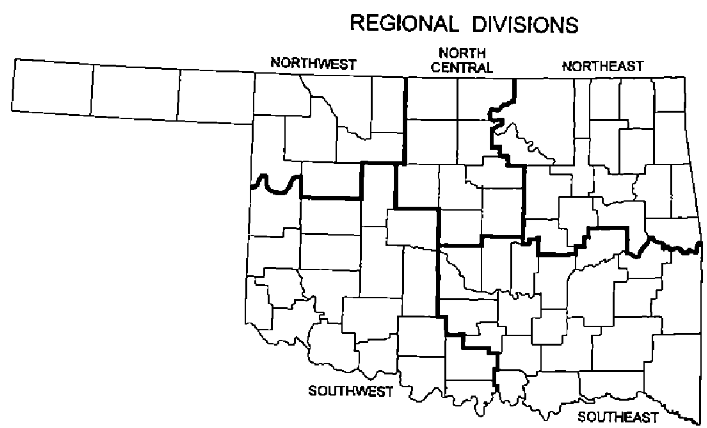
SPECIAL PUBLICATION 94-4. ***Oklahoma Oil and Gas Production by Field, 1990–93.*** Five parts (A–E). Price: Single copies, $10; complete set of five, $40.

The Oklahoma Geological Survey has published SP 94-4, *Oklahoma Oil and Gas Production by Field, 1990–93,* in five separate parts: (A) Northwest, (B) North-Central, (C) Northeast, (D) Southwest, and (E) Southeast. Included in the publication are the following types of field data:

- Field name
- County or counties in which the field is located
- Total acreage of the field
- Date the Oklahoma Nomenclature Committee named the field and date of the last revision of field boundaries
- Annual production from 1990 through 1993 by type of product: oil, condensate, total liquids, associated gas, natural gas, and total gas
- Cumulative production from 1979 through 1993 by type of product

Other data include county and state annual production totals from 1990 through 1993 and cumulative production totals from 1979 through 1993, by type of product, and a list of discontinued field names.

This publication has been developed from data contained in the Natural Resources Information System (NRIS), a computerized data base of oil and gas information for the State of Oklahoma. NRIS currently contains data files of monthly oil and gas production by lease that can be aggregated by such categories as field, producing interval, geologic play, petroleum province, and political area (e.g., county). NRIS also contains digitized records for almost 40,000 well completions and recompletions dating from Statehood (1907) to present. The well records include latitude/longitude coordinates that permit plotting and use in a GIS system.



(Example of a Record)

Oklahoma Oil and Gas Production by Field 1990–1993

WATONGA-CHICKASHA TREND — ONC Dates: Named – 1976, Last Update in 1991
Counties – CADDO, GRADY, BLAINE, CANADIAN, DEWEY — Estimated Total Acres – 396,160

Production	Oil	Condensate	Total Liquids	Assoc. Gas	Natural Gas	Total Gas
1990	1,762,434	512,317	2,274,751	3,327,614	126,652,106	129,979,720
1991	1,594,771	359,990	1,954,761	2,994,680	112,254,982	115,249,662
1992	1,747,415	317,190	2,064,605	2,608,689	105,281,695	107,890,384
1993	2,138,440	289,934	2,428,374	2,958,089	96,039,816	98,997,905
1979–1993	41,529,185	10,866,258	52,395,443	91,103,318	2,239,630,740	2,330,734,058

SP 94-4 can be purchased over the counter or by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031 or (800) 330-3996; fax 405-325-7069. Add 10% to the cost of publication(s) for mail orders, with a minimum of 50¢ per order.

OGS Coal Group Participates in Annual Forum of Western Interior Coal Basin Geologists

Samuel A. Friedman[1]

The 18th Annual Forum of Coal Geologists of the Western Interior Coal Basin was convened at the State Office Building in Fort Smith, Arkansas, July 20–21, 1994, by William V. (Bill) Bush, Assistant State Geologist of the Arkansas Geological Commission. Geologists from three states (Arkansas, Kansas, and Oklahoma) attended the oral sessions and field trip. Geologists from two states (Iowa and Missouri) did not attend but sent their coal reports to the meeting. Coal of bituminous rank is mined in this basin (Fig. 1).

During the first morning session, participants reported on their states' coal productions and coal industry developments, and also on their coal liaison work. Progress on coal-related research and mapping was included in the afternoon session.

Assistant State Geologist Dr. Lawrence L. Brady reported on Kansas. He indicated that the two active Kansas surface mines produced 341,209 tons of high-sulfur (3.5–4.5%) Croweburg and Mineral coals in 1993 (Fig. 2), a decrease of 6% compared to 1992, because Kansas power and cement plants consumed less. Indeed, Kansas ranked 24th of 27 states that produced coal in 1993. Cumulative coal production is 304.2 million tons through 1993. Electric power production in the Empire utility district is expected to increase, which may result in greater coal production in 1994.

In 1993, Kansas ranked 22nd of the 50 states in coal distribution, which totaled 17 million tons of coal shipped to power plants and other industries. Power plants, which produced 5.1 thousand megawatts per hour (MW/hr) (= 5.1 million kilowatts per hour), consumed most of the coal. The coal was shipped from both Kansas and out-of-state mines. About 15.9 million tons was subbituminous coal from Wyoming. Kansas has a total of 2.8 billion tons of strippable coal resources in beds <100 ft deep and ≥12 in. thick and a total of 53.5 billion tons of nonstrippable coal resources in beds ≥14 in. thick. Nevertheless, due to economics coupled with environmental constraints and regulations, most of the coal consumed in Kansas came from Wyoming.

A coal resources and coal-bed methane study of the Forest City basin has produced nine stratigraphic cross sections from 84 geophysical logs in northeastern Kansas.

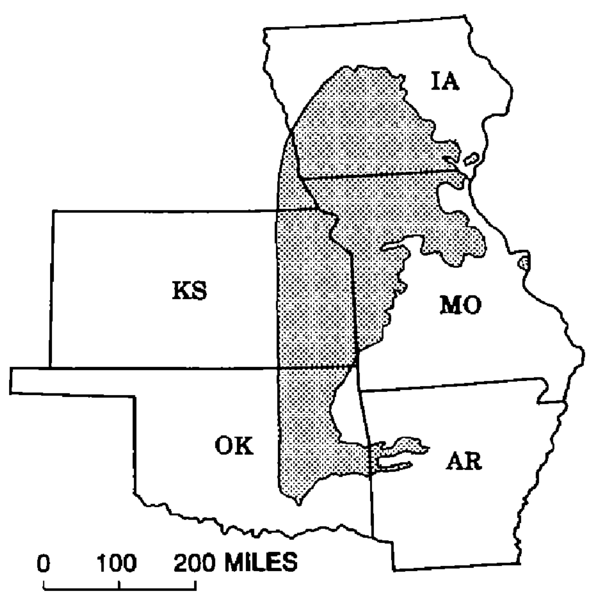


Figure 1. Map showing location of Western Interior Coal Basin.

[1]Oklahoma Geological Survey.

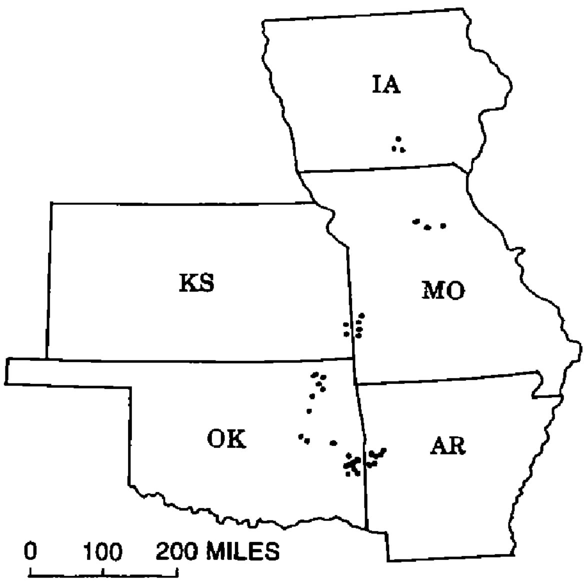


Figure 2. Map showing location of coal mines active in 1993 in the five states that participated in the 18th Annual Forum of Western Interior Coal Basin Coal Geologists.

Mary Howes, geologist with the Iowa Geological Survey Bureau, reported that in 1993 Iowa produced 170,000 tons of high-sulfur (3.5%) bituminous coal, a decrease of 41% from the 1992 total of 289,101 tons. (Howes expects production to decrease further in 1994.) Production was from three mines (Fig. 2), one of which closed mid-year. Production and shipping were affected by the great floods in 1993. Most of the coal was shipped to small power plants in Cedar Rapids, Ames, and Iowa City. Two of the plants contain small, fluidized-bed combustion cogeneration units. Iowa ranked 25th in U.S. coal production in 1993; cumulative coal production was 376.2 million tons through 1993.

In 1993, Iowa ranked 19th of the 50 states in coal distribution. A total of 18.3 million tons of coal was shipped from both Iowa and out-of-state mines to power plants and other industries in Iowa. Of the total, 14.8 million tons of subbituminous coal was shipped by rail from Wyoming's Powder River basin. Electric power plants, which produced 5.9 thousand MW/hr, consumed most of the coal. Although strippable coal resources in Iowa total 2.7 billion tons and non-strippable coal resources total 4.5 billion tons, most of the coal consumed in Iowa came from Wyoming in 1993 due to economics and environmental constraints and regulations.

Editing has been completed on the Iowa part of the National Coal Resources Data System (NCRDS) of the U.S. Geological Survey, and all corrections to the Geological Information Systems (GIS) coverage have been completed. These two computerized sets of data have proved to be valuable resources for developing resource-impact statements for proposed construction projects and for interpreting coal mine data for environmental consultants.

Joy Bostic, geologist with the Missouri Division of Geology and Land Survey, reported that in 1993 seven surface mines (Fig. 2), operated by four companies in five counties in Missouri, produced 622,235 tons of high-sulfur (3.1–7%) bituminous coal from five coal beds, a huge decrease of 78% from the 1992 total of 2,772,306 tons. The closing of Associated Electric's large Prairie Hill mine (which had produced 2.4 million tons in 1992) accounted for most of the decrease. The mine operators closed Prairie Hill when their main market, Thomas Hill Energy Center, switched to low-sulfur subbituminous coal from Wyoming because of economic factors and environmental regulations. Two new mines began production in 1993, but they did not affect total production significantly.

Most of Missouri's 1993 coal production was shipped to the state's power plants, which included one 20 MW/hr fluidized-bed combustion cogeneration unit. Some of Missouri's coal production was shipped to a cement plant and to a small power plant in Kansas. Although Missouri's cumulative coal production of 426,600,582 tons led the coal-forum states, its 1993 production ranked only 23rd (of 27) in the United States.

In 1993, Missouri had a total coal distribution of 20 million tons; it ranked 17th (of 50) in the U.S. and was first among coal-forum states. Of the total, 11.7 million tons was shipped by rail from Wyoming, 5.4 million tons was shipped from Illinois, and smaller quantities were shipped from Colorado, Indiana, Kansas, Kentucky, and Utah. Electric power plants, which produced 10.8 thousand MW/hr (more than in any other coal-forum state), consumed most of the coal.

