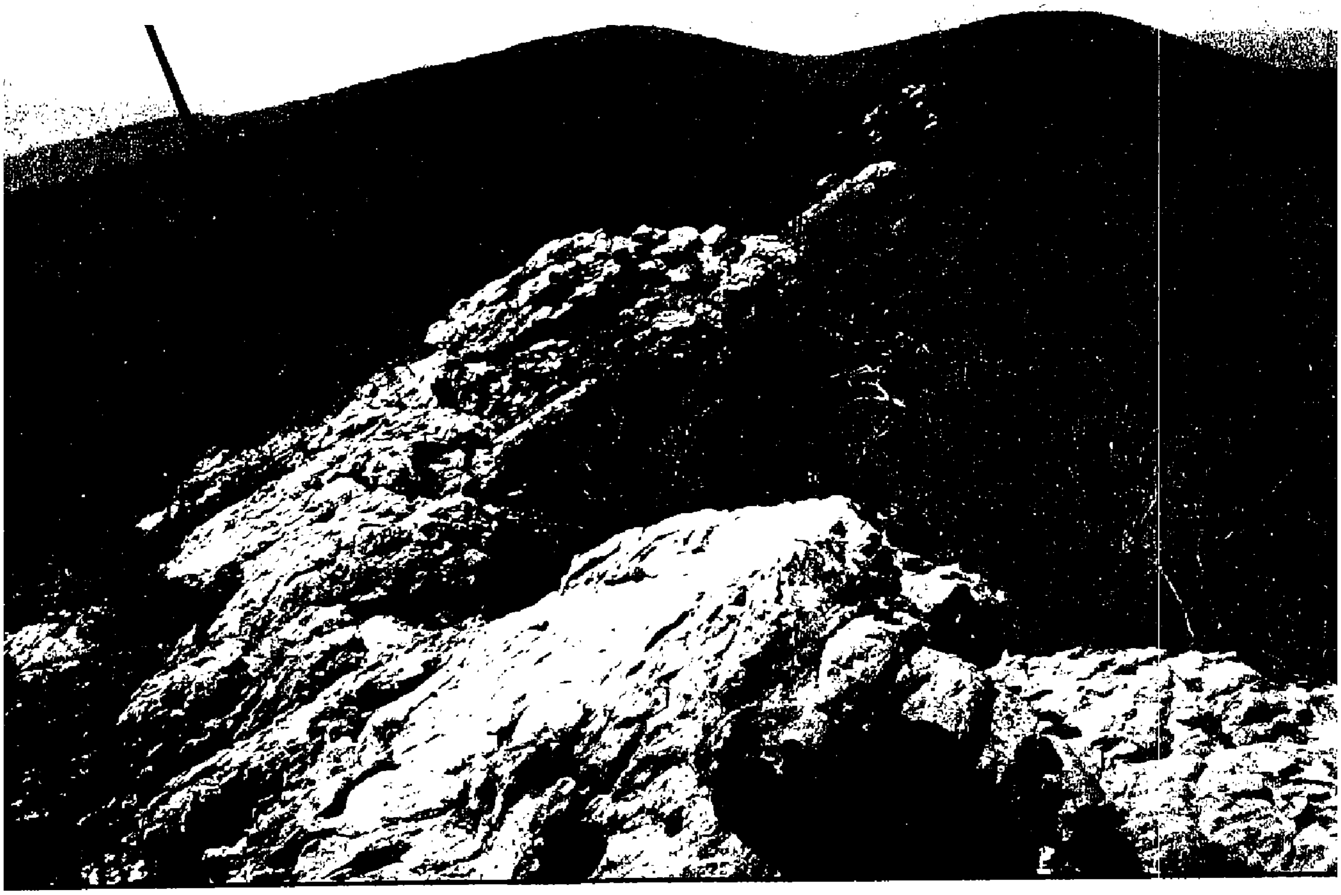
OKLAHOMA GEOLOGY



June, 1994

Vol. 54, No. 3

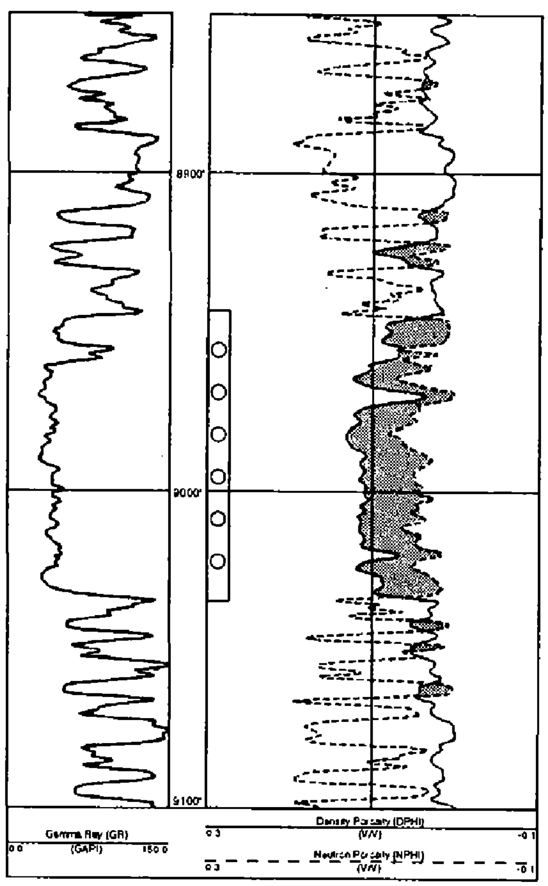
On The Cover —

McKinley Rocks, Ouachita Mountains, Oklahoma

McKinley Rocks in the Ouachita Mountains, Pushmataha County, Oklahoma (sec. 6, T. 1 N., R. 20 E.). This view is looking west along the ridgeline and is almost identical to the photograph used as the frontispiece to Pitt and others' (1982) book on the geology of Pushmataha County.

Recent natural-gas exploration in the Ouachita Mountains frontal belt in southern Latimer County has proven that there are reservoir-quality strata in the Jackfork Group (Morrowan) (Fig. 1). Previous recognition of potential reservoir sandstones in the Johns Valley Shale and basal part of the Atoka Formation to the south (Legg and others, 1990)

(continued on p. 136)



I.P. = 4.6 MMCFGPD
"Lower" Jackfork

Figure 1. Part of electric log (8,850–9,100 ft) from H&H Star No. 1-28 Lady Luck (sec. 28, T. 4 N., R. 21 E.). From Pauli (in press, fig. 19).

OKLAHOMA GEOLOGICAL SURVEY

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OKLAHOMA GEOLOGY *Notes*

VOL. 54, NO. 3

Subsurface Structural Geology of the Potato Hills, Ouachita Mountains, Oklahoma

Mark W. Allen[1]

Abstract

Interpretation of seismic data, electric and sample logs, and surface geology indicates that the thrust faults in the Potato Hills are the surface expression of an imbricate-fan thrust system. With the exception of the North Potato Hills thrust, these thrusts are imbrications that developed out of sequence, that is, sequentially from north to south after north-directed, horizontal translation on a basal detachment.

Introduction

The Potato Hills area, located in southern Latimer and northern Pushmataha Counties, Ouachita Mountains, southeastern Oklahoma (Fig. 1), is structurally complex. It is comprised of lower and middle Paleozoic strata situated in the anticlinorial Kiamichi Valley ~3 mi south of the trace of the Windingstair fault. The topography in this area consists of a series of low, isolated hills rising 200–500 ft above the surrounding valley. Strata exposed in the Potato Hills range from Middle Ordovician Womble Shale to Mississippian Stanley Group and consist of interbedded incompetent shale and competent chert and sandstone (Fig. 2).

Surface traces of major thrusts in the Potato Hills (North Potato Hills thrust, South Potato Hills thrust, Cedar Creek thrust) locally juxtapose Womble Shale–Stanley Group against Stanley Group. The Jackfork Mountain and Buffalo Creek thrusts juxtapose Stanley against Stanley along their surface traces, and the fault locations are located inexactly on Figure 1. The major thrusts strike approximately east–west and, except for the North Potato Hills thrust, dip south.

Previous Structural Interpretations

Detailed subsurface mapping in the Potato Hills is difficult due to sparse well and seismic data. The first detailed cross sections not based solely on surface geology were those of Arbenz (1968) using data from the Sinclair No. 1 Reneau well (CSE¼NW¼ sec. 32, T. 3 N., R. 20 E., Latimer County). Data from this well were analyzed first by Unruh (1963) who described several repeated Bigfork–Womble sections above the sub-Womble Ordovician units (Mazarn Shale, Crystal Mountain Sandstone, Collier Shale) found at total depth. Arbenz's (1968) analysis was essentially the same except that his interpretation showed Stanley Group in fault contact below the Womble.

Arbenz's (1968) cross sections support the window hypothesis, first proposed for the Potato Hills by Miser (1929). The North and South Potato Hills thrusts were interpreted to be a single thrust (named the Potato Hills thrust), which was folded by subthrust stacking. The proposed window was created by erosion through the folded thrust. I have shown that the North and South Potato Hills thrusts are separate faults (Allen, 1991,1992,1993) and a different interpretation is needed.

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[1]EnecoTech Inc., Tulsa, Oklahoma.

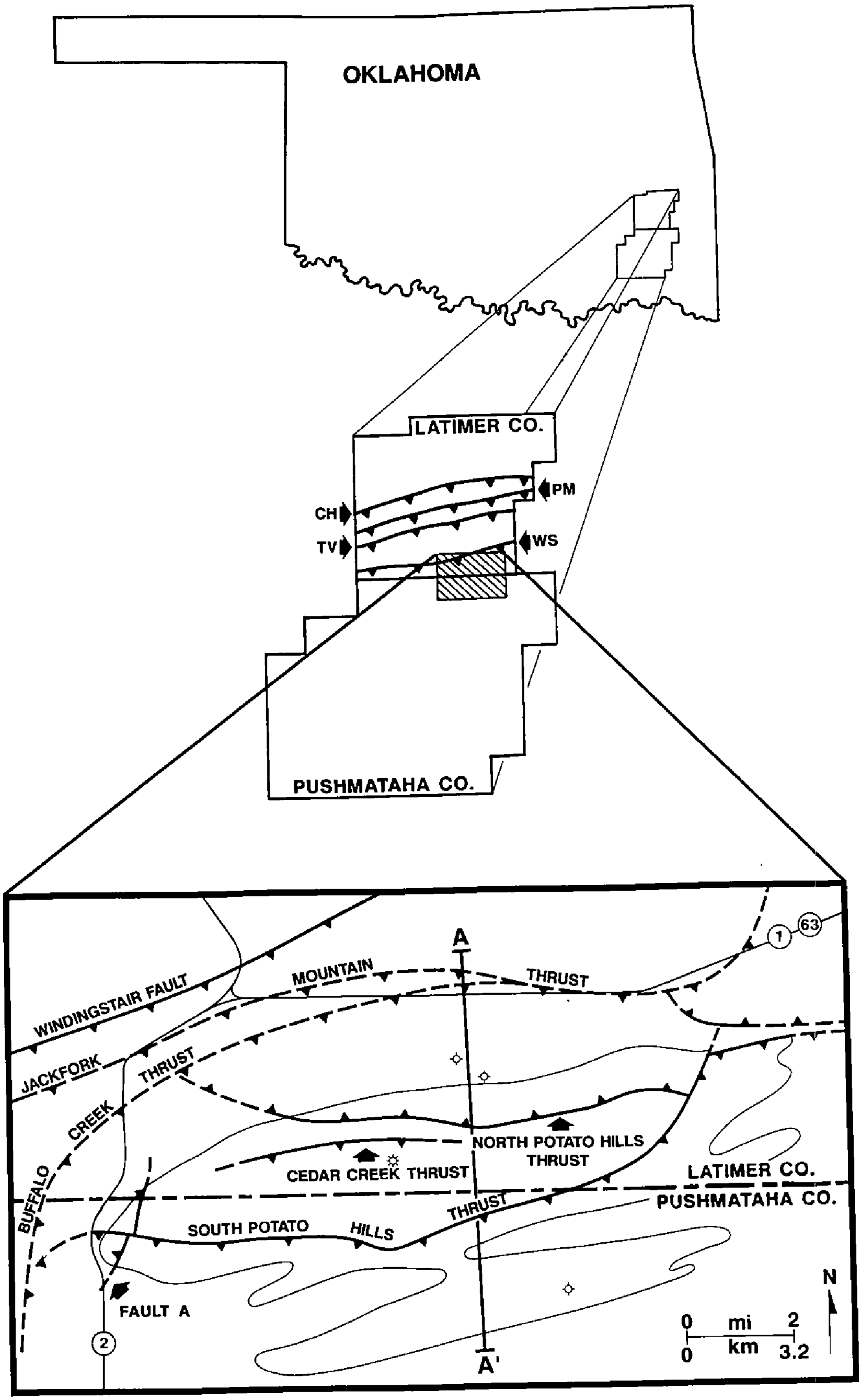

Figure 1. Potato Hills location map. See Figure 3 for cross section A–A′. CH = Choctaw fault, PM = Pine Mountain fault, TV = Ti Valley fault, WS = Windingstair fault.

In 1977, the American Quasar No. 1-11 Cabe (NW¼SE¼SE¼ sec. 11, T. 2 N., R. 20 E., Pushmataha County) was drilled to 15,485 ft. To the best of my knowledge, interpretation of this well has not been published previously. In 1991, the No. 1-21 Shaw (CSE¼SE¼ sec. 21, T. 3 N., R. 20 E.) and the No. 1-22 Bruce (SW¼SW¼ sec. 22, T. 3 N., R. 20 E.), drilled by Montgomery Oil and Gas in the hanging wall of the North Potato Hills thrust, helped to define the orientation of the fault plane (Allen, 1993). In addition, a proprietary seismic line through the north-central Potato Hills was made available to me. This subsurface information, plus the Sinclair well data, are sufficient to construct a new structural cross section showing the North and South Potato Hills thrusts as separate faults.

