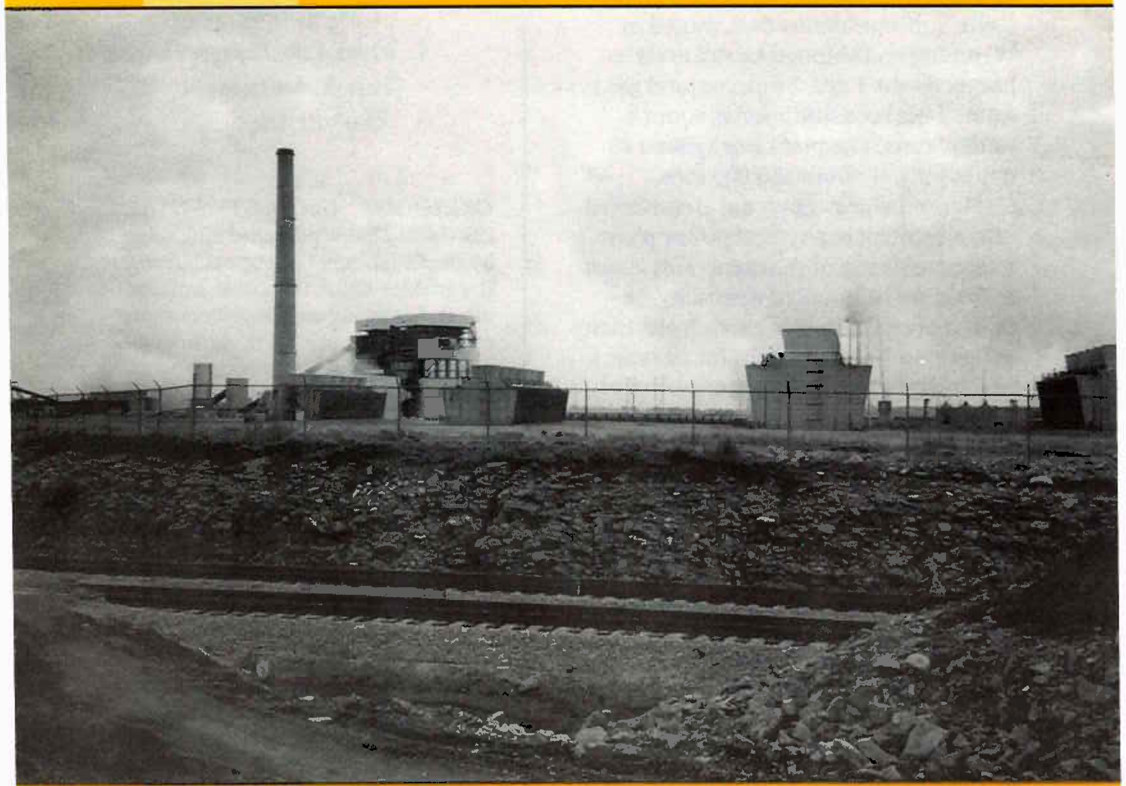
Oklahoma Geology Notes



August 1999

Vol. 59, No. 4

On The Cover —

The PSO Power Plant at Oologah, Oklahoma

The coal-fired electric power plant shown on the cover is at Oologah, Oklahoma, about 1 mi west of Oologah Dam; the plant is owned and operated by the Public Service Company of Oklahoma (PSO). In the foreground, ~10 ft of the Oologah Limestone is exposed in a cut made for a 10-mi-long railroad spur between the plant and the Burlington Northern Santa Fe Railway near Sequoyah.

The Oologah power plant (units 3 and 4) burns daily about 12,000 tons of low-sulfur subbituminous coal, mined in Wyoming and shipped by rail to Oklahoma. (Units 1 and 2 burn natural gas.) Annual coal consumption is about 4 million tons. The plant stockpiles a 45-day supply — about 550,000 tons.

Figure 1 shows how coal is converted into electricity in a typical power plant. In general, a ton of coal generates about 2,000 kilowatt hours of electricity. (A pound of coal supplies enough electricity to light ten 100-watt bulbs for an hour.) In the United States, coal consumption in the 1990s is about 20 pounds per person per day (Energy Information Administration, 1995, p. 30, 33), and (according to statistics in the *World Almanac,* based on the 1990 Census) 2.7 persons live in a typical home. Thus the Oologah power plant supplies electricity for roughly 440,000 homes.

The Oologah plant, rated at 910 net megawatts per hour, serves primarily Tulsa and the area north and east of that city, but can transmit the electricity as far as western Texas.

(continued on p. 139)

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OKLAHOMA GEOLOGY

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GEOLOGY ALONG THE NEW PSO RAILROAD SPUR, CENTRAL ROGERS COUNTY, OKLAHOMA

LeRoy A. Hemish[1] *and James R. Chaplin*[1]

Abstract

A 10-mi railroad spur connecting the Public Service Company of Oklahoma power plant at Oologah with the Burlington Northern Railroad near Sequoyah was built in 1994–95. (The railroad was renamed Burlington Northern Santa Fe Railway in September 1995, when Burlington Northern merged with the Santa Fe Pacific Corporation.) Several cuts excavated during construction expose extensive sections of rocks in the Senora, Fort Scott, Labette, and Oologah Formations (Pennsylvanian System, Desmoinesian Series). Geologic descriptions of these rocks at seven locations in the cuts indicate predominantly fossiliferous marine limestones, gray silty shales containing some siltstones and very fine grained sandstones, and minor black shales and coals.

Minable coals in the area include the Croweburg, ~1.5 ft thick, and the Iron Post, ~1.2 ft thick. In the past, these bituminous-rank coals have been extensively strip-mined. Now the Iron Post coal has the most remaining reserves, and could be strip-mined in T. 22 N., R. 16 E., in the vicinity of the PSO Railroad.

Introduction

Prior to 1995, subbituminous coal from Wyoming was shipped to the electric-power plant at Oologah (Fig. 1) via the Union Pacific Railroad, the only railroad nearby. In the early 1990s the plant's owner, the Public Service Company of Oklahoma (PSO), felt a need for an alternative freight carrier and began planning a new railroad spur in central Rogers County. The Benham Group of Tulsa, Oklahoma, was selected for the design work. Construction of the spur, nearly 10 mi long, began in 1994 and was completed in 1995. The new railroad linked the plant at Oologah with the Burlington Northern Santa Fe (BNSF) Railway near Sequoyah (Fig. 1). Construction cost about $18–$20 million but, according to plant officials, savings on freight rates enabled the PSO to recover the cost in about 3 years.

The coal is delivered by unit trains that run on the average about once a day. (Unit trains are made up of specialized cars designed to handle one commodity.) Each unit train delivers ~12,000 tons, which satisfies the daily raw-material needs of the plant. A train consists of about 115 railroad cars, each carrying about 100 tons of coal. The plant unloads an entire unit train in about four hours, or one car every two minutes (PSO Coalyard Supervisor, Northeast 3 and 4, personal communication, 1999).

As excellent bedrock exposures of varying depths resulted from construction of the railroad spur, the authors secured permission from PSO to study the exposures and to describe the rocks in detail along the entire route. Figure 2 shows this route, the geology of the area, and locations where sections of exposed rock were described and photographed.

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[1]Oklahoma Geological Survey.

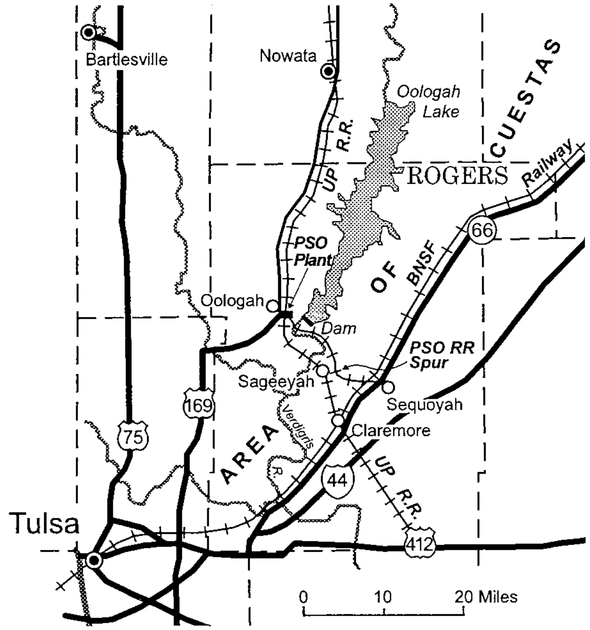


Figure 1. Map shows the location of the PSO plant at Oologah in northeastern Oklahoma, the new railroad spur and its connection with the Burlington Northern Santa Fe (BNSF) Railway near Sequoyah, and the study area (see Fig. 2). Modified from Hemish, 1999, fig. 1, after Oklahoma Department of Transportation, 1996.

This paper provides a preliminary report on the stratigraphy of the study area. Other geologic information such as (1) a structural profile along the tracks, (2) economic aspects of surface-to-subsurface correlations of reservoir rocks, (3) detailed descriptions of measured sections, and (4) reevaluation of the stratigraphic relations of the interval from the Verdigris Limestone and underlying black shale through the Oologah Limestone, will be published later by the Oklahoma Geological Survey.

Geology Along the PSO Railroad Spur

The new PSO Railroad spur crosses some of the most scenic country in the State. Central Rogers County lies within the Claremore Cuesta Plains—a geomorphic province characterized by resistant Pennsylvanian sandstones and limestones that dip gently westward, forming cuestas between broad shale plains (Curtis and Ham, 1972, p. 3).

At its junction with the BNSF Railway (Fig. 2), the spur is built on one such shale plain underlain by an unnamed shale member of the Senora Formation (Fig. 2, segment I; see Fig. 3 for a stratigraphic column showing rock units exposed in the study area.) About 1 mi west the track crosses an area of strip mines (once abandoned, but since reclaimed) where the Croweburg coal was mined (Fig. 2, segment II). About 0.25 mi farther northwest, the railroad grade crosses another abandoned strip mine (Fig. 2, segment III). The final cut is now filled with water.

About 0.25 mi yet farther northwest, the tracks climb up onto a subtle escarpment (or cuesta) formed by resistant limestones (Breezy Hill, Blackjack Creek) that have been preserved in a syncline as an outlier east of the main outcrop boundary

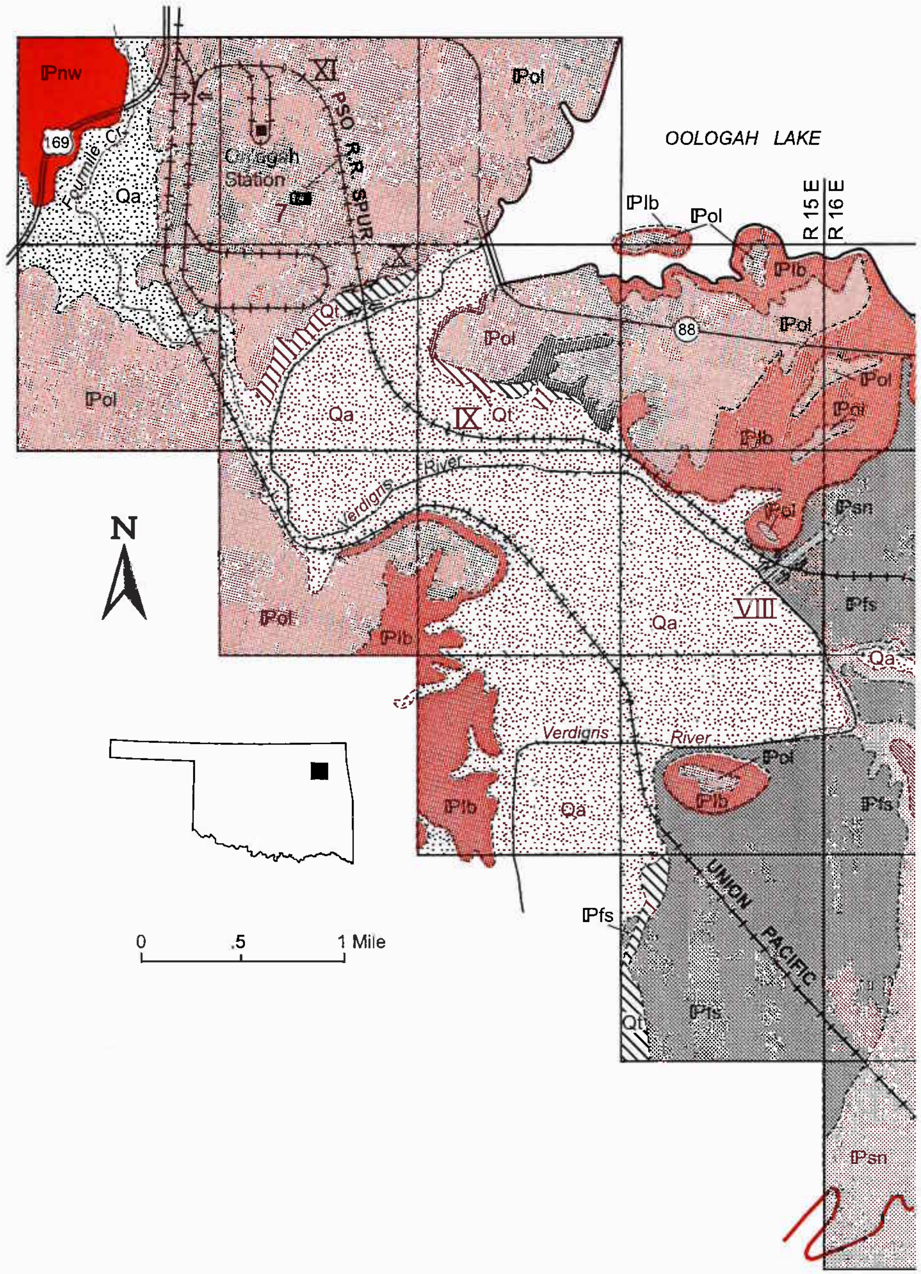


Figure 2. Generalized geologic map depicts the area of the PSO Railroad spur. Roman numerals mark segments discussed in the text; Arabic numerals correspond to the figure numbers (photographs). The base map is from the Benham Group, 1994.

