Oklahoma GEOLOGY Notes

OKLAHOMA GEOLOGICAL SURVEY VOL. 48, NO. 5 OCTOBER 1988

On the cover—

Granite in the Wichita Mountains of Southwestern Oklahoma

Aerial view of granite mountains composed of Mt. Scott Granite in the Cambrian (500–525 m.y. old) Wichita Granite Group. These unnamed peaks in secs. 5, 6, 7, and 8, T. 4 N., R. 15 W., Comanche County, make up a part of the extensive Wichita Mountains of southwestern Oklahoma. The mountains here rise ~800 ft above the surrounding plains that consist of Permian red beds. Pink granites here show joints, fractures, and faults as conspicuous tree-lined linear depressions where the rock has weathered more readily than the adjacent unfractured rock. View looking to the east–northeast.

Kenneth S. Johnson

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Oklahoma GEOLOGY Notes

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CHANGES IN THE PLANFORM OF THE RED RIVER, McCURTAIN COUNTY, OKLAHOMA, 1938–84

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Abstract

Changes in the meandering planform of the Red River in McCurtain County, Oklahoma, are thought to be associated with the upstream closure of Denison Dam in 1943. Maps constructed from aerial photographs dating from 1938, 1963, 1969, 1978, and 1984 were overlaid in pairs to identify areas of channel migration and to quantify rates of erosion. Measurements of meander geometry were used to examine the symmetry of the channel through time. The channel displays an inherent asymmetry of form, as 20 of 24 traverses are indicative of asymmetry. Average rates of channel migration were calculated for each meander bend during four time intervals (1938–63, 1963–69, 1969–78, and 1978–84). Total mean migrations of 10 m/yr channelward and 12 m/yr bankward for the north bank and 16 m/yr channelward and 8 m/yr bankward for the south bank were computed. The attempt to identify a causal relation between Denison Dam and changes in the channel pattern is, at best, tenuous. Sporadic gaging records make it difficult to discern changes in the volume of sediment and water through time. The addition of dams to upstream tributaries and climatic fluctuations within the study area may also have influenced the planform.

Introduction

When viewed as systems, rivers are dynamic features on the landscape. Changes in the discharge, sediment load, or course of a river can affect humans, who in turn bring about changes in the river through dams, diversions, irrigation, and land use. Between 1900 and 1936 three major and five minor floods occurred in the Red River basin of Oklahoma and Texas. These floods inundated 95% of Denison, Texas, and 45% of Alexandria, Louisiana (Ware, 1979). The U.S. Army Corps of Engineers (1936) determined that the floods affected ~6,881 km^2. Construction of a dam and reservoir near Denison, Texas, was initiated in 1939 to reduce flooding problems along the Red and Mississippi Rivers. Construction of the dam, spillway, and outlet works was completed in February 1944.

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During the period between 1923 and the beginning of flow regulated by Denison Dam in 1943, the average discharge of the Red River, near the dam site, was 161 m^3/s (Oklahoma Water Resources Board, 1984). The U.S. Army Corps of Engineers (1981) estimated that after 1943 Denison Dam trapped ~98% of the sediment that the Red River carried into Lake Texoma. The reduction in the discharge and sediment load of the Red River below the Denison Dam may contribute to changes in the meandering planform of the Red River in McCurtain County, Oklahoma.

Examination of meander symmetry and migration is significant from the perspective of human occupancy and utilization of flood plains, and from the geomorphic viewpoint of sediment budget and thresholds. Therefore, the purpose of this study is to determine (1) whether the meander pattern of the Red River in the study area is symmetrical or asymmetrical; (2) whether the symmetry or asymmetry has changed through time; (3) the rate of meander migration and changes, if any, over time; and (4) whether the rate of meander migration has changed since the construction of Denison Dam.

Study Area

A 29-km segment of the Red River, 192 to 221 km downstream of Denison Dam, was selected as the study area (Fig. 1). The site is bounded by McCurtain County, Oklahoma, on the north; Red River County, Texas, on the south; the Choctaw, Oklahoma, county line on the west; and the Oklahoma State Highway 37 bridge on the east. The Oklahoma State Highway 37 bridge, currently in use, was constructed in 1954 (Oklahoma Highway Commission, 1955). Prior to bridge construction, the Albion ferry was used at the same location.

This site was selected because of (1) the availability of aerial photographs that predate construction of the dam, (2) the absence of bedrock and presence of alluvium in the channel, (3) the absence of major tributaries entering the main channel, (4) the meandering planform of the river, and (5) the distinctive landmarks (the county line and the bridge) used for locating the ends of the study reach.

McCurtain County is the only county downstream of Denison Dam for which aerial photographs predate 1939. These pre-dam photos were used as a baseline for determining changes in the channel pattern over time. Aerial photos of the area were also available for 1963, 1969, 1978, and 1984. The presence of alluvium and the absence of bedrock within the channel allow the river to change its planform freely in response to changes in the variables that disrupt equilibrium. According to Davis (1959), the study area is underlain by Quaternary deposits of stream-laid unconsolidated gravel, sand, and clay in intergrading and intertonguing beds up to 33.5 m thick (Fig. 2).

No major tributaries and only five minor perennial streams enter the Red River within the study reach. Examination of aerial photographs and 1:24,000-scale maps reveals that the tributaries probably contribute <2% of the total flow of the river within the study reach; therefore, the discharge and sediment load should not be significantly altered by the minor tributaries that enter the river in the study area.

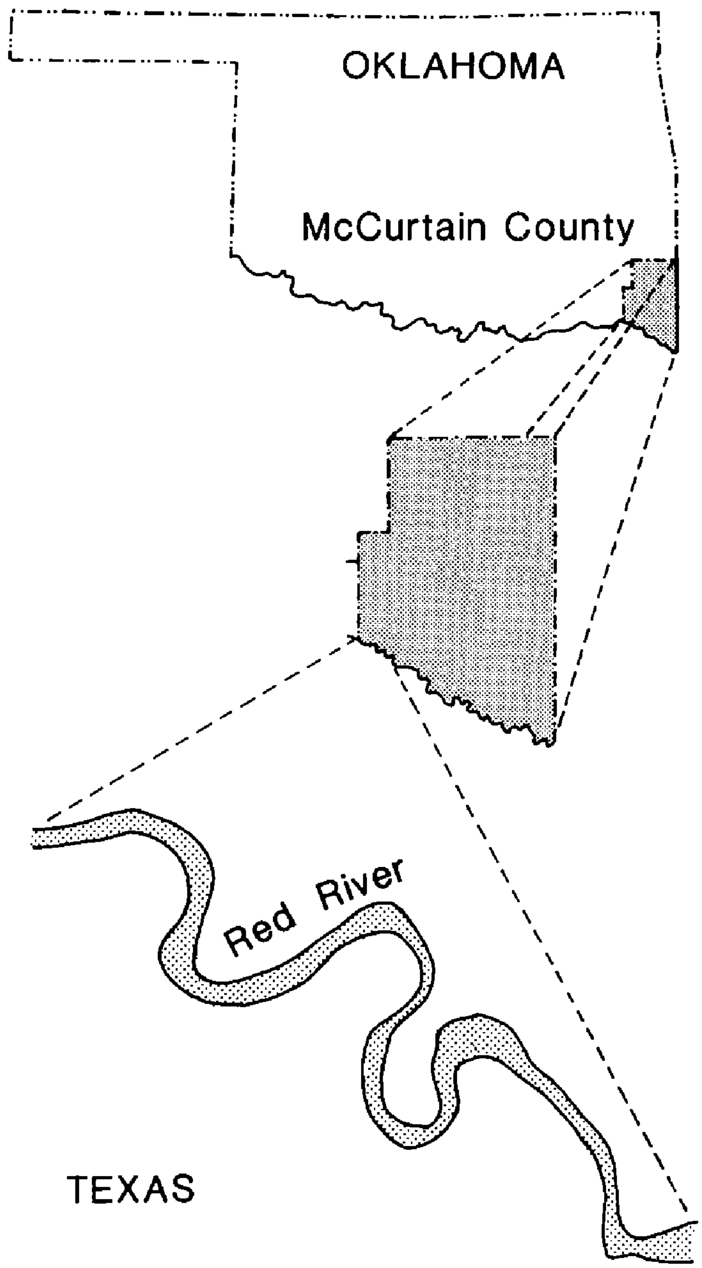

Figure 1. Study area: a segment of the Red River in McCurtain County, Oklahoma.

Symmetry Versus Asymmetry

Streamflow dynamics determine whether the pattern of a stream channel will be straight, meandering, or braided. The Red River is a meandering stream. Changes in meander sinuosity, symmetry, and rate of migration of a channel have been used to demonstrate how meanders change through time. Sinuosity, defined as the ratio of the length of the stream channel to the length of the stream valley, is a measure of stream-channel curvature. The concept of meander symmetry is

