OKLAHOMA GEOLOGY notes

Oklahoma Geological Survey

Vol. 62, No. 1 Spring 2002

Featuring:

- *Depositional environments of the Savanna Formation*
- *Desmoinesian flora from the Savanna Formation*
- *Springs of Ellis County*

on the cover

Savanna Formation Near Lequire, Haskell County, Oklahoma

The cover photograph is an oblique view of part of the Desmoinesian Savanna Formation exposed along Oklahoma State Highway 82 ~1 mi southwest of Lequire, Oklahoma. In this issue of *Oklahoma Geology Notes* (see p. 4), Andrews and Suneson divide the Savanna exposed near Lequire into 9 units; the cover photograph shows the upper part of unit 6 (dark gray, lower left), unit 7 (light gray, center), and the lower part of unit 8 (brown and maroon, upper right). Unit 6 is dominantly shale; unit 7 is mostly sandstone; and unit 8 consists of shale, siltstone, and sandstone.

Most of the Savanna Formation exposed in the Lequire road cut was deposited on the middle to lower parts of a delta plain. Several lines of evidence suggest that the dominantly fine-grained units, such as unit 6, represent bay-fill and swamp and marsh deposits. Coal beds and coaly horizons mark periods or areas of very low sedimentation rates. For much of the length of the road cut, these shaly units are interbedded with sandstone-dominated units, such as unit 7, which probably represent crevasse-splay deposits. Each individual sandstone bed within a sandstone-dominated unit was deposited during a flood event. Trunks of small lycopods are preserved in some of the sandstone beds (unit 5); locally, they are uniformly bent in one direction, which indicates the paleocurrent direction of the flood waters. Unit 8 consists of interbedded bay-fill and crevasse-splay sediments.

Also visible in the cover photograph is a mostly shale-filled distributary channel eroded into unit 7. The base of the channel, however, is filled with sandstone. Distributary channels are common features of middle and lower delta plains and typically are associated with bay-fill, swamp and/or marsh, and crevasse-splay deposits.

The maroon color of unit 8 is visible in the cover photograph and in the photograph below. The coloration typically is parallel to bedding planes, but locally it is highly oblique to bedding planes. The unusual color, the presence of calcareous nodules, and what Hemish (1998) identified as root casts and pedogenic slickensides are evidence that periodically many of the shale and siltstone beds of unit 8 were exposed long enough for incipient soil horizons to form. This interpretation suggests that unit 8 may have been located higher on the delta plain than the other units.

The Lequire road cut is a classic example of a delta-plain deposit. Many lithologic, sedimentologic, and paleontologic features typical of middle and lower delta plains are exceptionally well exposed. In addition, the section exposed at the road cut was drilled and logged in a petroleum well ~0.5 mi to the southeast. The gamma-ray wireline log from the well is very similar to the measured gamma-ray profile of the outcrop. Based on Andrews and Suneson's interpretation of the strata exposed in the road cut, delta-plain deposits have gamma-ray log patterns similar to those of the petroleum well and the outcrop.

Reference Cited

Hemish, L. A.,1998, Engineering and geologic aspects of the new segment of State Highway 82, Haskell and Latimer Counties, Oklahoma: Oklahoma Geology Notes, v. 58, p. 96–115.

—Neil H. Suneson

Close-up view of the contact between unit 7 and unit 8. The maroon color is commonly parallel to the stratification, but in detail it is oblique locally. The sandstone beds of both units are flood deposits; the interbedded shale and siltstone beds of unit 8 were deposited between flood events, and periodically many were exposed long enough for incipient soil horizons to form. Hammer for scale.

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Interpretation of Depositional Environments of the Savanna Formation, Arkoma Basin, Oklahoma, from Outcrops and Surface and Subsurface Gamma-Ray Profiles

Richard D. Andrews and Neil H. Suneson
Oklahoma Geological Survey

ABSTRACT.—The upper part of the Desmoinesian Savanna Formation is well exposed in a new road cut along Oklahoma State Highway 82 just south of Lequire in southern Haskell County. The outcrop is subdivided into nine major units based on exposed rock types, sedimentary structures, fossils, and contact relations between the rock types. Most of the units were deposited in a mid- to lower-delta-plain environment and include interdistributary bay-fill and crevasse-splay sediments, as well as organic material deposited in marshes and/or swamps. Evidence that supports such an interpretation includes interbedded sandstones and shales, common fining-upward textures of the sandstones, and the presence of coal, all characteristic of mid- to lower-delta-plain deposits. In contrast, the basal unit probably was deposited in a delta-fringe environment, and the upper part of the outcrop contains evidence of subaerial exposure.

Gamma-ray values measured on the outcrop closely reflect rock types. Sandstone-dominated intervals have low gamma-ray values; shale-dominated intervals have high values; and intervals of muddy sandstones and/or interbedded thin sandstones, siltstones, and shales have intermediate gamma-ray values. A gamma-ray profile of the entire outcrop was constructed from the measured values. The sharp basal contacts of thick sandstones overlying shales that are observed in outcrop are recorded on the profile, as are units that contain decreasing amounts of sandstone upward. The presence of coal also is reflected on the surface gamma-ray profile.

The surface gamma-ray profile is very similar to a subsurface gamma-ray wireline log for the same stratigraphic interval from a petroleum well ~0.5 mi southeast of the outcrop. The similar profiles illustrate what delta-plain deposits look like on wireline logs and demonstrate the usefulness of surface gamma-ray profiles for interpreting the depositional environment of strata encountered in a wellbore.

INTRODUCTION

This paper has two primary purposes. The first is to describe and interpret a new and exceptionally well exposed outcrop of the Pennsylvanian Savanna Formation near Lequire in Haskell County, Oklahoma. The second is to show the similarity of the gamma-ray profile of the outcrop to the gamma-ray log of the same part of the Savanna Formation from a nearby petroleum well. The goals of this paper are to document that surface gamma-ray profiles accurately reflect the rock types present in a sequence of strata and that certain depositional environments result in particular surface gamma-ray profiles and subsurface gamma-ray logs.

An exposure in the upper part of the Savanna Formation (Desmoinesian) in the Arkoma Basin just south of Lequire (Fig. 1) is one of the best examples of delta-plain strata in Oklahoma. The strata were exposed between 1994 and 1996 during construction of an addition to Oklahoma State Highway 82. The exposure is essentially unweathered and consists of ~240 ft of mostly nonmarine sandstone, siltstone, shale, and thin coal beds that represent multiple crevasse-splay and interdistributary bay-fill, swamp, and marsh deposits. Plant fossils are abundant and include conspicuous, large, erect, in situ *Calamites* and lycopods. (See Lupia and others, 2002 [this issue, p. 19–26], for a preliminary survey of the flora from the outcrop.) Common sedimentary structures in the sandstones that are characteristic of episodic and rapid deposition on a delta plain include soft-sediment deformation features, cross bedding, and load casts.

The Savanna Formation near Lequire also is important for reconstructing the formation's paleogeographic environment of deposition in southeastern Oklahoma. Much of the Savanna Formation ~5 mi to the southeast described by Hemish (1996) (e.g., Lodi section) appears to be marine and probably was deposited in a subaqueous delta-front environment, the basinward equivalent of the delta plain exposed at Lequire. The different depositional setting of the Savanna Formation at Lequire compared to that near Lodi requires further study; such detailed paleoenvironmental reconstructions are important for resource assessment of coal, natural gas, and coalbed methane, all of which are present in the Savanna.

Gamma-ray profiles of surface exposures—where rock types, textural variations, and sedimentary structures provide visible evidence for interpreting depositional environments—are useful for interpreting subsurface strata for

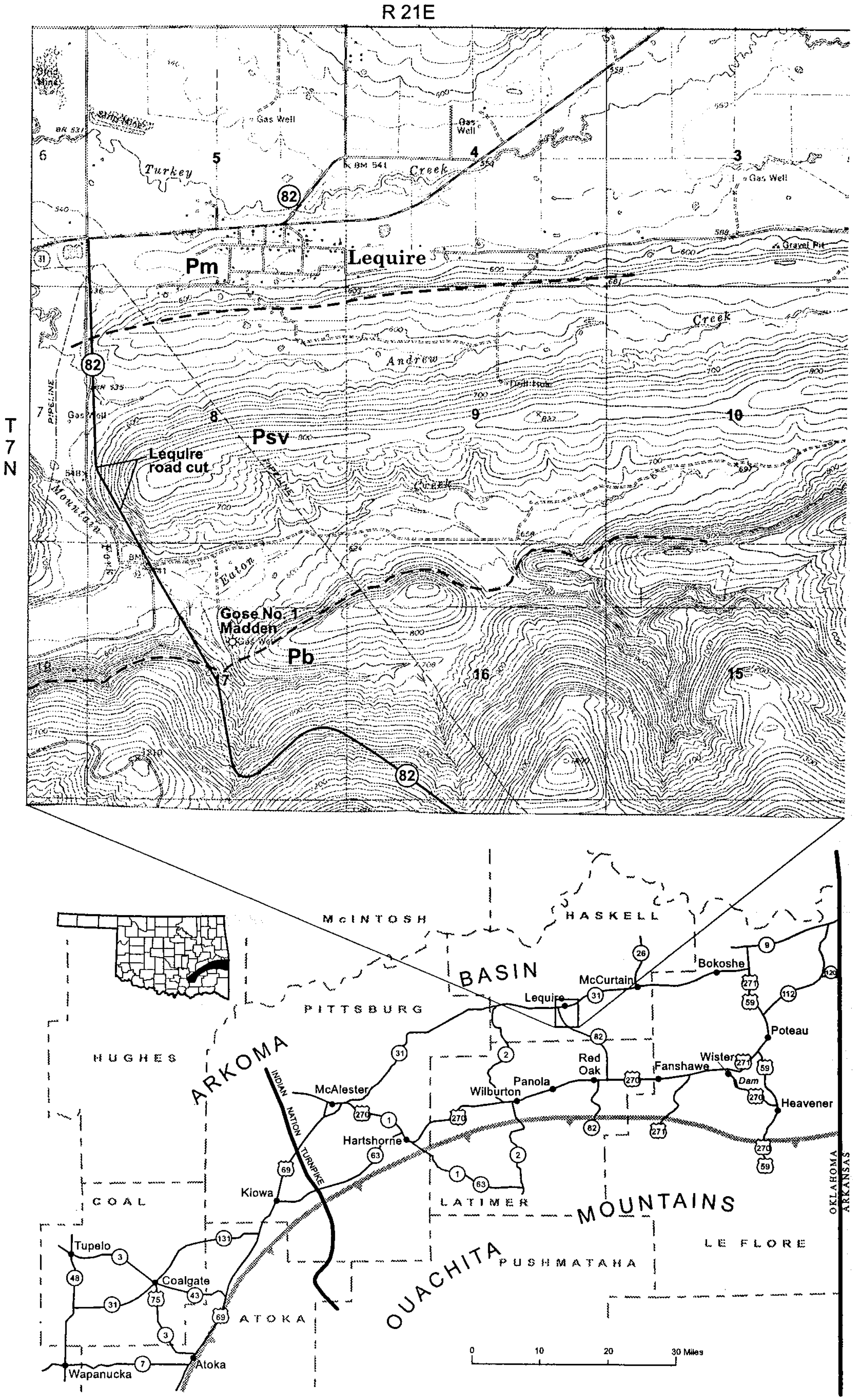


Figure 1. Map showing the locations of the Lequire road cut (SW¼ sec. 8, T. 7 N., R. 21 E.) and the Steve Gose No. 1 Madden well. (Geologic map modified from Hemish, 1998; location map modified from Suneson, 1998, inside front cover.) Pm—McAlester Formation; Psv—Savanna Formation; Pb—Boggy Formation; dashed lines—geologic contacts.

which only wireline logs are available. Gamma-ray profiles generally measure the relative abundance of shale or interstitial clay, both of which produce relatively large amounts of gamma radiation compared to other common sedimentary rocks such as sandstone, limestone, or coal. Therefore, a gamma-ray profile (or a wireline log) can be used to distinguish between these rock types. Generally speaking, sandstone with little interstitial clay or interbedded shale exhibits low gamma-ray values and is called "clean." Sandstone or siltstone having larger amounts of interstitial clay and/or interbedded shale have gamma-ray values between those of a clean sandstone and a shale and may be called "dirty." A wireline log, therefore, records the relative amounts and thicknesses of shale and of clean and/or dirty sandstone in a wellbore; it also records the nature of the contacts (sharp vs. gradational) between the sandstones and shales.

This study is similar to Andrews and Suneson's (1999) study of the Desmoinesian Hartshorne Formation, and the delta-plain origin of the Savanna at Lequire is similar to that of the Hartshorne at Heavener (p. 54–56). In this paper, however, we more carefully describe those outcrop features that support our interpretation for a delta-plain environment of deposition. In addition, the outcrop gamma-ray profile and the wireline log of the Savanna are far more strikingly similar than are the Hartshorne profiles. Both studies, however, confirm the general log signature of delta-plain deposits as described by Brown (1979) and Coleman and Prior (1982).

PREVIOUS STUDIES OF THE SAVANNA FORMATION

The Desmoinesian Savanna Formation is within the Krebs Group, which consists (from bottom to top) of the Hartshorne, McAlester, Savanna, and Boggy Formations (Fig. 2). It is exposed along the eastern side of the Cherokee Platform area from the Kansas state line in Craig and Ottawa Counties (Branson and others, 1965) south to Muskogee (Oakes, 1977) (Fig. 3). The Savanna is not recognized as a separate formation in Kansas, where its stratigraphic equivalent is within the Krebs Formation (Brady and others, 1994). The Savanna Formation also is widely exposed in the Arkoma Basin of Oklahoma and Arkansas (Hart, 1974; Marcher and Bergman, 1983; Haley, 1976; Hemish and Suneson, 1997; and references cited therein).

The geology of the Savanna Formation in southeastern Oklahoma was summarized recently by Hemish (1996) and Hemish and Suneson (1997). Those studies focused on the history of nomenclatural changes; thickness variations, particularly from the platform area in the north to the Arkoma Basin in the south; lithologic variations; and resources. The depositional environment of the Savanna Formation is poorly understood (Hemish and Suneson, 1997, p. 27), but its numerous coal beds and widespread limestone beds containing marine, invertebrate fossils are evidence that the Savanna includes continental and marine strata. The Savanna probably consists of a variety of offshore marine, marine bar, deltaic, and alluvial facies; however, an understanding of the distribution of these facies and an accurate picture of Savanna paleogeography await future study.

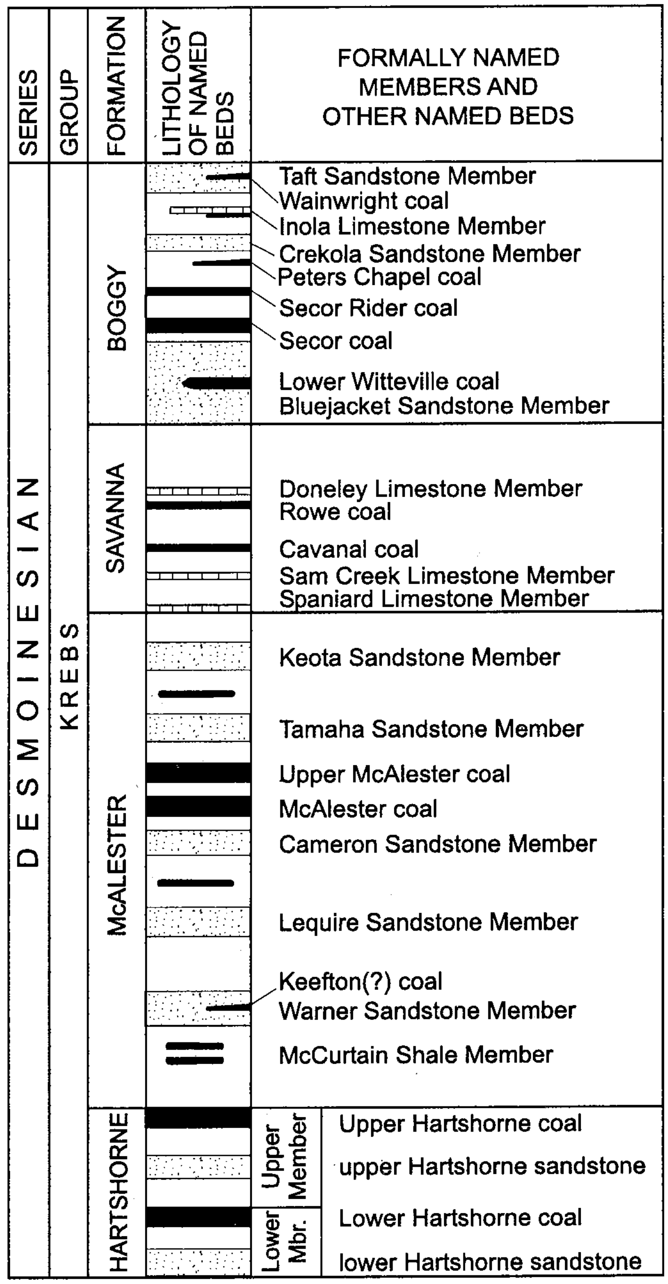


Figure 2. Generalized stratigraphic column of the Krebs Group showing the relative positions of formally named members, names of coal beds, and other informally named beds. Of the members of the Savanna Formation, only the Rowe coal has been tentatively identified in the Lequire road cut. (Modified from Hemish and Suneson, 1997, fig. 3).

MID- AND LOWER-DELTA-PLAIN DEPOSITS

Deltas generally consist of a distinctive sequence of rock types, and the different deltaic environments can be interpreted from outcrops and from surface and subsurface gamma-ray profiles (e.g., Brown, 1979; Coleman and Prior, 1982) (Fig. 4). This study focuses on the identification and characterization of mid- and lower-delta-plain deposits of the Savanna Formation, in particular, sediments deposited in crevasse-splay, distributary-channel, and interdistributary (in-

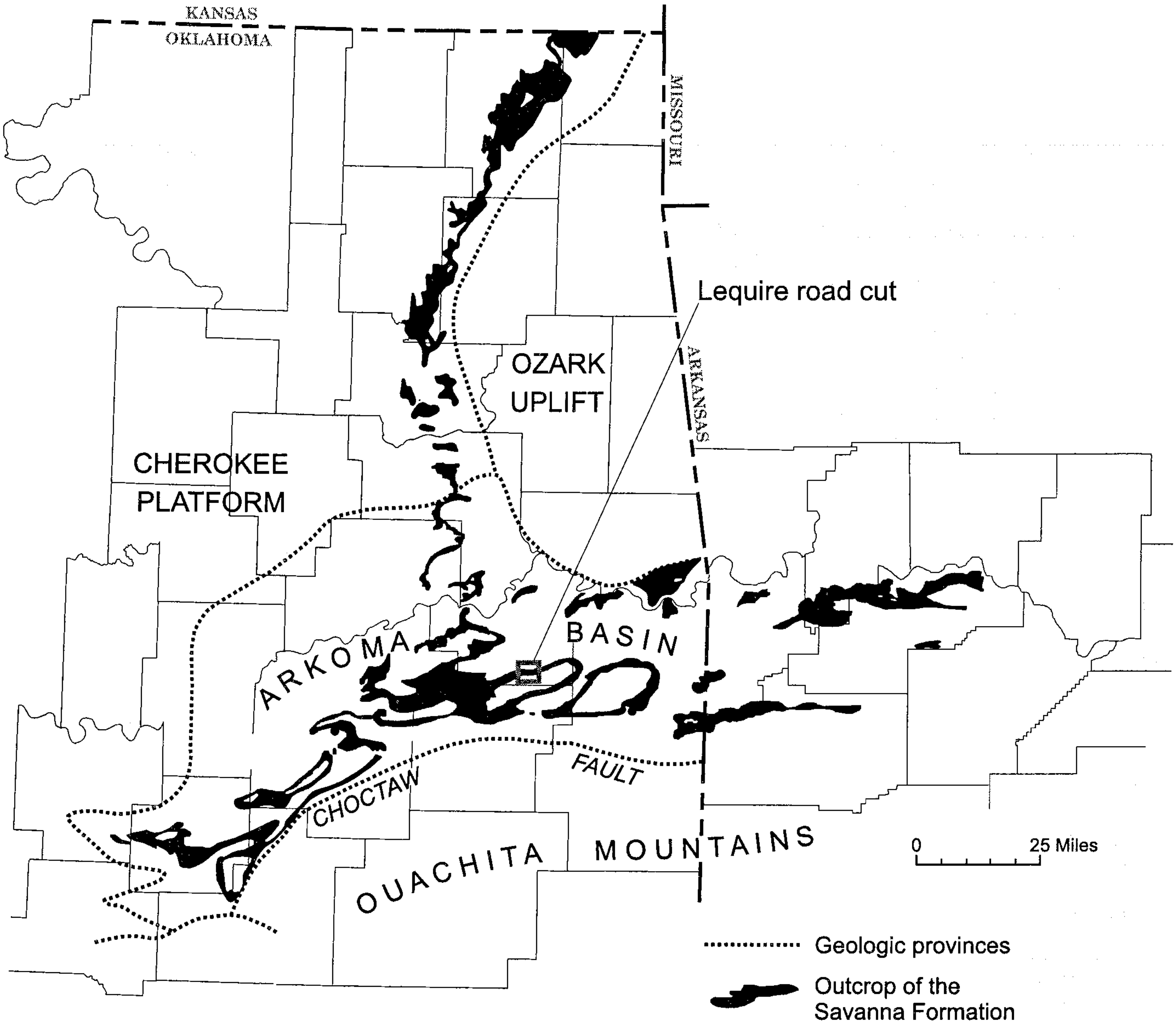


Figure 3. Map showing the outcrop belt of the Savanna Formation in Oklahoma and Arkansas and the location of the Lequire road cut. (Modified from Hemish and Suneson, 1997, fig. 15; outcrop of Savanna Formation in Cherokee Platform area from Miser, 1954).

cluding bays, marshes, and swamps) environments (Fig. 4). These deposits include sandstones, siltstones, shales, and coal beds. In overbank deposits (crevasse splays), sandstone beds commonly are relatively thin but widespread; in contrast, sandstones in distributary channels are restricted spatially and may be thick. Siltstones and shales commonly occur in bay-fill environments, but may occur also in abandoned channels. Coal beds are diagnostic of marsh or swamp environments. Interdistributary-bay and marsh or swamp sequences commonly are interbedded with crevasse-splay sandstones.

Crevasse-Splay Deposits

Crevasse-splay sandstones typically are thinner than the depth of the interdistributary bay in which they are deposited. In most of the Pennsylvanian deltas of Oklahoma, bays rarely exceeded depths of a few tens of feet. However, the lateral extent of crevasse-splay sandstone beds is large and reflects the area of the receiving bay and the amount of sand available. Crevasse-splay sandstones may have either a coarsening-upward or a fining-upward textural profile, and both patterns are common in a single stratigraphic sequence in which more than one splay event occurred.

Textural profile is a function of depositional energy. (Textural profile in this article refers to sediment grain-size distribution, or specifically, the number and thickness of siltstone and/or shale beds interstratified with sandstone beds.) Proximal splay sands are deposited close to the distributary channels from which they were derived, and depositional energy in a proximal splay environment typically is high, as it is in a break-out channel. In a vertical profile, therefore, the sand body resembles that deposited in a river or channel. Proximal splay sandstones commonly have blocky to fining-upward textural profiles and sharp, erosional basal contacts with their underlying bay-fill siltstones and shales. In contrast, in distal parts of the interdistributary bay, splay energy is much lower and little, if any, erosion of the substrate occurs. Fine sediments are deposited rapidly ahead of current-induced bed-load transport of coarser sand, and, thus, distal crevasse-splay sandstones have coarsening-upward textural profiles. In summary, the textural profile of splay deposits changes spatially and is an indication of depositional energy and the direction of sediment transport.

Distributary-Channel-Fill Deposits

In contrast to the relatively thin and laterally extensive character of the crevasse-splay sandstones of the mid- and lower-delta plain, distributary-channel-fill sandstones commonly are thicker and restricted spatially. Distributary channels have scoured, erosional bases and are filled with sandstone unless they were abandoned; abandoned distributary channels may be filled with siltstone or shale. Distributary-channel sandstones, therefore, have sharp bases with blocky to fining-upward (more common) textural profiles.

Interdistributary-Bay-Fill Deposits

Interdistributary-bay-fill sequences are dominated by siltstone and shale. In general, the sediments are highly burrowed, rich in organic material, and, when lithified, they are characterized by siderite nodules (e.g., Coleman and Prior, 1982). In some cases, tidal channels and/or marine or brackish-water fossils are present. Coal seams are evidence for marshes and swamps, and they mark areas of shallow water where sediment input was negligible. Because bay-fill sequences consist mostly of fine-grained, organic-rich sediments, they have a relatively featureless profile characterized by moderately high gamma-ray values.

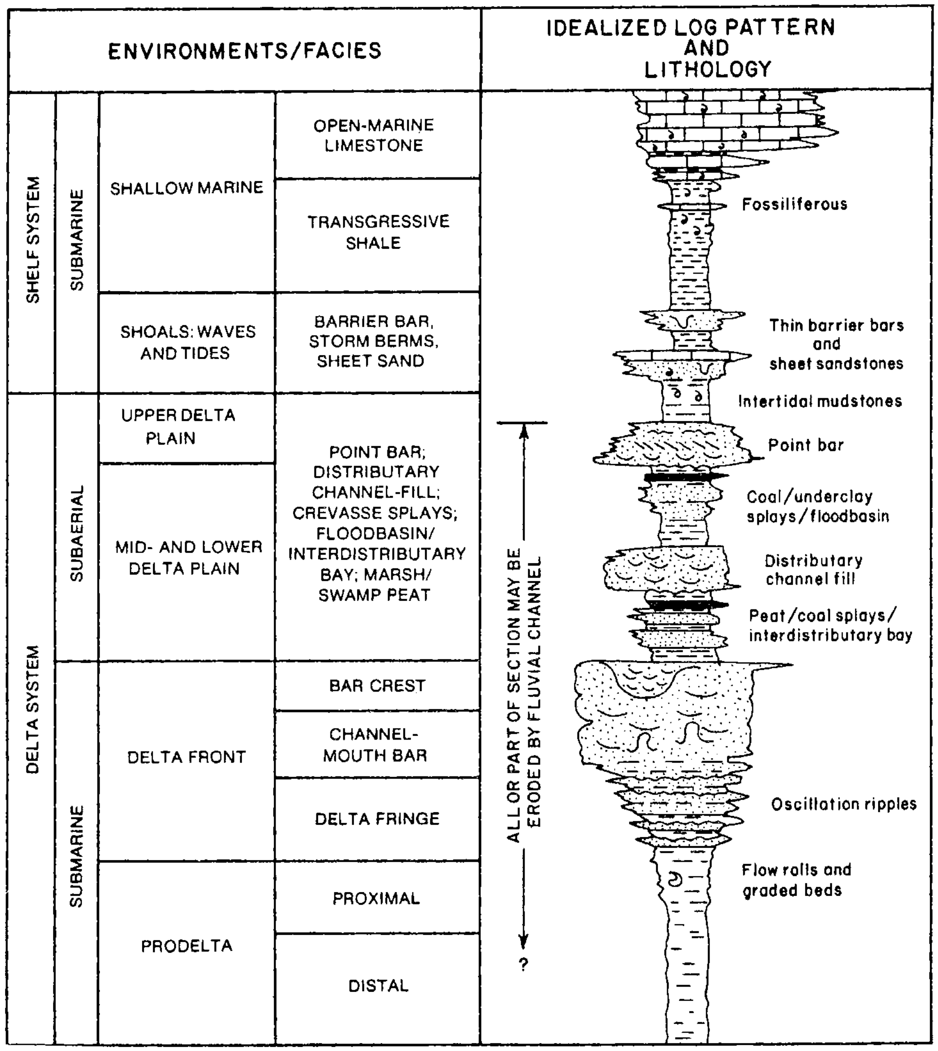


Figure 4. Idealized delta sequence showing principal depositional phases and idealized electric-log pattern. (Modified from Brown, 1979, p. 50).