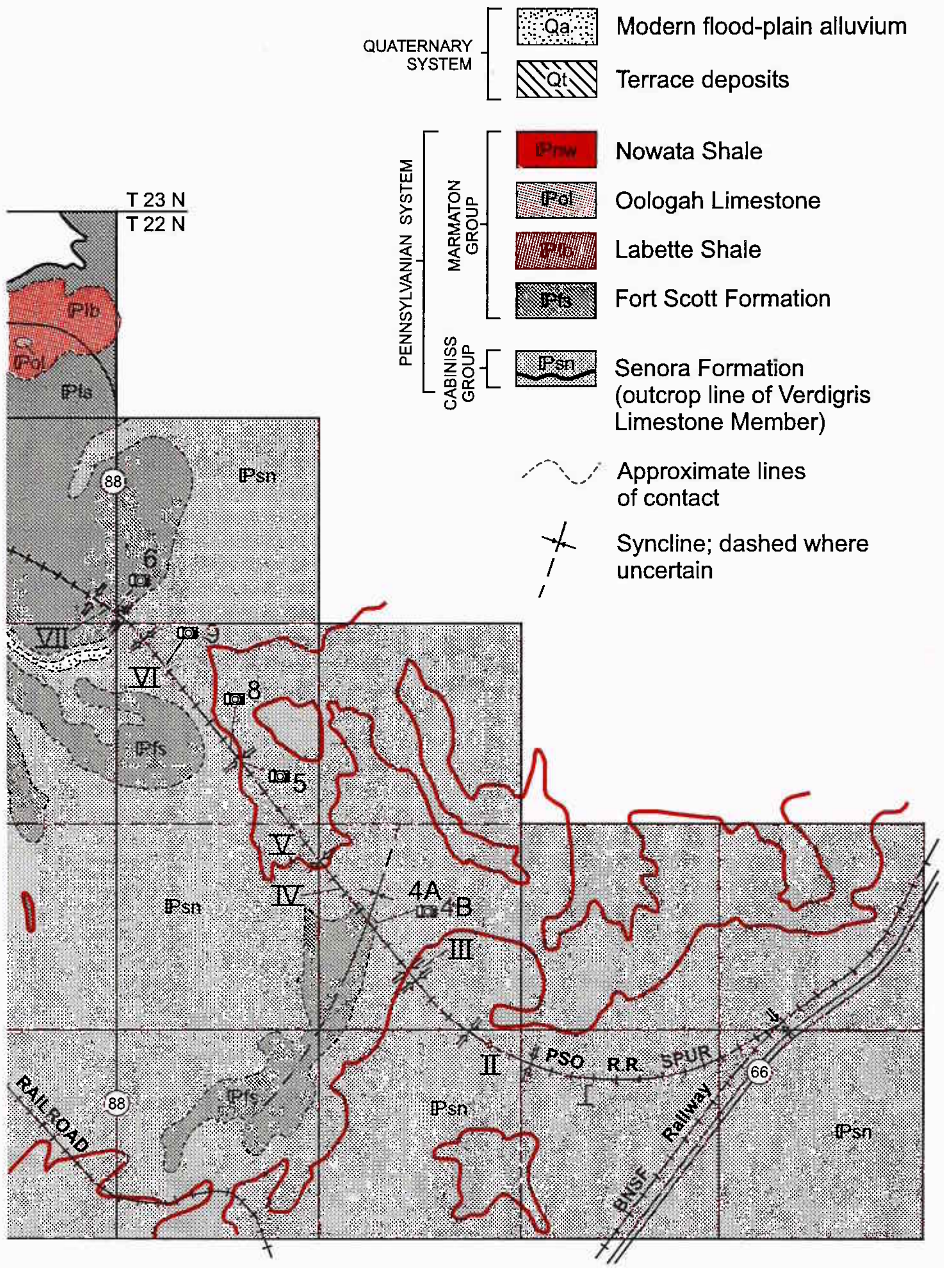
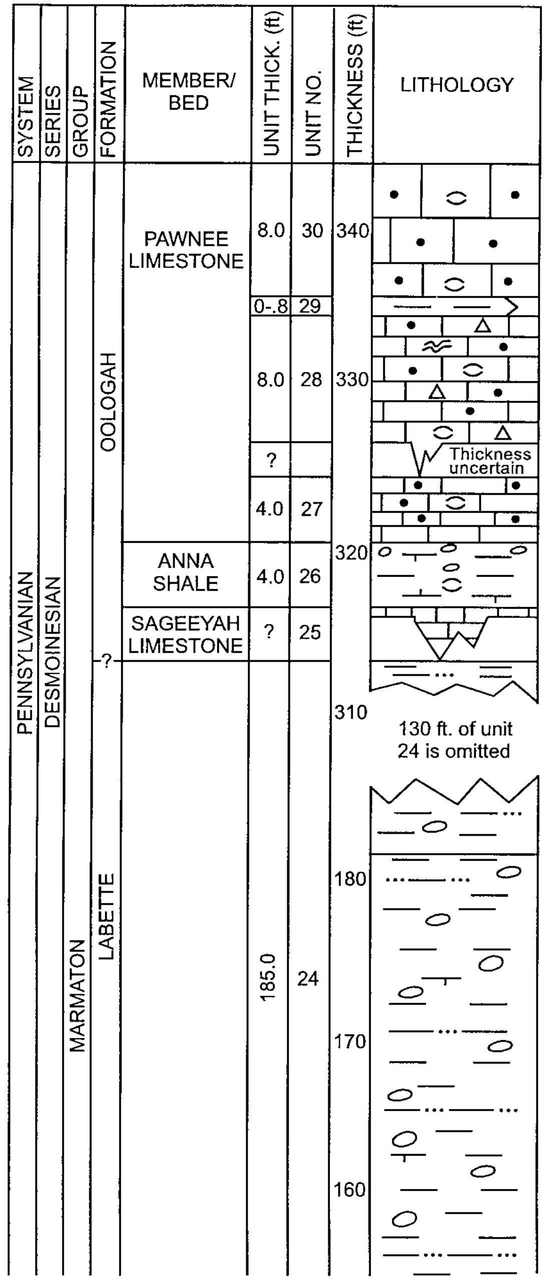


Figure 2 *(continued)*.



30. Limestone (skeletal wackestone), light gray, weathers grayish orange, thick bedded to massive, phylloid-algae rich; fossiliferous.

29. Shale, moderate red; discontinuous parting.

28. Limestone (skeletal wackestone), very pale orange to medium light gray, thin to medium bedded, algae rich; contains chert nodules; fossiliferous.

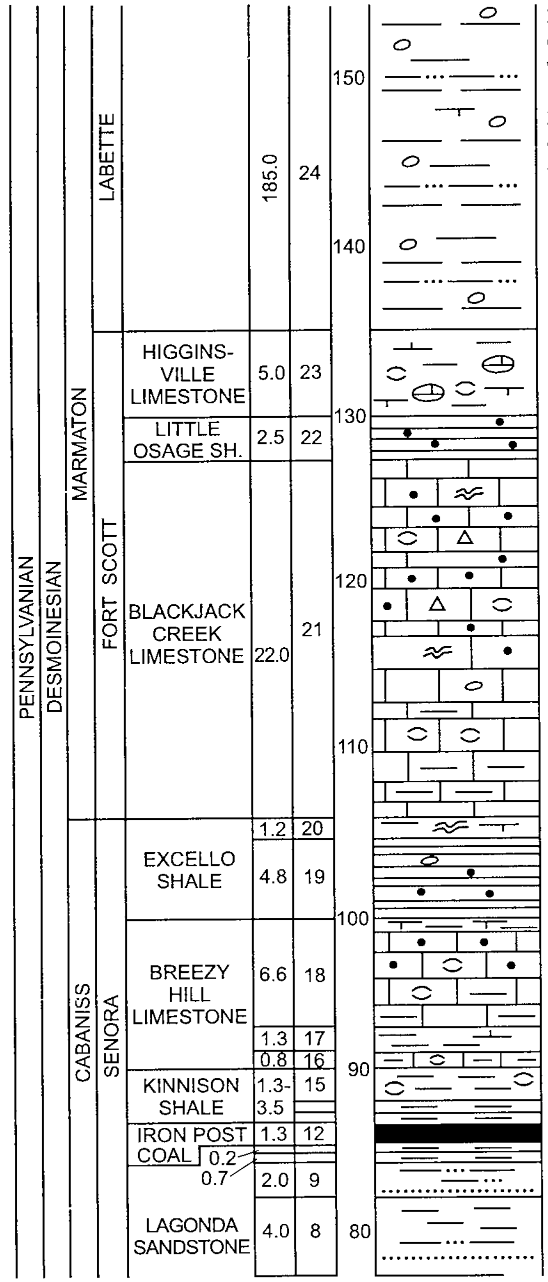
27. Limestone (skeletal wackestone), light gray, weathers grayish orange; phylloid-algae rich, very fossiliferous.

26. Shale, medium dark gray to dark gray, very calcareous; contains phosphatic nodules; fossiliferous.

25. Limestone, medium light gray, only about 1 ft exposed.
Covered interval–thickness uncertain.

24. Shale, moderate yellowish brown, slightly to highly silty; contains dusky red to moderate reddish brown ferruginous siltstone layers and ironstone concretions; some shale layers medium dark gray to olive gray and calcareous.

Figure 3. Composite stratigraphic column shows the sequence and general composition of rocks exposed along the PSO Railroad spur. (Note: Some unit numbers were omitted from the column where space was inadequate.)



23. Shale, grayish black, highly calcareous; contains limestone nodules with fossils.

22. Shale, black, brittle, platy; stained dark reddish brown on parting surfaces; contains abundant phosphatic nodules.

21. Limestone (skeletal lime mudstone and skeletal wackestone), light gray to medium light gray, very fossiliferous; algae rich in select intervals; stromatolitic bedding; contains dark gray fusulinid-rich chert; fusulinids pervasive throughout; locally shows karst up to 6 ft in depth with terra-rossa clay fills.

20. Shale, dark gray to olive black, calcareous, very fossiliferous.

19. Shale, dark gray to black, brittle, fissile, noncalcareous; contains abundant phosphatic nodules.

18. Limestone (lime mudstone and skeletal wackestone), light brownish gray; lime mudstone grades upward to skeletal wackestone with abundant crinoid fragments; calcareous shale at top.

17. Shale, medium dark gray to dark gray, friable, calcareous.

16. Limestone (lime mudstone), light gray, dense; contains brachiopods.

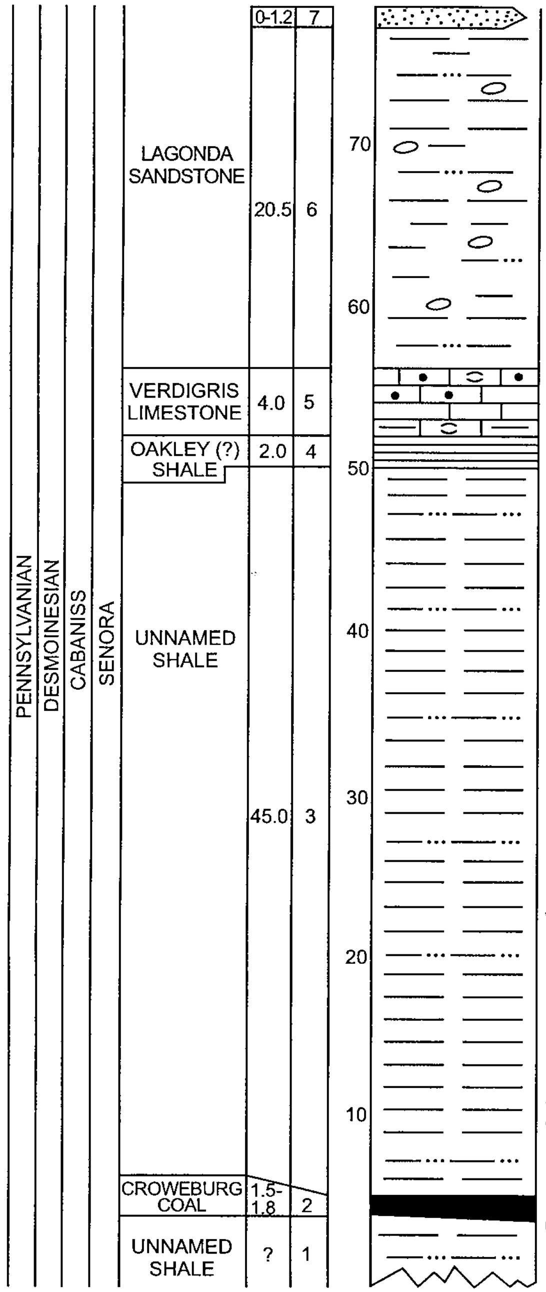
15. Shale, medium gray to dark yellowish orange, plastic, soft, noncalcareous.

