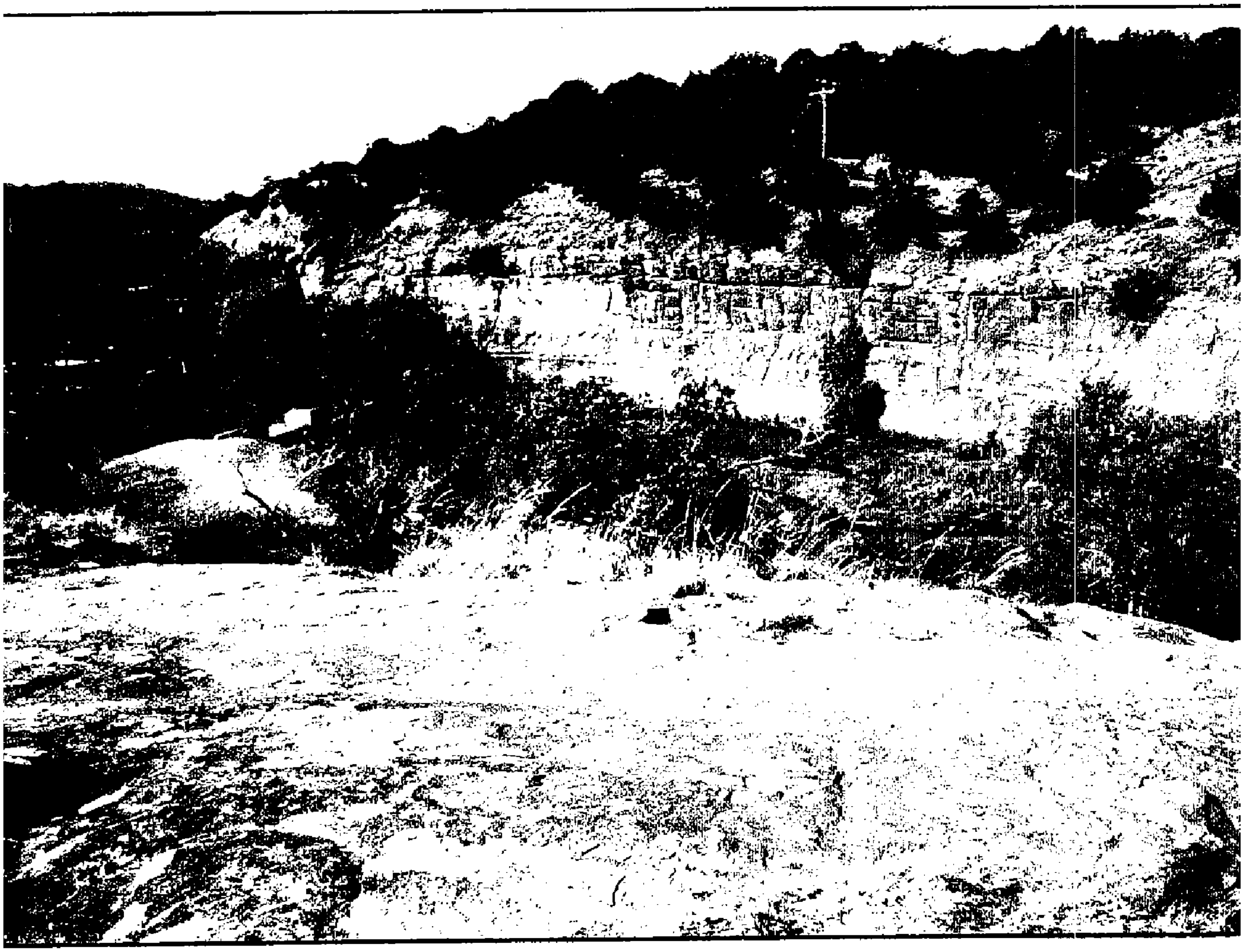
OKLAHOMA GEOLOGY



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On The Cover —

Red Rock Canyon, Caddo County, Oklahoma

View of Red Rock Canyon looking south from near the top of Balancing Rock across the pond and dam (visible on left side of photo) to the west wall of the canyon. Permian Rush Springs Sandstone makes up the beautifully colored bedrock throughout Red Rock Canyon State Park. Mostly horizontally bedded sandstone is exposed in the vertical cliff face; cross-bedded sandstone is exposed on the tree- and grass-covered slopes above the cliff.

The canyon is partly filled with unconsolidated sediments eroded from the surrounding outcrops of Rush Springs Sandstone. These sediments were deposited during the latter part of the Pleistocene, when Oklahoma's climate was much wetter than it is today. It is possible that Red Rock Canyon was eroded, filled with sediment, and re-eroded four times in the last million years, but the evidence is not conclusive. (Also see feature article, this issue.)

Neil H. Suneson

Photograph by Fred W. Marvel
Oklahoma Tourism and Recreation Department

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OKLAHOMA GEOLOGY

Notes

CONTENTS

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GEOLOGY OF RED ROCK CANYON STATE PARK

Neil H. Suneson[1] *and Kenneth S. Johnson*[1]

Location and Topography

Red Rock Canyon State Park (cover photograph) is located along U.S. Highway 281 just south of Hinton, in northeastern Caddo County, Oklahoma (Fig. 1). The park is dissected by a south-flowing tributary of Sugar Creek, which in turn flows south–southeast into the Washita River. The elevation of the highest point in the park is about 1,650 feet above sea level; that of the lowest point is about 1,450 feet above sea level. Red Rock Canyon itself is about 150 feet deep; locally, the vertical canyon walls and overhanging cliffs are as much as 60 feet high, but generally they are about 45 to 50 feet high.

Red Rock Canyon is only one of several beautiful canyons in northeastern Caddo County and extreme southwestern Canadian County. Some of the streams that have formed these canyons drain south into the Washita River, or into Sugar Creek, which also drains into the Washita; others drain northeast into the Canadian River.