GAMMA-RAY PROFILES

Andrews and Suneson (1999) reviewed the theory relating gamma radiation and rocks and the usefulness of comparing surface and subsurface gamma-ray profiles for identifying particular sequences of lithofacies. Recognizing such sequences on gamma-ray profiles is key to interpreting their depositional environments (Howe, 1989; Jordan and others, 1991; Slatt and others, 1995). As described in the section on delta-plain deposits above, the mid- and lower-delta-plain environment consists of sandstone-filled or, more rarely, shale-filled distributary channels separated by wide expanses of interdistributary-bay-fill shales, siltstones, and coals. Crevasse-splay sandstones are interbedded with the fine-grained, bay-fill material. The interbedding of these very different rock types results in a very irregular gamma-ray profile. Distributary-channel and splay sandstones are of particular interest because their textural profiles typically are very distinct (Fig. 4).

Surface and subsurface gamma-ray profiles of the same stratigraphic interval are very similar in appearance except that the intensity of radiation is much less on a surface profile because only a small surface area is sampled on an outcrop as compared to that sampled in a wellbore. In a wellbore, rocks completely surround the gamma-ray measuring tool, resulting in much higher gamma-ray measurements. Gamma radiation on surface gamma-ray profiles is in counts per second (CPS); on subsurface gamma-ray profiles (wireline logs) gamma radiation is in API (American Petroleum Institute) units. Although CPS and API units both are measures of the amount of naturally occurring radioactivity in rocks, they cannot be converted from one to the other.

CURRENT STUDY

This study focuses on a well-exposed road cut through part of the Savanna Formation on the east side of State Highway 82 just south of Lequire in southern Haskell County, Oklahoma (Fig. 1). The outcrop, located in the SW¼ sec. 8, T. 7 N., R. 21 E., was initially described by Hemish (1998) during highway construction (October 1994). At that time, ~100 ft of section, dipping south at 18°, was exposed. Hemish (1998, appendix) measured ~70 ft of exposed section. Since Hemish's work, the road cut has been cut back further and ~240 ft of strata now are exposed (Fig. 5).

Based on gamma-ray correlation with the Steve Gose No. 1 Madden well located ~0.5 mi southeast of the outcrop (Fig. 1) (discussed below in the section on correlation of surface and subsurface gamma-ray profiles) and mapping by Hemish (1998, fig. 9A), the base of the outcrop is ~645 ft above the base of the Savanna Formation, which is ~1,085 ft thick in the study area. In this area, the Savanna is underlain by the McAlester Formation (Fig. 2), which underlies the north-facing slope of the ridge immediately south of the town of Lequire. (The Keota Sandstone Member of the McAlester Formation is exposed in the town [Hemish, 1998, fig. 9A].) The exposed section is ~240 ft thick; therefore, the top of the outcrop is ~200 ft below the top of the Savanna, which is the base of the Bluejacket Sandstone Member of the Boggy Formation (Fig. 2).

Depositional Environments

We subdivide the Lequire outcrop into nine major units based on exposed rock types, sedimentary structures, fossils, and contact relations between rock types. Five sandstone-dominated zones (units 1, 3, 5, 7, and 9) separated by siltstone- and shale-dominated zones (units 2, 4, 6, 8) (Fig. 6) are exposed at the outcrop. We interpret the Savanna Formation exposed in the Lequire outcrop to have been deposited mostly in a mid- to lower-delta-plain environment. The interpretation is supported by the features emphasized in the general descriptions of the units in this section. (Detailed descriptions of the units are given in the Appendix.)

Unit 1

Sandstone unit 1 is interpreted to be dominantly marine and probably represents a delta-fringe facies. Distinctive sedimentary features that contrast with the other sandstones include excellent small-scale stratification and local ripple-cross-stratification with thin shale drapes. Plant fossils and trace fossils are absent.

Unit 2

Unit 2 is mostly shale with a 4-in.-thick coal bed in the lower half. The shale below the coal contains ostracodes, which are either Carbonita sp. or Darwinula sp. (Faye Simms, Northwestern State University, personal communication, 1999). Both genera are evidence for a brackish- to fresh-water environment (e.g., Kietzke and Kaesler, 1992). Some beds are highly calcareous and may grade into muddy limestones. The shale above the coal contains abundant coaly laminations and siderite(?) concretions containing plant compressions. The siderite(?) occurs as isolated nodules, nodules concentrated along bedding planes, and discrete beds. A discontinuous, 1-in.-thick coal bed is present ~6 ft below the top. Unit 2 is interpreted to be alternating marsh or swamp and interdistributory-bay facies deposited in brackish to fresh water.

Unit 3

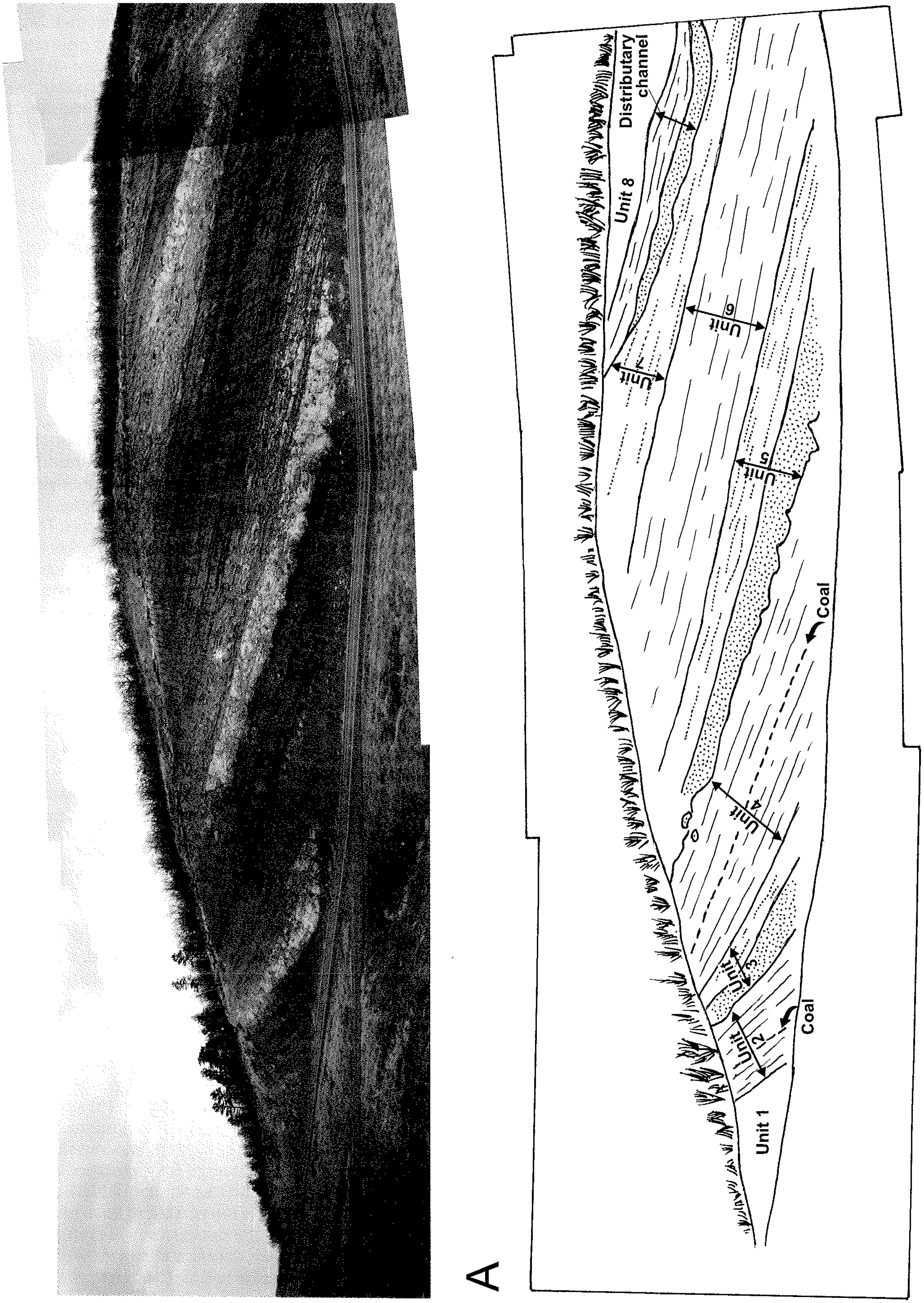
Sandstone unit 3 (Fig. 7) fines upward as evidenced by the increasing number and thicknesses of shale and siltstone layers and decreasing thicknesses of sandstone layers from the base to the top of the unit. All of the sandstones are fine-grained to very fine grained and relatively clean. The basal sandstone is ~9 ft thick and contains abundant soft-sediment-deformation features. Bedding planes are marked by shale rip-up clasts and plant debris. The base is slightly irregular and the underlying shale (unit 2) has locally squeezed up into the sandstone, but there is no evidence for channeling or erosion. The basal sandstone was deposited during a single event, probably a flood. Stratigraphically higher sandstone beds in unit 3 range from 1 ft to 1 in. thick, are discontinuous, show much pinch and swell, and locally erode into underlying beds. Like the massive basal sandstone, the thinner sandstone beds also contain shale rip-up clasts and plant fragments. The sandstone beds are separated by thin laminated shales and siltstones. A 6-ft-thick channel filled with massive, soft-sediment-deformed sandstone locally erodes into the sandstone beds in the upper part of unit 3. Unit 3 is interpreted to be a fining-upward crevasse-splay sequence.

Unit 4

Shale unit 4 consists of shale, siltstone, sandstone, and coal, in decreasing order of abundance. Key environmental features include abundant plant fossils, burrows, and siderite(?) nodules, which are evidence for a bay-fill sequence of dominantly fine-grained rocks. The presence of coal near the middle of the unit is evidence for a period of low sedimentation rates.

Unit 5

Unit 5 is similar in many respects to unit 3 and consists of multiple sandstone beds that become thinner upward (Fig. 8); shale and siltstone beds increase in abundance and become thicker upward. The sandstones are very fine grained and quartzose. The base of this unit is marked by a massive sandstone, the base of which is undulatory and marked by numerous upright carbonized tree trunks as much as 6 ft high and 14 in. in diameter (Fig. 9). Most of the trunks appear to be leaning generally south (Hemish, 1998, p. 109). The basal sandstone is soft-sediment deformed (Fig. 10) and contains abundant shale rip-up clasts and plant fragments. Overlying sandstone beds range from 1 in. to 1 ft thick, show much pinch and swell, and locally exhibit large-scale crossbedding. Macerated carbonized plant debris is common; small burrows are rare. Each sandstone bed is interpreted to have been deposited by rapidly moving water during a single event, such as a flood. The abundant plant debris, some in growth position, is evidence for a nonmarine to brackish environment. Most


A
Distributary channel
Unit 8
Unit 7
Unit 6
Unit 5
Coal
Unit 4
Unit 3
Coal
Unit 2
Unit 1

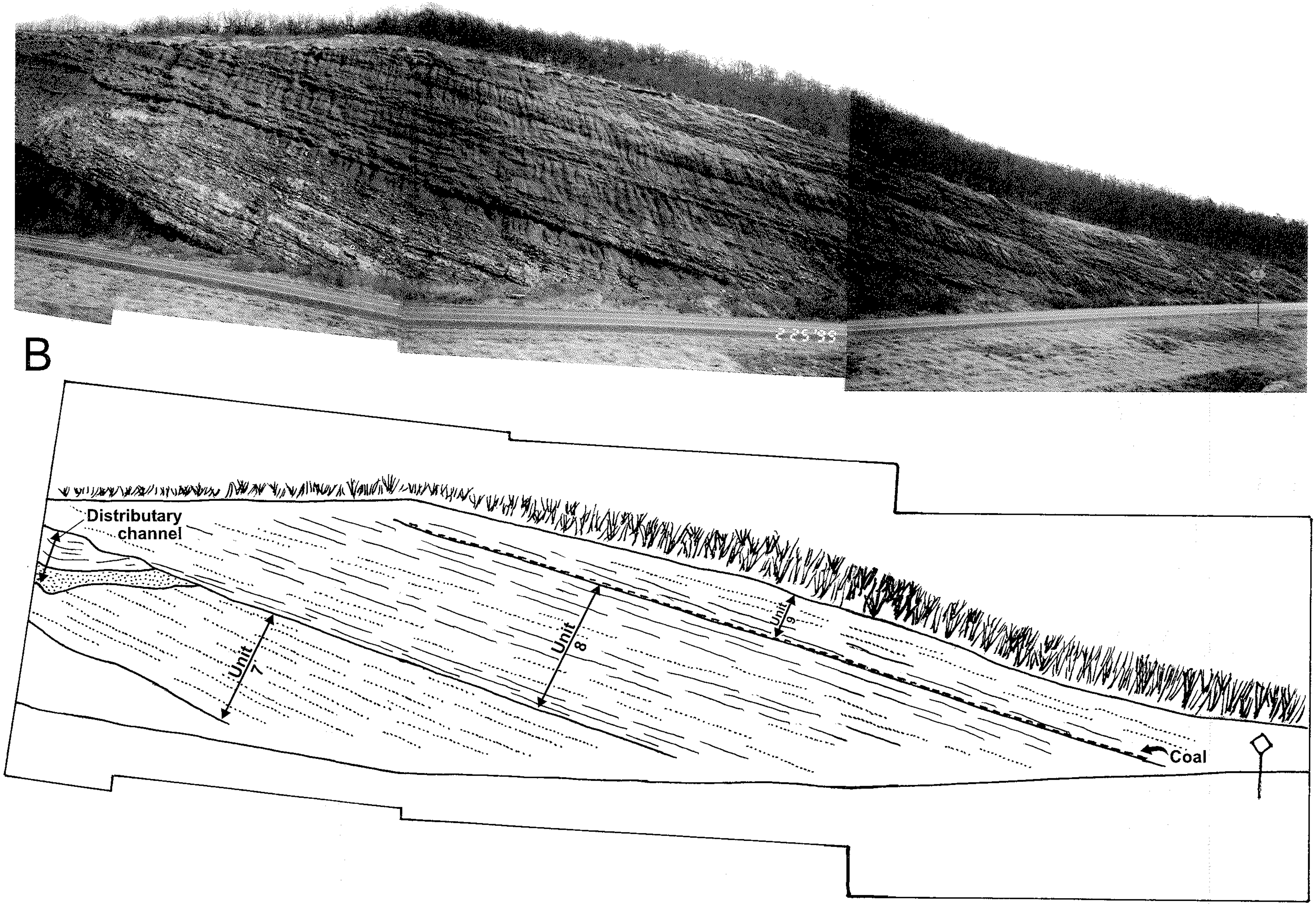


Figure 5. Photographic panorama of the Lequire road cut on the east side of Oklahoma State Highway 82 (SW¼ sec. 8, T. 7 N., R. 21 E.) and a sketch of the road cut showing the numbered units in the section. The road cut is ~900 ft long and ~60 ft high. (A, *facing page*)—North end of the road cut. (B, *above*)—South end of the road cut.

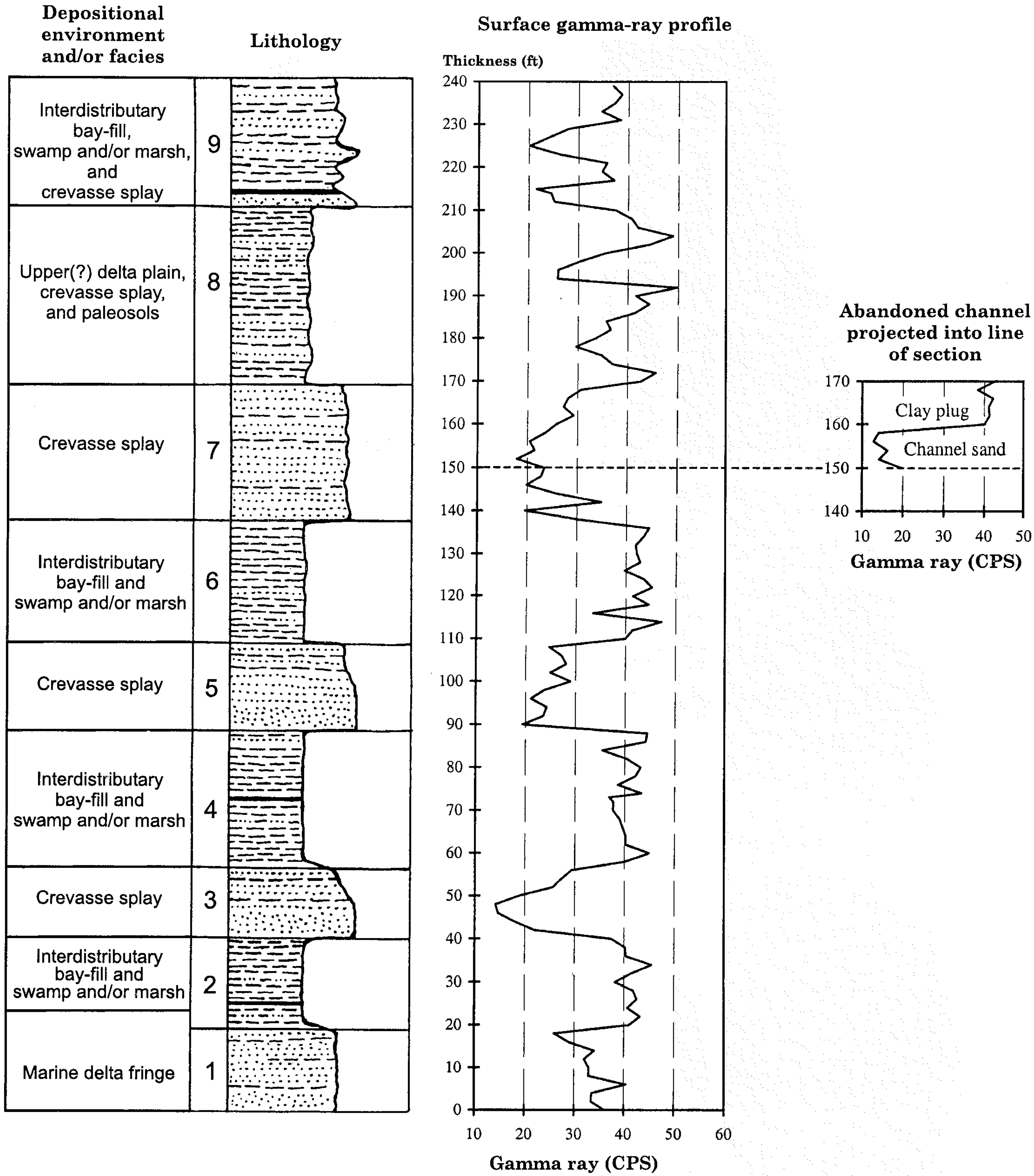


Figure 6. Graphic columnar section of the Lequire road cut showing the generalized distribution of rock types. Units are described by number (1 through 9) in the text and in the Appendix. Interpretation of the depositional environment is shown on the left, and the gamma-ray profile of the outcrop is shown on the right. Lithologic symbols: Dots—sandstone; dashes—shale; dots-dash—siltstone; heavy solid line—coal.

likely, unit 5 represents a series of crevasse-splay sandstones that were deposited during floods.

Unit 6

Shale unit 6 is similar to shale unit 4; however, plant fossils are relatively rare except for *Calamites* stems in the upper part. Siderite(?) concretions are abundant throughout the unit and a single, thin, ripple-bedded, very fine grained sandstone contains trace fossils. A thin, discontinuous coal bed is present ~12 ft from the top of the unit. Like unit 4, this shale probably was deposited mostly in an interdistributary-bay environment and more rarely in a marsh.

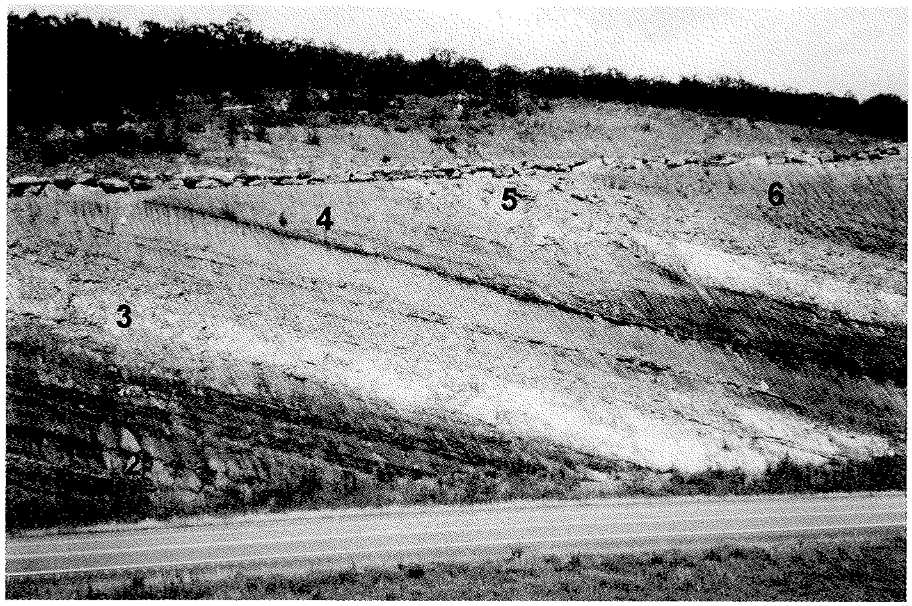


Figure 7. Photograph of sandstone unit 3 (center of photograph). The top of unit 2, weathered units 4 and 5, and the base of unit 6 also are visible. Note the thinning-upward character of the sandstone beds in unit 3. The prominent white sandstone in the lower part of unit 3 is ~9 ft thick.

Unit 7

Most of sandstone unit 7 (Fig. 11) is similar to sandstone units 3 and 5. Similarities include multiple sandstone beds that generally become thinner upward (although the trend is less pronounced in unit 7 than in those lower units); are fine-grained to very fine grained quartzose sandstone; contain soft-sediment-deformation features and cross-stratification; exhibit much pinch and swell; contain abundant upright *Calamites* (molds) in growth position and uncommon trace fossils; and are interbedded with siltstone and shale. Unit 7, however, is distinctive from the other sandstone units because it is eroded by a channel ~20 ft deep near the top of the outcrop (Fig. 11). The channel is filled with ~10 ft of very soft-sediment-deformed sandstone containing uncommon, small shale rip-up clasts, and an overlying shale and thin, continuous siltstone beds that are laminated, but not crossbedded. Like sandstone units 3 and 5, unit 7 is a series of crevasse-splay sandstones. Unlike the lower sandstone units, however, unit 7 contains a distributary channel that is partly filled with sandstone, and partly with a plug of siltstone and shale. The absence of current indicators (such as crossbedding) and the predominance of shale in the plug are evidence that the channel was abandoned prior to being filled completely.

Figure 8. Photograph of sandstone unit 5 (center of photograph). The base of the massive, basal sandstone is sharp, but undulatory. Note the thinning-upward character of the sandstone beds. Geologist for scale.

Unit 8

Shale unit 8 is heterolithic and consists mostly of shale with two sandstone-rich intervals. The shale-rich intervals at the base, middle, and top of unit 8 differ slightly from shale units 4 and 6; carbonized plant impressions are common but coaly layers and siderite(?) concretions are absent. In addition, the shales locally contain isolated soft-sediment-deformed sandstone masses as long as 4 ft. The most distinctive feature of the shales is their color—the typically dark gray shales grade irregularly to a maroon color parallel to and highly oblique to the stratification. The color, the presence of irregularly

Figure 9. Carbonized tree trunk in growth position at the base of sandstone unit 5. The fossil tree is tilted slightly to the right (south). Like this large trunk, most of the upright fossil trees (mostly *Calamites*) in unit 5 are tilted to the south. This unidirectional tilting is a paleocurrent indicator that shows the direction of flood-water movement associated with deposition of the crevasse-splay sandstones. The flood waters probably inundated a forested marsh or swamp, partially knocking the trees over. Hammer for scale.

shaped calcareous nodules in the upper shale, and what Hemish (1998, p. 114, units 1, 4, 6, and 7) identified as root casts and pedogenic slickensides, are evidence for extensive paleosol development throughout the shales of unit 8.

The sandstones in unit 8 are similar to those in units 3, 5, and 7, except that there are no thick, massive beds. Some of the sandstone beds have load casts on their bases, and several are cross-stratified and vary in thickness. Unit 8 probably was deposited in a delta-plain environment, possibly higher on the delta than the underlying units. The sediments were exposed subaerially, which suggests that they were deposited above mean high tide. However, the sandstone layers are similar to the crevasse-splay sandstones described in units 3, 5, and 7.

Unit 9

Like unit 8, sandstone unit 9 is heterolithic and consists of sandstone, shale, siltstone, and coal. Key environmental features include compressed carbonized logs as long as 7 ft and burrows in the basal sandstone; common plant fossils in siderite(?) nodules in the shale overlying the coal; and an upper, medium-bedded, sandstone-rich zone with commonly cross-stratified, soft-sediment-deformed, and highly lenticular sandstone beds. Hemish (1998) suggested that the coal may be the Rowe coal, but he was unsure. Our interpretation of the sediments of unit 9 is that they were deposited in an interdistributary-bay environment and as crevasse-splay sandstones.

Summary of Depositional Environments

In summary, the sedimentary structures, rock types, and fossils support our interpretation that the Savanna Formation exposed in the Lequire road cut was deposited mostly in a mid- to lower-delta-plain environment. The evidence for this interpretation includes the repetitive series of sandstone- and shale-dominated units believed to represent overbank crevasse-splay sandstones and interdistributary-bay shales and swamp or marsh coals, respectively. These deposits comprise the vast majority of sediments in the outcrop, and they overlie marine strata of unit 1 that are interpreted as delta-fringe deposits.

The sedimentary structures that are key to our interpretation that most of the sandstones are crevasse-splay deposits include ubiquitous soft-sediment deformation (flowage displaying convolute bedding), load casts at the base of thicker sandstone beds, abundant shale rip-up clasts, plant debris ranging from large casts to macerated carbonized hash, and engulfed *Calamites* in growth position. Evidence for shale deposition in interdistributary bays includes abundant siderite(?) concretions; common carbonized plant fossils; and the several coal beds, which probably represent marsh or swamp deposits. The bay-fill deposits of unit 8 appear to have been exposed subaerially, as evidenced by the presence of poorly developed paleosols.

Thus, we conclude that the Lequire outcrop represents a progradational sequence. Mostly marine sediments (unit 1) are overlain by deposits of mid- to lower-delta-plain origin.

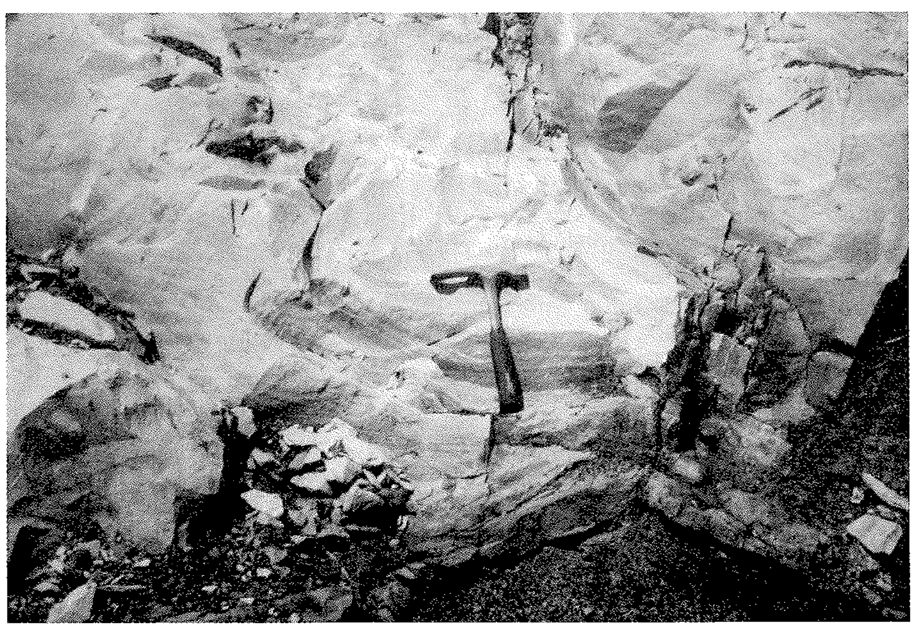


Figure 10. Convolute bedding (soft-sediment deformation) typical of crevasse-splay sandstones in unit 5. Such deformed bedding is characteristic of sand deposited rapidly during a single event. Hammer for scale.