Bill Bush reported that the same six Arkansas mines (Fig. 2) that produced 63,193 tons of low-volatile bituminous Hartshorne coal in 1992, produced 63,798 tons in 1993, an increase of 1%. Almost all this coal was from surface operations; 29 tons of coal was mined at a developing underground drift mine in 4.5 ft of the Lower Hartshorne coal. Most of the 1993 coal production was premium quality, low-sulfur (≤1%) coal, which was high in heating value (~14,000 Btu/lb), and it was shipped to plants in Arkansas, Missouri, and Texas for charcoal briquette manufacture. A few thousand tons of this coal was shipped to Oklahoma for electric power generation.

Arkansas ranked 26th (of 27) in coal production in the U.S. in 1993; its cumulative coal production through 1993 was 106,098,233 tons. The state's coal production may increase in 1994, if the new, small, underground drift mine operates successfully.

Although Arkansas has approximately 2 billion tons of identified, bituminous coal resources, unit trains delivered 10.6 million tons of low-sulfur (0.4%) subbituminous coal from Wyoming to electric power plants in Arkansas in 1993. In addition, at least 300,000 tons of bituminous coal was shipped from other states, primarily Oklahoma, for use in cement and other industrial plants in Arkansas. Arkansas ranked 29th of the 50 states in coal distributed to its markets in 1993. Most of this coal was consumed by power plants, which produced 3.8 thousand MW/hr.

Since 1979, under the Abandoned Mined Land reclamation program (funded by the U.S. Department of the Interior Office of Surface Mining and Reclamation), 1,458 acres of (surface) coal-mined land in Arkansas have been reclaimed for a total of $8,395,800, an average of $5,758 per acre.

Oklahoma Geological Survey (OGS) senior coal geologist Samuel A. Friedman reported that 16 surface mines and one underground slope coal mine (Fig. 2) produced 1,796,351 tons of bituminous coal in Oklahoma in 1993, an increase of 3% from 1992. These mines were operated by nine companies in eight counties in 10 coal beds, which had a total weighted average sulfur content of 2.7%, heating value of 13,187 Btu/lb, and bed thickness of 2.5 ft. These three coal characteristics in 1993 had increased from 1992. Oklahoma's cumulative coal production was 266,589,786 tons through 1993. Nevertheless, Oklahoma ranked only 21st of 27 coal-producing states in 1993. About 1 million tons of the 1993 state coal production was shipped by truck to a new fluidized-bed combustion non-public-utility cogeneration power plant (see cover photo and description, p. 178). The remainder was shipped to a rubber-tire factory, two cement kilns, a recycled-paper plant, and a major automobile-assembly plant, all located in the state, and to a cement plant in Arkansas. Friedman expects Oklahoma coal production to increase slightly in 1994 and to remain close to 2 million tons annually into the 21st century.

Although Oklahoma has about 8 billion tons of identified coal resources with weighted sulfur content averaging only 2.3%, 16.4 million tons of low-sulfur (0.4%) subbituminous coal was shipped by unit train from the Powder River basin of Wyoming to five public utility plants. Ten large (475–515 MW/hr) electric generators at the plants produced 4.9 thousand MW/hr in Oklahoma in 1993. Oklahoma ranked 19th of the 50 states in total coal distribution in 1993, and it was second only to Texas in coal received from Wyoming.

In Oklahoma, as in the other coal-forum states, public utilities have chosen to use readily available, inexpensive, low-sulfur Wyoming coal in order to comply with Phase I of the federal Clean Air Act Amendments of 1990. (Phase II takes effect January 1, 1995.) The coal-forum member states received a total of 69.4 million tons of Wyoming coal in 1993, as reported by the U.S. Department of Energy, Energy Information Administration. The coal-forum states produced only 3 million tons of coal in 1993, as reported by state agencies.

Friedman continued to gather reliable, company-drilled coal-test well data, which was used to locate an additional 1.5 million tons of strippable coal resources in the Cavanal coals in the Savanna Formation in Cavanal Mountain, Le Flore County, and in the Sans Bois Mountains, Haskell County. Company geophysical logs obtained from coal-bed methane exploration suggest that additional coal-bed methane and coal resources are present in the Rowe, Drywood, Bluejacket, Croweburg, and Iron Post coals in Nowata County. These coal beds were interpreted to be 1–3 ft thick and 1,000–1,450 ft deep.

LeRoy A. Hemish, OGS coal geologist, reported that four coal beds contain 496 million tons of identified remaining coal resources in Okmulgee and Okfuskee Counties; these beds will be the subjects of a coal report in the OGS Special Publication (SP) series. Hemish also reported that, in another manuscript for an SP on Muskogee County, he has mapped 10 coal beds that show 95.6 million tons of identified, remaining coal resources, the majority of which are in the Stigler coal bed.

Brian J. Cardott, organic petrologist, OGS, reported on nomenclatorial revisions of terms used in the maceral group vitrinite as proposed by the International Committee for Coal and Organic Petrology. He also distributed copies of an abstract of a talk, "The Modern Maceral Analysis: One Size Fits All," that he presented at the 1994 Annual Meeting of The Society for Organic Petrology. In it,

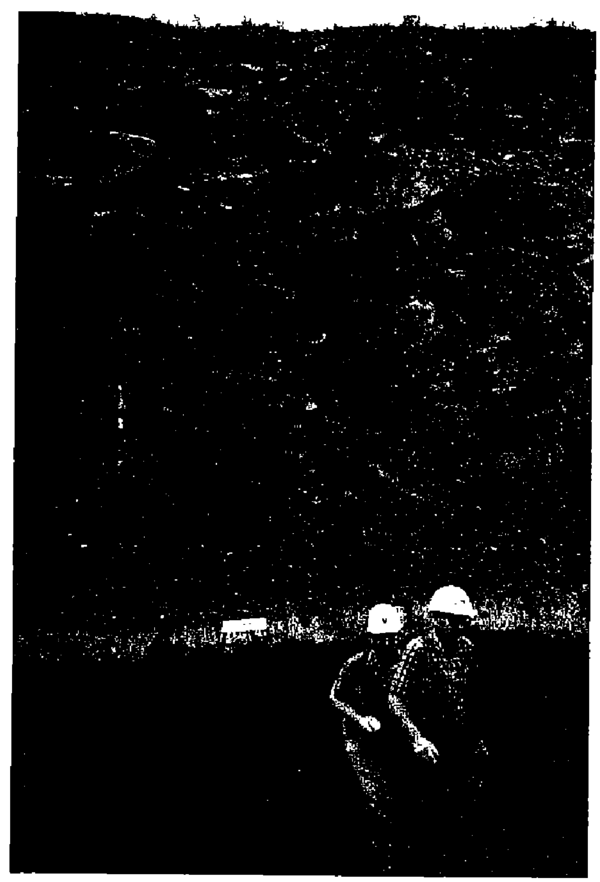


Figure 3. Geologists Bill Prior (left) (Arkansas Geological Commission) and LeRoy Hemish (OGS) leaving one of three entrances to developing underground drift mine in Lower Hartshorne coal, near Hartford, Arkansas.

he concluded that "a complete maceral analysis, attempting to meet any purpose, should include terminology for partially inert (pseudovitrinite) and partially reactive (semi-inertodetrinite, semimacrinite) macerals."

The second morning of the coal forum, the participants traveled to Hartford, Arkansas, to observe the developing, underground drift mine of Mid America Mining, Inc. Three high-wall entries were driven into the 46-in. thick, low-sulfur Lower Hartshorne coal, which is overlain by buff, medium-bedded, fine-grained sandstone that is ~40 ft thick (Fig. 3). The coal contracts called for coal to be delivered to power plants at $29/ton and to charcoal plants at $36/ton.

The participants of the 18th Forum of the Western Interior Coal Basin accepted Larry Brady's invitation to meet in Kansas in the spring of 1995.

OKLAHOMA CITY GEOLOGICAL SOCIETY ELECTS NEW OFFICERS

Officers of the Oklahoma City Geological Society for the 1994–95 term are:

President: ROBERT A. NORTHCUTT, Consulting Petroleum Geologist
President Elect: LEONARD C. DIONISIO, JR., Capitol Exploration, Inc.
Past President: DAVID G. BRYANT, Bryant & Associates
Vice President: STEVEN J. BOONE, Coastal Oils, Inc.
Treasurer: LINDELL C. BRIDGES, Bogo Energy Corp.
Secretary: MARK A. THOMAS, Consulting Geologist
Library Director: M. STUART KIRK, Triumph Investments
Shale Shaker Editor: WILLIAM E. JACKSON, Consulting Geologist
1st Presidential Appointee: STEPHEN C. BURNS, Jolen Production Co.
2nd Presidential Appointee: LANCE RUFFEL, Ruffel Oil and Gas Corp.
AAPG House of Delegates Chairman: CARROLL L. KINNEY, Mewbourne Oil Co.
AAPG Midcontinent Section Representative: KATHY LIPPERT, Southwestern Energy

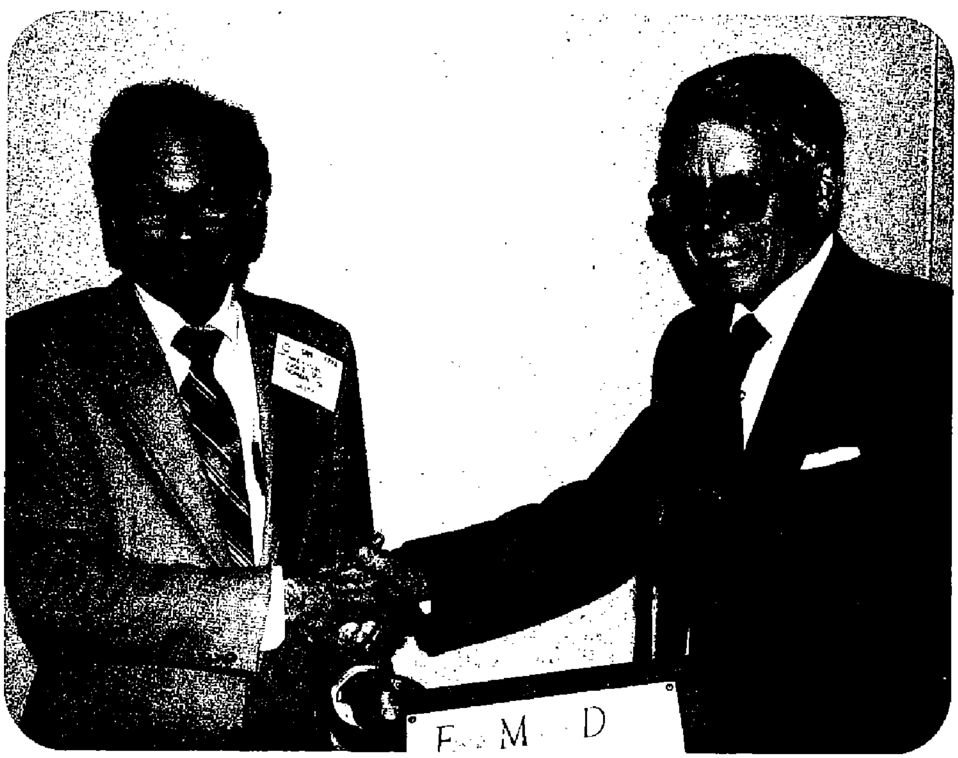
Friedman Receives EMD Founders Award

Samuel A. Friedman, senior coal geologist at the Oklahoma Geological Survey, has been honored by the AAPG Energy Minerals Division (EMD) for "significant and extended contributions leading to the founding of the AAPG Energy Minerals Division and for constant continuing service to EMD."

