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On the cover—

Vitrinite from Woodford Shale, Arbuckle Mountains, Oklahoma

The Woodford Shale (Upper Devonian–Lower Mississippian) is considered to be one of the most important hydrocarbon source rocks in Oklahoma. Three criteria used to evaluate hydrocarbon source rock potential are: (1) amount of organic matter (minimum of 0.5% total organic carbon content for shales), (2) predominance of oil- and gas-generative types of organic matter, and (3) level of thermal maturity.

The vitrinite reflectance analysis is one of the most commonly used thermal maturation indicators. Vitrinite reflectance measures the percentage of monochromatic light reflected from the vitrinite maceral (type III kerogen) derived from the woody tissues of vascular plants. The vitrinite reflectance range considered necessary for the generation and preservation of oil is approximately 0.5–1.3%.

The photomicrograph on the cover shows vitrinite (medium-gray particle) from an outcrop sample of the Woodford Shale from the Arbuckle Mountains (reflected white light, oil immersion, 200× magnification, diameter of field 140 μm; sample 40 in Cardott and others, 1990). The vitrinite clast is surrounded by epoxy in a kerogen concentrate preparation. The mean random (plane-polarized light) vitrinite reflectance value for the sample is 0.52% (average of 60 measurements). Cardott and others (1990) indicated that the Woodford Shale in the Arbuckle Mountains is immature to marginally mature with respect to the generation of oil.

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C O N T E N T S

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BIBLIOGRAPHY OF WOODFORD SHALE (UPPER DEVONIAN–LOWER MISSISSIPPIAN) AND AGE-EQUIVALENT ROCKS OF OKLAHOMA

Brian J. Cardott[1]

The Woodford Shale (Upper Devonian–Lower Mississippian) occurs in Oklahoma, Texas, and New Mexico (Conant and Swanson, 1961). It was named Woodford Chert by Taff (1902) for outcrops north of Woodford, Carter County, Oklahoma (Morgan, 1924; Gould, 1925; Jordan, 1957). Age-equivalent rocks, in part or entirely, of the Woodford Shale in Oklahoma are the Chattanooga Shale in northeastern and eastern Oklahoma, and the Arkansas novaculite in the Ouachita Mountains of southeastern Oklahoma.

In recent years the Woodford Shale has been studied with renewed interest as a potential hydrocarbon source rock. The purpose of this bibliography is to provide references covering a wide variety of topics on the Woodford Shale and age-equivalent rocks of Oklahoma to aid further research. Topics covered in the bibliography include geology, environments of deposition, paleogeography, lithostratigraphy, biostratigraphy, palynology, fauna, flora, geochemistry, and hydrocarbon source rock potential. Limited references have been included that discuss the Chattanooga Shale of Kansas and Arkansas, Woodford Shale of West Texas and southeast New Mexico, and the paleogeography of the Late Devonian–Early Mississippian.

The bibliography is not exhaustive, and therefore does not include every reference where the Woodford Shale, Chattanooga Shale, or Arkansas novaculite in Oklahoma have been mentioned. Hopefully, most of the main references have been included.

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FLOODING IN THE ARKANSAS, RED, AND TRINITY RIVERS

Kenneth L. Wahl[1]

In spring 1990, unusual amounts of rain produced record or near-record flooding during April and May in northeastern Texas, southeastern Oklahoma, western Arkansas, and along the Red River in Louisiana. The flooding was the culmination of an extremely wet winter and early spring. In Oklahoma, the statewide average precipitation for the first four months of 1990 was the largest January to April total reported since record keeping began in 1892; the four-month total exceeded the previous high for the period by ~15%. The Dallas–Fort Worth Airport reported total precipitation for January to March of 22.05 in., 129% above normal.

These extremely wet conditions were conducive to extensive flooding: by mid-April, soils were saturated, flows in the principal river systems were already near flood stage, and reservoirs and lakes were at or near capacity. Because of these conditions, two major storm sequences in late April and early May produced widespread flooding and caused new record-high levels in most major lakes and reservoirs in the area.

Photo by Dale Boyle

Red River at Arthur City, Texas, on May 7, 1990, shortly after flood crest of 34 ft.

[1]U.S. Geological Survey, Denver.

From April 16 to 26, a series of slow-moving storms developed along a storm front that was centered over southeastern Oklahoma and extended into northern Texas and western Arkansas. These storms produced >8 in. of rain over the area, and >15 in. were reported at several locations southwest of Dallas, Texas. The late-April rains, which fell on already saturated soils, produced widespread flooding; many rivers and streams crested on April 25 or 26. On the morning of April 30, as the floods were beginning to recede, an abnormally strong, cold air mass moved across the region. The leading edge of this cold air mass stalled on a line from northern Texas to southwestern Arkansas, and the system remained stationary until May 3.

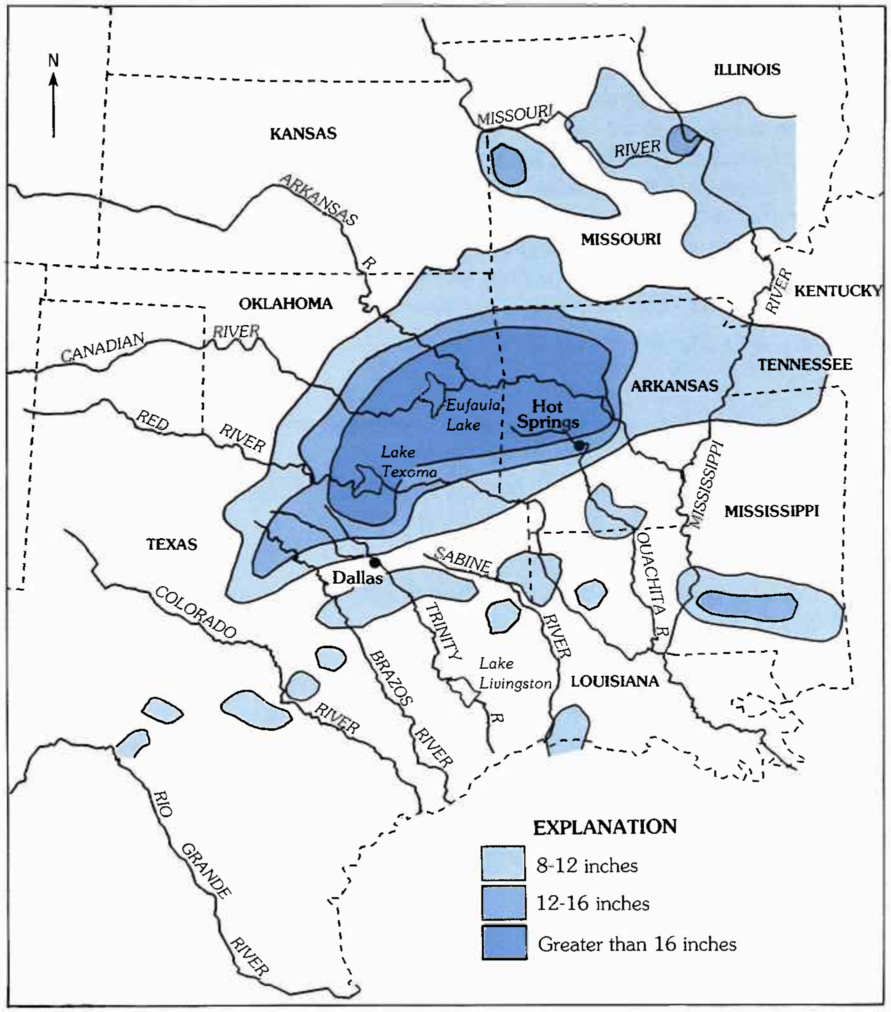
During these four days, the warm moist air being lifted over the cool stationary front produced torrential rains that caused record flooding in northern Texas, southeastern Oklahoma, and western Arkansas. Rain continued sporadically through mid-May. Total precipitation from April 15 to May 19 averaged >16 in. over the affected area and >24 in. on the Arkansas/Oklahoma state line. Rainfall recorded at numerous individual precipitation stations, however, greatly exceeded the averaged amounts.