<table>
<tr><th>PERIOD</th><th>SERIES</th><th>UNIT</th></tr>
<tr><td rowspan="4">Mississippian</td><td>Chesterian</td><td rowspan="2">Stanley Group</td></tr>
<tr><td>Meramecian</td></tr>
<tr><td>Osagean</td><td rowspan="5">Arkansas Novaculite</td></tr>
<tr><td>Kinderhookian</td></tr>
<tr><td rowspan="2">Devonian</td><td>Upper</td></tr>
<tr><td>Lower</td></tr>
<tr><td rowspan="2">Silurian</td><td>Upper</td></tr>
<tr><td>Lower</td><td>Missouri Mountain Shale</td></tr>
<tr><td rowspan="3">Ordovician</td><td rowspan="2">Upper</td><td>Polk Creek Shale</td></tr>
<tr><td>Bigfork Chert</td></tr>
<tr><td>Middle</td><td>Womble Shale</td></tr>
</table>

Figure 2. Stratigraphic relationships in the Potato Hills.

Structural Analysis

Subsurface Data

Structural relationships in Figure 3 are based on seismic interpretation, multiple well control, and surface geology. The key wells are the Sinclair No. 1 Reneau and the American Quasar No. 1-11 Cabe because they are the only wells that penetrate the Potato Hills basal detachment (Fig. 3). Analysis of electric and sample logs from the No. 1 Reneau indicates that there are three major and two minor faults above the basal detachment (Fig. 4). The well penetrated the basal detachment at 5,780 ft where strata interpreted as Mississippian Stanley Group were found. Analysis of electric and sample logs from the No. 1-1 Cabe indicates that there are several repeated Bigfork–Womble intervals above the basal detachment, which separates Womble and Stanley at 7,812 ft (Fig. 5). In the well, 4,542 ft of the Stanley Group lie above the fault contact with underlying sandstone of the Pennsylvanian Jackfork Group.

The proprietary seismic line indicates several subhorizontal faults that ramp and imbricate as they approach the surface. The chert units and sandstone beds in the Stanley and Jackfork Groups produced reflection markers on the seismic line. Electric logs from the No. 1 Reneau and the No. 1-11 Cabe were superimposed on the seismic line and lithologies seen in the electric logs were correlated with the reflections on the seismic line.

Interpretation

Analysis of electric and sample logs from the No. 1 Reneau and No. 1-11 Cabe indicates multiple thrust faults separating repeated and sometimes overturned lower Paleozoic strata. Cross section A–A′ (Fig. 3) shows that the major thrusts in the Potato Hills cut up-section from a basal detachment but do not appear to rejoin at a higher level. The interpretation that the thrusts do not rejoin is supported by the anticlinal folds found over most of the major thrusts and by the tendency of the thrusts to splay after moving over a ramp.

In Figure 3, several of the major subhorizontal thrusts are shown by dashed lines at their northern ends or where they approach the land surface because some may be blind thrusts and do not reach the surface, and because some juxtapose Stanley against Stanley and their trace cannot be identified in the field. The thrust faults shown by solid lines can be identified on the seismic data and their traces can be mapped in the field. No attempt was made to extrapolate the extent of the faults beyond what actually could be identified by the data.

Thrust Belt Models

An imbricate fan is a thrust system in which faults cut up-section from a basal detachment but do not rejoin at a higher stratigraphic level (Marshak and Woodward, 1988). Displacement of each thrust in an imbricate fan decreases up-section and eventually dies out by transferring slip to a fold at its tip, or by distributing slip along several splays (Mitra, 1986). A duplex is a thrust system in which faults cut up-section from a basal detachment and merge at a higher stratigraphic level to form another continuous detachment (Marshak and Woodward, 1988).

One faulting sequence in thrust belts is called a break-forward sequence. In such a sequence, structurally lower faults (faults at greater depths) are younger

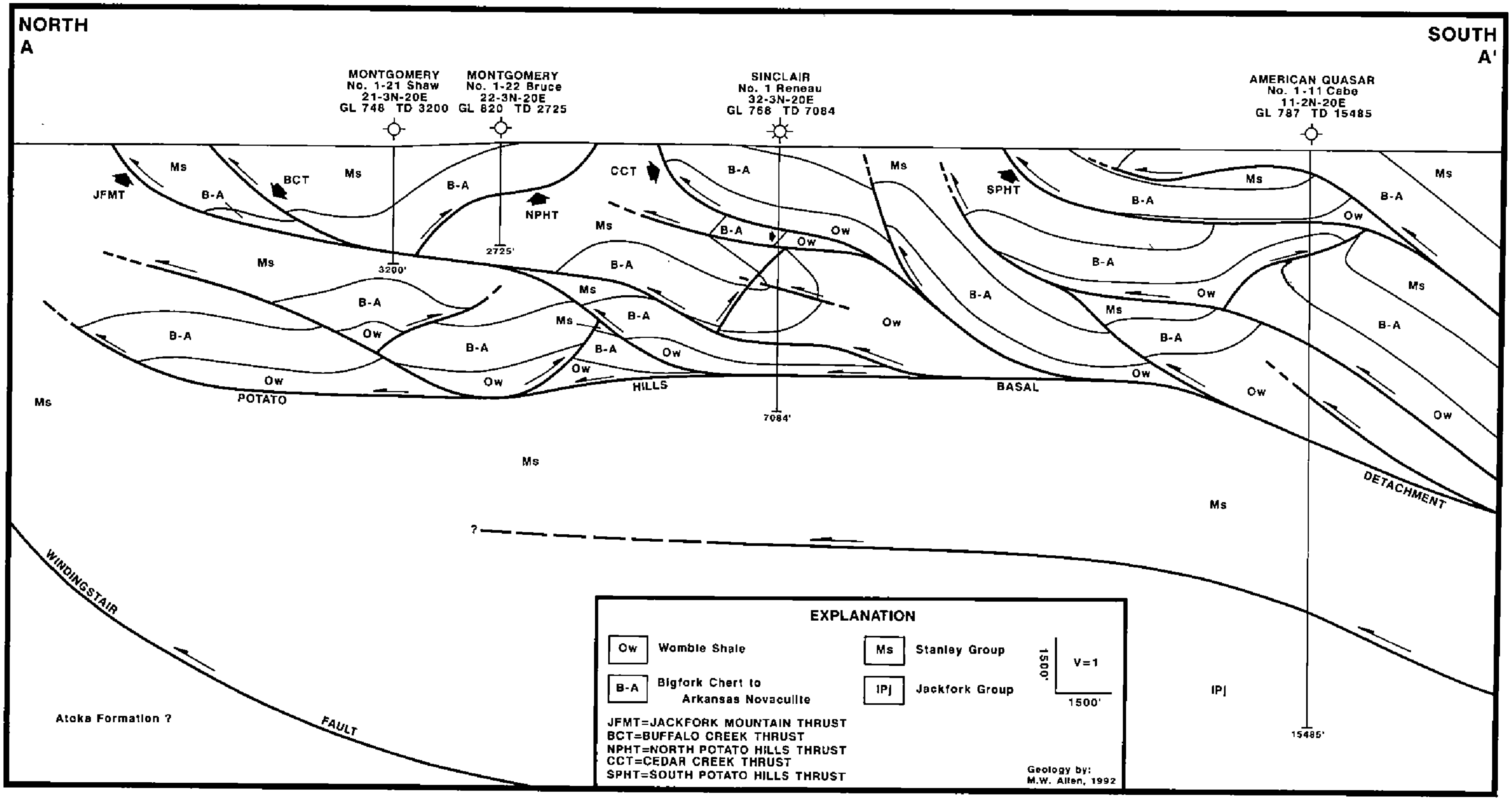

Figure 3. Structural cross section through the Potato Hills based on interpretation of seismic data, electric and sample logs, and surface geology. Small arrow pointing to Sinclair No. 1 Reneau well indicates productive zone in Bigfork Chert. See Figure 1 for locations of cross section and wells.

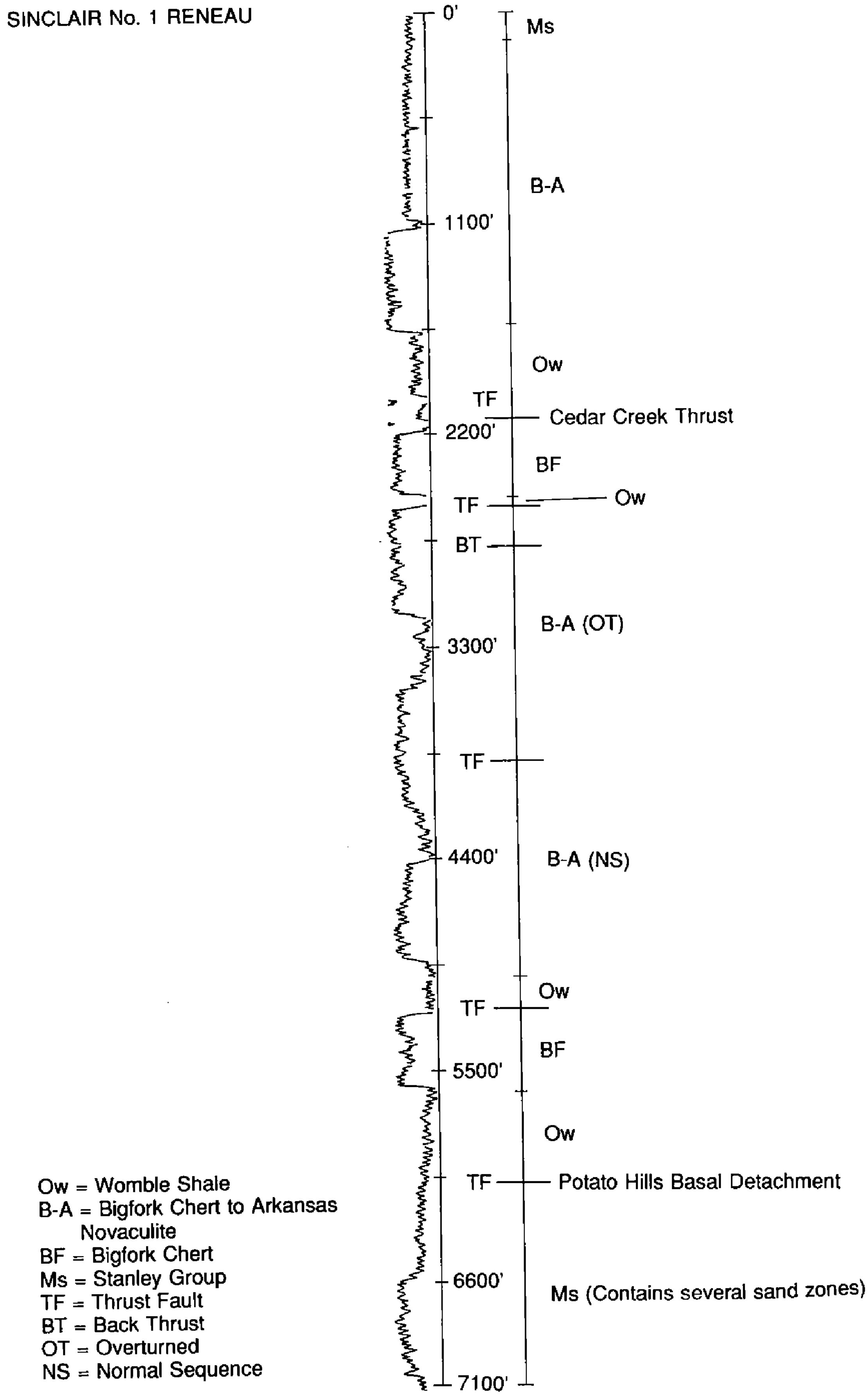

Figure 4. Electric and sample log interpretation of the Sinclair No. 1 Reneau.