14. Shale, grayish black, slightly fissile.

13. Shale, medium dark gray to medium gray, soft, plastic, noncalcareous.

(Unit description 12-8 on next page)

Figure 3 *(continued)*.



12. Coal, grayish black, bright, bituminous; moderate reddish brown staining on cleats.

11. Shale, dark gray, silty, carbonaceous.

10. Clay shale, dark yellowish orange, locally discontinous; punky, with locally cemented zones.

9. Siltstone, dark yellowish orange to light brown, micaceous; contains plant material; grades into very fine grained sandstone at base.

8. Shale, grayish green to medium light gray, slightly silty, soft, plastic.

7. Sandstone, medium light gray, micaceous, noncalcareous, slightly bioturbated; laterally discontinuous; contains climbing-ripple cross laminations.

6. Shale, medium light gray to light gray, silty, noncalcareous, nonfossiliferous; contains reddish brown noncalcareous sideritic concretions, lenses, and stringers.

5. Limestone (skeletal lime mudstone and skeletal wackestone), medium light gray; grades from skeletal lime mudstone at base to skeletal wackestone at top; very fossiliferous.

4. Shale, grayish black, fissile, brittle, noncalcareous; contains phosphatic nodules.

3. Shale, yellowish gray, slightly silty, noncalcareous, soft; base not exposed (thickness estimated from Hemish, 1989).

2. Coal, black, bright, bituminous (thickness from Hemish, 1989, pl. 3).

1. Shale, yellowish gray, silty, noncalcareous, soft; base not exposed.

Figure 3 *(continued)*.

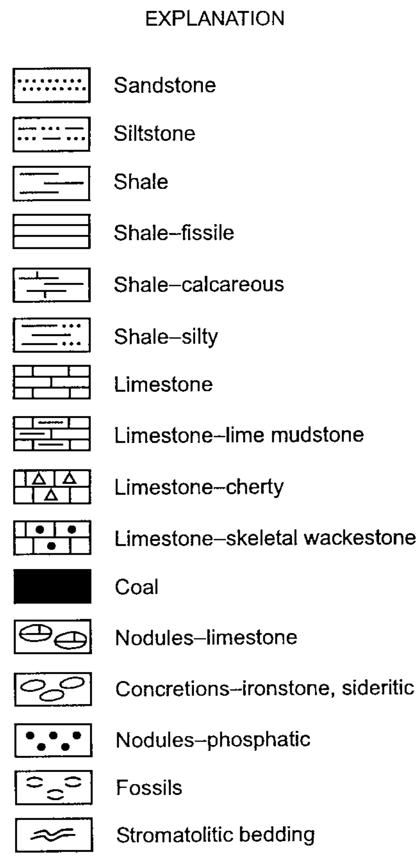


Figure 3 *(continued)*.

of these units. In this cut, spectacular exposures of the upper part of the Senora Formation or the lower part of the Fort Scott Formation (or both) extend continuously on both sides of the track for more than 0.5 mi (Fig. 2, segment IV; Figs. 4A,B).

Continuing to the northwest, the track crosses >0.5 mi of another reclaimed strip mine (Fig. 2, segment V) where the Croweburg coal was mined in the late 1970s and early 1980s (Hemish, 1989). Cuts through the upper part of the Senora Formation northwest of the reclaimed mine (Fig. 2, segment VI) expose a continuous section from the Oakley(?) Shale (Fig. 3) and associated Verdigris Limestone (Figs. 2, 5) through the Breezy Hill Limestone.

The contact between the Senora Formation and the Fort Scott Formation is well exposed in the cut made for the underpass at the S.H. 88 crossing (Fig. 2, segment VII; Figs. 3, 6) as well as under the bridge over the Fort Scott gorge in the SE¼ sec. 12, T. 22 N., R. 15 E. (Fig. 2, segment VIII; Hemish, 1999, figs. 3, 5).

For the next 3 mi the railroad runs in the Verdigris River valley (Fig. 2, segment IX), mostly on Quaternary floodplain deposits. Scenery along this stretch of track is spectacular because of downcutting by the Verdigris River and its ancestral tributaries. High hills on both sides of the valley are capped by resistant limestone of the Oologah Formation. The Labette Formation, which is ~185 ft thick in the area and consists mostly of shale (Hemish, 1999, p. 3), forms the steep slopes below the limestone caprock. Several isolated hills ~150 ft high, called "mounds," dot the landscape on both sides of the track. Notable are Lipe Mound, Brushy Mound, and Claremore Mound (Fig. 2). The mounds—the counterparts of buttes in arid regions—are outlying remnants of the Oologah Formation escarpment, and as such are capped by 10 to 20 ft of the basal limestone of the Oologah, which overlies the Labette Shale (Hemish, 1999, measured section 1, appendix).

Across the Verdigris River a short section of the track runs on a terrace (Fig. 2, segment X) composed of gravels that have as a primary constituent brown, water-worn chert pebbles whose provenance is to the north, in Kansas. Most of these gravels have been quarried for road metal, and in places the underlying limestone of the Oologah Formation is exposed on the floor of the old pits.

The northwesternmost 1.5 mi of track runs through cuts 10 to 15 ft deep in the Oologah Formation (Fig. 2, segment XI) just to the east and north of the PSO plant (Fig. 7). Two units of the Oologah are exposed in these cuts: the Anna Shale Member and the Pawnee Limestone Member.

Stratigraphy

Figure 3 is a composite stratigraphic column made from seven sections measured by the authors along the spur. Presentation of all the data gathered is not feasible for this short article, but the information will be published later by the OGS. That publication will be far more comprehensive, focusing on detailed stratigraphy and formal naming of stratigraphic units, and also on other geologic aspects.

The oldest stratigraphic unit along the PSO Railroad spur is an unnamed shale, poorly exposed, moderate yellowish brown, slightly silty, and noncalcareous. This unnamed member of the Senora Formation is intermittently exposed at the bottoms and sides of slightly eroded drainage ditches paralleling the railroad grade.

Within this shale, a 1.5–1.8-ft-thick bituminous coal bed named the Croweburg is present but

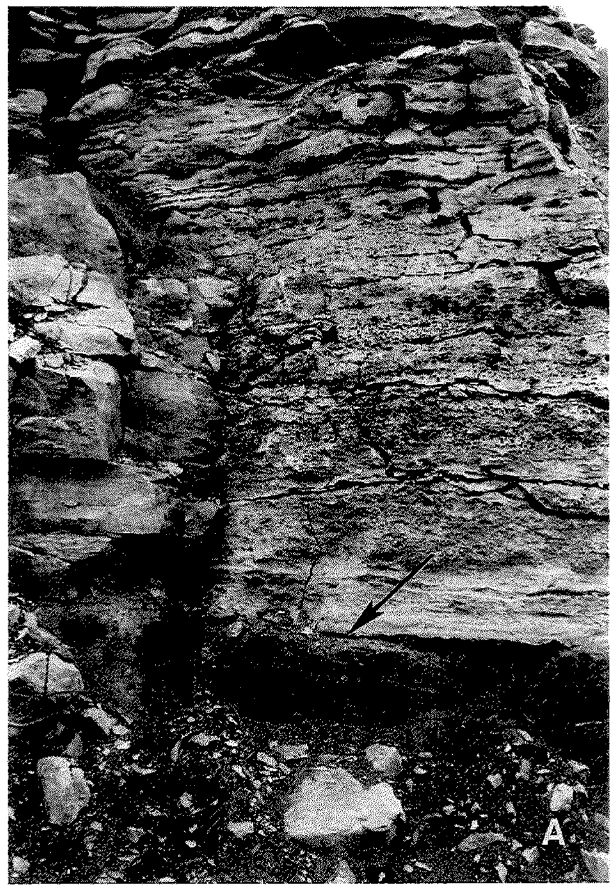
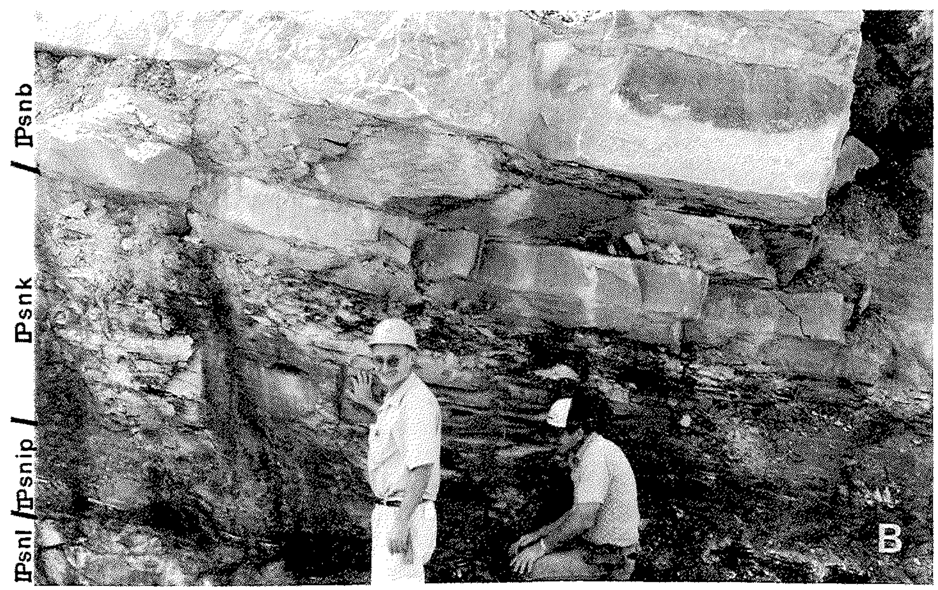


Figure 4 *(above and opposite page)*. A—Arrow marks the contact between the Excello Shale Member of the Senora Formation and the overlying Blackjack Creek Limestone Member of the Fort Scott Formation. About 12 ft of not exposed in the cuts. The coal has been extensively strip-mined at unknown times in the past, and in the late 1970s and early 1980s (in sec. 17 and 20, T. 22 N., R. 16 E., by the Sweetwater Coal Company [Hemish, 1989, p. 73]). The coal occurs ~47 ft below a black phosphatic shale unit informally called the Verdigris black shale (Branson, 1954, p. 5). The Verdigris black shale may correlate with the Oakley Shale Member (Iowa terminology; Ravn and others, 1984). The Oakley(?) Shale of the Senora Formation is exposed at only one place—in the SW¼SE¼NW¼SE¼ sec. 17, T. 22 N., R. 16 E. (Fig. 5), where it underlies the Verdigris Limestone Member of the Senora at the southeast end of a cut nearly a half mile long. The Verdigris Limestone here is ~6 ft thick, medium light gray (grayish orange where weathered), hard, and very fossiliferous.

Overlying the Verdigris is a silty and sandy shale, 28.6 ft thick—the Lagonda Sandstone Member of the Senora Formation. It is exposed in its entirety along the track in cuts extending through the middle part of sec. 17, T. 22 N., R. 16 E. The Lagonda contains better-developed sandstone beds in other parts of the area as a whole, but in the section measured by the authors (Chaplin and Hemish, in preparation), it is predominantly shale (Fig. 8). Along the northwestern end of the railroad cut in sec. 17, riprap confined in heavy-gauge wire prevents erosion of the shale (Fig. 9).

The next named unit (stratigraphically the top bed of the Lagonda Sandstone Member) is the Iron Post coal bed, exposed in three cuts along the route. It is generally 1.2 ft thick, and has been mined adjacent to the cuts in sec. 17. Combined



the lower part of the Blackjack Creek is shown here. B—The upper part of the Lagonda Sandstone Member (IPsnl), shown in this photograph, includes the Iron Post coal bed (IPsnip), the Kinnison Shale Member (IPsnk), and the Breezy Hill Limestone Member (IPsnb). All are in the Senora Formation.