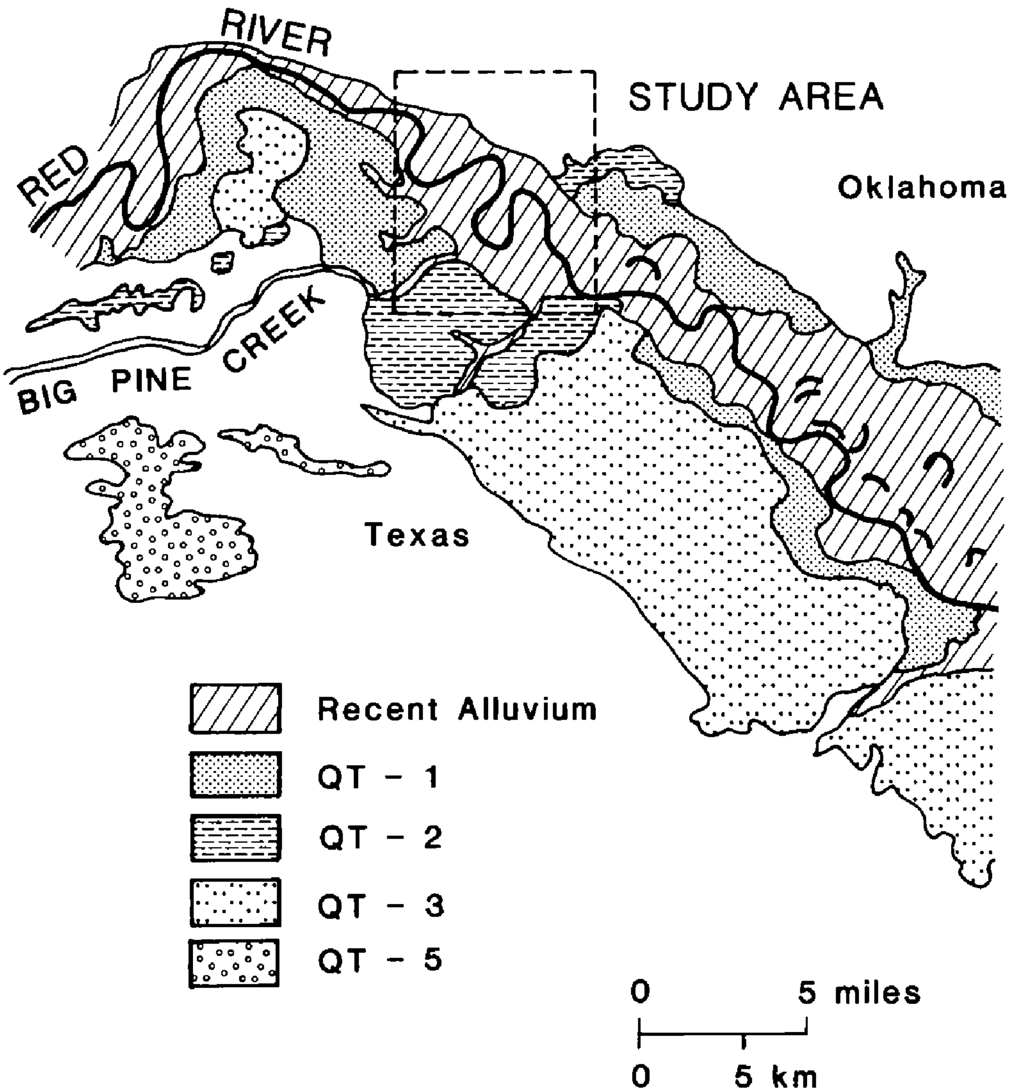

Figure 2. Quaternary geology of the study area (after Davis, 1959).

widely accepted. Langbein and Leopold (1966) found that most of the meanders they studied produced the symmetry of a sine-generated curve. Figure 3 defines the variables of wavelength, L, amplitude, A, and the radius of curvature, r_c, which are commonly used to characterize the symmetry of meanders.

Although the theory of meander symmetry has been used for the last 20 years, Carson and Lapointe (1983) stated that meanders show well-defined and consistent asymmetry. The z-value, or asymmetry index, has been defined as the percent of the length of the traverse that is convex down-valley. A traverse is the distance between two successive inflection points (Fig. 4). The equation used to define the z-value is as follows:

$$z = 100\, u \,/\, (u + d), \qquad (1)$$

where u is the length of an upstream traverse, and d is the length of the subsequent downstream traverse.

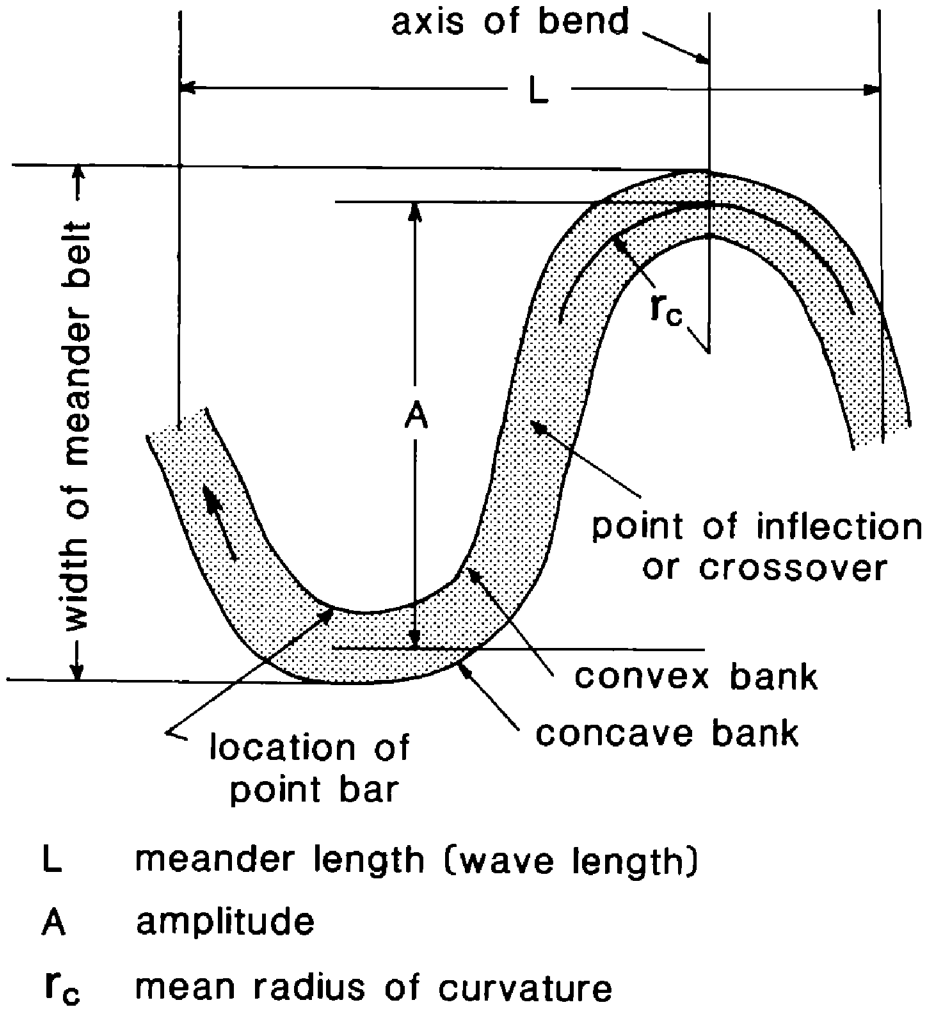

Figure 3. Definition diagram for meander geometry (after Leopold and Wolman, 1960).

Dynamic Equilibrium and Thresholds

Using flume models of stream channels, Leopold and Wolman (1957) developed a basic relationship showing that the discharge of a stream, Q, is equal to the product of the width, w, the depth, d, and the velocity, v, of a stream:

$$Q = wdv. \tag{2}$$

At least 30 variables are now recognized as being involved in the sediment-transport process, and the interrelationships among these variables are not completely understood (Heede, 1980).

The concept of dynamic equilibrium is the dominant hypothesis used to explain how channels change with time. Dynamic equilibrium implies that because streams can be considered as open systems and all parts are interrelated, changes in one or more of the variables will cause an alteration in some or all of the remaining variables until a new equilibrium state is reached. Leopold and Wolman

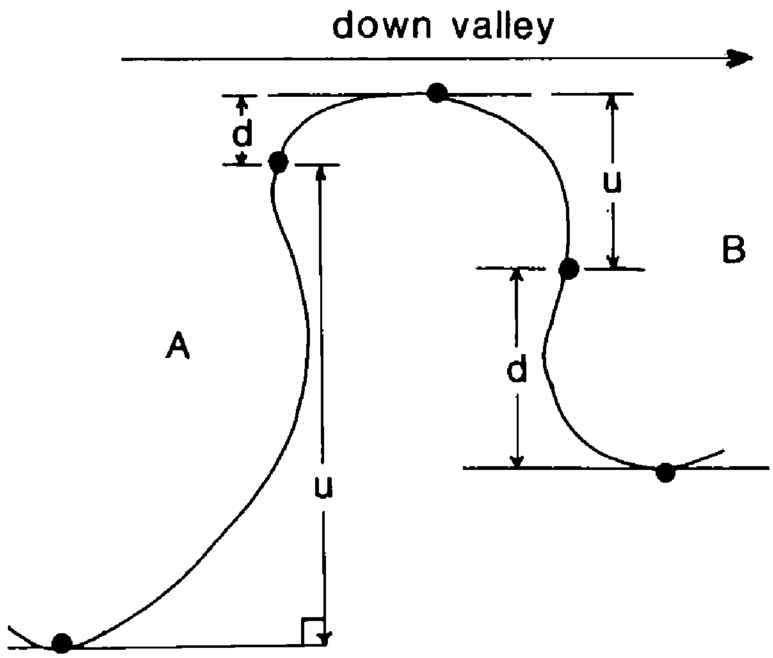

Figure 4. Definition for the asymmetry index. Traverse A shows delayed inflection asymmetry (z >55); traverse B is symmetric (z = 50). After Carson and Lapointe (1983).

(1960) found that channel equilibrium is constantly approached, although rarely attained, by a process of continual adjustment. Heede (1981) described equilibrium as a condition permitting rapid adjustment to a new situation.

Many workers in the field believe that the changes in equilibrium are not continuous: rather, thresholds are met and exceeded before change occurs in the system. Only small amounts of energy may be needed to initiate changes which may affect the entire system (Coates and Vitek, 1980). Petts (1979) has shown that a threshold will not be surpassed at the same time throughout a river system; change instead occurs along discrete segments of the channel. Howard (1982) found that the initial stages of adjustment to changes in equilibrium tend to move downstream, whereas later stages of adjustment occur simultaneously throughout a reach.

Dams and Dynamic Equilibrium

The downstream effects of dams and reservoirs have been examined in recent years. Petts (1980) found that reservoir construction induces changes in the equilibrium of a river. Construction of dams has been shown to have numerous impacts on rivers because of reductions in average flow rates. Impacts include alteration of the channel shape, width, and depth (Kennon, 1966); a decrease in the amount of bank erosion downstream of the dam (Schoof and others, 1980); an increase in bank erosion and the number of downstream boulder rapids (Graf, 1980); and degradation of the river channel for as much as 650 km downstream (Han and Tong, 1982). Channel width can be dramatically altered downstream from a dam, either widening or narrowing, depending on the relative changes in peak discharge, sediment supply, and vegetation (Howard and Dolan, 1981).