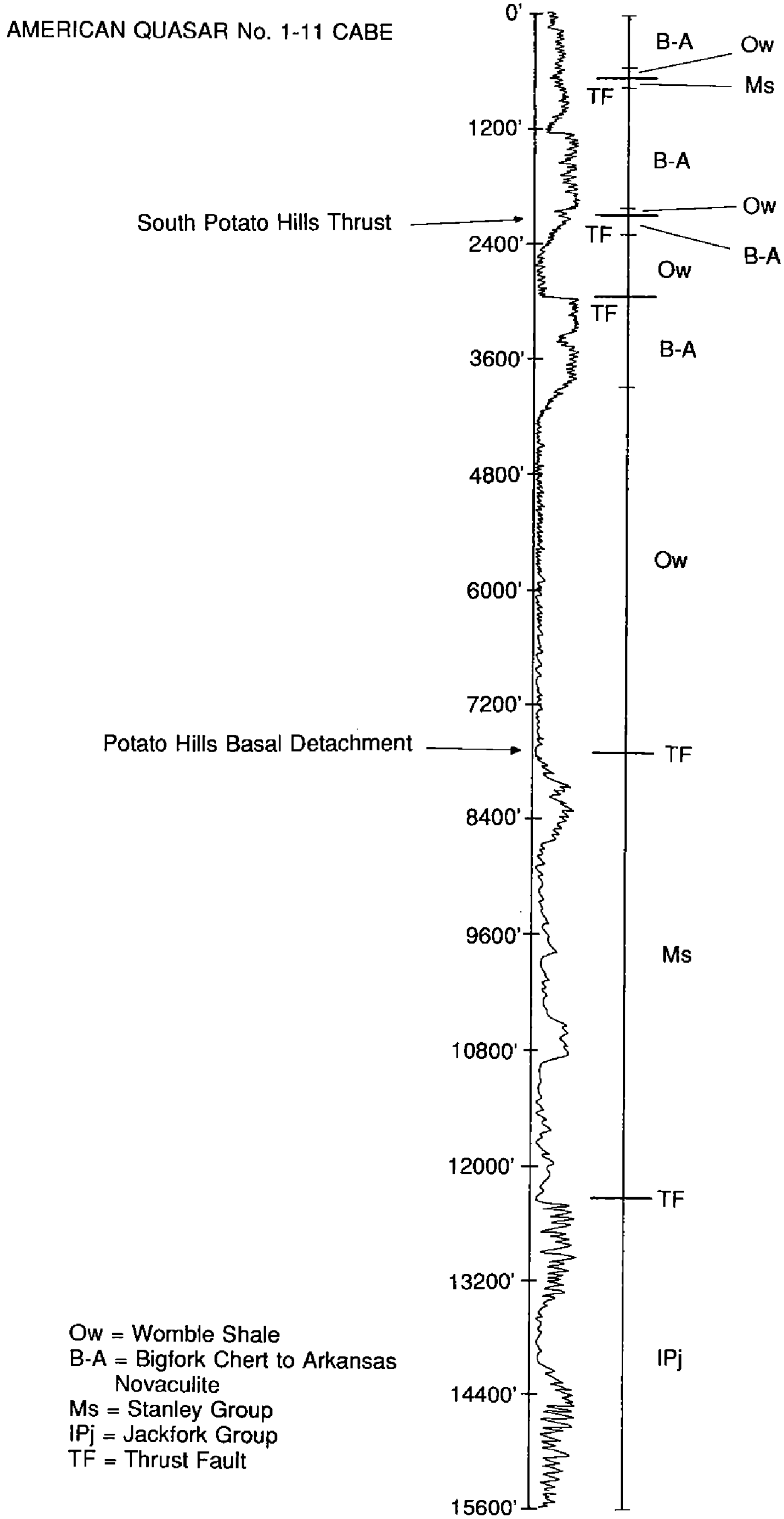

Figure 5. Electric and sample log interpretation of the American Quasar No. 1-11 Cabe.

than overlying faults (Marshak and Woodward, 1988). In a thrust belt of this type, the more external faults (farthest toward the foreland) are generally the youngest, whereas the more internal faults are the oldest. Break-forward sequencing (Marshak and Woodward, 1988) would suggest that the faults are progressively younger toward the foreland; this is considered a "normal" sequence of thrusting. The spatial arrangement of these faults implies that older faults can be folded by younger faults.

A different faulting sequence in thrust belts, in which structurally lower faults are older than overlying faults, is called out-of-sequence faulting (Marshak and Woodward, 1988). Minor thrusts rooted in a major thrust are sometimes interpreted as imbrications in the hanging wall of an existing thrust sheet and are believed to develop out of sequence (Jones, 1987). Boyer and Elliott (1982) stated that an imbricate-fan thrust system is a structure in which out-of-sequence thrusting could occur.

Field relationships show only the sequence of terminations of events and not the sequence in which those events started (Jones, 1971). Thus, the locations and orientations of thrust faults reveal little about when each thrust developed, and they cannot be used as sequence indicators. A timing indicator that may be used is whether or not the major thrusts have been folded by subthrust stacking. Folded faults may be expected to occur in any thrust belt if the stratigraphic section consists of interbedded competent and incompetent strata and the sequence of thrusting is normal (Jones, 1971).

Implications

Interpretation of subsurface data (Fig. 3) indicates that the faults cut up-section but did not rejoin at a higher stratigraphic level as indicated by the folded strata above the fault planes. Each thrust appears to have lost displacement up-section and transferred slip to a fold or distributed slip along several splays. The major thrusts are not folded by subthrust stacking. These observations suggest an imbricate-fan thrust system.

The tectonic implications of this interpretation are that thrusting in the Potato Hills was north-directed translation on a subhorizontal thrust fault defined as the Potato Hills basal detachment. Imbrications developed from the basal detachment sequentially from north to south. Evidence for this out-of-sequence thrusting is the absence of folded faults in the southern part of the Potato Hills (Fig. 3).

Conclusions

Based on interpretation of seismic data, electric and sample logs, and surface geology, and on a comparison of Figure 3 with the classification of different systems of thrusts (Boyer and Elliott, 1982, fig. 12, p. 1200), I suggest that the Potato Hills are an imbricate-fan thrust system. General north–south compression resulted in north-directed, subhorizontal translation on the Potato Hills basal detachment. Imbrications then developed out of sequence from north to south. Most thrusts lost displacement and eventually died out by transferring slip to a fold or by distributing slip along several splays.

The hypothesis that erosion through a folded thrust (i.e., the Potato Hills thrust) produced a window does not accurately explain the structural geology of the

Potato Hills. The folding of overlying thrust faults by subthrust stacking cannot occur in an out-of-sequence, imbricate-fan thrust system. I have previously demonstrated that the North and South Potato Hills thrusts are separate faults, and there is no window. Such an interpretation is supported by out-of-sequence thrusting.

Acknowledgments

I thank Neil Suneson, Kenneth R. Neuhauser, and John Simms for critically reviewing drafts of this manuscript. Montgomery Oil and Gas provided proprietary well logs and the seismic line used in this study. I appreciate the insight of R. Doden and L. Gerken in interpreting the seismic information. J. Roberts provided the sample log for the American Quasar No. 1-11 Cabe.

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Oklahoma Geological Survey Biennial Report for Fiscal Years 1992 and 1993

Charles J. Mankin[1]

Introduction

The Oklahoma Geological Survey (OGS), a Constitutionally created State agency, is charged with investigating Oklahoma's land, water, mineral, and energy resources, and disseminating the results of those investigations to aid in the responsible development of the State's nonbiological natural resources. The First State Legislature passed the enabling legislation and placed the OGS on the campus of The University of Oklahoma. Upon creation of the Oklahoma State Regents for Higher Education, the original governing board of the OGS was abolished and the agency was placed under The University of Oklahoma Board of Regents for fiscal and administrative control, and the Oklahoma State Regents for Higher Education for program authority and budget.

The OGS began operations on July 25, 1908, and, with completion of this biennium, has served the citizens of the State for 85 years. The agency has had six directors and two acting directors, with the present director having served 27 years.

While changes have occurred in the kinds of studies and the methodologies and techniques used to conduct those investigations through the years, the primary focus of the agency still is on applied investigations designed to respond to the public's need for information and technical assistance. Although the emphasis has been on applied studies, at least 20% of the geological staff's efforts are devoted to fundamental investigations that keep them at the forefront of research in their fields.

The OGS ranks in the top 10% of all state geological surveys in external funding through grants and contracts. This is despite the fact that the Survey is in the mid range in terms of budget and personnel when compared to the other 49 state geological surveys.

The main offices of the OGS are located in the Sarkeys Energy Center on The University of Oklahoma campus (Fig. 1), with approximately 20,000 square feet of office, laboratory, and public-service space in use. In addition, the OGS maintains a core and sample library at 2725 South Jenkins, a log library at 1425 George Street, and a storage warehouse at Broce Park, all in Norman, Oklahoma (Fig. 1). A nationally recognized seismological observatory (the TUL station) is operated by the

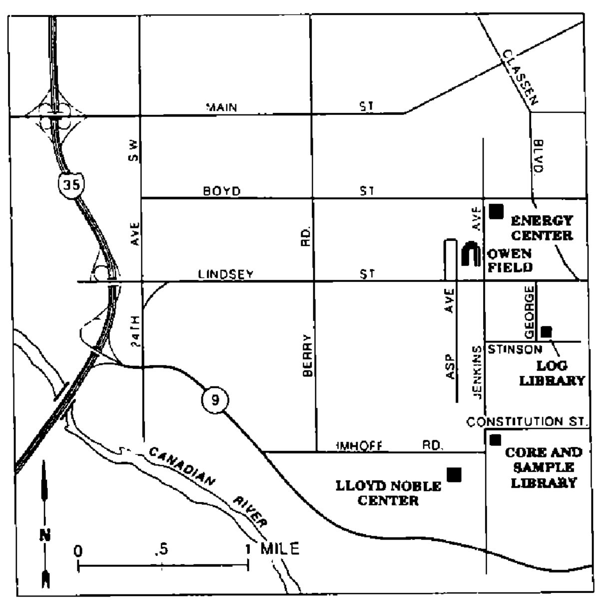

Figure 1. Location map, Norman, Oklahoma.

[1]Director, Oklahoma Geological Survey.

OGS on a 160-acre tract of land located south of Leonard, in Tulsa County.

Budget

The budgets for the OGS for the fiscal years 1992 and 1993 (July 1, 1991 through June 30, 1993) are shown in Table 1.

Table 1. — Budgets for the OGS, Fiscal Years 1992 and 1993, Showing Source of Funding

Source of Funds	FY 1992	FY 1993
State Appropriations	$2,056,586	$2,098,485
Revolving Funds	125,000	125,000
Grants and Contracts	418,477	621,893
Total	$2,600,033	$2,845,378

The amount of funding spent by the OGS from grants and contracts during the past biennium does not reflect the total funding received by the agency. A substantial amount of funding on OGS contracts from the U.S. Department of Energy goes to fund staff in Geological Information Systems (GIS) on the development of the Natural Resources Information System (NRIS) and on the Fluvial-Dominated Deltaic Reservoir (FDD) study. The School of Petroleum and Geological Engineering also shares in the FDD funding. In addition, GIS received support from the OGS natural-gas-atlas project that was funded, in part, by the Gas Research Institute.

Revolving-fund income is derived from publication sales, copy shop, core-and-sample-library usage, and external reimbursements; income for the past 10 years is shown in Figure 2.

Revolving-fund income was a record high in the first half of the biennium, followed by a record decline in the second half. The decline reflects the closure of operations by several major petroleum companies in the State, and a general decline in domestic petroleum activity. Income for fiscal year 1994 will increase over that of 1993 because of several new publications that will be released next year.

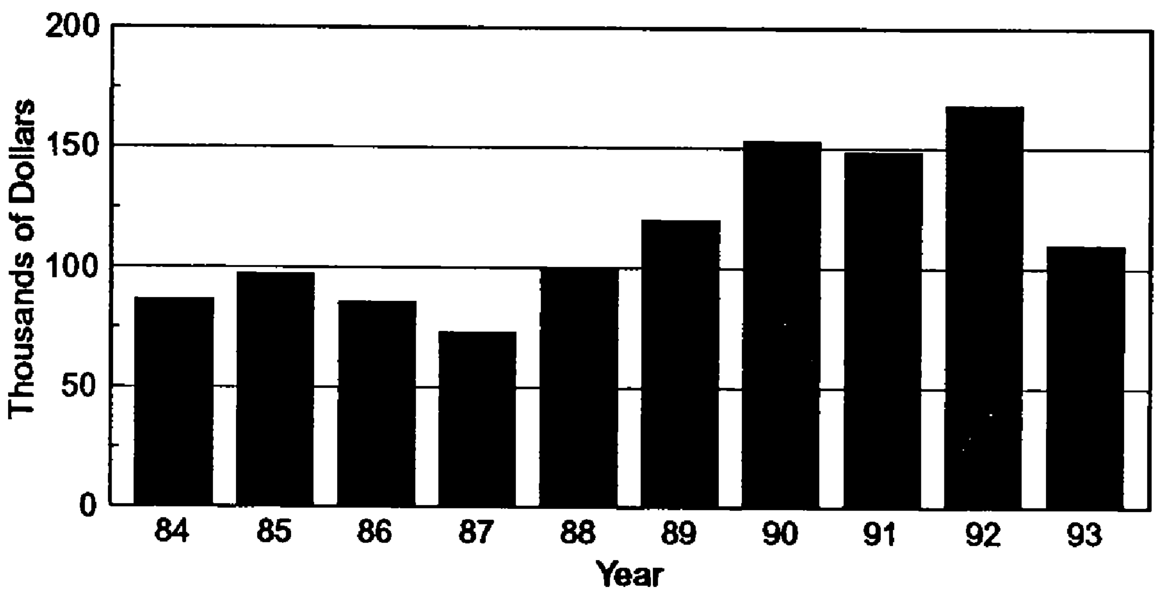

Figure 2. Graph showing revolving fund income for the past 10 years. That income is derived from publication sales, core-and-sample-library and well-log-library usage, print shop, and other miscellaneous sources.

Programs

The OGS conducts ongoing investigations in a number of areas and publishes the results of these studies in accordance with the agency's charter responsibilities. These areas include geologic mapping, resource investigations, environmental studies, and seismology. External funding is an important part of several program areas.

Geologic Mapping

Geologic mapping determines the type, geologic age, and configuration of rock units in the State. Such mapping is the foundation for resource assessments, the identification and mitigation of natural hazards, and environmental studies. Important geologic resources for Oklahoma include not only oil and gas, but nonfuel minerals.

The foundation of the geologic-mapping program is the collection of map data at the scale of the standard topographic map, or a scale of about 2.5 inches = 1 mile. These geologic maps are prepared in black-line copy and placed in the agency's open-file report series. Multicolored maps are compiled from these data and are published at a smaller scale, commonly 1 inch = 1 mile. While the smaller-scale geologic maps provide a good overview of the geology of a region, the larger-scale, black-line geologic maps are useful for detailed studies in a particular area. For example, a site that contains limestone resources or rock units that may be amenable for location of sanitary landfills can be delineated on the smaller-scale maps, but site-specific studies for resource assessment or facility sittings require the use of the larger-scale maps.