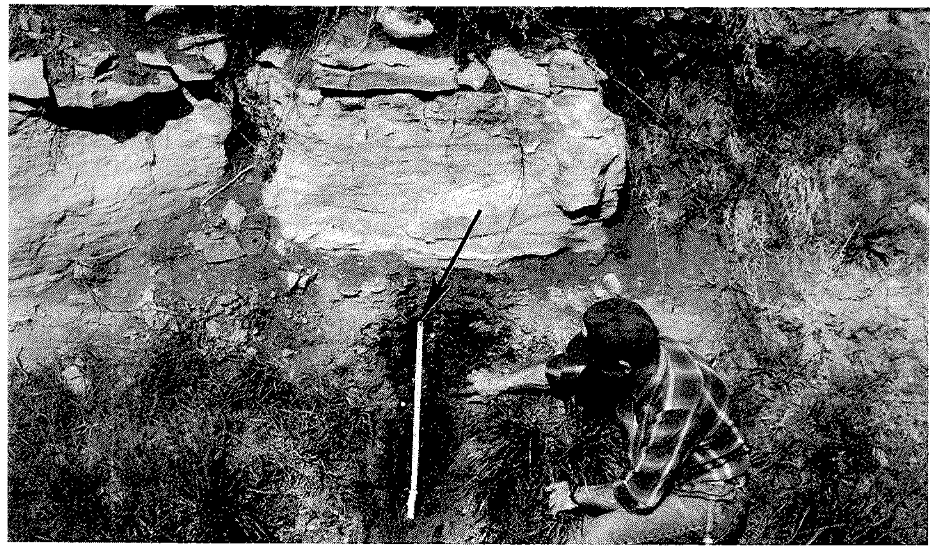


Figure 5. The Oakley(?) Shale Member, 2 ft thick, is overlain by the 4-ft-thick Verdigris Limestone Member of the Senora Formation. The man is pointing to the Oakley(?) Shale. An arrow marks the contact between the two units.

reserves of >8 million tons of the Croweburg and Iron Post coals are present in T. 22 N., R. 16 E. (Hemish, 1989, p. 34), mostly within 2 to 3 mi of the spur.

The Kinnison Shale Member of the Senora Formation overlies the Lagonda Sandstone Member. In the study area it is 1.3 to 3.5 ft thick and is generally dark gray to grayish black, calcareous to noncalcareous, and locally contains pyritized brachiopods.

The Kinnison is overlain by the Breezy Hill Limestone Member of the Senora Formation. The Breezy Hill is 7.5 to 8.7 ft thick, a light brownish gray, orange-weathering, limy mudstone that grades into a skeletal wackestone. It is very fossiliferous, with brachiopods and crinoids common. The upper and lower contacts are sharp (Chaplin and Hemish, in preparation).

The Excello Shale Member—the youngest member of the Senora Formation—overlies the Breezy Hill Limestone and is generally about 5 to 6 ft thick. The Excello is predominantly a black, brittle, fissile, jointed shale; it contains abundant ovoid to spheroidal phosphatic nodules that range from 0.5 to 2.0 in. in diameter.

The top of the Excello Shale marks the contact between the Cabaniss Group and the Marmaton Group. The Blackjack Creek Limestone Member of the Fort Scott Formation is the oldest stratigraphic unit in the Marmaton Group. It conformably overlies the Excello Shale. The Blackjack Creek Limestone, ~20 ft thick in the study area, is a light gray to medium light gray skeletal limy mudstone to skeletal wackestone. Phylloid algae, brachiopods, and other invertebrate fossils are abundant. At the surface the weathered limestone exhibits karst features such as sinkholes and vertical joints filled with terra-rossa clays (Fig. 7) (Chaplin and Hemish, in preparation).

The Blackjack Creek Limestone Member of the Fort Scott is overlain by the Little Osage Shale Member, which is ~2.5 ft thick in the study area and looks rather like the Excello Shale. It is black, brittle, platy, and contains abundant phosphatic nodules.

The Higginsville Limestone Member of the Fort Scott is either absent or is represented in places by a 5-ft-thick, grayish black, highly calcareous shale containing knobby, fossiliferous limestone concretions (Hemish, 1999, fig. 2 and p. 94).

Overlying the Fort Scott Formation is the Labette Formation, a thick, moderate yellowish brown to olive gray silty shale containing ferruginous siltstone layers and ironstone concretions. Although the Labette is ~185 ft thick in the area (Hemish, 1999, fig. 2 and p. 94) it is poorly exposed along the railroad spur, and is mostly buried under Quaternary alluvium where the track crosses the Verdigris River valley. The shale crops out intermittently on the flanks of Brushy Mound, just north of the spur (Fig. 2). The caprock on Brushy Mound is the basal limestone of the Oologah Formation, directly overlying the Labette Formation.

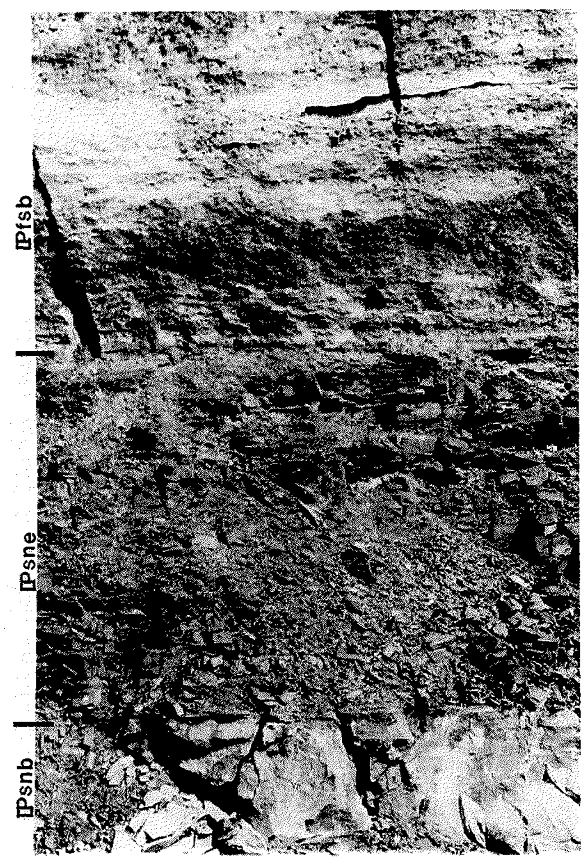


Figure 6. The Breezy Hill Limestone Member of the Senora Formation (IPsnb) is overlain by the Excello Shale Member of the Senora Formation (IPsne) and the Blackjack Creek Member of the Fort Scott Formation (IPfsb). The Excello Shale is 6 ft thick in this exposure, just east of the S.H. 88 underpass.

In this paper the sequence of limestone, dark gray shales with phosphatic nodules, and limestone that is exposed in cuts just west of the Verdigris River and westward to the PSO plant is called the Oologah Formation. These rocks were named the Oologah Limestone by Drake (1897, p. 377). Price (1984) discussed various interpretations of the Oologah Limestone by subsequent investigators. Schmidt (1959) applied the term "Sageeyah Limestone Member of the Pawnee Limestone" to the limestone below the Anna Shale and directly above the Labette Shale. Because only the extreme uppermost Sageeyah Limestone (Fig. 3) is exposed along the spur, no definitive statement about this

Figure 7. The Oologah Limestone is exposed in a cut 12 ft deep on the east side of the PSO Railroad spur near the center of sec. 34, T. 23 N., R. 15 E. The Anna Shale Member is not exposed here. Karst features (marked by arrows) are filled with terra-rossa clays.

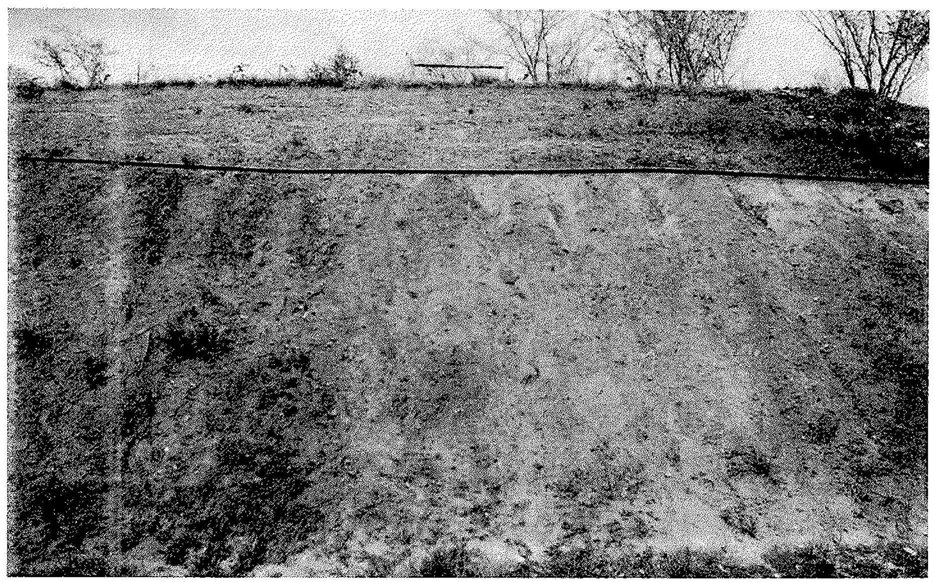


Figure 8. The Lagonda Sandstone Member of the Senora Formation is exposed in its entirety (28.6 ft) in this cut in the NW¼SE¼ sec. 17, T. 22 N., R. 16 E. Here the Lagonda is predominantly silty shale with thin sandstone layers and lenses in the upper part (above the line on the photograph). Elsewhere the sandstones of this interval are thicker.

Figure 9. Riprap consisting of crushed limestone is confined in heavy-gauge wire mesh along this cut, nearly 0.25 mi long, in the NW¼ sec. 17, T. 22 N., R. 16 E. The riprap prevents erosion of shales in the Lagonda Sandstone Member of the Senora Formation. The light colored, resistant rock at the top of the cut is the Breezy Hill Limestone, underlain by a covered interval containing the Kinnison Shale and Iron Post coal.

unit can be made here. Price (1984, p. 386) noted that "The Sageeyah interval reaches maximum thickness of 21 meters and makes up the lower one-half of the Oologah Limestone in the Tulsa region." However, he recommended (p. 386) "that the Sageeyah be considered a member of the Labette Shale." Problems of stratigraphic nomenclature concerning this sequence of rocks will be addressed later by Chaplin and Hemish (in preparation).

Based on work by Price (1984), the dark gray, calcareous shale containing phosphatic nodules is herein correlated with the Anna Shale Member and placed in the Oologah Formation (Fig. 3). The overlying limestone, which is medium light gray, algae-rich, and fossiliferous, is designated the Pawnee Limestone Member of the Oologah (Fig. 3). The top of this member has been eroded, so the total thickness in the vicinity of the terminus of the spur is not known.

Summary

The new railroad spur linking the PSO power plant at Oologah with the BNSF Railway near Sequoyah has reduced freight costs for the PSO and led to lower rates for its customers. A fringe benefit is that several new cuts were made in the hilly terrain, producing excellent exposures of bedrock. A better understanding of the geology of the area has resulted from work by the authors during investigation of the exposures.

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The PSO Power Plant at Oologah, Oklahoma *(continued from p. 122)*

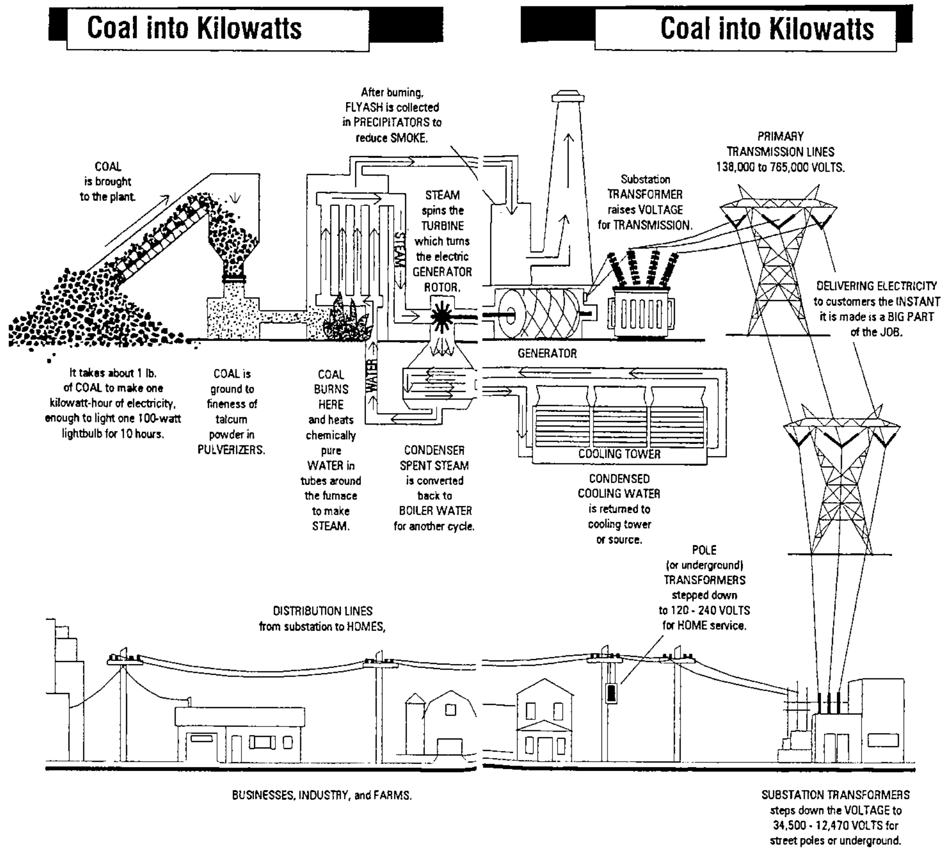

Figure 1. Coal into kilowatts (from Kentucky Coal Marketing and Export Council and the Kentucky Coal Association, 1995, p. 42–43).