Bedrock Geology of the Park

Red Rock Canyon is a beautiful canyon that has eroded into sandstone that is part of the Rush Springs Sandstone formation of Late Permian age (Fig. 2). The Late Permian extended from about 270 to 250 Ma (million years ago). (For definitions of geologic terms and names, see the Glossary, based in part on Bates and Jackson, 1987.) Most of the surface rocks in this part of Oklahoma are Permian; in general, if the rocks (and soil that has developed on the rocks) are red, they're Permian. Older to younger Permian formations are exposed from the northeast to the southwest, respectively, because the rock layers are tilted gently to the southwest, about 10–20 feet per mile, into the Anadarko basin. (The Anadarko basin is described more fully below in the section on Regional Geology.)

The total thickness of the Rush Springs Sandstone in the Hinton area is about 300 feet, and about 150 feet of the middle part of the formation is exposed in the park. The next older formation, the Marlow Formation, can be seen beneath the Rush Springs Sandstone along the stream that forms the canyon about 2 miles south of the park, and along Sugar Creek north of Binger. The upper part of the Rush Springs Sandstone and the overlying Cloud Chief Formation (Fig. 2) have eroded away in the area.

The Rush Springs Sandstone is reddish brown to orangish brown in color; it is mostly very fine grained to fine-grained sandstone, although layers of siltstone and thin layers of shale are present in places. The sandstone consists of small sand grains (0.06–0.25 mm in diameter), mostly of translucent quartz, but also of feldspar and some dark iron-magnesium silicate minerals. These sand grains are loosely cemented together by iron oxides, gypsum, and calcite. (The "cement" in sandstone is natural and consists of one or more minerals that precipitate or crys-

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[1]Oklahoma Geological Survey.

tallize out of ground water that slowly moves through the rocks. At first, these minerals form a thin coating on individual sand grains. As minerals continue to precipitate from ground water, the coatings on adjacent grains grow together. In this manner, sand becomes sandstone.) In places, the cement is concentrated along fractures in the Rush Springs Sandstone, imparting a "webbed" appearance to some outcrops.

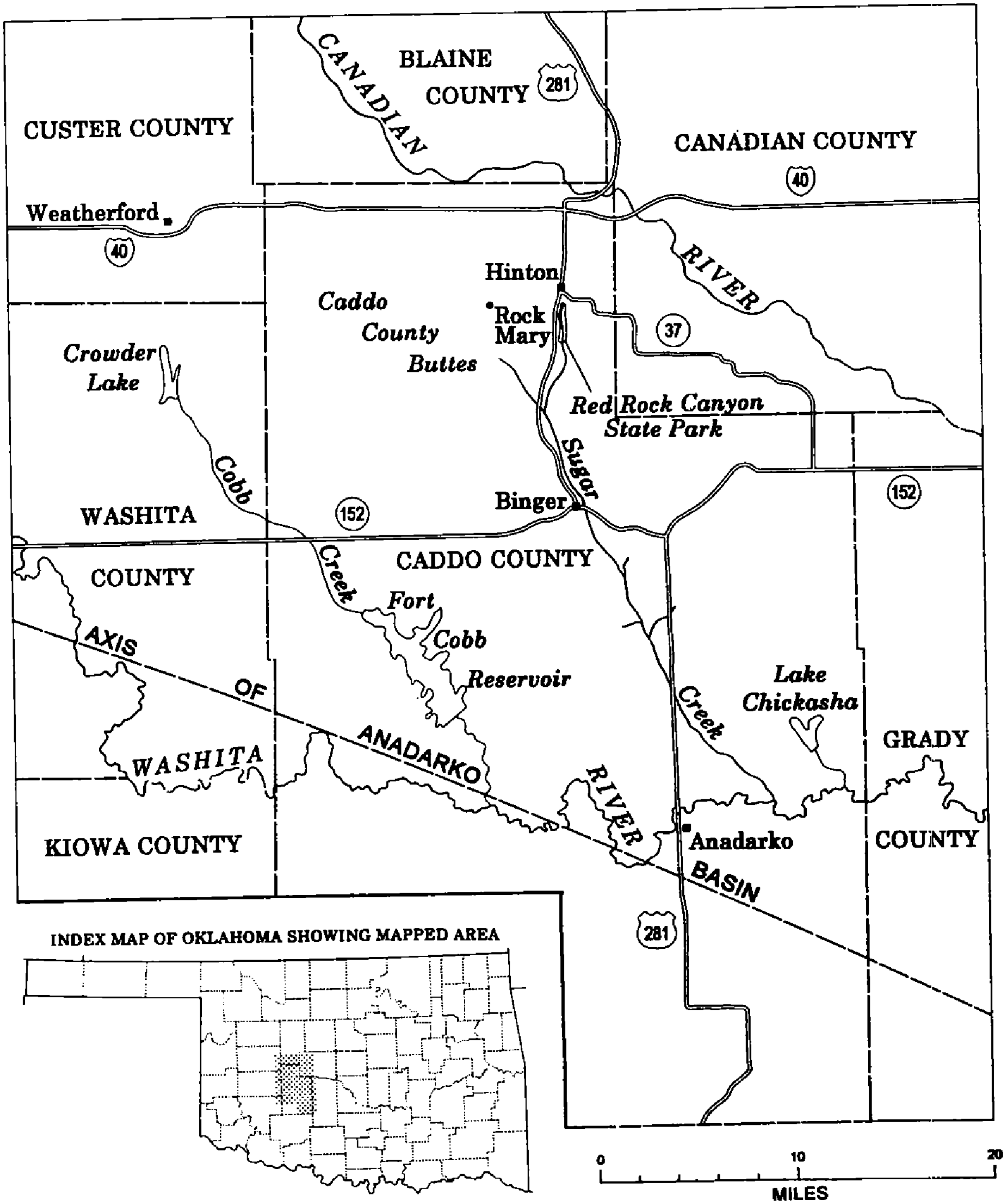

Figure 1. Map showing location of Red Rock Canyon State Park and local geologic features.