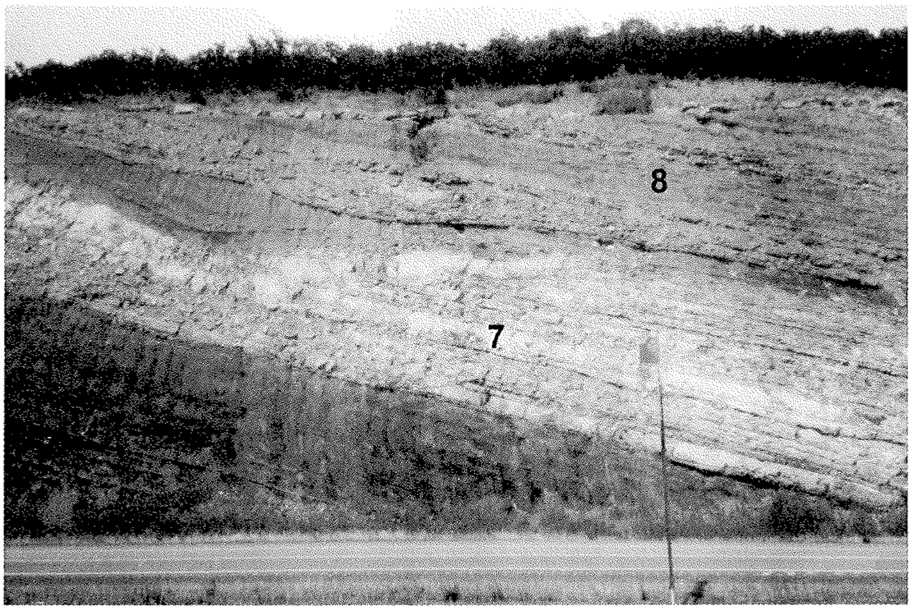


Figure 11. Photograph of sandstone unit 7, which is ~30 ft thick. In the upper left part of the photograph, a distributary channel erodes about two-thirds of the way through the sandstone sequence. Sandstone forms the base of the channel, but most of it is filled with shale. Shale unit 8 overlies unit 7 and consists mostly of dark gray and maroon-colored beds.

Correlation of Surface and Subsurface Gamma-Ray Profiles

One of the primary goals of geologists who study subsurface wireline logs is to interpret the depositional environment of the strata in a wellbore and thereby predict depositional trends and characteristics of petroleum reservoir rocks. Where cores have not been retrieved, this interpretation must be accomplished without examining any rocks. In outcrops—where rock types, sedimentary structures, contact relations between different beds, and fossils can be observed directly and studied—interpretations of depositional environments are more straightforward. By measuring the gamma-ray profile of an interpreted outcrop, a geologist can characterize a particular depositional environment. This surface log can then be used to interpret subsurface logs. However, to be useful for interpreting wireline gamma-ray logs, the surface profile should be compared to the subsurface profile of the same stratigraphic interval.

A gamma-ray profile for the entire Lequire outcrop was constructed from measured gamma-ray values. All field measurements and graphing were completed by the authors. We used a Scintrex GRS-500 gamma-ray spectrometer/scintillometer. The GRS-500 utilizes two time constants (sampling rates), 1 second and 10 second. For better statistical results, we used a 10-second time constant, measuring total gamma radiation (uranium plus thorium plus potassium) above 400 keV. Readings from an analog display were recorded in a field notebook.

The gamma-ray intensity of the outcrop strata was measured according to a set procedure. We checked the batteries to be sure they were fresh and adjusted the instrument to the proper spectral and time-constant settings. We placed the instrument against the outcrop where there were no significant overhangs or other rock protrusions that would partially surround the instrument (such as in a small gully or rock cavity) and cause the gamma-ray values to be enhanced or attenuated. Covered intervals were avoided. We took readings 2 ft apart stratigraphically and five readings per station.

To construct the surface gamma-ray profile, we entered the five gamma-ray values from each station into an MS Excel spreadsheet, where they were numerically averaged. Using a scatter plot, we graphed the average gamma-ray values (CPS), adjusting the vertical scale to fit the graphic columnar section of the Lequire outcrop (Fig. 6).

Surface gamma-ray measurements on the Lequire outcrop ranged from ~15 CPS to 50 CPS. Correlation of the gamma-ray profile with the outcrop rocks indicates that values greater than approximately 35–40 CPS represent shale-dominated intervals and values of less than ~35 CPS represent increasingly cleaner sandstones. Very clean sandstones always have values of less than 25 CPS.

The surface gamma-ray profile clearly depicts the major sandstone- and shale-dominated units and their gross textural characteristics (Fig. 6). Unit 1, interpreted as a marine, delta-fringe facies, is different from the other sandstone-dominated units; it contains more siltstone and shale, as reflected in its higher gamma-ray values. Shale units 2, 4, and 6 have similar profiles and are from similar depositional environments. The sharp bases and fining-upward characters of crevasse-splay sandstone units 3, 5, and 7 can be observed in outcrop and are evident on the profile. The heterolithic character of units 8 and 9, interpreted as bay-fill and crevasse-splay sediments, are also evident on the profile. However, evidence for subaerial exposure, observed in outcrop, is not apparent on the profile.

To determine whether the surface gamma-ray profile is similar to a typical subsurface well log, we compared the surface profile to the gamma-ray log from the Steve Gose No. 1 Madden well (SW¼NE¼ sec. 17, T. 7 N., R. 21 E.) (Fig. 12), which is located ~0.5 mi southeast of the Lequire road cut. Based on the dip of the beds and the base of the Savanna Formation as mapped by Hemish (1998), and on the position of the base of the Savanna Formation on the wireline log (1,645-ft drilled depth), the interval between ~730 ft and ~980 ft in the well corresponds to the surface outcrop.

The three clean-sandstone-dominated units can be seen on the well log (Fig. 12). The base of unit 3 is ~922 ft deep; base unit 5 is ~890 ft deep, and base unit 7 is ~840 ft deep. The wireline log profiles of the other units also are similar to those on the surface gamma-ray profile. Therefore, based on our interpretation of the Lequire road cut, the gamma-ray profile of the road cut, and our correlation of the surface

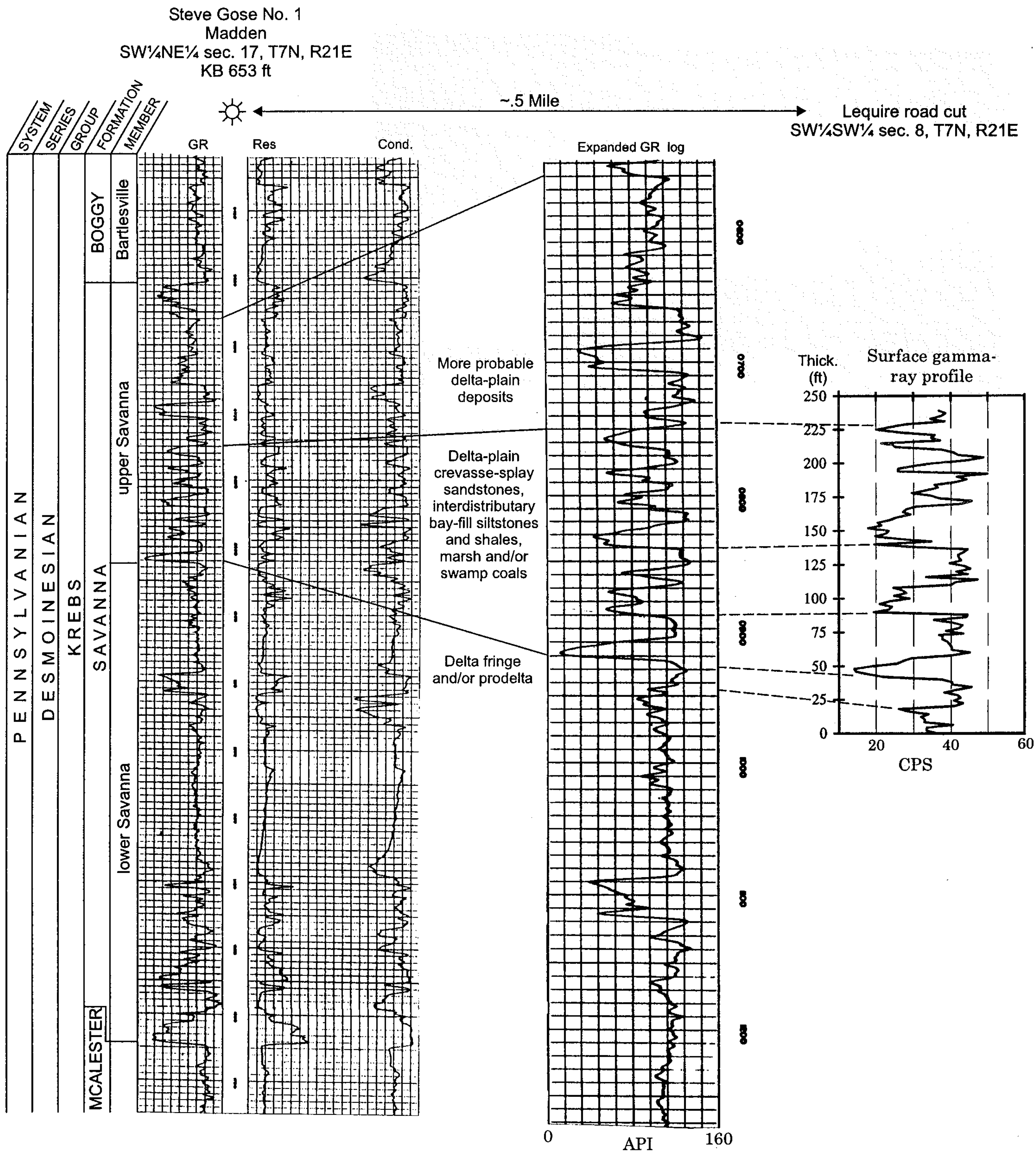


Figure 12. Part of the wireline well log from the Steve Gose No. 1 Madden well (located ~0.5 mi southeast of the Lequire road cut). The wireline gamma-ray (GR) log is expanded in the center of the figure. The surface gamma-ray profile of Lequire road cut, plotted at the same vertical scale as the expanded subsurface gamma-ray profile, is shown on the right. The log signature of the upper Savanna sandstone interval in the Gose No. 1 well correlates well with the surface gamma-ray profile of the Lequire outcrop, and the subsurface interval is interpreted as delta-plain strata. Res = resistivity; Cond. = conductivity.

gamma-ray profile with the subsurface gamma-ray log of the Gose well, we interpret the sandstone and shale interval within the Gose well to be a mid- to lower-delta-plain sequence composed of crevasse-splay sandstones, interdistributary-bay fill, and swamp and/or marsh deposits. The strata beneath the correlated interval of delta-plain deposits probably are marine (delta-fringe or prodelta) deposits and those above the interval probably are more delta-plain sediments.

CONCLUSION

By examining surface outcrops, measuring their gamma-ray profile, and correlating that profile with the gamma-ray track on wireline logs, the depositional environment of subsurface strata can be interpreted more accurately. Our study of the Lequire road cut and comparison with a nearby wireline log confirm that mid- to lower-delta-plain sediments have a distinctive log character. Interbedded fine-grained shale and siltstone (interdistributary bay-fill), coal (marshes and swamps), and coarser-grained sandstone (crevasse-splays) results in a very irregular gamma-ray profile. As recorded on the outcrop and in the Gose well, surface and subsurface logs show that the sandstone-dominated units commonly have sharp bases and, in some cases, fine upward. This character contrasts sharply with that of delta-front deposits such as those described in most of the Hartshorne Formation by Andrews and Suneson (1999).

ACKNOWLEDGMENTS

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APPENDIX — Description of Units, Lequire Road Cut

East side of Oklahoma State Highway 82, SW¼ sec. 8, T. 7 N., R. 21 E., Haskell County, Oklahoma. Rock-color terms are those shown on the rock-color chart (Rock-Color Chart Committee, 1991). Thicknesses are approximate.

Unit 1. Sandstone (very fine grained), siltstone, and silty shale, interbedded. Sandstone and siltstone, yellowish gray (5Y7/2) to light olive gray (5Y5/2); shale, olive gray (5Y 3/2). Sandstone and siltstone, very well parallel-stratified to slightly ripple-bedded; thin shale drapes on some ripple beds. Abundant siderite(?) concretions, nodules, and irregularly shaped masses in upper 6 ft. Sharp contact with unit 2. 19 ft thick.

Unit 2. Shale, minor siltstone, two coal beds (lower one ~4 in. thick and upper one discontinuous, ~1 in. thick). Shale, grayish black (N2) to olive black (5Y2/1). Shale below lower coal slightly silty, fissile; contains uncommon 1–3-in.-thick calcareous beds that may grade into muddy limestones, one with coaly laminations. Shale locally contains loose, clear, acicular crystals (gypsum?); ostracodes; and thin, coaly laminations for ~1 ft below lower coal bed. Lower coal ~4 in. thick, very laminated, also contains gypsum(?) crystals, rarely in radiating pattern. Shale above lower coal with common coaly laminations, plant compressions, abundant siderite(?) concretions as isolated nodules, concentrations of nodules parallel to bedding, and beds. Rare, thin, silica-cemented siltstone beds, medium dark gray (N4). 21 ft thick.

Unit 3. Sandstone, minor siltstone and shale. Sandstone, thick-bedded (9 ft) to thin-bedded (1 in.), fine to very fine grained, bluish white (5B9/1) to light bluish gray (5B7/1), relatively clean and quartzose, hard. Soft-sediment-deformation features, shale rip-up clasts, macerated plant debris common. Thinner beds show thickening and thinning, minor erosion of underlying beds. Base of basal sandstone slightly irregular, with underlying shale (unit 2) squeezed-up into sandstone locally. Thicknesses of sandstone beds decrease upward. Laminated siltstone and shale separate thinner sandstone beds. Upper part locally eroded by 6-ft-thick channel filled with soft-sediment-deformed sandstone. 16 ft thick.

Unit 4. Shale, minor siltstone, sandstone, and coal. Shale, medium dark gray (N4), fissile, slightly silty, locally contains siderite(?) nodules with well-preserved carbonized plant fossils. Plant compressions also present in shale. Contains conspicuous 1- to 2-in.-diameter burrows. Coaly laminations abundant immediately over coal. Locally contains irregularly shaped masses very oblique to bedding. Siltstone, medium gray (N5), occurs as thin cross-stratified beds within shale. Sandstone, in beds 3–6 in. thick ~5 ft below top of unit, very fine grained, cross-stratified, with vertical burrows (as much as 0.5 in. in diameter) extending into immediately underlying shale. Coal, near middle of unit, 6 in. thick, laminated. 32 ft thick.

Unit 5. Sandstone, minor siltstone and shale. Sandstone light gray (N7), greenish gray (5G6/1), to light bluish gray (5B 7/1), quartzose, thick- to thin-bedded; soft-sediment-deformation features, shale rip-up clasts, plant fragments (ranging from molds of branches to macerated plant hash) common. Thinner sandstone beds show thickening and thinning, local large-scale cross-stratification, burrows. Base of basal sandstone irregular, contains upright molds of carbonized trees as much as 14 in. in diameter that extend as much as 6 ft above base. Thicknesses of sandstone beds decrease upward; thicknesses of siltstone and shale beds (0.5–4 in.) increase upward. 21 ft thick.

Unit 6. Shale, minor siltstone, sandstone, and coal. Shale olive black (5Y2/1), fissile, extremely well laminated. Contains siderite(?) nodules and beds, plant fossils (leaves and *Calamites* stems) in upper part. Siltstone layers silica-cemented, hard. Single ripple-bedded, very fine grained sandstone bed with abundant carbonized macerated plant debris. Discontinuous 0.5-in.-thick coal bed ~12 ft below top. 29 ft thick.

Unit 7. Sandstone, minor siltstone and shale. Sandstone light gray (N7), very fine grained. Sandstone beds ~3 ft to 2 in. thick, stratified, cross-stratified, locally soft-sediment-deformed and/or showing much thickening and thinning. Trace fossils on tops of some sandstone beds near top of unit. Upright molds of trees in many beds. Sandstone beds generally become thinner upward. Siltstone and shale laminated. Unit locally eroded near top by channel filled with sandstone, siltstone, and shale. Sandstone in channel fine grained, light olive gray (5Y6/1) to yellowish gray (5Y7/2); soft-sediment-deformation features common, small shale rip-up clasts uncommon. In channel, siltstone and shale overlie the sandstone. Siltstone, light olive gray (5Y5/2), occurs as flaggy, parallel-laminated, very continuous beds. Shale mostly olive black (5Y2/1), locally grayish red (10R4/2) mostly parallel to bedding, though irregular in detail; slightly silty, locally contains small siderite(?) concretions. 31 ft thick.

Unit 8. Shale, minor sandstone. Shale mostly grayish black (N2) to medium dark gray (N4), locally grayish red (5R4/2) parallel to stratification and as irregular streaks and wisps; contains carbonized plant fossils; also contains irregularly shaped calcareous nodules in upper 8 ft. Sandstone dark greenish gray (5G4/1), very fine grained, quartzose, hard; occurs as 1-ft- to 1-in.-thick beds, unstratified to parallel stratified to rarely cross-stratified, and also as irregularly shaped masses as long as 4 ft entirely surrounded by shale. Upper part described by Hemish (1998, units 1–7). 41 ft thick.

Unit 9. Sandstone, minor shale, coal. Sandstone very fine grained, medium light gray (N6) to medium bluish gray (5B5/1) to light olive gray (5Y5/2), clean. Basal sandstone contains compressed carbonized tree trunks as long as 7 ft and uncommon burrows, 0.25 in. in diameter and ≤5 in. long. Sandstone beds throughout unit unstratified to laminated to cross-stratified, locally soft-sediment deformed; thinner sandstone beds lenticular, show much thickening and thinning. Shale olive black (5Y2/1) to light olive gray (5Y5/2) to yellowish gray (5Y 7/2), slightly silty, laminated; contains abundant carbonized plant debris; also occurs as drapes between sandstone beds. Coal, 10 in. thick, overlies basal sandstone. 30 ft thick.

Preliminary Survey of a Desmoinesian Flora from the Upper Savanna Formation (Pennsylvanian) of Oklahoma

Richard Lupia[1,2], Rhiannon Brinkley[3], Tiffany Naeher[2], and Roger Burkhalter[1]

ABSTRACT.—Pennsylvanian adpression floras are numerous in Oklahoma, but descriptions of these floras have not been published extensively. A flora from a new outcrop of upper Savanna Formation (Desmoinesian, Middle Pennsylvanian) near Lequire, Haskell County, is preserved primarily as impressions in ironstone (siderite) nodules. Fifteen morphotypes recovered from mudstones represent eight plant taxa (best estimate of discrete biological entities). The Lequire assemblage is similar to other published floras of comparable age and is dominated by seed ferns with subordinate lycopsids, tree ferns, and horsetails and relatives. Animal remains are rare, but linguloid brachiopods occur near the base of the section.

INTRODUCTION

During the Pennsylvanian period the North American Plate lay at the equator, and by the Middle Pennsylvanian the assembly of Pangaea and deformation leading to the Ouachitas was well under way (Arbenz, 1989a,b; Scotese, 2001). Pennsylvanian climate was governed by glaciation in southern Gondwana (Frakes and others, 1992; Gastaldo and others, 1996). Perhaps as a result of the glaciation (Ziegler and others, 1987), tropical swamps flourished along the coasts of equatorial North America. Middle Pennsylvanian clastic-swamp floras were commonly dominated by medullosan seed ferns (e.g., *Neuropteris, Alethopteris*) with subordinate tree ferns (*Pecopteris*; Gillespie and Pfefferkorn, 1979; Pfefferkorn and Thomson, 1982) and usually possessed a taxonomic composition differing from that of peat-accumulating mires (Pfefferkorn and Thomson, 1982; DiMichele and others, 1991). Throughout this time, clastic swamps and peat-accumulating mires were common in Oklahoma (e.g., Friedman, 1974, 1978; Hemish, 1984). Numerous adpression and coal-ball assemblages illustrate the diversity of these floras (Oklahoma Museum of Natural History collections, unpublished), but few publications describe Pennsylvanian macrofossil floras of Oklahoma (White, 1899; Hendricks and Read, 1934; Hendricks, 1937; Read, 1938; Knechtel, 1949; Branson, 1958; Russell, 1960, Wilson, 1963, 1973; Mamay, 1959; Mamay and Yochelson, 1962; Robison, 1978; DiMichele and others, 1991; Hemish, 1996, 1997; Krings and others, 2001). This paper describes the flora in fossil material recovered from a new outcrop of the upper Savanna Formation (Desmoinesian, Middle Pennsylvanian) in eastern Oklahoma.

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MATERIAL AND METHODS

We collected plant fossils from the outcrop (Locality OPC#2000) on the east side of Oklahoma State Highway 82, just south of Lequire in Haskell County, in W½SW¼SW¼, sec. 8, T. 7 N., R. 21 E. (Fig. 1; see also Andrews and Suneson, 2002 [this issue], fig. 1).

The outcrop exposes the upper part of the Savanna Formation (Desmoinesian series, of Middle Pennsylvanian age). The Savanna is part of the Krebs Group, one of several coal-bearing units in the Arkoma Basin (Fig. 2). It contains both marine and coastal-deltaic sediments, but paleoenvironments have not been mapped in detail. (See Hemish, 1996; and Hemish and Suneson, 1997.)

Andrews and Suneson (2002 [this issue, p. 4–18]) describe the complete 73-m section, which consists primarily of terrestrial sediments. They divide the section into nine alternating sandstone- and shale-dominated units representing mostly middle and lower delta-plain environments. Several of the units contain thin coal seams (2–25 cm thick) and coaly stringers representing peat-accumulating mires, but most of the terrestrial component appears to have been deposited in a clastic swamp.

The plant fossils are primarily impressions, occasionally containing coalified organic material on the surface of or in ironstone nodules in shale horizons. A roof-shale flora above the uppermost coal seam (unit 9) contains well-preserved compression material. Fragmentary plant remains, carbonaceous debris, and impressions and casts of arborescent lycopsids and *Calamites* occur throughout the section (units 2–9). Ironstone nodules (concretions) containing fossils were collected almost exclusively from talus at the foot of the outcrop because in situ nodules were less abundant and excavated nodules tended to show poor fossil preservation. Ironstones were rinsed under water to remove sediment, prepared as necessary, and sorted (207 specimens). A small roof-shale flora above the uppermost coal seam was collected (11 specimens) and allowed to dry.

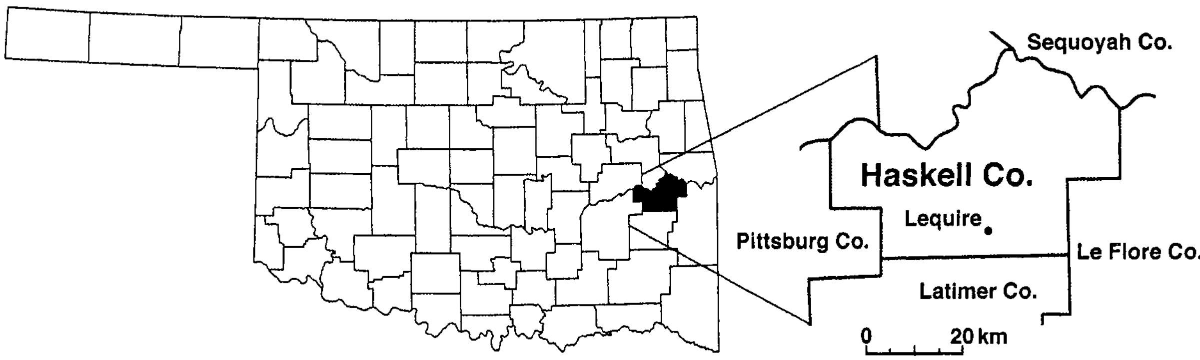

Figure 1. The town of Lequire is in Haskell County, Oklahoma. The fossil locality is about 3 km south of Lequire and on the east side of State Highway 82.

We measured the abundance of each taxon by the quadrat method of Pfefferkorn and others (1975)—in which only the first fragment of each taxon on a surface (or quadrat) is counted regardless of the number of fragments. This method increases the apparent relative abundance of rare taxa and decreases the relative abundance of common taxa (Lamboy and Lesnikowska, 1988). For this paper, we treated each side of an ironstone or shale block as a separate quadrat if the side contained at least one identifiable impression. We counted 290 quadrats.

Specimens were photographed with an Olympus C-3030 digital camera and Olympus SZX-9 dissection microscope. To increase contrast, some specimens were immersed in water before being photographed. Our taxonomy follows Kenrick and Crane (1997). All specimens are housed in the Paleobotany Collections at the Sam Noble Oklahoma Museum of Natural History, Norman (OMNH accession #P/2001/3).

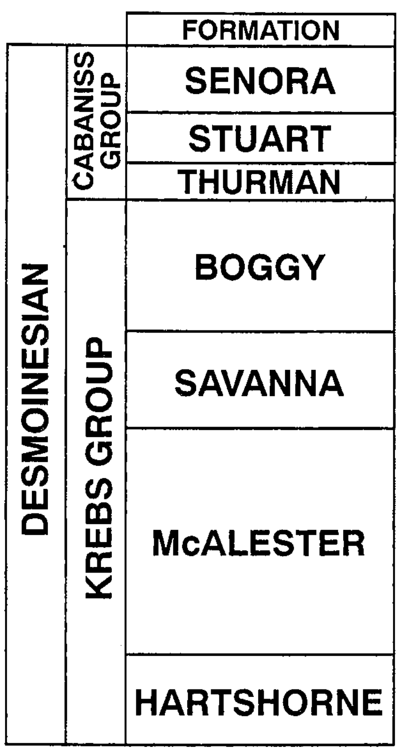

Figure 2. Generalized stratigraphic section of the coal-bearing formations of the Desmoinesian Series (Pennsylvanian) in the Arkoma basin. Modified from Hemish (1988).

TAXONOMIC INVENTORY

Class LYCOPSIDA (Scale Trees and Club Mosses)

Lycopsid leaf (Fig. 3)

The dispersed foliage of arborescent lycopsids from Lequire are narrow, 0.5–3.5 mm wide. No leaves are complete. They were attached in a spiral pattern around the trunk or branch (Fig. 4). Lycopsid leaves are common at Lequire (51 quadrats).

Decorticated *Sigillaria* trunk (not shown)

Sigillaria is an arborescent lycopsid. A single incomplete specimen, 265 mm tall and 220 mm wide, was found in situ near the top of the outcrop and excavated. Numerous impressions of upright trunks of arborescent lycopsids occur throughout the section, although attached root systems could not be found.

Stigmaria (Fig. 5)

"Stigmaria" is a name used for the subterranean axes of arborescent lycopsids. Only two fragmentary specimens were found—one is 160 mm long by 80 mm wide and the other 120 mm by 110 mm. Both possess the characteristic spiral dimple pattern. A stigmarian axis with attached rootlets, but lacking a trunk, was observed in situ, rooted in the uppermost coal seam and extending into the overlying roof-shale.

Class EQUISETOPSIDA (Horsetails and Allies)

Calamites sp. (Fig. 6)

This genus was erected for casts of stem piths of plants belonging to this order that have ribs that meet at internodes in an alternating pattern. Small, oval, infranodal canals, about 1.5 mm long by 1 mm wide, appear at the apex of the ribs. The absence of details of node/internode length and branching prevent species-level identification. *Calamites* appear on 11 quadrats in our sample, but more are found as in situ axes at Lequire.

