# OKLAHOMA GEOLOGY NOTES

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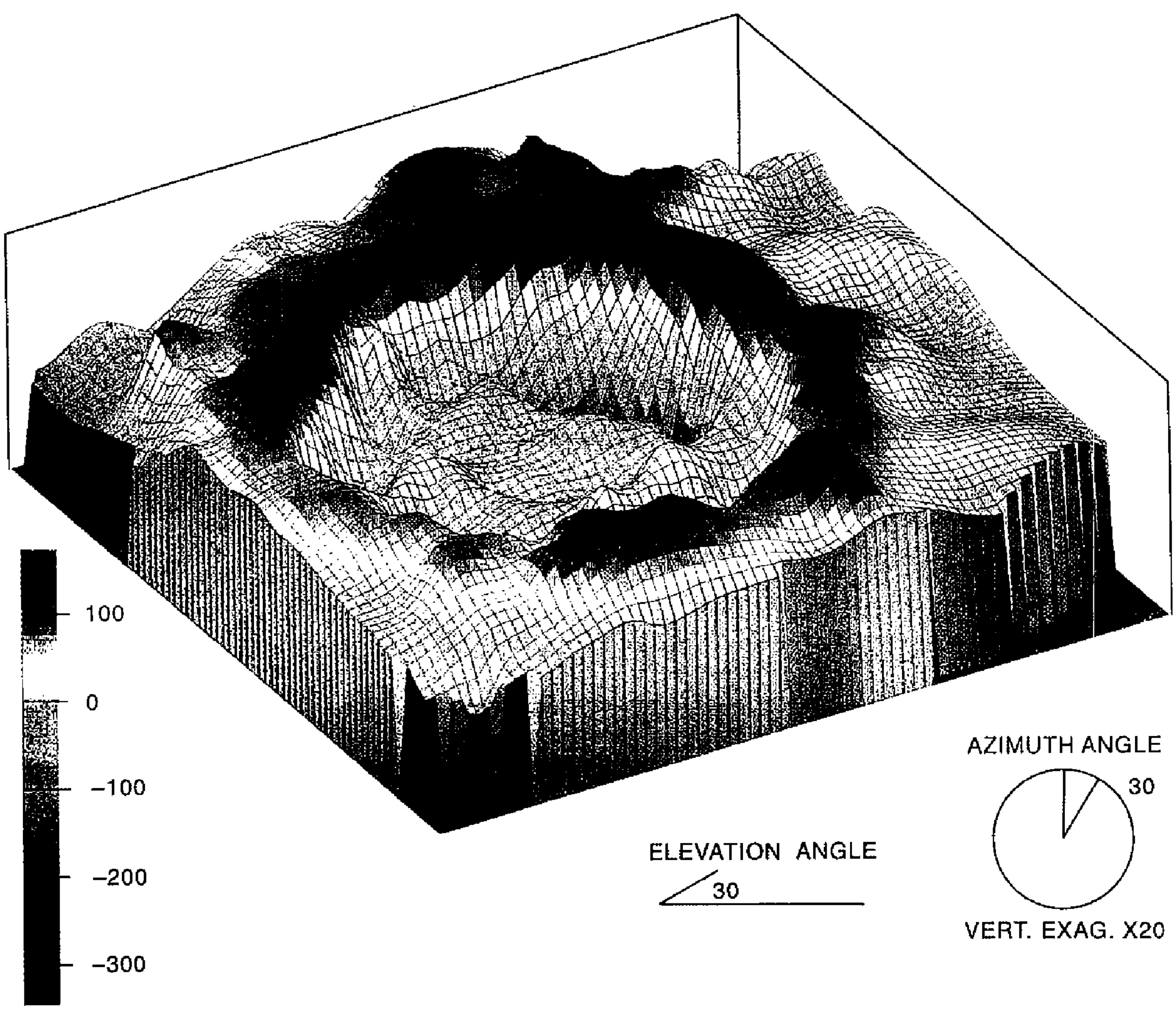

*On the cover—*

## 3D Diagram of the Ames Structure

Computer-generated, three-dimensional diagram of the Ames astrobleme structure. Reference: top of the Sylvan Shale (Upper Ordovician). The Arbuckle Group (Cambrian–Ordovician) lies ~800 ft below the Sylvan. All data were obtained from well logs. Trend-surface fitting was used to remove the southwesterly regional dip. The residual surface is viewed from a perspective elevated 30°, looking to the south–southwest. A vertical exaggeration of 20× has been applied to show the details of the uplifted rim, the inner ring, and the crater floor. The entire structure is ~10 mi in diameter. Subsequent drilling has found the Sylvan surface morphology to be an accurate representation of the base of the Oil Creek Formation (Middle Ordovician), which overlies the partially eroded Arbuckle Group on the crater rim, and the brecciated Arbuckle and granite basement within the crater.

The DLB Cecil discovery well was drilled on the high on the western rim (shown in red at right center). The J. L. Thomas wells were drilled on the northern rim shown closest to the viewer. The D. & J. Gregory 1-20 well was drilled on a local high located on the inner ring (yellow) nearest the viewer. The "Hunton graben" is located in the far southwest portion of the crater and is shown as a deep blue low. The color scale for the structural scale is shown in feet. Zero corresponds to the regional trend surface used to establish the residual Sylvan surface.

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# OKLAHOMA GEOLOGY NOTES

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OKLAHOMA
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# THE AMES IMPACT CRATER

***Bruce N. Carpenter*[1] *and Rick Carlson*[2]**

## Introduction

Since the first recognition of an anomalous structural low near the town of Ames, in the southeastern part of Major County, Oklahoma, the origin of this and possibly related subsurface structural features in the area of T. 20–21 N., R. 9–10 W., has been the subject of much speculation. Detailed maps on subsurface horizons from the Devonian up to the Late Pennsylvanian show an intriguing circular-shaped closure around a low that occupies ~20 $mi^2$, approximately centered near the town of Ames. Because drilling in secs. 1 and 2 of T. 20 N., R. 10 W., had revealed an unusually thick and low Hunton (Silurian–Devonian) section, an early characterization of this part of the larger multi-pay Ringwood Field was as the "Hunton graben." Recent deeper drilling has established oil and gas production from the Arbuckle dolomite on a circular rim around this low, leading to the characterization as the "Ames hole." The Oil Creek shale (Middle Ordovician), which seals the structure and directly overlies the Arbuckle Group, indicates the age of the crater is late Lower Ordovician. Figure 1 is a stratigraphic column for the Anadarko Basin.

Subsequent drilling and mapping has provided enough new data to allow description of the deep structure as an impact crater or astrobleme. Initial Arbuckle wells by J. L. Thomas Engineering, Inc. and DLB Oil and Gas , Inc. (DLB), now known to be located on the rim of the impact crater, were significant Arbuckle dolomite discoveries; however, the discovery of prolific oil production in wells located on the crater floor from brecciated granite, granite wash, and dolomite has proved to be even more significant.

The first crater-floor well, the D. & J. Oil Co. (D. & J.) Gregory 1-20, sec. 20, T. 21 N., R. 9 W., may be the most productive oil well established from a single pay in Oklahoma. The pay zone is in an essentially continuous section of brecciated granite that formed as a central rebound structure, a common feature in impact craters larger than a few miles in diameter. More than 200 ft of very effective porosity and very low water saturation combine to provide a conservatively estimated primary recovery of >4 million bbl of oil.

Other crater-floor wells have established production from granite overlying brecciated dolomite and from outstanding solution-enhanced porosity and fracture systems that are developed in intact, but not in-place, blocks of Arbuckle dolomite. Oil and gas production from both the rim and the crater-floor features, all sealed by shales within the Oil Creek Formation, will probably make the Ames impact feature the most productive known astrobleme.

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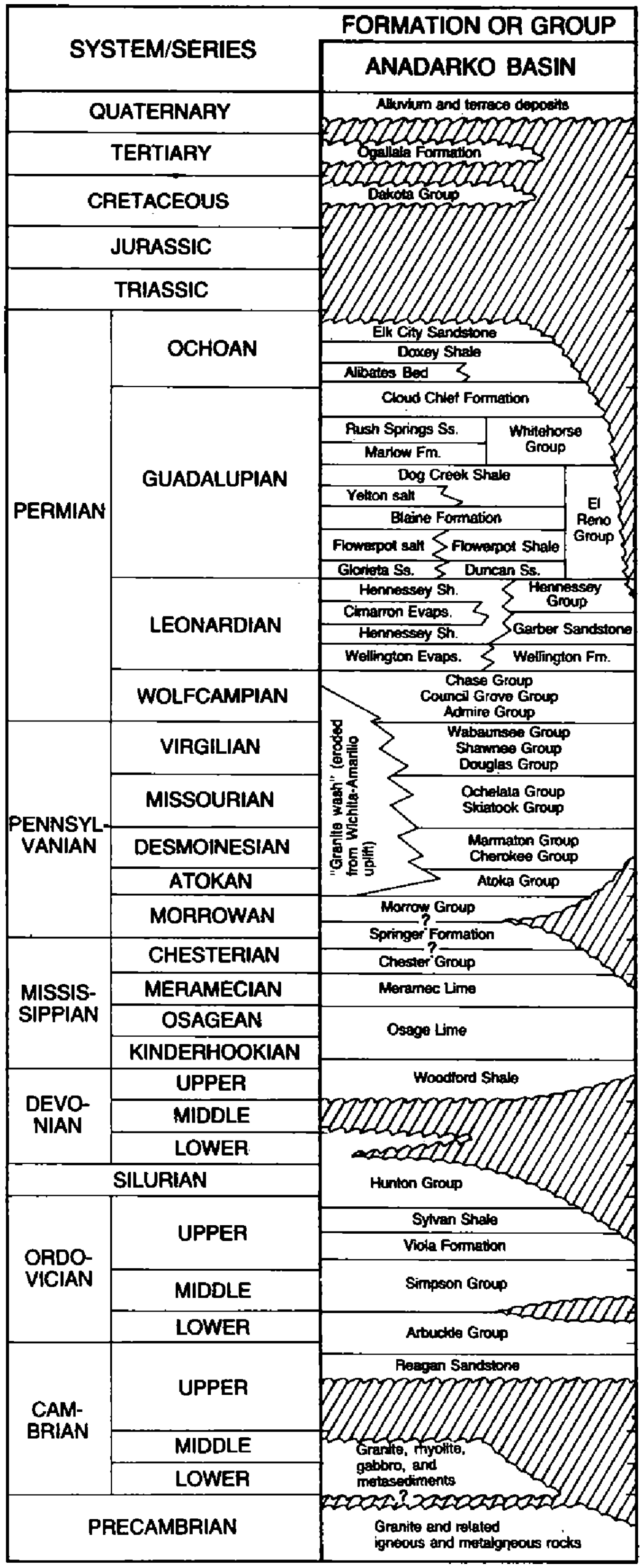



**Figure 1. Stratigraphic column for the Anadarko Basin. The Oil Creek Formation is in the lower part of the Simpson Group. (Modified from Johnson, 1989.)**

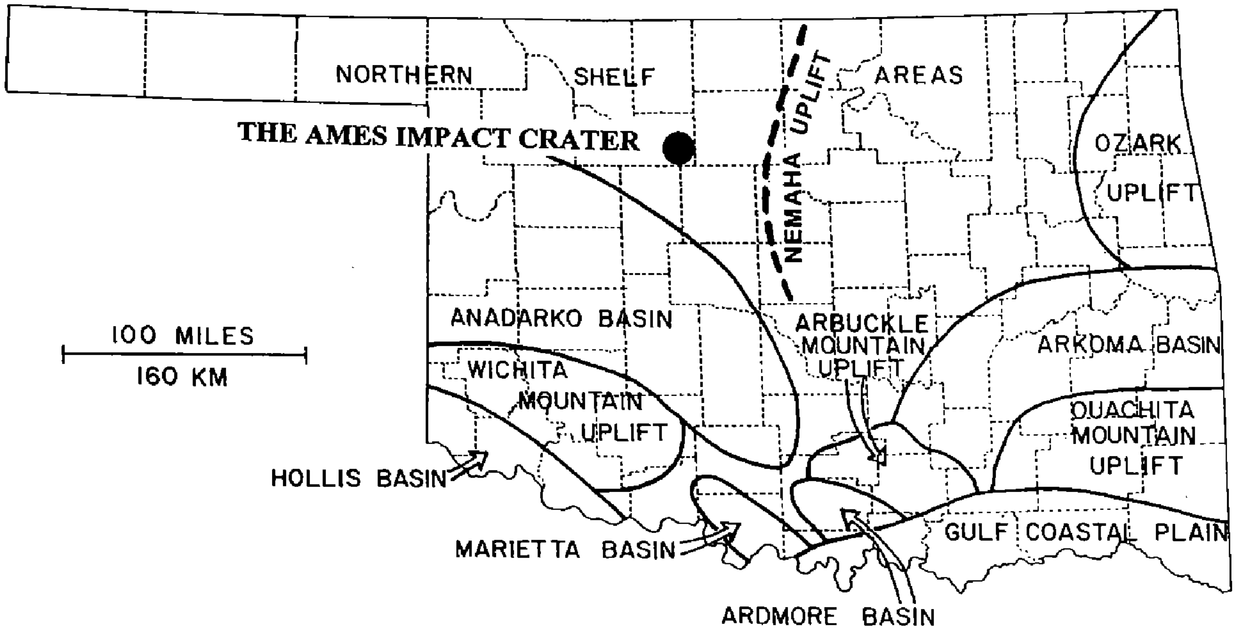



**Figure 2. Major geologic provinces of Oklahoma and the location of the "Ames hole" in the southeast corner of Major County, Oklahoma. (From Johnson and others, 1980.)**

## Background

A structural feature near the southeast corner of Major County, Oklahoma, has been known for years as the "Hunton graben" to geologists who study the subsurface geology of the northern Anadarko shelf area. The feature is centered ~2 mi southwest of the town of Ames. The Hunton thickens from 225 ft to as much as 475 ft in the local area. The base of the Hunton is locally as much as 200 ft lower than regional. This local preservation of thick and structurally low Hunton carbonates suggests a graben.