New record-high flows occurred at many streamflow-gaging stations because of the early May storm. Flooding equal to or greater than the 50-year recurrence interval occurred in streams originating in the areas of greatest precipitation; floods of the magnitude of 100-year or greater recurrence-interval floods occurred on many streams. A 100-year flood has a 1% chance of being exceeded in a given year; thus, on a long-term average, the 100-year flood could be expected to be equalled or exceeded at least once in a 100-year period. Regularity of occurrence, however, is not implied: a 100-year flood might be exceeded in consecutive years or might not be exceeded in a given 100-year period.

Most major rivers in this area are controlled by dams, many of which have been in place for >25 years. The levels of most of the reservoirs upstream from these dams reached new record highs during this period. Because these reservoirs were full before the storm abated, the runoff from the floods could not be contained. As the runoff from the tributary streams reached the major rivers, the flooding that occurred exceeded all previous floods since the major storage reservoirs were completed.

The Arkansas, Red, and Trinity Rivers are the principal river systems that had the greatest flooding. Because of the size of the area affected by the storms and the saturated condition of the soil, the flooding extended far downstream from the source areas. In addition, the relatively flat slopes of the rivers and the need to reduce the storage levels in the reservoirs increased the duration of downstream flooding. Downstream from Livingston Reservoir on the Trinity River, for example, flood stage usually corresponds to a discharge of ~52 billion gal/day (80,000 cubic feet per second [cfs]); the discharge from the reservoir exceeded that amount for 10 consecutive days (May 17–26).

Because the main-stream impoundments, such as Eufaula Lake on the Canadian River (tributary to the Arkansas River), Lake Texoma on the Red River, and Livingston Reservoir on the Trinity River, have large storage capacities, major reductions in flooding would be expected to occur as the flood peaks passed though the storage systems. All three impoundments were full, however, when the April 30 to May 3 storm occurred. In addition, the extremely large inflows to the reservoirs would have taxed the systems even if the pool levels had been normal for early May.



Total precipitation (in inches) for April 15 through May 19, 1990 (modified from Weekly Weather and Crop Bulletin, published by NOAA–USDA Joint Agricultural Facility).

The total maximum daily inflow to Eufaula Reservoir is estimated to have exceeded 259 billion gal/day (400,000 cfs). On one day alone, ~800,000 acre-ft (an acre-ft is the volume of water that covers an acre of land to a depth of 1 ft) of water entered the reservoir; this is ~20% of the total capacity of the reservoir. The inflow to Livingston Reservoir was >200,000 acre-ft (~10% of capacity) per day for seven consecutive days (May 10–16). Maximum daily inflow to Lake Texoma was also ~10% of total reservoir capacity.

A separate and somewhat isolated thunderstorm during May 19–20 produced 13 in. of rain in about eight hours and caused severe flooding in Hot Springs, Arkansas. The resulting flood peak on the Ouachita River (tributary to the Red River) ~20 mi downstream from Hot Springs was ~103 billion gal/day (160,000 cfs). This peak was 14% greater than the previous record peak that occurred in 1923.

Seventeen deaths and millions of dollars in damage to public and private property are attributed directly to the storms and related flooding in the four-state area. Agricultural losses were extensive. In Arkansas and Oklahoma alone, the homes of >2,000 families were either damaged or destroyed. Public facilities in the entire area that were damaged or destroyed include roads, bridges, and water and sewage treatment facilities. Before the flooding subsided, 104 counties in the area had been declared eligible for federal disaster assistance.

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AAPG SOUTHWEST SECTION CONVENTION
Midland, Texas, April 12–14, 1992

Hosted by the West Texas Geological Society, the theme of this year's AAPG Southwest Section Convention is "Something Old, Something New—Concepts for Exploration and Exploitation."

The program calls for papers and posters to be presented in technical sessions dealing with stratigraphy and sedimentology, field studies, log analysis, regional studies, and exploration/development techniques.

A 2½-day, pre-convention field trip, led by the Permian Basin Section of the SEPM, will visit the Franklin Mountains west of El Paso to observe karstification of carbonate rocks.

Two pre-convention short courses are offered: "Log Evaluation Techniques for Carbonate Reservoirs," taught by George Asquith, and "Carbonate Reservoir Characterization," taught by Jerry Lucia.

For further information about the meeting, contact West Texas Geological Society, P.O. Box 1595, Midland, TX 79702; (915) 683-1573.

NEW OGS PUBLICATION

CIRCULAR 94. *Recent Advances in Middle Carboniferous Biostratigraphy — A Symposium,* edited by Patrick K. Sutherland and Walter L. Manger. 181 pages, 12 contributions. Price: Clothbound, $14; paperbound, $10.

From the editor's preface:

A symposium entitled "Recent Advances in Middle Carboniferous Biostratigraphy" was held at Stillwater, Oklahoma, on March 5, 1990, as part of the annual meeting of the South-Central Section, Geological Society of America. We organized this symposium under the aegis of the South-Central Section of the Paleontological Society. Fourteen invited papers were presented at the symposium by speakers representing institutions and organizations in both the United States and Canada. The symposium included a discussion session, open to all participants, on advances in Middle Carboniferous biostratigraphy to determine progress on the various series boundaries, divisions, and their correlations. This volume contains 12 revised contributions arising from the symposium as documentation of the current status of Middle Carboniferous biostratigraphy.