During the past biennium, the geologic mapping of Kay County was completed and the large-scale, black-line maps for this county will be placed in the OGS open-file series during the next year. Geologic mapping was continued in the Ouachita Mountains with the completion of 15 large-scale, black-line maps. The six quadrangle maps released during the biennium are: Blackjack Ridge, Gowen, Summerfield, Hodgen, Hontubby, and Loving Quadrangles. Geologic mapping in western Osage County was initiated, and three large-scale maps were completed during the biennium: the Hardy, Kaw City, and Charley Creek East Quadrangles.

External funding from the U.S. Geological Survey was received in each year of the biennium. About $60,000 in cash and in-kind services was received in each of FY92 and FY93 under the CO-GEOMAP program. Funding under a new National Geologic Mapping Program is expected to increase next year.

Resource Investigations

The OGS conducts resource studies and other related investigations on petroleum, coal, industrial minerals, and water. These commodities are critical to Oklahoma's economy. The combined value of petroleum, coal, and industrial minerals exceeded $5 billion in each year of the biennium. In comparison, the value of agricultural production in the State was slightly more than $3 billion annually. While water cannot be valued in a comparable manner, it is without question fundamental to the existence of life in the State.

Petroleum

Because petroleum has been and continues to be a mainstay of the State's economy, the OGS has placed emphasis on oil and gas studies throughout its history. Such investigations have included case-history field studies, analyses of the State's three major sedimentary basins, resource assessments, and the collection of an array of statistics on the State's petroleum industry.

The OGS also maintains an extensive collection of cores and samples from wells drilled in the State, and is the State's repository for well logs. These cores, samples, and other materials and information must be preserved for future generations of Oklahomans that will be exploring our State to find its mineral wealth and solve its environmental problems. With the departure of several major companies from the State, the OGS has received extensive donations of Oklahoma cores and samples. The largest of these was six trailer-truck loads of cores and samples from Mobil Oil Corporation. The OGS now has available for public examination 77,400 boxes of cores from 3,200 wells, and samples from more than 35,000 wells. In addition, logs from more than the 200,000 wells drilled in Oklahoma are available in the log library.

The OGS, in cooperation with Geological Information Systems (an organized research unit of the University), is developing the Natural Resources Information System (NRIS) for the State. When completed, NRIS will contain computerized data on petroleum, coal, industrial minerals, and water. The first phase of NRIS development is directed toward the collection of information on petroleum. Almost $3 million has been received from DOE to date, and has been matched with about $1 million from OGS and industry sources.

The NRIS production files contain monthly oil and gas production, by lease, from 1979 to present. These data can be aggregated by field, producing interval, geologic "play," petroleum province, and political area (e.g., county or legislative district). These files also can be used to determine the number of producing leases in a given area, lease ownership, and the size of leases in area and production.

An example of the use of these files serves to illustrate their utility. Figure 3 portrays the number of oil-producing leases by size of production.

Note that of the 35,000 producing crude-oil leases in Oklahoma, one-third produce two barrels per day, or less. Of the State's 100 million barrels of crude-oil production last year, 25% came from leases that made less than 10 barrels per day. These analytical ca-

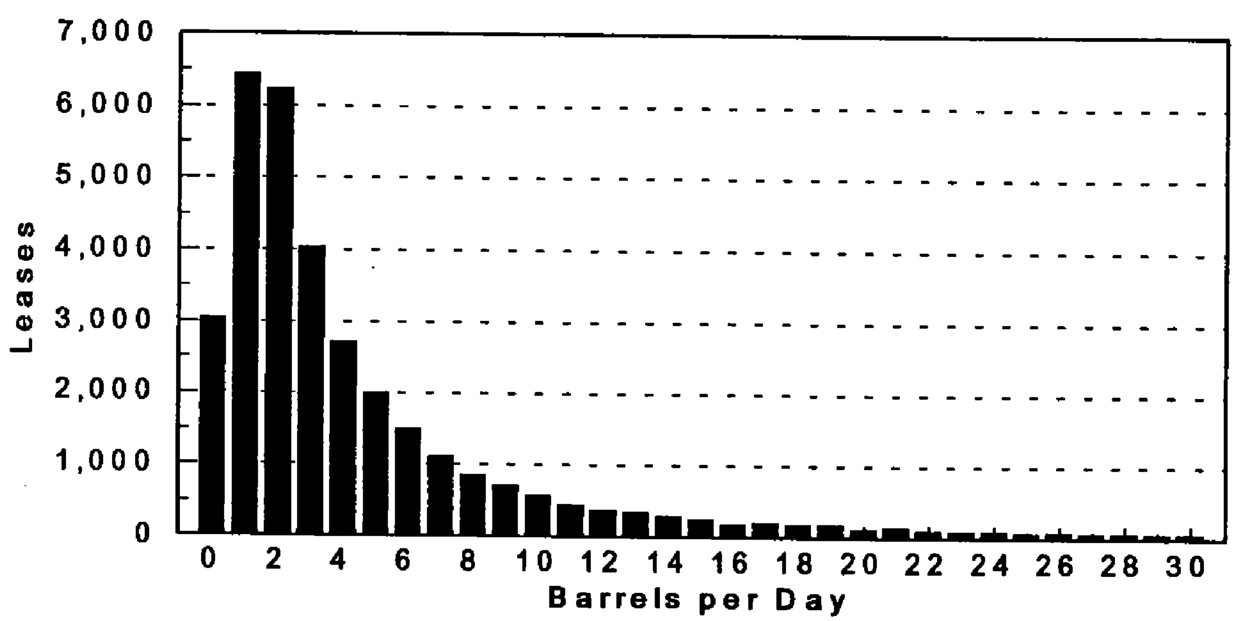

Figure 3. Graph showing number of producing leases versus the amount of daily production in barrels.

pabilities of NRIS are being used by industry and public-sector policy analysts for a variety of applications.

A project involving the development of a natural-gas atlas for the southern Midcontinent region was completed during the biennium. The Survey, in cooperation with GIS, developed the information contained in the atlas for Oklahoma. This project involved identifying all fields in the State that have produced at least 10 billion cubic feet of natural gas. These fields were aggregated into geologic "plays," and geologic and reservoir information on each play was developed. The resulting publication, *Atlas of Major Midcontinent Gas Reservoirs*, provides geologic and production information on each natural-gas play in the State, and allows industry and policy analysts to evaluate the current status and future potential of natural gas.

A major, five-year project on fluvial-dominated deltaic (FDD) petroleum reservoirs in Oklahoma was initiated during the biennium. Funded in part by the U.S. Department of Energy, the project involves the Survey as the principal agency, with supporting work by GIS and the School of Petroleum and Geological Engineering. The project will identify all FDD reservoirs in the State, organize them into plays, and develop information about the geological and engineering characteristics of each play. From this information, opportunities to improve recovery from existing fields will be developed. Such improved recovery will come from a better understanding of the architecture of the reservoirs so that we can identify regions of bypassed oil. The focus will be on recovery methods and current technologies that can be implemented at oil prices in the $15–$20 range. Such technologies include: targeted in-fill drilling, recompletion, profile modification, and improved water floods. Of these, improved water floods probably offer the greatest opportunity to recover additional oil from existing fields.

The information developed from this project will be presented to the operators of these fields and other interested parties in a series of workshops beginning in early 1995. The information also will be incorporated into a computerized data base that will be accessible to industry representatives and others through a computer-user laboratory being developed by the Survey and GIS. That laboratory will be operational in late 1994.

As with other areas of Survey responsibility, information and technology transfer to the petroleum industry is an important activity. Information is conveyed through individual consultations with petroleum operators, consultants, and other interested parties on a daily basis. The staff spend about 25% of their time in such activities.

Publications and conference presentations are additional ways in which the information and analyses developed by the Survey are made available to the public. During the past biennium, Survey staff members made more than 100 presentations to various professional and public-interest groups. A substantial portion of these were focused on various aspects of petroleum geology and resources. A list of publications released by the Survey during the past biennium is appended.

A major feature of the Survey's information and technology transfer efforts in petroleum geology has been the series of workshops initiated in 1988. Through the last biennium, a total of seven workshops focused on petroleum have been held. During the past two years, three workshops examined the Arbuckle Group, Structural Styles, and Fluvial-Dominated Deltaic Reservoirs. Each of these workshops was attended by 125–260 persons.

Coal

The Survey's many years of investigations on coal geology have led to a good understanding of the State's coal resources and associated production issues. Map information has been developed and resource analyses of the State's coal-producing counties have been completed, and publication of the remaining areas is expected next year.

While coal studies continue, the level of staff involvement has been substantially reduced, and one staff member has been transferred to essentially full-time geologic mapping. A second staff member has extended his coal-related investigations to include organic petrology associated with petroleum source rocks. The remaining member of the original three-person staff in coal studies will be responsible for dealing with public requests for information and maintaining resource and production data.

The annual value of coal production in the State is about $50 million. Although coal continues to be an important energy resource, production in Oklahoma has declined and is not expected to increase in the foreseeable future. Production and related reclamation costs make Oklahoma coal marginally competitive in the U.S. market.

Industrial Minerals

Industrial minerals are a small, but important part of the State's economy, especially in the communities where such production occurs. The value of industrial-mineral production in Oklahoma in 1993 was about $280 million, which was an increase of $30 million over 1992. Crushed stone, along with sand and gravel, provided more than half of the total value, followed by portland cement, iodine, and gypsum. Oklahoma continues to be the only producer of iodine in the United States.

During the past biennium, the Survey completed and published a *Directory of Oklahoma Mining Industry*, in cooperation with the Oklahoma Department of Mines. This directory is cross-indexed to provide users with commodity lists by county, operator lists by county, and an alphabetical listing of all mining operations in the State. Information on production and other related statistics are available for those operators who responded to a questionnaire.

Resource studies on industrial minerals continue to be a focus of the Survey's geologic-mapping program. As geologic mapping proceeds, industrial minerals that have the potential for development are assessed. This information is used in consultation with individuals and organizations who contact the Survey for such data.

Because most of the Survey's information and technology transfer on industrial minerals is through individual consultations rather than publications, a workshop on industrial minerals was held in 1992. The workshop was cosponsored with the Oklahoma Department of Mines and the U.S. Bureau of Mines, and was attended by 110 people. The participants were enthusiastic about the subject matter and felt that this meeting proved to be very beneficial to the industry.

Water

The Survey's program in water-resources investigations is conducted in cooperation with the Water Resources Division of the U.S. Geological Survey. Over the years, this program has developed map and related information on the distribution and quality of the State's ground-water resources. The hydrologic-atlas series provides a good overview of Oklahoma's water resources, and forms the basis of studies that are being conducted on the State's principal ground-water aquifers. These atlases are now being digitized to be incorporated into an emerging geographical information system (GIS) for the State. In particular, the digitization of the principal ground-water aquifers is a priority in addressing plugging procedures under the State's "orphan-well" program. The Survey continues to work cooperatively with the U.S. Geological Survey and the other State agencies that have responsibility for some component of Oklahoma's water supply.

Environmental Geology

The Survey's program in environmental geology is directed toward the identification and mitigation of natural hazards (landslides and other forms of ground failure, seismic risk, health hazards from natural causes [e.g., radon], and natural contamination of surface and ground water). Much of the information needed to address these issues is developed from the program in geologic mapping and amplified through various site-specific studies.

Each year the Survey responds to a large number of public inquiries regarding various environmental issues. These range from concerns over contamination of water supplies to reviews of construction and renovation of public facilities. The Survey reviews all new and major repair projects on Oklahoma highways with respect to geologic conditions that may contribute to concerns for the project. We also review all hazardous- and toxic-waste siting projects with respect to the suitability of geologic conditions and related seismic risk.

The Survey operates the State's seismic network of 11 stations located around the State, with the base station (TUL) situated at the geophysical observatory near Leonard, Oklahoma. During the last biennium, a station was installed east of Norman, with a recording unit for the seismometer located in the Sarkeys Energy Center. This has become a popular site for students, faculty, and visitors to observe the "earthquake of the day." It also has become a popular location for the electronic news media to film discussions about major seismic events in the U.S.

The geophysical observatory is undergoing a substantial improvement in recording and communication capability. Through federal funding, additional seismic equipment is being added, and the facility is now on Internet. Consequently, anyone with a computer and modem can obtain copies of the most recent worldwide seismic events recorded at the observatory. The installation of two broad-band, three-component, digital seismometers will make the observatory the best-equipped facility of its kind in the region. One seismometer is installed in a 300-foot-deep borehole, and the second soon will be installed in a 0.5-mile-deep borehole. This will allow the Survey staff to study worldwide seismic events free from any surface disturbance, and allow discrimination of wave forms from different sources. The recent approval by The University of Oklahoma Board of Regents for funding from Section 13 and New College Funds to expand the main building at the observatory will provide much-needed space for the additional recording and communications equipment. The observatory is a test site for some of the new equipment being developed to monitor seismic activity, and with the added space we hope to expand our activity in this area.

Conclusion

The Oklahoma Geological Survey has had a long history of investigating the State's nonbiological natural resources, then compiling and disseminating that information for the public good. Throughout the years, this work has been conducted in cooperation with faculty and students from departments at The University of Oklahoma and other universities in the State. In recent years, a close working relationship has been developed with several State agencies that have regulatory responsibility for Oklahoma's natural resources. This has resulted in an improvement in performance for all concerned, and has provided tangible benefits for the State. Cooperative work with federal agencies has been greatly expanded with a substantial increase in federal grants and contracts resulting from this activity.