Data from Aerial Photography

Aerial photographs of the study area dating from 1938 to 1984 (Table 1) were used to examine changes in the planform of the river. To avoid problems with maps of debatable cartographic accuracy, investigators have relied on maps of study areas constructed from aerial photographs (Hickin and Nanson, 1975; Nadler and Schumm, 1981; Monsalve and Silva, 1983; Bradley and Smith, 1984; and Nanson and Hickin, 1986). Martinson (1984) recommended using a stereoplotter to remove parallax errors and changes in scale between photographs. Howard and Dolan (1977) found that differences in the river stage between sets of photographs can cause apparent erosion or deposition. Variations in the stage can be overcome by mapping the approximate bankfull stage (Nanson and Hickin, 1986). Guccione (1984) mapped the bankfull stage as the channel width plus any unvegetated sandbars. Bankfull stage was approximated for the present study in the same manner.

Differences in the formats and scales of the available aerial photographs produced several problems. The 1938, 1963, and 1969 photographs were available as overlapping 9-in. stereopairs, whereas the 1978 and 1984 photographs were printed as 30-in. plates which joined along the edges. Because all of the photographs did not overlap, stereoscopic viewing was not attempted. To reduce

TABLE 1.—SUMMARY OF AERIAL-PHOTOGRAPH SOURCE DATA[a]

Date	Approximate Scale	Source
Sept. 23, 1938	1:20,000	ODLA[b]
June 9, 1963	1:20,000	OGS[c]
Nov. 1, 1969	1:20,000	OSU[d]
Dec. 21, 1978	1:12,000	ASCS[e]
Sept. 5, 1984	1:7,920	ASCS[e]

[a]All photos are from U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service coverage of McCurtain County, Oklahoma.
[b]Oklahoma Department of Libraries Archives, Oklahoma City, Oklahoma.
[c]Oklahoma Geological Survey, Norman, Oklahoma.
[d]Oklahoma State University Library, Stillwater, Oklahoma.
[e]U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service, Idabel, Oklahoma.

image-displacement errors, only the central portion of each of the 1938, 1963, and 1969 photographs was used in compiling the maps. The 1978 and 1984 channels were mapped from the entire photo.

For the purpose of co-registration, it was necessary that all of the maps derived from the photographs be of the same scale. Because the 1963 map had the smallest scale, it was used as a base map. In order to determine the amount of reduction necessary for each map, the distance between two landmarks "A" and "B", common to all of the maps, was measured and compared (Fig. 5). Because of the large size of the maps, xerographic reduction was utilized. These second-generation maps were printed on vellum stock and registered to the base (1963) map. A kail projector was used to make any minor corrections needed in response to changes in scale across the maps. The scale of the registered maps was approximately 1:20,833.

Data Collection

Random selection of points for data collection introduces a great deal of subjectivity into meander investigations. To remove some of the subjectivity from the data collection, Hooke (1984) recommended digitizing the centerline of the channel at about 1-channel-width intervals. Digitizing aids in locating the points of inflection, where changes in the direction of curvature occur within a bend.

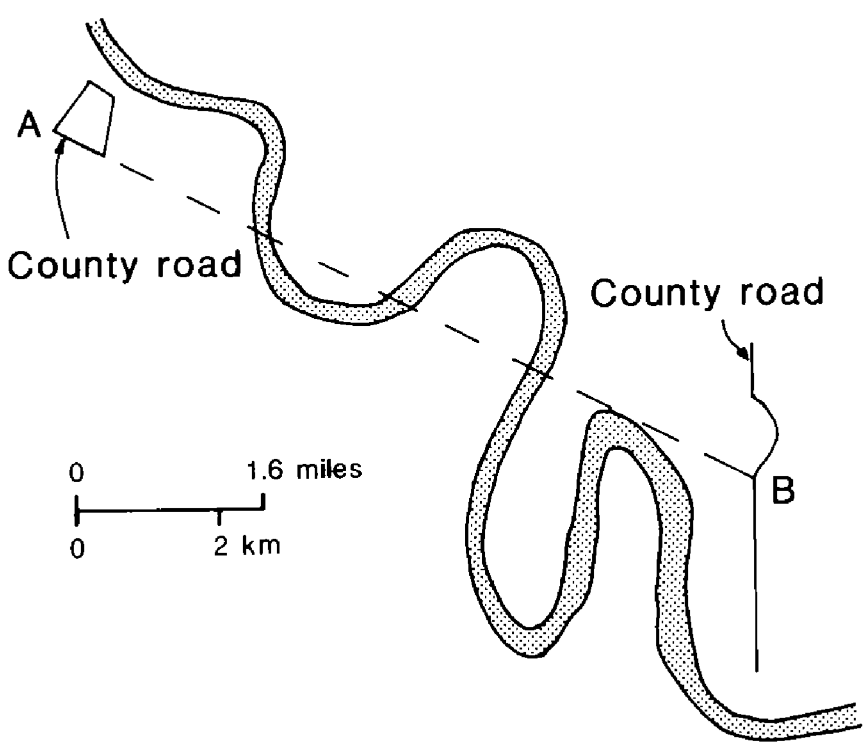

Figure 5. Location of line A–B that was used to register aerial photographs from different years.

Ten measurements of the channel width were made at approximately 3-km intervals on each map, and average width values were calculated. The points to be digitized were plotted on each of the maps at 1-channel-width intervals, using a pen and a ruler. Digitizing equipment in the Center for Applications of Remote Sensing (CARS) at Oklahoma State University was utilized to produce a data set containing the *X* and *Y* coordinates of the channel centerline points for each of the five maps.

A computer program was developed to calculate the angle between each pair of data points. The difference in the angles between each pair of points was used to locate the inflection points. The inflection points, or points to divide the meander bends into discrete segments, were found where the difference in angles was zero (Hooke, 1977). Satisfactory results were produced with a digitizing interval of 2 channel widths. Following the methodology of Brice (1983), measurements of the amount and direction of bank movement were made at 2-channel-width intervals along the centerline of the channel, for each of the overlaid map pairs. Ten combinations for overlaying the maps two at a time were used (Table 2). The shortest distance between the sequential banklines of the overlays was measured to the nearest 1⁄60 in., using an engineering scale. Measurements were converted from inches of map distance to meters of ground distance, then recorded. The direction of movement was recorded as either negative (channelward), or positive (bankward).

Measurements of the variables required to calculate Carson and Lapointe's (1983) asymmetry index include the lengths of the bend segments that are convex in the down-valley direction, *d*, and the lengths of segments concave down-valley, *u* (Fig. 4). These variables were measured on the maps in the manner explained above.

TABLE 2.—MAP COMBINATION USED FOR DATA COLLECTION

Base Year	Years Overlaid
1938	1963, 1969, 1978, 1984
1963	1969, 1978, 1984
1969	1978, 1984
1978	1984

Data Analysis

The data sets for channel migration were analyzed with the Statistical Program for the Social Sciences (SPSS), which calculated the maximum, minimum, and average amounts of channel movement for each bend segment during each of the 10 time periods. Average migration rates were calculated by dividing the average movement value by the number of years in the time period observed. An analysis of variance (ANOVA) was applied to the 10 migration rates to determine if the overall rate has been constant or varies significantly through time.

Asymmetry indices were calculated for each bend traverse during each of the time periods to determine whether the channels were asymmetrical. An ANOVA was utilized to determine whether the differences in asymmetry values changed significantly through time.

The meander wavelength was measured in average channel widths and recorded for each of the five individual maps. The wavelength values were examined using an ANOVA to determine whether changes were significant.

Results

Pattern Symmetry/Asymmetry

Because meander wavelengths can be defined and measured, evidence for symmetry of the channel pattern exists. Evidence has also been presented, in the form of z-values, which points toward asymmetry of the planform. The U.S. Army Corps of Engineers (1968, p. 58) referred to the meanders below Denison Dam as a "series of reverse irregular curves," alluding to asymmetry of the channel. Because 83% (20 of 24) z-values (Table 3) indicate asymmetric meander traverses, the findings of this study support Carson and Lapointe's (1983) theory, and provide an example of an asymmetrical, broad alluvial channel.

TABLE 3.—WAVELENGTH, L^a, AND z-SCORE VALUES BY YEAR

Year	L	z^b
1938	15	50
	15	59
	14	36
	20	39
		70
1963	22	60
	13	80
	13	56
	14	11
		41
1969	16	63
	14	72
	13	24
	13	50
		27
1978[c]	16	56
	13	80
	15	43
	13	88
1978[d]	16	56
	25	31
1984	18	63
	24	46
		9

[a]Wavelengths are measured in average channel widths.
[b]z-scores of 45–55 indicate symmetry; z-scores of <45 or >55 indicate asymmetry. More z-scores exist than wavelength values because z-scores are not calculated from wavelength values.
[c]Morphology of the meander loop.
[d]Values for the cutoff channel.

Changes in Symmetry/Asymmetry

Results of an analysis-of-variance test on the mean z-values indicate that no significant differences occur between the asymmetry-index values through the four time periods, 1938–63, 1963–69, 1969–78, and 1978–84. Therefore, construction of Denison Dam did not significantly affect the asymmetry of the river planform. Although the use of all 10 possible time intervals produced similar results, the within-groups error values were larger than the between-groups error values. Therefore, the hypothesis—that the dam has had no significant impact on the planform of the river—was accepted.

Magnitudes and Rates of Migration

During 1960 and 1969, the U.S. Army Corps of Engineers (1981) surveyed 37 cross sections on the Red River downstream of Denison Dam. One of their cross sections, DR-28, is within the current study area. The Corps survey detected migration values of ~10 m for the north (Oklahoma) bank, and ~30 m for the south (Texas) bank. These values are comparable with the average measurements of 26 m for the north bank and 32 m for the south bank computed in this study.

Examination of the individual bends reveals that average rates of migration within a time period are easily calculated. The average values are not considered to be absolutes, but merely estimates of the directions, magnitudes, and rates of migration. Errors made during map construction, reproduction, registration, and measurement of migration rates are believed to be compensating and produce an overall error value of ±27 m.