The past decade has seen formalization of a bipartite division of the Carboniferous into subsystems using the Madrid (1983) mid-Carboniferous boundary definition. Considerable progress has been made toward more precise and consistent recognition of the Morrowan–Atokan boundary since publication in 1984 of our previous symposium proceedings (Sutherland and Manger, Oklahoma Geological Survey Bulletin 136, now out of print). Attention has also begun to focus on recognition of the Atokan–Desmoinesian boundary and its correlation. The present volume provides contributions on a spectrum of topics related to refinement of Middle Carboniferous biostratigraphy. We are gratified by the continued interest in the Middle Carboniferous shown by our colleagues through their participation in our field trip held prior to this meeting, and also their support of the activities of the Subcommission on Carboniferous Stratigraphy (SCCS).

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

INDUSTRY GIVES SUPPORT TO OU PROGRAMS

• **Mr. and Mrs. Charles C. Stephenson, Jr.**, of Tulsa have established one endowed professorial chair and will create another if the University of Oklahoma meets the couple's challenge to raise funds for two more endowed chairs. The Stephensons' initial $500,000 gift will fund the Charles and Peggy Stephenson Chair in Petroleum Engineering. An additional $500,000 will be provided when the University secures the matching contributions. OU will request matching funds from the Oklahoma State Regents Endowment Program to fully endow the Stephenson chairs. A 1959 OU petroleum engineering graduate, Charles Stephenson is chairman of the board and chief executive officer of Vintage Petroleum, Inc. of Tulsa.

• **Unocal Foundation** of Los Angeles has contributed $250,000 to establish a joint professorship in OU's School of Petroleum and Geological Engineering and the School of Geology and Geophysics. Matching funds from the Oklahoma State Regents Endowment Program will complete the $500,000 funding for the Unocal Centennial Professorship.

• **MAPCO Foundation** of Tulsa has established an endowed professorship at OU that will focus research and teaching on the quality of the environment. MAPCO's $250,000 gift, together with matching funds from the Oklahoma State Regents Endowment Program, will endow the $500,000 MAPCO Professorship of Environmental Quality.

• **Phillips Petroleum Company** marked the 25th consecutive year of contributions to the University of Oklahoma with a gift of $83,800 to assist programs in the 1991–92 academic year. The gift brings the company's total support since January 1, 1990, to $383,758. More than $30,000 of the gift has been designated for scholarships in engineering, chemistry, management information systems, law, accounting, and journalism. Of those funds, more than one-third will support minority scholarships. Fellowships will be supported with $25,000 toward chemical engineering, mechanical engineering, accounting, geophysics, and management information systems. More than $13,000 was designated for other programs, including the College of Law, Minority Education Programs, and OU Career Planning and Placement Services. The remainder of the Phillips gift, more than $15,000, will be used to support professional development activities in the colleges of arts and sciences, business administration, engineering, geosciences, and law.

• **Mobil Foundation** has continued its support of the University of Oklahoma with a gift of $52,400. The funds will be used for scholarships and general support of programs within the colleges of engineering, geosciences, and business administration, as well as Career Planning and Placement Services. Recipients of the funding are chemical engineering—$3,400 in general support; geology—$3,000 in general support and $5,000 to support the research of Paul Philp, professor of geology and geophysics; petroleum engineering—$3,000 for scholarships and $5,000 in general support; and petroleum land management—$4,000 in general support. The American Indian Engineering Program received $5,000 in general support; Minority Engineering Program—$6,000 in general support; mechanical engineering—$3,000 in general support; management information systems—$2,000 for scholarships and $3,000 in general support; and Career Planning and Placement Services—$10,000 for the Minority Intern Program.

- **Texaco U.S.A.** has given funds totaling $20,000 to the University of Oklahoma to support five scholarships in various academic areas and a fellowship in the School of Petroleum and Geological Engineering. One-half of the Texaco gift will sponsor the fellowship. The remaining $10,000 will fund scholarships in accounting, chemistry, engineering, geology and geophysics, and for a student in Minority Engineering Programs.

UPCOMING MEETINGS

Oklahoma Geological Survey and U.S. Department of Energy, Workshop on Structural Styles in the Southern Midcontinent, March 31–April 1, 1992, Norman, Oklahoma. Information: Kenneth S. Johnson, OGS, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031; fax 405-325-3180.

Society of Engineering and Mineral Exploration Geophysicists, Annual Meeting, "Geophysics Applied to Engineering and Environmental Problems," April 26–29, 1992, Oakbrook, Illinois. Information: Mark Cramer, ExpoMasters, 11100 E. Dartmouth Ave., Suite 190, Aurora, CO 80014; (303) 752-4951, fax 303-752-4979.

U.S. Environmental Protection Agency, American Water Resources Association, and Ecological Society of America, International Meeting, "Ground-Water Ecology," April 27–29, 1992, Tampa, Florida. Information: John Simmons, EPA, Ground-Water Protection Division, Mail Code WH550G, 401 M St., S.W., Washington, D.C. 20460; (202) 382-7091.

Sixth National Outdoor Action Conference on Aquifer Restoration, Ground-Water Monitoring, and Geophysical Methods, May 9–13, 1992, Las Vegas, Nevada. Information: National Water Well Association, 6375 Riverside Dr., Dublin, OH 43017; (614) 761-1711.

American Nuclear Society, Annual Meeting, June 7–12, 1992, Boston, Massachusetts. Information: Meetings Dept., ANS, 555 N. Kensington Ave., La Grange Park, IL 60525; (312) 352-6611.

33rd U.S. Symposium on Rock Mechanics, June 8–10, 1992, Santa Fe, New Mexico. Information: Wolfgang R. Wawersik, Geomechanics Division 6232, Sandia National Laboratories, Albuquerque, NM 87185; (505) 844-4342, fax 505-844-7354.

American Association of Petroleum Geologists, Annual Meeting, June 21–24, 1992, Calgary, Alberta, Canada. Information: Convention Dept., AAPG, P.O. Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

The Midcontinent of the United States: Permissive Terrane for an Olympic Dam-Type Deposit?