Water drawn from Oologah Lake is used in the form of steam in the generating turbines. For more particulars concerning the PSO power plant and the new railroad spur, see the feature article in this issue (p. 124).

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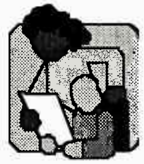
LeRoy Hemish

Activities Slated for Earth Science Teachers



The Oklahoma Geological Survey and the Oklahoma City Geological Society will host two programs in September to help teachers who want to brush up on earth science concepts:

September 17—afternoon workshop, Oklahoma City (free!):

The OGS, the OCGS, and other State agencies and groups will present technical information on a variety of topics, offer demonstrations, and provide activity sheets that can be given to students in the classroom. Subjects include: • mineral identification and other classroom projects (Debbie Jensen) • oil and gas and the environment (Oklahoma Energy Resources Board) • "Project Wet" (Oklahoma Conservation Committee) • Earth Science Week kits (American Geological Institute) • Resources available from the OGS (James R. Chaplin)

September 25—all-day field trip to the Arbuckle Mountains ($15/ person, transportation provided, snacks and literature included)

The goals of the field trip are to **(1)** introduce teachers to topographic maps; **(2)** demonstrate basic geological principles; **(3)** show geologic structures that participants can put their hands on, such as faults, anticlines, synclines, and unconformities; **(4)** provide an opportunity to collect rocks and fossils; **(5)** demonstrate how scenery is related to geological processes; and **(6)** explain how economically valuable materials are extracted for everyday use.

For more details about either of these activities, contact the Oklahoma City Geological Society, 227 W. Park Ave., Oklahoma City, OK 73102, (405) 236-3436; or *James R. Chaplin, Oklahoma Geologicial Survey, 100 E. Boyd, Room N-131, Norman, OK 73019, (405) 325-3031.*

Partners for Earth Science

The OCGS and the OGS want to make teaching earth science easier—and more fun—for teachers. Professional geologists from these organizations are happy to visit classrooms and talk about a wide range of geological subjects, from plate tectonics to rocks and minerals to natural hazards. For information about speaker availability, call us at the numbers above.

OGS Holds Second Waterflooding Workshop

The Oklahoma Geological Survey, in cooperation with the Petroleum Technology Transfer Council (PTTC), will present a one-day program, "Geological Perspectives of Reservoir Engineering: A Waterflood Workshop" on Oct. 20, 1999, at the Moore-Norman Technology Center, 4701 12th Ave. N.W., in Norman. This workshop will address aspects of evaluating a waterflood candidate that were not covered in the waterflooding workshop held in July 1998.

The workshop will acquaint geologists and engineers with the hazards that can jeopardize the potential success of a waterflood candidate. It addresses how to answer these two fundamental questions: Is there enough oil to make a waterflood project profitable, and approximately how much oil will be produced from secondary recovery?

A standard practice of using the amount of primary production as an indicator for the secondary potential of a waterflood prospect can lead to disastrous consequences for a company, because many factors that should be scrutinized to make an educated estimate of secondary reserves often are ignored. This program will show participants how to determine the amount of oil in place and how much oil they can expect to recover.

"Geologists must have a basic knowledge of a reservoir's rock and fluid properties for three reasons: First, to be able to do an initial evaluation of a reservoir's primary and secondary reserve potential; second, to be able to communicate with the engineering department about the rock and fluid properties of a waterflood candidate; and third, to understand how those properties affect the origination, migration, and entrapment of hydrocarbons," says Kurt Rottmann, the coordinator and principal presenter of both waterflooding seminars.

The first waterflooding workshop addressed the topics of determining reservoir data, deciphering production data, determining and isopaching net pay, sand geometry boundaries, coring and core results, distinguishing natural and induced fractures, water-supply evaluation, and permitting. (The workshop publication, OGS SP 98-3, is still available.) Both workshops are part of the Survey's ongoing effort to help geologists broaden their knowledge of various geologic subjects through seminars, workshops, and publications.

Rottmann, a consultant geologist based in Oklahoma City, also contributed to several of the workshops on fluvial-dominated deltaic oil reservoirs held by the OGS from 1995 to 1997.

Assisting Rottmann will be David R. Crutchfield, consulting petroleum reservoir engineer, Oklahoma City.

For more details about the workshop, or for registration forms, contact Michelle Summers, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 or (800) 330-3996; fax 405-325-7069.

More OGS Workshops Scheduled for This Year

In cooperation with the PTTC, the OGS will host a workshop on the Morrow gas play in the Anadarko basin and shelf of Oklahoma on Nov. 10, and a workshop on coalbed methane on Dec. 1. Both will be at the Moore-Norman Technology Center. For more information contact Michelle Summers at the address and phone numbers given above.

GSA Annual Meeting
Denver, Colorado
October 25–28, 1999

The proximity of the 1999 GSA Annual Meeting both in space to the Continental Divide and in time to the end of the 20th century inspired the theme of "Crossing Divides." The intent is to celebrate the cross-disciplinary nature of the geosciences and to encourage a scientific program that crosses divides among the various chemical, biological, and physical disciplines of our science. Our hope is that the program will instill in attendees a broadened sense of the contributions the geological sciences can make as a discipline and the degree to which an individual's research is linked to many other specialties. An exciting set of field trips, controversial Hot Topics, and a diverse group of exhibitors round out the meeting.

We encourage you to come to the meeting early or stay late and enjoy the cultural wonders of Denver and the natural wonders of the Rocky Mountains. To enhance your visit, we suggest that you find out more about Denver's colorful history, sights and attractions, lodging, and dining, as well as interesting facts about the city at http://www.denvergov.org.

—From the 1999 GSA Annual Meeting
Final Announcement, *GSA Today,* June 1999, p. 2

GSA Annual Meeting Agenda

Topical Sessions

Origins of Carbonate Mounds: Crossing the Divides of Sedimentology, Diagenesis, and Paleontology

Geochemical and Isotopic Tracers Applied to Sedimentary Provenance, Drainage Systems, and Related Tectonics

Alloformations, Synthems and Sequences

Applied Integrated Stratigraphy in Exploration and Development Geology: New Techniques and Perspectives

Effects of Impact Events in the Sedimentary Record
Faulting and Folding: Crossing the Divide Between 2-D and 3-D
Dates of Faults and Rates of Deformation
Active Faulting and Earthquake Behavior in Complex Orogens: A Multidisciplinary Approach
Origin of Orogenic Plateaus: Interactions of Plate Convergence, Mantle Processes, and Surficial Processes in Continental Tectonics
Cenozoic Tectonics of the Southern Rocky Mountains in Colorado and New Mexico: Connections with Global Processes
Making Crustal Souffles: High Mountains and Thin Crust in the Sierra Nevada
The International Space Station: New Opportunities for Earth Science Research and Education
Mars, the Next Generation: The Emergent New Geology of Earth's Neighboring World
Morphological and Mineralogical Biomarkers for Mars Exploration
Beryllium: Mineralogy, Petrology, and Geochemistry
Uranium: Minerals, Chemistry, and the Environment
New Insights into the Giant Butte Hydrothermal Deposit
Application of Advanced Geochemical Modeling to Mining-Related Environmental Issues
Energy Mix of the Future: Meeting the Needs of Society and a Changing Environment
Geology—The Bedrock of the Ecosystem: Biological Uses of Geologic Data
New Advances in Mine Site Remediation and Reclamation: Taking a Landscape Perspective
Dam Geology: New Science Applied to Old Problems
De-icing Salts and Their Effect on Crushed Rock Aggregate
Digital Field Mapping and Data Collection
Engineering and Environmental Geology: State Geological Surveys and Academic Committees
Expansive Materials Along the Front Range of Colorado: Identification, Clay Mineralogy, Mapping Programs, and Depth of Wetting Resulting from Development
Geologic Input to Public Decision-Making: The Need for Greater Predictive Capability
Geologic Hazard Mapping: The State of the Art
Coastal Geologic Risk: Mapping the Hazards and Influencing Public Policy
Communication Divides: Perspectives on Supporting Information Bridges in the Geosciences
Geoscience Ethics Guidelines: A Discussion of Their Development, Utility, and Implementation
Crossing the Greatest Divide: The Earth Sciences, the Humanities, and the Needs of Society
Environmental Justice: Geoecological, Social, and Philosophical Perspectives
Crossing Disciplinary Boundaries in the Geosciences: Historical Perspectives
The Tropics Compared: Icehouse and Greenhouse States
From Greenhouse to Icehouse: The Marine Eocene-Oligocene Transition
A Multidisciplinary Study of Coalbed Methane in the Ferron Coals, Utah: An Unusual Resource with Potential for Global Environmental Impact
The Hell Creek Formation and the Cretaceous-Tertiary Boundary in the Northern Great Plains: An Integrated Continental Record of the End of the Cretaceous
High-Resolution Stratigraphic Approaches in Paleontology
Beyond Phylogeny Reconstruction: Tree-Based Analyses in Paleontology

DENVER

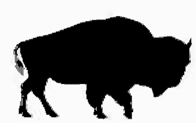
Fire and Geology: Surface Processes and Stratigraphic Records
Geomorphic and Ecological Responses to Natural and Anthropogenic Disturbances
Integrated Landscapes: The Colorado Front Range
Glaciation and Reorganization of Asia's Network of Drainage: The Effects on Late Quaternary Global Change
North Atlantic Crossroads: Terrestrial and Marine Environmental Records of Iceland
Landscape Erosion and Sedimentation Modeling
Geologic and Biologic Evidence for Late Cenozoic Drainage Rearrangements in North America: Implications for Aquatic Biogeography
Shallow Subsurface Mapping: Using Geophysics for Geological, Groundwater Resource, and Contamination Studies
Subglacial Processes and the Behavior of Ice Sheets
Granite Systems and Proterozoic Lithospheric Processes
Role of Supercontinents in Earth History: Assembly and Dispersal of the Rodinian Supercontinent (1300–750? Ma), and Impacts on Evolution of the Proterozoic Biosphere, Hydrosphere, and Crust-Mantle System
Multidisciplinary Studies in Volcanology, Planetary Geology and Economic Geology: A Tribute to 50 Years of Research by Professor Wolfgang Elston, University of New Mexico
Building the Quantitative Skills of Nonmajors and Majors in Geoscience Courses
Undergraduate Research: Strategies for Success
Tectonics, Topography, and Climate: The State of the Art in Earth Systems Science Teaching and Research
Evaluation and Assessment of Multimedia Computer-Assisted Geoscience Education: A Hard Look at What Works and Why
Successes in Creating Multimedia-Assisted Learning Environments: The Sage on the Stage Versus the Guide on the Side—Yet Another Divide to Cross
Teaching Science by Example: Real Problems, Real Data, All Classes, Every Day
Successful Assessment Case Studies of Common Concerns in the Geoscience Classroom
People and Landscapes: Earth Systems Interpretation in Park Areas
Teaching Earth Science with Art
Teaching Geologic Time: Methods and Relevance
The Significance of the National Academy of Sciences–National Research Council's National Science Education Standards to the Public Understanding and Future of the Geosciences
Isotopic Records of Microbially Mediated Processes in Natural Environments
Geomicrobiology and Biogeochemistry
Global Biogeochemical Cycles and Climate
The Geology of Geomicrobiology: The Links Between Mineralogy and Microbial Ecology
Calibration, Inversion, and Uncertainty of Groundwater Models
Dynamics of Mass Transport in Fractured Rocks and Fine-Grained Sediments: Contributions from Laboratory and Field Analyses to Conceptual and Mathematical Modeling
Measurement and Description of Flow and Transport in Highly Heterogeneous Aquifers
Investigations into the Effect of Measurement Scale on Determining Hydraulic Conductivity: Field and Modeling Studies