GENERALIZED STRATIGRAPHIC COLUMN

PERIOD/ EPOCH		FORMATION	FEATURES
PLEISTOCENE		"CANYON FILL"	*RED ROCK CANYON STATE PARK*
PERMIAN	UPPER	ELK CITY SANDSTONE	
		DOXEY SHALE	*HILLS WEST OF CLINTON*
		CLOUD CHIEF FORMATION	
		RUSH SPRINGS SANDSTONE	*CADDO BUTTES* *ROCK MARY* *RED ROCK CANYON STATE PARK*
		MARLOW FORMATION	
		DOG CREEK SHALE	
		BLAINE FORMATION	*ROMAN NOSE STATE PARK*
		FLOWERPOT SHALE	
		DUNCAN SANDSTONE	
	LOWER	HENNESSEY GROUP	*OUTCROPS NEAR OKLAHOMA CITY*
		GARBER SANDSTONE	*ROSE ROCKS NEAR NOBLE*

Figure 2. Stratigraphic column showing relative ages of geologic formations near Red Rock Canyon State Park and local geologic features in these formations. The double line between "canyon fill" and Elk City Sandstone represents an unconformity—a break or gap in the geologic record separating rock units of very different ages.

Perhaps the most spectacular feature of the Rush Springs Sandstone is its red color. The color results from a thin coating of oxidized iron minerals (mostly hematite) that stains individual sand grains in the rock. Iron oxide generally makes up only 2–3% of the rock, but just a little red stain goes a long way in coloring a rock that consists mostly of otherwise colorless and translucent quartz grains. It is uncertain whether the sandstone in the Rush Springs Sandstone was red when it was

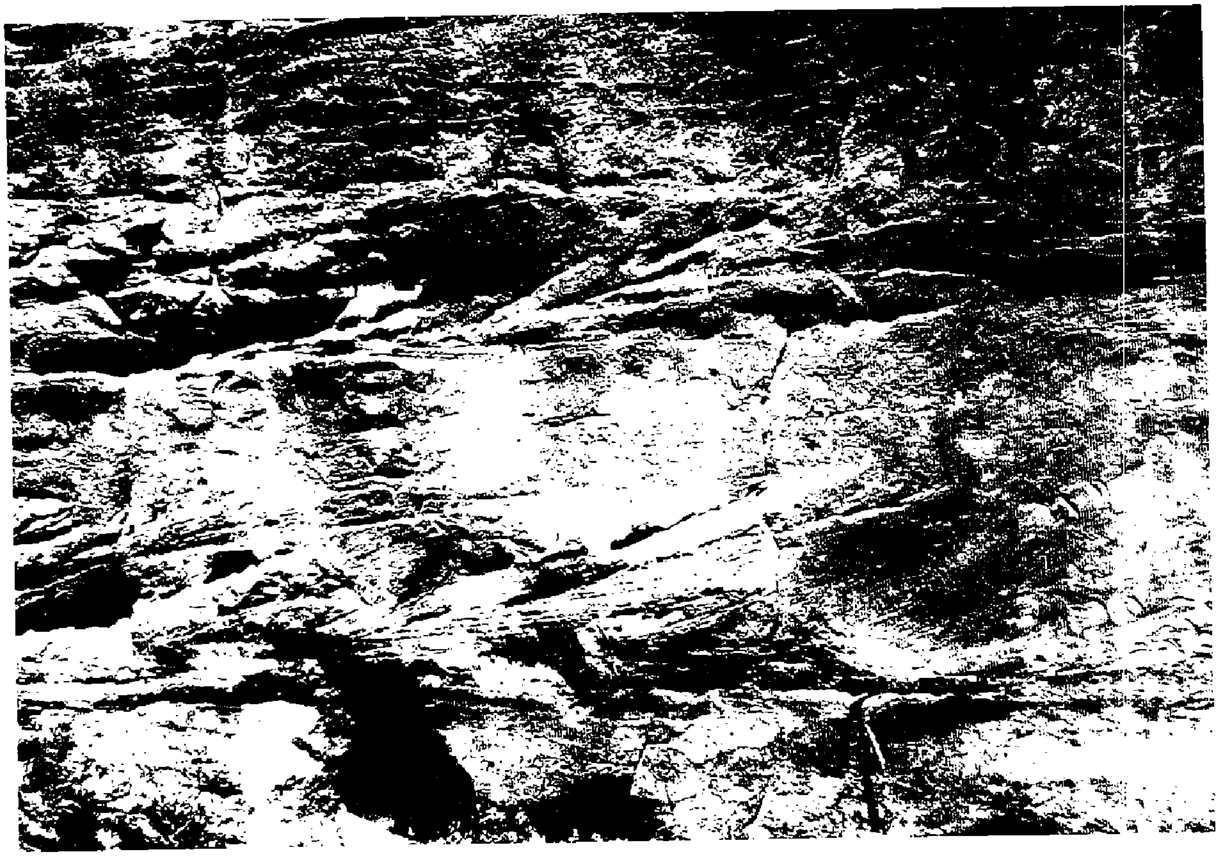

Figure 3. Two cross-bedded layers in the Rush Springs Sandstone in the canyon wall near Group Camp. These layers are in the lower, mostly non-cross-bedded part of the exposed sandstone. Note rock hammer (13 inches long) at lower right, for scale.

deposited, or whether the red color is due to chemical changes after deposition. Most geologists think that the sediment was red when deposited: the red color, salt, and gypsum in Permian-age sediments throughout the world is evidence for widespread arid conditions, and supports the theory that these sediments were oxidized (red-colored) before they were deposited. The red color extends back behind the canyon walls, and this formation, like most Permian formations, is red throughout western Oklahoma.