The staff remain committed to producing high-quality information about Oklahoma and its natural resources and to conveying that information to the citizens of the State in a most effective way. We believe that the use of good information concerning the State's resource base is a cornerstone for the creation of quality jobs and long-term economic growth and development for Oklahoma.

APPENDIX

Publications Released by the Oklahoma Geological Survey, July 1, 1991 through June 30, 1993

Bulletin 145.—*Special Papers in Paleontology and Stratigraphy: A Tribute to Thomas W. Amsden* (James R. Chaplin and James E. Barrick, editors), 1992.

Circular 92.—*Late Cambrian–Ordovician Geology of the Southern Midcontinent, 1989 Symposium* (Kenneth S. Johnson, editor), 1991. Proceedings of a symposium held October 18–19, 1989, in Norman, Oklahoma.

Circular 93.—*Source Rocks in the Southern Midcontinent, 1990 Symposium* (Kenneth S. Johnson and Brian J. Cardott, editors), 1992. Proceedings of a symposium held February 6–7, 1990, in Norman, Oklahoma; cosponsored by the Oklahoma Geological Survey and U.S. Department of Energy.

Circular 94.—*Recent Advances in Middle Carboniferous Biostratigraphy—A Symposium* (Patrick K. Sutherland and Walter L. Manger, editors), 1992. Proceedings of a symposium held March 5, 1990, in Stillwater, Oklahoma, at the South-Central Section meeting of the Geological Society of America.

Guidebook 28.—*Geology of Wister State Park Area, Le Flore County, Oklahoma,* by LeRoy A. Hemish, 1993.

Special Publication 91-3.—*Arbuckle Group Core Workshop and Field Trip* (Kenneth S. Johnson, editor), 1991. Proceedings of a workshop and field trip held October 29–31, 1991; cosponsored by the Oklahoma Geological Survey and the U.S. Department of Energy.

Special Publication 92-1.—*Petroleum Core Catalog, Oklahoma Geological Survey—August 1992,* compiled by Eldon R. Cox and Michelle J. Summers, 1992.

Special Publication 93-1.—*Directory of Oklahoma Mining Industry, 1993* (Robert H. Arndt and Robert Springer, project coordinators), 1993.

Oklahoma Geology Notes, v. 51, nos. 4–6; v. 52, nos. 1–6; v. 53, nos. 1–3.

Open-File Reports

Geologic Map of the Blackjack Ridge Quadrangle, Le Flore County, Oklahoma, by Neil H. Suneson, 1991.

Geologic Map of the Gowen Quadrangle, Latimer County, Oklahoma, by LeRoy A. Hemish, 1992.

Geologic Map of the Summerfield Quadrangle, Le Flore County, Oklahoma, by LeRoy A. Hemish and Colin Mazengarb, 1992.

Geologic Map of the Hodgen Quadrangle, Le Flore County, Oklahoma, by Neil H. Suneson and LeRoy A. Hemish, 1993.

Geologic Map of the Hontubby and Loving Quadrangles, Le Flore County, Oklahoma, by Colin Mazengarb and LeRoy A. Hemish, 2 sheets, 1993.

OUACHITA MOUNTAINS/ARKOMA BASIN WORKSHOP AND FIELD TRIP

Poteau, Oklahoma, November 15–17, 1994

A workshop and field trip on the "Geology and Resources of the Eastern Frontal Belt, Ouachita Mountains, and Southeastern Arkoma Basin, Oklahoma," sponsored by the Oklahoma Geological Survey, will be held November 15–17, 1994, at the Robert S. Kerr Conference Center in Poteau, Oklahoma.

The workshop is designed to be an introduction to recent research in the northern part of the Ouachita Mountains and southern part of the Arkoma basin near the Oklahoma/Arkansas state line. An informal format is planned; slide and poster presentations will be made with ample time for questions and discussion.

The field trip will focus on the structure and stratigraphy of the Carboniferous strata near the Arkoma basin/Ouachita Mountains transition zone. Most of Day One will be spent examining "shallow"-water upper Atokan and lower Desmoinesian strata in the Arkoma basin. Most of Day Two will be spent in the Ouachita Mountains looking at the "deep"-water Morrowan and Atokan section.

Participants will look at surface exposures of the Warner ("Booch") Sandstone, Desmoinesian channel sandstones and coal-bearing strata, the Spiro sandstone, submarine slide blocks in the Johns Valley Shale, turbidites in the Atoka Formation, and many other outcrops. Visits to the active Wister Coal Mine (Secor and Secor Rider coals), Runestone State Park (Savanna Sandstone), Talimena Drive (Jackfork Group), and the Potato Hills (Ordovician to Mississippian strata) are also planned, as well as an optional field trip after the meeting to the Page impsonite mine.

Below is the field-trip itinerary:

Stop 1. Spaniard Limestone near Kerr Conference Center

Stop 2. Keota Sandstone, McAlester Formation, Poteau River crossing

Stop 3. Upper Atoka Formation sandstone, Wister Dam spillway

Stop 4. Bluejacket Sandstone Member, Boggy Formation

Stop 5. Secor and Secor Rider coals, Boggy Formation, Wister Mine

Stop 6. Warner (Booch) Sandstone Member, McAlester Formation

Stop 7. Cameron Sandstone Member, McAlester Formation

Stop 8. Atoka Formation/Hartshorne Formation contact, Cravens Road

Stop 9. Folds in Atoka Formation

Stop 10. Spiro sandstone

Stop 11. Atoka Formation turbidites

Stop 12. Woodford Chert/Caney Shale olistolith (slide mass) in the Johns Valley Shale, Bengal

Stop 13. Johns Valley Shale at Compton Cut

Stop 14. Johns Valley Shale

Stop 15. Stanley Group strata, Lake Carl Albert spillway

Stop 16. McCurtain Shale and Warner Sandstone Members, McAlester Formation, Howe

Stop 17. Savanna Sandstone and Heavener Anticline Overlook, Runestone State Park

Stop 18. Atoka Formation/Hartshorne Formation contact, Heavener road cut

Stop 19. Johns Valley Shale, Stapp

Stop 20. Atoka Formation turbidites

Stop 21. Chickasaw Creek Siliceous Shale, Stanley Group/Jackfork Group contact, Talimena Drive

Stop 22. Sugarloaf Vista, Talimena Drive

Stop 23. Womble Shale, Bigfork Chert, Polk Creek and Missouri Mountain shales, Arkansas Novaculite, Potato Hills

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For further information about the workshop and/or field trip, contact Neil Suneson or LeRoy Hemish, Oklahoma Geological Survey, at (405) 325-3031.

NEW OGS *Publication*

SPECIAL PUBLICATION 94-2. ***A Geochemical Study of Crude Oils and Possible Source Rocks in the Ouachita Tectonic Province and Nearby Areas, Southeast Oklahoma,*** by Jane L. Weber. 32 pages. Price: $2.

Author's abstract:

Thirty oils from the Oklahoma part of the Ouachita tectonic belt plus 15 oils from adjacent areas were characterized to determine their genetic relations. All tectonic belt oils in Oklahoma, including those from Isom Springs, belong to one major family; an oil from north of the trace of the Ti Valley fault belongs to a subtype. The oils are predominantly marine and moderately mature to mature; their source rock was deposited in a mildly reducing environment. Geochemical features of these oils are: *n*-alkane maximum at C_{15} or C_{17}; moderate amount of isoprenoids; pristane/phytane ratio close to 1.5; an odd-even carbon-number preference close to unity; abundant C_{27} and C_{29} steranes and diasteranes; C_{30} greater than C_{29} hopane; moderately abundant homohopanes; prominent tricyclic terpanes; carbon-isotope (saturate) values around –30‰; sulfur content averaging 0.4%; and the presence of 28,30-bisnorhopanes (tentative identification).

Oils found in Cretaceous strata immediately south of the Ouachita Mountains are mildly biodegraded and exhibit characteristics associated with a carbonate-evaporite origin. They are chemically similar to Talco, Texas, oil and are probably additional examples of Sassen's (1989) Type I migrated (Jurassic) Smackover oil.

Some Ardmore basin oils adjacent to the buried Ouachita tectonic belt are geochemically similar to the tectonic belt oils. The significance of this finding warrants a new, interdisciplinary attempt to explain the petroleum system(s) of the Ouachita tectonic belt.

Twenty-five shale samples and one tar sand from outcrops in the Ouachita Mountains were also examined. Of eight stratigraphic intervals tested, the Caney, Woodford, Arkansas Novaculite, and Polk Creek show evidence of having good hydrocarbon-source potential. Maturity levels range from immature to mature, following no discernible geographic, stratigraphic, or structural pattern; none of the rocks with good potential is mature enough to have served as a source for Ouachita oils. However, biomarker distributions of some of the rocks resemble those of the oils, suggesting that where more deeply buried, those formations—representing both foreland and Ouachita facies—merit consideration as possible sources for Ouachita oils. Insufficient data were generated to conclude whether a Stanley tar-sand bitumen correlates with oils from nearby wells.

SP 94-2 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, fax 405-325-7069. Add 10% to the cost of publication(s) for mail orders, with a minimum of 50¢ per order.

Ames Structure Workshop Set for March 1995

The Oklahoma Geological Survey will sponsor a two-day workshop on "The Ames Structure and Similar Features." The workshop will be held March 28–29, 1995, in Norman, Oklahoma, and will have 200–300 attendees.

The Ames structure, located on the Anadarko basin shelf in northwestern Oklahoma, is a prolific source of oil and gas. Discovered in 1991, the Ames structure has generated much exploration and geologic interest. Ames is a circular-shaped structure, buried beneath >9,000 ft of sediments. It is 6–10 mi in diameter, and has a structural relief of at least 600 ft. The structure has been interpreted as either a meteorite-impact crater, or a volcanic caldera. The event occurred in Early Ordovician time (upper part of the Arbuckle Group), and it influenced structure and sedimentation throughout the remaining Paleozoic Era, and possibly through Recent geologic time.

We welcome papers, posters, and core/sample displays dealing with any and all aspects of the Ames structure, and also reports on similar structures elsewhere in the region and the world. For further information, contact Kenneth S. Johnson or Jock A. Campbell, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031, fax 405-325-7069.

Midcontinent Exploration Research Opportunity

Looking for the chance to try a new geophysical technique in your exploration program at no cost to you? A project studying seismic amplitude variation with offset (AVO) in the Midcontinent is underway at the Houston Advanced Research Center (HARC). The goal of the project is to determine if gains in drilling success can be made using AVO analysis in Midcontinent reservoirs. AVO analysis is the examination of the amplitude behavior of CMP gathers as offset increases. The presence of gas in many reservoir rocks causes a change in the amplitude response that can be used as a direct detection tool.

Funded by the Gas Research Institute, the project is headed by Drs. James L. Allen and Carolyn P. Peddy. Peddy and Allen have conducted a similar research project in the Gulf Coast, focusing primarily on the Eocene Yegua Formation. In the Yegua, drilling success ratios have been increased from 10–15% to 50% by the use of AVO analysis. Allen and Peddy recently published a book detailing the results of this study (*Amplitude Variation with Offset: Gulf Coast Case Studies,* available through the Society of Exploration Geophysicists in Tulsa).

To participate in the Midcontinent project, Allen and Peddy require field tapes of at least one seismic line crossing a well site in the Anadarko, Arkoma, Ardmore, or Marietta basins. The well should have been logged by a complete suite of tools, including a sonic log. Portions of both the seismic data and well logs will be published in technical articles that will appear in 1995 or 1996. Line and well locations and field names will not be published. In return for the donation, the participating company will have immediate access to all results of the AVO analysis for their data set.

For further information on participation in the project, contact James Allen or Carolyn Peddy; phone (713) 363-7915, fax 713-363-7924.

Summers Receives Award

Michelle J. Summers, OGS geological data coordinator, received the Waintroob/Myers Award for Distinguished Service from the University of Oklahoma's Professional Staff Association at a ceremony held April 25 in the ballroom of Oklahoma Memorial Union. The award was presented by Dr. Richard Van Horn, outgoing OU president.

The $500 cash award was given to Summers for her job performance and service to OU and the community. In addition to her normal duties as data coordinator, Summers does the registration for OGS-sponsored meetings, helps coordinate meals and refreshments, and helps with the displays taken to national meetings.

She also works with many professional organizations such as the Association of Independent Petroleum Geologists, American Association of Petroleum Geologists, Association of American State Geologists, and the Mid-Continent Oil and Gas Association Nomenclature Committee, which defines boundaries of Oklahoma oil and gas fields.

Summers believes that participation on employee councils, boards, and committees benefits the OGS, OU, and her fellow workers. She has served as a council member for the Professional Staff Association, and has represented this group at Employee Executive Council meetings. She has served on staff-week committees for three years, and worked with the Health Fair held in conjunction with that event. She has been instrumental to the OGS Teddy Bear Tea Party for the past seven years, helping with this fund raiser that donates toys to various charities and shelters for abused and battered children. She also has worked with the Women's Resource Center in Norman, and received their recognition award for 1993.

— *Connie Smith*

At the awards ceremony (left to right): OU President Richard Van Horn, Michelle Summers, PSA President Jean Simmons, and EEC Chair Neal Stone.

UPCOMING *Meetings*

Environmental Issues in Oil and Gas Operations Meeting, July 11–13, 1994, Golden, Colorado. Information: Office of Special Programs and Continuing Education, Colorado School of Mines, Golden, CO 80401; (303) 273-3321, fax 303-273-3314.