Friedman was presented the Distinguished Founders Award by EMD President John W. Gabelman on June 14, 1994, at the AAPG Annual Convention in Denver, Colorado.

Friedman was active on the AAPG Committee on Energy Minerals (1974–77), before EMD became a division, and was a founding member of EMD in 1977. He served as EMD vice-president (1980–81), vice-president/president-elect (1989–90), president (1990–91), and was the first EMD councillor for programs (1978). Friedman was EMD program chairman at the 1978 AAPG/EMD convention in Oklahoma City, and from 1980 to 1989 he served EMD as chairman of the committee on conventions and as delegate to the AAPG Committee on Conventions. He has served EMD on the best paper award committee, judged papers, and chaired sessions at many annual meetings. Other committees Friedman has chaired are: Nominating Committee (1991–92), Coal Committee (1993–95), Liaison Committee (1993–95), and Honors and Awards Committee (1992–93). He has also edited the EMD newsletter, "The Energy Minerals Geologist."

The purpose of the EMD is to advance the science of geology as it relates to any earth materials, other than conventional oil and gas (namely coal, coal-bed methane, uranium, oil shale, tar sands, and geothermal fluids), capable of being used for energy production.



Presentation of the Distinguished Founders Award plaque to Samuel A. Friedman (left) by EMD President John W. Gabelman.

Notes ON NEW PUBLICATIONS

Oil and Gas Fields of Oklahoma, Volume 2

The Oklahoma City Geological Society has released this 181-page publication, edited by Suzanne Takken and Edwin P. Kerr, containing descriptions, geological interpretations, reservoir data, production data, type log, and a geological map of 31 oil and gas fields in Oklahoma. Ringwood, Cheyenne Valley, Kinta, and Cottonwood Creek fields are included, as well as numerous other old and new fields in Oklahoma.

Order from: Oklahoma City Geological Society, 227 West Park Ave., Oklahoma City, OK 73102; phone (405) 235-3648. The price is $43, including postage. Oklahoma residents add $3.34 tax ($46.34).

The Future of Energy Gases

In this 890-page professional paper edited by D. G. Howell, the future of energy gases—natural gas and hydrogen—is explored in 57 individually authored papers. This compilation of papers is an outgrowth of a USGS-sponsored conference on the future of energy gases that was held in Palo Alto, California, October 1992. Topics addressed include: the origins and habitats of natural gas, including habitats such as deep gas and gas hydrates with potentially vast amounts of natural gas; resource estimates of natural gas; environmental and technological concerns of natural gas drilling and production; analysis of economics, environmental impact, and technology for use of hydrogen gas; economics and modeling of natural gas consumption; experiences and insights of explorationists on natural gas; and the role of gaseous fuels in the energy mix of the future.

Order P 1570 from: U.S. Geological Survey, ESIC, Open-File Report Section, Box 25286, MS 517, Federal Center, Denver, CO 80225; phone (303) 236-7476. The price is $59 for a paper copy; add 25% to the price for foreign shipment.

Petroleum Exploration Plays and Resource Estimates, 1989, Onshore United States; Region 7, Mid-Continent

Edited by R. B. Powers, this 97-page USGS open-file report contains petroleum exploration plays and resource estimates for 12 Mid-Continent provinces.

Order OF 94-0024 from: U.S. Geological Survey, ESIC, Open-File Report Section, Box 25286, MS 517, Federal Center, Denver, CO 80225; phone (303) 236-7476. The price is $4 for microfiche and $15.25 for a paper copy; add 25% to the price for foreign shipment.

Plays for Assessment in Region VII, Mid-Continent, as of October 4, 1993; 1995 National Assessment of Oil and Gas

Compiled by D. L. Gautier and K. L. Varnes, this 17-page USGS open-file report contains plays of assessment in Region VII, Mid-Continent, as of October 4, 1993.

Order OF 93-0596-G from: U.S. Geological Survey, ESIC, Open-File Report Section, Box 25286, MS 517, Federal Center, Denver, CO 80225; phone (303) 236-7476. The price is $4 for microfiche and $2.75 for a paper copy; add 25% to the price for foreign shipment.

Oklahoma Rock Clubs

Ada Hardrock & Fossil Club
P.O. Box 1202
Ada, Oklahoma 74820
(405) 436-5444
President: Kevin Rumery
Meets 3rd Monday
Ada Public Library

Enid Gem & Mineral Society
2614 West Oklahoma
Enid, Oklahoma 73703
(405) 234-5827
President: Stan Nowak
Meets 1st Thursday
Hoover Building
Garfield County Fairgrounds

McCurtain County Gem & Mineral Club
P.O. Box 481
Idabel, Oklahoma 74745
(405) 286-3133
President: Doris Perkins
Meets 3rd Tuesday
Idabel Public Library

Mount Scott Gem & Mineral Society
P.O. Box 481
Apache, Oklahoma 74006
(405) 588-3870
President: Dorothy Dowling
Meets 3rd Wednesday
Lawton Town Hall
5th and B Avenue

NW Arkansas Gem & Mineral Society
Route 1, Box 288A
Colcord, Oklahoma 74338
(918) 422-5867
President: Larry McGarrah
Meets 4th Tuesday
Highway 43
Siloam Springs, Arkansas

Oklahoma Mineral & Gem Society
P.O. Box 25632
Oklahoma City, Oklahoma 73125
(405) 677-7698
President: Jack Haynes
Meets 3rd Thursday
Will Rogers Garden Center
3400 N.W. 36th

Osage Hills Gem & Mineral Society
P.O. Box 561
Bartlesville, Oklahoma 74005
(918) 333-3165
President: Jeff Freeman
Meets 3rd Thursday
First Presbyterian Church
5th and Dewey

Shawnee Gem & Mineral Club
10 Donna Lane
Shawnee, Oklahoma 74801
(405) 273-0094
President: Nancy Hicks
Meets 1st Tuesday
Northridge Church of Christ
1001 E. MacArthur

Stillwater Mineral & Gem Society
Route 2, Box 23B
Tryon, Oklahoma 74875
(405) 624-3448
President: Charles Reming
Meets 4th Thursday
United Methodist Church
7th and Duck

Tulsa Rock & Mineral Society
P.O. Box 2292
Tulsa, Oklahoma 74101
(918) 241-1455
President: Leon Reeder
Meets 2nd Monday
Aaronson Auditorium
Tulsa Downtown Library

Western Oklahoma Gem, Rock, & Mineral Society
817 Standifer
Elk City, Oklahoma 73644
(405) 225-3223
President: Bob Harness
Meets 2nd Tuesday
Berlin Community Building

Source: *The Lapidary Journal*, April 1994.
(We advise calling in advance to verify meeting times.)

Guide to Oklahoma Earth-Science Information Planned

We Welcome *YOUR* Suggestions

Geology has played a key role in the development of Oklahoma's economy, and many of the State's major attractions contain features of geological interest. Yet no single publication exists that shows the general public how best to discover and explore this aspect of the State.

The Oklahoma Geological Survey is planning to produce a guide to resources for earth-science information in Oklahoma for everyone interested in the nontechnical aspects of Oklahoma geology, for example:

- ***Earth-science teachers***
- ***Earth-science students***
- ***Visitors and tourists to Oklahoma***
- ***Amateur rockhounds and collectors***
- ***Local gem and mineral societies***
- ***Scout and Camp Fire leaders***

The publication will consist of a number of annotated lists, for example:

- ***Museums with an earth-science component***
- ***Gem and mineral societies and clubs***
- ***Professional geological organizations***
- ***Fee (private) and non-fee collecting areas***
- ***Rock shops***
- ***References on mineral and fossil collecting in Oklahoma***
- ***Popular (nontechnical) field trips in Oklahoma***
- ***Suppliers (businesses) of earth-science materials***
- ***Sources of maps (all kinds)***
- ***Major mining and quarrying companies and oil and gas companies in Oklahoma***
- ***Sources of information on soils and water***
- ***Nontechnical books on different aspects of Oklahoma geology***

As a reader of *Oklahoma Geology Notes*, you obviously are interested in various aspects of Oklahoma geology. Please consider these questions:

1) Who else, beyond those listed above, would find this book helpful?
2) What other resource information could be listed in the book?

Please send your suggestions to:

Neil Suneson
Oklahoma Geological Survey
100 East Boyd, Room N-131
Norman, OK 73019
FAX: (405) 325-7069

Call for Papers

AIPG AND OGS JOINT CONFERENCE

"The Profession of Geology"

The American Institute of Professional Geologists, Oklahoma Section, and the Oklahoma Geological Survey are hosting a joint conference on "The Profession of Geology—Geology as a Critical Vocation in Service to Society," to be held April 21–23, 1995, at the Sarkeys Energy Center, University of Oklahoma, Norman.

Proposed session topics include:

- Petroleum geology (exploration and development) and geophysics
- Hydrology/contaminant hydrogeology and environmental geology/geologic hazards
- Economic geology (nonmetallic and metallic)
- Potpourri (engineering geology, forensic geology, etc.)

Individuals interested in presenting a paper must submit an abstract by *January 15, 1995*, to:

Skip Honeyman
Davis Bros., L.L.C.
One Williams Center, Suite 2000
Tulsa, OK 74172

Final papers must be submitted by February 15, 1995, for inclusion in the proceedings volume. For further information, contact Michelle Summers, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031, fax 405-325-7069.

Oklahoma Geological Survey Colloquium Schedule

The colloquium program is designed to disseminate and exchange information about OGS and Geological Information Systems (GIS) programs and activities to other staff members, University of Oklahoma faculty and students, and to the public. The colloquia are held at 3:00 p.m. in the Sarkeys Energy Center, 100 E. Boyd, Room P-130, Norman, Oklahoma.

December 12, 1994 (Monday) — "Secondary-Gas-Recovery Project, Tonkawa Sand, Beaver County, Oklahoma," by Tom L. Bingham.

January 9, 1995 (Monday) — "Oceanographic Investigations (Biological, Chemical, Geological, Physical) at Sea—Nearshore to Offshore," by James R. Chaplin.

February 13, 1995 (Monday) — "Geology of the Magnetic North Pole Region, Canada," by Robert O. Fay.

UPCOMING *Meetings*

Petro-Safe Meeting and Exhibit, January 31–February 2, 1995, Houston, Texas. Information: Petro-Safe, 3050 Post Oak Blvd., Suite 205, Houston, TX 77056; (713) 621-8833, fax 713-963-6284.

3rd SIAM Conference, "Mathematical and Computational Issues in the Geosciences," February 8–11, 1995, San Antonio, Texas. Information: SIAM Conference Coordinator, 3600 University City Science Center, Philadelphia, PA 19104; (215) 382-9800, fax 215-386-7999.