It is now recognized that the Hunton graben is a small part of a much larger feature that has become known as the "Ames hole." This unusual feature has no relationship to major faults or uplifts on a map of major geologic provinces (Fig. 2); the location of an impact structure occurs randomly and is unrelated to other tectonic features.

A three-dimensional map of the Ames structure (Fig. 3; cover) illustrates common features of an impact crater: an outer rim with local closed highs and an interior low, including an irregular central high area that is also characterized by local closed highs (Sawatztsky, 1975; Cannon, 1977; Roddy, 1977; Donofrio, 1981; Hartung and others, 1990; Anderson and Hartung, 1992; Kirschner and others, 1992). Although the local structural closures on the outer rim had been recognized on a structural contour map on the Sylvan Shale (Late Ordovician), the relationship of the rim to the deepest part of the structure in the southwestern part was not recognized prior to the construction of the computer-generated model (Fig. 3; cover).

Several Arbuckle tests had been conducted in the area before the actual origin of the feature was recognized. J. L. Thomas drilled the Ott no. 1 and no. 2 wells in the

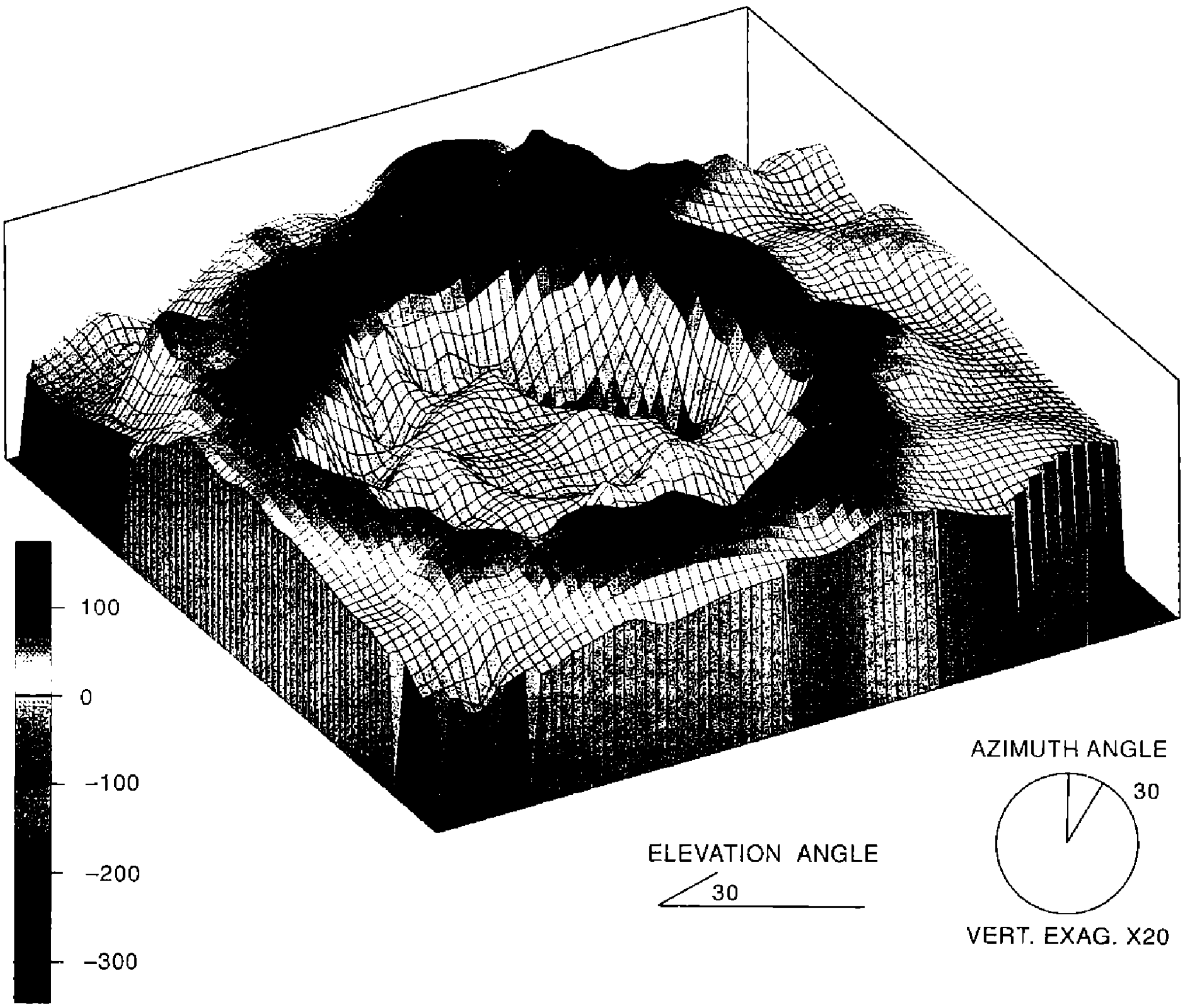



**Figure 3. Computer-generated three-dimensional structure map on the top of the Sylvan Shale on the Ames impact structure. View is elevated 30° above the surface, and toward the south–southwest with regional dip removed so that the residual surface more clearly shows the nearly circular shape, a distinct outer rim, and the central low comprising an inner ring of local highs. Vertical exaggeration, 20×. Map control is provided by approximately four penetrations of the Sylvan Shale per square mile. (Also see cover illustration.)**

SW¼ and SE¼, respectively, sec. 4, T. 21 N., R. 9 W., on mapped north dip. When DLB Oil and Gas, Inc. drilled their Cecil well in the NW¼ sec. 27, T. 21 N., R. 10 W., these Ott wells were recognized by DLB as being positioned, like the Cecil well, on small structures high on a common rim surrounding a central low. The realization that a substantial gas and oil column was present in Arbuckle dolomite with significantly enhanced reservoir properties led to early speculation about the origin of the structurally high Arbuckle feature and its possible association with the Hunton graben. Later discovery of brecciated granite in the inner ring of the central feature provided additional evidence that it had been created by the impact of an asteroid. This suggested that the rim had been uplifted and fractured by crater-forming processes associated with the impact.

## Origin of the Ames Structure

An interpretation for this structural anomaly is as follows. Sometime shortly before or soon after the end of the Arbuckle deposition, an asteroid exploded low over the surface of what is now the southeast corner of Major County, Oklahoma, creating a bowl-shaped crater centered near the present town of Ames. It is apparent that ~2,000 ft of Cambrian–Ordovician carbonate and some basement rock was excavated by the explosion. Basement granite under the bottom of the crater was subjected to enormous compressive stress, and fractured as the result of the exploding meteorite. The granite basement subsequently rebounded, particularly in the central portion of the crater (Figs. 3,4). Brecciated granite is the major component of the ridges that form the inner ring. Some of the ridges are as much as 1 mi across and 2 mi long, and as much as 1,600 ft thick.

Part of the crater was filled with breccia that had become airborne and fell back after the explosion. That breccia is a mix of basement granite and Arbuckle dolomite rocks. The outer ring, composed mostly of fractured blocks of Arbuckle dolomite, was formed when part of the crater rim collapsed into the central low along arcuate normal faults. There is evidence that fragments of Arbuckle rock and granite excavated by the explosive event were heated sufficiently to resemble pyroclastic rock. Several feet of such pseudopyroclastic rock occurs locally on the crater floor, overlying the more abundant granite and carbonate breccia (Fig. 5). It may have been some time before deposition of shales of the overlying Oil Creek Formation began.

The rim and breccia highs were exposed to subaerial weathering and erosion. The rim, composed mostly of Arbuckle Group, became karsted. The highs eroded and were redeposited as carbonate and arkosic clastics that occur on the crater floor, lying on top of brecciated rock that had previously fallen back into, and partially filled, the crater. A stratified cap of tight dolomite overlies the crater-floor breccia, and these strata grade upward into the Oil Creek Formation. The entire feature is overlain by Oil Creek shales, forming structural traps that may have hydrocarbon columns of several hundred feet.

The Ames hole was filled during Paleozoic and Mesozoic deposition, during which time the underlying breccia continued to compact. Strata from the Oil Creek Formation (Middle Ordovician) through the Flowerpot Shale (Upper Permian) are preserved within and beyond the structural low. Structure maps on the base of the Woodford Shale (Upper Devonian) (Fig. 6A), and on the top of the Oswego lime (Middle Pennsylvanian) (Fig. 6B), clearly show the closed low. These maps document the continuing compaction and collapse of crater-floor breccia despite the progressive masking of the structure by sedimentation.

Astrogeologists Roddy (1977; personal communication, 1992) and Cannon (1992) concur that the feature is an astrobleme on the evidence of its circular shape, the central high composed of fractured crustal rock, the outward-dipping rim, and the presence of shock-metamorphosed quartz (Fig. 7).

## Exploration and Development

Arbuckle discoveries at Cottonwood Creek (Read and Richmond, in press), Wilburton (Carpenter and Evans, 1991), and in the subject area have caused renewed

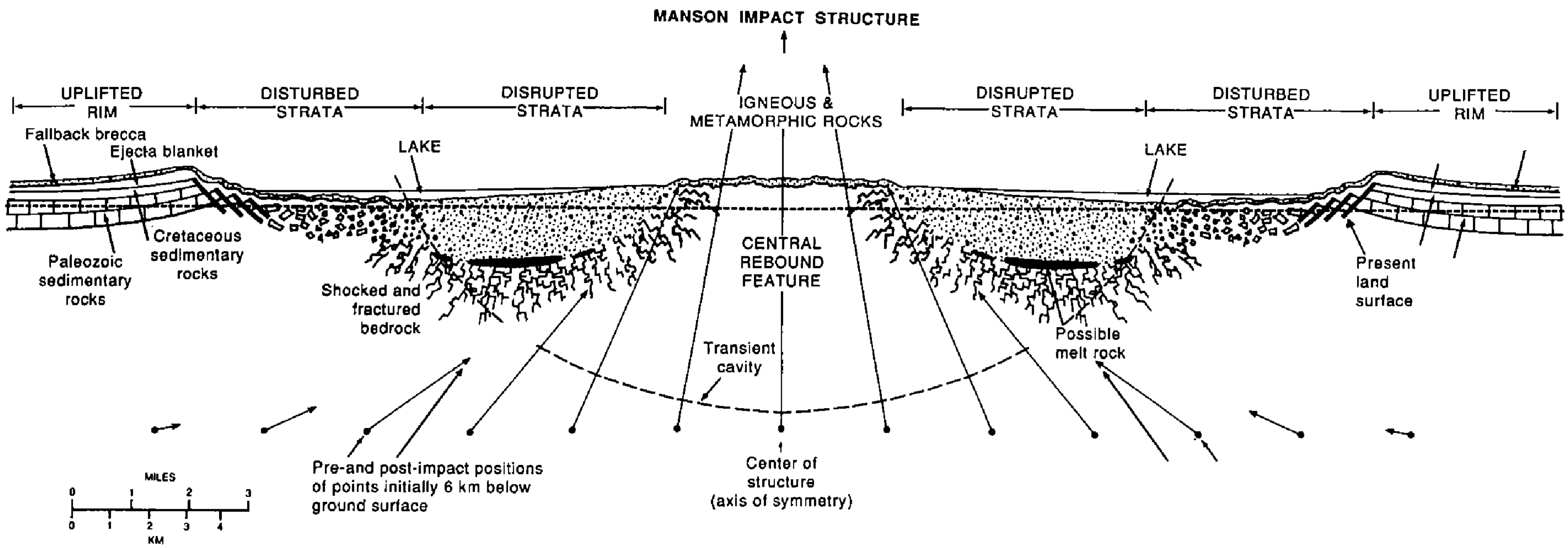



Figure 4. Interpretive cross section of a larger and younger, analogous impact crater near Manson, Iowa. The position of the transient cavity present during formation of the structure is indicated by the curved dashed line. Rough estimates of the movement of material required to fill the transient cavity and produce the central peak are indicated by the arrows. Arrows extending above the ground surface suggest some material in the rising central peak may have been airborne for a short time before crashing back to Earth and producing an impact breccia. (Modified from Hartung and others, 1990.)