Because of changes in the location of the bend segments through time, the average rates of migration between time intervals are difficult to compare. Several analyses of variance were performed in an attempt to compare the migration rates through time. The method of analysis used in this study does not permit the calculation of only one overall rate of migration. The total mean migration rate was computed for channelward accretion (negative) and bankward erosion (positive); movements of the north and south banks provide the best overall estimates of the migration along the channel through time. Total mean migration of 9.6 m/yr channelward accretion and 11.9 m/yr bankward erosion for the north bank, and 15.8 m/yr channelward accretion and 7.8 m/yr bankward erosion for the south bank were computed. F-tests on the mean erosion rates for the north and south banks show no significant differences through time. Consequently, no significant changes in the rates of migration have occurred since the construction of Denison Dam.

Extrinsic Factors

Visual inspection of the map of channel planform (Fig. 6) indicates that the channel pattern has been substantially altered during the last 46 yr. No human activities in or near the study area have been found to explain the changes in bank erosion. William Bookout, McCurtain County soil scientist with the USDA Agricultural Stabilization and Conservation Service, indicated that no major irrigation, dredging, or bank stabilization projects have been undertaken in the study area during the period under investigation (personal communication). Close examination of the aerial photographs used for map construction shows only minor changes in land use.

Changes in the flow of the river are difficult to ascertain. Discharge and sediment-load records for the study area are sporadic, at best, and in many cases unavailable. The actual discharge on or near the dates of the photographs used in this study can only be estimated. The period of record for the gaging station at Arthur City, Texas, ~20 km upstream of the study area, is from 1946 through 1977. The 39 discharge samples for 1946 produced a mean annual discharge of ~1,360 m^3/sec, whereas the 22 samples for 1977 produced a mean annual discharge of 477 m^3/sec (Blumer, 1983). The period of record for the Index,

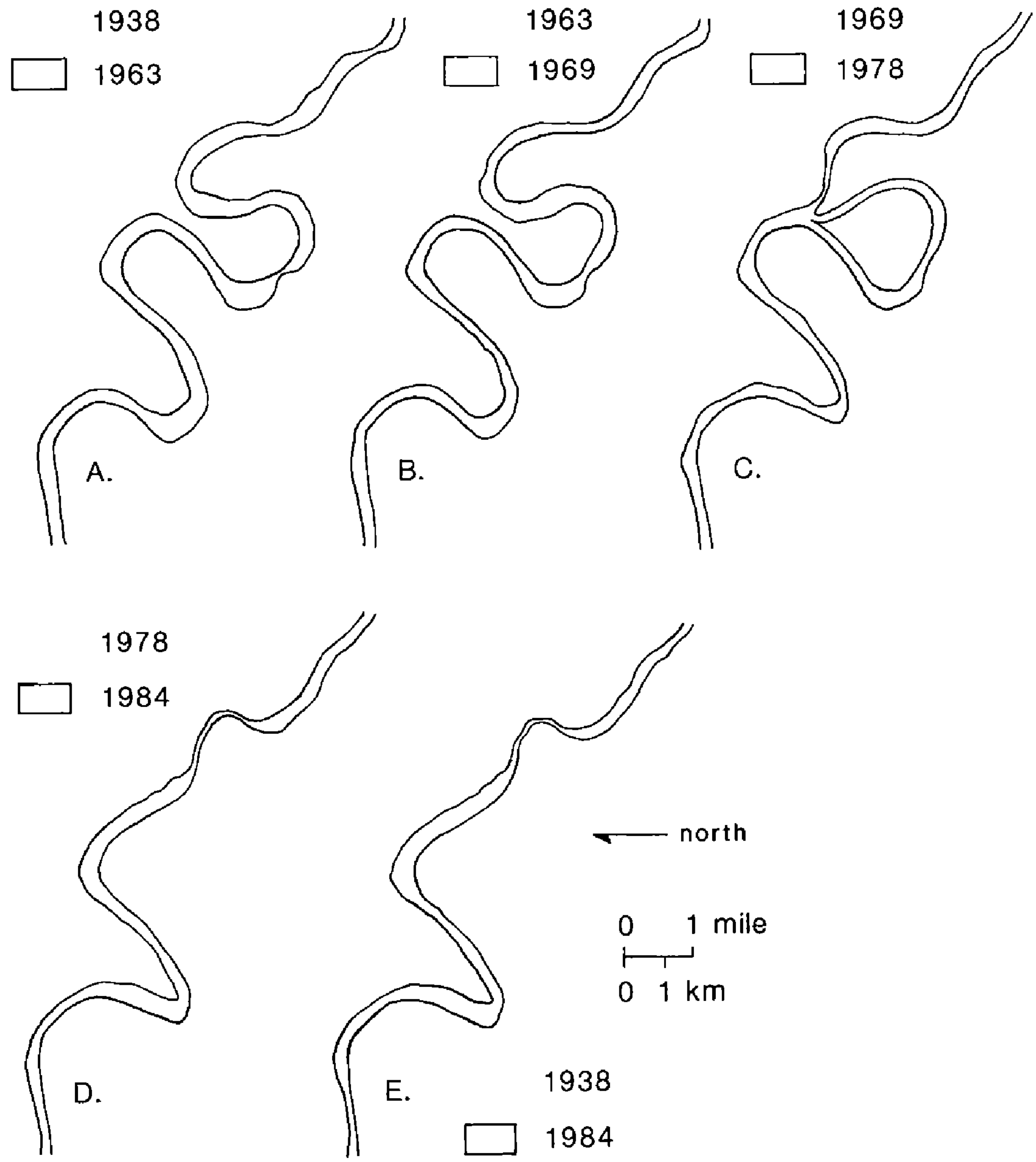

Figure 6. Changes in the Red River, 1938–84.

Arkansas, gage, 76 km downstream, extends from 1918 through 1975. The mean discharge for 1938 was ~240 m^3/sec, whereas the mean discharge for 1969 was 1,961 m^3/sec. The irregular nature of the records and the large distance between the gages and the study area provide little information about the discharge through the study reach.

Because of the interactions of the variables involved in channel migration, it is difficult to identify all of the sources of variation in the system. Other factors which must be accounted for include changes in the climate and tectonic activities. Idabel, Oklahoma, ~21 km northeast of the study area, is representative of the climate of the area. Precipitation data for Idabel from 1941 to 1984 are shown in Figure 7. Increased rainfall within the study area would increase the discharge of the river and could affect the channel pattern. Each of the four time periods has more years of below-average rainfall than above-average rainfall, but the minimum amount of rainfall increases following the drought of 1956. Changes in the nature of precipitation events, i.e., frontal vs. convectional, could affect the intensity and rapidity with which surface runoff enters the fluvial system. Temperature fluctuations may also interact in a complex fashion so as to decrease or increase surface evapotranspiration and therefore the amount of surface runoff.

In a study of a reach of the Red River ~160 km downstream of the current investigation, Guccione (1984) found that tectonism was not a significant force in the area during periods of $<10^{2-3}$ yr. Therefore, the 46-yr period of this study is sufficiently small to disregard tectonic effects.

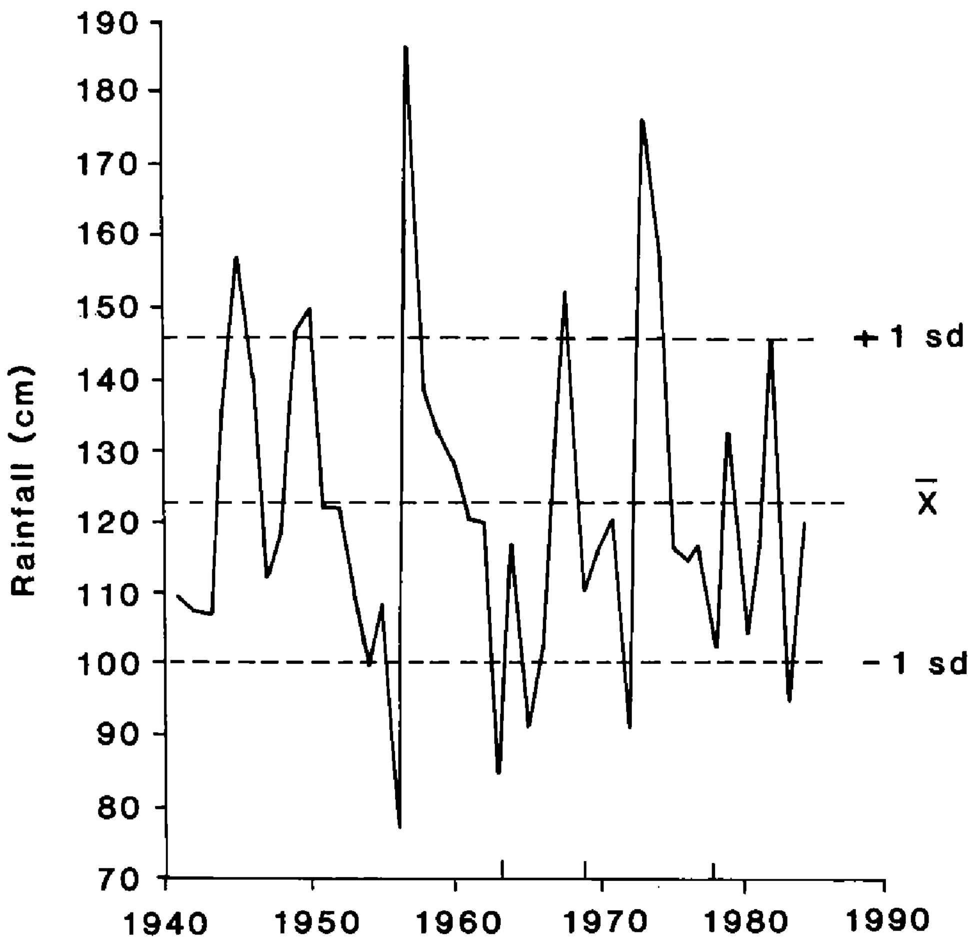

Figure 7. Total rainfall reported for Idabel, Oklahoma, 1941–84.

Conclusions

This study has shown that the Red River in McCurtain County displays an inherent asymmetry. Asymmetry-index values did not change significantly during the studied period. Migration rates of meander bends have not been altered significantly, but channel pattern has changed substantially since dam construction. The effects of Denison Dam cannot be ruled out as causing the changes, but the dam cannot be viewed as the only factor involved in the changes. Differences in the discharge through the area may be significant, and the increase in the average effective precipitation through time undoubtedly contributes to the changes in the planform of the river channel. Climate and geomorphic processes interact in complex fashions in Oklahoma (Hall and Lintz, 1984; Nusz and others, 1987), so that continued studies examining climate, surface processes, and human activity are indeed warranted.