6th UNITAR Conference, "Fueling for a Clean and Safe Environment," February 12–17, 1995, Houston, Texas. Information: Thomas Reid, DOE Bartlesville Project Office; (918) 337-4233.

USGS McKelvey Forum: "Energy and the Environment," February 13–16, 1995, Washington, D.C. Information: Dudley D. Rice, U.S. Geological Survey, MS 971, Box 25046, Denver, CO 80225; (303) 236-5711, fax 303-236-8822.

Mixed Wastes and Environmental Restoration Meeting (sponsored by University of Arizona), February 26–March 2, 1995, Tucson, Arizona. Information: WM Symposia, 245 S. Plumer, Suite 19, Tucson, AZ 85719; (602) 624-8573, fax 602-792-3993.

American Association of Petroleum Geologists, Annual Meeting, March 5–8, 1995, Houston, Texas. Information: Convention Dept., AAPG, Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

Society for Mining, Metallurgy, and Exploration, Annual Meeting, March 6–9, 1995, Denver, Colorado. Information: Meetings Dept., SME, P.O. Box 625002, Littleton, CO 80162; (303) 973-9550, fax 303-979-3461.

Lunar and Planetary Science Meeting, March 13–17, 1995, Houston, Texas. Information: LeBecca Simmons, Lunar and Planetary Institute, Publications and Program Services, 3600 Bay Area Blvd., Houston, TX 77058; (713) 486-2158.

The Ames Structure and Similar Features, Workshop, March 28–29, 1995, Norman, Oklahoma. Information: Kenneth S. Johnson, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031; fax 405-325-7069.

Sinkholes and the Engineering and Environmental Impacts of Karst, 5th Multidisciplinary Conference, April 2–5, 1995, Gatlinburg, Tennessee. Information: Barry Beck, P.E. LaMoreaux & Associates, Box 4412, Oak Ridge, TN 37831; (615) 483-7483.

Geological Society of America, South-Central/North-Central Sections, Joint Annual Meeting, April 27–28, 1995, Lincoln, Nebraska. *Abstracts due January 6, 1995.* Submit completed abstracts to: David Loope, 332 Bessey Hall, University of Nebraska, Lincoln, NE 68588; (402) 472-2647. Information: Robert F. Diffendal, Conservation and Survey Division, 133 Nebraska Hall, University of Nebraska, 901 N. 17th St., Lincoln, NE 68588; (402) 472-7546.

American Association of Petroleum Geologists, International Meeting, September 10–13, 1995, Nice, France. *Abstracts due November 15, 1994.* Information: Convention Dept., AAPG, Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

The Oklahoma Geological Survey thanks the American Association of Petroleum Geologists, the Geological Society of America, and the authors for permission to reprint the following abstracts of interest to Oklahoma geologists.

Lithologic and Stratigraphic Evidence for the Impact Origin of a Buried Ordovician Age Crater and Reservoir Near Ames, Major County, Oklahoma

KEVIN E. NICK, Target Reservoir Analysis, 6901 N. Robinson, Oklahoma City, OK 73116

An anomalous circular depression present in the subsurface beneath the town of Ames, Major County, Oklahoma is the site of oil and gas production from around 9,000 feet. Characteristics of the Ames crater correspond to criteria that identify meteor impact sites. The gross shape and details of the geomorphology of the crater are consistent with an impact origin. Details of the textures, mineralogies and stratigraphic relations of lithologies samples by cuttings, drilled sidewall cores, and conventional cores also provide a weight of evidence supporting an impact origin. Six major lithologies are encountered inside the crater. Wells near the center of the crater are completed in uplifted, brecciated granite. Other wells are completed in fractured and karsted Arbuckle dolomite, distal to the crater center. Mixed granite-dolomite breccias and conglomerates are encountered between pure granite and dolomite units. In these breccias granite abundance decreases and dolomite content increases with depth and dolomite clasts are highly fractured. An altered tuff-like melt unit dominated by vesicular textures with microtektite shaped, siliceous grains is locally present above the Arbuckle material but is not continuous within the crater. Most of the crater is filled with a thin unit of water transported, dense, very poorly sorted arenite. The detrital grains in the arenite are dolomite, quartz, feldspar, accretionary peloids, and clay. Many quartz grains in this unit contain multiple sets of shock lamellae. Dark fossiliferous shales fill the remainder of the crater. Brecciated reservoir facies are overlain by directly emplaced and reworked air fall material.

Reprinted as published in the American Association of Petroleum Geologists, *1994 Annual Convention Official Program*, p. 224.

Reservoir Characterization of a Complex Impact Crater: "Ames Crater," Northern Shelf, Anadarko Basin

M. D. KUYKENDALL, Solid Rock Resources, Inc., Tulsa, OK; *C. L. JOHNSON*, Petra Technologies, Tulsa, OK; and *R. A. CARLSON*, DLB Oil and Gas, Inc., Oklahoma City, OK

The concentric structural feature known as the "Ames Hole," or "Ames Crater," on the northern shelf of the Anadarko basin contains several heterogeneous and uniquely associated hydrocarbon reservoirs within extensively brecciated, fractured, and faulted Cambrian–Ordovician Arbuckle Group dolomites, Precambrian granites, and pseudo-

pyroclastic (impact melt) rocks. Critical diagnostic structural features and petrographic evidence from cores and cuffings strongly support an impact origin of the structure. Numerous trapping mechanisms exist in and around the crater, which is estimated to contain ultimate reserves of 50 million bbl of oil and 20 bcf of gas.

A detailed reservoir characterization study was conducted in the Ames Crater, which included subsurface data from all available wells (65 as of June 1993), including three horizontal wells. Petrophysical evaluation included digital log analysis and petrographic and standard core analyses of whole cores, rotary sidewall core plugs, and cuttings. Correlation and calibration of log-rock characteristics of distinct reservoir lithofacies from key wells provided the basis for field-wide inferences about rock and pore type, permeability, fluid saturations and contacts, and related production characteristics.

The crater is 8–10 mi in diameter and buried at 8,500–9,500 ft. Morphologically distinct areas, based on analogy with well-documented complex-type impact craters, include a central rebound feature composed of a concentric peak-ring horst and graben structure and associated collapse zone, a steep crater wall, and an uplifted inner rim and hummocky outer rim. Reservoir porosities and permeabilities are quite variable, but can be exceptional, as shown by the tremendous production and reserve potential of some wells. For example, individual granite breccia wells may contain up to 285 ft of net pay and estimated primary oil reserves of 10 million bbl. Geochemical data suggest that the principle source rock is contained in the lower portions of the organic-rich black shales of the overlying (crater-filling) Middle Ordovician Oil Creek Formation.

The Ames Crater contains unique structural features and complex heterolithic reservoirs. Future development and exploration success must be based on a thorough understanding of the genesis, distribution, and petrophysical properties of the various reservoir lithofacies. The Ames Crater may prove to be the most extensively explored and hydrocarbon-productive impact crater in the world, as well as a future exploration and development analog for similar impact structures.

Reprinted as published in the American Association of Petroleum Geologists, *1994 Annual Convention Official Program*, p. 191.

Source Rock Potential of Impact Craters

JOHN R. CASTAÑO, DGSI, the Woodlands, TX; *JAMES H. CLEMENT*, Consultant, Houston, TX; *MICHAEL D. KUYKENDALL*, MASERA Corp., Tulsa, OK; and *VIRGIL L. SHARPTON*, Lunar and Planetary Institute, Houston, TX

A number of impact craters have associated hydrocarbon production; for example, Red Wing and Newporte fields in North Dakota, and the Ames structure in Oklahoma. Our thesis is that a meteorite impact can create a closed basin which is favorable for the deposition of hydrocarbon source rocks. The Bosumtwi crater in Ghana is a modern analogue; the crater encloses a deep lake which contains organic-rich sediments and abundant methane seeps.

We interpret the structure at the Newporte field in North Dakota as an astrobleme; production is obtained from the Cambrian Deadwood Sandstone and brecciated, weathered granite. The locally developed lower Winnipeg Shale (Ordovician) has been identified as the source rock. Compared with Red River (Ordovician) oils, Newporte oils have a much higher isoparaffin content; they have a higher C_{20+} content; they are waxy (65–90°F pour point); and they lack the marked odd predominance typical of the Red River. Red River source rocks are dominated by alginite while the Winnipeg contains only amorphous kerogen.

The Ames structure produces from brecciated granite and brecciated and fractured Arbuckle dolomite (Ordovician). The Oil Creek Shale (Ordovician) provides the seal. The lower part of the Oil Creek is the likely source of the oil; this facies is 8 to 225 feet thick and is restricted to the crater. Curiously, the oil is similar to Newporte oils with a high wax content and relatively high isoprenoid contribution; the source rocks are also comparable.

The development of thick source rock units in impact craters, particularly where source rocks would not be present otherwise, enhances the exploration prospects for these features.

Reprinted as published in the American Association of Petroleum Geologists, *1994 Annual Convention Official Program*, p. 118.

Petroleum Exploration Strategies for Impact Features

RICHARD R. DONOFRIO, AGR Inc., Rowayton, CT

After you stumble upon an impact crater or succeed in finding one the old-fashioned way (by looking for it), where do you drill? The initial exploration wells into Viewfield, Red Wing Creek, Newporte, and the Ames Hole were not based on the astrobleme model. Red Wing Creek, later proven to have major oil reserves, was abandoned by an operator after two unsuccessful wells. Had a key Ames Hole well been drilled just half a section south, the ensuing dry hole could have discouraged further exploration efforts into brecciated granite, which in this feature has the potential for over 50 million barrels of reserves. Drilling strategies are in their infancy because of the limited number of wells into suspected astroblemes. But what have we learned so far about drilling these esoteric features?

While astroblemes share certain morphological similarities, the differences can have a profound effect on hydrocarbon migration and accumulation. Unlike other classical reservoirs, astroblemes are unique dynamic basins affecting the thermal and depositional regimes of the target rock. They afford an opportunity for exploration into what is truly the final frontier, crystalline basement rock. It is here where drilling strategies will prove their ultimate worth and where the giant fields of the future will be discovered.

Reprinted as published in the American Association of Petroleum Geologists, *1994 Annual Convention Official Program*, p. 138.

Carter-Knox Anticline: An Example of Inversion Tectonics and Fault-Propagation Folding along the Ancestral Margin of the Oklahoma Aulacogen, Anadarko Basin

WENDOLYN SUMNER, DANIEL L. HANSEN, and *JAMES B. CEARLEY*,
Chevron USA Production Co., Inc., P.O. Box 36366, Houston, TX 77236

The Carter-Knox field, located in the southeastern portion of the Anadarko basin, has a complex growth history controlled by early positioning of the structure along the northeastern edge of the Oklahoma Aulacogen. Later contractional deformation at Carter-Knox was focused along an early basin bounding normal fault resulting in structural inversion during the post-Wichita orogeny in the late Pennsylvanian. The early growth history, from the Cambrian to the Mississippian, was characterized by basin subsidence and stratigraphic growth across the Knox basement flexure. By Morrow time, a monoclinal flexure developed and significant stratigraphic growth occurred west of the Knox flexure. Reactivation and inversion of the Knox normal fault began post-Deese and all later contractional deformation is focused along this hinge line. The major faulting and folding of the Knox anticline occurred post-Hoxbar with the development of a fault propagation fold. With continued contraction, Pennsylvanian sediments were detached from the lower-Paleozoic sediments, resulting in the translation of the shallower fold crest to the northeast resulting in over 8,000 ft of vertical separation in the Springer section. Inversion along a paleo rift zone has resulted in a world class structural trap that may serve as an exploration analog for inverted rift basins.