The Olympic Dam (Roxby Downs) deposit in South Australia is one of the world's largest ore deposits, containing an estimated 32 million tonnes Cu, 1.2 million tonnes of uranium oxide, 1.2 million kg Au, and significant concentrations of rare-earth elements and silver. Host rocks are multistage breccias containing a large component of granitic and some possible felsic debris in a hydrothermal iron oxide-dominated matrix. The Precambrian basement in the Midcontinent region, especially the St. Francois and Spavinaw Proterozoic anorogenic granitic terranes in and adjacent to southern Missouri, may have high potential for an olympic dam-type deposit. In February 1988, the USGS convened a workshop in Denver to review current data and hypotheses on the type deposit and on the permissive Midcontinent terranes and to design plans for a research project to try to identify potential olympic dam target regions in the Midcontinent. This 81-page volume, edited by W. P. Pratt and P. K. Sims, presents four of the papers from the workshop (three full texts and one abstract) and one modified paper, as well as the integrated project proposal. An epilogue contains two short papers constituting an update on one aspect of the project proposal: mapping of the possibly analogous Pea Ridge iron ore deposit of southeast Missouri.

Order B 1932 from: U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The price is $4.50; add 25% to the price for foreign shipment.

Hydrogeologic Maps of the Central Oklahoma Aquifer, Oklahoma

Three over-sized sheets at a scale of 1:250,000 (1 in. = ~4 mi) were prepared by S. C. Christenson, R. B. Morton, and B. A. Mesander.

Order OF 90-0579 from: U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The price is $2.25 for microfiche and $12.75 for a paper copy; add 25% to the price for foreign shipment.

Chemical Analyses of Water Samples and Geophysical Logs from Cored Test Holes Drilled in the Central Oklahoma Aquifer, Oklahoma

Chemical analyses of water from eight test holes and geophysical logs for nine test holes drilled in the Central Oklahoma aquifer are presented in this 58-page report by Jamie L. Schlottmann and Ron A. Funkhouser. The test holes were drilled to investigate local occurrences of potentially toxic, naturally occurring trace substances in ground water. These trace substances include arsenic, chromium, selenium, residual alpha-particle activities, and uranium.

Order OF 91-464 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 231-4256. A limited number of copies are available free of charge.

Mineralogy and Petrography of Permian Rocks in the Central Oklahoma Aquifer

This 50-page USGS open-file report was written by G. N. Breit, C. A. Rice, K. J. Esposito, and J. L. Schlottmann.

Order OF 90-0678 from: U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The price is $4 for microfiche and $7.50 for a paper copy; add 25% to the price for foreign shipment.

Water-Level Changes in the High Plains Aquifer Underlying Parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas; Predevelopment through Nonirrigation Season 1988–89

J. T. Dugan, D. E. Schild, and W. M. Kastner are the authors of this 29-page USGS water-resources investigations report.

Order WRI 90-4153 from: U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The price is $23.50 for a paper copy; add 25% to the price for foreign shipment.

Oklahoma, A Summary of Activities of the U.S. Geological Survey, Water Resources Division, in Fiscal Years 1988–90

Included in this 101-page report, compiled by John S. Havens, are summary statements of current and recently completed projects, an updated bibliography of reports dealing with Oklahoma hydrology, a table of ground-water sites included in the mass-measurement network, and a listing of continuous and partial-record ground-water sites.

Order OF 91-492 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 231-4256. A limited number of copies are available free of charge.

Density and Magnetic Susceptibility Measurements of Rocks in the Wichita Uplift and Slick Hills, Southwestern Oklahoma

Written by Lee-Ann Bradley and Meridee Jones-Cecil, this USGS open-file report contains 31 pages.

Order OF 91-0269 from: U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The price is $4 for microfiche and $5 for a paper copy; add 25% to the price for foreign shipment.

OKLAHOMA ABSTRACTS

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

Retardation of the Thermal Decomposition of Organic Matter in Shales Under Hydrous Conditions

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Thermal decomposition of organic matter in shale is retarded in the presence of liquid water. This retardation is observed in a series of isothermal pyrolysis experiments on aliquots of a Woodford Shale sample in the presence and absence of liquid water. The original organic matter is thermally immature and consists predominantly of oil-prone, type-II kerogen. Experimental temperatures of 300, 330, and 350°C were maintained for 72-hour durations. Analyses of the soluble and insoluble organic matter following these experiments indicate thermal cracking, carbon-bond crosslinking, and aromatization reactions are retarded under hydrous conditions. An important aspect in understanding this retardation is that the solubility of water in hydrocarbons is two-orders of magnitude greater than the solubility of hydrocarbons in water. At temperatures in excess of 300°C more than 10 weight percent of water may be dissolved in the soluble organic matter of a shale. This dissolved water appears to be important as a readily available hydrogen donor for terminating free-radical sites before they initiate beta-scission, polymerization, or disproportionation reactions.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991*, v. 23, no. 5, p. A24.

Geochemistry of Cambro–Ordovician Arbuckle Limestone, Oklahoma: Implications for Diagenetic $\delta^{18}O$ Alteration and Secular $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ Variation

GUOQIU GAO and LYNTON S. LAND, Dept. of Geological Sciences, University of Texas, Austin, TX 78713

Isotopic analyses of 227 limestone samples from the Cambro–Ordovician Arbuckle Group, Oklahoma, document slow secular changes in the chemistry of the limestones. From late Cambrian to early Ordovician, the $\delta^{18}O$ values of the limestones increase from –10‰ to –7‰ (PDB); $\delta^{13}C$ values decrease from 0‰ to –2‰ (PDB); and $^{87}Sr/^{86}Sr$ ratios decrease from 0.7091 to 0.7088.

The light $\delta^{18}O$ values suggest that all Arbuckle limestones underwent diagenetic alteration, probably caused by meteoric water recharged during the development of the overlying, pre-middle Ordovician unconformity. The gradual $\delta^{18}O$ increase from late Cambrian to early Ordovician reflects reduced ^{18}O depletion with decreasing burial temperature during alteration, although the presence of additional primary secular $\delta^{18}O$ variation cannot be ruled out. The $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ variations, in accord with $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ variations in the literature, represent primary secular variations. The variations indicate that the $\delta^{13}C$ value and $^{87}Sr/^{86}Sr$ ratio of early Paleozoic surface seawater decreased from late Cambrian to early Ordovician. The $\delta^{13}C$ variation during this time period seems to correlate with sea-level variation. Specifically, during sea-level fall, an increase in the rate of oxidation of organic matter caused ^{13}C depletion of inorganic bicarbonate in seawater. As a result, early Ordovician carbonates, probably deposited during the regression stage of the latest Precambrian to latest early Ordovician cycle, became ^{13}C depleted, relative to late Cambrian carbonates. The decrease of seawater $^{87}Sr/^{86}Sr$ ratio from late Cambrian to early Ordovician may have resulted from decreased riverine Sr input caused by decreased rate of continental weathering.

Reprinted as published in *Geochimica et Cosmochimica Acta*, v. 55, p. 2911, 1991.