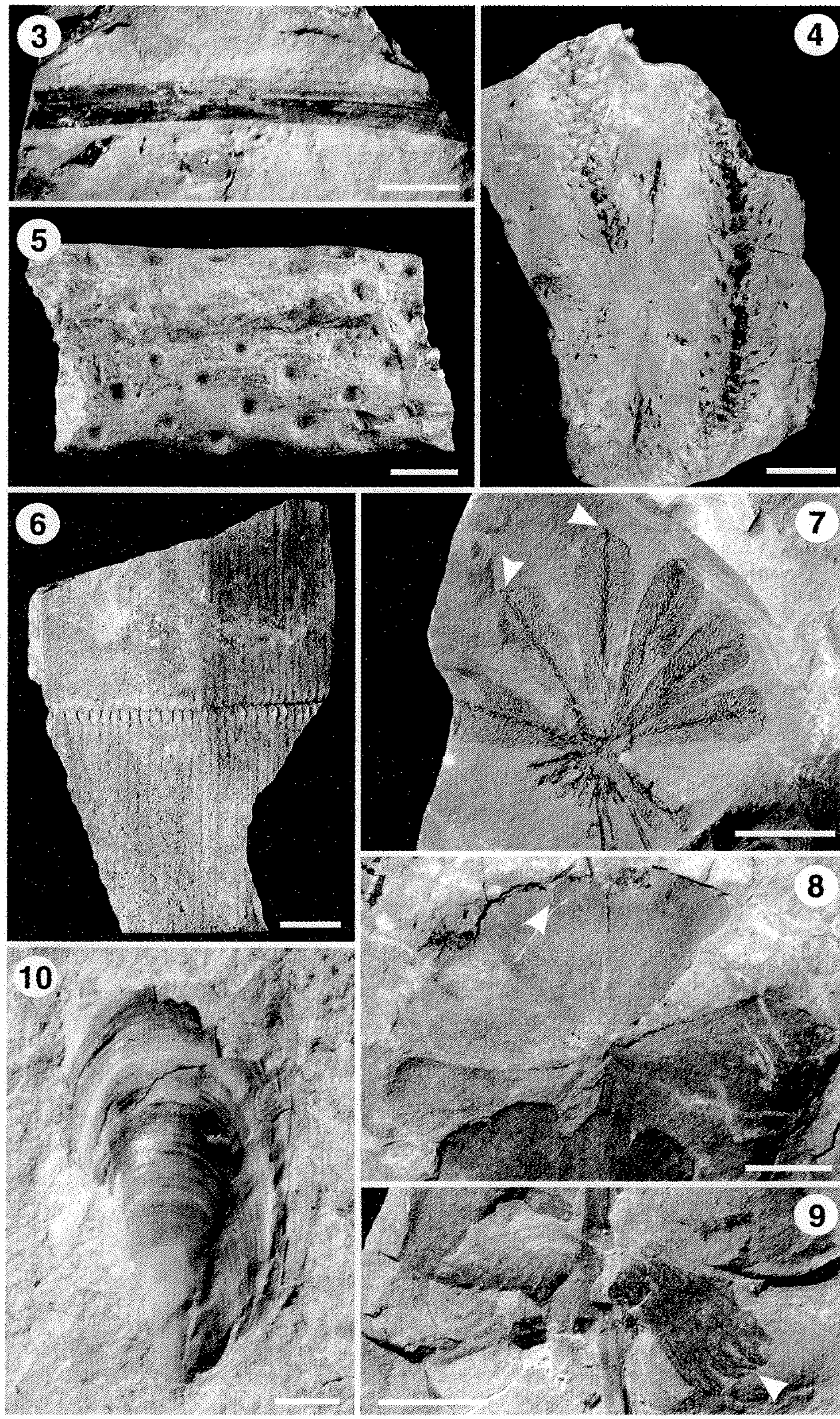

Figure 3. Lycopsid leaf. Scale bar = 5 mm. (PB00001)

Figure 4. Lycopsid foliage. Scale bar = 10 mm. (PB00002)

Figure 5. Stigmaria. Scale bar = 25 mm. (PB00003)

Figure 6. *Calamites* sp. Scale bar = 10 mm. (PB00004)

Figure 7. *Annularia sphenophylloides*. Note the apical extension (mucro) of the leaflets (arrows). Scale bar = 5 mm. (PB00005)

Figure 8. *Sphenophyllum* cf. *emarginatum*. Note the shallow division in the middle of the leaflets (arrow). Scale bar = 5 mm. (PB00006)

Figure 9. *Sphenophyllum* cf. *emarginatum*. Note the teeth at the distal margin of the leaflet (arrow). Scale bar = 2.5 mm. (PB00007)

Figure 10. Linguloid brachiopod. Scale bar = 2.5 mm. (PB00008)

Annularia sphenophylloides (Fig. 7)

Annularia is one of two form-genera for the foliage associated with *Calamites* stems. Lequire specimens possess a ribbed internode and 12–15 leaflets arranged in a whorl that bear a mucro (an apical extension; Fig. 7, arrows). The leaflets are 5–11 mm long and 1.5–3.5 mm wide with a single medial vein. This taxon is rare at Lequire (9 quadrats).

Sphenophyllum cf. *emarginatum* (Figs. 8, 9)

Although relationships are uncertain, *Sphenophyllum* is usually allied with Equisetopsida even if not belonging to the clade (Kenrick and Crane, 1997). Most Lequire leaflets belonging to *Sphenophyllum* are characterized by 6 or more leaflets per whorl; the leaflets are 3.5–5 mm long and 3.5–5 mm wide. Venation is open dichotomous. Most specimens assigned to *S.* cf. *emarginatum* do not have distinct teeth on the distal margin but most are shallowly incised and form two lobes (Fig. 8, arrow). One specimen consists of an axis bearing *Sphenophyllum* leaflets (the largest partial leaflet is 9 mm long and 4 mm wide) with distinct teeth on the distal margin of the leaflet (Fig. 9, arrow). Internodes of this specimen are 11–13 mm long and 1–2 mm wide. In view of the variation in leaflet morphology within *Sphenophyllum* species (W. A. DiMichele, personal communication, 2001), both forms are considered a single species. Isolated leaflets of *S.* cf. *emarginatum* are common at Lequire (25 quadrats).

Class FILICOPSIDA (Ferns)

Lobatopteris aff. *vestita* (Figs. 11–13)

Lobatopteris pinnules are the foliage of tree ferns related to extant maratiallean trees ferns and are common at this locality (39 quadrats). *Lobatopteris* pinnules at Lequire occur in two distinct forms that intergrade in several specimens suggesting polymorphism (e.g., within a single frond) rather than distinct species. At one extreme, pinnules are characterized by undulating lateral margins and somewhat constricted bases (Fig. 11); at the other, pinnules are widely spaced and alternate, with smooth, entire margins (Figs. 12, 13). Veins of both morphologies divide once immediately after departing the midvein and again about a quarter of the way to the margin. Distalmost veins of each pinnule are unbranched. Pinnules are 7–9 mm long by 1.5–4 mm wide.

Sphenopteris? sp. (Fig. 14)

Although *Sphenopteris* pinnules are usually included with seed plants, this foliage type is also associated with ferns (Gillespie and others, 1978). The pinnules are alternate, lobed, and 5.5–6 mm long and 3–4 mm wide, with a decurrent midvein. The two specimens we recovered might be terminal pieces of *Lobatopteris* fronds.

Cohort SPERMATOPHYTATA (Seed Plants)

Pteridosperm? rachis (Fig. 15)

Pteridosperms are a mixed group of seed plants bearing foliage that resembles fern pinnules. Without attached seeds, it is often difficult to separate fern from pteridosperm foliage. Two of the most frequently encountered genera are *Neuropteris sensu lato* and *Alethopteris*—medullosan pteridosperms. Fragmentary, coalified rachii, probably derived from pteridosperms, and without attached pinnules, are common (39 quadrats).

Macroneuropteris scheuchzeri (Figs. 18, 19)

Macroneuropteris scheuchzeri is characterized by long, slightly curved pinnules, 11–65 mm long and 6–18 mm wide, with a midvein that reaches nearly to the tip (Fig. 18). A distinguishing feature of this taxon is impressions of tiny hairs on the lower surface of the pinnules. Pinnules subtended by cyclopterid pinnules (Fig. 19) characterize *M. scheuchzeri*, but in this assemblage are rarely preserved. We did find numerous specimens of pinnules without evident hairs but otherwise indistinguishable from *M. scheuchzeri*. Assuming that all these specimens belong to *M. scheuchzeri*, this is the most abundant species at Lequire—found on 166 of the 290 quadrats counted.

Other neuropterid pinnules (Figs. 20, 21)

Cyclopterid pinnules are nearly round pinnules and lack a distinct midvein (Fig. 20). These pinnules are attached to branches and stems of medullosan seed ferns assigned to several genera of pteridosperms, and are known to be associated with both *M. scheuchzeri* and *Laveineopteris rarinervis* (Gillespie and others, 1978). Cyclopterids at Lequire are rare (8 quadrats). Terminal pinnules of *Macroneuropteris scheuchzeri* are often odontopterid. We found only one specimen, 28 mm long and 10 mm wide, with pinnules 6–11 mm long and 2–3 mm wide; it is believed to be *M. scheuchzeri* (Fig. 21).

Laveineopteris cf. *rarinervis* (Figs. 22, 23)

This taxon is characterized by very small pinnules, 4.0–7.0 mm long and 2.5–4.0 mm wide. Most pinnules show a cordate base, but terminal pinnules may be attached along their entire base. Venation is simple, most veins dichotomizing once. This morphotype is rare (15 specimens).

Alethopteris cf. *serlii* (Fig. 24)

Alethopteris is another medullosan seed fern, characterized by strongly decurrent midveins and confluent pinnule bases. The most complete pinnule is 10 mm long and 5 mm wide; most veins fork once, some are unbranched, and a few fork twice. We recovered only one specimen.

Neuropteris cf. *obliqua* (Fig. 25)

Pinnules of this taxon are 9–15 mm long and 5–8 mm wide with slightly decurrent midveins that are visible for about three-fourths of the pinnule length. Veins depart the midvein at an acute angle and dichotomize two or—usually—three times before reaching the margin. Although similar to *Macroneuropteris scheuchzeri*, the marginal venation of *N.* cf. *obliqua* is less dense and no hairs or attached cyclopterid leaflets were observed. This morphotype is rare (8 quadrats).

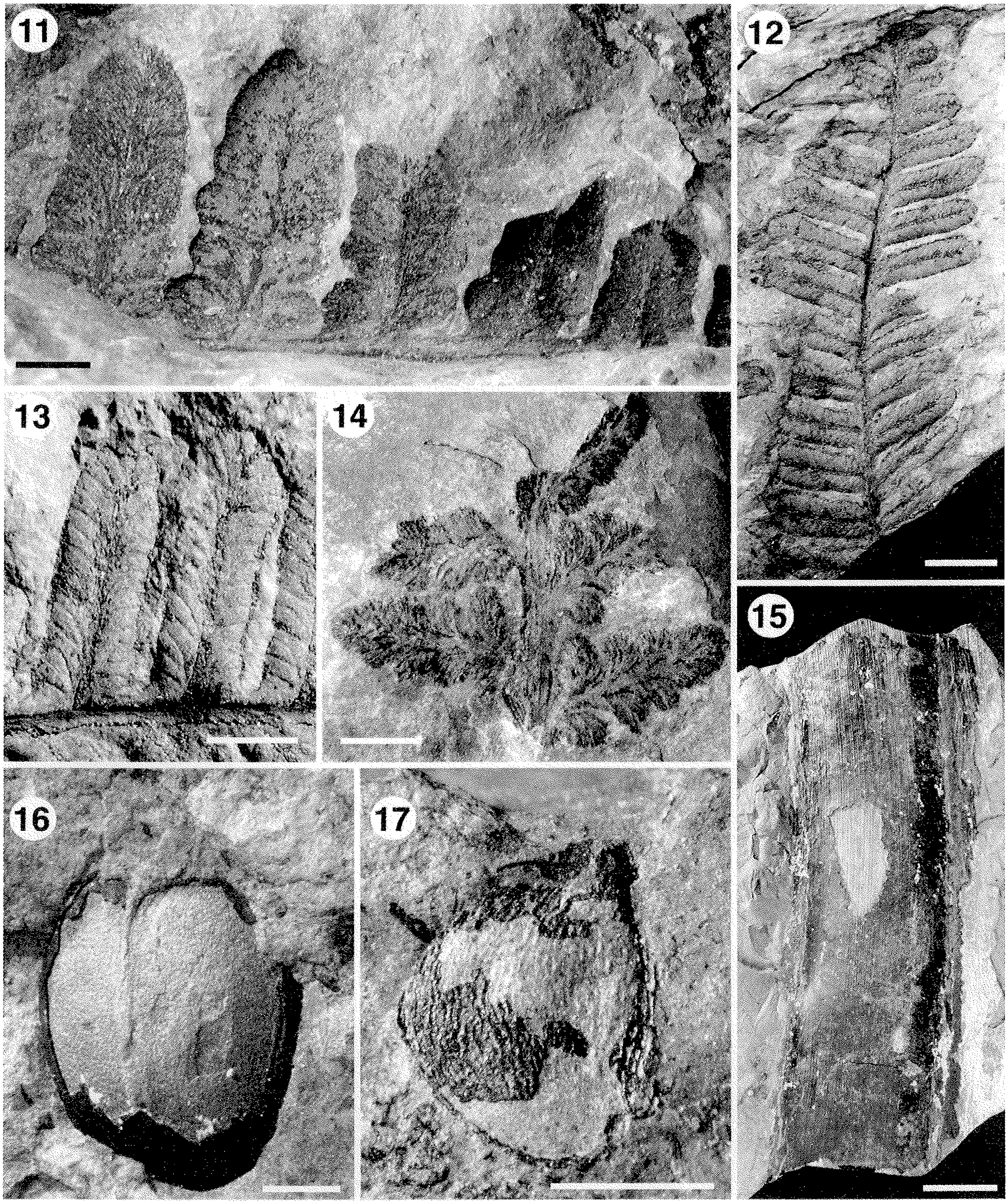

Figure 11. *Lobatopteris* aff. *vestita*. Scale bar = 2.5 mm. (PB00009)

Figure 12. *Lobatopteris* aff. *vestita*. Scale bar = 5 mm. (PB00010)

Figure 13. *Lobatopteris* aff. *vestita*. (Closeup of Fig. 12.) Scale bar = 2.5 mm. (PB00011)

Figure 14. *Sphenopteris*? sp. Scale bar = 2.5 mm. (PB00012)

Figure 15. Pteridosperm? rachis. Scale bar = 10 mm. (PB00013)

Figure 16. Seed type A. Scale bar = 1 mm. (PB00014)

Figure 17. Sporangium type A. Scale bar = 1 mm. (PB00015)

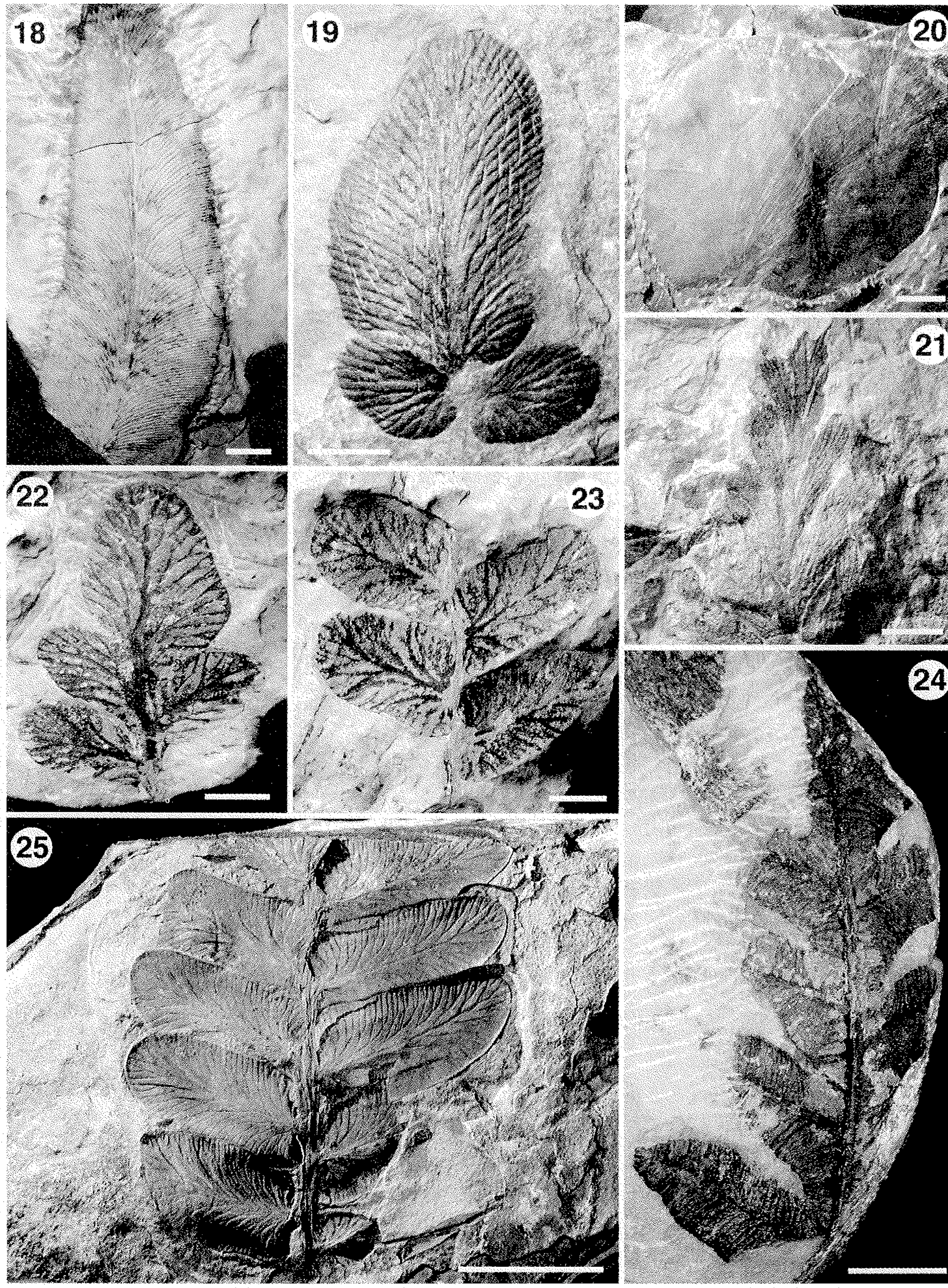

Figure 18. *Macroneuropteris scheuchzeri*. Scale bar = 5 mm. (PB00016)

Figure 19. *Macroneuropteris scheuchzeri*. A pinnule is associated with two apparently subtending cyclopterid pinnules. Note the impressions of numerous hairs. Scale bar = 5 mm. (PB00017)

Figure 20. Cyclopterid pinnule. Scale bar = 5 mm. (PB00018)

Figure 21. Odontopterid pinnules. Scale bar = 5 mm. (PB00019)

Figure 22. *Laveineopteris* cf. *rarinervis*. Terminal pinnule. Scale bar = 2.5 mm. (PB00020)

Figure 23. *Laveineopteris* cf. *rarinervis*. Scale bar = 2.5 mm. (PB00021)

Figure 24. *Alethopteris* cf. *serlii*. Scale bar = 5 mm. (PB00022)

Figure 25. *Neuropteris* cf. *obliqua*. Scale bar = 10 mm. (PB00023)

Seed type A (Fig. 16)

We recovered only one specimen, 5 mm long and 3.5 mm wide, of this morphotype. The outer testa is very finely striate. In overall morphology, this form resembles trigonocarpalean seeds.

Sporangium type A (Fig. 17)

This taxon, probably from a fern, is recognized by undulate ridges on the thin outer epidermis. Its size is 2–3 mm long and 1.5–2 mm wide. The morphotype is rare (6 quadrats).

ANIMALS

Only one type of animal fossil was encountered at the Lequire locality. Near the base of the outcrop is a limestone bed; in talus below this bed, we found a limestone block containing 21 complete or incomplete linguloid brachiopods with original shell material (chitinophosphate; Rudwick, 1970). The brachiopods (Fig. 10) are 5.5–8.0 mm long and 3.0–4.0 mm wide.

DISCUSSION

Fifteen form taxa of plants are represented in our collection. Collapsing probable form taxa of the same biological species yields eight distinct taxa that characterize most of the preserved assemblage. The species composition resembles other fossil assemblages of the same age (i.e., Desmoinesian; DiMichele and others, 1991). Dominance of seed ferns is consistent with vegetational structure of clastic swamps before the late Desmoinesian (e.g., Pfefferkorn and Thomson, 1982; Pryor and Gastaldo, 2000). The abundance of lycopsid foliage, matched in part by the number of in situ lycopsid stumps or subterranean axes, differs from another Desmoinesian (albeit younger) clastic flora in Oklahoma (Secor flora; DiMichele and others, 1991). However, this compositional difference probably reflects different depositional systems. The great abundance of lycopsids, which grew in standing water, and the dominance of *Macroneuropteris scheuchzeri*, which also tolerated high water (DiMichele and others, 1985), might indicate parautochthonous deposition—deposition without significant transport—within a clastic swamp. In contrast, the Secor flora is interpreted as plants buried by a crevasse splay (or other catastrophic flooding event) and thus were transported for some distance (DiMichele and others, 1991). The intermittent occurrence of *Calamites* stems in the Lequire section, despite the rarity of its foliage (i.e., *Annularia*), is consistent with intermittent disturbance of the swamp by channel breach (e.g., crevasse-splay deposits; Gastaldo, 1987; DiMichele and Hook and others, 1992).

The taxa recovered from this outcrop in the Savanna Formation are consistent with its assignment to the Desmoinesian Series, Westphalian D equivalent, when compared to megafloral studies in other North American coal basins (Wagner, 1984; Wagner and Lyons, 1997). However, more work is needed to refine its stratigraphic position. In particular, the recovery of *Lobatopteris vestita* (very tentative until more specimens, better preserved, can be studied) from the Savanna Formation seems relevant because it gives its name to the *Lobatopteris vestita* Zone, equivalent to the middle to upper Desmoinesian (Wagner, 1984; Cleal, 1997; Wagner and Lyons, 1997).

SUMMARY

A preliminary flora from a new exposure of the Savanna Formation (Middle Pennsylvanian) includes 15 fossil taxa, probably representing eight biological species. The flora is dominated in diversity and abundance by medullosan seed ferns, with subordinate lycopsids. Much work on the Lequire flora, and on Pennsylvanian floras in general, remains to be done in Oklahoma. Future work should focus on integrating plant fossil occurrences into a sequence stratigraphic framework (Gastaldo and others, 1993; Pfefferkorn and others, 2000) to test hypotheses and to increase our understanding of the biological diversity, biogeography, and paleoecology of Pennsylvanian vegetation.

ACKNOWLEDGMENTS

We thank Neil H. Suneson for encouraging us to investigate this locality and for reading a draft of this manuscript. We also thank William A. DiMichele and Robert A. Gastaldo for critical reviews that greatly improved the text of this report, our identifications (including *L.* aff. *vestita*, suggested by DiMichele), and our interpretations.

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Inventory and Water Quality of Springs of Ellis County, Oklahoma

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INTRODUCTION

From 1992 through 1993, the U.S. Geological Survey, in cooperation with the Oklahoma Geological Survey, made an inventory of springs in Ellis County, Oklahoma. It was part of a 4-year Statewide project begun in 1983, suspended in 1986, and reactivated in 1990. The Ellis County work is reported here.

Purpose and Scope

The objective of the project is a Statewide inventory of springs including water-quality analyses and discharge measurements. Water-quality parameters analyzed include major ions and nutrients; temperature, pH, alkalinity, and specific conductance were determined in the field.

Ellis County, the area examined here, lies in western Oklahoma at the Texas state line, north of the Canadian River, and just southeast of the Oklahoma Panhandle; see Figure 1 and also the discussion of physiography and land use below.

This report presents water-quality tables, a table of discharge measurements and water use, a table of current land-use, and bar charts showing monthly precipitation for 1992 through 1993 and a 30-year running average. A map shows the geology, streams, springs, roads, and towns.

Acknowledgments

Cooperation of the landowners on whose property these springs are located is greatly appreciated; without their help this survey could not have been made. Land-use information was provided by the Soil Conservation Service, of the U.S. Department of Agriculture. The Oklahoma Climatological Survey contributed climatic information, and Scott Christenson of the U.S. Geological Survey provided information and help with water-quality interpretation.

Methods of Study

A list of legal descriptions was compiled from a survey of wells and springs made in the 1930s by the Works Projects Administration. Then field crews for the U.S. Geological Survey obtained from the county treasurer's office the names and addresses of current landowners. Next, letters asking permission to measure and sample the springs were sent to many of the landowners; others were contacted by telephone or in person. Field crews were given locations of other springs by landowners and local residents. The crews observed the areas around springs for land and water use, took photographs when possible, measured discharge, collected water samples, and measured field parameters. Specific conductance, pH, and temperature were measured with portable meters. Alkalinity was determined by incremental titration of filtered samples. Water-quality samples were collected with churn samplers or sample bottles (depending on size of the spring), and analyzed by the Oklahoma Geological Survey.

The Local Identifier

Spring locations are specified by latitude and longitude to the nearest second and by a local identifier based on the Oklahoma public-land survey grid. The local identifier con-

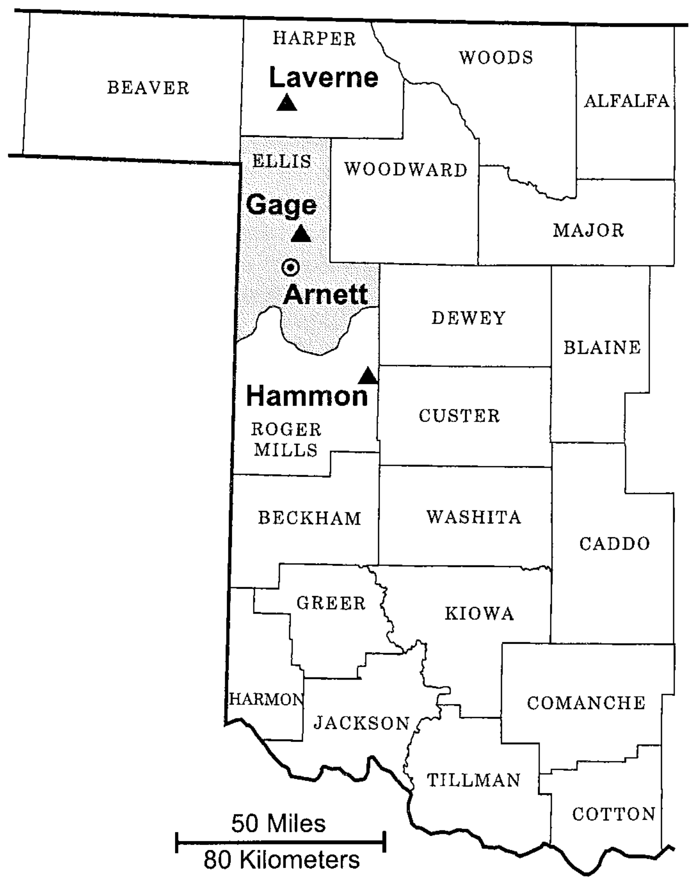

Figure 1. Ellis County is located in northwestern Oklahoma. The towns of Laverne, Gage, and Hammon contain weather stations (▲); Arnett is the county seat.

sists of township and range followed by the section number and a series of letters designating quarter-section subdivisions from largest to smallest. Then a sequence number is added to make the local identifier unique, as shown in Figure 2. An arbitrary number is assigned to each spring, in numerical order of latitude and longitude.

For example: spring 1 is identified as 355234099425201—which is to say lat 35°52′34″N, long 99°42′52″W, sequence number 1. (A zero separates latitude and longitude, and another sets off the sequence number.)

Spring 1 is further identified as 16N–24W–11–ACD, which expands to Township 16 North, Range 24 West, and in Section 11 the spring is found in the southwest quarter (D) of the southwest quarter (C) of the northeast quarter (A).

PHYSIOGRAPHY

Ellis County lies in the Osage Plains section of the Central Lowland physiographic province (Havens and Christenson, 1983, p. 6). The altitude above sea level is 2,100 ft in the north, 2,400 ft at center, and 2,000 ft near the Canadian River in the south. The Osage Plains are generally flat and featureless, but in Ellis County canyons have been cut by streams leading to the Canadian River in the south and to Wolf Creek, which flows northeasterly across the center of the county.