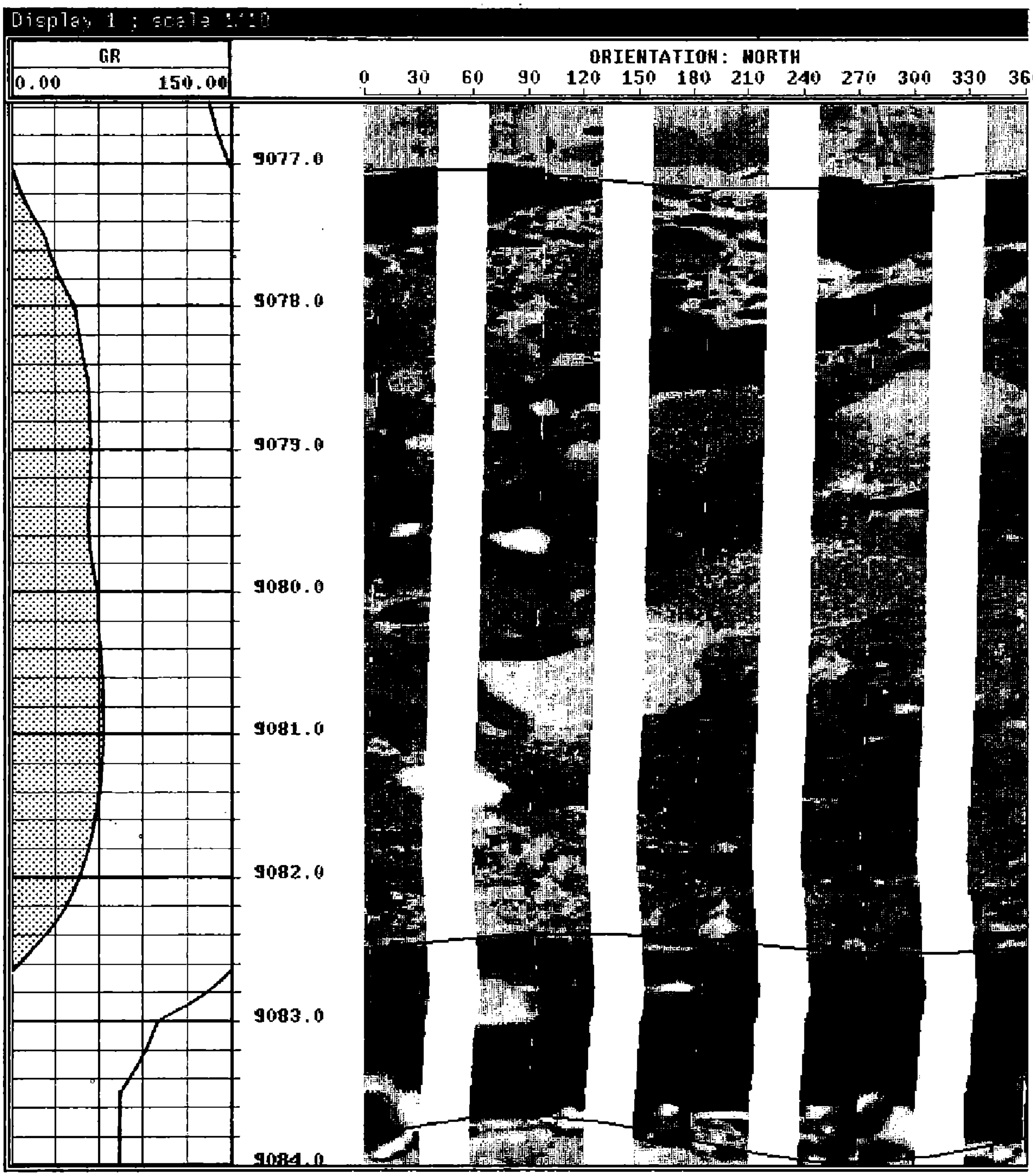



**Figure 5. Black and white reproduction of false-color print of one of many Formation Microscanner Images (FMI, a trademark of Schlumberger, Inc.) taken in unidentified Ames crater-floor well. Sine-wave-shaped lines are oriented dip-planes and/or geologic contacts projected onto the image of the bore hole wall. Brecciated Arbuckle dolomite below 9,083.75 ft; cave-fill (probable collapse) below 9,082.5 ft (fill consists of dust and microbreccia carried down from above); pseudopyroclastic breccia-to-microbreccia below 9,077 ft; overlain by finely stratified dolomite dust above 9,077 ft. This is overlain, in turn, by Oil Creek Shale (not shown). Image has been reduced 50% vertically at the workstation; objects, therefore, appear flattened. Dark areas are the most conductive; white areas are the most resistive. Gamma-ray response at left illustrates very high radioactivity associated with pseudopyroclastic material.**

interest in drilling exploration wells into the Arbuckle. The Arbuckle dolomite does not normally have significant matrix porosity or permeability, and reservoir size and quality are commonly limited. However, in April 1991, DLB completed the no. 27-4 Cecil well (N½NW¼ sec. 27, T. 21 N., R. 10 W.) and discovered excellent flow rates on separate tests for both gas and oil (Fig. 8).

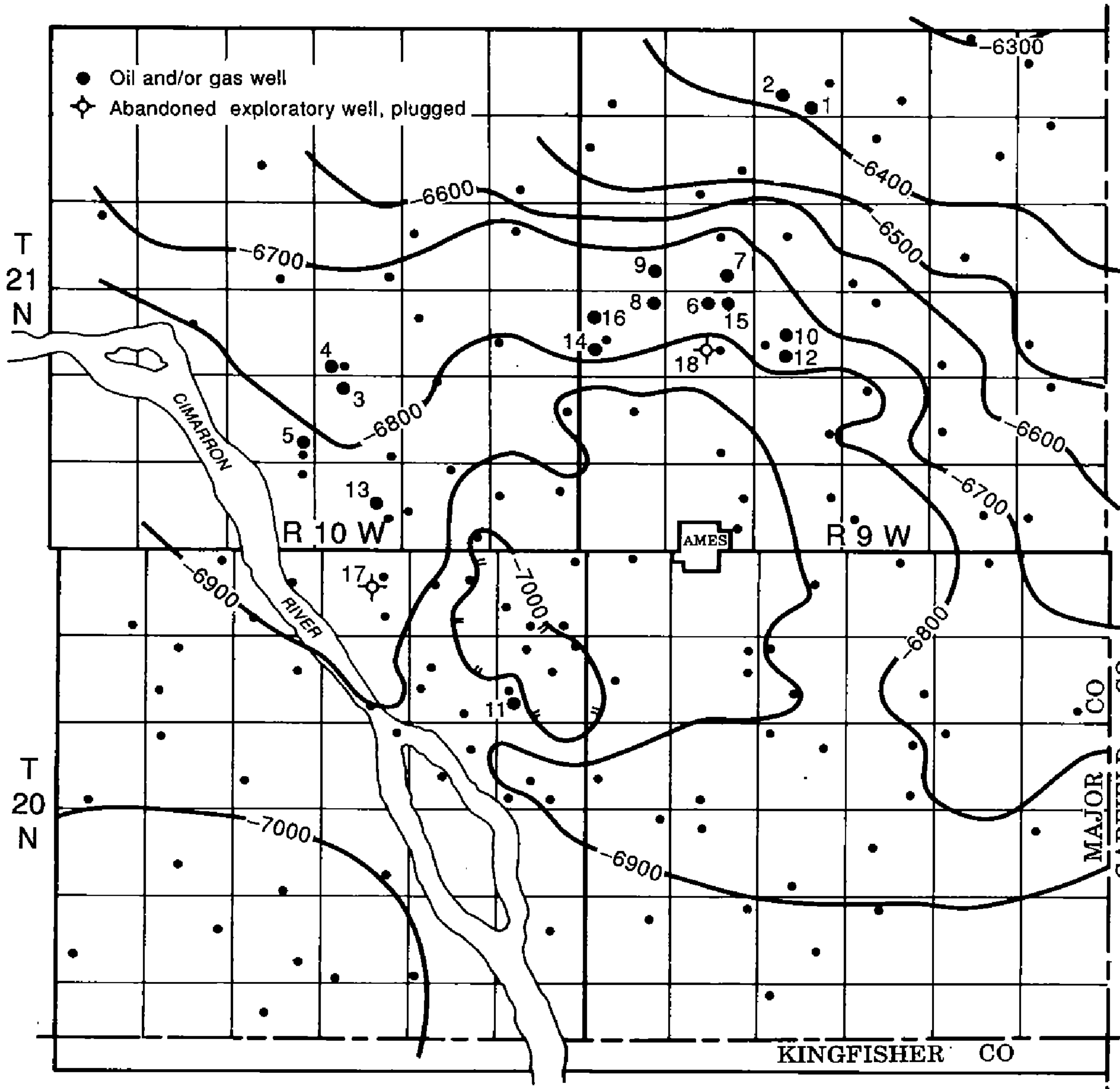
The upper Arbuckle produced gas at a rate of 3,440 MCFGPD by drill-stem test in DLB's discovery well. The well was initially completed without stimulation, flowing 300 bbl of oil per day (BOPD) from a lower Arbuckle dolomite zone, which was then commingled with a portion of the gas zone. Seismic data indicated closure on the Arbuckle at this location, but the indicated hydrocarbon column exceeded the trap mapped as a local closure. The original closure is now recognized to be a small feature on a much larger structure, the northwestern rim of the crater.

Continental Resources, Inc. (CRI) offset the Cecil well with their Mary Ellen well (SE¼SW¼SW¼ sec. 22, T. 21 N., R. 10 W.), just across the section line to the north, but the oil-bearing portion of the Arbuckle was less fractured and porous than in the Cecil. A whole core from this interval exhibits many collapsed karst features. The well was finally completed a gas producer, from an interval near the top of the Arbuckle dolomite.

During this period, DLB completed their no. 28-9 Bierig (NE¼SE¼ sec. 28, T. 21 N., R. 10 W.), an excellent gas well southwest of their Cecil well. These Arbuckle successes on the crater rim encouraged DLB and CRI to join with D. & J. to drill the first test on a small feature within the crater. This test, completed in November 1991, was the very successful Gregory well (NE¼NW¼ sec. 20, T. 21 N., R. 9 W.) (Shirley, 1992).