Cambrian–Ordovician Subsurface Stratigraphy of the Black Warrior Basin in Mississippi

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The stratigraphy of the Cambrian–Ordovician sequence in the Black Warrior basin of northern Mississippi is known only from subsurface data. Little has been published on this thick sequence of carbonates, and a great deal of confusion exists with regard to formational boundaries and ages. A recent study using conodonts from the Magnolia Petroleum 1 Pierce well (Monroe County, Mississippi) affords a much better understanding of the age relationships of the sequence than was previously available. The present study is an effort to differentiate the Cambrian–Ordovician strata based on the available conodont data and the lithologic character of the strata.

Of the 152 wells that have reached at least the Ordovician, only two have penetrated the entire Cambrian–Ordovician sequence. These two wells are the 1 Pruet & Hughes 1 Dunlap Brothers (Lafayette County, Mississippi) and the 1 Exxon Fulgham (Oktibbeha County, Mississippi). The sequence as revealed in the Dunlap well consists of an apparently "complete" section of 7,950 ft of carbonates with minor amounts of quartzitic sand in the base of the section. The 6,744-ft section of Cambrian–Ordovician strata in the Fulgham well is incomplete; much of the Cambrian section is absent apparently due to nondeposition.

Because only eight wells have reached the Cambrian, it is difficult to ascertain what a "normal" section is, but the subsurface in Mississippi as it is presently known is similar to the Cambrian section exposed in the southern Appalachians of Alabama. The Cambrian System attains a maximum composite thickness of 6,343 ft and is differentiated into five formations. In ascending order, these are Weisner Quartzite, Shady Dolostone, Rome Formation, Conasauga Limestone, and Copper Ridge Dolostone.

The Ordovician System is represented by a maximum composite thickness of 6,778 ft of nearly pure carbonate strata. Only Lower Ordovician and earliest Middle Ordovician (White Rockian) strata are present, and these sediments are differentiated into four formations based on lithology. In ascending order, these are the Knox Dolostone, Longview Limestone, lower Stones River Dolostone, and upper Stones River Limestone.

Despite the fact that only a small amount of oil (7,811 bbl) and gas (800,000 mcf) has been produced from the Cambrian–Ordovician section to date in Mississippi, large reservoirs may be present in these strata analogous to the prolific Ellenburger–Arbuckle trend of Texas and Oklahoma. All production to date has occurred in what is informally referred to as the "Snow Zone" of the lower Stones River Dolostone. Numerous hydrocarbon shows, excellent reservoir rocks, and the existence of large undrilled structures suggest that commercial oil and gas fields in this vast relatively unexplored trend await the drill bit in Mississippi.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1525, September 1991.

Biostratigraphic Investigations of Late Paleozoic (Upper Devonian to Mississippian) Radiolaria within the Arbuckle Mountains and Ardmore Basin of South-Central Oklahoma

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Upper Devonian and Mississippian Radiolaria-bearing samples were collected from the Woodford, Sycamore, "Caney," and basal Goddard Formations in the Arbuckle Mountains, and Criner Hills of Oklahoma. Using the event line method, biostratigraphically useful taxa were identified and documented or described, including two new subfamilies, four new genera, and fifty new species. Also, radiolarian biostratigraphic data from the Ouachita Mountains of Oklahoma (provided by Cheng, 1986) was re-examined and integrated with this study.

A radiolarian zonation (consisting of ten zones) is proposed for portions of the Upper Devonian (Famennian) and Mississippian. This zonation has been calibrated using biostratigraphic data supplied by co-occuring conodonts and goniatites. This data links the proposed zonation to North American and European standard zones and the geochronometric time scale.

In addition, this study reports: (1) New radiolarian and conodont faunas recovered from the uppermost Woodford indicate a higher chronostratigraphic position than previously thought; (2) a limestone bed displaying a Bouma sequence discovered within the upper Sycamore indicates that this formation is partially turbiditic in origin; (3) reworked conodont assemblages (containing *Cavusgnathus charactus, Taphrognathus–Cavusgnathus* transitional forms, and *Gnathodus texanus*) reported

from 4'0"–4'3" above Sycamore base indicate that at least 98% of this unit is "no older than middle Meramecian" (A. Harris, 1989); (4) radiolarian data from the Ouachita John's Valley Shale indicate that this strata underwent partial mixing of its sediment by hydrologic processes; and (5) radiolarian assemblages from the John's Valley represent displaced faunas. The distribution of these assemblages do not reflect their chronostratigraphic position in the fossil record.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991*, v. 23, no. 5, p. A468.

Basement Influence on the Structural Geology of Southern Oklahoma Inferred from Residual Aeromagnetic Maps

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This poster display illustrates magnetic basement control on the structural pattern of southern Oklahoma with a few examples of its influence on petroleum accumulation, including potential fracture reservoirs (i.e., Arbuckle, Viola–Bigfork, Woodford–Arkansas novaculite formations, etc.). Exploration for fractured petroleum reservoirs requires knowledge of structural dynamics, structural mechanics, and present state of stress as well as paleostress.

High-resolution residual aeromagnetic mapping provides a particularly useful display of areal continuity of basement block pattern that, when considered in context of tectonic plate movements, allows predictions of specific fault reactivation, timing, and sense of displacement. Study of aeromagnetics often provides better understanding, downward and lateral projection of known faults, support for suspected faults, and inference of previously unrecognized faults.

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Probable Ancestor to Permian Richthofenid Brachiopods in Early Pennsylvanian (Morrowan) Jolliff Formation of Southern Oklahoma

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The brachiopod *Teguliferina*, characterized by a conical pedicle valve anchored by rhizoid spines and an operculiform brachial valve, has previously been known only from an interval extending from the Late Desmoinesian to the Wolfcampian. The appearance of this genus in the Fort Scott Limestone of Kansas (Late Desmoinesian, Marmaton Group) would appear to represent an abrupt punctuation. Now, a new occurrence of the genus has been found much lower stratigraphically in the Jolliff Formation (Early Pennsylvanian, Morrowan Series), in the Ardmore Basin, southern Oklahoma. The stratigraphic gap, represented by the Atokan and Early Desmoinesian, can clearly be attributed to the incompleteness of the fossil record.

The Jolliff species is represented by abundant silicified specimens that form small bioherms up to 0.70 m in diameter. The specimens occur in growth position and form closely packed small clusters resting on top of earlier clusters and all are attached by rhizoid spines. This form is similar to typical species of the genus *Teguliferina* from Late Pennsylvanian strata in west Texas, with which it has been compared. The Jolliff form is more primitive, with a more distinctly developed umbo, and is more nearly like the productid ancestor from which it must have arisen.

Teguliferina is believed to have given rise in the Early Permian to the more aberrant forms with a more extreme conical predicle valve that are included in the Superfamily Richthofeniacea.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991*, v. 23, no. 5, p. A167.