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HYDROLOGIC ATLAS OF FORT SMITH QUADRANGLE AVAILABLE AGAIN

Hydrologic Atlas 1, *Reconnaissance of Water Resources of the Fort Smith Quadrangle, East-Central Oklahoma*, by Melvin V. Marcher, which has been out of print, is now available. HA-1 is made up of four sheets, at a scale of 1:250,000, that show the geology, availability of ground water, chemical quality of ground water, and surface-water information of the area.

First printed in 1969, this atlas was the first of nine hydrologic atlases designed to provide reconnaissance-level ground-water information on the State, exclusive of the Panhandle. Other atlases available in the series are the Ardmore and Sherman, Oklahoma City, Clinton, Lawton, Enid, Woodward, and McAlester and Texarkana Quadrangles. The Fort Smith Quadrangle includes ~6,300 mi^2 in east-central Oklahoma.

Hydrologic atlases can be purchased over the counter or postpaid from the Oklahoma Geological Survey at the address given inside the front cover of this issue. The price is $6 per set.

UPCOMING MEETINGS

American Bar Association/Southwestern Legal Foundation, National Institute on Natural Gas Law, November 2–4, 1988, Dallas, Texas. Information: American Bar Association, Division for Professional Education, 750 North Lake Shore Dr., Chicago, IL 60611; (312) 988-6200.

Association of Ground Water Scientists and Engineers, Conference and Exposition, "Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration," November 9–11, 1988, Houston, Texas. Information: National Water Well Association, 6375 Riverside Dr., Dublin, OH 43017; (614) 761-1711.

Geochemistry of Gulf Coast Oils and Gases, December 4–7, 1988, New Orleans, Louisiana. Information: Dietmar Schumacher, Pennzoil Co., P.O. Box 2967, Houston, TX 77252; (713) 546-4028; or Mahlon C. Kennicut, Geochemical and Environmental Research Group, Texas A&M University, Ten South Graham Road, College Station, TX 77840; (409) 690-0095.

American Geophysical Union, Fall Meeting, December 5–9, 1988, San Francisco, California. Information: Ann E. Singer, American Geophysical Union, 2000 Florida Ave., N.W., Washington, DC 20009; (202) 462-6903.

U.S. Environmental Protection Agency/Association of Ground Water Scientists and Engineers, Wellhead Protection Conference, December 6–8, 1988, New Orleans, Louisiana. Information: National Water Well Association, 6375 Riverside Dr., Dublin, OH 43017; (614) 761-1711.

National Water Well Exposition, December 12–14, 1988, Las Vegas, Nevada. Information: National Water Well Association, 6375 Riverside Dr., Dublin, OH 43017; (614) 761-1711.

Geophysics of the Rocky Mountains, Front Range, and High Plains, February 13–14, 1989, Golden, Colorado. Abstracts due October 14, 1988. Information: Front Range AGU Service Center, P.O. Box 18-P, Denver, CO 80218; 1-800-525-6338.

Society of Mining Engineers, Annual Meeting, February 27–March 2, 1989, Las Vegas, Nevada. Information: Society of Mining Engineers, Meetings Dept., P.O. Box 625002, Littleton, CO 80162; (303) 973-9550.

Geological Society of America, South-Central Section, 23rd Annual Meeting, March 12–14, 1989, Arlington, Texas. Abstracts due October 24, 1988. Information: C. I. Smith, Dept. of Geology, University of Texas, P.O. Box 19049, Arlington, TX 76019; (817) 273-2987.

American Association of Petroleum Geologists, Annual Meeting, April 23–26, 1989, San Antonio, Texas. Information: AAPG, Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 584-2555.

NOTES ON NEW PUBLICATIONS

Oklahoma—A Summary of Activities of the U.S. Geological Survey, Water Resources Division, in Fiscal Years 1986–87

Compiled by John S. Havens, this 141-page open-file report summarizes the activities of the Oklahoma District, USGS Water Resources Division, including statements of current and recently completed projects, alphabetical and numerical listings of surface-water stations, and a bibliography of Oklahoma reports.

Order OF 88-172 from: U.S. Geological Survey, Water Resources Division, 215 Dean A. McGee Ave., Room 621, Oklahoma City, OK 73102; (405) 231-4256. A limited number of copies are available for distribution free of charge.

GEONAMES Data Base of Geologic Names of the United States Through 1986

Geological names in Arkansas, Oklahoma, Kansas, and Missouri are compiled by G. W. Luttrell, M. L. Hubert, and C. R. Murdock in this 11-page data base on one ¼-in. diskette.

Order OF 88-0044-H from: U.S. Geological Survey, Books and Open-File Reports, Federal Center, Bldg. 41, Box 25425, Denver, CO 80225. The price is $7.75; add 25% to the price for shipment outside North America.

South-Central United States Well-Bore Breakout-Data Catalog

Written by R. L. Dart, this USGS open-file report contains 95 pages.

Order OF 87-0405 from: U.S. Geological Survey, Books and Open-File Reports, Federal Center, Bldg. 41, Box 25425, Denver, CO 80225. The price is $4 for microfiche and $14.75 for a paper copy; add 25% to the price for foreign shipment.

OKLAHOMA ABSTRACTS

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

Dolomites Formed Under Conditions of Deep Burial: Hunton Group Carbonate Rocks (Upper Ordovician to Lower Devonian) in the Deep Anadarko Basin of Oklahoma and Texas

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Progressive burial diagenesis of Hunton Group (Upper Ordovician to Lower Devonian) rocks of the deep Anadarko basin of Oklahoma and the Texas Panhandle is evident from petrographic and geochemical study of cores and cuttings from more than 25 boreholes up to 30,000 ft deep. Limestone of the Hunton Group, which originated as shallow shelf carbonates, has been replaced, chiefly below present depths of about 10,000 ft, by dolomite that is commonly ferroan and is associated with shale. This diagenetic dolomite is inferred to have formed under deep-burial conditions.

The dolomite occurs as finely disseminated, 10μm and larger rhombic crystals, and is most abundant near the base of the Hunton Group, particularly where an oolite unit (the Keel Formation) overlies the thick marine Sylvan Shale that is inferred to be the chief source of Fe^{2+} and Mg^{2+} ions. Ferroan dolomite also occurs where clay minerals are abundant in the Middle Hunton Group. In shallow wells, dolomite crystals are euhedral. Below 10,000 ft (3.0 km), where dolomitization of the oolite has been more complete, hypidiotopic and xenotopic textures result. Hydrocarbon-associated fluids are inferred to have dissolved the calcite that was not replaced, and to have created intercrystalline and moldic porosity.

X-ray diffraction verifies a trend of higher dolomite concentrations with increasing depth in the same oolite horizon. For example, oolite samples from outcrop lack dolomite and are 100% $CaCO_3$; cores from 9,200 ft (2.8 km) are about 25% dolomite; and cores from 15,000 ft (4.6 km) and below are more than 85% dolomite. Radioisotope-induced x-ray fluorescence shows that dolomites below 10,000 ft (3.0 km) are iron-enriched relative to both non-dolomitized oolite and dolomites of surface origin. Where the Hunton Group and the Sylvan Shale are buried below 10,000 ft (3.0 km), well logs show high densities in the lowermost Hunton (above the Sylvan Shale) which can be interpreted as the occurrence of Fe^{2+}-rich dolomite. Stable isotope ratios suggest a higher temperature of origin for burial dolomites than for dolomites of surface origin. Formation waters recovered from within the shale and carbonate are greatly depleted in Mg^{2+} ions compared to normal marine waters.

General restriction of this shale-associated ferroan dolomite to strata that are currently buried below 10,000 ft (3.0 km) in the Anadarko basin supports other lines of evidence for the belief that previously deeply buried strata can be recognized even if the strata have been subsequently uplifted. The transformation of smectite to illite in the Sylvan Shale (conformably underlying the oolite) is suggested as a possible source of Mg^{2+} and Fe^{2+}. Smectite/illite ratio decreases with increasing depth in the Sylvan Shale. Furthermore, Sylvan Shale below 10,000 ft (3.0 km) is depleted in iron by 70% relative to Sylvan Shale less than 10,000 ft (3.0 km) deep, suggesting that under deep conditions shales have given up their iron (and magnesium), presumably to the overlying carbonates.

Reprinted as published in *Carbonates and Evaporites*, v. 1, no. 1, p. 61.

Seismic Expression of Upper Morrow Channel Sandstone, Western Anadarko Basin

JENS R. HALVERSON, Diamond Shamrock Exploration Co., Amarillo, TX

In the western Anadarko basin, the Lower Pennsylvanian Upper Morrow sandstones are a prolific but elusive exploration target. Initial production from some of these wells can reach over 1,000 BOPD, and yet an offset well just 1,000 ft away from a prolific producer may miss the sandstone entirely. High-resolution seismic data, along with advanced geophysical modeling, seismic inversion processing, and seismic facies mapping, are useful in detecting the sandstones before drilling begins.

Two upper Morrow fields in the Texas Panhandle have been studied: the Lear and Darden fields. The Morrow sandstones reach an isopach thickness of 40–50 ft at a depth below surface of 8,000–10,000 ft. The sandstones are within the "thin bed" regime. They are also below the "tuning point" where there is a linear relationship between the amplitude of the seismic reflection and the thickness of the sandstone. The sandstones have an interval velocity of about 1,000 m/sec faster than the encasing shales, and are detectable on good signal-to-noise ratio seismic data. The comparison of geologic isopach mapping and geophysical seismic facies mapping shows a good correlation in the delineation of the upper Morrow sandstones.

The use of these seismic-stratigraphy methods should substantially increase exploration and development success when high-resolution seismic data and advanced interpretation techniques are employed.

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Crestal Unconformities as Indicators of Clastic Stratigraphic Traps: Genetic Relation of Berlin Field and Elk City Structure, Deep Anadarko Basin

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The Berlin fan-delta gas reservoir in the deep Anadarko basin was deposited during the late Atokan (Pennsylvanian) as a response to the initial uplift and erosion of the Elk City structure. During the late Atokan pulse of the episodic Pennsylvanian orogeny in the south-central United States, abrupt epeirogenic uplift and brittle deformation created an interregional unconformity on positive areas around foreland and cratonic basins. The Elk City structure within the deep Anadarko basin originated as a distinct, subaerially exposed upthrust-block during the late Atokan tectonic event.