The Arbuckle was expected in the Gregory at a depth of ~8,800 ft, based on seismic data. At 8,838 ft, below an unusually thick Oil Creek shale, a drilling break occurred with drilling rates reaching <1 min/ft. This very fast drilling was accompanied by cuttings of brecciated granite with excellent shows. These cuttings contain abundant shattered quartz and feldspar with cleavage faces, causing the rock to be prematurely characterized as "glass rock" (Hamm and Olsen, 1992). A drill-stem test over the upper 60 ft of the zone flowed 40.4° API gravity oil to the surface at a rate in excess of 50 bbl of oil per hour (BOPH) (Fig. 9). Final flowing tubing pressure (FTP) was 4,025 psi, as compared to a final shut-in pressure (SIP) of 4,045 psi, a bottom-hole pressure (BHP) of 4,055 psi, and a hydrostatic pressure of 4,181 psi. Surface flowing pressure was 1,200 psi through a 16/64-in. choke. More than 320 ft of brecciated basement rock were penetrated without encountering carbonates of the Arbuckle Group. This well produces from only 30 ft of perforations without stimulation. The top perforation is located ~110 ft below the top of the breccia, and well above any indications of water. Initial flow was 713 bbl of oil in 14 hrs., at a flowing tubing pressure of 1,080 psi using a 18/64-in. choke. No water was produced on any test. A conservative estimate of reserves from the Gregory well is >4 million bbl by primary recovery. Subsequent drilling has established a deeper water level in the granite breccia and suggests a water drive. The well has flowed its allowable since completion in November 1991 and produced >113,000 bbl of oil and 3,700 MCFG in less than one year without water production or significant loss of pressure.

Cuttings and thin sections of the basement rock were examined, using scanning electron microscope and X-ray diffraction techniques, to identify the mineral composition. The analysis indicated that the rock is granitic, composed of 31% quartz,




1 J. L. Thomas no. 1 Ott
2 J. L. Thomas no. 2 Ott
3 DLB no. 27-4 Cecil (discovery)
4 CRI no. 1-22 Mary Ellen (offset to discovery)
5 DLB no. 28-9 Bierig (gas well)
6 D. & J. no. 1-20 Gregory (first well within the crater)
7 D. & J. no. 1-17 Lloyd
8 CRI no. 1-19 Dorothy
9 D. & J. no. 1-18 Peggy
10 CRI no. 1-21 Stansberry
11 DLB no. 13-11 Allen
12 DLB no. 21-11 DeHaas
13 CRI no. 1-34 Terry
14 CRI no. 1-19 Chet (horizontal extension)
15 D. & J. no. 1-20 James
16 CRI no. 1-19 Heinrich
17 CRI no. 6-3 Fisher (plugged and abandoned)
18 D. & J. no. 1-20 Herman (plugged and abandoned)

**Figure 6A. Geologic structure at the base of the Woodford Shale (Upper Devonian). Contour interval 100 ft; sea-level datum. The –7,000-ft contour identifies the approximate location of the "Hunton graben." Small, closed circles identify well control for this map. Larger, numbered symbols identify more recent drilling discussed in text. Base map from Herndon Map Service, Inc. (From Smith, 1985; also see Smith, 1989, fig. 3.)**

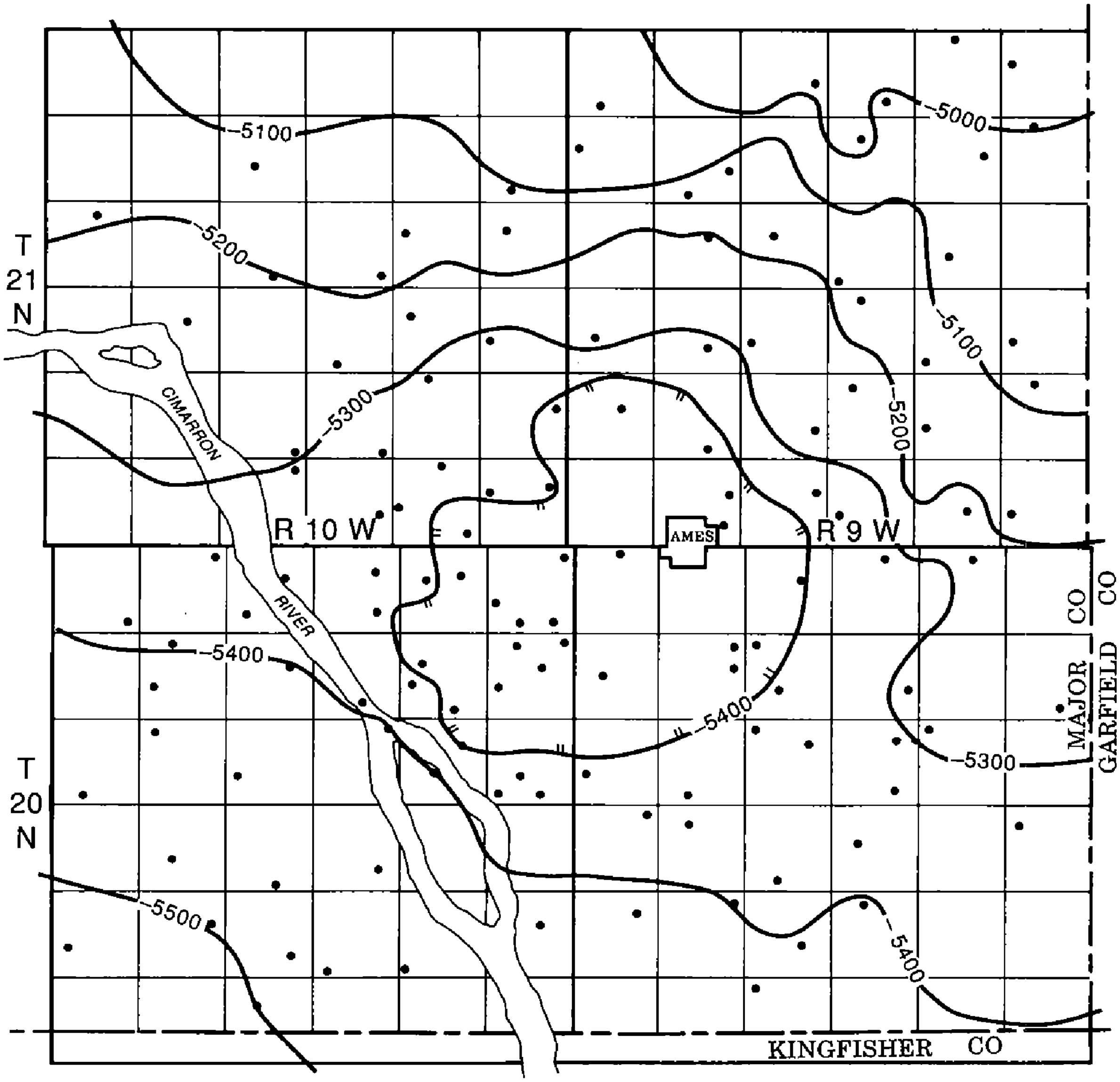



**Figure 6B. Geologic structure on top of the Oswego lime (Fort Scott Limestone, Desmoinesian). Contour interval 100 ft; sea-level datum. Note that the Cimarron River is deflected to a more southerly course at the crater rim. Closed circles identify well control. Base map from Herndon Map Service, Inc. (From Smith, 1985; also see Smith, 1989, fig. 3.)**

11% potassic-feldspar, and 52% sodic-feldspar. This analysis was reconfirmed by later examination of rotary sidewall cores from the D. & J. no. 1-17 Lloyd (SW¼SE¼ sec. 17, T. 21 N., R. 9 W.) drilled to the northeast of the Gregory. The age of the granite is 1,690 million years, according to Rb–Sr isotopic analysis. This is similar to other basement rock dates in the area when adjusted for strontium enrichment from the Arbuckle dolomite (Roberts and Sandridge, 1992).

Several confirmation wells have been drilled. The D. & J. Herman (NE¼SW¼ sec. 20) to the south also penetrated brecciated granite but was low and encountered water. Two wells to the west, the CRI Dorothy (NE¼NE¼ sec. 19) and D. & J. Peggy (SE¼SE¼ sec. 18), as well as the D. & J. Lloyd (SW¼SE¼ sec. 17) to the northeast, are oil productive, although apparently none of the three is producing from the same reservoir as the Gregory well. The Dorothy and Peggy wells are completed in granite wash and in the underlying brecciated Arbuckle dolomite. One well penetrated an abnormally thick section of Oil Creek shale, followed by granite breccia, overlying Arbuckle breccia (Fig. 10). It is apparent that the granite breccia was deposited in this position as the result of mass movement.

The Gregory well continues to flow with little difference between shut-in and flowing tubing pressures. Its direct offset is the D. & J. James, which flowed 492 BOPD from granite breccia. CRI drilled successful offsets of the Gregory well, to the

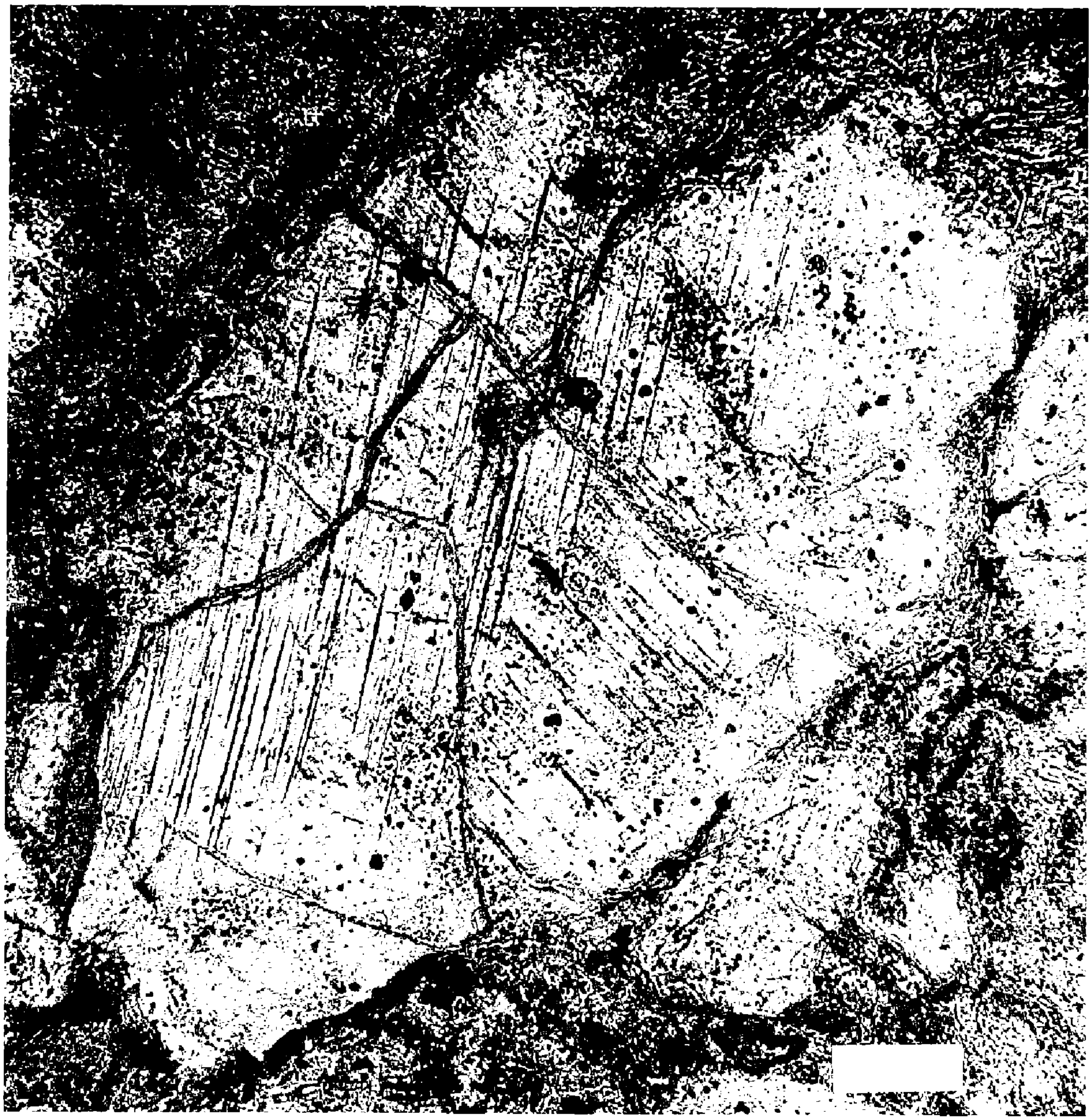


**Figure 7. Shock lamellae in quartz, as seen in a photomicrograph of a thin section of granite from a drilled sidewall core, at about 8,990 ft in the DLB DeHaas well (sec. 21, T. 21 N., R. 9 W.), in the northeast part of the crater floor of the Ames impact crater (see cover illustration and Fig. 3). The large quartz grain exhibits two sets of deformation (strain) lamellae, resulting from high-pressure shock metamorphism. Scale bar is 100μm. Rock sample provided by DLB Oil and Gas, Inc. (Photograph by Bruce Carpenter.)**