Reprinted, with author modifications, from the American Association of Petroleum Geologists, *1994 Annual Convention Official Program*, p. 267.

Long Distance Migration and the Morrow Formation of Southeast Colorado

PAUL H. WIEMANN, West Bay Production Co., Denver, CO; *JON S. NELSON*, Colorado School of Mines, Golden, CO; and *DANIEL L. PEARSON*, Phillips Petroleum Co., Bartlesville, OK

Hydrocarbon migration out of the Denver and Anadarko basins to the Pennsylvanian Morrow Formation of the Las Animas Arch has been accepted prima facie because the Morrow has yet to be an accepted source rock. Problematically, neither basin meets all three requirements for long distance migration (gradient, migration pathway and source rock). Suggested migration along Morrow fluvial channel systems, requires migration up a dip of less than 0.67° prior to the formation of faults, fractures, and permeability barriers which would result in trapping or loss from the pathways.

While the Anadarko has source rocks for hydrocarbon generation, structural deformation occurred in both basins during and after the deposition of the Morrow and prior to hydrocarbon generation. Migration of oil out of the Denver Basin, into the Morrow, would require either generation from continental orogenic sediments (Fountain Formation) or migration from the Cretaceous units. The Cretaceous units are the only source rocks richer than the Morrow. Migration from the Cretaceous would require crossing 2,300 stratigraphic feet of continental and evaporite sediments and the downward penetration of the Morrow cap rock.

The absence of a gradient, migration pathway, and in the case of the Denver basin, accessible source rocks, renders long distant migration implausible. Reexamination of published source rock data and previously unpublished Phillips Petroleum Company data, shows the Morrow to be thermally mature, with sufficient total organic carbon to be the hydrocarbon source for the Morrow in southeast Colorado.

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Distribution and Character of Known Deep Natural Gas Resources Based on Data from Large Fields and Reservoirs

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Known deep natural gas accumulations occur in many U.S. basins in widely different geologic settings. Three-hundred seventy-seven significant oil and gas reservoirs (reservoirs having known recoverable production of at least 6 Bcf of gas or 1 MMB of oil) produce from depths greater than 14,000 ft, and 256 reservoirs produce from depths below 15,000 ft out of more than 15,000 significant reservoirs in the U.S. according to NRG Associates (1990). Nearly 75 percent of all reservoirs below 14,000 ft produce natural gas and occur in the Gulf Coast, Permian, Anadarko, Williston, San Joaquin, Ventura, Rocky Mountains, and Cook Inlet basins.

Thirteen states contain all of the deep significant oil and gas reservoirs below 14,000 ft in the U.S. Texas has the largest number (121), which are in the Anadarko, Permian, and Gulf Coast basins. The 1970s was the most prolific decade for deep discoveries in the U.S. The Gulf Coast basin led the U.S. with 72 new deep significant oil and gas fields during the decade. Most fields containing deep significant reservoirs (203 of 329 below 14,000 ft) are classified as gas producers (62 percent) although data are incomplete for the Anadarko basin. An additional 25 reservoirs are classified as oil and gas producers. Gas and oil and gas reservoirs outnumber oil reservoirs in all states except Alabama, Florida, and California.

Sixty-seven percent of all significant reservoirs below 14,000 ft (253 of 377) are classified as having structural or combination traps. Stratigraphic traps outnumber structural traps only in the Anadarko and California basins. Sixty percent of all deep significant reservoirs below 14,000 ft (227 or 377) produce from clastic rocks. Clastic reservoir rocks are most abundant in Rocky Mountain basins, and in the Anadarko, Gulf Coast, California, and Alaska basins whereas carbonate reservoirs are most abundant in the Permian and Williston basins. The number of reservoirs decreases with increasing depth, but 26 percent of the total significant reservoirs occur below 17,000 ft.

Of the total cumulative natural gas production in the U.S. (698 Tcf; U.S. Geological Survey), reservoirs deeper than 15,000 ft account for 7 percent (50 Tcf) of the total, and deep significant reservoirs (NRG reservoirs) account for nearly half (22.4 Tcf) of the deep reservoir total. More than half of the gas from deep significant reservoirs (12.4 Tcf) was produced from the Permian basin. Significant reservoirs below 14,000 ft have a known recoverable production of 36.4 Tcf of gas. Although the Gulf Coast basin has only produced 6.2 Tcf of gas from these reservoirs, an additional 6.6 Tcf of gas exists as proven reserves. In the entire U.S., deep natural gas reservoirs account for only a small, but important, portion of the total natural gas production.

Of the total U.S. natural gas resources (nearly 1,300 Tcf), 519 Tcf is considered unconventional including coalbed methane, gas in low-permeability shale and sandstone reservoirs, and deep-basin gas accumulations. The need for new geologic research dealing with all aspects of natural gas exploration and production is obvious.

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Sequence Stratigraphy of the Upper Pennsylvanian Cleveland Formation: A Major Tight-Gas Sandstone, Western Anadarko Basin, Texas Panhandle

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The upper Pennsylvanian (lower Missourian) Cleveland formation has yielded 459 bcf of natural gas and 18.6 million bbl of oil from low-permeability (<0.10 md) fluvial and deltaic reservoirs in a seven-county tight-gas area of the northeastern Texas panhandle. Regional study of the Cleveland and underlying Desmoinesian Marmaton Group siliciclastics using tight well control and cores established the sequence-stratigraphic framework to clarify the vertical and areal occurrence of Cleveland reservoirs, seals, and possible source rocks.

Regionally distinctive facies stacking patterns in the study interval compose a sequence-stratigraphic framework of several westerly sourced systems tracts and three depositional sequences (S). S1 is characterized by landward-and seaward-stepping deltaic and strand plain cycles (parasequences) deposited on the top-of-Oswego type 1 sequence boundary that define (in ascending order) Marmaton late-stage lowstand-wedge (LST:pw) and transgressive systems tracts (TST) and a lower Cleveland highstand systems tract (HST). A regionally correlative, organic-rich marine-condensed section at the top of the Marmaton TST, equivalent to the Nuyaka Creek black shale bed of mid-continent cyclothems, represents maximum flooding conditions during eustatic rise. A relative sea level drop with the onset of S2 deposition initiated development of a lowstand incised-valley system (LST:iv) in the middle to upper Cleveland that extended basinward of the lower Cleveland depositional shelf edge. Subsequent coastal onlap by thin deltaic systems of the overlying TST marks the start of decreased sediment influx during late Cleveland time, resulting in thinning of parasequences and an increase in carbonate beds of high-frequency cycles in upper S2 and S3.

Stratigraphic traps and pinch-out of reservoir facies within small, southeast-plunging anticlines make up most traps in the producing area. Proximal delta-front and fluvial sandstones of the Cleveland upper HST and overlying LST:iv, respectively, are the primary reservoirs. The high-total-organic-carbon, top-of-Marmaton marine-condensed section and thick prodeltaic and lower distal delta-front shales within the lower Cleveland HST are the probable source rocks. Distal deltaic shales of the middle Cleveland TST form most reservoir seals. Potential new reservoirs should be targeted at the updip terminations of systems tracts, at lap-out positions of individual sand-rich HST and TST parasequences, and along LST:iv valley-margin stratal terminations.

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Petroleum Geology of the Woodford Formation, Anadarko Basin, Oklahoma and Texas

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The Upper Devonian Woodford Formation is an important source rock in the Anadarko Basin. The formation is cherty black shale with organic carbon ranging up to 20% locally. The Woodford Formation is directly correlative with the Bakken Formation of the Williston Basin, and the Devonian Shales of the Appalachian Basin, in part.

A vitrinite reflectance map of the Woodford illustrates thermal maturity patterns throughout the Anadarko Basin. Comparison of the map with a basin-wide map of electrical resistivity suggests that it is possible to map areas of elevated Woodford hydrocarbon saturation using well logs.

Cross-plotting average Woodford interval transit time from sonic logs versus depth suggests pore-fluid overpressuring in the Woodford below certain depths. Areas where such elevated pressure gradients occur are partially correlative with the mapped areas of elevated Woodford resistivity. This may represent a relationship between overpressuring and hydrocarbon generation.

Calculation of Poisson's ratio was performed using interval velocities of compressional and shear waves in the Woodford Formation. This allowed the estimation of the natural "frack gradient" for the Woodford.

With this information, a trend was mapped in which the Woodford Formation may be in a naturally fractured state by virtue of elevated pore-pressure due to hydrocarbon generation. As such, this trend may represent a new fractured gas and condensate play fairway.

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A Geochemical Study of Potential Source Rocks and Crude Oils in the Anadarko Basin, Oklahoma

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Source rocks and crude oils from several non-Woodford Paleozoic formations in the Anadarko Basin, Oklahoma have been characterized by organic geochemical techniques. Since the Woodford Shale is an important source rock in the basin and has been investigated intensively in previous studies, the Woodford shale and associated oils was also characterized and used as a reference formation to compare with other formations and oils examined in this study.

Based on the results of screening analyses and geological information, a new source rock evaluation model (in forms of PGI maps) has been built to evaluate five formations. Besides the Woodford (which is proved by the model to be a very good source rock) the model indicates that the Viola Limestone is a good source rocks, especially in the eastern Anadarko basin. The Sylvan shale is not a very good source rock in the basin. The black shales in the Springer and Morrow are fairly good source rocks, especially for generation of natural gas. These results support the proposal of multi-source oil and a gas generation in the Anadarko basin.

Source rock and crude oil samples were characterized using more organic geochemical techniques, which included δ^{13}>C, GC, GC/MS, GC/MS/MS, and pyrolysis GC/MS. The variations of biomarker distribution, concentration, and quantitation with maturity, migration, and weathering were investigated. The biomarker characteristics were combined with other geochemical and geological information to interpret the sources, depositional environments, diagenesis, migration, and weathering of the source rocks and associated oils. Apparent oil-source rock correlations were found between the source rocks studied and a number of crude oils using biomarker characterization.

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Basin Scale Overpressured "Megacompartments": Three Dimensional Diagenetic, Hydrologic, Mechanical Predictive Modeling

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The presence of a basin scale overpressured megacompartment has been identified in the Anadarko basin. The basal seal follows the Woodford shale, while the top seal crosses several stratigraphic units with distinct petrologic characteristics and the lateral seal, adjacent to a fault, is in coarse clastic rocks that are highly cemented. This interesting configuration indicates complicated mechanisms and controlling factors of the formation of seals and compartments. Here we show how this domain comes to develop its three dimensional closure through the coupling of the reaction-transport and mechanical processes active during basin diagenesis. The role of thermal and tectonic history, sedimentary mineralogy and stratigraphic sequence and their configuration is assessed by geological petrological study and numerical simulations. The structure and location of the megacompartment, its time of formation and pattern of external and internal sealing structures are predicted and compared to those of the Anadarko basin.