LAND USE

Ellis County is L-shaped, bounded on the north by Harper County, on the east by Woodward and Dewey Counties, on the south by Roger Mills County (across the Canadian River), and on the west by the state of Texas. This county is predominantly rural, with 563,833 acres of rangeland, 208,355 acres of cropland, and 5,327 acres of pastureland (Charles Cail, U.S. Department of Agriculture, Consolidated Farm Service Agency, personal communication, 1993; see also Table 1). The northern part of the county is mostly open grassland with nonirrigated cropland and some low- and high-density

TABLE 1. — LAND USE IN ELLIS COUNTY

Category	Name	Acres
1	Cropland	189,377.44
2	Cropland — irrigated	18,977.28
4	Rangeland — open grassland	173,128.14
5	Rangeland — sagebrush and sand, low density — canopy <20%	70,285.13
6	Rangeland — sagebrush and sand, high density — canopy >20%	200,210.30
7	Rangeland — shinnery oak, low density — canopy <15%	10,081.68
8	Rangeland — shinnery oak, high density — canopy >15%	98,780.70
11	Rangeland — juniper or Eastern red cedar, low density <100 plants per acre	2,164.60
12	Rangeland — juniper or Eastern red cedar, high density >100 plants per acre	2,441.35
16	Rangeland — cottonwood, elm, hackberry, willow, high density — canopy >20%	6,622.28
24	Rangeland — yucca or cactus — high density >100 plants per acre	118.61
25	Pastureland	4,082.09
27	Pastureland — irrigated	1,245.38
45	Farmsteads — area >5 acres	158.14
51	Quarries and gravel pits — area >5 acres	39.54
57	Cemetery (rural)	9.88
96	Water and bare sand channel	8,500.24
97	Urban and built-up land	1,897.73
98	Water	474.43
	Total	788,594.94

Source of data: U.S. Department of Agriculture, Soil Conservation Service, Consolidated Farm Service Agency.

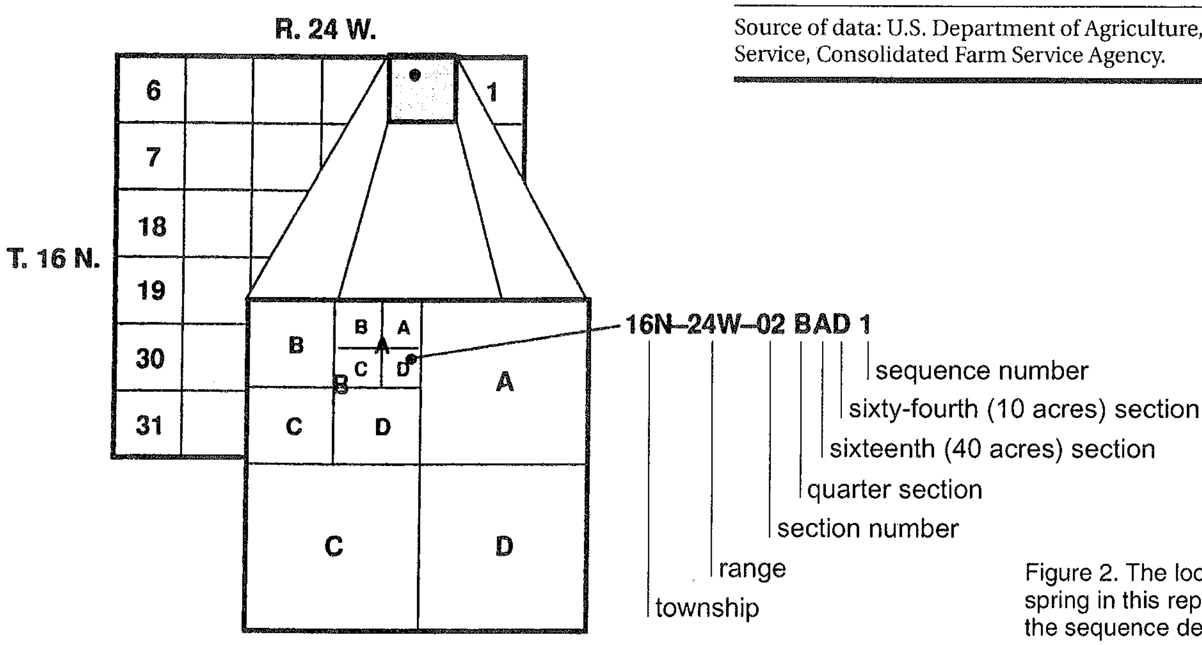

Figure 2. The local identifier for each spring in this report is determined by the sequence depicted here.

rangeland of sagebrush and sand. The southern part is mostly nonirrigated cropland with some open grassland and irrigated cropland. The southeastern part of the county is mostly low-density rangeland with shinnery oak, some open grassland, and a few acres of cropland. The county population, according to the 1990 census, totals 4,497; Arnett, the county seat, has a population of 547 (1990 census); other towns are Fargo—population 299, Gage—473, and Shattuck—1,454 (Oklahoma State Department of Commerce, Oklahoma City, personal communication, 1993).

HISTORICAL NOTES

Springs have contributed financial and historical worth to nearby communities. Presence of a spring has been considered a promise of good fortune; the lack of a spring, or lessened flow, could reverse fortune. In Ellis County, two springs (7 and 8 in Table 2) on the site of the old Grand settlement have affected local history. Grand, now a ghost town, was established in 1892 when the Cheyenne Arapaho Reservation was opened for settlement. Grand became the county seat in 1893 after the courthouse in Ioland burned (Ioland was about 10 mi south of Harmon), but another reason for the change was the exceedingly bad quality of Ioland's water (Morris, 1978, p. 94–95). Grand, in a grove near a spring then called Robinson Springs, was reported to have good water. But Grand was so far from the center of the county that the people voted to move the county seat to Arnett in 1908. The move left Grand almost deserted; today a dirt road leads to the site of the old settlement, and only a grove and remnants of an old bank vault mark the town site (Morris, 1978, p. 94–95).

CLIMATE

Cool winters and hot summers dominate the climate. The average annual temperature is about 57° Fahrenheit. Daily maximum temperatures average 47°F in January and 95°F in July; daily minimum temperatures average 19°F in January and 68°F in July. The average annual precipitation is about 22 in. Precipitation increases slightly from west to east across the county. Precipitation is at a maximum in the spring and at a minimum in winter, with the next highest rainfall in late summer. The average monthly precipitation ranges from ~3.5 in. in May to ~0.4 in. in January. About 70% of the average annual precipitation falls during the warm season (April through September). Snow falls on about 7 days a year, with an average annual accumulation of ~12 in. (Howard Johnson, Oklahoma Climatological Survey, personal communication, 1993). Monthly precipitation for the inventory period, 1992 and 1993, at Laverne, Gage, and Hammon is graphed in Figures 3, 4, and 5. Those sites were chosen to illustrate the trend of increasing precipitation from west to east (Fig. 1).

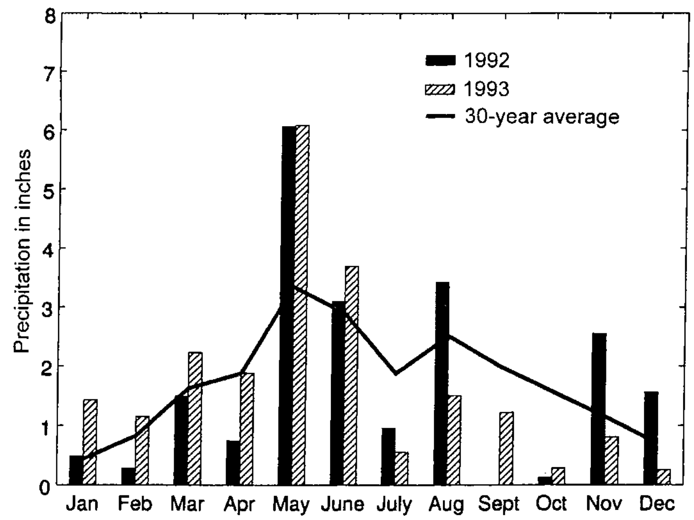

Figure 4. Precipitation in 1992 and 1993, at Gage, Ellis County. (National Oceanic and Atmospheric Administration, Climatological Data, Oklahoma.)

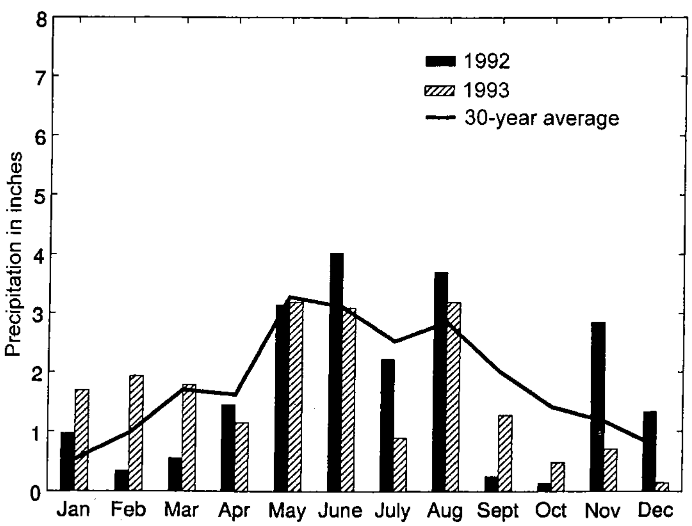

Figure 3. Precipitation in 1992 and 1993, at Laverne, Harper County. (National Oceanic and Atmospheric Administration, Climatological Data, Oklahoma.)

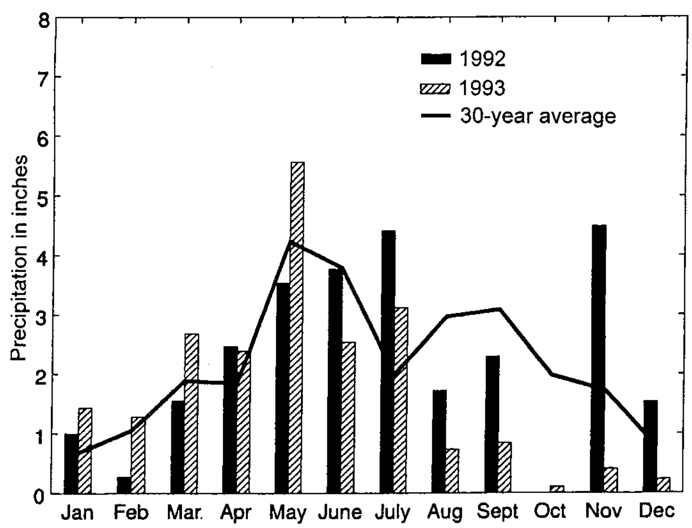

Figure 5. Precipitation in 1992 and 1993, at Hammon, Roger Mills County. (National Oceanic and Atmospheric Administration, Climatological Data, Oklahoma.)

TABLE 2. — LOCATION, DISCHARGE, AND WATER USE OF ELLIS COUNTY SPRINGS

Spring no.	Site identifier	Local identifier	Spring name	Date discharge measured	Discharge (gal/min)	Water use
1	355234099425201	16N–24W–11 ACD 1	Okla. Wildlife Spring 3	08-14-92	0.07	Livestock and wildlife
2	355337099431301	16N–24W–02 BDB 1	Okla. Wildlife Spring 2	08-14-92	28.0	Livestock
3	355340099430801	16N–24W–02 BAD 1	Okla. Wildlife Spring 1	08-14-92	27.6	Household and livestock
4	355404099435301	17N–24W–35 CAC 1	West Creek Spring 3	07-30-92	1	Livestock and wildlife
5	355411099435001	17N–24W–35 CAB 1	West Creek Spring 2	07-30-92	1	Livestock and wildlife
6	355419099435001	17N–24W–35 BDC 1	West Creek Spring 1	07-30-92	7.5	Livestock and wildlife
7	355847099473601	17N–24W–06 ADA 1	Grand Spring 1	07-30-92	31.9	Household and fishing; site of old Grand settlement
8	355848099474101	17N–24W–06 ADB 1	Grand Spring 2	07-30-92	45.4	Household and fishing; site of old Grand settlement
9	355903099470201	18N–24W–32 CDD 1	Johnson Spring 3	08-13-92	20.9	Livestock and wildlife
10	355906099364601	18N–23W–36 CCC 1	Davison Ranch Spring 2	08-21-92	1.08	Livestock and wildlife
11	355917099363601	18N–23W–36 CBD 1	Davison Ranch Spring 1	08-21-92	2.36	Livestock and wildlife
12	355947099531201	18N–26W–32 ADA 1	Jenkins Springs	07-27-93	123	Livestock
13	355958099462701	18N–24W–29 DDD 2	Johnson Spring 2	08-13-92	0.09	Livestock and wildlife
14	355958099462801	18N–24W–29 DDD 1	Johnson Spring 1	08-13-92	1.33	Livestock and wildlife
15	360051099500601	18N–25W–23 CDD 1	Parker Spring	NA	NA	Irrigation
16	360056099305401	18N–22W–23 DCC 1	Gillispie Spring 1	09-23-92	19.2	Livestock and wildlife
17	360059099570001	18N–26W–23 CCA 1	Flock Springs	07-27-93	10	Livestock and wildlife
18	360107099475401	18N–24W–19 DBC 1	Word Springs	07-22-93	35	Household and livestock
19	360119099551601	18N–26W–24 ACD 1	Henderson Springs 4	08-04-93	25	Livestock and wildlife
20	360123099462101	18N–24W–21 BCB 1	Peck Spring 1	09-11-92	18.4	Livestock and wildlife
21	360132099551101	18N–26W–24 AAC 1	Henderson Spring 1	08-04-93	5	Livestock and wildlife
22	360134099550401	18N–26W–24 AAD 1	Henderson Spring 2	08-04-93	20	Livestock and wildlife
23	360144099545901	18N–26W–13 DDA 1	Henderson Spring 3	07-27-93	5	Livestock
24	360156099561901	18N–26W–14 DBD 1	Trails End Farm Spring	08-04-93	0.10	Livestock and wildlife
25	360202099513301	18N–25W–15 CBA 1	Richards Spring	07-20-93	0.25	Livestock
26	360222099304701	18N–22W–14 ABC 1	Harris Spring 3	08-28-92	12.9	Livestock and wildlife
27	360222099523201	18N–25W–16 BAC 1	Wayland Spring 1	07-20-93	0.10	Livestock
28	360226099524901	18N–25W–16 BBB 1	Wayland Springs 2	07-20-93	1	Livestock
29	360240099540601	18N–25W–07 DDB 1	Peck Spring 2	09-11-92	21.1	Livestock and wildlife
30	360245099480701	18N–24W–07 CDA 1	Elmer Knowles Spring	07-22-93	50	Livestock and wildlife
31	360251099295301	18N–22W–12 CAD 1	Harris Spring 2	08-28-92	9.35	Livestock and wildlife
32	360254099513301	18N–25W–10 CBA 1	Marvel Spring	08-04-93	0.29	Livestock
33	360300099442701	18N–24W–08 BCC 1	McCorkle Springs	07-22-93	210	Livestock and wildlife
34	360321099374301	18N–23W–11 BBA 1	Wagnon Spring 1	09-18-92	6.73	Livestock
35	360321099374501	18N–23W–11 BBB 1	Wagnon Spring 2	09-18-92	4.49	Livestock
36	360323099381101	18N–23W–10 ABA 1	Cadwell Spring 3	09-18-92	22.7	Livestock
37	360333099383501	18N–23W–03 CDB 1	Cadwell Spring 2	09-18-92	0.10	Livestock
38	360336099303701	18N–22W–02 DDB 1	Hutchison Spring 2	08-26-92	4.71	Livestock and wildlife
39	360336099305001	18N–22W–02 DCB 1	Hutchison Spring 1	08-26-92	3.27	Livestock and wildlife
40	360342099300701	18N–22W–01 CBD 1	Berry Spring 1	09-01-92	27.3	Livestock and wildlife
41	360343099465601	18N–24W–05 DBC 1	Davis Spring	07-22-93	50	Livestock and wildlife
42	360349099384101	18N–23W–03 CAB 1	Cadwell Spring 1	09-18-92	0.17	Livestock
43	360355099305901	18N–22W–02 BDD 1	Harris Spring 1	09-01-92	15.3	Livestock and wildlife
44	360433099273801	19N–21W–32 DCB 1	Baker Spring 4	09-23-92	240	Livestock and wildlife
45	360441099273701	19N–21W–32 DBB 1	Baker Spring 3	09-23-92	4.37	Livestock and wildlife
46	360445099510501	19N–25W–34 DBD 1	Redelsperger Springs	07-20-93	450	Livestock and wildlife
47	360454099274801	19N–21W–32 BDA 1	Baker Spring 2	09-23-92	17.9	Livestock and wildlife

(continued on next page)

TABLE 2. — Location, Discharge, and Water Use of Ellis County Springs *(continued)*

Spring no.	Site identifier	Local identifier	Spring name	Date discharge measured	Discharge (gal/min)	Water use
48	360459099273601	19N–21W–32 ABC 1	Baker Spring 1	09-23-92	5.13	Livestock and wildlife
49	360515099575101	19N–26W–27 CDC 1	Herbel Springs 2	07-27-93	1.50	Livestock, fishing, and wildlife
50	360530099573701	19N–26W–27 DBB 1	Herbel Springs 1	07-27-93	0.10	Livestock
51	360620099572101	19N–26W–22 DAC 1	Farris Springs	07-22-93	22	Livestock and wildlife
52	360629099280101	19N–21W–20 CBA 1	Coram Spring 3	09-25-92	1.68	Livestock and wildlife
53	360632099562101	19N–26W–23 ADC 1	Knowles Spring	08-04-93	0.50	Livestock and wildlife
54	360635099574501	19N–26W–22 BDD 1	Pudwill Springs	07-22-93	4.90	Livestock
55	360637099275601	19N–21W–20 BDB 2	Coram Spring 2	09-25-92	0.31	Livestock and wildlife
56	360639099275501	19N–21W–20 BDB 1	Coram Spring 1	09-25-92	1.80	Livestock and wildlife
57	360712099274801	19N–21W–17 CAD 1	Bowman Spring 4	09-25-92	37.0	Livestock and wildlife
58	360716099281201	19N–21W–17 CBB 2	Bowman Spring 2	09-25-92	19.2	Livestock and wildlife
59	360716099281401	19N–21W–17 CBB 1	Bowman Spring 1	09-25-92	3.20	Livestock and wildlife
60	360717099281001	19N–21W–17 CBB 3	Bowman Spring 3	09-25-92	25.7	Livestock and wildlife
61	360728099283501	19N–21W–18 ACD 1	Bowman Spring 5	09-29-92	45.2	Livestock and wildlife
62	361119099553701	20N–26W–24 CDD 1	Higginbotham Spring	09-16-93	18.3	Livestock
63	361327099394501	20N–23W–09 CAB 1	Molloy Spring 1	09-24-93	0.10	Livestock
64	361339099390801	20N–23W–09 ADB 1	Molloy Spring 3	09-24-93	60	Livestock
65	361340099394001	20N–23W–09 BDB 1	Molloy Spring 2	09-24-93	0.10	Livestock
66	361353099535301	20N–25W–05 CCC 1	Wayland Spring 3	07-20-93	2.20	Livestock and wildlife
67	361616099482601	21N–24W–30 ADB 1	Berry Spring	08-05-93	42.6	Livestock
68	361642099364401	21N–23W–24 DCB 1	Reininger Spring	09-18-92	10	Livestock and wildlife
69	361657099482301	21N–24W–19 DBA 1	Barnes Springs	08-05-93	42	Livestock
70	361925099362301	21N–23W–01 DAD 1	Benbrook Spring	09-24-93	0.10	Livestock
71	362120099453901	22N–24W–27 BDC 1	Harris Spring	09-24-93	10	Livestock and wildlife
72	362209099473001	22N–24W–20 DBB 1	Elliott Springs	07-29-93	54	Livestock and wildlife
73	362215099474001	22N–24W–20 BDD 1	Herber Springs	07-29-93	48	Livestock and wildlife
74	362329099482101	22N–24W–18 AAB 1	Miller Springs	07-29-93	35	Livestock and wildlife
75	362829099395201	23N–23W–16 ACA 1	Eight-Mile Springs	07-20-93	77	Livestock and wildlife
76	362845099383101	23N–23W–10 DDD 1	Brewers Spring	07-28-92	1	Livestock and wildlife
77	363036099415801	24N–23W–31 DCA 1	Murphy Springs	07-23-93	1.70	Livestock and wildlife
78	363126099470501	24N–24W–29 DDA 1	Dugger Spring 2	09-29-93	0.60	Livestock and wildlife
79	363209099471601	24N–24W–29 AAB 1	Dugger Spring 1	09-29-93	54	Livestock and wildlife
80	363328099395401	24N–23W–16 DBA 1	Burgess Springs	07-23-93	4.80	Livestock and wildlife
81	363444099525601	24N–25W–09 ABB 1	Corless Spring	09-29-93	30	Livestock

GEOLOGY

Narrow bands of the Rush Springs Formation and Cloud Chief Formation, both of Permian age, crop out in northeastern and southern Ellis County (Fig. 6). The Rush Springs Formation, consisting of orange-brown fine-grained sandstone, with some interbedded red-brown shale, silty shale, and gypsum beds, is overlain by the Cloud Chief Formation, which consists of red-brown and greenish-gray shale and siltstone, with some thin dolomite beds at the base of the formation (Morton, 1980). A small outlier of the Kiowa Formation (Cretaceous), composed of shale and limestone, is found in the northeast corner. Most of the county is covered by the Ogallala Formation (Tertiary), consisting of gravel, sand, silt, clay, caliche, and limestone, locally cemented with calcium carbonate. Quaternary alluvial and terrace deposits occur along the major streams (Morton, 1980).

GROUND WATER

The High Plains aquifer consists of the Ogallala Formation (Tertiary) and Quaternary alluvium and terrace deposits that are in hydraulic continuity. In some areas of bedrock highs, parts of the underlying Triassic, Jurassic, or Cretaceous rocks contain fresh water and are considered to be part of the High Plains aquifer (Havens and Christenson, 1983, p. 11). The High Plains is a water-table aquifer, except in some areas where lenses of clay may cause local confinement. Water in the aquifer moves generally to the east-southeast; the water table slopes ~14 ft/mi. Discharge to streams along major valleys

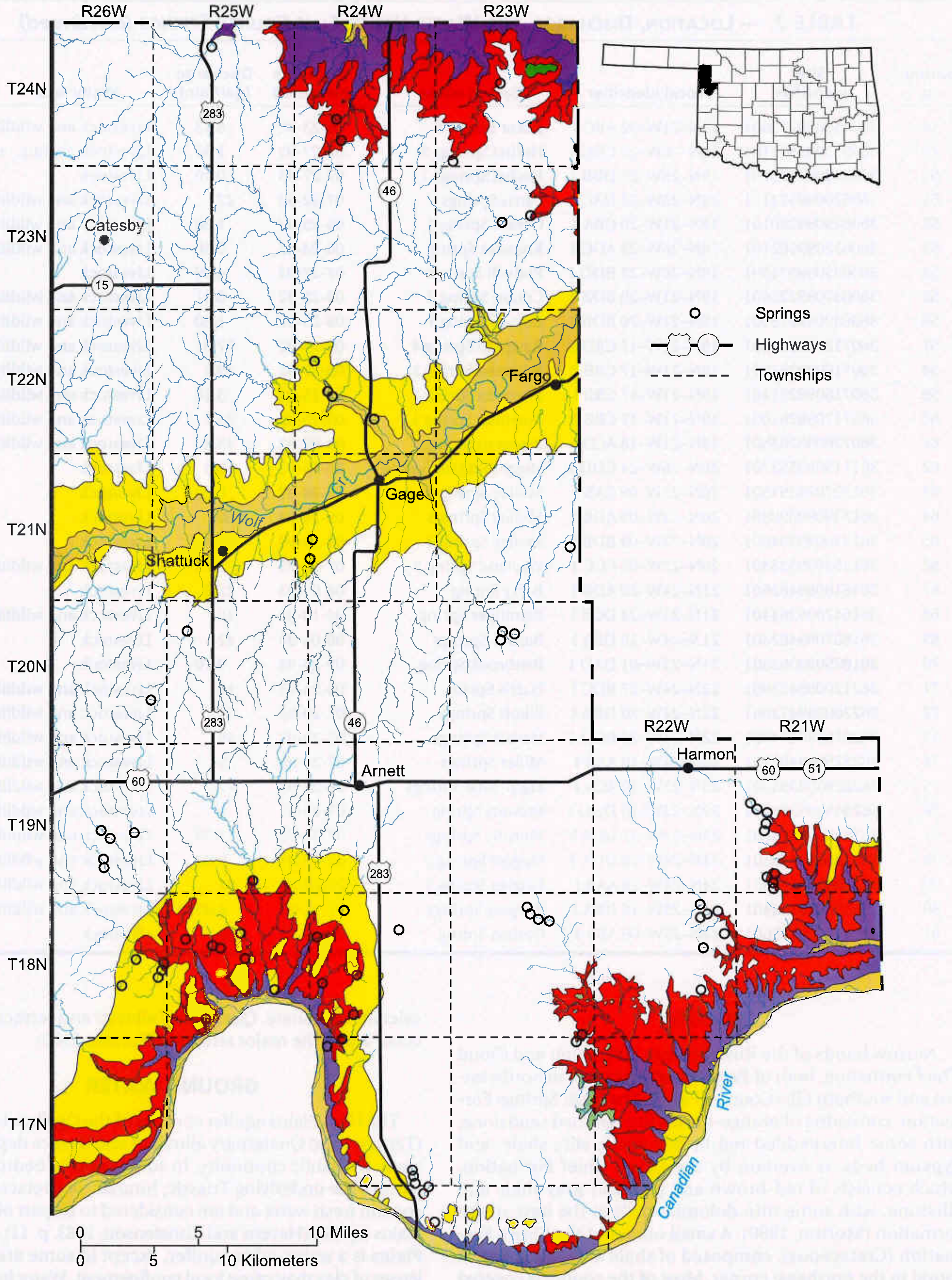

Figure 6. The geology and drainage of Ellis County determine the location of springs and also affect highway routes and town sites. *(Explanation on facing page.)*

Explanation for Figure 6

The stratigraphic nomenclature and age determinations used herein are those accepted by the Oklahoma Geological Survey and do not necessarily agree with those of the U.S. Geological Survey.

Qal ALLUVIUM
Lenticular and interfingering deposits of gravel, sand, silt, and clay, generally light tan to gray. Thickness along major streams ranges up to 100 feet and probably averages 40 feet; along minor streams the thickness ranges up to 45 feet and probably averages 20 feet.

UNCONFORMITY

Qt TERRACE DEPOSITS
Lenticular and interfingering deposits of light tan to gray gravel, sand, silt, clay, and volcanic ash. Sand dunes are common in many places. Thickness ranges up to 150 feet and averages about 60 feet.

UNCONFORMITY

To OGALLALA FORMATION
Gravel, sand, silt, clay, caliche, and limestone, locally cemented with calcium carbonate. Generally light tan to gray to white. Thickness ranges up to 400 feet and probably averages 150 feet.

UNCONFORMITY

Kk KIOWA FORMATION
Gray and yellow shale and limestone, with many Texigryphaea shells locally. At base is 5 to 10 feet of greenish-gray sandstone in places. Thickness ranges up to 140 feet with top eroded.

UNCONFORMITY

Pdy DOXEY FORMATION
Red-brown shale and siltstone, with greenish-gray calcareous siltstone at base. Exposed thickness is 30 feet, with top eroded.

Pcc CLOUD CHIEF FORMATION
Red-brown and greenish-gray shale and siltstone with some orange-brown fine-grained sandstone and siltstone. Thickness ranges up to 160 feet, with top eroded in many places.

Pr RUSH SPRINGS FORMATION
Orange-brown fine-grained sandstone, commonly cross-bedded, with some interbedded red-brown shale, silty shale, and gypsum beds. Thickness is about 190 feet in southern part and 90 feet near Kansas border, with top eroded in many places.

causes local variations in the water table (Havens and Christenson, 1983, p. 11).