Probable Reservoir Facies of the Wapanucka Limestone (Morrowan), Frontal Ouachita Mountains, Southeastern Oklahoma

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Considerable recent exploration and significant discoveries in the frontal Ouachita Mountains can be attributed to structural and stratigraphic relationships within the overthrust belt. Although, most of the production has been from the early Atokan Spiro Formation, the late Morrowan Wapanucka Formation has locally proven to be a gas reservoir. Surface imbrications allow outcrop study of the Wapanucka lithofacies and form a basis for predicting the character of rocks in the subthrust region.

Repetitive sequences of platform, platform margin, and basinal facies characterize the Wapanucka Formation in outcrop. These sequences record several southward progradations of the ramp-like shelf margin. Oolitic and bioclastic calcarenites accumulated on the shallow shelf, while algal micrites developed near the shelf edge. Spiculitic limestones characterize the platform margin, and slope and basinal depositional environments are inferred for the noncalcareous spiculites and shale.

Within the Wapanucka, several facies are potentially hydrocarbon reservoir rocks. These include oolitic grainstone and spiculitic packstone. The former lithology might preserve primary porosity, while the latter facies could develop significant fracture porosity in certain structural configurations. Thus, mapping their surface extent is significant because well control and seismic data do not provide this kind of information. However, detailed surface work in association with the subsurface geology can aid in locating potential hydrocarbon reservoirs.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1396, August 1991.

Elemental Mobility During Diagenesis and Low-Grade Metamorphism of Shales

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Considerable disagreement exists concerning whether shales behave as open or closed systems during diagenesis and low grade metamorphism. Because of their low abundances, trace elements and rare earth elements are particularly suitable for a test of element mobility.

Samples collected from the Stanley Shale (Mississippian) in the Ouachita Mountains of Oklahoma and Arkansas were analyzed using XRF and INAA methods. The Stanley is part of a thick flysch sequence deposited within 20 m.y. that grades from shale to slate to phyllite toward the core area of metamorphism. The data obtained were related to the areal distribution of maximum burial temperatures as determined using vitrinite reflectance data of Houseknecht and Matthews (1985).

Whole rock chemical abundances show no statistical correlation with thermal maturity across the wide range of reported reflectance values. Both major and trace element concentrations exhibit little variation. Rare earth element ratios (La/Lu, La/Sm) do not correlate with vitrinite reflectance and remain essentially constant.

The results of this study indicate that shales are a closed system during diagenesis. Significant amounts of inorganic material are neither imported nor exported. The close system behavior of trace and rare earth elements during diagenesis and low grade metamorphism contributes to their usefulness in discriminating provenance and tectonic environment.

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The Rome Trough and Evolution of the Iapetan Margin

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Recent structural mapping of the Rome trough suggests a complex structure very different from the symmetrical and laterally continuous graben commonly depicted. Early and Middle Cambrian extension in the Rome trough of eastern Kentucky and adjacent areas resulted in a series of alternately facing half-grabens with variable displacement. These half-grabens are bounded by southwest–northeast-trending normal faults (e.g., Kentucky River and Warfield faults), which are laterally continuous only on the order to tens of kilometers. The Rome trough is laterally segmented by north–south-trending faults (e.g., Lexington fault) commonly expressed as flexures in younger rocks (e.g., Burning Springs anticline and Floyd County channel). Many of these north–south-trending faults have significant left-lateral displacement, and probably represent reactivated thrust faults of the Grenville tectonic front.

The Rome trough and the associated Mississippi Valley, Rough Creek, and Birmingham fault systems were initiated during an Early Cambrian shift in sea-floor spreading from the Blue Ridge–Pine Mountain rift to the Ouachita rift along the Alabama–Oklahoma transform fault. These fault systems have been proposed as having originated from extensional stress propagated northward from the Ouachita rift across the transform fault. In the alternate model proposed here, faulting was brittle, extensional failure resulting from subsidence and flexure of the continental margin to the east. Following initiation of sea-floor spreading at the Blue Ridge–Pine Mountain rift in the latest Proterozoic, margin subsidence in the presence of the Alabama–Oklahoma transform boundary and the inherited Grenville tectonic front resulted in this interior cratonic fault system.

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Syndeformational Magnetization in the Ordovician Bigfork Chert at Black Knob Ridge, Western Ouachita Mountains, Southern Oklahoma

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Paleomagnetic and rock magnetic results from unweathered samples of the Ordovician Bigfork Chert at Black Knob Ridge in southern Oklahoma indicate the presence of a pervasive magnetization residing in magnetite that has a southeast and steep down direction. The results from small- and medium-scale folds indicate the magnetization was acquired during or after Carboniferous folding. The declination in sites along Black Knob Ridge shows a north to south 28° counterclockwise shift.

The Bigfork Chert at Black Knob Ridge was folded and thrusted along the Ti Valley fault system in the late Paleozoic. The laterally equivalent Viola Limestone in front of the thrust and in the Arbuckle Mountains contains a late Paleozoic magnetization with a shallow inclination that can be used as a reference for comparison with the Bigfork Chert at Black Knob Ridge. Based on the comparison, the steep inclinations in the rocks at Black Knob Ridge are interpreted to be primarily the result of rotation around a horizontal axis as a result of thrusting. The declination change along the ridge is also interpreted to be the result of rotational movements during thrusting.

The pervasive magnetization at Black Knob Ridge is interpreted to have been acquired during deformation. The low thermal history of the Bigfork Chert suggests that the pervasive component is a chemical remanent magnetization (CRM). A strain-related mechanism, however, cannot be definitely ruled out. The proposed CRM may be related to fluid migration through fractures produced during folding and thrusting. Alternatively, an in situ chemical process (e.g., maturation of hydrocarbons) may have caused the remagnetization.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991,* v. 23, no. 5, p. A92.

The Wilburton–Ouachita Trend—A Gas Giant for the 1990s

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The Wilburton–Ouachita trend of southeastern Oklahoma runs roughly northeast–southwest from the town of Atoka near the Texas line to the town of Poteau and the Arkansas line. This 120-mi trend is a narrow system 25–35 mi wide with a strong horst-graben structure that separates the Arkoma basin in the north from the Ouachita basin hidden under the thrust system to the south. Recent seismic shooting shows that the basin was downwarped during the rift period of the Acadian orogeny. A fracture system of normal faults was formed in these lower Paleozoic carbonates. These faults were rejuvenated during the Morrow–Springer deposition, and subsequent Wichitan tensional faulting caused many of the horst blocks to move thousands of feet upward. During Atokan time massive shales were deposited into this faulted basin, causing differential loading and more movement. The final period of movement came in Late Pennsylvanian time with the compressional forces of the suturing of the South Oklahoma aulacogen and the thrusting of the Ouachita plate over the deformable Pennsylvanian shales. We will examine how these forces formed the productive structures that are being drilled today in the Arkoma basin. A series of seismic lines crossing the Wilburton–Ouachita trend will be shown along the extent of the play from Poteau to Atoka.