A crestal unconformity developed on the emergent upthrust block concurrent with its uplift. Terrigenous, detrital Atoka dolomite, originally sourced from the Arbuckle dolomite (Cambrian–Ordovician) of the Amarillo–Wichita uplift, was eroded from the upthrust block and recycled northward as the Berlin fan-delta. Today, the Berlin recrystallized, recycled detrital dolomite fan-delta is a large 41 mi^2 overpressured gas reservoir with 242–362 bcf reserves at 15,000 ft.

The Berlin field is genetically related to the late Atokan crestal unconformity of the Elk City structure, and is an example of the association of crestal unconformities and clastic stratigraphic traps. Such stratigraphic traps originate in marine environments proximal to active structures that have become subaerially exposed. With adequate seals and favorable structural position, detrital deposits recycled from local uplifts can form significant stratigraphic traps. Such stratigraphic traps can occur in compressional, extensional, and diapiric regions.

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Controls on Sand Body Orientation in Upper Morrow Formation, Deep Anadarko Basin

A. R. BAY, J. M. CASEY, and M. A. FOSTER, Standard Oil Production Co., Dallas, TX

Upper Morrow Formation (Lower Pennsylvanian) chert-and-quartz pebble conglomerates and coarse sandstones, in the depositional axis of the deep Anadarko basin of western Oklahoma and the eastern Texas Panhandle, collectively represent a wedge deposited during lowstands of base level. These sediments were deposited in nonmarine to shallow marine environments as fluvial channels, reworked sand ridges, and braid deltas sourced from the Amarillo–Wichita uplift to the south and west. Changes in base level are interpreted from regionally mappable sand trends, subsurface log character, core and micropaleontological sample interpretation, and seismic data analysis. Understanding the relationship between relative changes in base level and sand orientation can lower the risk in drilling successful exploitation wells in these thin, discontinuous, overpressured gas reservoirs in the upper Morrow Formation.

Sandstones and conglomerates comprise only a minor portion of the seismically defined wedge and occur in two packages; one is a general upward-coarsening package locally capped by thin, chert sandstones and conglomerates, informally called the Puryear sands. In the second package stratigraphically above the Puryear sands, the minor occurrences of sandstone are laterally discontinuous and not mappable beyond 3–4 mi.

Regional interpretations suggest that during maximum lowstands, chert sand- and conglomerate-filled fluvial channels, which are oriented normal to the basin axis, incised both fan deltas along the mountain front and marine shales distal to the basin margin. As base level rose, sands and conglomerates were reworked into longitudinal sand ridges parallel with the basin axis. Puryear sands that cap the upward-coarsening sequence are interpreted as retrogradational channel-fill deposits.

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Genetic Sequence Stratigraphy of Upper Desmoinesian Oswego Limestone Along Northern Shelf Margin of Anadarko Basin, West-Central Oklahoma

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The Pennsylvania Oswego limestone (upper Desmoinesian) in the vicinity of the northern shelf break of the Anadarko basin contains stratigraphic sequences and associated depositional facies that were controlled by eustatic variations in a slowly subsiding basin. Core descriptions, detailed well-log correlations, and facies maps of Oswego limestone in Dewey and Custer Counties, Oklahoma, supplemented by seismic data along dip profile, define at least two principal stratigraphic sequences separated by regional unconformities. In this area, oil and gas have been produced from phylloid algal-bank deposits that formed at the shelf margin. The algal-bank deposits that contain vuggy and moldic porosity are bound northward by wackestones of shelf facies and southward by tightly calcite-cemented packstones that formed on the seaward margin in relatively high-energy environments.

The detailed well-log correlations that consider genetic units illustrate the evolution of these carbonate and locally clastic deposits along Oswego shelf-ramp-basin profiles as a consequence of sea level oscillations. Repeated successions of upward-coarsening shelf wackestones, algal-bank deposits with fringing pack-stones and scattered terrigenous clastics, and basinal shales are a depositional system tract associated with sea level lowstand. This lowstand system is capped in one of the principal stratigraphic sequences by a thin shale that reflects an episode of rapid relative sea level rise and flooding of the Oswego carbonate shelf. Black shales deposited during this rapid flooding event form a problematic downlapping unit, because terrigenous sediment was evidently supplied from both the Oklahoma–Kansas area to the north and the Wichita–Amarillo high to the south. Highstand carbonate facies system are not present in the shaly cyclic sequences indicating drowning or backstepping of carbonate sources.

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Ultimate Recovery Analysis by Formation and Play for Deep Anadarko Basin and Estimation of Undiscovered Gas Potential

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Deep gas resources have assumed a growing role in the United States gas picture since the mid-1960s. The deep Anadarko basin has been one of the areas of heavy activity, and is thought to contain a significant portion of the remaining unproven deep gas resource in the lower-48 states. A detailed analysis of gas production and proven reserves in the deep basin has established the characteristics and historical importance of each of the major plays and productive formations. The analysis should prove to be a valuable tool in estimating the undiscovered gas potential of the deep basin.

Through 1985, there were 908 completions in the deep Anadarko basin. These completions accounted for 6.10 tcf of proven ultimate recovery, an average of 6.72 bcf per completion. In general, there is one completion per well and one well per section. Thus, ultimate recovery per completion represents ultimate recovery per section. The Hunton Group has the highest mean ultimate recovery at 15.3 bcf, followed by the Arbuckle Group at 10.1 bcf. The Springer Group, the focus of much of the basin's activity during the exploration boom, has a mean ultimate recovery of 5.3 bcf per completion. Within the eastern Springer stratigraphic play, the average is 4.8 bcf. This figure substantiates reports that the productive characteristics of this interval have fallen short of initial expectations.

In an attempt to evaluate existing resource appraisals of the deep basin, the areal distribution of production by formation was determined for the mature, shallow part of the basin. Over 20,000 completions were included in this analysis, demonstrating a significant database application. By using this distribution as a guide, along with certain other constraints, a range of 15–47 tcf of undiscovered potential was estimated.

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Formation Resistivity as an Indicator of Oil Generation in Black Shales

TIMOTHY C. HESTER and JAMES W. SCHMOKER, U.S. Geological Survey, Denver, CO

Black, organic-rich shales of Late Devonian–Early Mississippian age are present in many basins of the North American craton and, where mature, have significant economic importance as hydrocarbon source rocks. Examples drawn from the upper and lower shale members of the Bakken Formation, Williston basin, North Dakota, and the Woodford Shale, Anadarko basin, Oklahoma, demonstrate the utility of formation resistivity as a direct in-situ indicator of oil generation in black shales.

With the onset of oil generation, nonconductive hydrocarbons begin to replace conductive pore water, and the resistivity of a given black-shale interval increases from low levels associated with thermal immaturity to values approaching infinity. Crossplots of a thermal-maturity index (R_o or TTI) versus formation resistivity define two populations representing immature shales and shales that have generated oil. A resistivity of 35 ohm-m marks the boundary between immature and mature source rocks for each of the three shales studied.

Thermal maturity-resistivity crossplots make possible a straightforward determination of thermal maturity at the onset of oil generation, and are sufficiently precise to detect subtle differences in source-rock properties. For example, the threshold of oil generation in the upper Bakken shale occurs at R_o = 0.43–0.45%

(TTI = 10–12). The threshold increases to R_o = 0.48–0.51% (TTI = 20–26) in the lower Bakken shale, and to R_o = 0.56–0.57% (TTI = 33–48) in the most resistive Woodford interval.

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Hydrocarbon Accumulations in Paleozoic Strata in Anadarko Basin in Kansas

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Crude oil samples from several different Paleozoic strata within a 5,000-mi^2 area in the Anadarko basin in western Kansas were analyzed for their organic compositions, trace element contents, and carbon isotopic compositions to determine genetic relationships among the hydrocarbons. The oils had moderately high API gravities (29°–47°) and low sulfur contents (less than 0.5% by weight). The pristane/phytane ratios ranged from 1.2 to 1.7. Based on the trend of normalized concentrations of the isoprenoids between iP-13 and iP-20, the oils may be broadly divided into two types, one enriched in iP-13 and iP-16 and the other enriched in iP-19. The latter type may be further differentiated into three subtypes based on relative depletions of other isoprenoids. The oils with iP-13 and iP-16 enrichment are restricted to the southern part, whereas the oils with iP-19 enrichment are located in the northern part of the area. Both vanadium and nickel contents, ranging between less than 0.4 and 57 ppm and between less than 0.2 and 11 ppm, respectively, increase northward (r = 0.52 for V and 0.42 for Ni). Following Lewan's interpretation of the V/(V + Ni) values, all the oils derived from a marine-dominated source in a moderately oxidizing environment. The $\delta^{13}C$ values of the oils, ranging between −28.8 and −30.4, correlate negatively with increased distance northward (r = −0.87). The geographic trends seen in the geochemical parameters of the oils are most easily explained by a mechanism of differential entrapment of multiple oil types.

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Effect of Water Washing on Crude Oil Compositions

ERIC LAFARGUE and COLIN BARKER, Geosciences Dept., University of Tulsa, Tulsa, OK

Crude oils from Venezuela, Oklahoma, and New Mexico were water washed in the laboratory at temperatures from room temperature to 80°C, and with water salinities from 0 to 300,000 mg/L in experiments lasting from 7 to 338 hours. The effects of water washing were determined by gas chromatographic and gas chromatography–mass spectrometric analysis of the residual oil. These experiments show that water washing is particularly effective for the C_{15-} fraction and hydrocarbons are removed in the sequence aromatics, then n-alkanes, then naphthenes. In the C_{15+} fraction, no loss of pristane, phytane, steranes, or terpanes occurs, but some aromatics and sulfur compounds, especially dibenzothiophene, are depleted. Although water washing reduces API gravity, water washing is unlikely to produce tar layers.

The effects of water washing were simulated with a numerical model based on the equation of diffusion. Predicted oil-water ratios were in good agreement with the experimental values for the light ends, and the model suggests that water washing is very fast in the subsurface. Comparison of oils that appeared to have been water washed in nature with the equivalent unwashed oils showed the expected compositional trends.