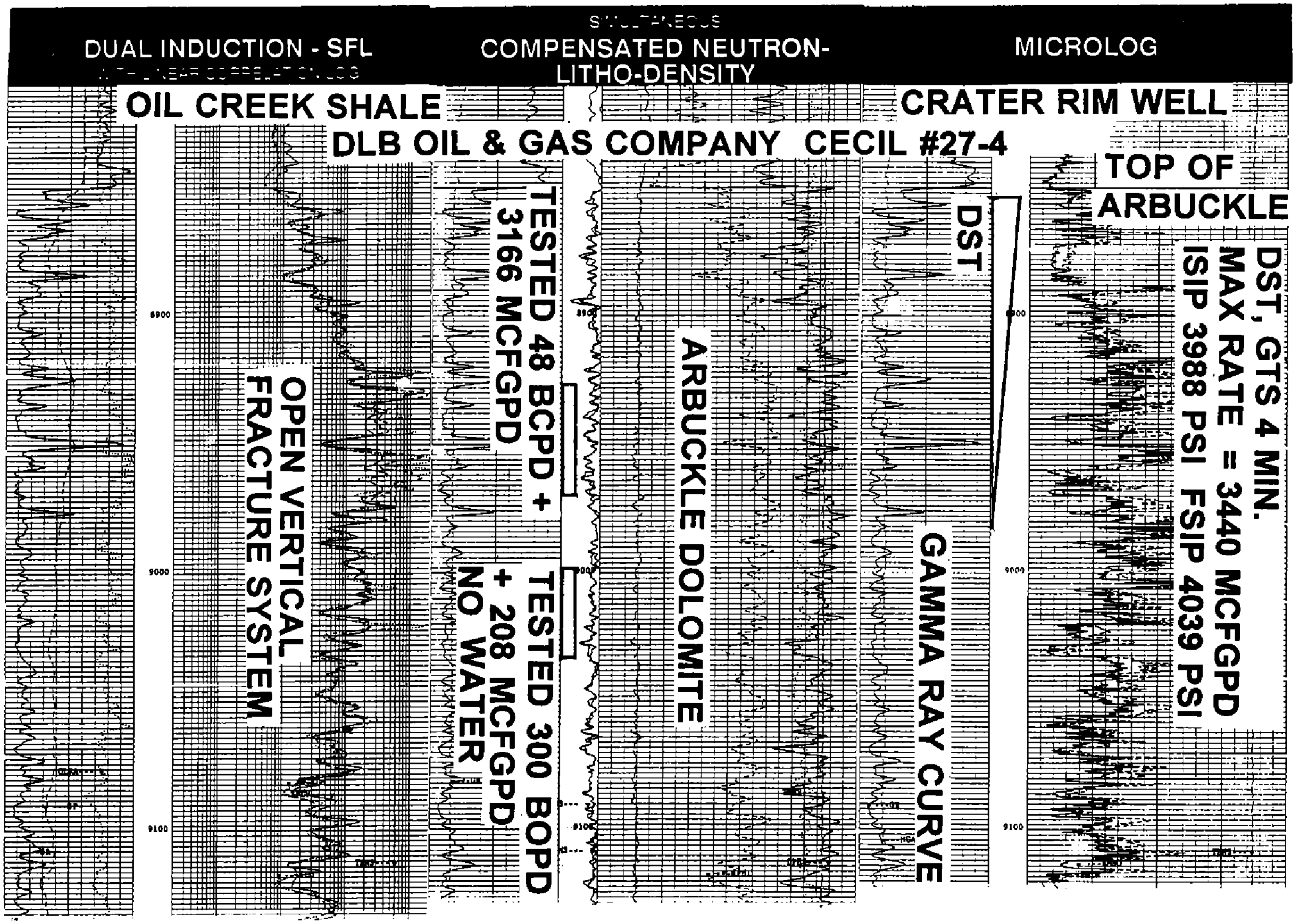



Figure 8. Resistivity, porosity, and micrologs of two Arbuckle dolomite intervals, tested separately by drill-stem test (DST) and through perforated intervals shown without major stimulation in the DLB 27-4 Cecil well, on the western rim of the structure in sec. 27, T. 21 N., R. 10 W.

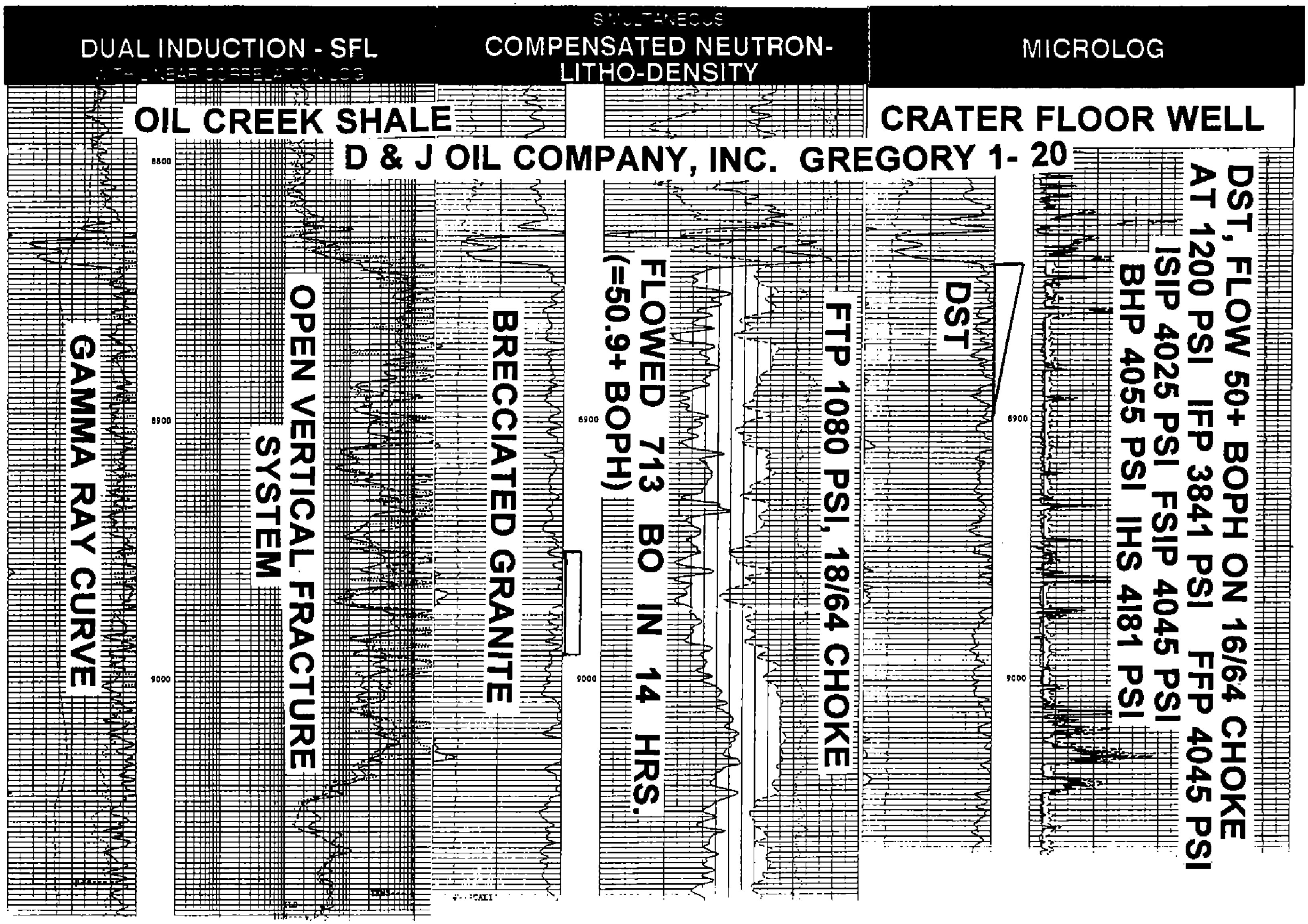



Figure 9. Resistivity, porosity, and micrologs of two brecciated granite intervals tested separately by DST and through perforated intervals shown without stimulation in the D. & J. Gregory 1-20 well, on the crater floor in sec. 20, T. 21 N., R. 9 W.

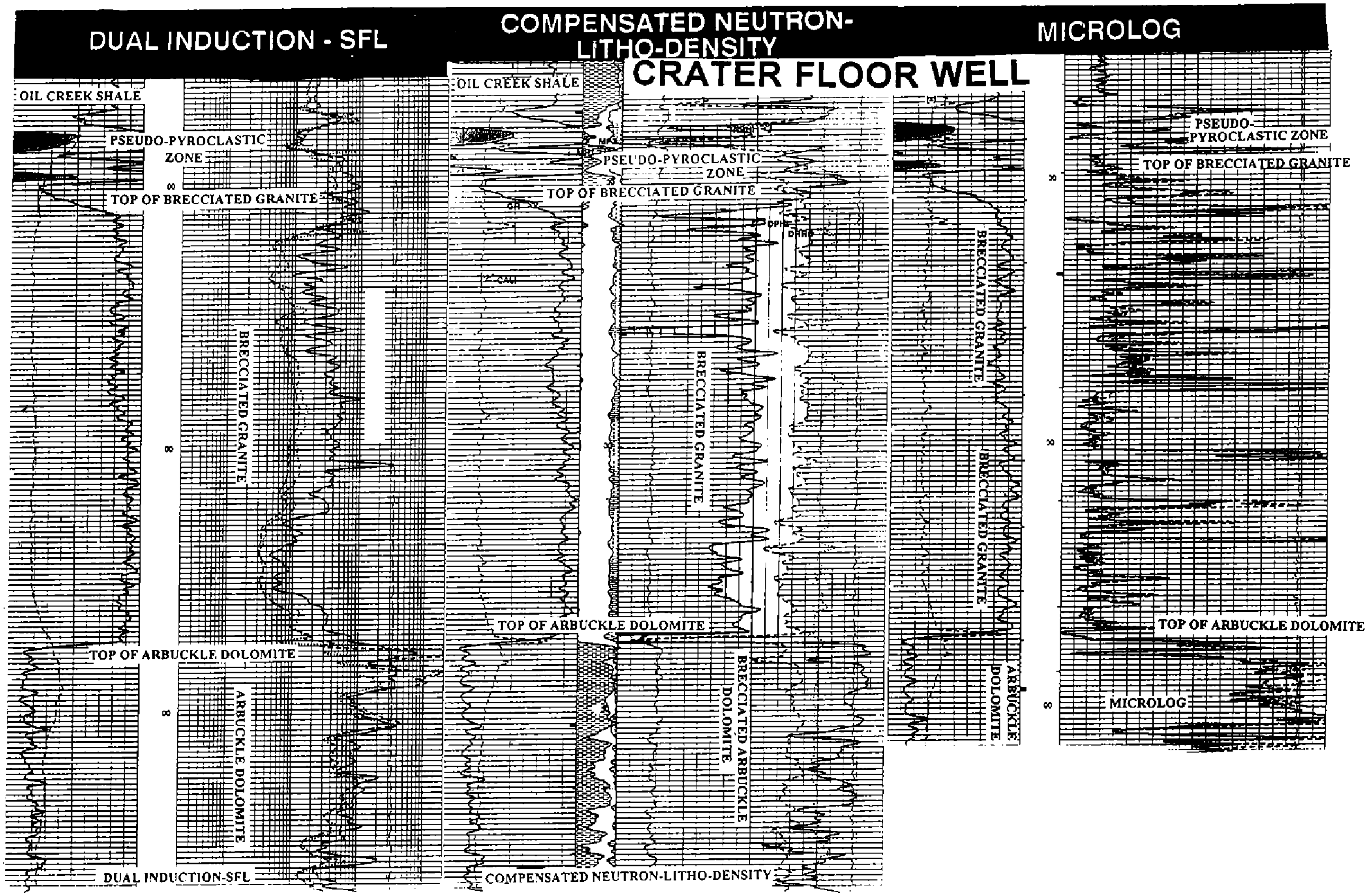



Figure 10. Resistivity, porosity, and micrologs of part of an unidentified Ames crater-floor well. Logs support drill-cuttings examination indicating the presence of brecciated granite underlying the Oil Creek Formation and overlying brecciated dolomite of the Arbuckle Group. Brecciation was determined in part from FMI imagery (Fig. 5).

east at the Stansberry (SE¼NW¼ sec. 21) and to the west at the Heinrich (S½NW¼ sec. 19), testing seismic closures. However, both of these wells produce from Arbuckle dolomite, with each well having tested at an initial rate of 50 BOPH. DLB also found Arbuckle production in their Allen no. 13-11 rim well (NE¼SW¼ sec. 13, T. 20 N., R. 10 W.) on the south side of the structure. They were also successful in establishing production from Arbuckle dolomite breccia in their DeHaas well (NE¼SW¼ sec. 21, T. 21 N., R. 10 W.). CRI drilled two rim wells on the west side. The Terry (SW¼NE¼ sec. 34, T. 21 N., R. 10 W.) is an Arbuckle gas well, and the Fisher (SW¼NE¼ sec. 3, T. 20 N., R. 10 W.) was not commercial.