A feature of the Rush Springs Sandstone, which can be seen in the park as well as in other locations, is that the red rocks appear to be stained with vertical stripes of darker material. Most of these stripes are surface coatings of manganese dioxide (MnO_2), which form as a result of weathering. Some of the dark stripes in the canyon walls are encrustations of lichen (a plant composed of an alga and a fungus that rely on each other to live). The manganese stain and lichen tend to occur where water has seeped out of the sandstone and trickled down the canyon wall. Over time, the lichen breaks down the sandstone into sand, contributing to the erosion of the canyon walls.

Cross-bedding is another conspicuous feature of some of the sandstone beds in the Rush Springs Sandstone (Fig. 3). The cross-bedding is particularly evident in layers that are 3–10 feet thick and about 20–30 feet above the canyon floor (Fig. 4). This feature resulted from wind transport and deposition of sand grains when the Rush Springs Sandstone was being deposited in this part of Oklahoma. Although

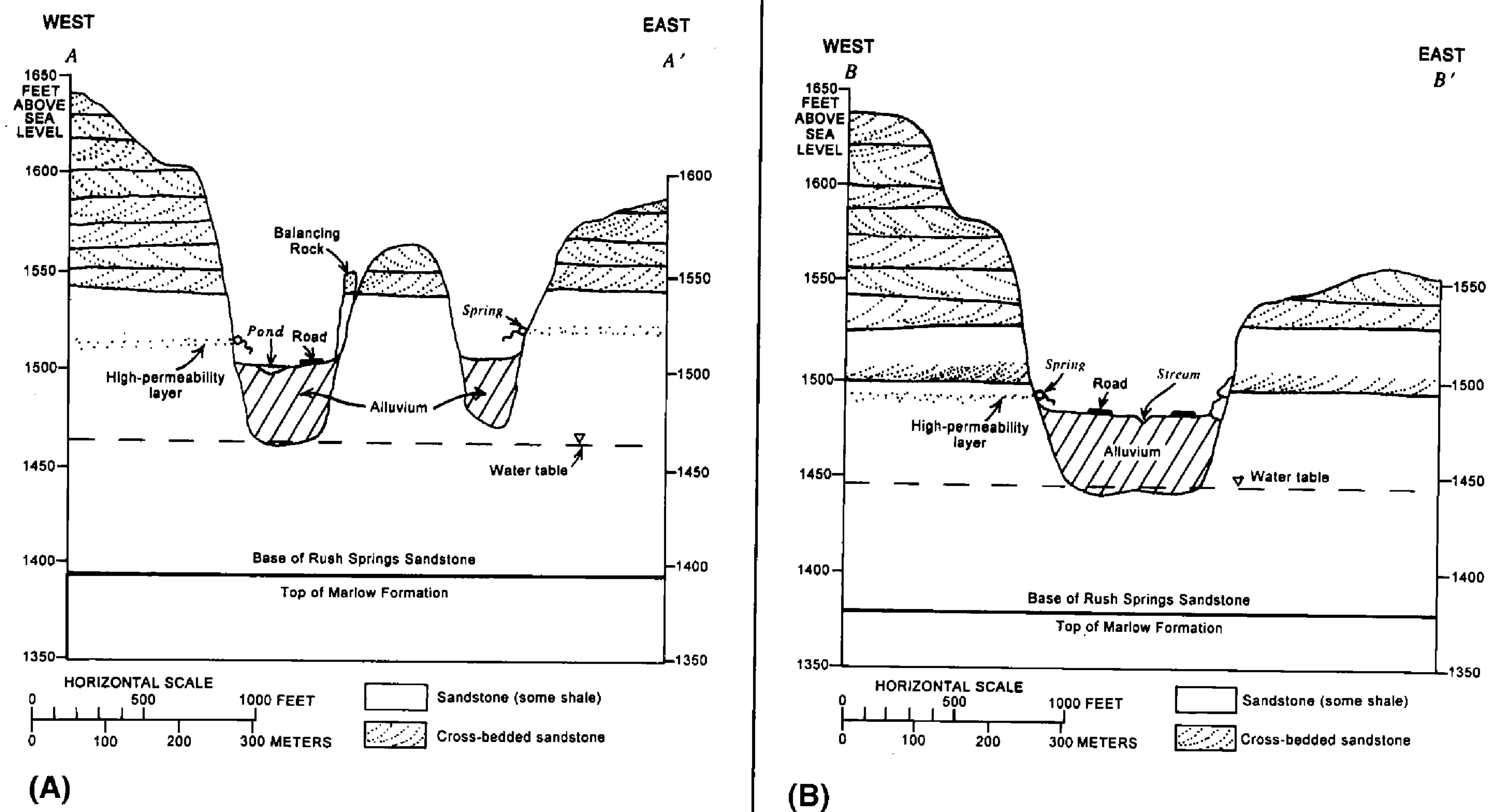

Figure 4. (A) East–west cross section across Red Rock Canyon State Park near Canyon Campground. (B) East–west cross section across Red Rock Canyon State Park near Group Camp. Both A and B show the canyon fill (alluvium) and features of the Rush Springs Sandstone. (Location of cross sections are shown in Figure 6.)

Figure 5. Cross-bedded sandstone layers along the California Road Nature Trail. The cross-bedding in the sandstone makes the rock layers appear steeply tilted. Regionally, however, the Rush Springs Sandstone in Red Rock Canyon is nearly horizontal.

the sand grains were transported to the park area by streams (see section on Geologic History), sediments in the cross-beds (exposed in the upper part of the canyon walls) were reworked during, and shortly after, deposition. A series of sand dunes were created and they migrated across the area, in the same way that sand dunes are now forming and migrating at Little Sahara State Park, near Waynoka. The cross-bedded layers are well exposed in cross section in the upper canyon walls and in three dimensions in the bare, bedrock exposures above and back from the canyon walls (Fig. 5).