Water washing is probably the dominant process affecting crude oil composition in the subsurface when water flows past oils under conditions where bacterial degradation is precluded by temperature (>80°C) or by lack of dissolved oxygen, and the temperatures are too low for thermal cracking.

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Recognition of Stratigraphic Anomalies Through Improved Acquisition and Processing Technology, Hugoton Embayment

J. I. YALCH, Mobil Oil Corp., Denver, CO

Oil has recently been discovered in the Hugoton embayment, Kansas, through the use of stratigraphic interpretation of seismic data. This oil is located in traps of channel sands in the Morrow and Chester formations.

Current seismic data, from which producing well locations were selected, were "deprocessed" to simulate older data. Field acquisition and seismic processing parameters were duplicated for six of the prior 24 years. This simulated data shows the logical progression of field acquisition and processing technology. This method also demonstrates the stratigraphic appearance of the anomaly on the data during those years.

Both field acquisition and processing parameters and techniques are reviewed on each of two lines. The resulting impact of the changes on each of the sections and its anomaly is noted as we progress through time.

In addition to showing full sections for each of the six years, blowups of the actual anomaly location on each of the simulations are shown with the original data for easy comparison.

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Natural Fractures, Mechanical Anisotropy, Stress, and Fabric in North-Central Oklahoma

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The regional fracture pattern exposed on surface outcrops of Permian and Pennsylvanian limestones and sandstones in north-central Oklahoma consists of a systematic set striking east–northeast and an orthogonal set striking north–northwest. Both sets are normal to bedding and show no evidence of shear offset. Detailed mapping of fractures exposed in Permian limestone in a quarry at Vap's Pass, Kay County, Oklahoma, reveals that individual fractures of both sets are comprised of joined straight-line segments of slightly different strike. The systematic set strikes between N70E and N85E and the non-systematic set between N10W and N45W.

Both the systematic and non-systematic fracture orientations are parallel to a (microcrack) fabric in the plane of bedding inferred from point load testing in the laboratory. Neither fracture set appears related to the depositional fabric as determined by thin-section analysis of the preferred orientations of grain boundaries and long axes.

Results of point load tests on oriented (Pennsylvanian) shale core from Conoco's Borehole Test Facility, 3 mi southwest of the Vap's Pass exposure, indicate a different orientation for mechanical anisotropy, N50E. That direction is roughly parallel to maximum horizontal in-situ stress determined from bore hole breakouts and to large-scale extensional fractures observed in the core.

The relations among surface and subsurface fracture orientation, depositional fabric, mechanical anisotropy, and the in-situ stress field are discussed.

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Paleodepth of Burial: Case History of Exposed Paleozoic Carbonates in Arbuckle Mountains, Oklahoma

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Using several reliable geothermometers, such as fluid-inclusion analysis, vitrinite reflectance, $\delta^{18}O$, illite crystallinity, and percent magnesium concentration in solid-solution, data obtained on formation temperatures of calcite cements from Paleozoic carbonates and shales in the Arbuckle Mountains of southern Oklahoma indicate that these temperatures can only be attained assuming a stable-platform geothermal gradient in a range of 23°C/km–25°C/km, at depths exceeding 2.0 km. These temperatures imply that these strata were once buried and are exposed today.

Homogenization temperatures of fluid-inclusions found in calcite cements and veins in the Paleozoic carbonates indicate precipitation at depths where temperatures exceed surface temperatures. Temperatures ranged from 108°C in the Pennsylvanian to 315°C in the Cambrian. Depths calculated ranged from 5.5 km (Pennsylvanian) to 8.3 km (Cambrian). An average freezing temperature of –4.09°C correlates with 5% NaCl. Brines from which cements precipitated had almost twice as much NaCl as normal seawater. The relationship between freezing and homogenization temperatures shows that as the homogenization temperatures increased, the salinity of the subsurface waters increased.

Vitrinite reflectance values for samples from the Woodford Shale (Devonian) and Sycamore Limestone (Mississippian) yield a mean value reflectance of 0.55%. LOM values determined from mean reflectance correspond to 7.8 (Devonian) to 8.0 (Mississippian). These values correspond to a maximum temperature of 98°–100°C for a linear relationship between LOM and depth. For a nonlinear relationship of LOM vs. depth, maximum temperatures of 50°–52°C are inferred. These temperatures (50°–52°C) are based on a nonlinear curve of vitrinite data for a well in Beckham County, Oklahoma. Both sets of temperatures (98°–100°C and 50°–52°C) are within the diagenetic stage boundary between immature and mature sediments, and are at the edge of the oil window according to the stages of petroleum generation. Reflectance values from shale samples imply a maximum depth of burial of 4 km based on a 25°C/km geothermal gradient.

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Paleomagnetic Dating of Dedolomitization in Cambrian–Ordovician Arbuckle Group Limestones and Pennsylvanian Collings Ranch Conglomerate, Southern Oklahoma

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Paleomagnetic and petrographic techniques have been used to date dedolomitization in stratigraphic and tectonic dolomites exposed in the Arbuckle Mountains, southern Oklahoma. We examined red dedolomites and their dolomite precursors from the Cambrian–Ordovician Arbuckle Group and dolomite clasts in the Pennsylvanian Collings Ranch Conglomerate. Authigenic hematite is associated with the dedolomite and precipitated as a result of the dedolomitization process. Dedolomite is associated with paleokarst and fractures, burrows, Liesegang bands, and red rims on conglomerate clasts.

Magnetic directions from these dedolomitized rocks range from Dec = 145° to 154° and Inc = 2° to 9°, with ks greater than 50 and α95s less than 5. The directions are constrained by fold tests to be post-structural (Late Pennsylvanian to Early Permian) and in the Collings Ranch to post-depositional. These directions correspond to a reversed Pennsylvanian pole position and the magnetizations are interpreted as chemical remanent magnetizations (CRM) acquired when hematite precipitated during dedolomitization. In contrast to the dedolomitized rocks, unaltered dolomite contains a Cambrian–Orodovician magnetization in magnetite (Dec = 105°, Inc = 4°, k = 27, α95 = 10°) that could be primary. The acquisition of the CRM is temporally related to uplift in this region and dedolomitization presumably resulted from exposure to meteoric waters. The results emphasize the importance of a regional, Late Pennsylvanian dedolomitizing and remagnetizing diagenetic event that affected some early Paleozoic magnetic directions and dolomite.

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Arbuckle Source for Atoka Formation Flysch, Ouachita Mountains Frontal Belt, Oklahoma: New Evidence from Paleocurrents

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The 10-mile-wide Ouachita Mountains frontal belt consists of Morrowan–Atokan flysch exposed in steeply south-dipping imbricate thrust slices. Two spatially distinct groups of paleocurrents were recognized during detailed mapping of 120 mi^2 in the frontal belt (between 95°15′W and 95°30′W). The east–westtrending Morrowan shallow-water shelf margin (now allochthonous) marks the boundary between these two domains. Westerly azimuths (259°n = 213), typical of almost the entire Ouachita flysch sequence, are from the Atoka Formation south of the shelf margin. Easterly azimuths (66°n = 75), previously unrecognized in the Ouachitas, are from the Atoka Formation where it overlies Wapanucka Limestone north of the margin. A third group of paleocurrents (193°n = 21) are from the Johns Valley Shale (an olistostrome that is the basinward equivalent of the Wapanucka Limestone).

Easterly paleocurrent azimuths indicate a western source for the Atoka Formation north of the Morrowan shelf margin. Sediment from the Arbuckle uplift was apparently channeled northeastward down a trough that was isolated from the Ouachita basin to the south where sediment had an Appalachian provenance. We suggest that a trough was formed by listric fault blocks (tilted toward the continent) of the foundered Morrowan shelf margin. The bounding faults would be the southernmost of a series of northward younging south-side-down growth faults that have been recognized in the subsurface of the Arkoma basin to the north.

There are two important implications of our work in the Ouachitas. High-angle thrust faults in the frontal belt may be reactivated listric normal faults. Proximal-fan facies equivalents of turbidites along the north edge of the frontal belt are to the southwest, and not to the north and east as has been previously suggested.

[Note: This abstract, as originally published in the American Association of Petroleum Geologists *Bulletin*, v. 72, p. 184–185, incorporated an introduced editorial error; the correct version appears here.]

Structural Profiles of Ouachita Mountains, Western Arkansas

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The Ouachita Mountains of Oklahoma and Arkansas are the largest exposure of the Pennsylvanian-age orogen rimming the southern margin of North America. The exposure consists of a thick Carboniferous flysch sequence overlying a thin early Paleozoic deep-water sequence and is generally interpreted to have been deformed in a south-dipping subduction zone. Two balanced cross sections (~40 km apart) of the Ouachita Mountains in western Arkansas are presented here, illustrating the regional structural style. Major features of the cross sections include (from north to south) (1) triangle zones along the northern border of the frontal thrust zone produced by imbrication at depth, (2) large-scale (~10-km wavelength) fault-propagation folds in the frontal thrust zone, formed primarily above normal faults that offset the basement and act as buttresses at depth, (3) a late-stage basement uplift along the reactivated Johns Valley normal fault system, resulting in the antiformal structure of the Benton uplift and backthrusts in the northern Benton uplift, and (4) small-scale (1–3 km) heavily faulted folds in the early Paleozoic deep-water rocks exposed in the Benton uplift. Greenschist metamorphism in these rocks is attributed to the estimated 13 km of Carboniferous overburden, which was later eroded.

Reconstructions of the late Paleozoic continental margin are made from the two cross sections. The reconstructed shelf-to-slope transition is interpreted to

underlie the southern flank of the Benton uplift. Using modern analogs for the across-strike width of the shelf-to-slope transition, a minimum regional shortening estimate of 30–50% (110–155 km) is obtained for deep-water rocks currently exposed in the Benton uplift.