## Current Activity

As of October 1992, 38 wells had been completed on the Ames feature. Of these, 31 are producing or waiting for production facilities. One of these is a horizontal extension of a vertical hole. Seven have been plugged or temporarily plugged, but some of these may be recompleted in shallower reservoirs or as horizontal extensions. Approximately eight wells were drilling as of November 1992. Two of these will be drilled as horizontal extensions in directions that will be determined by information obtained from the vertical hole. There are locations or spacing and increased density applications pending with the State Corporation Commission for an additional 90 wells. One company (DLB) accounts for most of these wells and locations. CRI and D. & J. each have 19. A total of 21 companies make up the balance of about 40 additional wells and locations, for a total of 121 potential wells. Many locations await the results of three-dimensional seismic surveys, currently being processed. Others await better completion and stimulation techniques to overcome problems related to high paraffin crude, early water coning, and possible migration of fines, which may have infiltrated into the open fractures on the rim and breccia on the crater floor.

A significant precedent was set with the redrilling of CRI's Chet well (NW¼NW¼ SW¼ sec. 19, T. 21 N., R. 9 W.). The original crater-floor well was drilled vertically and intersected a hydrocarbon-saturated reservoir in the breccia. CRI made the decision to recomplete the well as a horizontal extension, which intersected the tops of several Arbuckle and granite breccia highs on the crater floor. The well tested >700 bbl per day before being shut in to apply for a special allowable. This technique promises to increase production rates and to salvage wells that are structurally low and close to water, or that lack sufficient fracturing and dissolution porosity in the hydrocarbon column to produce at commercial rates.

DLB has acquired three-dimensional seismic over a structurally complex portion of the inner ring near the Gregory well. This approach is intended to reduce the risk of drilling off-structure wells and to provide locations that will not be drained by conventional well patterns.

## Acknowledgments

The authors acknowledge the cooperation of DLB Oil and Gas, Inc., and Continental Resources, Inc., for providing well logs and other well data that make the publication of this study possible. Thanks to Jock A. Campbell for his critical review and helpful suggestions.

## References Cited


Anderson, R. R.; and Hartung, J. B., 1992, The Manson impact structure: its contribution to impact material observed at the Cretaceous/Tertiary boundary: Proceedings of Lunar and Planetary Science, v. 22, p. 101–110.

Cannon, P. J., 1977, Meterorite impact crater discovered in central Alaska with Landsat imagery: Science, v. 196, p. 1322–1324.

_______ 1992, The Ames anomaly: Oral presentation before the Oklahoma City Chapter of the Society of Independent Professional Earth Scientists (SIPES), September 16, 1992.

Carpenter, B. N.; and Evans, M. C., 1991, Comparison of the Arbuckle Group at Wilburton Field, Latimer County, with N.E. Alden Field, Caddo County, Oklahoma, *in* Johnson, K. S. (ed.), Arbuckle Group core workshop and field trip: Oklahoma Geological Survey Special Publication 91-3, p. 111–132.

Donofrio, R. R., 1981, Impact craters: implications for basement hydrocarbon production: Journal of Petroleum Geology, v. 3, p. 279–302.

Hamm, Harold; and Olsen, R. E., 1992, Oklahoma Arbuckle lime exploration centered on buried astrobleme structure: Oil and Gas Journal, v. 90, no. 16, p. 113–116.

Hartung, J. B.; Kunk, M. J.; and Anderson, R. R., 1990, Geology, geophysics and geochronology of the Manson impact structure, *in* Sharpton, V. L.; and Ward, P. D. (eds.), Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 207–221.

Johnson, K. S., 1989, Geologic evolution of the Anadarko Basin, *in* Johnson, K. S. (ed.), Anadarko Basin Symposium, 1988: Oklahoma Geological Survey Circular 90, p. 3–12.

Johnson, K. S.; Luza, K. V.; and Roberts, J. F., 1980, Disposal of industrial wastes in Oklahoma: Oklahoma Geological Survey Circular 80, 82 p.

Kirschner, C. E.; Grantz, A.; and Mullen, M. W., 1992, Impact origin of Avak structure, arctic Alaska, and genesis of Barrow gas fields: American Association of Petroleum Geologists Bulletin, v. 76, p. 651–679.

Read, D. L.; and Richmond, G. L. [in press], Geology and reservoir characteristics of the Arbuckle Brown zone in the Cottonwood Creek Field, Carter County, Oklahoma, *in* Johnson, K. S.; and Campbell, J. A. (eds.), Petroleum reservoir geology in the southern Midcontinent, 1991 symposium: Oklahoma Geological Survey Circular.

Roberts, Craig; and Sandridge, Bob, 1992, The Ames hole: Oklahoma City Geological Society Shale Shaker, v. 42, no. 5, p. 118–121.

Roddy, D. J., 1977, Large-scale impact and explosion craters, comparisons of morphological and structural analogs, *in* Roddy, D. J.; Pepin, R. O.; and Merrill, R. B. (eds.), Impact and explosion cratering, planetary and terrestrial implications: Pergamon Press, New York, p. 185–246.

Sawatsky, H. B., 1975, Astroblemes in Williston Basin: American Association of Petroleum Geologists Bulletin, v. 59, p. 694–710.

Shirley, Kathy, 1992, Overlooked "hole" found: American Association of Petroleum Geologists Explorer, v. 13, no. 5, p. 1, 12–13.

Smith, D. J., 1985, Subsurface geology of the northern shelf of the Anadarko Basin, Woods, Woodward, Alfalfa, and Major Counties, Oklahoma: Oklahoma Geological Survey unpublished report.

_______ 1989, Subsurface geology of the northern shelf of the Anadarko Basin, *in* Johnson, K. S. (ed.), Anadarko Basin Symposium, 1988: Oklahoma Geological Survey Circular 90, p. 245–251.

# MINERAL INDUSTRY OF OKLAHOMA, 1991

The value of nonfuel mineral production in Oklahoma was estimated at approximately $261 million by the U.S. Bureau of Mines. This was a $500,000 increase over the 1990 figure. Although Oklahoma was one of a limited number of states whose nonfuel mineral value increased during the recessionary period, its mineral industry was obviously impacted by the recession. The growth curve for several minerals produced in-State was essentially flat. Increased output and value of portland and masonry cement, clays, feldspar, lime, and construction sand and gravel offset a declining demand for gypsum, iodine, industrial sand, and crushed stone. Oklahoma moved from 35th to 34th in nonfuel mineral value ranking nationally.

**Employment.**—Oklahoma's nonfuel mining employment in October 1991, the latest month with available data, totaled 42,000, a 1.9% decline from the 43,900 employed in October 1990. Employment in the oil and gas extraction sector was also down 1.9%, from 42,100 in October 1990 to 40,200 in 1991.

**Environment.**—In January, the U.S. Department of the Interior announced that Oklahoma would receive a $643,500 grant to help pay for abandoned surface coal mine reclamation in 16 eastern counties. In August, a reclamation project in Haskell County was completed when six acres of abandoned mine land was graded and converted to pasture. A total of 47 acres in Haskell County have been reclaimed at a cost of approximately $4,700 per acre.

A State appellate court decision strengthened Oklahoma's ability to enforce the reclamation of mineral lands. The court ruled in the case of Duane's Granite Pit vs. the Oklahoma Department of Mines that an operator cannot be relieved of the obligation to reclaim lands as mandated by a previous agreement with the landowner to not reclaim the property.

At year end, Latimer and Pittsburg County residents expressed concern over a proposed permit change sought by P & K Mining Co. The company requested that the Oklahoma Department of Mines reclassify 55.5 acres in the Gowen area from pasture land to industrial use. The change would allow the mining company to extract "iron and other unspecified minerals." A local stream had been polluted by acid mine drainage, and the citizens were concerned about new mining creating additional pollution problems.

In November, the Cherokee Nation filed a petition with the Nuclear Regulatory Commission to revoke the license of the Sequoya Fuels Co. uranium processing plant at Gore. During the year, contamination was discovered within the plant boundary.

**Legislation and Government Programs.**—Section 5 of Senate bill 326, which became law in June, directed the formation of a task force to examine "the quality and quantity of environmental regulations in Oklahoma by State agencies." Nine State agencies, including the Department of Mines, regulate and manage environmental concerns. A 33-member task force was given the responsibility for conducting this examination.

The Oklahoma Geological Survey hosted a workshop in September on the role of industrial minerals in the rebuilding of the infrastructure of major cities in the midcontinental United States. The Oklahoma Department of Mines, Oklahoma Miner Training Institute, and the U.S. Mine Safety and Health Administration co-sponsored a health and safety converence in July. The conference featured workshops with speakers from mining, manufacturing, labor, and government.

## NONFUEL MINERAL PRODUCTION IN OKLAHOMA

| Mineral | 1990 Quantity[b] | 1990 Value (thousands) | 1991[a] Quantity[b] | 1991[a] Value (thousands) |
|---|---|---|---|---|
| Cement: | | | | |
| Portland (thousand short tons) | 1,544 | $60,457 | 1,686 | $65,754 |
| Clays (metric tons) | 631,302 | 3,156 | 686,480 | 3,391 |
| Gypsum (crude) (thousand short tons) | 2,184 | 11,154 | 2,036 | 10,624 |
| Iodine (crude) (kilograms) | 1,972,849 | 30,486 | 1,926,478 | 29,558 |
| Sand and gravel: | | | | |
| Construction (thousand short tons) | 9,235 | 21,993 | 9,300[c] | 22,300[c] |
| Industrial (thousand short tons) | 1,258 | 22,984 | 1,250 | 22,800 |
| Stone: | | | | |
| Crushed[d] (thousand short tons) | 25,300[c] | 89,500[c] | 24,500 | 83,100 |
| Dimension (short tons) | 8,138[c] | 684[c] | 8,000 | 700 |
| Tripoli (metric tons) | 18,801 | 155 | — | — |
| Combined value of cement (masonry), feldspar, gem stones, lime, salt (1990–91), stone (crushed granite) | — | 19,608 | — | 22,416 |
| Total | — | 260,177 | — | 260,643 |

Source: USBM Denver Regional Office of State Activities in cooperation with the Oklahoma Geological Survey.
Dashes indicate data not available, withheld to avoid disclosing company proprietary data, or not applicable.
[a]Preliminary figures.
[b]Production as measured by mine shipments, sales, or marketable production (including consumption by producers).
[c]Estimated.
[d]Excludes certain stones; kind and value included with "Combined value" data.

The U.S. Bureau of Land Management (BLM) proposed that the royalty rates for federally owned coal in nine Oklahoma counties be reduced. The BLM noted that the rates had been "out-of-line" with the eastern Oklahoma coal market for several years, resulting in federal coal mined at a loss or bypassed by mining companies.

**Fuels.**—Coal production during the first three quarters of 1991 totaled 1,524,431 tons, and increase of 20% over the 1,275,032 short tons mined during the same period in 1990.

**Review by Nonfuel Mineral Commodities.**—Crushed stone continued as the leading mineral commodity, in terms of value, in Oklahoma, followed by portland cement and iodine. The three accounted for 68% of the total mineral value.