Although most rain falls in spring and summer, most ground-water recharge occurs in late winter and early spring, when vegetation is dead or dormant and evaporation and transpiration are at a minimum. Thus water levels are highest in early spring and begin to decline in late spring or early summer. The levels continue to decline during summer and into autumn, when they are at their lowest. In late autumn they begin to rise as evaporation and transpiration decrease. The cycle may be disrupted if rain in summer is abnormally heavy—or light (Morton 1980).

SPRINGS

Ground water becomes a flowing spring where the water table intersects the ground surface. Some springs are formed by a perched water table: as rainwater percolates downward it may encounter an impermeable layer creating a localized zone of saturation, perched at a distance above the regional water table. The quality of spring water is related to the type of rock through which the water flows, for the water dissolves minerals in the rock and acquires some of their qualities.

Discharge

For this inventory, discharge measurements were made by estimation, by wading while using a current meter and wading rod, and by volumetric methods. Discharge was estimated by measuring flow channel depth and width and estimating the flow velocity. Wading measurements were made by multiplying the width of the spring channel times average depth times average velocity. Volumetric measurements were made by recording the time necessary to fill a container of known volume. In this report, discharge is given in gallons per minute (Table 2). Spring 46 had the greatest discharge at 450 gal/min; spring 1 had the least, at 0.07 gal/min.

Water Quality

Water-quality samples were collected from 24 of 81 springs in Ellis County. Results of chemical analysis are shown in Table 3. Water from 18 of 24 springs had dissolved solids less than 500 milligrams per liter. Water from 20 of 24 springs (exceptions were springs 3, 25, 31, and 32) had calcium as the dominant cation and bicarbonate as the dominant anion (Table 4). A cation or anion is considered to be dominant if it constitutes more than 50% of the total dissolved cations or

TABLE 3. — WATER-QUALITY ANALYSES FOR SPRINGS IN ELLIS COUNTY, OKLAHOMA

Spring no.[a]	Date sampled	Temp., water (°C)	Temp., air (°C)	Agency collecting sample[b]	Agency anayzing sample[b]	Specific conductance (µS/cm)[c]	pH, water whole, field, standard units	Carbonate, water, dissolved, IT[d], field (mg/L)	Bicarbonate, water dissolved, IT[d], field (mg/L)	Nitrogen, nitrate total (mg/L as N)	Nitrogen NO_2+NO_3 dissolved (mg/L as N)	Hardness total (mg/L as $CaCO_3$)	Hardness noncarbonate dissolved field (mg/L as $CaCO_3$)
3	08-14-92	16.5	—	1028	84041	893	7.1	0	254	4.53	4.53	340	130
10	08-21-92	16.5	—	1028	84041	676	7.2	0	320	0.160	0.160	250	0
12	08-27-93	17.0	24.0	1028	84041	523	7.6	0	256	3.25	3.25	220	5
14	08-13-92	22.0	—	1028	84041	376	8.2	0	234	1.12	1.12	180	0
16	09-23-92	17.0	—	1028	84041	490	7.3	0	242	5.09	5.09	210	14
18	07-22-93	18.0	30.0	1028	84041	550	7.6	0	267	1.74	1.74	220	1
23	07-27-93	20.0	39.0	1028	84041	505	7.7	0	221	4.82	4.82	180	0
25	07-20-93	19.0	30.5	1028	84041	1,570	7.2	0	217	9.06	9.06	540	360
29	09-11-92	18.0	—	1028	84041	522	7.7	0	209	5.20	5.20	200	26
31	08-28-92	18.0	—	1028	84041	—	7.8	0	278	0.700	0.700	130	0
32	08-04-93	20.5	27.0	1028	84041	644	7.9	0	395	1.71	1.71	260	0
37	09-18-92	19.0	—	1028	84041	408	7.2	0	273	—	<0.100	200	0
43	09-01-92	16.5	—	1028	84041	520	7.4	0	326	0.980	0.980	180	0
46	07-20-93	17.0	34.0	1028	84041	510	7.2	0	257	2.66	2.66	210	0
48	09-23-92	15.0	—	1028	84041	700	7.2	0	294	2.93	2.93	280	35
49	07-27-93	17.0	38.0	1028	84041	426	7.7	0	216	0.810	0.810	200	25
52	09-25-92	16.0	—	1028	84041	780	7.2	0	428	0.130	0.130	290	0
53	08-04-93	16.5	22.5	1028	84041	598	7.4	0	393	—	<0.100	290	0
64	09-24-93	17.5	19.5	1028	84041	620	7.3	0	313	4.29	4.29	260	0
67	08-05-93	21.5	26.0	1028	84041	656	7.8	0	390	—	<0.100	300	0
74	07-29-93	17.0	33.0	1028	84041	559	7.8	0	312	0.770	0.770	270	10
75	07-19-93	22.0	34.5	1028	84041	580	7.6	0	315	0.110	0.110	250	0
79	09-29-93	17.5	25.0	1028	84041	517	7.4	0	246	1.14	1.14	210	8
81	09-29-93	17.5	23.0	1028	84041	397	7.4	0	244	1.38	1.38	200	3

[a]See Table 1.

[b]Agency codes: 1028—U.S. Geological Survey, 84041—Oklahoma Geological Survey.

[c]µS/cm, microsiemens per centimeter.

[d]IT, incremental titration.

anions calculated in milliequivalents per liter. Thus water from most of the sampled springs generally was low in dissolved solids and of a calcium-bicarbonate water type. Of the four springs that did not fit this general pattern, springs 3 and 25 had dissolved solids concentrations greater than 500 mg/L, spring 31 had sodium as the dominant cation (although bicarbonate remained the dominant anion), and spring 32 had enough dissolved calcium and sodium such that calcium does not constitute more than 50% of the cations. Most of the springs sampled discharged hard water—180 milligrams per liter or more of calcium carbonate.

Hardness is expressed in terms of calcium carbonate. If water requires an excessive amount of soap to form a lather, or forms incrustation on faucets or vessels in which it stands or is heated, it is hard water (Symons, 1946).

Water-quality Table 5 shows the median concentration in milligrams per liter of each major ion. The table also shows the 25th and 75th percentiles for each ion; 25% of the data are less than the 25th percentile and 75% of the data are less that the 75th percentile. Percentiles show the distribution of the concentrations of major ions in water produced by springs in Ellis County.

No spring sampled exceeded the water-quality limits for drinking water set by the Environmental Protection Agency (U.S. Environmental Protection Agency, 1994) for any measured constituent. The primary maximum contaminant levels are set to protect public health. The secondary maximum contaminant levels are for aesthetic reasons related to public acceptance of drinking water (U.S. Environmental Protection Agency, 1994). Water from spring 25 came close to exceeding the primary and secondary maximum contaminant levels for nitrite plus nitrate, chloride, and sulfate. The nitrite plus nitrate concentration was 9.06 milligrams per liter (the primary maximum contaminant level is 10 milligrams per liter). The chloride concentration was 240 milligrams per liter (the secondary maximum contaminant level is 250) and the sulfate concentration was 210 milligrams per liter (secondary maximum contaminant level, 250).

TABLE 3. — WATER-QUALITY ANALYSES FOR SPRINGS IN ELLIS COUNTY, OKLAHOMA *(continued)*

Spring no.[a]	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Sodium adsorption ratio	Sodium (%)	Potassium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Silica, dissolved (mg/L)	Total alkalinity water, dissolved, IT[d], field (mg/L as $CaCO_3$)	Solids, residue at 180°C, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Solids, dissolved (tons per acre-ft)
3	97	23	48	1	24	2.2	120	52	34	208	654	521	0.89
10	82	11	43	1	27	2.0	51	20	32	262	410	399	0.56
12	74	7.4	23	0.7	19	1.7	16	28	29	210	334	319	0.45
14	51	12	21	0.7	20	2.0	14	12	38	192	278	270	0.38
16	73	7.4	16	0.5	14	1.8	17	13	27	198	322	297	0.44
18	73	9.2	32	0.9	24	1.5	14	36	35	219	356	340	0.48
23	62	6.3	8.7	0.3	9	1.0	3.4	<10	23	181	262	—	—
25	150	37	99	2	29	2.2	240	210	23	178	1,140	912	1.55
29	68	6.7	31	1	25	0.80	31	30	21	171	340	314	0.46
31	44	6.0	63	2	50	1.8	4.9	32	24	228	316	315	0.43
32	61	26	43	1	26	1.3	6.0	22	21	324	396	382	0.54
37	72	3.8	22	0.7	20	0.80	18	<10	32	224	302	—	—
43	60	6.2	57	2	41	2.2	5.4	21	28	267	348	344	0.47
46	71	7.2	30	0.9	24	1.9	22	18	31	211	344	319	0.47
48	89	13	32	0.8	20	2.7	55	30	29	241	463	408	0.63
49	74	4.2	6.9	0.2	7	0.80	22	13	46	177	320	277	0.44
52	94	14	47	1	26	2.8	37	22	35	351	480	463	0.65
53	99	11	9.6	0.2	7	0.40	7.2	<10	82	322	436	—	—
64	87	9.6	18	0.5	13	0.30	19	10	33	257	378	350	0.51
67	86	20	21	0.5	13	3.5	28	<10	37	320	404	—	—
74	77	18	18	0.5	13	3.8	21	24	44	256	402	363	0.55
75	86	8.1	26	0.7	18	2.0	17	12	44	258	378	350	0.51
79	70	8.4	24	0.7	20	1.6	28	22	41	202	346	321	0.47
81	69	7.6	9.2	0.3	9	1.8	12	12	31	200	291	269	0.40

Most of the springs sampled were used by livestock or wildlife. Water from springs 3, 7, 8, and 18 was used by households.

SUMMARY

In 1992–1993, the median discharge of 81 springs in Ellis County was 9.68 gal/min, ranging from 450 gal/min by spring 46 down to 0.07 gal/min by spring 1. Water from 18 of 24 springs had dissolved solids <500 mg/L. Water from 20 of 24 springs had calcium as the dominant cation and bicarbonate as the dominant anion. Water was generally low in dissolved solids and of a calcium-bicarbonate water type. No spring sampled violated the water-quality standards for drinking water set by the Environmental Protection Agency, but spring 25 came close.

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TABLE 4. — CHEMICAL ANALYSES OF MAJOR IONS IN MILLIEQUIVALENTS PER LITER FOR SPRINGS IN ELLIS COUNTY, OKLAHOMA

	Cations				Anions			
Spring no.[a]	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Potassium, dissolved	Chloride, dissolved	Sulfate, dissolved	Bicarbonate, dissolved, IT[b], field	NO_2+NO_3, dissolved as nitogen
3	4.841	1.893	2.088	0.057	3.386	1.083	4.164	0.324
10	4.092	0.906	1.871	0.052	1.439	0.417	5.245	0.012
12	3.693	0.609	1.001	0.044	0.452	0.583	4.196	0.233
14	2.545	0.988	0.914	0.052	0.395	0.250	3.836	0.080
16	3.643	0.609	0.696	0.047	0.480	0.271	3.967	0.364
18	3.643	0.758	1.392	0.039	0.395	0.750	4.377	0.125
23	3.094	0.519	0.379	0.026	0.096	<0.208	3.623	0.345
25	7.685	3.045	4.307	0.057	6.771	4.373	3.557	0.647
29	3.394	0.552	1.349	0.021	0.875	0.625	3.426	0.372
31	2.196	0.494	2.741	0.047	0.139	0.667	4.557	0.050
32	3.044	2.140	1.871	0.034	0.170	0.459	6.475	0.123
37	3.593	0.313	0.957	0.021	0.508	<0.208	4.475	<0.007
43	2.994	0.511	2.480	0.057	0.153	0.438	5.344	0.070
46	3.543	0.593	1.305	0.049	0.621	0.375	4.213	0.190
48	4.442	1.070	1.392	0.070	1.552	0.625	4.819	0.210
49	3.693	0.346	0.301	0.021	0.621	0.271	3.541	0.058
52	4.691	1.153	2.045	0.072	1.044	0.459	7.015	0.010
53	4.941	0.906	0.418	0.011	0.204	<0.208	6.442	<0.007
64	4.342	0.790	0.783	0.008	0.536	0.209	5.131	0.307
67	4.292	1.646	0.914	0.090	0.790	<0.208	6.393	<0.007
74	3.843	1.482	0.783	0.098	0.593	0.500	5.114	0.055
75	4.292	0.667	1.131	0.052	0.480	0.250	5.163	0.008
79	3.493	0.692	1.044	0.041	0.790	0.459	4.032	0.082
81	3.444	0.626	0.401	0.047	0.339	0.250	4.000	0.099

[a]See Table 1.
[b]IT, incremental titration.

TABLE 5. — STATISTICAL SUMMARY OF SELECTED WATER-QUALITY DATA COLLECTED FROM AUGUST 1992 TO SEPTEMBER 1993 FOR ELLIS COUNTY SPRINGS

					Percent of samples in which values were less than or equal to those shown (median in percentage)				
Water-quality constituent	Sample size	Max.	Min.	Mean	95	75	50	25	5
Specific conductance in microsiemens per centimeter at 25°C	24	1,570	376	610	1,434	656	550	505	380
pH, whole, field (standard unit)	24	8.2	7.1	7.5	8.1	7.7	7.4	7.2	7.1
pH, whole, laboratory (standard unit)	24	8	7.2	7.5	8.0	7.7	7.5	7.4	7.2
Carbonate, dissolved, incremental titration (mg/L as carbonate)	24	0	—	—	—	—	—	—	—
Bicarbonate, dissolved (mg/L as bicarbonate)	24	428	209	288	420	319	270	242	211
Nitrite plus nitrate dissolved (mg/L as nitrogen)	24	9.06	<0.10	2.20[a]	5.20	3.25	1.14	0.16	<0.10
Calcium, dissolved (mg/L as calcium)	24	150	44	78	137	87	74	68	46
Magnesium, dissolved (mg/L as magnesium)	24	37	3.8	12	34	14	8.8	6.8	3.9
Sodium, dissolved (mg/L as sodium)	24	99	7	31	90	43	25	18	7
Sodium adsorption ratio	24	2.0	0.2	0.8	2.0	1.0	0.7	0.5	0.2
Potassium, dissolved (mg/L as potassium)	24	3.8	0.3	1.8	3.7	2.2	1.8	1.1	0.3
Chloride, dissolved (mg/L as chloride)	24	240	3	34	210	30	18	12	4
Sulfate dissolved (mg/L as sulfate)	24	210	<10	28[a]	52	28	20	12	<10
Silica, dissolved (mg/L as silica dioxide)	24	82	21	34	73	38	32	27	21
Alkalinity, dissolved, IT[b] (mg/L as calcium carbonate)	24	351	171	236	344	261	222	198	172
Residue, dissolved at 180°C (mg/L)	24	1,140	262	404	1,018	408	352	320	266
Specific conductance (μS/cm)[c]	24	1,510	399	609	1,364	659	549	495	408
Alkalinity (mg/L as calcium carbonate)	24	348	170	236	341	262	227	200	171

[a]Value is estimated by using a log-probability regression to predict the values of data below the detection limit.
[b]IT, incremental titration.
[c]μS/cm, microsiemens per centimeter.

new OGS publications

CIRCULAR 106

• **Kenneth S. Johnson and Daniel F. Merriam, *editors***

• **198 pages**

• **Paperbound, laminated cover**

• **$13**

Petroleum Systems of Sedimentary Basins in the Southern Midcontinent, 2000 Symposium

Contained in this volume are papers dealing with the search for, and production of, oil and gas resources from reservoirs in major sedimentary basins of the southern Midcontinent. The research focuses on the reservoirs, geologic events, and petroleum of rocks that were deposited in these oil and gas provinces. Clastic and carbonate reservoirs are major sources of oil and gas in the southern Midcontinent, and they have great potential for additional recovery using advanced technologies.

The 26 papers and abstracts in this book concentrate on geology, depositional settings, diagenetic and thermal history, reservoir characterization, geophysical studies, exploration, petroleum production, and enhanced oil recovery. The research originally was presented at a two-day workshop held in March 2000 in Oklahoma City, cosponsored by the OGS and the National Petroleum Technology Office of the U.S. Department of Energy. The meeting drew about 150 representatives from industry, government, and academia. In describing these petroleum provinces and reservoirs, the researchers have increased our understanding of how the geologic history of an area can affect reservoir heterogeneity and the ability to efficiently recover hydrocarbons.

Study areas include many major fields in Oklahoma, as well as sites in Kansas, Texas, and western Missouri. As oil prices have increased recently, a greater interest in drilling in the State makes these papers a valuable resource for explorationists and operators in Oklahoma.

SPECIAL PUBLICATION 2001-2

Michelle J. Summers, *coordinator*

• **393 pages**

• **Paperbound**

• **$15**

Oklahoma Oil and Gas Producation by Field, 1996–1999

This publication provides data on reported oil and gas production and related information for each formally recognized field in the State. The volume contains the following types of field data:

- Field name;
- County or counties in which the field is located;
- Total acreage of the field;
- Date the Oklahoma Nomenclature Committee named the field and date of the last revision of field boundaries;
- Annual production from 1996 through 1999 by type of product: oil, condensate, total liquids, associated gas, natural gas, and total gas;
- Cumulative production from 1979 through 1999 by type of product.

Part 1 of this publication includes oil and gas production by county; Part 2 is a summary of production within each county that is not assigned to any formally recognized field. Part 3 is an alphabetical list of all fields, districts, and gas areas that have been formally recognized by the Oklahoma Nomenclature Committee. Part 4 is a list of inactive field names. Part 5 is a listing of discontinued field names.

This publication has been developed from data contained in the Natural Resources Information System (NRIS), a computerized data base of oil and gas information for the State of Oklahoma. NRIS currently contains data files of monthly oil and gas production by lease that can be aggregated by such categories as field, producing interval, geologic play, petroleum province, and county. NRIS also contains digitized records for 442,489 well completions and recompletions dating from statehood (1907) to present. The well records include latitude/longitude coordinates that permit plotting and use in a GIS system.

The NRIS data base can be used by the public at the OGS Computer Facility, 1218-B W. Rock Creek Road, Norman, Oklahoma. It is open by appointment only; for information call Jane Weber at (405) 360-2886, (405) 325-3031, or (800) 330-3996.

SPECIAL PUBLICATION 2002-1

• **Robert O. Fay and Douglas C. Brockie**

• **32 pages**

• **Paperbound, laminated cover**

• **$3**

Metallic-Mineral Resources of Oklahoma

Although metallic minerals are not currently being produced in Oklahoma, many companies continue to be interested in the metallic-mineral deposits of Oklahoma. These resources consist mainly of zinc, lead, and copper, with minor occurrences of iron, titanium, manganese, aluminum, gold, silver, uranium, vanadium, and zirconium. Some germanium, gallium, and cadmium have been extracted from zinc ores. Silver was extracted as a by-product at one copper mine.

This publication describes the history of mining in Oklahoma and the mineral resources of each of the seven mining districts: Tri-State, Ozark, Ouachita, Arbuckle, Wichita, Red Bed, and Black Mesa. Copper and uranium occur in most of the districts. Lead and zinc occur in the first five districts. Iron occurs in the Arbuckle, Wichita, and Tri-State Districts. Manganese occurs in the Arbuckles and Ouachitas. Aluminum, titanium, and zirconium occur in the Wichitas. Gold and silver occur in trace quantities in copper–lead–zinc minerals in most of the districts.

Circular 106 and **Special Publications 2001-2** and **2002-1** can be purchased by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; fax 405-325-7069. To mail order, add 20% to the cost for postage, with a minimum of $2 per order.

All OGS publications can be purchased over the counter at the OGS Publication Sales Office, 1218-B W. Rock Creek Road, Norman; phone (405) 360-2886, fax 405-366-2882, e-mail ogssales@ou.edu. Request the OGS *List of Available Publications* for current listings and prices.

AASG Mentored Field Research program boon to OGS

The Oklahoma Geological Survey (OGS) is participating for a third year in the Mentored Field Research Experience program, administered by the Association of American State Geologists (AASG) and co-sponsored by the National Science Foundation and the U.S. Geological Survey (USGS). This education program trains undergraduate geoscience students in field-observation and geologic-mapping techniques and encourages them to pursue careers in geology and related fields. Students in the program spend the summer field mapping under the supervision of OGS geologists. To date, most of this field mapping has been done in the Oklahoma City metropolitan area in conjunction with the STATEMAP program, sponsored by the USGS. (As part of the STATEMAP program, the OGS has been mapping the Oklahoma City metro area at a scale of 1:24,000 since 1997.)

The mentoring program has been a great success. Summer interns have helped in the geologic mapping of six 7.5′ quadrangles within the Oklahoma City metro area; these include the Midwest City and Choctaw quadrangles (OGS Open-File Report [OF] 4-2000), the Denver and Norman quadrangles (OF 3-2002), and the Newcastle and Blanchard quadrangles (OF 4-2002). Mentored students also have helped develop guidebooks featuring the geology of several State parks, including the geology of Arcadia Lake Parks (OGS Information Series 7) and the geology of Lake Thunderbird State Parks (to be published later this year).

Ivan London and Nicole Baylor, mentored students, examine samples collected from their field areas.

The maps produced through the STATEMAP program have increased our understanding of the surface extent of the Garber-Wellington recharge area. In addition, the information provided about the characteristics of surficial materials is important to the region's economic and environmental well being. The students in the AASG Mentored Field Research Experience program have made significant contributions to this ongoing work of the OGS, which is happy to continue its participation in providing field research experience to student geologists.

—*Thomas M. Stanley*

AAPG Spring Student Expo hosted by OU

The American Association of Petroleum Geologists held its second Spring Student Expo at the University of Oklahoma on March 15–16, 2002. The Spring Expo is a follow-up to the highly successful Fall Expos, held annually at Rice University in Houston.

The Spring Student Expo offers mutually beneficial opportunities for geoscience students interested in energy careers to showcase their work and to network with industry representatives who formally recruit on campus.

Co-sponsored by the OU School of Geology and Geophysics, Oklahoma Geological Survey, and Sarkeys Energy Center, the Spring Expo was attended by 126 students.

Abstracts for four poster presentations pertaining to Oklahoma geology are reproduced here.

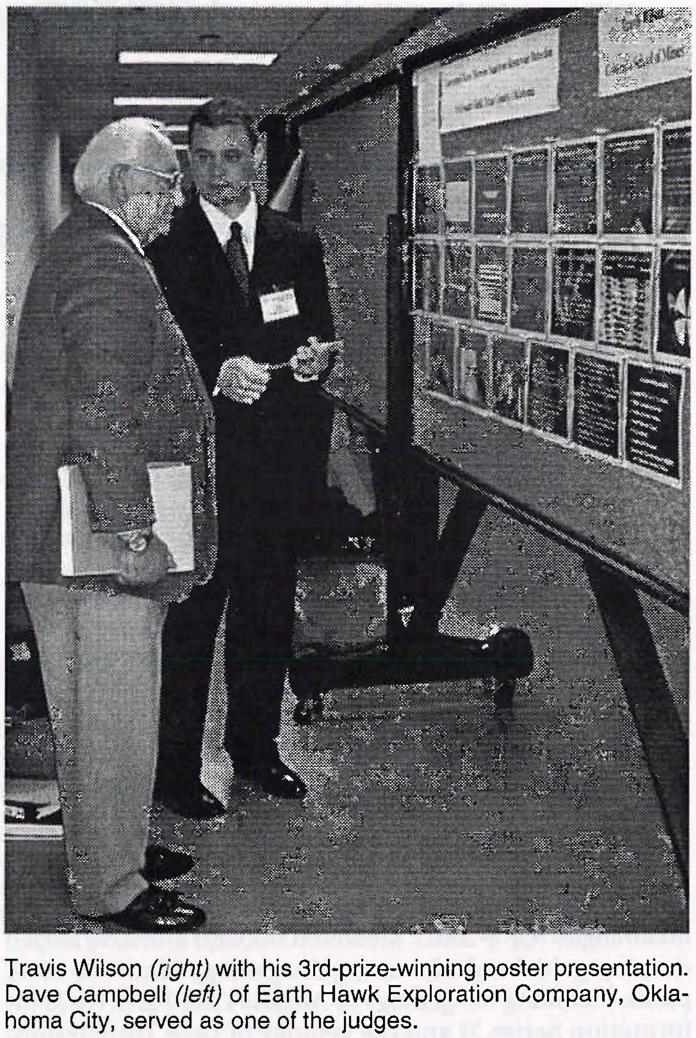
3rd Place Award for Best Poster

Converted-Wave Morrow Sandstone Reservoir Delineation, Eva South Field, Texas County, Oklahoma

TRAVIS C. WILSON, Colorado School of Mines, Golden, Colorado

Morrow valley-fill sandstone reservoirs in Oklahoma, Kansas, Colorado, and Texas are very elusive petroleum exploration targets. Traditional P-wave seismic methods often fail to image these thin, discontinuous sandstone bodies. The primary reason for this lack of success is the low *acoustic* impedance contrast between Morrow sandstones and the surrounding Morrow shales. This low contrast often renders Morrow sandstone reservoirs acoustically invisible to P-waves. Fortunately, a substantial *elastic* impedance contrast exists between these sandstones and shales. The Reservoir Characterization Project Phase 5 study at Sorrento field, Colorado, demonstrated that pure shear waves (S-S) are capable of detecting these elusive Morrow sandstones. The focus of the Eva South study is to demonstrate that mode-converted shear-waves (P-S) can also be successfully used for Morrow sandstone reservoir detection in an area where P-waves fail.

The data set for this study is a 4.25 square mile 3D-3C seismic survey that was acquired over the Eva South Morrow Sand Unit, Texas County, Oklahoma. The converted-wave data vividly delineate the extent of the reservoir sandstone at the Eva South field. Numerous P-wave interpretation techniques (P-wave amplitude, AVO, coherency, etc.) were unable to equal the success of the converted-wave data. The converted-wave data at the Eva South field have aided in the delineation of the reservoir and have provided new drilling locations for additional reservoir exploration and development. This technology has the potential to make a dramatic impact on Morrow sandstone exploration and development throughout the region.



Travis Wilson *(right)* with his 3rd-prize-winning poster presentation. Dave Campbell *(left)* of Earth Hawk Exploration Company, Oklahoma City, served as one of the judges.

Depositional Analysis of the Lower Skinner Sandstone on the "Cherokee" Platform of Payne County, Oklahoma

JAMES R. KINSER, Kansas State University, Manhattan, Kansas

Middle Pennsylvanian, Desmoinesian sandstones are well known for their hydrocarbon production in the mid-continent of the United States. The lower Skinner sandstone is an oil- and gas-producing member of the Senora Formation ("Cherokee" Group) in north-central Oklahoma. This study examines the sandstone, as well as the mud-rich facies of the lower Skinner sandstone sequence. Although the sandstone sequences are of primary interest because of their hydrocarbon production, the mud-rich sequences function as seals of hydrocarbon reservoirs and inhibitors to permeability. In addition, the mud-rich sequences are potentially more sensitive indicators of depositional environment than are the sandstones.

The lower Skinner sandstone has commonly been interpreted as a fluvial-dominated deltaic reservoir sand. However, other researchers assert that some facies commonly interpreted as deltaic or prodeltaic, in the U.S. mid-continent, should be reinterpreted as fluvio-estuarine sequences. Furthermore, they also indicate that estuary mouth marine sands have potentially been misinterpreted as offshore bars or barrier islands. Thus, much of the older interpretations as fluvio-deltaic, should be reexamined with estuarine models in mind.

Depositional Environments and Conodont Biofacies of the Council Grove Group (Early Permian) in the Hugoton Embayment, Southwestern Kansas and Oklahoma Panhandle

NICK PIERACACOS, Dept. of Geology, Baylor University, Waco, Texas

Detailed examination of cores from nine wells in the southern Hugoton Embayment indicates that strata of the Council Grove Group of Early Permian age consist of laterally continuous, mixed carbonate-siliciclastic depositional sequences. The strata can be grouped into vertically repetitive units of marine carbonates and local thin marine siliciclastic units interbedded with nonmarine siliciclastics. The purposes of the study are to describe the lithofacies that make up the depositional sequences and to apply conodont biofacies analysis to interpreting the paleoenvironments.