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Internal Stratigraphy and Organic Facies of the Devonian–Mississippian Chattanooga (Woodford) Shale in Oklahoma and Kansas

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The Devonian–Mississippian Chattanooga (Woodford) Shale and equivalent formations are widely distributed in North America. Deposited under generally anoxic conditions during the Kaskaskian marine transgression, they are known to be important petroleum source rocks in many intracratonic basins of the Midcontinent.

The formation can be divided into several members, including the basal Misener Sandstone, and informally designated lower, middle, and upper shale members. The middle shale member is the most radioactive part of the formation, although the radioactivity of all three members decreases to the north. Isopach maps of the shale members in northwestern Oklahoma and Kansas show that the middle shale member has the greatest areal extent and thickness, indicating that it was deposited when the Kaskaskia I transgression was at its maximum. Total organic carbon content of the three shale members decreases to the north, but the middle shale member is the most organic-rich part of the formation and has the greatest component of hydrogen-rich type I and II organic matter, making it the part of the Chattanooga (Woodford) Shale likely to be the best petroleum source rock where the formation is thermally mature.

The shale members of the Chattanooga (Woodford) Shale represent a third-order depositional sequence that is bounded below and above by unconformities. The distribution and organic geochemistry of the shale members suggest that the lower, middle, and upper shale members are the transgressive and early and late highstand systems tracts of the sequence.

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Kerogen Networks and Hydrocarbon Generation in the Chattanooga (Woodford) Shale of Oklahoma and Kansas

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The middle shale member of the Upper Devonian–Lower Mississippian Chattanooga (Woodford) Shale of Oklahoma and Kansas consists of two distinct organic facies in the study area. In Oklahoma and southern Kansas, the middle shale member is a black shale, containing oil-prone type I and type II kerogen and total organic carbon (TOC) values as high as 13%. In northern Kansas, closer to the paleoshoreline at deposition, the middle shale member is commonly a gray shale, containing gas-prone type III kerogen and TOC values as low as 0.5%. In black shale samples examined using the transmission electron microscope (TEM), kerogen apparently flowed into cracks in the shale matrix, as demonstrated by clay domains within the kerogen that have their long axes oriented parallel to the walls of the cracks. For black shale samples that were within the oil generation window, the TEM electron beam heated the kerogen to the point where

oil droplets were generated, and which then moved along the kerogen-filled cracks. This artificial generation and primary migration of hydrocarbons within kerogen networks in high TOC, oil-prone samples of the middle shale member of the Chattanooga (Woodford) Shale will be contrasted with the behavior of low TOC, gas-prone samples of the middle shale member.

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Reasons Why Vitrinite Reflectance Values May Be Precisely Inaccurate

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Maximum vitrinite reflectance is measured on coal samples to determine coal rank. In general, large vitrinite particles in coal are abundant, easily identifiable, and usually indigenous (first cycle). Application of the vitrinite reflectance analysis to dispersed vitrinite in shale samples has numerous sources of error.

Caving contamination from well cuttings is a major source of error. Examination of whole-rock particles allows the identification of vitrinite in the most lithology. However, vitrinite dispersed in shale is often in low abundance and of small size, requiring kerogen isolation and measurement of random reflectance (stationary stage). When isolated, vitrinite from caving contamination and drilling mud must be properly interpreted: vitrinite-like bitumen may be mistaken for vitrinite. Random reflectance may be low at high thermal maturity (>1.0% R_o) owing to the anisotropy of vitrinite.

Recycled vitrinite can be identified on a reflectance histogram. The reflectance spread of first-cycle vitrinite is usually about 0.3–0.4% at low maturity (<1.0% R_o) and increase to >1.0% at higher maturity (>3% R_o). Caving contamination will have a lower reflectance than the first-cycle vitrinite, while recycled vitrinite will have a higher reflectance. Poor quality vitrinite particles (small size, scratched, pitted, etched) should be rejected.

The vitrinite reflectance analysis is a quantitative thermal maturity indicator. The reported vitrinite reflectance value is the mean of numerous (>20) measurements determined precisely to 0.01%. However, misidentification of vitrinite-like organic matter, contamination, and high standard deviation from vitrinite anisotropy at high thermal maturity and too few measurements can result in inaccurate determination of thermal maturity.

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Gypsum Dissolution Kinetics and Karst Formation in the Blaine Formation, Southwestern Oklahoma

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Gypsum dissolution in aqueous solutions is controlled by diffusive mass transport through a hydrodynamic boundary layer at the solid-fluid interface. This has interesting consequences for the coupled processes of dissolution and mass transport during karst formation in gypsiferous strata, because the boundary layer thickness varies directly with fluid flow conditions. We report on a set of experiments studying gypsum dissolution rates in a combined mixed flow/rotating disc reactor. In this system polished gypsum discs mounted beneath an impeller are rotated at speeds up to 1,500 rpm; a peristaltic pump maintains a constant rate of fluid flowing through the reactor. Effluent solutions are monitored for gypsum reaction products.

Our goal is to derive a rate law for gypsum dissolution as a function of fluid flow rate, temperature, solution saturation state, and lithological impurities. Dissolution rates increase linearly with the square root of disc rotation speed up to a transition point, which is indicative of transport control (the boundary layer thickness is theoretically proportional to the inverse of disc rotation speed, and diffusive flux rate through the layer will increase with decreasing layer thickness). Above a critical rate of disc rotation, corresponding to the transition from laminar to turbulent flow conditions, the dissolution rate jumps above the linear, laminar trend. Thus even at a constant rate of fluid flux, turbulent conditions will result in a faster rate of dissolution than laminar conditions. This has important implications for the auto-widening of fractures during the initial stages of karst development.

One curious experimental result is the development, at large degrees of reaction progress, of dissolution-produced etches on the disc surfaces that follow theoretically derived stream lines. These may be the experimental analog to commonly observed *rillenkarren* lining cave walls in gypsum and carbonate karst. Because of the increase in surface area, dissolution under these conditions auto-accelerates; i.e. the rate of dissolution accelerates as dissolution extent increases.

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Ovoid Rapakivi Feldspars of the Mount Scott Granite, Oklahoma

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The Cambrian Mount Scott alkali feldspar granite of southwestern Oklahoma is easily distinguished by the presence of ovoid alkali feldspar phenocrysts. Textural evidence and geochemical data point to a complex crystallization history. Early crystallization produced plagioclase, quartz, alkali feldspar, hornblende, apatite, and possibly biotite. Projection of normative composition on to A-Ab-Or and amphibole geobarometry yield estimates of ~2 kbar, suggesting early crystallization occurred at a depth of ~6.8 km. Later crystallization produced a matrix of quartz and alkali feldspar, along with sphene, zircon and fluorite. The matrix is microgranite and granophyre. Stratigraphic constraints indicate that late crystallization pressures were near surface conditions (~0.1 kbar).

Ovoid rapakivi alkali feldspar phenocrysts are common as are similar angular phenocrysts. The figure illustrate a typical example of an ovoid phenocryst. Although all phenocrysts appear to have resorbed cores, the ovoid grains are more strongly resorbed. Additionally, alkali feldspar phenocrysts are mantled by zoned plagioclase rims that range from 0.05 to 0.8 mm in width. The composition changes from An_{810} at the core/mantle interface to as much as An_{17} at the center of the mantle, and decreases towards An_{10-12} at the mantle edge. Both ovoids and angular feldspar phenocrysts are exsolved, consisting of patchy cores composed of perthite (Or_{68-70}) and/or antiperthite (Ab_{89-91}). Exsolution blebs range from tens of microns to less than 7 microns.

The formation of rapakivi fedlspars in the Mount Scott Granite may be the result of decompression during magma ascent. However, exsolution during cooling has modified the chemistry and distribution of feldspar components in these grains.

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Shallow Drilling Investigations of the Mount Scott Granite–Sandy Creek Gabbro Contact, Wichita Mountains, Oklahoma

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Understanding contact relationships between major bodies of gabbroic and granitic rocks in the Southern Oklahoma Aulacogen is critical to interpreting the temporal relationship between magmatism and continental breakup during the Cambrian. Although granite-gabbro contacts are well exposed regionally, they are obscure at the outcrop scale. The cryptic nature of the granite-gabbro contact has long hampered direct resolution of fundamental questions concerning evolution of these magma types during rifting.

A shallow drilling program, using the Oklahoma Geological Survey's rig, has been initiated in the Wichita Mountains to provide (1) direct observation of contacts between major rock units by retrieval of complete core, (2) the freshest possible sample for detailed petrologic and geochemical analysis, and (3) documentation of internal variations within igneous units as the granite-gabbro contact is traversed. Based on surface mapping the first drill site was located with the expectation the granite-gabbro contact was at a depth ≈100 ft. Three holes were attempted. The first hole achieved a depth of ≈289 ft without intersecting the contact. Preliminary petrographic analysis indicates the modal abundance of plagioclase and mafic minerals increases with depth. Alkali-amphiboles, rare elsewhere in the Mount Scott granite, are present in the last few feet. The second hole was cored to a depth of ≈30 ft, entirely in gabbro, and the third hole to a depth of ≈20 ft, entirely in granite. Both holes had to be abandoned because of technical difficulties. However, this information already demonstrates models concerning the attitude of the granite-gabbro contact must be reevaluated.

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Orbicular Granite, Wichita Mountains, Oklahoma

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A new occurrence of orbicular granite has been discovered along the margin of the Reformatory Granite adjacent to a stopped block of Headquarter Granite. The orbicular granite crops out over an area <10 m^2 in which orbicules with radii of <1 mm to >40 mm are abundant.

The orbicules are spherical structures of single or multiple concentric shells arranged around a central core. In hand sample, individual shells have a dark interior that gradually fades towards the exterior. In thin section, individual shells consist of radially arranged, elongate, tabular, quartz and feldspar grains. Within each shell quartz crystals become coarser-grained, more elongate, and organized in a braided or branching pattern towards the exterior margin. Darker portions of shells result from scattering of light due to numerous inclusions in quartz and to a lesser degree feldspar. The majority of these inclusions appear to be fluid inclusions rather than opaque minerals. These shells surround cores of multiple, closely spaced, "proto-orbicules" which consist of very fine-grained granular quartz, feldspar and magnetite.

Proto-orbicules, separated by an interconnected network of coarser-grained quartz also comprise the matrix surrounding orbicules. Early separate subhedral alkali-feld-

spar crystals millimeters in size are common within the matrix, within orbicule shells, and to a lesser degree in orbicule cores. The matrix commonly exhibits linear banding diverging around orbicules. Septa of matrix may also pierce outer orbicule shells. Fragments of shells also occur within the matrix.

We interpret these features to indicate these orbicules crystallized from a melt rather than having formed in the subsolidus as a result of devitrification or recrystallization of a xenolith.