Humble Sand and Gravel Co., Picher, continued shipments of bagged sand to Dammann, Saudi Arabia, for pipeline coating. Demand was unaffected by the United Nations–Iraq conflict. The company shipped 3,000–6,000 bags to the Saudis during the 1988–91 period.

Uranium oxide, extracted during phosphoric acid manufacture in Florida, was shipped to Sequoya Fuels Corp.'s plant in Gore. The plant was licensed to produce uranium hexafluoride used in making reactor fuels. It also produced depleted uranium tetrafluoride used to produce solid depleted uranium. During the year, company inspectors discovered 21,100 pounds of uranium contamination under plant buildings.

## NEW OGS PUBLICATION

**GEOLOGIC MAP OF THE SUMMERFIELD QUADRANGLE, LE FLORE COUNTY.** Scale 1:24,000. Xerox copies.
Price: $6 each, rolled in tube.

The Ouachita COGEOMAP Project is a joint effort of the U.S. Geological Survey, Oklahoma Geological Survey, and Arkansas Geological Commission to prepare a series of new geologic maps of the Ouachita Mountains in Oklahoma and Arkansas. The project includes review and compilation of existing information and maps on the Ouachita Mountains, and new geologic mapping at a scale of 1:24,000 (7.5′ topographic base). The purpose of the mapping is threefold: The new maps should provide a basis for (1) resource exploration and development, (2) land-use planning such as highway construction, and (3) university field trips and future theses.

Based on existing geologic maps and resource interest and potential, the Oklahoma Geological Survey elected to focus its mapping effort on a west-to-east strip of 7.5′ quadrangles starting immediately southeast of Hartshorne, Oklahoma, and ending at the Arkansas state line. The mapping effort was designed to begin where the geologic map by Hendricks and others (1947) ended, and to include all the area within the quadrangles south of the Choctaw fault. Later, it was decided to map those parts of the Arkoma basin affected by Ouachita tectonics and included in quadrangles that contain the Choctaw fault.

Mapping began in 1986 and is continuing. The first three maps (Higgins, Damon, and Baker Mountain) were released in 1989; the Panola, Wilburton, and Red Oak Quadrangles were released in 1990; the Leflore, Talihina, Blackjack Ridge, and Leflore SE Quadrangles were released in 1991; and the Gowen Quadrangle was released earlier this year.

The Summerfield Quadrangle, by LeRoy A. Hemish and Colin Mazengarb, is now available as black-and-white, author-prepared xerox copies, comprising geologic map, cross sections, description and correlation of units, and a list of wells.

COGEOMAP geologic quadrangle maps of the Ouachita Mountains 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. For mail orders of 1–10 maps, add $1.50 to the cost for postage and handling.

## OGS GEOLOGISTS RECEIVE AWARDS

Two Oklahoma Geological Survey geologists received special awards at this year's annual meeting of the Geological Society of America in Cincinnati. The awardees were Kenneth S. Johnson, associate director, and Samuel A. Friedman, senior coal geologist.

Johnson received an award from the Geoscience Information Society for the best geological field-trip guidebook prepared in 1991. The annual award was presented to him as editor of OGS Special Publication 91-3, *Arbuckle Group Core Workshop and Field Trip.*

Friedman received the Distinguished Service Award of the GSA Coal Geology Division. The award is presented annually to individuals for outstanding service to the division and/or for contributions to coal geology.

# GSA SOUTH-CENTRAL SECTION MEETING
# Fort Worth, Texas, March 14–16, 1993

The Department of Geology of Texas Christian University will host the 27th meeting of the South-Central Section of the Geological Society of America. The meeting will be held jointly with the Texas Section of the National Association of Geology Teachers and the South-Central Section of the Paleontological Society. The following meetings and field trips are planned.

## Symposia

Microcomputer Applications in Geology
Urban and Environmental Geology
Shallow Groundwater Systems
Environmental Concerns in the Dallas/Fort Worth Metroplex
Precambrian Connections across Southern North America
Geologic Problems to be Solved by Scientific Drilling
Fractionation Processes in High-Temperature Systems
Petroleum Geology of the South-Central United States
Carbonate Rocks of the Southern Midcontinent
Caves and Karst
Sequence Stratigraphy of Cratonic Cycles
Geographic Information Systems (GIS) and Land Use Planning
The Role of Planetary Geology in Teaching Geology Today

## Field Trips

Structural and Stratigraphic Correlations across the Grenville Deformational Front in West Texas, *March 11–14*
Sequence Stratigraphy of Middle and Late Pennsylvanian Cycles: North-Central Texas, *March 13–14*
Environmental Geology and Hydrogeology of the Dallas/Fort Worth Metroplex, *March 17*
Geology of the Slick Hills of Southern Oklahoma: The Northern Boundary of the Wichita Uplift, *March 17–18*

## Short Courses

Valley Fills—A Core Workshop
Subsurface Facies Analysis from Well Logs and Core

For further information about the meeting, contact John A. Breyer, Dept. of Geology, P.O. Box 30798, Texas Christian University, Fort Worth, TX 76129; (817) 921-7270. The pre-registration deadline is February 19.

# UPCOMING MEETINGS

**Lunar and Planetary Science, Annual Meeting**, March 15–19, 1993, Houston, Texas. Information: Pamela Jones, Program Services Dept., Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058; (713) 486-2150.

**Society of Petroleum Engineers, Annual Meeting**, March 21–23, 1993, Oklahoma City, Oklahoma. Information: SPE, 222 Palisades Creek Dr., Richardson, TX 75080; (214) 952-9393, fax 214-952-9435.

**Fluvial-Dominated Deltaic Reservoirs in the Southern Midcontinent, A Workshop**, March 23–24, 1993, Norman, Oklahoma. Information: Kenneth S. Johnson, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031, fax 405-325-3180.

**Mid-America Paleontology Society, Extinct Echinoderms Symposium**, April 16–18, 1993, Macomb, Illinois. Information: Tom Witherspoon, MAPS, 6611 Miller Rd., Dearborn, MI 48126; (313) 582-3139.

**Society of Economic Geologists/Society of Exploration Geophysicists, Integrated Methods in Exploration and Discovery Meeting**, April 17–20, 1993, Denver, Colorado. Information: J. Alan Coope, SEG Conference '93, Box 571, Golden, CO 80402; (303) 837-5819, fax 303-837-5851.

**Application of Geophysics to Environmental and Engineering Problems, 6th Annual Symposium**, April 18–21, 1993, San Diego, California. Information: R. Allan Payne, Spectrum Environmental Geophysics, 1000 N. Maclay Ave., San Fernando, CA 91340; (818) 365-9371, fax 818-361-1680.

**American Association of Petroleum Geologists, Annual Meeting**, April 25–28, 1993, New Orleans, Louisiana. Information: Convention Dept., AAPG, Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

## Deltaic-Reservoirs Workshop Set for March 23–24

The Oklahoma Geological Survey and the Bartlesville Project Office of the U.S. Department of Energy will co-sponsor a two-day workshop on "Fluvial-Dominated Deltaic Reservoirs in the Southern Midcontinent." The workshop will be held March 23–24, 1993, in Norman, Oklahoma, and will have 200–300 attendees.

Fluvial-dominated deltaic reservoirs that have been discovered contain large volumes of remaining oil and gas, and they have a large potential for additional recovery using advanced recovery technologies. The workshop will present discussions and reports on surface or subsurface studies dealing with the geologic setting, depositional environments, and diagenetic history of such reservoirs, as well as reservoir characterization and the engineering factors that influence hydrocarbon accumulation or hydrocarbon production.

The full program will be announced in the next issue of *Oklahoma Geology Notes*.

# OKLAHOMA ABSTRACTS

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.

## Pennsylvanian Pseudozygopleurid Microgastropod Biostratigraphy in the Mid-Continent of the United States

JOHN R. ANDERSON, JR., Division of Science, DeKalb College, Dunwoody, GA 30338; and DARWIN R. BOARDMAN, II, Dept. of Geology, Oklahoma State University, Stillwater, OK 74074

Recent studies have shown that microgastropods are useful for biostratigraphic zonation within the Pennsylvanian strata complementing those for fusulinids, conodonts, and ammonoids. Microgastropods have been found in units in which these other groups were not found, thus, correlations of these strata, which traditionally have been difficult, have been able to be made.

The subgenus *Plocezyga (Plocezyga)* has been used to establish a Desmoinesian to Virgilian biostratigraphic zonation in North-Central Texas. This zonation has also been observed in the Appalachian Basin. First occurrence species-level range zones for the Desmoinesian–Virgilian interval include: (from oldest to youngest) *Plocezyga (Plocezyga) excellens, P. (P.) robustus, P. (P.) costata, P. (P.) subquadrata, P. (P.) ornata, P. (P.) acuminata, P. (P.) obscura, and P. (P.) procerus.* The Desmoinesian–Missourian boundary has been marked by the first occurrence of *Plocezyga (Plocezyga) costata* where the first occurrence of *P. (P.) obscura* is slightly above the Missourian–Virgilian boundary.

The Desmoinesian–Missourian boundary has been recognized in Oklahoma based on the first occurrence of *Plocezyga (P.) costata.* Other *Plocezyga* species have also been found in the Oklahoma Pennsylvanian strata which conform with the zonation of North-Central Texas. Also around the Missourian-Virgilian boundary in Oklahoma, *P. (P.) obscura* has been found.

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## Mass-Balancing the Climatic and Tectonic Influences on Deposition of Pennsylvanian Coal-Bearing Cyclothems

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Recalibrated sedimentological determinations of the magnitude of sea-level changes associated with deposition of North American Pennsylvanian cyclothems show that they accumulated in water depths ranging from 40 to 160 m in the

Midcontinent, 12 to 30 m in the Illinois basin, and 20 to 31 m in the Appalacian basin. Average sea-level change for Midcontinent cyclothems is 96 and 86 m for proposed sea-level curves of Heckel and Gerhard, respectively.

Determination of per-cycle tectonic subsidence establishes the tectonic contribution to sea-level change. In the Midcontinent, tectonic subsidence accounts for approximately 5 to 20% of sea-level change, whereas in the Illinois basin it accounts for 11 to 92% of sea-level change. In the Appalachian basin, 9 to 100% of sea-level change is tectonic.

Paleoclimate modeling suggests that 70% of sea-level change is controlled by glacio-eustasy in the Midcontinent. In the Illinois and Appalachian basins, glacio-eustasy accounts for a range of sea-level change from 8 to 89% and 0 to 91% respectively.

In the Illinois and Appalachian basins, concurrent tectonic and glacio-eustasic forcing appears to be in balance to account for Pennsylvanian sea-level change. In the Midcontinent, up to an additional 15% of sea-level change is required to balance the total magnitude of sea-level change. Long-term climate change, perhaps controlled by paleotectonic shifts of North America from the tropical belt into the Hadley zone may account for these additional changes in sea-level.

These findings suggest that away from orogenic belts, the sedimentary record indicates a stronger preservation of climate-forced deposition, whereas in orogenic belts, climate influences become subordinate, even though indicators of climate change appear to be preserved.

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## Depositional Setting and Sandstone Diagenesis of the Upper Pennsylvanian (Missourian) Hepler Formation, Cherokee Shelf of the Midcontinent

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The Hepler Formation marks the base of the Pleasanton Group which is recognized as the base of the Upper Pennsylvanian in southeastern Kansas. This formation consists of interstratified units of shales, siltstones, and sandstones, as well as a localized coal bed. These lithologies are interpreted as having formed in a prograting, fluvially dominated deltaic sequence that was deposited as the Late Pennsylvanian sea temporarily withdrew from the Cherokee shelf. Hepler sandstone bodies in the study area are predominately quartz arenites and sublitharenites.

The diagenetic history of the Hepler consisted of alternating periods of authigenic mineral precipitation and dissolution of both detrital grains and cements. Petrographic observations indicate that silica cementation, in the form of quartz overgrowths, took place early in the paragenetic sequence. Changes in the meteoric water chemistry, resulted in partial quartz and feldspar dissolution, and alteration of feldspars to clays. Precipitation of carbonate into dissolution features was initiated by acidic surface waters (fluvial) followed by a sea level rise allowing carbonate-saturated marine waters to flush these sediments. Further burial and compaction destroyed much of remaining porosity and left concavo-convex contacts and sutured quartz grains. This was followed by anoxic conditions which allowed pyrite crystallization to take place. A subsequent fall in sea level exposed Hepler deposits once again to meteoric, low pH waters, resulting in carbonate dissolution. All observed porosity is secondary, formed by carbonate dissolution. Surface samples were subjected to weathering of iron-bearing components to iron-oxide, a product not observable in subsurface core samples.