Twelve marine and nonmarine facies and subfacies can be recognized. Marine lithofacies range from carbonate mudstones to grainstones and boundstones, shales, and sandstones deposited on a low-relief shelf. Nonmarine depositional systems are primarily represented by variegated mudrocks (red beds) that accumulated as coastal mud-rich sabkhas and form a large portion of the depositional sequences.

Carbonate depositional systems developed during progradation across a deeper water open shelf that resulted in a shallowing-upward succession of facies. Each carbonate shallowing-upward succession is disconformably bounded by nonmarine mudrocks at the base and top. The lithofacies represent depositional environments that include deeper water open-shelf, shallow-water inner shelf, shallow-water to emergent shoals, and a marginal marine to nonmarine sabkha complex that comprises intertidal to supratidal algal mud flats and terrigenous mud flats.

The marine strata contain a modest, but varied conodont fauna. Relative frequency analysis indicates that five nominative and one mixed biofacies dominate the samples and reflect environmental controls. Conodont biofacies substantiate lithofacies interpretations that indicate that the carbonate successions represent a regressive sequence passing from open- to shallow-shelf shoal deposits.

Impact of Brine Contamination on Overall Water Quality in Seminole County, Oklahoma

LAURIE A. WHITESELL, University of Tulsa, Tulsa, Oklahoma

The purpose of this project is to assess the impact of produced brines on surface and subsurface water quality in Seminole County, Oklahoma. Surface water samples have been taken for all major rivers, streams, and minor tributaries throughout the county. The samples have stream velocity, pH, conductivity, salinity, dissolved oxygen, and temperature data associated with them. Additionally, subsurface samples were accessed via individual water wells. The sampling of the water wells allows top of water table data to be used for ground water flow modeling. Geographical Information Systems (GIS) is employed to display cation, anion concentrations, all stream and road data, as well as brine scars as determined from Digital Ortho Photo-Quadrangles.

upcoming meetings

JUNE

American Society for Surface Mining and Reclamation/International Affiliation of Land Reclamationists, Joint Meeting, June 9–13, 2002, Lexington, Kentucky. Information: Richard I. Barnhisel, ASSMR, 3134 Montavesta Rd., Lexington, KY 40502; phone and fax (877) 701-2086 *or* (859) 335-6529; Email: rbarnhis@ca.uky.edu. Web: http://ces.ca.uky.edu/asmr/.

Oklahoma City Geological Society/Oklahoma Geological Survey/Petroleum Technology Transfer Council, Red Fork Play Workshop, June 19, 2002, Oklahoma City, Oklahoma. Information: OCGS, 120 N. Robinson, Suite 900 Center, Oklahoma City, OK 73102; (405) 236-8086 *or* (405) 235-3648, ext. 40; fax 405-236-8085; Email: ocgs@oklahoma.net.

Tulsa Geological Society/Oklahoma Geological Survey/Petroleum Technology Transfer Council, Red Fork Play Workshop, June 20, 2002, Tulsa, Oklahoma. Information: TGS, 4308 S. Peoria, Tulsa, OK 74105; (918) 582-4762.

JULY

National Conference on Earthquake Engineering, July 21–25, 2002, Boston, Massachusetts. Information: Earthquake Engineering Research Institute, 499 14th St., Suite 320, Oakland, CA 94612; (510) 451-0905; Email: eeri@eeri.org. Web: http://www.eeri.org/.

American Association of Petroleum Geologists, Hedberg Research Conference, "Late Paleozoic Tectonics and Hydrocarbon Systems of Western North America—The Greater Ancestral Rocky Mountains," July 21–26, 2002, Vail, Colorado. Information: Debbi Boonstra, AAPG Education Dept., P.O. Box 979, Tulsa, OK 74101; (918) 560-2630; fax 918-560-2678; Email: debbi@aapg.org. Web: http://www.aapg.org/education/hedberg/.

AUGUST

American Quaternary Association, Bienniel Meeting, August 8–11, 2002, Anchorage, Alaska. Information: Margaret J. Guccione, Dept. of Geosciences, 113 Ozark Hall, University of Arkansas, Fayetteville, AR 72701; (501) 575-3354; fax 501-575-3177; Email: guccione@comp.uark.edu. Web: http://www4.nau.edu/amqua/.

Society of Exploration Geophysicists/Society of Petroleum Engineers, Development and Production Forum: "Improved Prediction, Productivity, and Profitability Using Geophysical Tools," August 25–30, 2002, Snowmass, Colorado. Information: Kristi Smith, Meetings Coordintor, SEG, P.O. Box 702740, Tulsa, OK 74170; (918) 497-5564; fax 918-497-5557; Email: ksmith@seg.org. Web: http://www.seg.org/.

APPEX—AAPG Prospect and Property Expo, August 27–29, 2002, Houston, Texas. Information: Michelle Mayfield, American Association of Petroleum Geologists, P.O. Box 979, Tulsa, OK 74101; (918) 560-2618 *or* (888) 945-2274; fax: 918-560-2665; Email: mmayfiel@aapg.org. Web: http://www.aapg.org/.

Society for Organic Petrology/Canadian Society for Coal Science and Organic Petrology, Joint Annual Meeting, August 31–September 4, 2002, Banff, Alberta, Canada. Information: Tracy Collier, Conference Secretariat, Elsevier Science, The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, United Kingdom; telephone +44(0) 1865 843297; fax +44(0) 1865 843958; Email: t.collier@elsevier.co.uk. Web: http://www.tsop.org/.

SEPTEMBER

Geospatial Information and Technology Association, GIS for Oil and Gas Conference and Exhibition, September 23–25, 2002, Houston, Texas. Information: GITA, 14456 E. Evans Ave., Aurora, CO 80014; (303) 337-0513; fax 303-337-1001; Email: info@gita.org. Web: http://www.gita.org/.

Association of Engineering Geologists/American Institute of Professional Geologists, Joint Annual Meeting, "Gambling with Geologic Hazards and Dealing with Sustainability," September 22–29, 2002, Reno, Nevada. Information: AEG, Dept. of Geology and Geophysics, Texas A&M University, TAMU 3115, College Station, TX 77843; (979) 845-0142; fax 979-862-7959. Web: http://aeg.tamu.edu/.

Society of Petroleum Engineers, Annual Technical Conference and Exhibition, September 29–October 2, 2002, San Antonio, Texas. Information: SPE, P.O. Box 833836, Richardson, TX 75083; (972) 952-9393; fax 972-952-9435; Email: spedal@spe.org. Web: http://www.spe.org/.

OGS Workshop

Methods for Identification and Correlation of Methane-Producing Coal Beds, Northeast Oklahoma Shelf

TULSA, September 18 and 19
OKLAHOMA CITY, September 24

The Oklahoma Geological Survey will co-host a half-day workshop on the stratigraphic relationship of methane-producing coal beds in the northeast Oklahoma shelf. The workshop will be held at the Geophysical Resource Center in Tulsa on Wednesday, September 18, 1–5 p.m.; it will be repeated at the same location on Thursday, September 19. The workshop also will be held at the National Cowboy Hall of Fame in Oklahoma City on Tuesday, September 24.

The workshop will provide information on Oklahoma coal geology with emphasis on the surface-to-subsurface correlation of methane-producing coal beds in an area of the State where more than 750 wells are already in production, and where interest in further development of the coal-bed-methane industry is high.

The meeting is designed to aid geologists, engineers, and operators in identification and correlation of methane-producing intervals through the use of geophysical logs. Hands-on laboratory exercises using copies of actual logs from the study area will be part of the workshop.

Information: Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 *or* (800) 330-3996; fax 405-325-7069; Email: tcreel@ou.edu. Web: http://www.ou.edu/special/ogs-pttc/.

notes on new publications

Summary of State Statutes and Regulations for Oil and Gas Production

Published by the Interstate Oil and Gas Compact Commission, this resource explains the rules and regulations enforced by 37 oil- and gas-producing states. This updated edition is now available on one easy-to-use CD-ROM.

Topics in the summary include administration, bond, casing and tubing, completion, documents required, drilling permit, land leasing, naturally occurring radioactive materials (NORM), pooling, spacing, taxation, underground injection, unitization, vertical deviation, and water and drilling-waste disposal.

The CD-ROM is in an html format, allowing interaction with the World Wide Web, and hot links provide direct access to the Web site of each state's regulatory agency for even more information.

Order from: Interstate Oil and Gas Compact Commission (IOGCC), Web site: http://www.iogcc.state.ok.us *or* phone (405) 525-3556. The cost is $30, including shipping and handling. The original edition, published in 1999, also is available as a three-ring binder complete with state dividers, or on a diskette in a text format.

U.S. Geological Survey Programs in Oklahoma

Brief discussions of some programs being conducted in Oklahoma by the U.S. Geological Survey are in this 4-page fact sheet. Topics include drought and streamflow monitoring, Statewide digital data partnership, delineation of the Oklahoma-Texas border, mapping watersheds using digital maps, natural gas in the Anadarko basin, radium associated with oil production, and biodegradation of pollutants in soils.

Order Fact Sheet 037-99 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone 1-888-275-8747. Fact sheets are available at no cost. This fact sheet also is available on the Web at http://water.usgs.gov/pubs/FS/FS-037-99/.

Simulation and Analysis of Soil-Water Conditions in the Great Plains and Adjacent Areas, Central United States, 1951–80

Written by Jack T. Dugan and Ronald B. Zelt, this 81-page USGS water-supply paper describes the results of an analysis of potential ground-water recharge and consumptive-irrigation requirements using long-term soil-water simulations in the Great Plains and adjacent areas. The study area encompasses approximately 560,000 mi^2 extending from Canada to Mexico and from central Arkansas to northwestern Montana. Also described are factors affecting soil-water conditions and resultant potential recharge and consumptive-irrigation requirements in the region. These factors include climate, soils, vegetation, and agricultural crop patterns. Particular emphasis was placed on the effect of climate, especially precipitation and evaporation, on soil-water conditions.

Order W 2427 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone 1-888-275-8747. The cost is $10.50, plus $5 per order for handling.

Conserving Oklahoma's Water

This colorful, 25-page booklet emphasizes the importance of using water more efficiently and economically in order to preserve and extend limited supplies. It suggests ways to conserve water in the home and garden, as well as in agriculture, business, industry, and public facilities.

Order from: Oklahoma Water Resources Board, 3800 N. Classen, Oklahoma City, OK 73118; (405) 530-8800. There is no charge for the booklet. This booklet also can be downloaded from the OWRB Web site at http://www.state.ok.us/~owrb/reports/publications.html.

My Water Well—What You Should Know About Water Well Construction

Published by the Oklahoma Water Resources Board, this 19-page booklet explains the State's program for water-well drillers and pump contractors, what landowners should know before constructing a well, how to protect the well from contamination, and it offers many other helpful tips.

Order from: Oklahoma Water Resources Board, 3800 N. Classen, Oklahoma City, OK 73118; (405) 530-8800. There is no charge for the booklet. It also can be downloaded from the OWRB Web site: http://www.state.ok.us/~owrb/reports/publications.html.

Oklahoma abstracts

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

Microstructural Analysis of Pennsylvanian Sandstones: Implications for the Ouachita Mountains Kinematic Development

JASON W. CURRIE and *KEVIN J. SMART*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The Ouachita tectonic system, like the Appalachians, formed following collision of Laurasia and Gondwana during the final assembly of Pangea in the Late Paleozoic. The clastic-dominated Ouachitas, however, contrast with the Appalachians and its thick, lower Paleozoic carbonate sequence. This study area offers an opportunity to study foreland structural processes in a clastic-dominated fold-thrust system.

The Choctaw fault separates imbricated Pennsylvanian strata in the Ouachita frontal zone from the mildly deformed, Pennsylvanian and younger Arkoma Basin. Although, macrostructures in the frontal zone are well-studied, the complete kinematics of this system, particularly small-scale processes, remains incomplete. Here, microstructural analyses are used to more fully constrain the kinematic development of the frontal zone and Arkoma Basin. The data set yields information on variations in shortening direction and intensity along with data on the relative timing of thrust movements.

The target units are the Pennsylvanian Spiro sandstone in the frontal zone and Pennsylvanian Krebs Group sandstones in the Arkoma Basin. These units are well-exposed in the study area, and provide appropriate markers for detailed microscale strain analysis. Oriented samples will be analyzed with thin sections that are photographed under transmitted light and cathodoluminescence. Normalized Fry and Rf/ϕ methods will yield finite strains that can be analyzed with maps and cross-sectional profiles. Abundance and relative timing of microscale deformation mechanisms will be determined via systematic point-counting of microstructures. This work complements on-going research on Ouachita structural development and provides a starting point for more complete and systematic kinematic analyses of the Ouachita tectonic system.

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Three-Dimensional Deformation Analysis of Quartzarenites: Implications for Ouachita Mountains Tectonic Development

JASON W. CURRIE and *KEVIN J. SMART*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The Ouachita Mountains are an exposed part of the Ouachita orogenic belt that extends from western Alabama through Mississippi, Arkansas, Oklahoma, and on to the Marathon region of southwestern Texas. The Ouachita system formed during the final assembly of Pangea in the Late Paleozoic. Consisting of clastic-dominated deposits from Cambrian to Early Atokan time, the Ouachita system represents a rather unique opportunity to study foreland structural processes in a clastic-dominated fold-thrust system. Although, the macroscale structure of the frontal zone has been well-studied, the complete kinematic history (i.e., micro- to macroscale) of this clastic-dominated fold-thrust system remains poorly documented. In this work, microstructural analyses are used to more fully constrain the kinematic development of a portion of the Frontal Zone and adjacent Arkoma Basin in the region around Hartshorne, Oklahoma. Our kinematic data set should yield information on variations in shortening direction and intensity along with data on the relative timing of thrust movements in the transition zone from the Frontal Ouachitas to the Arkoma Basin. The target units are the Pennsylvanian Spiro sandstone in the Frontal Zone and sandstones in the Pennsylvanian Krebs Group to the north in the Arkoma Basin. These quartz-rich sandstones provide appropriate markers for detailed microscale strain analysis. Oriented samples are analyzed with the aid of three mutually-perpendicular thin sections that are photographed under both transmitted light and cathodoluminescence. Finite strain magnitudes and orientations are being measured with the normalized Fry and Rf/ϕ methods. These results can be combined to yield maps and cross-sectional profiles of depict variations in deformation intensity and direction. In addition to finite strain analysis, the abundance and relative timing of microscale deformation mechanisms will be determined via systematic point counting of microstructures. This work provides a starting point for a more complete kinematic analysis of the Ouachita Mountains tectonic system.

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Tectonic Evolution of the Ouachita Mountains Frontal Zone and Arkoma Basin: Insights from Microstructural Analyses

JASON W. CURRIE and *KEVIN J. SMART*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The Ouachita Mountains in southeastern Oklahoma and western Arkansas represent the exposed part of the larger Ouachita Orogenic System that extends from western Alabama to southwestern Texas. The system was dominated by Paleozoic shallow to deep-water deposition on the rifted, southern margin of Laurentia after the break-up of Rodinia. Convergent processes replaced tectonic quiescence in the late Paleozoic as subduction developed during the final assembly of Pangea. As a result, imbricated Pennsylvanian rocks in the Ouachita frontal zone are separated from the mildly-deformed, Pennsylvanian (and younger) Arkoma Basin by the Choctaw fault. While frontal zone macrostructures are well-studied, the kinematics

remain incomplete since the role of smaller-scale processes is poorly understood. Here, we present microstructural analyses that focus on more fully constraining the kinematics in the frontal zone and Arkoma Basin. The data includes spatial variations in shortening direction and intensity along with changes in deformation conditions as reflected by deformation mechanisms.

The target units are the Pennsylvanian sandstones that are well-exposed and provide appropriate markers for detailed microscale strain analysis. Oriented samples were photographed and analyzed with transmitted light and cathodoluminescence. Normalized Fry and Rf/ϕ methods yield finite strains that are used to assess variations in magnitude and orientation both across and along strike. Microscale shortening computed across the frontal zone and Arkoma Basin can be added to established macroscale estimates to provide a more complete kinematic analysis. Deformation mechanism timing and abundance determined via microstructural point counts provide indications of spatial and temporal changes in deformation conditions.

Reprinted as published in the Geological Society of America *2001 Abstracts with Programs*, v. 33, no. 6, p. A-82.

Assessing the Role of Deep Structures on Shallow Deformation in the Potato Hills, Central Ouachita Mountains, Oklahoma

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The Ouachita Mountains of southeastern Oklahoma are part of the larger Ouachita Orogenic System. Paleozoic shallow to deep-water deposition on the rifted margin of Laurentia was replaced by convergent processes in the late Paleozoic. The Potato Hills region in the central Ouachita Mountains represents a structural window through the uppermost folded thrust sheet. The Potato Hills are unique in that they expose moderately to strongly deformed Ordovician to Mississippian rocks within what is otherwise only mildly deformed Mississippian to Pennsylvanian rocks. Unlike many orogenic belts, there is not clear/convincing evidence for basement involvement in the Ouachita orogenic system. Recent natural gas exploration and production has focused interest on this structural anomaly and provided access to well-logs and high-resolution aeromagnetic data. Together with recently completed 1:24,000 scale geologic mapping, this offers an opportunity to reassess the role that deep structures played in the deformational history of this portion of the Ouachita orogenic system.

Geologic mapping and mesostructural analyses document tightly-folded and highly-fractured Ordovician through Mississippian siliceous shales and cherts throughout the Potato Hills that reflect the overall doubly-plunging, east–northeast trending anticlines and synclines. Previously undocumented Womble Shale in the hanging wall of the Potato Hills Thrust, together with consistent north vergence of mesoscale folds both within the window (footwall) and outside the window (hanging wall), further supports the window interpretation. Preliminary analysis of the aeromagnetic data suggests that surface and near surface structures (recorded during geologic mapping) can be traced to deeper levels. Mapping demonstrates that the "pre-window" geometry consists of a thrust fault that cuts upsection both to the north (in the transport direction) as well as laterally from east to west. Lineations in the magnetic data offer insight into the cause for lateral ramping and suggest a correlation between the position/geometry of shallow structures and deeper levels. Ultimately, this research may offer the first clear and convincing evidence for true basement-involved structures in the Ouachita Mountains.

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Structural Development of the Potato Hills: How Meso- and Macro-Scale Studies Aid in the Understanding of the Development of the Ouachita Orogeny, Southeastern Oklahoma

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The Ouachita Mountains in southeastern Oklahoma represent a portion of a 2000+ km long fold and thrust belt that record a long history of Paleozoic, clastic-dominated deposition prior to the closure of the Iapetus Ocean during the final assembly of Pangea. The Potato Hills region in the central Ouachitas exposes Ordovician to Mississippian stratigraphic units that are otherwise only exposed in the Black Knob Ridge area and the Broken Bow Uplift. Understanding the processes that led to the formation of the Potato Hills in southeastern Oklahoma is critical to our understanding of the overall development of the Ouachita Mountains. The Central Ouachitas are characterized by large open folds of Late Mississippian and to Early Pennsylvanian strata. The Potato Hills, in contrast, consist of tightly-folded and highly-fractured Ordovician through Mississippian siliceous shales and cherts. The elliptical Potato Hills exposure reflects the overall doubly-plunging anticlines and synclines that trend approximately 065–075°. During the course of this study, previously undocumented Womble shale was found in the hanging wall of the Potato Hills Thrust on the northern side of the window. The mapping and mesostructural analyses also document the consistent north vergence of the mesoscale folds both within the window (footwall) and outside the window (hanging wall). Finally, new exposures (courtesy of gas exploration) reveal the presence of a weakly-developed cleavage in selected shale intervals. To summarize, our new 1:24,000 scale geologic map and structural analyses, aided by the recent exploration, provides data that help to resolve the structural history of the Potato Hills. Our research confirms that the Potato Hills structure is an erosional window through a folded thrust sheet domed up by deeper thrust duplexing.

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Geochemical and Microbiological Aspects of Two Terrestrial Methane Seeps, Oklahoma, USA

GALEN MILLER, JOHN SENKO, and *LEE KRUMHOLZ*, Oklahoma Geological Survey, Norman, OK 73019; and *THOMAS DEWERS*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

We report on geochemical and microbiological studies of two terrestrial methane seeps in Oklahoma. Recent 1:24,000 scale geologic mapping in the Potato Hills, Ouachita Mountains in southeastern Oklahoma, has located an active methane seep along the southern exposure of the Potato Hills Thrust. The Potato Hills represent a window through a folded thrust duplex,

and are currently a target of extensive gas exploration. The gas is likely escaping along fractures in the hanging wall of the thrust and is found conspicuously bubbling through a nearby creek. A second locality is found at Zodletone Mountain near the frontal faults of the Wichita Mountains in SW Oklahoma. The spring is brackish, discharges at approximately 19 L/min year round and is chemically anomalous with respect to surrounding surface waters in that it is supersaturated with respect to barite, fluorite, and carbonate minerals. A slightly radioactive barite-calcite precipitate is actively forming in direct spatial association with biomass. Methane bubbles continuously at the spring source. Active populations of methanotrophic and sulfur-oxidizing microbes have been studied via microcosm and in situ methods. Inverse chemical modeling and isotopic constraints in both scenarios suggest methane and deeper fluid migrating to the surface via faults, and mixing with shallow meteoric water. These springs offer insight into the operative biogeochemistry at modern and paleo methane seeps in terrestrial environments.

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Outcrop/Behind Outcrop Characterization of Deepwater (Turbidite) Petroleum Reservoir Analogs: Why and How

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Increased emphasis on exploration for deepwater (turbidite) reservoirs during the past 25 years has resulted in many discovered fields. The current trend is for companies to fast-track field development, with minimum drilling, no workovers or intervention, increased use of subsea tiebacks, optimal individual well rates and ultimate recoveries, and expanded perforated intervals. To accomplish this requires a good understanding of the architecture of these reservoirs, and early prediction of their production performance based upon reservoir simulation.

Geologic models that are used for simulation are often built using a limited number of appraisal wells, which may hinder accurate bed correlations, and 3-D seismic, which may not resolve subseismic scale geologic features that control production, and thus the economic viability of the project. During the past few years, quantitative characterization of outcrops has supplemented subsurface data in the model-building process. To adequately document important reservoir properties at the wellbore, interwell and reservoir scales, however, requires studying large, continuous outcrops, preferably in 3-D. Unfortunately, such outcrops are rare, so that incomplete characterizations of reservoir analogs are normally the end product. In addition, mud-prone, thin-bedded deposits, which form a major portion of global deepwater reservoirs, normally do not provide as good an outcrop exposure as do sand-prone, thicker bedded deposits. Thus, accurate characterizations of the thin-bedded deposits are difficult to achieve. Incomplete models, or use of the wrong model for simulation, have given rise to one school of thought that regards outcrop data as being of limited value.

Despite these shortcomings, a second school of thought considers quantitative outcrop characterization as providing valuable information, particularly at the critical interwell scale. Information on shale- and sandstone-bed continuity, vertical connectivity, internal geometry and hierarchy of architectural elements, as well as stratigraphic variations in permeability are all important input attributes for understanding well performance, as well as for geostatistical modeling, upscaling geologic parameters, and providing well-log recognition criteria for predicting continuity away from a wellbore.

Several tools and techniques are used to characterize outcrops. Photomosaics and immersive 3-D visualization photoimaging provide a means of capturing architectural information in an electronic format amenable to overlay onto seismic sections or between wells. Logging, coring, and collecting seismic reflection data behind outcrops, as well as collecting gamma-ray, sonic velocity, and permeability profiles along outcrop faces provide data that can be directly compared with subsurface well logs and seismic. Ground-penetrating radar (GPR) provides the only means currently available for continuously imaging small-scale features behind an outcrop face.

These techniques have been successfully applied to outcrops of three mud- and mud/sand-prone deepwater (turbidite) deposits. Studies of the Upper Cretaceous Lewis Shale (southwest Wyoming) have provided (a) a high-frequency sequence stratigraphic framework for detailed correlation purposes; (b) borehole image criteria to distinguish sheet from leveed-channel sandstones; (c) quantitative 2-D bed continuity and connectivity information; (d) GPR images of the complex nature of the critical boundary between channel and levee/overbank deposits; and (e) a framework for development of a partial 3-D model of sheet and leveed channel deposits at reservoir scale. Studies of the Lower Pennsylvanian Jackfork Group (Arkansas and Oklahoma) have provided (a) a sequence stratigraphic framework; (b) interwell-scale 3-D geologic models of channel and sheet sandstones, including one that has been subjected to "reservoir" simulation; (c) quantitative bed continuity data at the interwell scale; and (d) GPR imaging for stratigraphic detail and paleocurrent analysis. Studies of the late Miocene Mt. Messenger Formation (New Zealand) have provided (a) a sequence stratigraphic framework; (b) dipmeter criteria to distingtush channel, proximal- and distal-levee deposits; (c) detailed thin-bed continuity and connectivity data; and (d) internal architecture of levee and channel-fill strata from outcrop and high-resolution seismic images.

Although complete 3-D outcrop geologic models of these deepwater (turbidite) deposits at reservoir scale are still elusive the results provide important information that is directly applicable to interpreting and predicting performance of analog reservoirs. Characterization of outcrops using the combination of tools and techniques described here should continue with the ultimate goal of providing the necessary quantitative information to help guide fast-track development of deepwater (turbidite) reservoirs.

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Surface Fracture Characterization of Jackfork Group Turbidite Sandstones in the Ouachita Mountains, Oklahoma: Implications for Gas Exploration

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The Ouachita Mountains fold-thrust system in southeastern Oklahoma and southern Arkansas represents the exposed portion of a >2000 km long orogenic system that includes the Marathon thrust belt in Texas, as well as the Appalachian orogenic system. The majority of the Oklahoma Ouachitas consist of Mississippian to Pennsylvanian clastic rocks of the Central Ouachitas that are deformed into broad, open synclines separated by tight anticlines and a few thrust faults. The Pennsylvanian Jackfork Group, a deepwater turbidite deposit, is a major exposed interval in the Central Ouachitas and plays an important role in the subsurface in Oklahoma as a tight gas reservoir interval (e.g., the Potato Hills field). Here we report initial results on characterizing outcrop scale fractures in the Jackfork. This work is part of a larger structural and stratigraphic study focused on fracture processes in deepwater turbidites and the implications of such fractures on tight gas reservoirs.

Fracture orientation and intensity measurements were collected via standard linear scanline techniques on several Jackfork bedding surfaces exposed in the north limb of the Lynn Mountain syncline south of Big Cedar, Oklahoma. Stratigraphic and mechanical bed thickness was also recorded for each surface. Two primary fracture orientations were observed. The more dominant set is approximately strike-parallel and bed-perpendicular with an average orientation of 104/60N. The second set is dip-parallel and bed-perpendicular with an average orientation of 017/89W. The second set generally terminates against the first. Both fracture sets show positive correlations between fracture spacing and bed thickness (particularly mechanical bed thickness) such that thicker beds exhibit larger spacings. Further work will focus on refining the areal fracture density, outcrop-scale connectivity, and also the relationship between lithology and fracture characteristics. As such, this research should aid current and future production from the Jackfork and similar stratigraphic intervals.

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Outcrop Fracture Characterization of Pennsylvanian Jackfork Group Sandstones in the Central Ouachita Mountains, Southeastern Oklahoma

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The Ouachita Mountains in southeastern Oklahoma and southern Arkansas represents the exposed portion of a >2000 km long orogenic system that includes the Appalachians as well as the Marathon thrust belt in Texas. This study focuses on the Central Ouachitas in Oklahoma, which is composed of primarily Mississippian to Pennsylvanian clastic rocks that are deformed into broad, open synclines separated by tight anticlines and a few thrust faults. The major exposed interval in the Central Ouachitas is the Pennsylvanian Jackfork Group, a deepwater turbidite deposit. Economically, the Jackfork Group plays an important role in the subsurface in Oklahoma as a tight gas reservoir interval, including the very prolific Potato Hills field. Here we report initial results on characterizing outcrop scale fractures in the Jackfork. This work is part of a larger structural and stratigraphic study focused on fracture processes in deepwater turbidites. As such, this research has implications for diverse areas ranging from the tectonic development of the Ouachita system to exploration in tight, natural gas reservoirs.