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Exploring a Self-Organization Hypothesis for Orbicule Formation

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A recent discovery of orbicular granites in the Reformatory Granite of southwestern Oklahoma (Hogan et. al., this session) has spurred renewed interest in mechanisms leading to their formation. Two schools of thought can be delineated concerning the question of boundary conditions during orbicule formation: do the concentric patterns result from an imposed periodicity (e.g. cyclic pressure drops accompanying eruption) or from an "internal forcing" (e.g. crystal growth coupled with mass transport). In order to properly address this question, we are developing a numerical model combining the processes of coupled diffusion in silicate melts, crystal growth kinetics by both interface and diffusion control, and energy (heat) transport through the melt.

In order for a pattern to arise spontaneously from a non-patterned state, a system must be driven sufficiently far from equilibrium, and positive feedback processes must be involved. Several means for achieving disequilibrium in a silicate melt, as well as several feedback scenarios, present themselves as possibilities.

In order to discern among mechanisms we propose a course of study combining computer simulation of orbicule formation with spatial chemical mapping achieved by combining microprobe analysis digitized orbicule images. The spatial distributions of major +/– minor elements from orbicule core to rim and in the surrounding matrix will be characteristic of a particular dynamic.

One further telling observation is the spatial distribution of minerals associated with orbicules such as the branching (i.e. dendritic) structures of some crystals. Such structures have previously been associated with diffusion-limited aggregation, which occurs when growth kinetics are limited by diffusional mass transport. An appropriate model for orbicule formation needs to reproduce these textures.

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Expression of Buried Thrust Features in an "Undisturbed" Sedimentary Blanket: Joint and Fracture Adjustment in Permian Sediments Overlying the Wichita Mountain Frontal Zone, Southwestern Oklahoma

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The Wichita Mountain Frontal Zone in Oklahoma is the boundary between the Wichita Mountain Uplift and the Anadarko Basin. The Frontal Zone is roughly defined by large scale geophysical surveys from Oklahoma to the Texas panhandle and beyond, however the geometry of this boundary is obscured by a blanket of Permian sediments.

Although the last major movement along the Frontal Zone was a period of uplift in the Pennsylvanian, minor adjustments, such as the Meers Fault of Holocene age, have continued to affect the area. These micro-adjustments give a sense of the complex thrusting and folding geometries of the Frontal Zone.

While the Permian cover has previously appeared to be devoid of information concerning the Frontal Zone beneath, subtle structures, zones of erosional susceptibility, joint/fracture patterns, as well as fracture offset all provide clues for interpreting the geometry of the Frontal Zone. These hints, found in surface, seismic and well-log data provide a more informed interpretation of the complex nature of the Wichita Mountain Frontal Zone

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Thrust Displacement Transfer Zone, Southern Oklahoma

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The southern Oklahoma foreland is comprised of numerous northeast-vergent asymmetric uplifts and basins which show a progressive south-to-north sequence of formation. Layer-parallel anisotropies in the "basement" including volcanic/volcaniclastic layering and pre-existing listric normal faults are believed to control the mechanical response to southwest-northeast regional stress. This paper proposes that several uplifts (the Arbuckle, Sholem Alechem, Doyle, and Carter-Knox) are related to a single regional sole thrust plane and are a product of dominantly northeast-directed reverse dip-slip motion. The style and sequence of deformation in the Arbuckles is reflected in the location of synorogenic conglomerates and by the progressive rotation of unconformities. Decreased shortening of the Arbuckle thrust is accompanied by northwest plunge of the Arbuckle uplift. This decrease in shortening is compensated by the progressive northwestward increase of shortening along the Doyle thrust and accompanying changes in hanging wall geometry between Sholem Alechem and Doyle Fields, forming a thrust displacement transfer zone. The northwest plunge of the Arbuckle uplift is believed to die out into a fault propagation fold which forms Carter-Knox Field. Such an interpretation would make the presence of a previously postulated regional strike-slip fault highly unlikely. This reinterpretation of the regional structural geometry provides for the development of numerous deep structures which are either untested or under-explored.

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Fractured Reservoir Analysis of a Horizontal Well Completion: Viola Ls, Marietta Basin, Oklahoma

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Analysis of Viola Ls production in Marietta Basin of Jefferson and Carter Counties, Oklahoma is indicative of strong fracture control on reservoir performance. A horizontal well was drilled to test fracture susceptibility and productive capacity from the lowermost 100–150 feet of Viola Ls in Marietta Basin. Reservoir potential of the basal Viola was considered favorable due to abundant secondary silica content which is conducive

to brittle deformation. Matrix permeability within the basal Viola is very low (<0.001 md), however due to the siliceous nature of this zone it was thought to be fracture prone along faults and flexures.

A horizontal well was completed openhole with approximately 1,000 feet of borehole open to reservoir in the basal Viola. Production data and reservoir performance analysis from the horizontal well was modeled with a dual porosity reservoir simulator. The reservoir model was calibrated to match actual well performance. As predicted, production on pump remained constant until the fracture system was depleted. Matrix permeability was inadequate to feed the fracture network and sustain economic production rate.

Reservoir properties fundamental to successful horizontal Viola completions are fracture spacing, fracture aperture, vertical and lateral fracture extent, and adequate matrix permeability to sustain flow to the fracture network. Simulator results and production forecasts indicate the majority of production will be made very early in the history of a fractured reservoir completion. Thus, critical elements to a successful horizontal well completion are minimizing drilling costs and identification of areas with better fracture-matrix permeability by very selectively choosing drill sites.

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Sequence Stratigraphic Model for Simpson Group of the Southern Mid-Continent: The Key to A New Stratigraphic Play

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Middle Ordovician Simpson Group in southern Oklahoma has significant reservoir potential, which can be predicted and exploited through sequence stratigraphic analysis. Historically, exploration for Simpson reservoirs has been structurally driven, consequently there has been little exploratory drilling for stratigraphic traps.

The Simpson Group consists of several third-order depositional sequences. The major Simpson sandstones (Oil Creek, McLish, and Bromide) represent local lowstand to widespread transgressive deposits. Siliciclastics transported across the exposed shelf during relative lowstand were deposited as discontinuous shoreface complexes, or as for the thick basal Oil Creek sandstone, as lowstand systems tract deposits within the southern Oklahoma aulacogen. During transgression, shoreline retreat resulted in deposition of retrogradational, shoreface complexes that overlie the third-order sequence boundary. Thinner sandstones along the more slowly subsiding cratonic margin represent widespread transgressive systems tract deposition. Upward gradation of basal sandstone to open marine shale represents continued transgression to a maximum flooding surface. Shelfal carbonates overlying the shales represent the highstand systems tract. Highstand deposition concluded with relative fall of sea level and development of a subaerial surface (sequence boundary) across which siliciclastics of the subsequent third-order sequence were transported basinward.

This regional model supports renewed Simpson Group exploration of laterally discontinuous retrogradational shoreface complexes. Incorporated into a well-log based exploration strategy, this stratigraphic architecture would aid definition of subtle stratigraphic traps that typically escape seismic detection.

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Horizontal Drilling a Success in West Cement Medrano Unit, Caddo County, Oklahoma

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In May 1993, Phillips Petroleum Company successfully completed the West Cement Medrano Unit #71 horizontal well for 1,806 barrels of oil per day. The horizontal leg is 4,070 feet long and was drilled at a true vertical depth of 6,047 feet in the Medrano Sandstone (Pennsylvanian), between the gas/oil and gas/water contacts. The well replaced nine vertical producers in the unit which were experiencing severe gas coning problems. An interactive, multidisciplinary, teamwork approach involving geology, engineering, land, and research was directly responsible for the success of the project.

The West Cement Medrano Unit is located in Caddo County, south-central Oklahoma. The target reservoir dips approximately 23° toward the southwest. The Cement structure occurs in the axial portion of the Anadarko basin and developed during Early Pennsylvanian time in response to the regional compressional tectonic regime associated with the Wichita Orogeny. Pennsylvanian strata were pushed upward and thrust northward, folding the beds on the up-thrown block into an anticlinal structure that is fault-bounded on its northern limit.

A good understanding of the petrologic character of the Medrano reservoir especially of the depositional framework, reservoir geometry, and lithologic character, was a significant factor in the success of the well. The thin- to thickly bedded, clean, well sorted, fine- to medium-grained, quartz arenite to sublitharenite reservoir sandstones were deposited as delta-front sands (primarily as distributary and distal mouth bar sands) along a NW-SE trending basin margin. Internally, the sandstones are massive or they exhibit fine ripple lamination, low-angle cross lamination, and parallel planar lamination. The good lateral and vertical uniformity of the sandstones produces a regional and stratigraphic homogeneity in reservoir character that makes the Medrano Sandstone an excellent candidate for horizontal drilling.

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Development Drilling in Correlation with Hydrocarbon Microseepage Signatures

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In mature hydrocarbon production regions it is necessary to identify offset and missed production. The detailed use of an exploration tool, the microbial oil survey technique (MOST), in a producing reservoir in Oklahoma in 1993 demonstrated the new application of a surface geochemical technique for development geology. Hydrocarbon microseepage patterns within the active waterflood production unit identified by-passed reserves, reservoir barriers, and predicted a successful offset well prior to drilling.

A total of 441 shallow soil samples were collected every 100 yards covering a total area of 1.25 sq mi of Sullivan and Company's Southeast Vassar Vertz Sand Unit in Payne County, Oklahoma. A permeability barrier is mapped through part of the reservoir. Microseepage signature patterns, as measured by select microbial populations, were mapped and compared to the sand unit thicknesses, well locations and waterflood sweep patterns, injection and production rates, and permeability barriers.

MOST is based on the presence of hydrocarbon microseeps above buried reservoirs. Microseeps are detected by observing the concentrations and distributions of hydrocarbon-indicating microoganisms found in shallow soils. When the upward-migrating hydrocarbon gases from hydrocarbon reservoirs enter the shallow soil environment, they are utilized by a specific group of microorganisms. High microbial population distributions are therefore reliable indicators of hydrocarbon gas migration. Microbial data is presented both in absolute and statistically smoothed format. Maps, tables, and charts demonstrate the correlation between microbial microseepage patterns and reservoir production parameters.

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Comparison of Borehole Image Logs, Conventional Logs and Cores in Fractured Sandstones

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Open, conductive-mud filled vertical fractures can be detected by conventional Induction-Laterolog type (LL8, LL3, SFL, FL) combinations, since high-conductivity vertical paths affect the laterolog type logs more than the induction logs. This method has been validated by the recent addition of borehole imaging logs which provide excellent documentation of the fractures along the borehole wall. However, these tools apparently make no distinction between naturally occurring and drilling-induced fractures. In most cases the origin of fractures can be determined by examination of core material.

Generation of fractures was considered to be more likely during coring than during rotary drilling since the coring bit transfers more torque to the formation. However, a study of fractured sandstones from two wells in the Cottage Grove Formation, Dewey County, Oklahoma, which were partially cored and partially rotary drilled, finds continuity of fractures that are drilling induced. Analysis of borehole image logs show similarities in fracture characteristics observed in the cores and in the logs and allowed comparisons of fractures in the cored and rotary-drilled hole.

Excessive weight on bit and/or elevated hydraulic pressure on the bottom of the hole appears to be the common cause of drilling-induced fractures. The fractures are created downward ahead of the bit and extend laterally beyond the part of the hole drilled or cored. Induced fractures are present in the borehole wall and can be detected by logging tools.