Geomorphology of the Park—Canyon Cutting and Filling

Red Rock Canyon is about 2½ miles long and averages 80 feet wide at its head and 750 feet wide at its mouth. In the northern part of the park, the canyon walls are vertical to overhanging. Downstream, toward the southern end of the park, the canyon walls are steep but no longer vertical. Farther downstream, they become less steep and eventually lose their character as walls altogether, where the soft, more easily eroded Marlow Formation is exposed.

The physiography of the park can be divided into three areas: the upland prairie, the box-head area, and the canyon. The upland prairie consists of fairly level to gently rolling farmland and is the dominant landform in west-central Oklahoma. The rolling farmland can be observed as you approach the park from any direction.

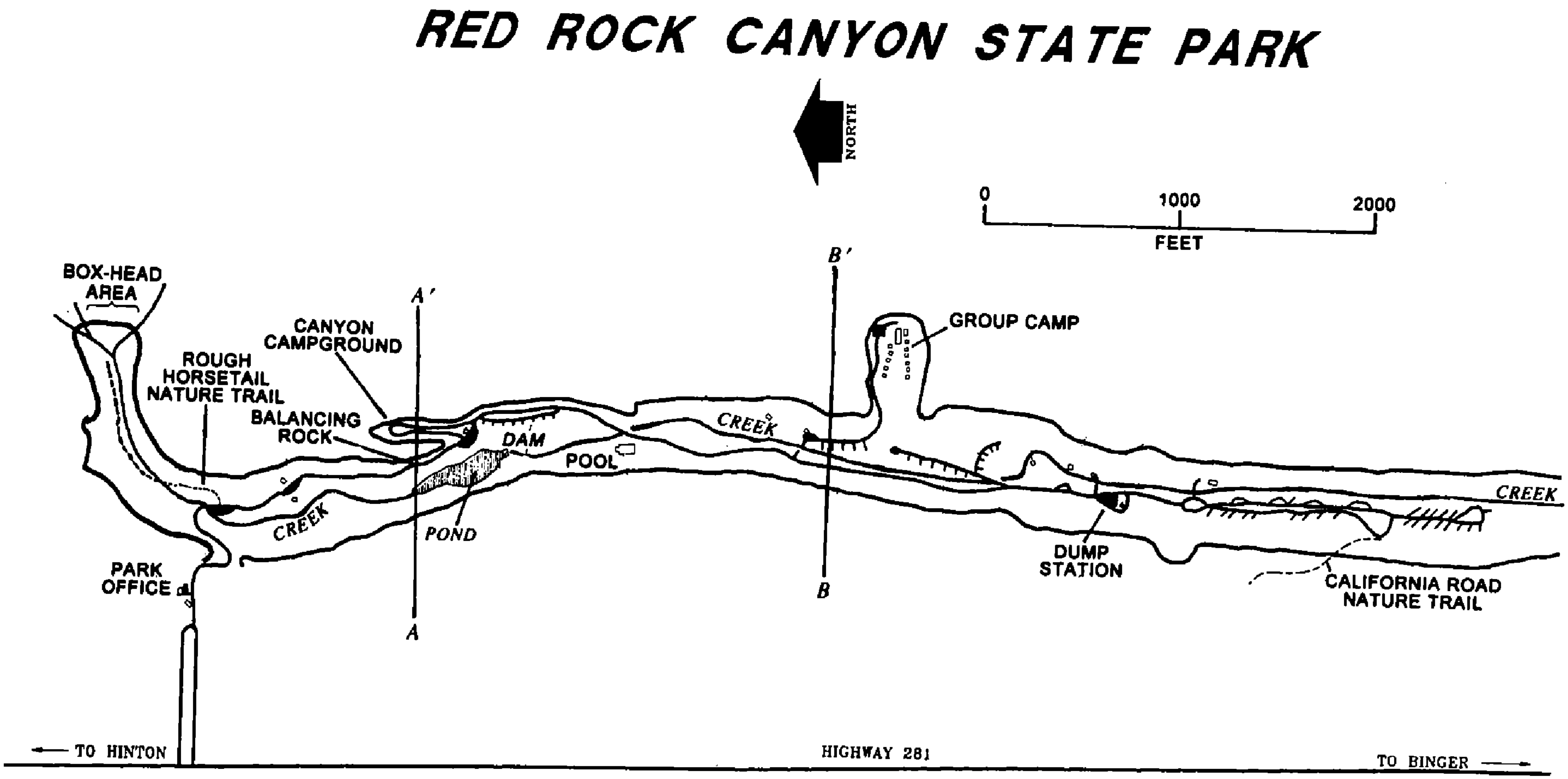

Figure 6. Map of Red Rock Canyon showing features mentioned in text and locations of the two cross sections depicted in Figure 4.

Figure 7. One of the box-heads at the end of Rough Horsetail Nature Trail. The V-shaped notch and vertical to overhanging cliff are characteristic features of box-heads.

In the park, itself, the upland prairie occurs between the canyon rim and the park boundary.

The box-head area of Red Rock Canyon can be seen at the end of the Rough Horsetail Nature Trail, at the northern end of the park (Fig. 6). It actually is three box-heads at this site, each of which consists of a vertical to locally undercut, semicircular cliff; a V-shaped notch at the top of each cliff is the present-day stream channel (Fig. 7). Beneath each box-head, a plunge pool is excavated below the general level of the soft sediments that fill the canyon. Two other box-heads have developed elsewhere in Red Rock Canyon State Park, each where a major stream enters the canyon from a side. One is at the head of the Canyon Campground facility and the other is at the head of the Group Camp facility (Fig. 6). Like those at the end of the nature trail, their cliffs are semicircular in outline, have varying degrees of steepness, and show the characteristic V-shaped notch at the top. Box-heads are a characteristic feature of most of the canyons that are eroded into the Rush Springs Sandstone near the park. The origin of box-heads is described in the section on Geologic History.