Fracture orientation, spacing measurements, and trace lengths were collected via standard scanline techniques on several Jackfork bedding surfaces exposed in the north limb of the Lynn Mountain syncline south of Big Cedar, Oklahoma. Both stratigraphic and mechanical bed thickness were recorded for each surface. Two primary fracture orientations were observed. The more dominant set, in terms of greater trace length, is nearly strike-parallel and bed-perpendicular with an average orientation of 104/60N. The secondary set is dip-parallel and bed-perpendicular with an average orientation of 017/89W. Our field observations show that the second set has a shorter average trace length and generally terminates against the first, although exceptions were observed. Both fracture sets show positive correlations between fracture spacing and bed thickness (particularly mechanical bed thickness) such that thicker beds exhibit larger spacings. Further work will focus on refining the areal fracture density, outcrop-scale connectivity, and also the relationship between lithology and fracture characteristics. As such, this research is an integral part of ongoing research into the tectonic development of the Ouachita orogenic system.

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Along-Strike Variation in Structural Styles Across the Ouachita Mountains: Effect of Stiff Layer vs. Weak Layer Ratio and Major Detachment Surfaces

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Map patterns illustrate a significant change in structural styles from east to west within the Ouachita Mountains. The frontal zone changes abruptly westward from broad faulted folds to narrow fault imbricates. Structural style of the central Ouachita Mountains changes westward from a core area of highly deformed pre-Meramecian rocks (Benton uplift) to broad northwest-vergent faulted folds. Morrowan to Atokan turbidites crop out in the cores of the synclines. In contrast to the central Ouachita Mountains, the southern Ouachitas change eastward from a core area of deformed pre-Meramecian rocks (Broken Bow uplift) to north-vergent broad faulted folds. The Mississippian Stanley Group turbidites which separate the eastern and western parts of the central and southern Ouachita Mountains encompasses as a wavelength transition zone. Differences in observed fold wavelengths for different formations result from variation in thickness ratio of stiff-layer versus weak-layer strata across the Ouachita Mountains. The shortest fold wavelengths are in the core areas of the central and southern Ouachita Mountains where thin stiff-layer cherts and sandstones are interbedded with thicker weak-layer shales. Longer wavelength folds are in the eastern part of the frontal and southern Ouachita Mountains, and in the western central Ouachita Mountains. These longer wavelength folds are restricted to the upper Stanley Group through Atoka Formation where thick units of stiff-layer sandstone and interbedded shale turbidites predominate. Several detachment horizons within the Paleozoic sequence affect the overall structure of the Ouachita Mountains. For example, along the eastern frontal belt, the Morrowan Johns Valley Shale (Y-City fault) detachment serves as a south-vergent delamination backthrust, where north-directed allochthonous strata are underplated and overturned southward beneath an extremely thick (8500 m) passively uplifted Atoka Formation. In the western part of the frontal zone of the Ouachita Mountains, where the Atoka Formation is much thinner (<1600 m), a lower Atoka Formation shale serves as a backthrust detachment.

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Regional Correlation of the Paleozoic Stratigraphy of the Ouachita Salient, and Implications for Tectonic History

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Mostly buried beneath the Mesozoic-to-Recent Gulf Coastal Plain, imbricated and folded Paleozoic rocks of the Ouachita-Marathon orogen extend sinuously southwestward from eastern Mississippi to southwest Texas. The Ouachita salient is a sharp deflection in the Ouachita-Marathon orogen that extends northwestward from eastern Mississippi to eastern Oklahoma, and then southwestward to central Texas. The Ouachita Mountains of eastern Oklahoma and western Arkansas are the largest exposure of Paleozoic rocks within the Ouachita-Marathon orogen. Comparison of stratigraphy of predominantly deep-marine facies Paleozoic formations of the Ouachita Mountains with shallow-water correlative formations located in the foreland provides clues to regional tectonic history.

A new chronostratigraphic correlation chart based upon a compilation of published sources correlates shallow-water facies formations within the foreland of the Ouachita salient. Another new chronostratigraphic chart correlates shallow-water facies formations with deep-water facies equivalents. Deep-water facies formations can be placed in approximated restorated position. Regional unconformities of varying lateral extent separate the Paleozoic section into discrete packages. In some areas, unconformity surfaces are highly time-transgressive.

A generalized restored stratigraphic cross section constructed across the center of the Ouachita salient shows regional variations in formation thicknesses and lateral facies changes. The cross section extends in zig-zag trace from the Ardmore basin of eastern Oklahoma east to the Broken Bow uplift region, southeast to northern Louisiana and northward towards the southern flank of the Ozark dome. Stratigraphic columns of allochthonous deep-water facies rocks from several locations within the Ouachita Mountains are approximately restored relative to the autochthon. This new restoration suggests a Late Ordovician transgression of deep-water facies shales and cherts onto the Paleozoic carbonate platform of eastern Oklahoma and to a lesser extent in Arkansas). The facies transition is near the southeastern edge of the Tishomingo anticline and may bend into the southeastern Ardmore basin.

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The Stress Field During Continent-Continent Closure Inferred from Joint Distribution in the Ouachita Belt and Arkoma Basin

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Three structural domains developed in the foreland of the Ouachita orogeny in Oklahoma and Arkansas during closure of South America into North America. To the south, a region of large, internally coherent, monoclinally-dipping thrust sheets known as the central thrust belt abuts a middle, internally-faulted, complexly-folded section known as the frontal imbricate zone, that is, in turn, bounded on the north by the gently folded cover rocks of the Arkoma basin. Fracture data collected from the three structural provinces indicate that in the relatively uniformly-dipping Arkoma basin and central thrust belt, the regional cross-fold joint sets are consistently oriented among outcrops. In contrast, joints in the frontal imbricate zone, where bedding dip domains are of limited extent, are less organized and occupy a larger range of orientations.

Joints in the Pennsylvanian section of the Ouachita belt and Arkoma basin document both regional and local stress fields present during the Ouachita orogeny. Most regionally traceable joints are sub-parallel to the transport direction within the Ouachita fold belt. In the Arkoma basin, cross-fold joint orientations range from 340–360°, in the central thrust belt, 355–010°, and in the frontal imbricate zone, 340–025°. Fringe cracks found within these strike ranges identify a clockwise evolution of stress, except in the southernmost central thrust belt, in which they suggest anticlockwise rotation. This clockwise trend is found on such a large scale that it reflects the convergence of South America upon North America. An initial, pre-folding compression is preserved in fractures throughout the autochthonous Arkoma basin. In the central thrust belt, these signature joints propagated early but were rotated 10–15° clockwise during thrust emplacement. Therefore, we infer that the fit between North and South America during continent-continent closure favored the regional realignment of the crustal-scale stress field in a clockwise manner.

Continued jointing accompanied faulting and folding in the frontal imbricate zone, where joint strike-domains change from the hanging wall to the footwall of faults. In addition, outcrops on fold noses and near thrust faults display a dominant joint set that is normal to the transport direction, indicating a local structural influence.

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Flexure, Bending Stresses, and Fluid Migration in Foreland Basins

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Foreland basins develop adjacent to mountain belts as a result of flexural downwarping and rapid sedimentation associated with uplift, thrusting, and erosion during orogeneis. Flexural compensation of surface loads in mountain belts and adjacent foreland basins has several effects that are potentially important in understanding hydrocarbon migration. First, flexural compensation acts as a buffer in development of topography. During accumulation/removal of surface masses, flexural compensation causes the surface to move downward/upward, thus reducing the net increase/decrease in topography. This effect has been ignored in some fluid migration models of foreland basins and thus paleotopography (and topography-driven fluid migration) has been overestimated. Instead, flexural compensation causes strata to tilt towards the fold-thrust belt during orogenesis. Subsequent erosion causes the tilt angle to decrease. These changes in dip angle with time can effect buoyancy-driven hydrocarbon migration. Flexural compensation also produces a bulge or upwarp at the edge of the foreland basin. A basement upwarp may act as structural trap and/or focus fluids upwards into a trap. Finally, flexure of the elastic portion of the lithosphere can generate tensional bending stresses in the vicinity of the flexural bulge. These stresses can exceed the tensile strength of rocks and should produce fractures and faults, which may act as pathways for fluid migration. Moreover, upwards movement of hot fluids out of the underlying basement may generate additional heating of overlying sediments and thus alter the extent or timing of thermal maturation. Using a two-dimensional profile across the Arkoma basin, where the thickness of eroded sediments can be estimated from coal rank, these four effects are quantitatively evaluated.

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Deep-Water Lower Atoka Formation, Ouachita Trough, Oklahoma

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Deep-water lower Atoka Formation (middle Pennsylvanian) crops out in road cuts along OK-2 south of Wilburton and OK-82 south of Red Oak, OK. Exposures are discontinuous and reveal complex structural geometry within the Ouachita fold-thrust belt (Choctaw to Winding Stair faults). A composite section is being constructed from detailed measured sections and natural gamma-ray (GR) emission logs. The emphasis to date has been on OK-2 exposures south of the Ti-Valley fault system and continuing southward to the Winding Stair fault, which is ~13 km south of Wilburton. Paleocurrent data indicate that coarse sediment was derived from several sources and delivered to the Ouachita trough mainly by turbidity currents.

From detailed studies along OK-2, mudrocks dominate the section with interstratified sandstone beds rarely exceeding 0.5 m thick. Both total and spectral GR logs have proven to be useful in correlating outcrop sections. Using conventional correlation approaches and total GR emissions, general correlation is possible, but ambiguous at the bed-to-bed scale. Because Th/K GR emissions is positively correlated with mica content in sandstones, detailed correlation of individual sandstone beds is unambiguous. Bouma Tc beds, with a thin Tb cap, are most common. Tc intervals are typically convoluted. Locally, Ta beds and thin Tb-c intervais are well developed. Paleocurrent indicators show a westward transport direction in the southern exposures and eastward transport direction in the northern exposures.

Exposures along OK-82 (~16 km west of OK-2) are also being studied with large-scale correlation being possible using an airborne radar image. Some preliminary findings include the mapping of a very large submarine slump block(s). The southern section is much thicker and sandier compared to the OK-2 and northern exposures; it also includes paleocurrent indicators showing northwestward transport. Other sections expose 1-m-thick, Ta-e sandstones.

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Structural Traps along the Frontal Ouachitas–Arkoma Basin Transition Zone, Southeastern Oklahoma

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We have studied the lower Atokan Spiro gas reservoirs along the Frontal Ouachitas–Arkoma Basin transition zone between the Wilburton gas field and Wister Lake in terms of their structural geometry, small-scale structures, pressure-depth gradient and mineralogy. In this area, the footwall block of the Choctaw Fault illustrates a transitional structural style into a foreland basin. The deep Woodford Detachment ramps up to the stratigraphically higher Springer Detachment and serves as the floor to the duplex that contains all the structural traps of the Spiro reservoirs. The Lower Atokan Detachment splays from the Springer Detachment forming both a roof to the duplex structure and a floor for a triangle zone. A north-dipping backthrust bounds the San Bois Syncline to the south, and serves as the northern boundary of the triangle zone. The thrust is at the surface in the Wilburton gas field area where it is called the Carbon Fault. Eastward along the strike of the transition zone, the backthrust becomes a blind backthrust and the duplex structure contains fewer horses. When restored to their position at the time of the Spiro deposition by using the "key-bed" restoration method, our balanced structural cross-sections indicate about 60% shortening in the Wilburton area but about 40% shortening in the Wister Lake area. In the duplex structures, the Spiro reservoirs that were brought to structurally higher positions by the thrust faults generally exhibit higher pressure-depth gradients. The Spiro sandstone contains well-developed deformation bands along the Choctaw fault zone. Considering that this may also be true for the thrust faults in the duplex structure, permeability barriers for gas accumulation in the Spiro may have been created by the thrust faults. These suggest to us that thrust faults of the duplex structure may have provided sealing for structural traps of the Spiro reservoirs.

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Depositional Delivery Systems for the Atoka Formation (Middle Pennsylvanian), Southern Midcontinent, United States

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The Atoka Formation (Middle Pennsylvanian) comprises three separate terrigenous clastic delivery systems along the southern margin of the North American midcontinent (Arkansas and Oklahoma). These systems consistently reflect system input to the east, along the present Mississippi Embayment, but petrographic data indicate sources in both the southern Appalachians and eastern craton. Thus, there are three coeval, homotaxial, but discrete systems that delivered terrigenous clastics to the southern Ozark shelf, the Arkoma basin, and the Ouachita orogen, respectively. The Atoka Formation of the Ozark shelf is characterized by cyclic, shallow, epeiric marine conditions, with a predominance of tidal to tidally-influenced sequences. Fluvial systems combined sediments derived from the eastern midcontinent and southern Appalachians. They entered the northern Arkoma shelf along what is now the Mississippi Embayment, where the clastics were distributed by east–west longshore currents. These delivery systems may have produced barrier islands high on the Arkoma shelf, but are mostly represented by a series of constructive and tidal delta systems oriented east–west along the axis of the Arkoma foreland basin. Fluvial systems feeding the Ouachita trough combined sediments derived from both the southern Appalachians and the active Ouachita Orogen producing turbidite sequences. The Ozark and Arkoma successions exhibit a change from open marine in the lower portion of the formation to more restricted conditions in the middle and upper Atoka. All three successions exhibit a flooding of MRFs in the middle and upper Atoka interval, indicating the proximity of a high rank metamorphic source produced by compressional tectonics in the southern Appalachians that were initiated in middle Atokan time.

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Sulfur and Organic Carbon Relationships Within the Fancy Hill Barite District, Mississippian Stanley Formation, Ouachita Mountains, Arkansas

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The Mississippian Stanley Formation is the basal formation of an extensive Carboniferous flysch sequence exposed in the Ouachita Mountains of west-central Arkansas and southeastern Oklahoma. Bedded barites occur near the base of the organic carbon-rich Stanley Formation and are exposed in the Fancy Hill district along the north rim of the Mazarn synclinorum. The barite-rich zone is between 18 and 30 meters thick and is generally within 30 meters of the basal contact with the Arkansas Novaculate (Devonian).

Sulfur and organic carbon distributions suggest a variable history of the sulfur within the Stanley Formation that is closely tied to the presence and nature of the organic matter in the system, and the association of sulfur to the more mobile organic compounds. The mean isotopic value for the $\delta^{34}S$ of the pyrites in the barite zone is –0.65 per mil, roughly 15 per mil lighter than coeval seawater. The sulfur to organic carbon relationship in the Stanley Formation reflects an increase of sulfur in the shale portion of the formation in the areas adjacent to the bedded barites, and a slight depletion of sulfur in the shales in areas outside the enrichment zones. The resulting pattern observed in the data is likely due to a two stage process which initially entrained excess sulfur through biologic processes and trapped it as barium sulfate, early diagenetic pyrite, and as organic sulfur. The second stage of the process is marked by remobilization of the organically bound sulfur, accompanied by migration of hydrocarbons, during burial and low grade metamorphism. Organic carbon contents of the altered Stanley samples rarely drop below 0.5 wt% organic C which is thought to represent the remnants of the resistant terrestrial material brought into the basin along with the flysch sediments. The relationship between sulfur and organic carbon content when combined with sulfur isotopic data suggests primary biologic activity may have been a significant factor in the development and long term preservation of the Fancy Hill deposits.

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A Basinward-Thickening Condensed Section, the Heebner Shale Member of Oread Formation (Virgilian), Southeastern Kansas and Northeastern Oklahoma

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The widespread Heebner Shale of the Pennsylvanian Oread Cyclothem was deposited on the inland Kansas shelf and adjacent basins in a paleoequatorial belt during a maximum marine flooding. It overlies persistent and thin (~50 cm) transgressive Leavenworth Limestone and underlies persistent but variably thick (1–8 m) regressive Plattsmouth Limestone on 30 measured sections in a 100 × 20 km² area in southeastern Kansas and northeast Oklahoma. On the shelf, the Heebner is thin (1–3 m) and dominantly black with abundant phosphatic nodules, indicating anoxic conditions. At the shelf margin and slope to the south, however, the Heebner thickens abruptly to ~10 m and consists of green, moderately fossiliferous shale and silty shale, indicating aerobic to dysaerobic conditions. Preliminary interpretation suggests that sediment source and dispersal pattern, oceanic circulation, eustasy, and depositional topography combined to cause the basinward changes of the Heebner Shale. The basinward thickening, which differs from the basinward-thinning trend of the passive-margin sequence stratigraphic model, was caused by prodeltaic progradation across the filled Arkoma Basin, suggesting an episode of deltaic progradation during maximum flooding. Shelf anoxia was probably caused by stagnant circulation induced by freshwater atop dense oceanic water on the shelf because of the large freshwater influx in the doldrums. In contrast, aerobic/dysaerobic conditions at the shelf margin and slope were caused by intensified oceanic circulation related to large influx of prodeltaic sediments and river runoff.

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Deltaic Progradation During Maximum Marine Transgression, the Heebner Shale Member of the Oread Limestone Formation (Virgilian), Southeast Kansas and Northeast Oklahoma

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The widespread Heebner Shale of the Pennsylvanian Oread Cyclothem was deposited on the Kansas shelf and adjacent basins in a paleoequatorial belt during a maximum marine flooding. It overlies persistent and thin (~50 cm) transgressive Leavenworth Limestone and underlies persistent but variably thick (0–8 m) regressive Plattsmouth Limestone along a 120-km outcrop in southeastern Kansas and northeast Oklahoma. In the northern and central outcrop belt, the Heebner is thin (1–3 m) and dominantly black with abundant phosphatic nodules, representing a condensed section deposited on an anoxic to dysaerobic starved shelf. In the southern belt, however, the Heebner thickens to 30 m over a distance of 30 km and consists of upward-coarsening green-gray plant-rich shale, siltstone, and sandstone, deposited in prodeltaic to delta-front environments. The delta was sourced by the Ouachita thrustbelts and prograded across the filled Arkoma Basin during maximum flooding and sea-level highstand. The sediment yield in the source area was copious because of efficient weathering due to the humid equatorial climate and the high topographic relief. Sediment transport was efficient due to the low wave energy in the inland sea, the large river discharge, and the steep topographic gradient between the source area and depositional site. The large river runoff also contributed to shelf anoxia by freshwater capping dense oceanic water, causing stagnant oceanic circulation. The findings are not predicted by the depositional sequence model and signify the interplay of oceanic and climatic processes, sediment yield and sediment supply, and topography of drainage basins during sequence formation.

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Where Layer-Cake Stratigraphy Breaks Down—The Coeval Development of Highstand Deltas, Condensed Sections, and Platform Carbonates of the Virgilian Oread Cycle, Southeast Kansas and Northeast Oklahoma

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The Oread cycle contains a succession of marine and nonmarine siliciclastic and carbonate rocks deposited on the epeiric Kansas shelf in Late Pennsylvanian. It has been a classic example of layer-cake stratigraphy because of its persistent component lithologies. Outcrop and subsurface facies analysis and cycle correlation using 45 sections along a 100-km outcrop and 200 logs covering 32,000 km^2 indicate great lateral thickness and lithologic changes that falsify layer-cake stratigraphy. The limestones, except the transgressive Leavenworth Limestone, thicken from 10's of cm in the lagoon to ~10 m in the phylloidal algal mounds, and thin on the basin slope where they developed a middle shale. They also pinch out into or juxtapose with thick deltaic deposits to the south. The condensed Heebner Shale on the shelf is black, thin (2 m), phosphatic but changes abruptly into thick (30 m) gray prodeltaic shale to the south. The regressive marginal marine and nonmarine siliciclastic deposits become thicker and more sandstone-rich to the south. Paleotopography, controlled by regional tectonics and local differential compaction, determined the facies mosaic, whereas eustasy controlled the facies migration and higher-order cyclicity. The proximity to the Ouachita source area caused the regional southward thickening and coarsening of siliciclastic deposits and, combined with the precipitation seasonality, caused development of Heebner delta during maximum transgression. The juxtaposition of condensed Heebner Shale and Plattsmouth Limestone on the shelf with the Heebner delta was controlled by alongshore currents associated with oceanic upwelling systems.

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Comparison of the Ouachita and Carpathian Fold Belts

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The Late Paleozoic Ouachita orogenic belt is a north-vergent thrustfold belt, related to an A-type subduction of the passive margin of North America. The thin-skinned Ouachitas and their deep foredeep basins were formed during this southward directed subduction. Synchronously with compression in the thrust-fold belt, thick Pennsylvanian to Permian marine sediments were deposited to the south of the Ouachita belt, in the Paleozoic Gulf of Mexico. The loop of the late Tertiary Carpathians surrounds the back-arc Pannonian basin, and it forms a continuous, thin-skinned thrust-fold belt that is coeval with the middle Miocene extension on its concave side. The evolution of the outer Carpathians is dominated by the formation of thick flysch nappes verging toward the foreland and an associated deep foredeep basin.

To compare these systems, two maps were compiled based on several sources showing the main structural features in both systems at the same scale. Certain generalizations had to be made to arrive at a compatible legend for both maps. Besides the map-view similarity, the cross-sectional expression of the two systems is also comparable, illustrated by a pair of crustal-scale sections drawn in analogous position through these fold belts.

Several specific details are strikingly comparable both in map and in cross-sectional view. The foreland basement promontories are of comparable size and kinematic role, such as the Llano uplift/Bohemian massif and the Arbuckle uplift/Holy Cross Mts. The Arkoma basin finds its counterpart in the Polish sector of the Carpathian foredeep basin. The strongly deformed zone of the Maumelle chaotic zone is directly comparable to that of the Pieniny Klippen belt.

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Comparative Analysis of the Exploration Potential of the Thrust Belts and Foreland Basins of North America

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The Phanerozoic thrust belts and foreland basins of North America were analyzed as part of a study of 27 petroliferous thrust belts and adjacent foreland basins from around the world to compare and contrast their petroleum systems. Those studied were the Appalachian, Ouachita, Arctic Canada, Brooks-Colville, Rocky Mountain, and Mexican systems. These petroleum systems vary significantly in their details, but have several overarching commonalities.

Even though each of these thrust belt systems has distinctive assemblages to make each unique, they have several, similar, key petroleum system factors. The distribution of source rock, which is spatially associated with thrusting, controls the extent of hydrocarbon productivity. In each system the primary source rock went through peak oil and/or gas generation during the main period of thrusting. Syn-orogenic traps captured some of the expelled hydrocarbons. At the same time, pre-orogenic source rocks typically passed through their full expulsion and thermal range, and previously trapped oil remigrated upward, or was catagenically converted to gas or destroyed. Where trap geometries were available, production has been established in preorogenic, syn-orogenic, and post-orogenic traps in both carbonate and siliciclastic reservoir rocks.

Analyses of mature hydrocarbon provinces, such as the Appalachians, Ouachitas, and Rocky Mountains, help assess the future potential of the Arctic Canada, Brooks-Colville, and Mexican thrust belts and foreland basins. Assessment of effective trap and product type also become less risky with these comparative analyses.

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Origin of Disharmonic Folding: Revisited

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Viele (1995) looked at the disharmonic folding pattern in the Central Ouachita Mountains and concluded that the "lower deck" represented an earlier stage of deformation in an accretionary wedge and that the "upper deck" consists of sediments that prograded across a quiescent accretionary wedge. Late Carboniferous thrusting subsequently deformed both. Recent mapping between the Boktukola and Octavia faults provides insight into this contact. Outcrops were located with DGPS, coupled with remotely sensed imagery. These data were overlain on a digital elevation model utilizing GIS, producing 2D and 3D surfaces. The discontinuity between the decks is well exposed at Big Eagle Creek. At road level, the younger shales of the Stanley Formation are gently dipping towards the west, while in the creek steeply dipping, thin, tightly folded turbidite beds are apparent. A zone of extremely fissile shale extends ~3 m from road to creek level. This fabric is believed to record significant flattening, although no strain markers have been found. A ~1 m brecciated zone separates these cleaved rocks from the steeply dipping and tightly folded rocks below. This contact is interpreted to be a low angle fault. The fault trace (Buffalo fault) was mapped across the area. It follows the broad fold patterns of the Boktukola syncline and Nanichito anticline. The Boktukola fault appears to truncate the Buffalo fault but the latter may be a splay. The proposed Buffalo fault is a low angle thrust fault whose footwall contains high frequency, highly strained, east–west trending structures similar to the Benton uplift of Arkansas, in contrast to the open structures of the hanging wall characteristic of the Boktukola syncline. No evidence for an unconformity was observed. These data do suggest an earlier folding history preserved in the footwall rocks. Assuming the entire sequence is allocthonous and displaced over the basement sequence of the Broken Bow uplift, then these early structures probably reflect deformation in the accretionary wedge.

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Along-Strike Diachroneity of Ouachita-Marathon Orogeny

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The trace of the late Paleozoic Ouachita-Marathon thrust belt mimics the outline of the pre-orogenic passive margin around the Ouachita and Marathon embayments of southern Laurentia. Passive-margin strata of both shelf and off-shelf deep-water facies are overlain by synorogenic clastic-wedge deposits, which are diachronous along strike.

Deposition of a thick succession of deep-water mud-rich turbidites (Tesnus Formation) began in the Marathon embayment in Early Mississippian time, before initiation of similar deposition (Stanley Shale) in the Ouachita embayment during Meramecian (early Late Mississippian) time. Progradation of synorogenic clastic sediment over the passive-margin shelf progressed from east to west along the Ouachita embayment, beginning in the Black Warrior foreland basin in Meramecian time and reaching the Arkoma foreland basin by Atokan (early Middle Pennsylvanian) time. Pennsylvanian synorogenic deposits overlap shelf strata in the Fort Worth, Kerr, and Val Verde basins. Subsidence of the Marathon foreland began in middle Pennsylvanian time, somewhat later than in the Ouachita (Arkoma) foreland.

In the Arkoma foreland basin, the facies succession and a decrease in sedimentation rates mark the end of orogeny in Desmoinesian (late Middle Pennsylvanian) time. Similarly, in the subsurface south of Ouachita thrust-belt outcrops, Desmoinesian to Permian shallow-marine clastic and carbonate facies overlie deformed pre-Desmoinesian Ouachita strata at a distinct angular unconformity. In contrast, final Marathon thrusting is documented by an angular unconformity in the middle of the Wolfcampian (lower Lower Permian) succession.

Along-strike, east-to-west progression of Ouachita-Marathon orogeny is generally recognized; however, in detail, the pattern of along-strike diachroneity is more complex. Heterogeneity of provenance indicators suggests multiple, composite arc terranes, including a Silurian–Devonian orogen and possibly older continental crust, along with obduction of oceanic crust. Along-strike diachroneity reflects accretion of multiple terranes around the embayments and promontories of southern Laurentia.

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Tectonic Implications of Crustal Scale Models of the Ouachita Orogenic Belt

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The southern margin of Laurentia was created by Neo-Proterozic to Cambrian age rifting. The resulting continental margin was relatively stable until the Ouachita-Appalachian orogeny which involved a complicated series of collisional events followed by Mesozoic rifting. However in the case of the Ouachita region, this margin is well preserved since the orogeny did not pervasively deform it. We have compiled geological and geophysical data along the Ouachita portion of the margin and have created updated models of lithospheric structure across and along it. One model starts on the craton in Tennessee, crosses the Black Warrior foreland basin, the Ouachita thrust belt, the Mississippi salt basin, and the Wiggins arch before ending in the Gulf of Mexico. The most prominent features on this model are the crustal-scale block associated with the Wiggins arch and the crustal thinning under the Mississippi salt basin. Another N–S trending model located to the west shows another crustal scale block which extends across much of western Louisiana. On both of these models, the continental margin is narrow suggesting the presence of transform faulting. In central Texas, no crustal block is found outboard of the Laurentian margin and the transition from continental to oceanic crust is broad which may reflect the effects of both Cambrian and Mesozoic rifting. The cratonal region adjacent to the margin has been significantly deformed creating large structures such as the Southern Oklahoma aulacogen, the Reelfoot rift, and a series of foreland basins all of which represent significant modification of the crust. In spite of subsequent events, it seems clear that the formation of the Laurentian margin formed the structural framework of the region that has lasted to the present.

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