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## Widespread Buried Precambrian Layered Sequences in the U.S. Mid-Continent: Evidence for Large Proterozoic Depositional Basins

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Large regions of the North American mid-continent are underlain by Precambrian layered rocks buried beneath Phanerozoic sedimentary strata. South of the Wichita Mountains, published seismic reflection profiles show a Precambrian layered assemblage extending for at least 40 km in both the north–south and east–west directions, and industry data show that it may continue 150 km to the southeast. Seismic reflection data in the Illinois region show a Precambrian layered assemblage extending 320 km in an east–west direction and 200 km in a north–south direction. In both cases, the layered rocks are as much as 12 km thick. Apparent sequence boundaries (onlap, downlap) within these assemblages suggest they are parts of large depositional basins with diffractions and dipping strata due to faulting. The layered sequences correlate with regions of relatively long-wavelength and low-amplitude magnetic anomalies; the extent of this magnetic signature suggests that about 200,000 $km^2$ of Illinois, Indiana, and western Ohio, about 50,000 $km^2$ of southernmost Oklahoma and north-central Texas, and about 32,000 $km^2$ of southern Missouri and northern Arkansas may be underlain by similar Precambrian strata.

Drill holes indicate that the top of the mid-continent Precambrian "basement" is composed largely of silicic igneous rocks. Such material may comprise a large part of the layered sequences. Alternatively, these igneous rocks could be intermixed with, or underlain by, nonvolcanic (meta?) sedimentary strata. The strong reflectivity of some layers suggest that minor mafic flows and/or sills may also be present. Analysis of U/Pb and Nd/Sm isotopes within the granites and rhyolites imply that the layered sequences postdate crustal formation at 1.7–2.0 Ga and predate or are contemporaneous with the 1.3–1.5 Ga crystallization ages of the granites and rhyolites. Though these layered rocks have a spatial association with igneous rocks and thus have likely been metamorphosed, the possibility that they contain Precambrian hydrocarbons that escaped heating is as yet untested.

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## Diagenetic History of Missourian (Upper Pennsylvanian) Chanute Shale, Cherokee Shelf, Midcontinent, U.S.A.

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The Chanute Shale consists of two sandstone bodies deposited in fluvial deltaic complexes separated by a shale unit and a coal. The lower Chanute is characterized by very fine- to medium-grained sandstone that fill channels at its base, while the upper Chanute includes silt to fine-grained sandstone bodies. Petrographic analyses of both units show that they consist of quartz arenites, subarkose, sublitharenite, feldspathic litharenites, litharenites and wackes of the same compositions.

Silica-supersaturated waters in the meteoric regime cemented the Chanute sands creating thin and discontinuous overgrowths on detrital quartz grains. Early calcite cement precipitated afterwards, inhibiting further silica cementation and shielding feldspars and other liable grains from extensive dissolution. A change in the composition of the meteoric waters, possibly due to sea level changes, caused calcite dissolution leaving patches of cement. As Chanute sands entered the compactional regime, saline and alkaline waters dissolved quartz grains and overgrowths as well as other liable grains no longer shielded by the early carbonate cement. The absence of cements and continued compaction resulted in concave-convex and sutured contacts. Dissolution and alteration of feldspars, and other liable grains, alteration of micas to clays, and chloritization of biotite and clays continued in the compactional regime. Acidified waters released from organic matter and coal altered micas and feldspars to kaolinite and other clays, releasing Fe, Mg, and Ca necessary for late precipitation of ankerite, dolomite, and calcite cements. Extensive clay and iron oxide coatings formed, filling embayments on the etched grains. During subsequent Pennsylvanian low sea level stands, ground water dissolved most carbonate cements, creating secondary porosity. Porosity was further enhanced on the outcrop belt (up to 44%) during weathering, leaving boxwork structures of iron oxide, and higher total iron oxide content on surface samples compared to core samples.

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## Regional Groundwater Mixing Processes in the Midcontinent: Origin and Evolution of Saline Groundwaters

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Groundwaters in Cambrian–Ordovician through Mississippian carbonates in southeastern Kansas, southwestern Missouri, and northern Oklahoma comprise portions of three regional flow systems. In southeast Kansas groundwaters are transmitted eastward in the Western Interior Plains aquifer system (WIPS) and in southwest Missouri, groundwaters in the Ozark Plateaus aquifer system (OPS) migrate westward. In the southern part of the WIPS groundwaters migrate to the northeast

from the Anadarko basin. Samples collected over a 40,000 $km^2$ area range from 200 to 290,000 mg/1 total dissolved solids (TDS) and exhibit extreme elemental and isotopic variations. Integration of regional hydrology, geochemical data, and geographic locations indicates that the three systems contain waters of markedly different origins. Elemental and isotopic mass balance modeling of fluid mixing processes closely accounts for geochemical variations throughout the study area. This provides an important basis for determining endmember water compositions in these flow systems and for evaluating hydrologic models. The three endmembers are: (1) Dilute meteoric waters recharged to the OPS. $\delta D$–$\delta^{18}O$ values are similar to present-day local rainfall. $^{87}Sr/^{86}Sr$ values range from 0.7099–0.7116. (2) Far-traveled Na–Ca–Cl saline (22,000 to 35,000 mg/l TDS) waters in the WIPS. Regional salinity variations and low $\delta D$–$\delta^{18}O$ values along the meteoric water line indicate that this endmember represents a mixture of dilute meteoric recharge from west of the study area and downward cross-formational flow of saline waters. $^{87}Sr/^{86}Sr$ values of 0.7121–0.7153 reflect interaction with silicate rocks along the waters' long migration path. Salinity is acquired via the subsurface dissolution of Permian halite and interaction with silicate rocks. (3) Na–Ca–Cl brines in the southern part of the WIPS. In contrast to the other endmembers, endmember 3 is (a) highly saline (avg. 240,000 mg/1 TDS), (b) has $\delta D$–$\delta^{18}O$ values displaced from the meteoric water line near values for modern seawater, and (c) has low $^{87}Sr/^{86}Sr$ values of 0.7091–0.7099. Models involving the modification of Paleozoic seawater can account for this endmember's elemental and isotopic composition, although extensive alteration of non-marine fluids by water-rock interaction cannot be excluded.

Two saline groundwaters in this regional system are indicative of distinct origins and evolutions: evaporite dissolution by meteoric waters and the modification of ancient marine waters. The operation of both of these mechanisms in a single groundwater system bears on generalized models for the origin of saline basinal fluids.

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## Biothems: Sequence Stratigraphic Units and Their Implications for Regional Tectono-Stratigraphic Interpretations

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Biothems are regional wedge- or lens-shaped bodies of strata that are bounded shelfward or cratonward by paleontologically recognizable unconformities; generally thicken on marine shelves, where they are typically conformable with underlying and overlying biothems; are commonly thinner or represent "starved" sequences further basinward; and in their most basinward extent, are either bounded by biostratigraphically recognizable unconformities or are conformable with underlying and overlying biothems. Biothems are practical units whose definition and degree of refinement are dependent on the quality and availability of biostratigraphic control. As recognized to date, biothems have a logical distribution of faunal and floral components, as well as facies groupings that represent internally consistent and logical sequences of depositional environments. The use of biothems as primary sequence stratigraphic units places the emphasis on relative time in a stratigraphic framework.

A west-to-east transect within the North American Mississippian System which extends from the Basin and Range Province, across the Transcontinental Arch (TA), into the Anadarko Basin, was constructed to demonstrate the regional distribution and tectono-stratigraphic significance of biothems relative to the axis of the TA. The relationships portrayed on the transect, tied to an understanding of North American Mississippian paleogeography, imply that biothems deposited during relative highstand events on one flank of the TA are time-equivalent to biothems deposited during relative lowstand events on the opposite flank of the TA. This distribution is interpreted to have been controlled by intraplate tectonic events that formed "piano key" basins along the flanks of the TA. The spatial patterns of these basins are not consistent with published models of basin evolution. A further conclusion is that the lack of coincident, transgressive or regressive Mississippian biothems on either flank of the TA suggests that it is inadvisable to impose the Mississippi Valley-derived eustasy curve on western flank depositional sequences.

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## Geometry and Lateral Slip Distribution along Large Thrust Fault Systems

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Quantitative relationships between fold and fault shapes allow detailed analyses of thrust fault geometries and slip histories. Fold limbs (kick bands) that grow by axial surface migration above bends in thrust faults record dip-slip motion. Folds imaged in high-resolution seismic reflection profiles record this total fault dip-slip and reflect causative thrust fault geometry. Growth (syntectonic) strata deposited during the active history of underlying thrusts develop limb widths equal to the amount of fault dip-slip since their deposition. Therefore, narrowing upward kink bands (growth triangles) form as sediments deposited earlier in the slip history record wider limb widths than do sediments deposited later. Ages of selected syntectonic strata (determined independently) in growth triangles allow estimates of long term fault-slip rates.

Maps of axial surfaces that bound kink bands, constructed through grids of high-resolutions seismic reflection profiles, highlight changes in thrust fault geometry along strike and record lateral fault-slip distribution. In many cases, map view kink band widths are equal to dip-slip thrust ramps from décollements. Therefore, narrowing kink band widths (converging axial surfaces) in map view suggest decreasing total fault slip along trend. In addition, ends and offsets of kink bands in map view highlight fault terminations and lateral changes in thrust fault geometry. Maps of axial surfaces in growth strata record lateral slip distribution along thrust faults through time. Examples from southern California and Oklahoma demonstrate how slip propagates along large thrust faults and show how lateral discontinuities in fault geometry affect slip distribution.

Detailed analyses of fold and fault geometries constrain balanced, three-dimensional structural models that show how large thrust faults develop and slip through time. These models and cross sections integrate G.P.S. measurements and seismicity from active thrust fault systems. Lateral variations in fold shape caused by changes in thrust fault geometry may form lateral closure along fold trends that trap hydrocarbons. In addition, axial surface maps highlight lateral changes that may segment faults and limit the area ruptured in single earthquakes. Combined, fault slip rates and fault geometry yield estimates of the size and recurrence of potentially damaging earthquakes on blind thrust fault systems.

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## The Implication of the Oxygen Isotopic Composition of Lower Devonian Micritic Limestone, Oklahoma

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The documented $\delta^{18}O$ values ($\leq -3.6‰$, PDB) of presumably well preserved lower Devonian marine carbonates are significantly lower than those ($\geq -2‰$, PDB) of post-Devonian carbonates. These have been interpreted to have resulted from either $^{18}O$-depleted ($<-2‰$, SMOW) or hot (40° to 60°C) oceans, relative to post-Devonian oceans. To test these hypotheses, micritic limestones were sampled for oxygen (as well as carbon and strontium) isotope analysis from the lower Devonian (Lochkovian) Haragan–Bois d'Arc formations of the Hunton Group, South-Central Oklahoma.

Of the 25 analyzed samples, 22 samples are characterized by high $\delta^{18}O$ values ranging from –1.9‰ to –2.9‰ (PDB). These are the highest $\delta^{18}O$ values ever documented for lower Devonian carbonates. Because the Haragan–Bois d'Arc limestones were deposited in a shallow normal marine setting and have both $\delta^{13}C$ values (+1.1‰ to +2.5‰, PDB) and $^{87}Sr/^{86}Sr$ ratios (0.70838 to 0.70847) similar to other lower Devonian carbonates elsewhere, the high $\delta^{18}O$ values of these limestones are unlikely to have originated either from any unusual depositional (such as evaporitic) setting or from diagenetic alteration at low temperatures by $^{18}O$- and $^{87}Sr$-enriched basinal brines.

The high $\delta^{18}O$ values of the Haragan–Bois d'Arc limestones are thus interpreted to represent near-primary signals. Using established relationship $10^3 \ln \alpha_{calcite-water} = 2.78 \times 10^6 T^{-2}$ (°K) –2.89 (Friedman and O'Neil, 1977; where $\alpha$ is the isotopic fractionation factor), the temperatures and $\delta^{18}O$ values of early Devonian seawater can be constrained to have been 25° ± 7°C and 0 ± 1‰ (SMOW), respectively. This implies that neither $^{18}O$ depletion nor high temperatures characterized early Devonian oceans.

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