The physiography of the canyon, itself, can be discussed in terms of the canyon walls, valley floor, and drainage system. The walls of Red Rock Canyon range in height from a few feet to 60 feet, but generally they are 45–50 feet high. In places, the walls are vertical and nearly planar, which suggests that joints or natural fractures partly controlled the location and direction of the canyon. Just north of the spire named Balancing Rock (Figs. 4A, 8), large vertical joints can be seen in the canyon wall. Eventually, these joints will widen, perhaps forming another spire, which ultimately will collapse, thus widening the canyon. In other places, the walls are vertical to overhanging and curviplanar ("scalloped" in appearance). The curved segments are concave towards the valley and are separated by cusps. The curved parts of the canyon walls probably were eroded by a meandering stream during a time when the canyon was not as deep as it is now. Small, hollow pockets that follow distinct layers within the sandstone high on the canyon walls may be evidence for such stream erosion; or, the pockmarks may merely follow more easily eroded rock layers in the Rush Springs Sandstone. The concept that Red Rock Canyon is currently undergoing a period of erosion, and may have undergone repeated episodes of erosion, filling, and re-erosion, is explained more fully in the section on Geologic History.

Figure 8. Balancing Rock. Erosion and widening of a nearly vertical joint in the canyon wall has formed this feature. Eventually, this spire will collapse and the sandstone rubble will erode to sand that will be carried out of the canyon. In this way, the canyon is gradually widened.

The valley floor of Red Rock Canyon is relatively flat and consists mostly of very fine grained to fine-grained sand derived entirely from erosion of the nearby Rush Springs Sandstone. In places, terraces of canyon-fill material lie above the general level of the valley floor; in other places, there are large spires (for example, Balancing Rock) and piles of broken blocks of sandstone. Locally, the vertical canyon walls meet the valley floor quite abruptly, which suggests that the canyon walls actually extend below the level of the alluvium in the canyon. In other words, Red Rock Canyon actually is deeper than it appears, but it is partly filled with sediment. Borings through the alluvium that partly fills the canyon have proved that the bedrock floor of Red Rock Canyon is about 20–50 feet below the present surface of the canyon fill; the average depth to bedrock is about 40 feet (Fig. 4). The borings also showed that the bedrock floor of the canyon is gently curved to flat.

The small stream that flows through Red Rock Canyon is fed by many perennial natural springs that seep through the sandstone of the Rush Springs Sandstone (see section on Hydrology). During and following rainstorms, additional water is supplied via surface runoff to the main stream and tributary streams. During periods of particularly heavy rainfall, the stream can overflow its banks, close the road into the park, and cause considerable damage.

One question that often is asked is why the direction (orientation) of the Canadian River differs from that of Red Rock Canyon. The answer relates to the age of the river in contrast to that of the canyon. The generally eastward direction of flow of most of the major rivers in Oklahoma, including an ancestral Canadian River, probably was established in the Early Tertiary (from about 67 to 50 Ma), during uplift of the Rocky Mountains. This uplift imparted an eastward tilt to the land surface throughout western Oklahoma. In places where they encounter easily eroded rocks, the rivers are deflected from the generally eastward direction of flow. In contrast, the southerly to southwesterly direction of Red Rock Canyon is the result of erosion during the much more recent Pleistocene (less than about 2 Ma) (see section on Geologic History) and is due largely to the tilt of the rocks into the Anadarko basin. On a more local scale, the remarkably straight courses of Red Rock Canyon and the several canyons near it may be caused by streams following natural joints or fractures in the rock.

Hydrology of the Rush Springs Sandstone

The sandstone in the Rush Springs Sandstone has only a small amount of natural mineral cement between the sand grains. As a result, it is very porous and permeable, which enables water to soak into the sandstone very rapidly; thus, the rock unit is an excellent ground-water aquifer. The Rush Springs aquifer in the Hinton area is recharged entirely from precipitation. Water percolates down through the soil or bedrock until it reaches the water table and thus replenishes the aquifer. As it percolates downward, some of the water encounters local, thin sandstone beds of especially high permeability; in these beds, the water flows laterally to canyon walls, where it is emitted as springs and seeps.

Ground water produced from local wells is of high quality; that is, a liter of water contains less than 500 mg of total dissolved solids. Well yields also are high: 100–500 gallons per minute. The water table probably was near the level of the canyon floor when Native Americans and early pioneers entered the area. A series of springs in the canyon made it a good campground and a welcome stop for travelers along the nearby trail, the California Road (Fig. 6).

Ground-water seepage is seen locally in the canyon walls where small clumps of vegetation grow due to extra moisture. In places, the thicker vegetation may follow a more permeable and water-charged sandstone bed. Above the canyon, vegetation can be seen growing along joints or fractures in the sandstone, because rainwater tends to accumulate and remain there. Also, a thin white mineral crust is present locally where mineralized ground water seeps to the walls; when the water evaporates, it leaves behind principally the minerals calcite, gypsum, and/or thenardite. Lichen, mosses, and algae also occur locally as organic encrustations on the rock surface.

Regional Geology of the Red Rock Canyon State Park Area

Most of the surface rocks in this part of Oklahoma are Permian in age. As you travel east, the rocks generally are progressively older; for example, the rocks near Oklahoma City, which are part of the Hennessey Group and the Garber Sandstone, are Early Permian in age (deposited between about 290 and 270 Ma) (Fig. 2). To the west and southwest of Red Rock Canyon, the rocks are slightly younger. The beautiful reddish-brown hills about 10 miles west of Clinton along Interstate 40 are formed by erosion of the Doxey Shale, which overlies (and therefore is younger than) the Rush Springs Sandstone (Fig. 2).