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A Sequence Stratigraphic Model for Midcontinent Pennsylvanian Foreland Basin

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Modeling of Pennsylvanian foreland basinal deposits along their outcrop belt throughout southeastern Kansas and eastern Oklahoma revealed considerable differences in the geometry of their sequences and system tracts compared to those widely accepted for passive marginal basins. The former trapped much more regressive deposits,

owing to bordering tectonic highlands complicated by interplay of sediments from opposing land masses.

The transgressive flood occurred commonly on eroded bedrock and/or soil and achieved maximum advance within the duration of a parasequence, owing to relatively fast meltdown of distant Gondwanan ice sheets. Organic limestone, coal and gray to black shales dominated the cratonic shelf, whereas the tectonic shelf featured redbeds and sandstones.

During the ensuing highstand phase, a fluctuating equilibrium involving subsidence, eustacy and deposition, resulted in alternating retrogradational and progradational beds lasting two or more parasequences and involving carbonate banks and black shale on the cratonic shelf and thick clinoform siliciclastic deposits on the tectonic shelf and slope. A shoaling phase followed when deposition began to exceed accommodation and deposits became increasingly aggradational.

The final depositional phase of a complete sequence was forced regression, when deposits shifted basinward in a down-stepping progradational mode. Soil formation (pedogenesis) followed.

Many sequences are incomplete, owing to renewed subsidence at almost any phase within the sequence, and a moderate transgression may precede the next major overlapping sequence.

Foreland basins commonly shift their depocenters toward their cratonic shelves, owing to the greater load of sediments from adjacent orogenic highlands.

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Architecture of Pennsylvanian Carbonate Shelf, Midcontinent, U.S.A.—Cycle Hierarchy and Reservoir Development

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Three orders of cyclicity are recognized in Middle and Upper Pennsylvanian carbonate-dominated strata in the Midcontinent, U.S.A. Long-term, 3rd-order cycles consist of 4 to 5 successive intermediate-scale, 4th-order (0.2 to 0.5 Ma) cycles, each varying from a few to 30 m thick. The 3rd-order cycles are distinguished by either regional backstepping and lateral accretion of successive intermediate-scale sequences of shifts in the stacking pattern and accompanying changes in the character of the 4th-order cycles. Backstepping during the late Desmoinesian and early Missourian is delimited by prominent condensed sections. Third-order cycles end with reduced sediment accommodation space accompanied by shelf incisement and sediment bypassing. This longer-term cyclicity is also traceable across the shelf through continuous profiles of Th/U ratios reflecting changing redox patterns, particularly expressed in deeper-water carbonate facies and paleosols.

The 4th-order cycles are unconformity-bounded, regionally correlatable, and temporally distinct depositional sequences. Each is commonly comprised of flooding units, condensed sections, and late-highstand deposits. Thickness, lithofacies, and early diagenesis of these intermediate-scale sequences are closely related to elevation, slope, and configuration of the shelf. Late-highstand carbonates include meter-scale, 5th-order grainstone-bearing cycles (small-scale sequences and parasequences) that exhibit offlap and onlap relationships associated with local inferred topography. These high-frequency cycles produce distinctive vertical and lateral reservoir compartmentalization. Stratal geometries of these grainstones are very similar along depositional strike at similar inferred elevations on the shelf resulting in a proposed "strandline grainstone model."

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Spiculitic Chert Reservoir Rocks: Glick Field, Kiowa and Comanche Counties, Kansas

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Glick field, discovered in 1957, has produced 362 Bcf from Mississippian Osage chert commonly referred to as the "Chat." Other "Chat" reservoirs in Kansas and Oklahoma produce mainly from mixed chert and dolomite beneath the pre-Pennsylvanian unconformity, but Glick field's reservoir is dominated by spiculitic chert. Glick field is partly a stratigraphic trap with production ending where the spiculitic facies pinches out into tight limestone to the south and west. Updip, to the northeast, the productive facies is truncated by the unconformity. Reworked chert conglomerates overlying the spiculitic reservoir at the unconformity also produce some gas.

The spiculitic chert forming the reservoir was deposited below wavebase and grades laterally into echinoderm and brachiopod-rich skeletal wackestones and lime mudstones. Even where completely silicified, these associated limestones are tight. They form the lateral seal in the field. Thus, the reservoir is an in situ oval-shaped complex of internally brecciated sponge mats and bioherms capped in part by the chert conglomerate. The spiculitic chert contains up to 50% porosity in molds after sponge spicules, matrix micropores, and vugs coupled with fracture and breccia porosity.

Distribution of the sponge bioherms which form the reservoir facies was partly controlled by a subtle change on the shallow Mississippian carbonate shelf from clean skeletal limestones southward into shaly (and probably more anoxic) carbonates known locally as the "Cowley Facies." This lithologic boundary can be mapped across southern Kansas and provides a potential exploration tool for other stratigraphically trapped spiculitic reservoirs in the area.

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Reversal of Fortune—Paleotopographic Control Over Diagenetic Gradients: Example from Stanton Cyclothem in Northern Midcontinent

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Oxygen and carbon isotopic compositions of similar types of carbonate cements from the Stanton Limestone/Cyclothem (Missourian, Upper Pennsylvanian) in northern and southern parts of the northern midcontinent reveal significant differences in their diagenetic histories. During Pennsylvanian time, the northern midcontinent was a ramp gently dipping southward and was situated in topical latitudes (<10°). Substantial diagenetic gradients existed during meteoric and subsequent burial diagenesis of the Stanton cyclothem from north to south. Paleotopography is considered to be the major control over these diagenetic gradients.

During meteoric diagenesis, the northern area (Iowa) was more strongly influenced by meteoric water, as indicated by dissolution of ooids in calcarenites, precipitation of bladed to equant calcite cements, and paleosol development at the top of the cyclothem. Oxygen and carbon isotopic compositions of these carbonate cements and micrites/microspars define the meteoric calcite line (with $\delta^{18}O$ about −4‰ PDB, $\delta^{13}C$ as low as −3.81‰ PDB) for this area at this interval, indicating a fairly water-dominant system. The degree of meteoric diagenesis significantly decreased southward, as suggested by less development of both paleosol and other dissolution features. Carbon isotopic composition of the meteoric cements (with minimum $\delta^{13}C$ of +1.67‰ PDB) and micrites/microspars (with minimum $\delta^{13}C$ of −0.98‰ PDB), though overprinted during later burial diagenesis, suggests less water-rock interaction and a more rock-dominant system in this region (Kansas).

This diagenetic gradient caused by paleotopographic difference was reversed during subsequent burial diagenesis. The southern area was more greatly buried (maximum depth about 1,500 meters) compared to the northern area (maximum depth about 500 meters). Intensity of diagenesis was much stronger in the deeply buried southern region. The effect of deep burial was enhanced by higher geothermal gradient (42°C/km) and possible intrusion of hot brine from the basinal region farther southward in Oklahoma. All previously precipitated cements and micrites/microspars were isotopically re-equilibrated at the elevated temperature. In contrast, in the northern area, shallow burial coupled with lower geothermal gradient (20°C/km) had little effect on earlier diagenetic products. Meteoric isotopic signatures were retained, and newly precipitated late cements show less negative $\delta^{18}O$ values (minimum of −6.95‰) than the southern counterpart (minimum of −10.75‰).

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Eustatic and Possible Tectonic Controls over Depositional Architecture of Pennsylvanian Basin Filling on Northern Midcontinent Shelf and Basin Margin

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During deposition of major Pennsylvanian cyclothems, glacial-eustatic sea level rise was rapid enough to deposit only thin transgressive limestone and shale over the entire northern midcontinent shelf. During highstand, so much accommodation space existed in relatively deep dysoxic to anoxic water that only thin, dark, phosphatic, conodont-rich shale was deposited across the entire region that is presently preserved. Thicker carbonate and siliciclastic sediments undoubtedly prograded at the highstand shoreline, but these have been erosionally removed north of the Iowa outcrop. Only during sea level fall did the sea bottom become reoxygenated, warm and sunlit enough for the shallowing-upward regressive limestone to form over most of the shelf. It would have initiated on higher areas (particularly near the highstand shoreline), and it prograded into lower areas as bottom conditions progressively improved while sea level continued falling, eventually exposing the limestone on higher areas. Occasional interruptions of general regression by minor sea level rises resulted in an en-echelon succession of shallowing-upward carbonate wedges prograding basinward. If a siliciclastic source became available, a wedge of deltaic sediment prograded into the decreasing accommodation space. This either smothered the regressive limestone, or just mantled its thinner basinward end, depending on where the accommodation space was accessible. During sea level lowstand either type of regressive deposit continued to prograde basinward, and each typically could form a thick mass of sediment in the remaining accommodation space. Sea level rise, however, drowned both types of deposits, and their wedge-shaped forms were preserved by draping of thin transgressive and highstand sediment-starved deposits over them. A succession of regressions that took shoreline to similar positions on the middle to lower shelf caused both upbuilding and outbuilding of a sedimentary shelf edge composed of these thick wedges of regressive/lowstand sediment. Greater regressions accompanied by abundant detrital influx caused rapid filling of more of the basin margin, covered previous depositional topography, and resulted in formation of a younger sedimentary shelf edge farther basinward of the previous ones.

Tectonic subsidence provided the general area of accomodation space, and increasing rates of subsidence provided progressively more space toward the foreland basin of central Oklahoma. This would have contributed to general upbuilding (i.e., stacking) of the more basinward depositional shelf edges in Marmaton strata of northern Oklahoma, compared to general outbuilding of depositional shelf edges in Missourian strata of eastern Kansas. The major immediate control over basin-filling architecture, however, was how far basinward regression took the shoreline before the next sea level rise, as most of the sediment on the preserved higher to mid-shelf was deposited during middle to late regression, and most of that on the lower shelf was deposited during late regression and lowstand, when it formed the depositional shelf edges.

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Electric Power Plant *(continued from p. 178)*

($CaSO_4.2H_2O$) and calcium oxide (CaO), is hauled by truck from the plant back to some of the coal surface mines for disposal.

The power plant uses high-sulfur (>3%) coal shipped by truck from five Oklahoma surface mines on Cavanal Mountain, and it uses low-sulfur (≤1%) bituminous coal from a surface mine south of Heavener. These six coal mines are operating in Le Flore County, which now, for the first time, ranks first in annual coal production in the State. Almost one-half of Oklahoma's coal production is shipped to this plant, which has contributed to increased State coal production since 1992. At the plant site, coal and limestone are stored in a novel geodesic dome.

The Poteau River provides 2,500 gallons of water per minute to the plant, which circulates a total of 150,000 gallons of water per minute. Water is used in the form of steam in the two generating turbines and in the CO_2 towers. Then it is stored and treated in a large settling pond, from which 500 gallons per minute, at a temperature of ≤85°F, is returned to the Poteau River.

An additional 60,000 tons of coal is stored on the ground for use should the normal supply be interrupted. To assure that the large Shady Point facility will continue to produce electric power well into the 21st century, AES has an alternate contract with Peabody Coal Co. to supply it with subbituminous coal from the Powder River basin of Wyoming if the Oklahoma bituminous coal operators fail to supply coal to the plant as contracted.

Samuel A. Friedman