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Potential for Subthrust Gas Fields: Results of Recent Deep Drilling in the Ouachitas

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The Broken Bow anticline, with dip closure of over 170 mi^2, is the Oklahoma culmination of a long regional trend extending from Arkansas to central Texas. The Standard Oil 1-22 Weyerhaeuser well, drilled to 18,980 ft, is the first crestal well on this feature to test the subthrust section beneath the Ouachita fold and thrust belt. The well spudded in and drilled a substantial section of slates, phyllites, and calcareous quartzites of presumed Ordovician and Cambrian(?) age. The basal Ouachita thrust was penetrated at 11,714 ft, where an interpreted Ordovician Simpson–Arbuckle section was encountered. Reflectance methods using pyrobitumen and visual determination of metamorphic grade indicated the presence of a significant maturity reversal at the thrust boundary. Although economic quantities of hydrocarbons were not found in this well, the following observations may influence future work. (1) A para-autochthonous section of shelf carbonates and sands exists in the subthrust, at least 60 mi from the leading edge of the Ouachita thrust belt. (2) The abundance of pyrobitumen observed in the Simpson section suggests the former presence of significant hydrocarbons. (3) The well encountered good dolomite reservoir at high maturities (R_o = 7–8%) that flowed formation water and unexpectedly contained dissolved C_1 to C_3. These observations suggest that high maturities alone may not be a condemning factor and should be considered in future exploration plays.

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Basement Structures Beneath Thrust Ouachita Rocks

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The Ouachita foldbelt in Arkansas and Oklahoma involves very complex structure. Generally all the exposed rocks in the Ouachita Mountains are strongly allochthonous in character. The allochthonous rocks have been thrust as far as 50 miles northward from their former position. In the northern part of the orogen the thrust surface is steep, to the south it is low angle, nearly horizontal, with two major elevated zones. The slope of the overthrust surface is dependent on the basement configuration.

The seismic surveys and well data indicate uplifted zones, and depression-graben zones in the basement beneath the Ouachita overthrust rocks. The northern uplift (coincident with the overthrust Potato Hills/Benton Uplift Zones) may be a continuation of the trend of the Arbuckle Mountains. It is bordered on the north by an extension of the Arkoma basin. The axis of the uplift trends northeast and east through Oklahoma and Arkansas. The depth to Precambrian basement varies from 5 to 9 kilometers.

The southern uplift (coincident with the overthrust Broken Bow Zone) trends northeast, and east through northeastern Texas, Oklahoma and south Arkansas and may connect with the buried Wichita Mountain trend. The depth to basement varies between 5 and 7 kilometers. In the depression zone between these two uplifts, the depth to basement varies between 9 and 17 kilometers. This depression aligns with an eastward continuation of the Ardmore basin and may be associated with the Mississippi graben to the northeast.

The strong connections between autochthonous and allochthonous structural features proves a renewal of basement activity during the overthrusting (Pennsylvanian) of the Ouachita orogenic belts and later. Additional seismic lines are needed to provide better definition of the basement configuration and its relationship to the Ouachita allochthon.

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Geologic Reservoir Characterization of Humphreys Sandstone (Pennsylvanian), East Velma Field, Oklahoma

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East Velma field is located in the Ardmore basin, Stephens County, Oklahoma, on the north flank of a truncated anticline with dips that range from 30°–60°. The discovery well of the Humphreys sand unit was drilled in April 1951 and an original oil in place of 32.7 million bbl was calculated. Primary depletion was by solution gas drive with gas reinjection and gravity drainage which was enhanced by the steep structural dip of the field. A waterflood that was initiated in 1983 and a proposed CO_2 miscible displacement program to further enhance field recovery prompted the need to develop a detailed geologic description of the reservoir.

Core studies indicate that the Humphreys sandstone was deposited in a shallow marine, tidally dominated environment. Subfacies include sand-rich tidal flat and tidal channel deposits. The unit is primarily composed of very fine to fine-grained, moderately to well-sorted quartzarenites. Dominant sedimentary structures include bidirectional and unidirectional current ripples, cross-laminations, common slump structures, and zones abundant and scattered burrows. Four types of heterogeneities have been identified within the Humphreys sandstone that affect reservoir quality and continuity; carbonate cemented zones; a mudstone interval that divides the sandstone unit into two lobes in the northeastern part of the field; two mud-filled, abandoned tidal channels that disrupt continuity in the southeastern part of the field; and filled fractures. Results of the geologic description are currently being used in reservoir simulation studies.

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Valley-Fill Deposits: Key to Stratigraphic Traps in Pennsylvanian and Cretaceous, Rocky Mountain and Mid-Continent Regions

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A valley fill is deposited during a rising sea level in an incised drainage that was cut during a relative sea level lowstand. Where thickest and most complete, the valley fill commonly has a vertical zonation from lowermost freshwater deposits to brackish and then marine deposits. The zonation results from deposition during rising sea level (transgression) by aggradational processes within the valley. This vertical facies order is contrary to the normal facies arrangement in typical regressive deposits.

Valley-fill deposits are bounded by surfaces of erosion. They overlie a lowstand surface of erosion associated with the valley incisement phase and a lowering of base level (this surface is a major sequence boundary in sequence stratigraphy analysis). They may be truncated at the top by a transgressive surface of erosion associated with shoreface erosion related to the transgressing marine shoreline. Marine shale, commonly an organic-rich condensed section (source rock), overlies the valley fill. Minor erosion surfaces that are found within the valley fill, associated with depositional processes, are called diastems.

Valley-fill deposits in the Pennsylvanian and Cretaceous are up to 120 ft thick, are less than a mile to as much as tens of miles in width, and may be hundreds of miles in length. The nature of the fill varies in percentage of sandstone, siltstone, and shale. The most important petroleum reservoir in the valley fill is the lenticular porous and permeable fluvial channel sandstones, normally in the lower portion. Of less importance are the estuary, tidal flat, and bayhead delta (estuarine) sandstones because they are thinner (<10 ft) and "tighter." Typical stratigraphic and unconformity traps in valley fills are present in the Rocky Mountain and Mid-Continent regions. Some valley fills can be recognized on seismic, but a future exploration challenge is to integrate improved seismic and geologic models, to improve the predictability.

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Production from Valley-Fill Deposits, Morrow Sandstone, Southeast Colorado: New Exploration Challenges and Rewards

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New exploration success in southeast Colorado indicates opportunities for future discoveries from the Morrow sandstones of many fields in the 10 million to 40 million bbl recoverable reserve category. Drilling depths from 5,000 to 6,000 ft and estimated per well recoveries averaging 200,000 bbl of oil in several fields provide favorable economics, even in times of depressed oil prices. In the past, major problems have been low discovery ratios in exploration wildcat drilling for elusive narrow channel sandstones and predictability of reservoirs in development drilling. Thus, a major challenge is to improve predictability of trends and traps through refinement of geologic and seismic models. This improvement is possible through analysis of existing fields by use of cores, samples, logs, and integrated seismic.

Four widely scattered areas illustrate typical fields in the Morrow play. These are McClave, Sorrento–Clifford, and Smokey Hill fields and the state line area extending from Stockholm field to Arapahoe field. Data needed for each producing area are structure, stratigraphy, sedimentology, reservoir characteristics, and production history.

Production in all four areas is from coarse-grained channel sandstones in the Morrow formation that are interspersed between marine black shales or marine gray shale and limestone. The channels are part of several valley-fill sequences that were deposited during major sea level changes during the Early Pennsylvanian.

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Application of Sequence Stratigraphic Analysis to Thin Cratonic Carbonate-Dominated Shelf Cycles (Upper Pennsylvanian) in Mid-Continent

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Seismic sequence analysis has proven extremely effective and practical in identifying potential petroleum reservoir plays. This analysis requires defining stratal units, 10s of meters in thickness, bounded by unconformities and translated on seismic traces. A similar approach, using different techniques, is applied to subsurface data to improve the resolution of the sedimentary architecture in thin Upper Pennsylvanian cratonic cycles.

These cycles reflect the relative rise and fall of sea level, aspects of which vary between cycles in terms of rate, magnitude, and duration. Understanding aspects of the fall of relative sea level and accordant sediment aggradation and progradation is important in order to recognize the character of the basinward migration of favorable shallow-water carbonate facies tracts.

Because of their short duration, individual aggradational and progradational events cannot be resolved via biostratigraphy. Correlatable events, bounded by omission surfaces, can be recognized through detailed lithofacies analysis of cores. Wireline logs provide a basis from which to extrapolate thicker (>0.7 m) core-derived lithofacies.

Very high resolution CMP seismic profiling (≤ 300-Hz) has been used successfully at penetration depths to about 450 m to distinguish and characterize reflections from beds (1.5 m minimum) within cycles and internal depositional surfaces within thicker deposits. Potential exists for using detailed seismic sequence analysis to assist in defining geometry of these component beds at reservoir scale.

The improved understanding of the character and causes of these cycles will be useful in developing sensitive predictive models that will address factors such as shelf setting and expected facies development.

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Laminated Black Shale–Chert Cyclicity in Woodford Formation (Upper Devonian of Southern Mid-Continent)

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The Woodford formation, a known hydrocarbon source rock, is contemporaneous with other mid-Paleozoic (Frasnian to Tournasian) black shales occurring throughout North America and Europe. Much of the Woodford formation in outcrop along the southern flank of the Arbuckle uplift (Carter County, Oklahoma) consists of rhythmic alternating beds of laminated black shale and chert. A time series analysis of the chert–black shale couplets displays an approximately 20-ka periodicity, suggesting that deposition was controlled by external orbital forcing of the earth (Milankovitch cyclicity).

Total organic carbon ranges from 3 to 9% in the chert and from 10 to 28% in the black shale; carbonate carbon content is essentially zero. Carbon isotope ($\delta^{13}C = -29$ per mil), pyrolysis-gas chromatography, and Rock-Eval analyses indicate that the kerogen is of marine origin and is oil-prone type II. Except for the difference in organic carbon contents, the kerogens of the chert–black shale couplets are analytically similar.

The high organic carbon concentrations and the presence of laminated black shales signify deposition under anoxic conditions. However, C/S values for both the chert and black shale are about 10, which is significantly higher than C/S values in sediments deposited in euxinic and normal marine environments. Iron availability, rather than sulfate, apparently limited pyrite formation in this anoxic depositional setting.

Presence of phosphorite-rich zones indicates that upwelling conditions were prevalent during parts of Woodford deposition. The chert–black shale cyclicity is interpreted to represent deposition during periods of upwelling and high productivity (siliceous ooze) alternating with deposition during times of lower productivity (laminated black shale) in a restricted basin (Southern Oklahoma aulacogen).

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