The rocks at the park are tilted gently to the southwest, toward the axis of the Anadarko basin (Fig. 1). The Anadarko basin is a major tectonic feature in Oklahoma, although it doesn't appear that way on the surface. It is one of the deepest sedimentary basins in the world, and as much as 40,000 feet of sedimentary rocks accumulated in it. The axis, or deepest part, of the basin in western Oklahoma extends southeast from Elk City, through Cordell and Fort Cobb.

The Anadarko basin is a prolific oil- and gas-producing province. Five wells were drilled within 2,000 feet of Red Rock Canyon State Park in the 1980s; the deepest is 13,380 feet deep. All produce oil and gas from Pennsylvanian-age sandstones that are at depths of about 10,000–13,000 feet. These sandstones were deposited about 315 Ma and are considerably older than the Permian rocks exposed at the surface. Pennsylvanian rocks are exposed in much of eastern Oklahoma, beginning just east of Shawnee (on Interstate 40).

There are several other interesting surface geological features near Red Rock Canyon State Park. Rock Mary, located about 4 miles west–southwest of Hinton, is an outcrop of Rush Springs Sandstone capped by a thin, unnamed layer of gypsum (Figs. 1, 9). A plaque on the top of Rock Mary reads:

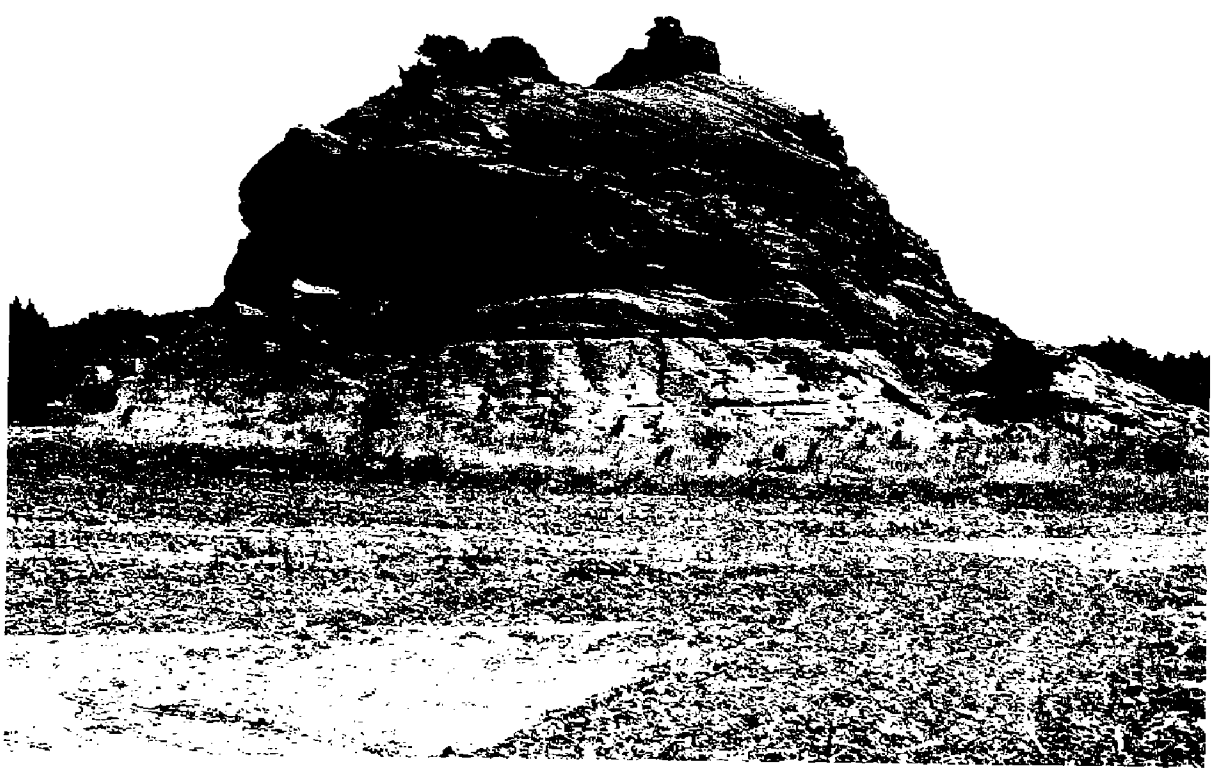

Figure 9. Rock Mary, located about 4 miles west–southwest of Hinton, is an outcrop of Rush Springs Sandstone capped by a thin layer of gypsum. Rock Mary is adjacent to the California Road and was a familiar landmark for emigrants traveling west during the gold rush.

May 23, 1849. This odd and unusual land feature was named on that date by Lieuts. J. H. Simpson and M. P. Harrison when they visited this site, planted a flag on the crest and named the rock for 17-year-old belle Mary Conway, an emigrant. Oklahoma Historical Society, 1960.

Caddo County Buttes cover a large part of northwestern Caddo County (Fig. 1). The buttes are capped by a thin, but locally hard, rock unit called the Weatherford Bed, which lies within and just below the top of the Rush Springs Sandstone. Locally the Weatherford Bed is gypsum, but in many parts of northwest Caddo County it is dolomite. Because dolomite is more resistant to weathering than the surrounding gypsum or underlying sandstone, it forms buttes in those places where it occurs. Eventually, however, the dolomite will erode and the buttes will disappear.

Geologic History of Red Rock Canyon State Park

Geologists can describe, although not always with total agreement, part of the geologic history of Red Rock Canyon State Park. By looking at the surface exposures (the Rush Springs Sandstone and those formations above and below it), they can piece together the history of west-central Oklahoma during Permian times. Similarly, by looking at the sediments that fill Red Rock Canyon, as well as other canyons in the area, geologists can infer something about when and how the canyon was eroded and later filled. (The geologic history of western Oklahoma before the Permian can be determined by looking at the rocks encountered in oil and gas wells; we will not attempt to describe that story here.) What happened between the end of the Permian Period and the time that the canyons were cut (between about 250 and 2 Ma) is unknown—all rocks and sediments deposited during that long time period have eroded away, if they ever were present at all. The evidence is gone (Fig. 2).