Society for Sedimentary Geology, Research Conference, July 12–14, 1994, Long Beach, Washington. Information: SEPM, P.O. Box 4756, Tulsa, OK 74159; 1-800-865-9765 or (918) 743-9765, fax 918-743-2498.

Clay Minerals Society, Annual Meeting, August 14–19, 1994, Saskatoon, Saskatchewan, Canada. Information: Ahmet R. Mermut, Dept. of Soil Science, Saskatchewan Institute of Pedology, University of Saskatchewan, Saskatoon, Saskatchewan S7N 0W0, Canada; (306) 966-6839, fax 306-966-6881.

American Association of Petroleum Geologists, International Meeting, August 21–24, 1994, Kuala Lumpur, Malaysia. Information: AAPG, Convention Dept., Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

Petroleum Engineering Symposium, August 29–31, 1994, Tulsa, Oklahoma. Information: Society of Petroleum Engineers, Meetings and Exhibitions Dept., Box 833836, Richardson, TX 75083; (214) 952-9393, fax 214-952-9435.

Geological Society of America, Annual Meeting, October 24–27, 1994, Seattle, Washington. *Abstracts due July 6.* Information: Vanessa George, GSA Meetings Dept., Box 9140, Boulder, CO 80301; 1-800-472-1988 ext. 113 or (303) 447-2020, fax 303-447-0648.

American Association of Petroleum Geologists, Annual Meeting, March 5–8, 1995, Houston, Texas. *Abstracts due September 1, 1994.* Information: AAPG, Convention Dept., Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

SEPM ELECTS NEW OFFICERS

1926 SEPM Society for Sedimentary Geology

Officers of the Society for Sedimentary Geology for the 1994–95 term are:

President: NOEL P. JAMES, Queen's University, Kingston, Ontario
President-Elect: LÉO F. LAPORTE, University of California, Santa Cruz
Paleontology Councilor: CARLTON E. BRETT, University of Rochester
Sedimentology Councilor: DAVID A. BUDD, University of Colorado
Secretary/Treasurer: STEVEN C. DRIESE, University of Tennessee
Research Councilor: MICHAEL A. ARTHUR, Pennsylvania State University
Editor, *Journal of Sedimentary Petrology:* JOHN B. SOUTHARD, Massachusetts Institute of Technology
Editor, *PALAIOS:* DAVID J. BOTTJER, University of Southern California
Editor, Special Publications: PETER A. SCHOLLE, Southern Methodist University

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.

Womble "Shale" (Middle Ordovician): A Taconian-Derived Submarine Fan Complex in the Broken Bow Uplift, Ouachita Allochthon, Oklahoma

MICHAEL C. DIX, DOUGLAS R. REID, and *JOHN F. CASEY,* Dept. of Geosciences, University of Houston, Houston, TX 77204

Across most of the Ouachita allochthon, the deep-marine Womble Shale (Middle Ordovician) comprises up to 1,100 m of dark grey to black shale, with minor sandstone, fine-grained limestone, and sandy bioclastic limestone. The quartzose nature of the sandstone and the presence of shallow-water carbonate debris clearly indicate derivation from the Laurentian continental shelf to the north.

In the Broken Bow uplift, however, the Womble "Shale" is distinctly different. It consists of an uncertain thickness (~1,500 m?) of green to grey, poorly sorted, fine- to coarse-grained greywacke interbedded with dark grey to black shale; chert and silty limestone are very minor constituents. Greywacke-shale pairs are typically 20–100 cm thick, have sandstone:shale ≥3:1, and are characterized by partial Bouma sequences (commonly T_{ae}, T_{abe}, T_{ace}, T_{bce}). Some amalgamated beds are at least 12 m thick, with sandstone:shale ≥15:1. Within the modified Mutti/Ricci-Lucchi facies scheme of Pickering et al. (1989), that great majority of the Broken Bow Womble can be assigned to Facies Class C ("classical turbidites"), with minor occurrences of Facies Classes D, E, and B. Bottom markings on greywacke beds (flutes and grooves) indicate north, northwest, and west-directed paleocurrents.

Detrital modes from this study and from Erickson (1990) show that Womble greywackes contain abundant lithic fragments (sedimentary and metasedimentary) and polycrystalline quartz, and plot in the recycled-orogenic QFL provenance-field. Although volcanic grains have not been recognized, low values of Al_2O_3/TiO_2 and La_N/Yb_N provide evidence for a mafic contribution to the sediment.

The Broken Bow Womble is interpreted as a submarine-fan complex that prograded into the Ouachita basin from the southeast. Womble greywackes were likely derived from a southwestern extension of a Taconian arc-continent collision, which deformed and uplifted the Laurentian passive margin on the Alabama promontory, and possibly also the outboard margin of a microcontinent south of the Ouachita basin. Progradation of the Womble fan complex was contemporaneous with the development of the Taconian Blount clastic wedge of Alabama, Georgia, and Tennessee, which contains sandstones broadly similar in composition to the Womble greywackes (Mack, 1985).

Because the lithology, petrology, and sediment-dispersal pattern of the Womble "Shale" in the Broken Bow uplift is strikingly different from the Womble Shale elsewhere in the Ouachita allochthon, this greywacke-dominated unit should be renamed and accorded status as a separate formation. We propose the new name "Mountain Fork Sandstone."

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Provenance of Ordovician–Silurian Siliciclastic Rocks in the Broken Bow Uplift, Ouachita Allochthon, Oklahoma

DOUGLAS R. REID, MICHAEL C. DIX, and *JOHN F. CASEY,* Dept. of Geosciences, University of Houston, Houston, TX 77204

Detailed mapping, whole rock geochemistry, and a compilation of new and existing petrographic data have been used to investigate the provenance of Ordovician–Silurian siliciclastic units in the Broken Bow uplift. Two distinctive sediment sources have been identified: (1) an Early to Middle Ordovician cratonic (Laurentian) source, and (2) a Middle Ordovician through Silurian orogenic (Taconian) source.

Craton-derived units include the Collier, Crystal Mountain, Mazarn, and Blakely(?) Formations (Early to Middle Ordovician). Sandstones in this sequence are moderately to very well sorted, quartzo-feldspathic (Collier only) to highly quartzose, and plot in the craton-interior field on the QFL provenance diagram. These units were clearly derived from the Laurentian craton to the north of the Ouachita basin.

A major shift to an orogenic provenance is recorded by the thick greywacke-shale sequence of the Womble Formation (Middle Ordovician), and continued with the minor greywackes interbedded in the Bigfork Chert and Polk Creek Shale (Middle to Upper Ordovician). All of these greywackes are poorly sorted, quartzo-lithic, and plot in the recycled-orogenic field on the QFL diagram. Geochemically, they are distinguished from Laurentian-derived sandstones by higher TiO_2, Al_2O_3, Fe_2O_3, Zr, V, Sc, Y, and ΣREE, and lower SiO_2. Relatively low Al_2O_3/TiO_2 and La_N/Yb_N suggest a mafic component in the source terrane. Sandstones in the Blaylock and Missouri Mountain Formations (Silurian) are finer-grained, slightly better sorted, and more quartzose than the greywackes, but their geochemical signature is very similar.

Paleocurrent data from both the Womble and the Blaylock Formations in the Broken Bow uplift indicate that orogenic sediment was funneled into the basin from the south, southeast, and east. The source was a predominantly sedimentary and low-grade metasedimentary terrane with a minor arc component. We suggest this terrane to be the southwestern extension of a Taconian (Middle Ordovician) arc-continent collision orogen that persisted as a sediment source through the end of Silurian time. Our data provide additional support for the recent findings of Gleason et al. (1993), based on Sr and Nd isotopic data, that an Appalachian–Ouachita sedimentary linkage was established by the Late Ordovician. Our results, however, extend the linkage even further back to the Middle Ordovician, at least for strata exposed in the Broken Bow uplift.

Reprinted as published in the Geological Society of America *1994 Abstracts with Programs*, v. 26, no. 1, p. 25.

Provenance of Carboniferous Tesnus and Haymond Formations, Marathon Basin, West Texas, in Light of Nd Isotopic Data

W. R. DICKINSON, J. D. GLEASON, P. J. PATCHETT, and *JOAQUIN RUIZ,* Dept. of Geosciences, University of Arizona, Tuscon, AZ 85721

Ten samples of Tesnus (n = 5) and Haymond (n = 5) sandstone and shale yield a compact Nd isotopic signature, with observed epsilon Nd of –11.6 to –14.6, which recalculate to initial epsilon Nd of –8 to –11 for Carboniferous time. Coordinate results for three sandstone-shale sample pairs from associated outcrops imply that Nd isotopic systems were not disturbed by diagenesis and thus reflect provenance sources. The Nd isotopic signature for Tesnus–Haymond strata is indistinguishable from that for fluvio-

deltaic Carboniferous units of the Black Warrior, Illinois, and Arkoma basins and the overthrust Ouachita turbidite assemblage of Arkansas–Oklahoma. This widespread and well-mixed detritus is inferred to have formed a regional sediment blanket recycled from the evolving Appalachian–Mauretanide orogen, a voluminous provenance terrane developed as Laurasia and Gondwana collided to form Pangaea. A distinctly more negative value (epsilon Nd –20 observed and –15 initial) for Alsate Shale (n = 1) is coordinate with results for coeval units of the Ouachita Mountains derived from Precambrian sources on the craton. A distinctly less negative value (epsilon Nd –6 observed and –2 initial) for Tesnus tuff (n = 1) is coordinate with results for Stanley tuffs of the Ouachita Mountains and is interpreted to reflect derivation from a mature magmatic arc ("Llanoria") with continental basement in its crustal profile but lying south of North America. Dispersal of sediment, indicated by both clast assemblages and paleocurrent trends, from the Ouachita orogen into the Tesnus–Haymond depositional basin was apparently limited mainly to recycling of sediment from a deformed accretionary prism without significant contributions from the associated magmatic arc. The Carboniferous deposystem of the Marathon basin shoaled from Tesnus subsea-fan turbidites and Dimple carbonate-apron turbidites to Haymond foredelta turbidites and fan-delta deposits as Ouachita orogenic collision evolved.

Reprinted as published in the Geological Society of America *1994 Abstracts with Programs*, v. 26, no. 1, p. 5–6.

Provenance of the Paleozoic Ouachita Sequence, Oklahoma and Arkansas: Implications from Nd Isotopic Data

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Forty-eight samples of sandstone, shale and tuff representing the entire Paleozoic Ouachita sequence yield a wide variation in Nd isotopic values which resolve into three distinct isotopic populations: (1) Mississippian tuffs, with initial epsilon Nd of –1 to –2; (2) Lower to Middle Ordovician (Pre-Bigfork) strata, with initial epsilon Nd of –13 to –16; (3) Upper Ordovician to Pennsylvanian (Post-Bigfork) strata (inclusive), with initial epsilon Nd of –6 to –10. Mississippian tuffs, derived from evolved volcanic arc sources to the south ("Llanoria"), are not a major component of Ouachita sediments, but instead form one end-member of a Nd mixing line with Mississippian Stanley shales. The Early to Middle Ordovician Pre-Bigfork sequence reflects an older provenance of mixed Archean and Proterozoic cratonal sources lying to the north of the Ouachitas. These cratonal sources were shut off during late Ordovician time with deposition of the Late Ordovician through Pennsylvanian Post-Bigfork sequence, which reflects dominantly Appalachian sources. We interpret this provenance shift as a direct response to the Taconic orogeny in the Appalachians. Isotopic data from Middle Ordovician (Taconic) turbidites of the Sevier basin, eastern Tennessee, support this hypothesis. The shift to Appalachian sources requires a change in regional dispersal pathways: one possible scenario is to direct Taconic clastic wedges around the Appalachian–Ouachita syntaxis and into the Ouachita turbidite basin, as has been suggested for Carboniferous Ouachita turbidites. Isotopic data from Carboniferous fluviodeltaic sandstones and shales of the Arkoma, Illinois, and Black Warrior basins suggests that by Pennsylvanian time, continental margin pathways were augmented by an influx of sediments with identical isotopic composition coming across the craton, an event we believe was linked to collisional events in the Appalachian–Mauretanide system at the end of the Paleozoic.

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Mineralogical and Geochemical Evidence of Ouachita Provenance

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Provenance of the extremely thick Ouachita flysch has not been specifically identified, despite several recent studies. Detrital mineral compositions, Sm–Nd model ages, and single zircon dates strongly suggest that several sources contributed sediment that became well-mixed before deposition.

Sm–Nd model ages are nearly uniform for flysch samples, regardless of geographic position or exact stratigraphic position. These ages appear to rule out significant contribution by a Paleozoic island arc, and suggest a single source, multiple sources with similar model ages, or thorough mixing of sources with different model ages. In contrast, single zircon ages are variable, including Archean, Proterozoic, and Paleozoic ages. These ages indicate multiple sediment sources, including some external to North America. The zircon ages, however, may not be generally representative of Ouachita sediment sources because they were obtained on zircons far larger than typical Ouachita detrital zircons.

The Sm–Nd model ages and single zircon ages can both be explained if sediment entering the Ouachita Trough came from multiple sources, but was already thoroughly mixed before entering the trough. Such mixing is also suggested by detrital mineral analyses. Muscovite, garnet, and tourmaline have been analyzed. Muscovite shows variable Ti, Fe, and Mg, whereas almandine garnet and schorl tourmaline show minor compositional variation. In none of these minerals is compositional variation related to geographic or stratigraphic position. The detrital phases suggest that both metmorphic and igneous sources were volumetrically important sediment sources. The thorough mixing suggests sediment may have passed through another basin, possibly the Black Warrior Basin, before entering the Ouachita Trough.