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Megaregional Project Progress Report

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The Megaregional Project is a cooperative effort between CGG American Services, 23 oil companies, and several other service companies. The goal of the project is to compile and interpret continuous regional seismic lines crossing major North American basins.

When completed, the first data segment will extend from the Arkoma basin of Arkansas to the east Cameron area, offshore Louisiana, and will be ~500 mi long. The line will cross the Arkoma basin, the Ouachita thrust belt, the State Line Graben trend, the North Louisiana Salt basin, the Lower Cretaceous shelf edge, and complex faults of southwest Louisiana. Additional Megaregional dip and strike lines are planned for the Gulf of Mexico basin as the project advances.

Megaregional seismic lines provide insight into (1) what is and is not basement, (2) maturation history and migration pathways, (3) regional structural geology, and (4) regional stratigraphy. They can, thereby, lead to an improved understanding of known plays and to the development of new exploration plays in apparently mature areas.

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Comparative Evolution of Pennsylvanian Platform Margins in Oklahoma and North-Central Texas

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Pennsylvanian evolution of the Midland basin's eastern shelf and the northern shelves of the Anadarko and Arkoma basins demonstrates a strongly contrasting pattern with regard to the facies composition and stability of the shelf margin. For the Midland basin a carbonate ramp system developed adjacent to the Eastern shelf during the early Desmoinesian but received no coarse-grained clastic sediment until after the central Fort Worth basin was completely filled by Ouachita orogenic debris in the late Desmoinesian. At that time, a distinct north–south hingeline formed between the shelf and incipient Midland basin that allowed for subsequent vertical accretion of a Missourian-age double bank system. Due to the absence of active deltaic depocenters across the southern two-thirds of the shelf, the Missourian shelf margin did not prograde basinward nor did a submarine fan system develop adjacent to this reciprocal bank complex. Later, during the Virgilian, a single shelf-edge bank and submarine fan complex prograded the shelf edge westward.

The shelf edges for the Anadarko and Arkoma basins demonstrate a significantly different pattern. Only during the late Desmoinesian (Marmaton Group) did a shelf-edge bank develop in association with shelf-slope reciprocal sedimentation. For the Anadarko basin, widespread submarine fans, fed from a northeasterly cratonic source, are first seen with Red Fork deposition. Subsequent backstepping of the shelf edge as a consequence of basinal subsidence enlarged the basin at the expense of shelf areas and resulted in deep-water fan deposits accumulating on top of older fluvio-deltaic shelf units. This back-stepping ended during the early Virgilian. Post-Tonkawa cyclic sedimentation prograded the shelf edge southward and gave rise to a more carbonate-dominated shelf sequence. In virtually all instances the regressive submarine fan units indicate eustatic lowstands of sea level.

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East-Trending Stratigraphic Transects—Western Interior Cretaceous (WIK) Project

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Four regional east-trending lithostratigraphic and time-stratigraphic transects and basin-wide interpretations of deposition within the Western Interior basin were prepared for the WIK project. The transects include the following regions from north to south: (1) northern Rocky Mountains and Great Plains, from southwestern Montana to southwestern Minnesota; (2) middle Rocky Mountains, from northern Utah to east-central Wyoming; (3) southern Rocky Mountains and Great Plains, from western Uinta basin, Utah, to eastern Denver basin, Nebraska and western Kansas; and (4) southern Rocky Mountains, from eastern Arizona to Oklahoma panhandle and including San Juan basin. Transects depict regional facies relations, sequence boundaries, and biostratigraphic and radiometric correlations for the entire Cretaceous sequence. More than 5,000 m of nonmarine strata typify the rapidly subsiding westernmost part of the basin, whereas less than 600 m of predominantly marine strata were deposited on the eastern shelf. This asymmetry resulted from different rates of subsidence due to tectonic and sediment loading. Most Cretaceous facies are basinwide; however, Maastrichtian sedimentation was dominated by local sediment sources derived from rising mountain ranges uplifted by early Laramide deformation. Cretaceous rocks consist primarily of sandstone, siltstone, claystone, and shale. However, conglomerate is abundant along the western margin of the basin, and limestone is common on the eastern shelf. Sediment was deposited in both marine and nonmarine environments while the shoreline fluctuated during tectonic and eustatic cycles.

WIK is a project of the Global Sedimentary Geology Program (GSGP). The International Union of Geological Sciences established GSGP as a new commission to extend understanding of the history of the earth, surficial processes, evolution of life, and biotic influences on earth processes through global-scale research on sediments, sedimentary rocks, and their contained organisms. The goal of WIK is to have a publicly available data base from which to reconstruct and interpret the depositional history of Cretaceous strata in the Western Interior, U.S.A.

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Cyclic Deposition of the Lower Permian, Wolfcampian, Chase Group, Western Guymon-Hugoton Field, Texas County, Oklahoma

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The Texas Panhandle field and adjoining Hugoton field of southwestern Kansas and the Oklahoma and Texas panhandles have produced 60 tcfg since discovery of the Texas Panhandle field in 1918. The two fields are structural-stratigraphic traps producing gas from the Lower Permian, Wolfcampian, Chase Group. The Chase Group in the Oklahoma Panhandle, Guymon-Hugoton area, is approximately 350 ft (107 m) thick and consists of cyclically deposited carbonate and fine-grained, siliciclastic units which can be traced laterally for tens of kilometers using wireline logs. A typical Chase Group depositional cycle in the western part of the Guymon-Hugoton field begins with a thin, light-gray to gray, structureless to burrowed, dolomitic siltstone unit reflecting the initiation of marine transgression and shallow drowning of underlying sediments deposited in supratidal environments. The siltstone is abruptly overlain by light-gray, burrowed, sparsely fossiliferous, very fine grained sandstone reflecting continued transgression and shoreface deposition generally near or below wavebase. The sharp contact of the siltstone and overlying sandstone may be a marine, transgressive surface of erosion. The sandstone grades upward into a relatively thick, transgressive-regressive limestone and dolomite sequence. Bioclast mudstone, wackestone, and packstone composing the lower part of this sequence record continued transgression and subtidal, open-marine deposition below wavebase in waters perhaps a few meters to a few tens of meters deep. Planar-, low angle-, and cross stratified bioclast and bioclast-intraclast grainstone and washed packstone composing the upper part of the carbonate interval suggest the end of marine transgression and a seaward progradation of carbonate sediments deposited above wavebase in moderate to high-energy, nearshore shoal, upper shoreface, or beach environments. Slightly sandy and argillaceous, dolomite mudstone and wackestone composing the uppermost part of some carbonate intervals may record restricted lagoon to lower tidal flat deposition. The trangressive-regressive carbonate sequence is characterized by primary intergranular and secondary moldic and intercrystalline porosity and is the main Chase Group reservoir facies in the Guymon-Hugoton field. Diagenesis of the carbonate interval included a relatively early dolomitization by downward-migrating, Mg-rich waters from overlying tidal flat environments, meteoric leaching of undolomitized carbonate grains and lime mud, meteoric calcite cementation, and in some cycles, anhydrite cementation of primary and secondary porosity. Chase Group cycles are capped by tan, very fine grained, burrowed, parallel- and ripple-laminated sandstone and reddish brown, dolomitic, siliciclastic mudstone displaying mud cracks, caliche glaebules, and plant root structures. These siliciclastics are a result of continued regression and lower to upper tidal flat deposition and paleosol development.