Field-Scale Hydrodynamic and Geochemical Interactions at the Interface of Groundwater and Surface Water
From Atrazine to Antibiotics: The Occurrence and Fate of Agricultural Chemicals in the Hydrogeologic System
Gulf of Mexico Hypoxia: A Multidisciplinary, Multiscale Problem
Hydrochemistry of Springs
Measurement Techniques and Modeling of Spatial and Temporal Variability in Groundwater Recharge in Response to Past, Present, and Future Climates
Sustainability of Water Resources in the High Plains
Hydrologic Resources of Synorogenic Strata
Role of Groundwater Models in Water Rights Disputes: An Evolution in the Understanding of Large-Scale Hydrologic Systems in the Western United States
Low-Recharge Groundwater Systems
Sediments in Karst Systems: Processes, Mechanisms, Interpretation
Impacts of Urbanization on Groundwater Quantity and Quality
Source Protection Planning for Springs and Tunnels: Problems and Solutions
Wetland Hydrology and Geochemistry: The State of the Science
Subsurface Transport, Fate, and Remediation of Nonaqueous Phase Liquid Contaminants in Multicomponent Biogeochemical Systems
Evolution and Remediation of Acid-Sulfate Groundwater Systems at Reclaimed Mine Sites
Sources, Transport, Fate and Toxicology of Trace Elements in the Environment: A Tribute to Jerome Nriagu
Biological Diversity in the Phanerozoic: In Memory of Jack Sepkoski

Field Trips

Premeeting

Cretaceous Hydrocarbon Plays—Southern Colorado, *Oct. 21–23*
Origin and History of the Heart Mountain Detachment and Associated Structures, Northeast Absaroka Range, Wyoming, *Oct. 21–24*
Hydrogeology and Wetlands of the Mountains and Foothills Near Denver, Colorado, *Oct. 23*
Coal Mining in the 21st Century, *Oct. 23–24*
K/T Boundary in the Raton Basin, New Mexico and Colorado: Evidence for Asteroid Impact, *Oct. 23–24*
Laramide to Holocene Structural Development of the Northern Colorado Front Range, *Oct. 23–24*
200,000 Years of Climate Change Recorded in Eolian Sediments of the High Plains of Eastern Colorado and Western Nebraska, *Oct. 23–24*
Active Salt Tectonics and Collapse in the Eagle Valley and Adjoining Areas of Western Colorado, *Oct. 24*
Bouncing Boulders, Rising Rivers, and Sneaky Soils: A Primer to Geological Hazards and Engineering Geology Along Colorado's Front Range, *Oct. 24*
Cave of the Winds and Springs of Manitou, Colorado: Geology and Hydrology, *Oct. 24*
Geological Reconnaissance of Dinosaur Ridge and Vicinity, *Oct. 24*



Kimberlites of the Colorado-Wyoming State Line District, *Oct. 24*

Walking Tour of Paleontologist G. G. Simpson's Boyhood Neighborhood, *Oct. 24*

Half Day—During the Meeting

Geology Tour of Denver Buildings and Monuments, *Oct. 25* or *Oct. 27*

Tour of the U.S. Geological Survey Mapping and Geologic Facilities, Denver Federal Center, *Oct. 26* or *Oct. 27*

Postmeeting

Geological Reconnaissance of Dinosaur Ridge and Vicinity, *Oct. 29*

Laramide Minor Faulting and Tectonics of the Northeastern Front Range of Colorado, *Oct. 29*

Soil-Geomorphic Relationships Near Rocky Flats, Boulder and Golden, Colorado, With a Stop at the Pre-Fountain Formation of Wahlstrom, *Oct. 29*

South Park Conjunctive Use Project: A Combined Look at Geology and Hydrology in the South Park Basin, Colorado, *Oct. 29*

Stratigraphy, Sedimentology, and Paleontology of the Cambrian-Ordovician of Colorado, *Oct. 29–30*

Geology and Paleontology of the Gold Belt Back-Country Byway: Florissant Fossil Beds and Garden Park Fossil Area, *Oct. 29–30*

Short Courses/Forums/Workshops

Applied Inverse Ground Water Modeling: Why Use Anything Less? *Oct. 23–24*

Digital Mapping Methods: Accurate Digital Data Capture and Analysis for the Field Geoscientist, *Oct. 23–24*

Introduction to Remote Sensing for Geologic Applications, *Oct. 23–24*

Modern Salt Tectonics, *Oct. 23–24*

3-D Seismic Interpretation: A Primer for Geologists, *Oct. 23–24*

Applications of Environmental Isotopes to Watershed Hydrology and Biogeochemistry, *Oct. 24*

Teaching Earth System History: A Computer-Assisted Approach, *Oct. 24*

Isotopic Dating of Ore Deposits, *Oct. 23*

National Association of Geoscience Teachers Workshop on Preparing Graduate Students for Teaching, *Oct. 23–24*

Uranium: Minerals, Chemistry, and the Environment, *Oct. 22–23*

The Evolution-Creation Controversy II: Perspectives on Science, Religion, and Geological Education, *Oct. 24*

Digital Database Forum, *Oct. 27*

For more information about the annual meeting, contact GSA, Meetings Dept., P.O. Box 9140, Boulder, CO 80301; (800) 472-1988, ext. 113, or (303) 447-2020; e-mail: meetings@geosociety.org; World Wide Web: http://www.geosociety.org. *The preregistration deadline is September 17.*

Ground-Water-Quality Assessment of the Central Oklahoma Aquifer, Oklahoma; Results of Investigations

Edited by Scott Christenson and J. S. Havens, this 179-page USGS water-supply paper is a collection of five papers intended to summarize the results of an assessment of the ground-water quality of the Central Oklahoma Aquifer. The papers include a summary of investigations, the diagenetic history of Permian rocks in the aquifer, a geochemical characterization of solid-phase materials, a summary of geochemical and geohydrologic investigations of the Central Oklahoma Aquifer, and a summary on naturally occurring trace substances that contaminated many wells completed in the aquifer.

Order W 2357-A from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone (303) 202-4210. Cost is $22, plus $3.50 per order for handling.

Freshwater Resources and Saline Water Near the Sac and Fox Nation Tribal Lands, Eastern Lincoln County, Oklahoma

Written by M. M. Abbott, this 58-page USGS water-resources investigations report was prepared in cooperation with the Sac and Fox Nation.

Order WRI 96-4173 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone (303) 202-4210. Cost is $16 for a paper copy or $5 for microfiche, plus $3.50 per order for handling.

Simulation of Effects of Wastewater Discharges on Sand Creek and Lower Caddo Creek near Ardmore, Oklahoma

The results of a project conducted by the USGS in cooperation with the City of Ardmore are described in this 124-page USGS water-resources investigations report, written by Edwin A. Wesolowski.

The USGS develops hydrologic and geochemical computer model software that is available to the public fee of charge. To demonstrate the application of USGS software to a real-world situation, a model was developed for reaches of Sand and Caddo Creeks in south-central Oklahoma. The model simulated the effects of wastewater discharge from a refinery and a municipal treatment plant. These creeks were a good test of the software because they were expected to have the unsteady streamflow and the dymamic water-quality conditions that these models represent well. The software applications used are the Diffusion Analogy Streamflow Routing Model (DAFLOW) and the branched Lagrangian transport model (BLTM) and BLTM/QUAL2E that, collectively, as calibrated models, are referred to as the Ardmore Water-Quality Model.

The model simulated, among many things, the marked daily pattern of dissolved oxygen that is attributable to waste loading and algal activity. Dissolved-oxygen measurements during this study and simulated dissolved-oxygen concentrations using the Ardmore Water-Quality Model, for the conditions of this study, illustrate that the dissolved-oxygen sag curve caused by the upstream wastewater discharges is confined to Sand Creek. This finding could significantly change treatment options.

Order WRI 99-4022 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 843-7570, fax 405-843-7712. A limited number of copies are available free of charge.

Hydrology, Water Use, and Simulation of Flow in the High Plains Aquifer in Northwestern Oklahoma, Southeastern Colorado, Southwestern Kansas, Northeastern New Mexico, and Northwestern Texas

Written by Richard L. Luckey and Mark F. Becker, this USGS water-resources investigations report describes the hydrology of the High Plains aquifer in Oklahoma and adjacent areas, estimates historical water use, and describes the construction, calibration, and use of a flow model of the aquifer. The 68-page report was prepared in cooperation with the Oklahoma Water Resources Board.

Order WRI 99-4104 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 843-7570, fax 405-843-7712. A limited number of copies are available free of charge.

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.

Evaporite Karst in the Southern Midcontinent

KENNETH S. JOHNSON, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019

Evaporites are the most soluble of common rocks; they are dissolved readily to form the same karst features typically found in limestones and dolomites. Evaporites, including gypsum (or anhydrite) and salt, are present in 32 of the 48 contiguous states, and they underlie 35–40% of the land area. They underlie western Kansas, western Oklahoma, the Texas Panhandle, and eastern New Mexico and Colorado, and locally can be a serious problem to petroleum exploration and development. In areas where gypsum crops out (or is less than 30 m deep), or where rock salt is less than 250 m deep, evaporites may be partly or wholly dissolved by unsaturated water. Evaporite outcrops typically contain sinkholes, caves, disappearing streams, and springs. Other evidence of evaporite karst includes surface-collapse features, saline springs, and saline plumes due to salt dissolution. Many evaporites in the deep subsurface also contain remains of paleokarst; such as dissolution breccias, breccia pipes, slumped beds, and collapse structures.

Human activities also have caused development of evaporite karst, primarily in salt deposits. Boreholes or underground mines may enable (either intentionally or inadvertently) unsaturated water to flow through or against salt deposits, thus allowing development of small to large dissolution cavities. If the dissolution cavity is large enough and shallow enough, successive roof failures can cause land subsidence or catastrophic collapse. At least 30 sites in the United States have reported land subsidence and/or collapse due to human-induced salt karst. Among these sites are Cargill and Panning sinks in Kansas, Wink sink in west Texas, and other sites in the southern Midcontinent. Evaporite karst, both natural and human-induced, is far more prevalent than commonly believed.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 83, p. 1200, July 1999.

Activation of Great Plains Dune Sand During the 1930s Drought

D. R. MUHS, U.S. Geological Survey, MS 980, DFC, Denver, CO 80225

Sand dunes occupy large tracts of the Great Plains of the U.S., but almost all are stabilized by grassland (prairie or steppe). One of the most severe droughts of the instrumental record for the Great Plains was during the A.D. 1931–1940 decade. Although there have been many studies of dust storms during this period, few studies have been made of dune activation. Comparison of aerial photographs from 1936–1939 to aerial photographs from the 1980s shows that at least 25 localities (with individual areas of 5–50 km^2) in North Dakota, Nebraska, Colorado, Kansas, Oklahoma, Texas, and New

Mexico had fully active sand during the 1930s where dunes are currently mostly stable. Full dune activity on aerial photographs is shown by high reflectance patterns, with sharp dune crests and steep slip faces when viewed stereoscopically. Most eolian sand active in the 1930s is in parabolic dune and sand sheet forms (North Dakota, Nebraska, Colorado, Kansas), but barchan and barchanoid-ridge dunes are also visible (Kansas, Oklahoma, Texas, New Mexico). At some localities, dunes were fed from newly exposed fluvial sources, such as unvegetated bars on the Canadian and North Canadian Rivers (Oklahoma and Texas) and Ute Creek (New Mexico). At most localities, however, the 1930s dunes were reactivated forms of previously stabilized sand. Cultivation-induced activation, also greater during the 1930s, can be distinguished on aerial photographs because such areas have distinct field boundaries and "fence-line" dunes. Regional studies in the western U.S. indicate that dune fields become fully or mostly active when the precipitation (P) to potential evapotranspiration (PE) ratio is ~0.35 or less, resulting in a loss of vegetation cover. Great Plains P/PE values from 1961–1990 range from 0.56 to 0.86; during the driest year (1934) of the 1930s, these values shifted to 0.28 to 0.68. In 1934, southeastern Colorado, northeastern New Mexico, southwestern Kansas, and the panhandles of Texas and New Mexico all had P/PE values of 0.37 or less. This moisture-balance shift reduced vegetation cover and allowed partial dune activation. Results from this study demonstrate the sensitive balance between climate, vegetation cover, and degree of dune activity in the Great Plains, and provide evidence for how quickly the landscape may respond to major droughts of the future.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 7, p. A-217.

Holocene Environments of the South-Central High Plains Region

CAROLYN G. OLSON, USDA-NRCS, National Soil Survey Center, Federal Building Room 652, 100 Centennial Mall N., Lincoln, NE 68508; and
DONNA A. PORTER, Larson and Assoc., St. Marys, KS 66536

Stratigraphic, biologic and paleopedologic evidence can be convincing proxies for past climate change. Within the Holocene, the availability of radio-isotopic methods further enhances the reliability of these methods.