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Subsidence History of the Alabama Promontory in Response to Late Paleozoic Appalachian–Ouachita Thrusting

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The Alabama promontory of North American continental crust was framed during late Precambrian–Cambrian rifting by the northeast-striking Blue Ridge rift and the northwest-striking Alabama–Oklahoma transform fault. A passive margin persisted along the western side of the promontory from Cambrian to Mississippian time, but the eastern side was affected by the Taconic and Acadian orogenies. Prior to initiation of Ouachita and Appalachian (Alleghanian) thrusting, the outline of the rifted margin of continental crust on the Alabama promontory remained intact; and the late Paleozoic thrust belt conformed to the shape of the promontory, defining northwest-striking Ouachita thrust faults along the southwest side of the promontory, north-striking Appalachian (Georgia–Tennessee) thrust faults on the east, and northeast-striking Appalachian (Alabama) thrust faults across the corner of the promontory. Strikes of the thrust faults imply that thrust loads were translated onto continental crust from three directions. Subsidence profiles perpendicular to each of the strike domains of the thrust belt have been constructed by calculating total subsidence from decompacted thickness of the synorogenic sedimentary deposits. The profile perpendicular to the Ouachita thrust belt shows increasing subsidence rates through time and toward the thrust front, indicating the classic signature of an orogenic foreland basin. The profile perpendicular to the Georgia–Tennessee Appalachian thrust belt similarly shows increasing subsidence rates through time and toward the orogenic hinterland. In contrast, the profile perpendicular to the Alabama Appalachian thrust belt shows only limited subsidence of the foreland immediately adjacent to the thrust front, and that increment of subsidence was initiated much later (during Early Pennsylvanian) than subsidence along either the Ouachita or Georgia–Tennessee Appalachian forelands, where subsidence was initiated during middle Mississippian time. These quantitative results support the conclusion that Black Warrior basin subsidence is tectonically rather than sedimentologically driven, and the timing of subsidence events reported here has implications for regional tectonic models.

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Provenance of the Jackfork Sandstone, Ouachita Mountains, Arkansas and Eastern Oklahoma

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The Jackfork Sandstone represents 6,000 ft of Carboniferous flysch deposited in the Ouachita geosyncline in deep water by currents which flowed in a dominantly westward direction. Provenance has been difficult to establish because of the paucity of diagnostic minerals and framework grains.

Monocrystalline quartz comprises as much as 96 percent of the framework grain population: with feldspar and mainly metamorphic and sedimentary rock fragments making up the rest.

Samples from widely spaced outcrops throughout the frontal and southern Ouachitas in Arkansas and central Ouachitas in eastern Oklahoma were collected and over 150 thin sections were prepared. Detailed framework grain analysis showed monocrystalline quartz decreasing in amount to the south, with feldspar and lithic grains increasing in that direction.

Triangular Q_m-F-L_t diagrams and petrographic maps support the notion of a mature Illinois basin source to the northeast, a less mature metamorphic and igneous source (Llanoria) to the south, and a source to the east which possibly routed sediment from the Ouachita/Appalachian orogen into the geosyncline.

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Factors Controlling the Deposition and Character of Submarine Fan Complexes: An Illustration from the Carboniferous Ouachita Basin

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The variable nature of deep sea fan sedimentation is well illustrated in the Carboniferous flysch sequences of Oklahoma and Arkansas. This variability is controlled by sedimentation source area, intra- and extra-basinal tectonics, climate, and local and global eustasy. These regional factors ultimately affect specific bed and bed set homogeneity through several basinal sedimentary processes.

The basinal Carboniferous siliciclastic units of the Ouachita Basin include the Mississippian Stanley shale and Pennsylvanian Jackfork, Johns Valley, and Atoka Formations. Diversity in the final sedimentary products, as well as resulting structural overprinting, is a function of the interaction, to varying degrees, of the four factors listed above.

	Source Area(s)	Eustasy	Climate	Tectonics
Atoka	Ozark Shelf Black Warrior Basin Ouachita orogen	Rising	Transitional	High
Johns Valley	Ozark Shelf Ouachita Basin(?)	Medium	Wet	Increasing
Jackfork	Black Warrior Basin Ozark Shelf, Ouachita orogen,	Low	Wet	Increasing
Stanley	Ouachita orogen, Black Warrior Basin	High	Arid	Low

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The Jackfork Formation of Arkansas: A Test of the Walker–Mutti–Vail Models for Deep Sea Fan Deposition

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The Jackfork Formation of the Arkansas and Oklahoma Ouachita Mountains is part of a large submarine fan complex. Geologists in the USA probably know more about it than many other deep water sedimentary complexes. By taking a detailed look at a single, complete transect of the Jackfork fan, well out into the depositional basin, one should be able to measure the effectiveness of the most popular deep sea fan models and judge whether the recommended abandonment of these models, in two instances by the authors themselves, is warranted.

The mood of most veteran submarine fan workers is to abandon generalized depositional facies models of the past, because no one model accurately predicts observations of all submarine fan complexes. Yet, the management of today's mineral and hydrocarbon exploration and production companies frequently request investment recommendations be explained in terms most commonly associated with these models. Additionally, geoscientists have demonstrated the need for viable, spatially oriented models as frameworks in which to bring observations, ideas, theories, and communication.

The Jackfork Formation at DeGray Lake and Dam is almost 6,200 ft (1,890 m) thick, without significant fault offset or interruption. The exposures in this area are approximately 150 mi (241 km) from the northern, southern, and eastern paleo-shelf edges.

Interpretation of outcrop and subsurface data makes understanding the depositional location of the area outcrops relatively straightforward, thus enabling an objective evaluation of these models.

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Preliminary Sequence Stratigraphic Framework, Pennsylvanian Jackfork Group Turbidites, DeGray Lake Area, Arkansas

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The Morrowan Jackfork Group consists of approximately 5,000 ft of fine-grained, quartz-rich sandstones interbedded with illitic shales and mudstones. These strata have been interpreted by previous workers to represent deep-water turbidites, debris flows and pelagites. Our preliminary interpretation of Jackfork strata in the DeGray Lake area recognizes five depositional sequences. Sequence boundaries were selected at the top of the thickest shale units, particularly where overlain by relatively thick sandstones. Depositional sequences consist of thick sandstones (10–30 m) at the base, overlain by 40 to 60 meters of thin interbedded sandstones and shales, overlain by a thick (10–15 m) shale and/or debrite. The sandstones at the base of each sequence and the overlaying interbedded sandstones and shales are interpreted to be basin floor submarine fan lobe deposits, and the overlying thick shale to reflect the deep water equivalent of the transgressive and highstand systems tracts, possibly containing a condensed interval. The debrites represent transgressive and/or highstand debris flows.

Deposition was strongly influenced by Morrowan sea level fluctuations. It is proposed that these fluctuations were eustatic in nature and related to the well-documented high-frequency sequences of Morrowan strata in the Midcontinent region. Although sea level greatly affected deposition, Jackfork sedimentation was probably also influenced by tectonically controlled changes in sediment supply and by autocyclic processes such as lobe-switching.

Restrictions in this study include the lack of biostratigraphy and regional physical stratigraphy. These limitations dictate that conclusions reached are highly interpretive, and are intended only as a starting point for further analysis of Jackfork sequence stratigraphy.

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Interpreting Formation Microscanner Log Images of Gulf of Mexico Turbidites by Comparison with Pennsylvanian Turbidite Outcrops, Arkansas

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A comprehensive picture recently has emerged of the wide variety of slope/base of slope depositional processes and resultant facies, lateral and vertical continuity, and gamma-ray log signature of the Pennsylvanian Jackfork Group turbidites in Ouachita Mountains of Arkansas. The details of our investigations have been reported on industry field trips and discussed in several recent publications. We now add another applied dimension to this picture by comparing small- and large-scale sedimentary features observed in the turbidite outcrops with what we interpret as identical features observed on Formation MicroScanner logs from Gulf of Mexico turbidites.

Small-scale features displayed on the Formation MicroScanner logs include slumps, erosional surfaces, thin sand-shale interbeds, mud-lined depressions/scours, isolated sandstone clasts in shaley debris flow beds, remnant bedding in various stages of disruption owing to flowage, and load structures. These features are similar in size and character to those observed in outcrop. On a larger scale, thin- and thick-bedded intervals and major, probably regionally correlative surfaces are recognized.

Based upon the outcrop criteria, recognition of these features on Formation MicroScanner images can lead to an improved understanding of Gulf of Mexico (and elsewhere) deep-water depositional processes, facies and their three-dimensional geometry, relative reservoir quality, and lateral and vertical continuity of beds. This understanding can prove valuable in resolving reservoir management, development drilling, and exploration issues.

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Microfabric and Petrology of the Hushpuckney Shale (Pennsylvanian), Midcontinent, U.S.A.

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Samples of the Hushpuckney Shale (Pennsylvanian) have been studied in transverse from the Forest City Basin, Iowa, to the Ozark Uplift Region in Kansas to the Arkoma Basin in Oklahoma to investigate the relationship of shale characteristics to position of deposition in a basin. Microfabric (using Scanning Electron Microscopy), macrofabric (by thin-section analysis), composition (by x-ray diffraction technique) and Total Organic Content (TOC) were studied to determine gross fabric, mineralogy, and total organic content. The fabric in all samples was found to be uniform laterally and characterized as organic hash (Classification by O'Brien and Slatt, 1991). X-ray traces show uniform distribution of kaolinite, illite and chlorite in all samples. Total Organic Content (TOC), however, increased from 12% in Iowa to 20% in Kansas to nearly 30% in the deepest basin in Oklahoma. From previous studies it has been determined that sedimentary processes influence the fabric of a clay rich rock. The Hushpuckney shows no lateral variation in fabric so it may be concluded that this shale formed under similar sedimentary conditions, throughout the area investigated.

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Investigations of a Deep Drill Hole in the Ouachita Trend, West Texas

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The Exxon 1 Gatlin well was recently drilled to a depth of over 25,000 ft in Terrell County, Texas, just north of the international boundary with Mexico. This well is the deepest penetration of the interior zone of the Ouachita system to date. The well is near the apex of the interior zone gravity high, which elsewhere has been shown to approxi-

mately mark the Paleozoic continental margin. Gravity models constructed in this region, including one that was tied to this well, confirm that this well is proximal to the Paleozoic margin.

The well was spudded in Lower Cretaceous rocks, and drilled through a 23,000-ft section of low-grade metamorphic rocks. Cuttings of this metamorphic section are composed predominantly of phyllite, fine-grained schist, metaquartzite, and impure marble. Based on their mineralogy and texture, the likely precursor for these rocks was a sedimentary sequence of marls and mudstones. However, no relict sedimentary structures or fauna were observed. Phyllite and schist fragments are graphitic and locally crenulated, and large fragments exhibit multiple phases of deformation. Minor coarse carbonate and quartz may represent vein fills. Downhole textural trends include a gradual change from phyllite to schist at approximately 7,500 ft, and a gradual increase in schist fragments to 19,600 ft. X-ray diffraction of bulk samples indicates a downhole decrease in total carbonate content. This metamorphic sequence appears similar to Ouachita interior zone rocks encountered in wells in central Texas and in outcrops in Oklahoma and Arkansas. However, the large thickness encountered in the well and the even larger thickness suggested by the gravity modeling is indicative of proximity to the continental margin and is likely the result of thrust faulting.

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Geology of the Ouachita Facies Overthrust in North Texas and Southern Oklahoma

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In any geologic study of North Texas, recognition and evaluation of the Fort Worth Basin are necessary. What is not as widely known is that North Texas is cut by the north-south-striking thrust front of the late Paleozoic Ouachita facies overthrust belt. It is this overthrust belt and its tectonic influence which helped to shape the structural configuration that we recognize as "North Texas geology."

In the North Texas area, the Ouachita facies is represented by the interval from the Ordovician Womble Shale to the Mississippian Stanley Shale. Within this sequence, fractured Ordovician Bigfork Chert and Devonian/Mississippian Arkansas Novaculite produce hydrocarbons at Isom Springs field, Marshall County, Oklahoma, approximately 70 miles north of Dallas. In that the Ouachita facies is generally very uniform throughout Texas, Oklahoma, and Arkansas, other commercially productive reservoirs should exist in the North Texas area, and along the strike of the thrust front across southeastern Oklahoma and western Arkansas.

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Extent and Style of Ouachita-Type Deformation, Southern Arkoma Basin, Eastern Oklahoma

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In eastern Oklahoma, the Choctaw fault separates the Ouachita Mountains fold-and-thrust belt to the south from the Arkoma basin to the north. However, Ouachita-type

compressional structures (décollements, reverse faults, tight folds) of Desmoinesian (post-Krebs, pre-Cabaniss) age extend into the Arkoma basin. At the surface, the general structure of the southern Arkoma basin is characterized by (1) widely spaced faults and fault zones; (2) widely spaced fold axes; (3) common open folds; and (4) uncommon asymmetric south-vergent map-scale folds. In contrast, the northern part of the Ouachita tectonic belt is dominated by (1) anastomosing imbricate faults; (2) locally closely spaced fold axes; (3) tight folds; and (4) asymmetric to overturned north-vergent folds. At the surface, strata immediately north of the trace of the Choctaw fault are upright and dip steeply to moderately north; to the south, strata dip and face steeply south. This suggests the Arkoma basin–Ouachita Mountains transition may be a triangle zone.