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Secondary Recovery from the Burbank Field, Northeastern Oklahoma, is Environmentally Attractive and Economically Feasible

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Mine workings in competent nonpermeable formations underlying the Burbank field could permit access for production wells drilled on one acre or closer spacing. Such wells would drain to a production pipeline within the mine workings for transport to the mine shaft for pumping to the surface. Drilling and well completion as described in U.S. patents 4,458,945 and 4,595,239 would permit controlled flow from each production well, thus adding gravity drainage to retained water, gas, or secondary field production systems.

Since the wells are drilled from below, drilling mud activities to aid cutting removal would not be needed; the wells could be drilled with clear water. Sealing of productive zones by drilling mud should not occur. Since there would be no wall cake, cementing of the production string should be easier and more effective.

Shafts for access to the mine would be 1 mi or more apart and could be located in areas with limited environmental impact. There would be no surface indication of the closely spaced production wells. Water produced during production should be returned to the reservoir to assist in retention of water drives.

Mine spoil produced in driving access ways might be used as concrete aggregate and/or road base material.

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Old Geologists, Old Fields, New Ideas, New Techniques—New Reserves

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The recent discovery of Viola production on the flank of the Lucien field has focused attention to the presence of fractured reservoirs on the flank of old producing structures along the Nemaha Ridge and elsewhere in Oklahoma.

Recognizing that many of these old fields have not been published in any detail, the authors have begun a series of field studies, concentrating on fields that were discovered before mid-1950. In order to do this job as quickly and economically as possible, computer technology is being employed. Databases have been purchased from services such as GDS. Computers have been employed to create a series of structure and isopach maps. The use of computers has made it possible to quickly develop second-derivative structure maps which indicate those areas most prone to fracturing. The authors then suggest that the development of these fractured reservoirs could best be accomplished by horizontal drilling.

For those "old" geologists who are intimidated by computers or don't care to become computer experts, the availability of published databases and computer mapping services lets the geologist combine his experience and knowledge with new technology in the development of prospects and new reserves.

A series of field studies will be presented as time permits.

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Mapping Surface Alteration Effects Associated with Hydrocarbon Reservoirs at Gypsum Plain, Texas, and Cement, Oklahoma, Using Multispectral Information

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Two test sites, Gypsum Plain, Texas, and Cement, Oklahoma, were selected to evaluate combined use of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and Thermal Infrared Multispectral Scanner (TIMS) for detection of alteration effects associated with hydrocarbon microseepage. Bleaching of redbeds, variations in carbonate cement, replacement of gypsum, oxidation of iron, and changes in clay mineralogy may correlate spatially with oil and gas production and subsurface structures. Spectral features due to iron oxides, calcite, gypsum, smectite, and kaolinite can be mapped using AVIRIS image data, using various techniques such as ratios, scene-dependent log residuals, and scene-independent radiative transfer approach using LOWTRAN7, and with TIMS data using DSTRETCH. Poor signal-to-noise in the 2.0–2.4 μm region limited the ability to map clay, gypsum, and carbonates both at Cement and Gypsum Plain. However, gypsum could be mapped using a 1.75 μm absorption feature, iron oxides could be mapped using features short of 1.0 μm. TIMS data were used to map gypsum at both Cement and Gypsum Plain, carbonate and quartz-rich sediments at Gypsum Plain, and differentiated soils developed on the Rush Spring sandstone from soil derived from the Cloud Chief Formation at Cement. Combined spectral and photogeologic interpretation of coreg-istered AVIRIS, TIMS, Landsat TM, and digital elevation data demonstrate the practical approaches for surface oil and gas exploration using presently operational commercial aircraft and future satellite systems.

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Processes Responsible for Large Concentrations of As, Cr, Se, U, and V in Water Produced from the Central Oklahoma Aquifer

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Water produced from Permian red bed sandstones of the Central Oklahoma aquifer locally has concentrations of arsenic (As), chromium (Cr), selenium (Se), uranium (U), and vanadium (V) that exceed drinking water standards. The aquifer and its entrained water are being studied to describe rock-water interaction, to identify mineral residences of the metals, and to determine processes responsible for the metal content of the ground water.

Core samples were analyzed by chemical (including sequential extraction) and petrographic methods. Average whole-rock abundances of As (7.3 ppm), Cr (56 ppm), Se (~1 ppm), U (3.6 ppm), and V (100 ppm) are similar to those of typical sedimentary rocks and only small zones of slight metal enrichment were detected. Therefore, the distribution of metals, and reactions in the aquifer suggest the metals are leached from a large volume of rock. Arsenic has maximum values (max. 64 ppm) in rocks containing goethite. Chromium is also concentrated in iron oxides (max. 176 ppm), but no unique mineralogic association was identified. Selenium is present in a reduced form in both typical and enriched rocks (max. 100 ppm).

Native selenium was detected in small (<0.5 cm) dispersed reduction spheroids. Uranium (max. 123 ppm) and V (max. 5,200 ppm) also are enriched in these spheroids. Secondary uranyl vanadates, uranium oxides (?), and iron oxides are important sinks for uranium that may become mobile. Vanadium is probably contained in hematite in most samples, but in the reduction spheroids reduced vanadium oxides with coatings of vanadate minerals are common.

Oxidation of As-, Cr-, Se-, U- and V-containing minerals by ground water converts the metals to soluble species. The high pH of the water (7–9) generally inhibits adsorption of As, Cr, Se, and V oxyanions. Solubility of the uranyl ion is enhanced by formation of uranyl carbonate species. These processes are part of ongoing alteration of the aquifer that includes dissolution of carbonate cements and ion exchange. The results are useful for forecasting trends in ground-water quality, and understanding conditions that favor transport of oxyanions and formation of V–U deposits.

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