In southwestern Kansas and northwestern Oklahoma, stratigraphic evidence indicates 2 major dune reactivation periods following periods of alluviation, stability, and soil development in the Holocene. Radiocarbon ages bracket these periods and $\delta^{13}C$ values provide evidence of a shift from a wetter, cooler climate in the early Holocene and late Quaternary to a warmer, drier mid-Holocene period. Although radiocarbon ages are reliable, isotopic results are less diagnostic proxies for vegetative composition for the late Holocene. In the last 2–3000 years BP, bioturbation and modern pedogenic processes cause significant isotopic variability among $\delta^{13}C$ values obtained from surface horizons.

In eastern Colorado and north central Nebraska, isotopic studies and phytolith contents demonstrate a warmer, drier mid-Holocene period following a cooler, wetter transition from the late Quaternary (Kelly et al., 1998). Arbogast and Johnson (1998) reports a shift in climate to drier conditions at around 8800 BP in central Kansas. These studies compare well with our results and imply that a regional Holocene climatic scenario for the central and south-central High Plains is evolving.

References Cited

Kelly, E. F., et al., 1998. Stable isotope composition of soil organic matter and phytoliths as paleoenvironmental indicators, Geoderma 82:59–81.

Arbogast, A. F., and W. C. Johnson, 1998. Late-Quaternary landscape response to environmental change in south-central Kansas, Annals Assoc. Amer. Geog. 88(1):126–145.
Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 7, p. A-168.

Changes in Patterns of Cyclicity in Upper Carboniferous through Lower Permian (Virgilian-Sakmarian) Depositional Sequences in the North American Midcontinent

DARWIN R. BOARDMAN II, School of Geology, Oklahoma State University, Stillwater, OK 74078

Analysis of outcropping Virgilian-Sakmarian depositional sequences from the North American Midcontinent reveals major changes in the nature of the cyclothemic-scale depositional sequences and patterns of cyclicity that is considered to result from allocyclic as well as autocyclic mechanisms.

Lower–Middle Virgilian (Douglas, Shawnee, and basal Wabaunsee) strata are grouped into mixed composite carbonate-siliciclastic sequences with a regular pattern of minor to major depositional sequences that have the thickest sequence containing well-developed marine condensed sections represented by non-skeletal phosphatic black shales. Incised valley fills and laterally extensive paleosols are well developed during lowstands.

Upper Virgilian (Wabaunsee, and Admire) strata are grouped into mixed composite carbonate sequences-siliciclastic sequences with a regular pattern of between two to three minor to intermediate sequences with no marine condensed sections but with updip maximum marine flooding surfaces that are either fossiliferous gray shales or phosphatic and glauconitic wackestones. Also, an upward trend towards more minor cycles is noted. Incised valley fills and laterally extensive paleosols are well developed during lowstands.

Lower Council Grove strata are grouped into mixed composite carbonate-siliciclastic sequences with a pattern of minor to major depositional sequences that have the thickest sequence containing well-developed marine condensed sections represented by black shales or laterally equivalent black shaly, phosphatic, and glauconitic wackestones. No non-skeletal phosphate is denoted in these sequences. Lowstands denoted by well-developed paleosols are represented in the majority of the outcrop belt with incised valley fills restricted to the Oklahoma part of the outcrop belt.

Upper Council Grove strata are grouped into mixed composite sequences with a pattern of minor to intermediate depositional sequences that have the thickest sequence containing no marine condensed sections but only minor condensation at the level that corresponds to maximtnn marine flooding.
Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 83, p. 1193, July 1999.

Upper Carboniferous and Lower Permian Marine Condensed Sections from the North American Midcontinent

DARWIN R. BOARDMAN II, School of Geology, Oklahoma State University, Stillwater, OK 74078

Analysis of outcropping Cherokee to Chase Group (Desmoinesian-Artinskian) depositional sequences from the North American Midcontinent reveals a number of different lithologic and paleontologic manifestations of the shelfal expressions of the marine condensed sections. Several types of marine condensed sections are recognized.

Black, fissile phosphatic shales are the most typical expression of the marine condensed section especially in the Cherokee through the basal Wabaunsee groups. These are characterized by radiolarian-bearing non-skeletal phosphate nodules, ammonoids, shark remains, and conodonts including the most diverse *Gondolella–Idioprioniodus* biofacies.

Black, moderately fissile shales represent the marine condensed sections from the lower half of the Council Grove Group. They are distinct in that they lack radiolarian-bearing non-skeletal phosphate and include abundant inarticulate brachiopods, *Ammodiscus* foraminiferans, ammonoids, and the *Streptognathodus*–conodont biofacies. The lack of radiolarians and the *Gondolella* biofacies is thought to be due to a restricted source for cool nutrient-rich waters to upwell on to the shelf.

Marine condensed sections also include abundantly fossiliferous gray shales (minor non-skeletal phosphate to no non-skeletal phosphate) that contain an abundance of conodonts from the *Streptognathodus–Idiognathodus* biofacies. These may represent the deepest phase of the depositional sequence or represent a slightly shallower facies of the black shale condensed section. This is common where the black fissile shale facies changes facies to the gray fossiliferous shale over paleotopographic high features such as intra-shelf arches.

Shaly, glauconitic fossiliferous wackestones with phosphatized molluscs and an abundance of the *Streptognathodus–Idiognathodus* biofacies represent maximum marine flooding in which water depths were insufficient to completely shut off carbonate sedimentation and are common in the Wabaunsee to Chase groups.

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Sequence Stratigraphic Analysis of Upper Carboniferous (Virgilian, Wabaunsee Group) from the North American Midcontinent

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Sequence stratigraphic analysis of outcropping Upper Carboniferous Wabaunsee Group of the North American Midcontinent strongly suggest a distinctive hierarchy of stratigraphic forcing. Fourth order depositional sequences from the Wabaunsee and overlying Admire Group represents the latest highstand sequence sets of a composite third order sequence (1–10 m.y.) that comprises the majority of the Virgilian sequences. These fourth order depositional sequences are comprised of two or three fifth order depositional sequences (.01–0.1 m.y.) each.

Strata from the Douglas, Shawnee, Wabaunsee, and Admire groups comprises one composite third order depositional sequence (1-10 m.y.), and is divisible into fifteen composite fourth order depositional sequences (0.1-1 m.y.). Each fourth order depositional sequence contains between two to four high frequency fifth order depositional cycles (.01–0.1 m.y.) that form the parasequences that stack into the retrogradational transgressive systems tract, and the aggradational to progradational highstand/forced regressive systems tracts.

Incised valley fill deposits or well developed paleosols separate the composite fourth order composite depositional sequences. The component fifth order depositional sequences are separated by weakly developed, laterally discontinuous paleosols (usually coaly shales, underclays, or coals) or marginal marine deposits.

Wabaunsee marine condensed sections occur in black fissile phosphatic shale, highly fossiliferous shale partings within carbonates, or glauconitic, fossiliferous wackestones.

The black fissile phosphatic shale facies that characterize marine condensed sections of the underlying Shawnee Group are restricted to the basal Wabaunsee Sequence. This is interpreted to be due to shallower water depths being attained on the shelf during maximum marine flooding.

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Evidence for Hierarchy of Stratigraphic Forcing in the Upper Carboniferous (Virgilian, Wabaunsee Group) in the Anadarko Basin

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Analysis of outcropping Upper Carboniferous (Virgilian, Wabaunsee Group) strata in the North American Mid-Continent suggests a hierarchy of stratigraphic forcing. Fourth order depositional sequences from the Wabaunsee Group represent the latest highstand sequence sets of a composite third order sequence (1–10 m.y.) that encompasses strata from the Douglas, Shawnee, Wabaunsee, and Admire Groups.

The composite third order sequence (1–10 m.y) is composed of fifteen composite fourth order depositional sequences (0.1–1 m.y.). The composite fourth order depositional sequences of the Wabaunsee Group contain between two and three fifth order cycles (0.01–0.1 m.y.). These fifth order cycles form retrogradational transgressive system tracks and aggradational to progradational highstand system tracks.

Lowstand units are comprised of incised valley fill deposits or laterally extensive paleosols. The fifth order cycles are separated by poorly developed, laterally discontinuous paleosols or marginal marine units. These poorly developed paleosols are expressed as coals, coaly shales, or underclays.

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Reservoir Characterization of the Council Grove Group, Texas County, Oklahoma

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Production from Permian age Council Grove Group carbonates was established on a regional basis in the mid-1950's. Panoma Field, extending from Kearny County, Kansas to Texas County, Oklahoma currently has 2,482 active wells that have produced over 2.4 TCF. Wells were generally fracture stimulated and then brought on production with a substantial amount of water production. Operators involved in recent exploration plays in Texas County have discovered new reserves in the Beattie, Neva and Howe Limestones. A completion technique of limiting the perforations to only a specific reservoir and then using an acid stimulation or small frac has cut the amount of water production.

Sedimentation patterns for the 4th order sequence sets in the Council Grove Group are characterized by coarsening upward carbonate shoals overiain by terrestrial redbeds. Shoal lithofacies generally consist of skeletal grainstones, packstones, and wackestones. Dissolution of carbonate allochems and matrix by meteoric diagenesis creates porosity that averages fifteen percent. Pore types vary from intergranular to touching vugs with 0.01 to 200 millidarcies of permeability.

A more accurate prediction of hydrocarbon and water productive reservoirs can be achieved if each reservoir is evaluated by lithofacies. A case history of constructing pickett plots and bulk volume water plots on the basis of lithofacies in the Beattie Limestone illustrates how a silty carbonate matrix can cause high water saturation calculations. A cementation exponent of 1.8 in the standard Archies equation is more appropriate for the skeletal wackestones.

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Depositional Facies and Petrophysical Properties of the Pennsylvanian Cottage Grove Sandstone Member (Osage-Layton Sand), Chanute Formation: East Newkirk Field, Cherokee Platform, Oklahoma

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Core and E-log interpretations indicate that the Cottage Grove Sandstone Member (Osage-Layton Sand) of the Pennsylvanian Chanute Formation, at least in this geographic setting, consists primarily of a heterogeneous, 120 ft (37 m) thick succession of delta-front deposits. The delta-front deposits can be subdivided into a proximal delta-front facies (distributary mouth-bar subfacies) and a distal delta-front facies. The delta-front facies grades seaward into prodelta deposits and is capped by a marine-transgressive black shale facies.

Compositionally, the sandstones are primarily lithic subarkoses. Quartz is the dominant framework grain with lesser amounts of feldspars, rock fragments, and clays. Clay content consists primarily of illite + smectite and ranges from 1–39%, averaging 18%, and is inversely correlated with grain size.

The sandstone succession shows significant degrees of internal heterogeneity including carbonaceous-lined laminae, comminuted plant material, shaly coal and coal spars, clay rip-up clasts, shale laminae and interbeds, and secondarily matrix-clay content and locally cemented zones.

Measured core porosities range from 2–20%, averaging 16%. Porosity is limited primarily by compaction of ductile rock fragments and muddy matrix. Measured core permeabilities range from 0.01 to 97 md, averaging 15.3 md. Illite + smectite is the main permeability-reducing component and is followed in decreasing order of importance by compaction, ferroan dolomite, and quartz overgrowths. Core porosities and permeabilities are consistently higher and more uniform in the proximal delta-front facies (distributary mouth-bar subfacies) and lowest in the distal delta-front, prodelta, and marine-transgressive shale facies.

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Lansing Reef and Stratigraphic Trapping on the Slope Front in the Douglas and "Tonkawa" at the Edge of the Hugoton Platform

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The Lansing and Kansas City Formations belong to the Missourian Series, Hoxbar Group of the Pennsylvanian. They are generally represented by a series of thin limestone beds (Avant, Hogshooter and Checkerboard) separated by thin shales having high gamma radiation readings. In the shelf and basin of Oklahoma, sandstones are present between these markers (Cottage Grove, Layton and Cleveland). These areas are representative of high clastic input. In the northern shelf of the Texas Panhandle the sandstones are absent. The limestone markers thicken dramatically over short horizontal distances, generally becoming the massive carbonate banks of the Hugoton Embayment. Hansford County, Texas, is bisected by an appendage of this carbonate bank. This Lansing reef is productive at the crest in stratigraphic traps in the Lansing itself. Production from stratigraphic traps has also come from the overlying clastic formations (Douglas and "Tonkawa") which lap out on the reef structure.

Cross-sections and other pertinent data will be presented that will demonstrate the regional geology which will illustrate the clastic to carbonate sequence. A discussion of the significance of these systems on hydrocarbon trapping and production trends will be included.

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An Example of a Carbonate Platform and Slope System and Its Stratigraphically Equivalent Basinal Clastic System—Springeran/Chesterian Relationships within the Anadarko Basin of Northwestern Oklahoma and the Texas Panhandle

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An extensive regional study covering the Anadarko Basin of Oklahoma and Texas has been conducted, which has included stratigraphic correlation with the generation of regional cross-sections, production allocation and reservoir characterization. While the entire stratigraphic section has been subjected to elements of this study, the Springer Group, Upper Mississippian and Lower Pennsylvanian, is the most demonstrative of a carbonate platform and slope system with its stratigraphically equivalent basinal clastic system.