However, the exact nature of the transition from Ouachita- to Arkoma-style of deformation, as interpreted from seismic reflection and e-log data, is controversial. The principal questions focus on (1) the vergence (north or south), level (Mississippian–Morrowan or Atokan), and extent of a basal décollement and whether it surfaces; (2) the relation between a single south-vergent backthrust and/or imbricate backthrusts or duplex zone and a triangle zone; (3) the possibility of multiple décollements, duplex zones, and/or triangle zones; (4) the role of transverse structures and/or middle-Atokan "growth" faults in subsequent Ouachita Mountains and Arkoma basin deformation. All of these structures have been identified in published interpretations of subsurface data and may reflect real differences in transition-zone structure.

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Three Dimensional Seismic Interpretation from the Triangle Zone Between the Ouachita Mountains and Arkoma Basin, Hartshorne, OK

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The boundary between the frontal Ouachitas fold and thrustbelt and the foreland Arkoma basin has been interpreted as a triangle zone. 3-D seismic reflection data from this triangle zone show details not recognized in conventional 2-D seismic data. The data indicates that the frontal Kiowa syncline in the Arkoma basin has been passively uplifted by blind thrusting at deeper levels. Blind thrusting takes place at two levels: the Morrowan Wapanucka Formation and the Silurian Hunton Formation. Detachments for the thrusting in the Wapanucka Formation are in the Springer Shale and the Woodford Formation. The thrusts offsetting the Hunton Formation have detachments in the Simpson Group and possibly in the Arbuckle Group or even deeper. Horizontal shortening in the Wapanucka Formation ranges from tens of meters to a few kilometers, and in the Hunton Formation from tens of meters to a few hundred of meters.

Four reflectors were interpreted: a reflector in the lower Atoka Formation, two repeated Wapanucka limestone sections and the Hunton Formation. All of the surfaces exhibit the same geometry with their fold axis plunging to the southwest. The surface geometry and fold axis data suggest that the first thrusting was in the Wapanucka Formation and later in the Hunton Formation. Faulting in the Hunton Formation has been traditionally interpreted as normal, although basement-involved reverse faults, such as the Carbon fault, have been mapped. The interpretation of some individual inlines or crosslines may also show normal faults, but the interpretation of the whole 3-D survey support the proposed compression in the older sequence.

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Estimates of Volume Loss Associated with Cleavage Development, Broken Bow Uplift, Ouachita Mountains of Oklahoma

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The slaty cleavage in Broken Bow uplift, Ouachita Mountains of southeastern Oklahoma, is pervasive in shales and more widely spaced in coarser grained rocks. On a microscopic scale, zones of pressure solution residues (PSR) consisting of mica, iron oxide, and other opaque materials are aligned parallel to cleavage traces. The lack of traditional strain markers such as deformed oolites and brachiopods in the Broken Bow uplift have made strain quantification very difficult. However, the volume loss associated with cleavage development has been estimated using deformed stylolites, apparent offsets of bedding, apparent offsets of microfold limbs, and dissolved grains. Although the various methods have their respective assumptions and limitations, calculations yield consistent values of approximately 40% volume loss using deformed stylolites, 37% using offsets of bedding, 31% using the truncated limbs of microfolds, and 38% using the dissolved grains, for the cleaved rocks in the Broken Bow uplift. It is apparent that pressure solution associated with cleavage formation involves significant volume loss. An estimate of regional volume loss within Broken Bow uplift including the depth to the inferred basement yields ~3×10^3 km^3 of dissolved soluble materials. While quartz veins are a common feature, it appears likely that a significant amount of soluble material has been removed from the system. These independent approaches for volume loss estimates associated with cleavage development can be used to estimate strain in other orogenic belts as well.

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Ouachita Mountain Rocks Retuned!!?

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Soon after the Co-Geo Map project was started, one of the authors stated "we are going to fine-tune the rocks." With that lofty aspiration in mind, we field-checked the geologic maps in many areas, applied strikes and dips, D symbols on the down side of normal faults, and daggers on the thrust plates of reverse faults. The resultant "fine-tuned" geologic map (scale 1:100,000) is a thing of beauty! However, a study of the multitude of geologic features depicted on the map has convinced us that the G string on our violin needs more attention.

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Quartz Veins and Crystal Deposits in the Ouachita Mountains

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Milky quartz veins are abundant in the complexly deformed Paleozoic rocks in the core of the Ouachita Mountains, occurring in a wide belt extending from Little Rock, Arkansas, to near Broken Bow, Oklahoma. Locally, they may be as much as 60 ft in width. The veins commonly have traces of adularia, chlorite, calcite, and dickite and

may contain rectorite, pyrophylite, and cookeite. Certain metals, including lead, zinc, silver, copper, antimony, and mercury may be associated with the quartz veins.

The milky quartz veins and associated minerals are hydrothermal deposits of tectonic origin. The veins formed during the closing stages of the Late Pennsylvanian–Early Permian orogeny in the Ouachita Mountains. They commonly fill fractures and joints in the rocks and some are closely associated with thrust faults. While a few veinlets are crenulated, most veins are not folded, but are often faulted, fractured, and crushed. Copious amounts of thermal pore fluids were generated from the argillaceous strata during this late deformation and abundant milky "bull" quartz veins and stockworks with minor crystals often formed in the shales. However, the small to large clear quartz crystals in fracture cavities developed concurrently in the less ductile sandstones and were also, in part, nutured by the thermal fluids dewatered from the adjoining thick argillaceous strata.

At certain localities, milky quartz veins have cavities containing eye-clear to milky crystal and clusters suitable for mining. Individual crystals up to 5 ft in length and weighing over 400 pounds and clusters 15 ft in length weighing over 10 tons have been produced from these mines. Most of the crystals mined have been from veins occupying fractures in the Ordovician Crystal Mountain and Blakely Sandstones. The principal crystal market has been for specimens in mineral collections worldwide. Other uses have been as oscillators in communications equipment, for fusing quartz, and as lasca—the chemical feedstock for vitreous silica or for growing cultured quartz.

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Ouachita Mountains Cambrian–Ordovician Conodonts Revisited

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Since first reported from the Ordovician in the core area of the Ouachitas two decades ago, conodonts have become the prime dating tool within these strata. The succession is dominantly siliciclastic, but all of the formations contain calcareous beds that have yielded conodonts. The faunas can be dated and assigned to current zonations, and their host-units can be correlated with those of adjacent areas. The oldest exposed unit, the Collier Shale, contains mid-Late Cambrian (Franconian protoconodonts dated by accompanying trilobites) and several early Ibexian conodont biozones, from *Cordylodus proavus* to *Rossodus manitouensis*. The Crystal Mountain Sandstone has yielded few conodonts; overlying Mazarn Shale faunas represent most of the subsequent Ibexian. Indigenous Mazarn faunas comprise two Arenigian zones, the lower characterized by *Acodus* aff. *A. deltatus*, the higher by *Oepikodus smithensis*. Shelf faunal components range from North American Midcontinent "Fauna D" through the *Oepikodus communis* Zone. Faunas from the Blakely Sandstone, both indigenous and presumably transported, are lower (but not lowest) to middle Whiterockian; correlative shelf units, also sandy, are the Everton in the Ozarks and Joins and Oil Creek in Oklahoma. The Womble Shale contains faunas from the *Pygodus serra* Zone to at least the *Baltoniodus gerdae* Subzone (Llanvirnian to lower Caradocian); North American Midcontinent faunal elements from upper Whiterockian (= Chazyan) to Blackriveran co-occur. The Bigfork Chert contains species dating it from late Mohawkian to at least early Cincinnatian.

Consistent with slope-to-basin deposition of the core Ouachita succession, the presumed indigenous conodont faunas are of the deep/cool-water North Atlantic province as well as cosmopolitan species. Most sampled intervals also contain penecontemporaneous species from the warm/shallow-water North American Midcontinent province. Admixture of these coeval shelf faunas, presumably by downslope gravity-flow deposition, provides evidence that the core Ouachita basin was not exotic to North America and also provides correlation tie-lines with the Ozark shelf and southern Oklahoma aulacogen successions.

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Trilobites from the Collier and Womble Shales and Bigfork Chert, Ouachita Mountains, Arkansas

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Redeposited shelf trilobites from the *Elvinia* Zone (Late Cambrian) have been recovered from new localities in the deep water Collier Shale in the Jessieville and Lena Landing areas in the Ouachita Mountains, including new species of *Erixanium, Cernuolimbus,* and *Anechocephalus.* Previously recovered trilobites from the *Elvinia* Zone from the Collier are characteristic of inner to middle Cambrian Shelf areas in Texas, Oklahoma, and Missouri. The three new species belong to genera known from outer shelf and slope deposits in the Great Basin, northwestern Canada, and Alaska. *Erixanium* has also been reported from localities in Australia, Siberia, Antarctica, Kazakhstan, and China, which suggests that *Erixanium* was a pelagic trilobite that lived in tropical to subtropical waters during the Late Cambrian.

Tiny silicified meraspids assignable to *Lonchodomas, Acanthoparypha, Dimeropyge,* and *Mesotaphraspis* occur in the lower part of the Middle Ordovician Womble Shale near Crystal Springs. Trilobite fragments have been recovered from the upper Womble near Norman and Manfred. Fragments of *Cryptolithus* were recovered from the lower Bigfork Chert west of Caddo Gap. These trilobite occurrences augment biostratigraphic correlations of these formations presently done using conodonts and graptolites.

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Regional Variations in Quartz Deformation Mechanisms, Eastern Ouachita Mountains, Arkansas

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Thirty-three samples were collected along a strike-normal traverse roughly following Arkansas Highway 7. Thin sections from the samples were cut normal to bedding and parallel to dip. Microstructural abundance was determined by point-counting 250 grains per thin section. All intragranular, intergranular, and transgranular structures were counted. Observed grain-scale deformation was accommodated by dislocation flow, pressure solution, recrystallization, and microfracturing. Microstructures related to dislocation flow include sweeping undulatory extinction, patchy extinction, deformation bands, and deformation lamella. Microstructures indicative of recrystallization are serrated grain boundaries and mortar texture. Pressure solution microstructures include sutured grain boundaries, overgrowth beards, and transgranular solution surfaces. Microfracture microstructures are fluid inclusion planes, microveins, and cataclastic bands. Because microstructures reflect the operative deformation mechanism in a rock, knowledge of regional variations in microstructural type and abundance can provide constraints on the conditions of deformation and allow delineation of areas deformed under different conditions. Viewed in the context of Groshong's (1988) deformation mechanism associations, microstructural abundance confirms the accepted boundaries of the internal subdivisions of the Ouachita orogen.

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Stratigraphic and Depositional Framework of Cambro–Ordovician Strata, Ouachita Mountain Core Area in Vicinity of East Shore of Lake Ouachita, Garland County, Arkansas

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Stratigraphic investigations in the vicinity of the eastern shoreline of Lake Ouachita from Blakely Mountain Dam in the south to Lena Landing in the north have described a number of excellent exposures of the Late Cambrian to Middle Ordovician formations that compose the core area of the Arkansas Ouachita Mountains. In ascending order, these units are the Collier Shale, Crystal Mountain Sandstone, Mazarn Shale, Blakely Sandstone, and Womble Shale. Comparison of the units in this part of the core area with the same strata exposed in the Crystal Mountains to the south and west shows that the stratigraphic interval to the east is significantly grainier, has a higher percentage of conglomerate and limestone, and possesses a richer assemblage of sedimentary structures. Paleocurrent and grain-size trends establish a south to southwest paleoslope.

Texture, geometry, and sedimentary structures of the units in question indicate deposition in a submarine fan, with the Crystal Mountain representing inner- to mid-fan deposits, the Blakely mid-fan deposits, and the shale units outer-fan to basin-plain deposits.

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Environmental Mercury Data for Arkansas

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Mercury contamination of fish in Arkansas and 28 other states has generated interest in the occurrence of mercury in the environment. Although only areas in southern Arkansas have fish advisories (>1.0 ppm Hg), fish concentrations exceeding 0.7 ppm Hg occur in other areas of the state. Because mercury can be concentrated in the food chain by bioaccumulation (10^4 to 10^5 times), low concentrations in the environment can become important. Methyl mercury, produced by bacteria under reducing conditions, is the mercury specie concentrated by organisms. Mercury volatilized during combustion of coal can be an important source for some areas; however, many areas contain sufficient natural concentrations for environmental concern, if methylation of the mercury occurs.

Although median total mercury concentrations for lake water (14 samples) is only 0.07 µg/L, lake sediment samples (110) have a median concentration of 0.55 ppm. Soil samples (120) from Northwest Arkansas have a median value of 0.04 ppm. Ground water concentrations for the Ozark Mountain region (17 samples) and Ouachita Mountains (102 samples) have median values of 0.4 and 0.1 µg/L, respectively. Surface water (16 samples) median concentrations for the Ozark region is the same as for the ground water. Three of the five ground water samples exceeding 1 µg/L are in the cinnabar district of the Ouachita Mountains. These data indicate that sufficient mercury is present in the environment of much of Arkansas for contamination of fish. Contamination of fish does not depend on anomalous mercury concentrations, but rather on conditions conducive for methylation.

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McKinley Rocks *(continued from p. 98)*

caused geologists with Weyerhaeuser Corp. to begin field studies in the Lynn Mountain syncline area in 1991. These studies led to the discovery of several thick sandstones with channel-like geometries and sedimentary features (Pauli, in press).

Channel sandstones similar to those exposed at McKinley Rocks occur throughout the Jackfork Group. Pauli (in press) describes others in the Lynn Mountain syncline area, and another occurs ~25 mi to the west on the west end of Jackfork Mountain (immediately east of the Indian Nation Turnpike). These strata are very different from the more "typical" turbidite sandstones that characterize most of the Lower Pennsylvanian section in the Ouachita Mountains. The distribution, origin, and reservoir potential of these sandstones are likely to be the focus of much research and (undoubtedly) controversy in the near future.

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