Historically, the first carbonate encountered below the Morrow/Springer clastic section has been called the Chester Limestone by convention. Regional correlations in both Oklahoma and Texas from the deep Anadarko Basin, through the slope and onto the shelf, indicate that the Springer clastics of the deep basin are stratigraphically equivalent to Springer carbonate facies on the slope and shelf. As a result, Britt and Boatwright Carbonates have been identified which heretofore have generally been considered to be Chester. A highly conductive Boatwright Shale directly above the true Chester Limestone provides a very reliable regional marker at the base of the Springer Group over Oklahoma and Texas. Regional cross-sections showing trapping mechanisms, production maps delineating trends and lithofacies maps indicating depositional environments will be presented covering the Anadarko Basin and Shelf areas of both Oklahoma and Texas.

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Significance of Accurate Carbonate Reservoir Definition and Delineation

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Reservoir definition is often vague or poor even in mature areas due to misidentified angular unconformities, facies changes, or poor understanding of the relationships existing in deep portions of a basin that were undrilled until late in the development history. Typically there does not exist any mechanism to correct misnamed reservoirs as it is often dismissed as being "purely academic," insignificant, or unnecessary. As a result of a recent Gas Research Institute project (GRI-96/0196), a classic example of the significance of accurate reservoir definition and delineation was identified. 1,232 well completions had been reported as being from the Chester (Mississippian), when, after detailed correlations, it was demonstrated that only 221 completions could be attributed to the Chester within the study area. Consequently, the ultimate recovery of the Chester diminished from 1,781 BCF to 277 BCF gas. Most of the gas was being produced from carbonate reservoirs belonging to the above lying Springer Group and could be identified as such through regional stratigraphic correlations. Although found at comparable depths, the carbonate reservoirs belonging to the Springer Group typically produce 50 to 80 percent more gas per completion than completions within the Chester.

This paper will present the findings which explain the significance of the disparity between the often misidentified reservoirs. These finding demonstrate that opportunities exist for significant infield development, trend extensions, and the further development of newly recognizable trends. Basinwide stratigraphic correlations and detailed geologic analysis will be presented.

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Detailed Reservoir Modeling on a Basinwide Scale and Implications on the Decision Making Process

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More than 3,500 wells producing from the sandstones belonging to the Morrow Group (Pennsylvanian) and underlying Springer Group (Mississippian-Pennsylvanian) were the subject of detailed reservoir analysis within portions of the Anadarko Basin (USA). Within the study area, these reservoirs will ultimately produce more than 8 TCF gas, with individual completions >25 BCF gas. Because the area has been drilled by many companies, a large variation in the drilling and completion techniques has been observed, consequently, large variation in the results exists. Detailed stratigraphic correlation resulted in accurate reservoir nomenclature throughout the study area, which allowed the examination by specific reservoir and within subsets of wells with similar parameters.

The results were unexpected and should have significant impact on the decision making processes in both exploration and development efforts. For example, mud balance influences how much invasion into a zone. When it is combined with pH of the water, the mud pH demonstrates the more impact on ultimate recovery than any single drilling or completion factor examined. Interestingly, mud water loss (typically below 8 ml) did not appear to have much impact upon this observation. Another observation suggests that the practice of perforating selected intervals of a reservoir has a direct relationship to ultimate recovery—usually not favorable. Extensive stratigraphic correlations, detailed geologic analysis, and the findings presented demonstrate that changes in the decision making process should result in opportunities for significant infield development, trend extensions, and the further exploration in what may be considered a "drilled out" play.

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The Origin of Stratigraphic Sequences

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A revolution is underway in understanding the causality of depositional patterns and sequences. The areal distribution of accommodation space is the primary control to interrelate the depositional setting, the depositional theme, and the genetic sequence of strata. Accommodation space is related to changes in sea level and rates and patterns of subsidence. These attributes are interrelated in space and time on scales of a few hundred km^2, and time periods of a few 1,000 years.

Depocenters can be related to patterns of lithospheric stress distribution associated with wrench faulting, and the areal variations in lithospheric thickness, density, and heat flow.

Determining the origin of stratigraphic patterns requires the development of a time-rock correlation framework at a scale sufficient to determine the geometry of genetic sequences. Depositional patterns may reflect vertical stacking, progradation or overlapping stratigraphic responses. These patterns are complexly related to rates of change in accommodation space, rates of sediment supply, and dispersive forces. The mapping of the geometry and pattern of terminations of bedding planes and disconformities is required in order to determine the depositional history.

The depositional history of Missourian and Virgilian strata in Oklahoma and Kansas reflect changing patterns of basinal subsidence, progradation and onlap. These are associated with wrench faulting, the history of sea level changes and patterns of basinal subsidence. These can be causally related to the development of deltaic depocenters, carbonate banks and onlapping euxinic shale intervals.

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Pennsylvanian History of the Chautauqua Arch, Oklahoma and Kansas

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The Chautauqua Arch experienced maximum uplift during Late Devonian Acadian movements and again, much later, during the Pennsylvanian. The Chautauqua Arch was episodically uplifted and eroded during the Pennsylvanian, a phase commonly omitted on many Pennsylvanian tectonic maps. This arch separates the northern ramp of the Arkoma Basin in southeastern Kansas and closely straddles the northeastern Oklahoma and Kansas border. These later uplifts coincide with tectonic movements of the evolving Ouachita Mountains and Ozark Uplift. Consequently, the Lower to Middle Pennsylvanian sedimentary pile along the Chautauqua Arch is about half the thickness of this interval in the Kansas Cherokee Basin and one fifth or less of a similar chronological interval in the Oklahoma Arkoma Basin.

Numerous Lower Pennsylvanian beds of northeastern Oklahoma are missing over this arch. Middle Pennsylvanian unconformities in southern Montgomery and Labette Counties result in complete absence of the Hepler Sandstone, the Lost Branch Formation, the Canville and Stark Shale Members of the Dennis Limestone, the Cherryvale Shale, the Corbin City Limestone of the Drum Limestone, and the Dewey Limestone. In addition, much thinning of other stratigraphic units exists over the arch including the Iola, Plattsburg, and Stanton Limestones. In contrast, thick silty to sandy sediments of the Bandera and Chanute Shales were deposited during brief periods of deltaic accumulation.

The Chautauqua Arch may be considered as a Pennsylvanian forebulge that separates the Arkoma foredeep basin and northward adjoining foreslope from the Cherokee backbulge basin.

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The Strike-Slip, Compressional Thrust-Fold Nature of the Nemaha Ridge in Eastern Kansas and Oklahoma

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Much has been written about the Nemaha Ridge in Kansas and Oklahoma since geologists first became aware of it from oil-well drilling in the early years of this century. It has been described as extensional, compressional, and strike-slip. In this talk I will present data to show that the Nemaha was formed in the usual manner of non-volcanic, non-intrusive uplifts, that is, by compressional, or thrust, faulting that began deep within the Precambrian crust to the west and extended in listric fashion to the ground surface coincident with the Humboldt fault zone or east bounding fault. Compressional effects observed from oil-well drilling and seismic surveys along its entire length are too numerous to ignore and to permit of an extensional origin, if it is even possible to consider an extensional origin for an uplift.

Two additional effects occurred simultaneously with the thrusting. A back-thrust evidently formed in a manner similar to that mapped in many compressional environments, for example, the Front Range of Colorado, the Uinta Mountains in Utah and the Wichita Mountains in Oklahoma, essentially making the ridge a V-shaped "pop-up block," thus explaining the up-to-the-east fault or fold on the west. Additionally, the thrusting had a strong component of strike-slip motion which resulted in the end closures of structures along it, i.e., the formation of petroleum traps, plus additional complexities that have made the Nemaha Ridge difficult to interpret and its origin controversial. Small normal faults indicate that extension played a minor role in post-Permian time.

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Paleoearthquakes and Late Paleozoic Recurrent Structural Movement in the Midcontinent (USA): Stratigraphic and Sedimentological Evidence

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With exception of continued minor adjustments and regional tilting, the present major structures and their subsidiary features in the Midcontinent were formed in late Mississippian/early Pennsylvanian time. These features were controlled by the inherent Precambrian basement fracture/fault pattern, which is reflected up through the overlying Paleozoic sedimentary section. The recognition of continued rejuvenation of these structures is based on stratigraphic and sedimentological evidence. The local folds

(plains-type folds) continued to develop after formation as chronicled by differential compaction, mostly in the shaly units over "buried hills," which for the most part are irregularities created by the differential movement of the basement fault blocks. Recurrent movement on the fault blocks is collaborated by convolute sedimentary bedding formed in the Pennsylvanian sequence. The compaction is greatest and convolute features are most abundant in the shaly units and in the older units, as would be expected, indicating the recurrent movement was most intense immediately following the Ouachita Orogeny and more abundant in the south near the deformation source. Convolute bedding generally is recognized as having been formed in special dewatering situations in the sediments and triggered by paleoearthquakes. The paleoearthquakes and the differential movement of fault blocks are a reflection of changing stress within the basement. Magnitude on some of the paleoearthquakes is estimated to be between 6½ and 7 on the Richter scale affecting between 13,000 and 20,000 km^2.

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Evidence from Gravity and Magnetic Data for Diffuse Extension along the Southern Termination of the Midcontinent Rift System

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Interpretation of gravity and magnetic maps from Kansas suggest that the southern Midcontinent rift system does not terminate abruptly in central Kansas, but becomes a much wider, diffuse zone of extension that continues southward into Oklahoma. Although the rift zone in this diffuse zone of extension does not exhibit the large gravity and magnetic anomalies typical of the Midcontinent rift north of central Kansas, it does exhibit subtler gravity and magnetic anomalies that suggest deeper seated intrusions, widespread faulting and dikes, and depositional basins that have the same general northeast-southwest trend of the rift zone to the north. These trends are particularly well imaged on vertical sun-shaded gravity and magnetic maps of Kansas. The longer wavelength, lower amplitude gravity highs are probably a result of deep seated mafic intrusions, while the narrower, higher amplitude gravity highs suggest upper crustal mafic dikes or other intrusions that were brought near the top of the basement by faulting. Linear gravity lows result from either lower density granites or relatively deep sedimentary basins. A broad magnetic quiet zone, most of which is associated with a magnetic low, occurs in central Kansas on the west flank of the Midcontinent rift. This quiet zone, and possibly other magnetic lows along the trend of the rift zone are due to a relatively thick accumulation of clastic rocks of the Rice formation. Narrow, northeast to southwest-trending magnetic anomalies in south central Kansas are probably caused by mafic dikes or faulting associated with the diffuse zone of extension. The change in the style of extension along the Midcontinent rift to a more diffuse zone occurs along the northwest-southeast trending boundary between the Southern Central Plains orogen and the Southern Granite Rhyolite Province, and thus may be related to changes in the basement rheology south of the boundary. The diffuse zone of extension also influences the trend of the Precambrian basement surface, as well as structures, sedimentation, and oil and gas accumulations in the Paleozoic units above the basement.

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Taphonomy of a Crinoid Lagerstätte Deposit, Barnsdall Formation (Upper Pennsylvanian), Northeastern Oklahoma

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An unusually rich deposit of articulated fossil crinoids occurs in a mudstone within the Upper Pennsylvanian Barnsdall Formation north of Bartlesville, Oklahoma. Over 1,150 individuals have been recovered, most from a 5–8 cm bed (the "main crinoid bed") within an area of 12 square meters. Forty-two genera are represented, making this the most diverse single occurrence yet reported from the Pennsylvanian System. In addition, the crinoids (mostly inadunates) are exceptionally complete: over 90% of recognizable individuals have arms attached.

Following the initial phase of recovering crinoids by screening bulk samples, an archeological-style excavation was conducted to provide the contextual data necessary for reconstruction of the unit's depositional and taphonomic history. The resulting evidence indicates that death and preservation was caused by rapid clay and silt deposition below wave base in the distal portion of a turbidity flow. Significant transport is contraindicated by fragile skeletal remains, including large fenestrate bryozoans and productid brachiopods with intact spines, as well as the articulated crinoids. The abundant and diverse epifauna demonstrates oxygenated benthic waters, and argues against death by anoxia. Likewise, the virtual lack of primary sedimentary structures, the dominance of burrow mottling as opposed to distinct biogenic structures, and the well-developed infauna preserved as body fossils rules out anoxic pore water in the underlying sediment. Siderite nodules, which are concentrated in the main crinoid bed and in a second crinoid-rich bed above it, formed as relatively early diagenetic cements at shallow depth within the sea-floor sediment, as shown by moderate compaction of crinoids and biogenic structures contrasted with extreme compaction in the surrounding mudstone. Coincidence of siderite nodule layers and articulated crinoids may be explained by the generation of carbon dioxide by the bacterial decay of organic matter after rapid burial isolated the obrution layer from sulphate ions in the benthic layer above. Thus, in this setting, the concentration of siderite nodules serves as a predictor of obrution horizons.

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