In Permian time, an extensive, relatively shallow seaway extended north from western Texas across the western half of the southern Midcontinent, including western Oklahoma (Fig. 10). This sea was bordered on the west by the ancestral Rocky Mountains (precursors to the present-day Rocky Mountains) and on the east by the Ouachita Mountains and Ozark uplift. Several kinds of marine rocks were deposited in the Permian sea, mostly evaporites (halite, gypsum, anhydrite, and dolomite), and some shale. Sand was deposited along the eastern edge of the sea as deltas; these deltas formed where rivers originating in the Ouachitas and Ozarks entered the Permian sea. At times, the area covered by the sea expanded, and marine rocks were deposited over a large area. At other times, the sea shrank, and sand from deltas covered the previously deposited evaporites. In places, the sand was reworked by the wind and formed sand dunes. The Rush Springs Sandstone in the park shows this mixture of stream- and wind-deposited material. The marine muds were compressed and cemented to form shale, and the deltaic and windblown sands became sandstone. The Permian sea expanded and shrank repeatedly, resulting in a complex interbedding of marine evaporites, shale, and sandstone. As time progressed, the Rush Springs Sandstone was buried by younger sediments.

Red Rock Canyon, itself, is much younger than the Permian rocks exposed in its walls (Fig. 2). Geologists know that the present-day small stream in the canyon bottom is not capable of cutting such a large canyon; clearly, the stream must have been much larger at one time. This suggests that Oklahoma had a wetter climate at some time in the past. Most likely, this time period was the Pleistocene Epoch (the Ice Age). The continental glaciers that once covered much of North America never

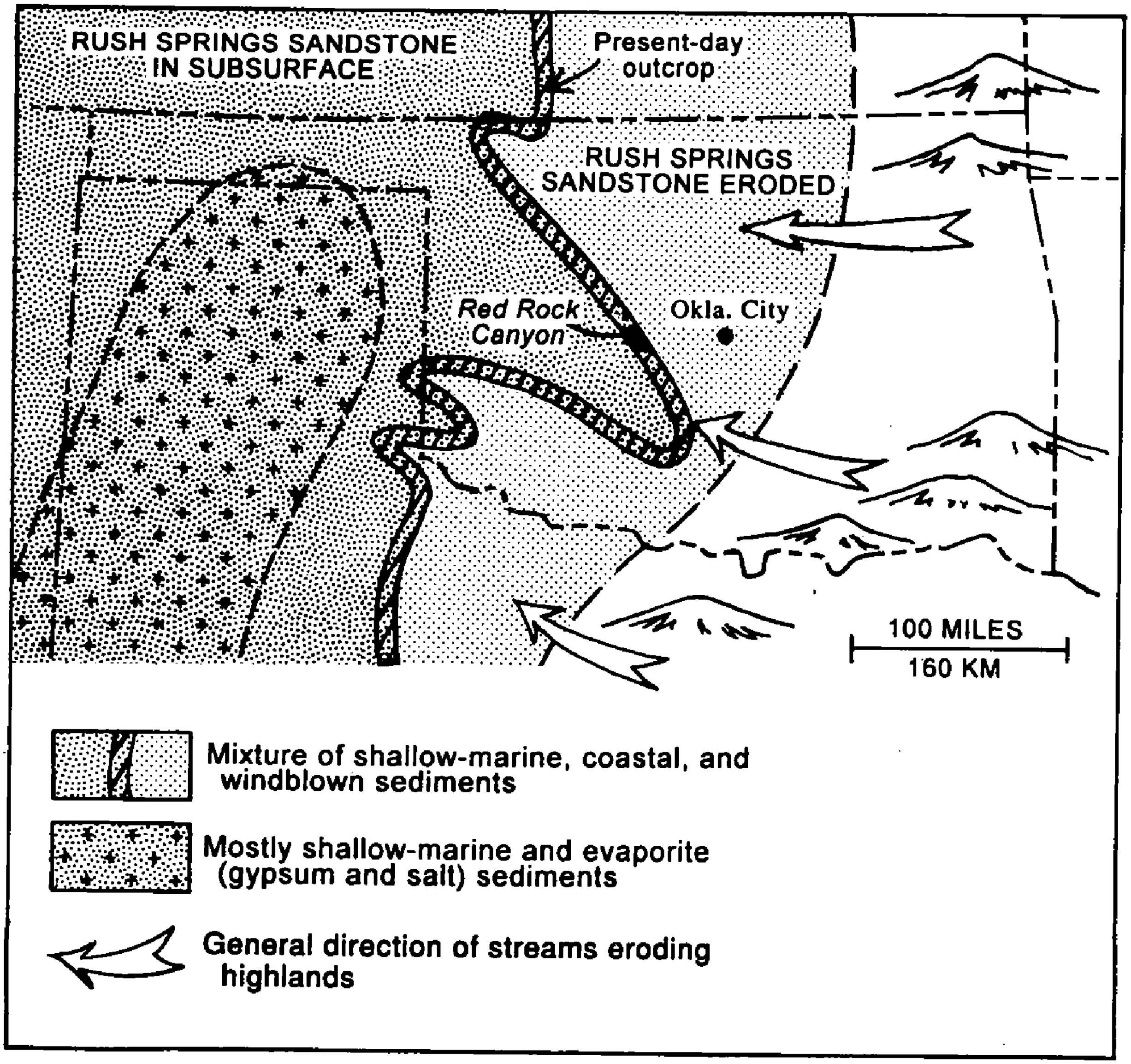

Figure 10. Paleogeographic map of Oklahoma in the Permian, when the Rush Springs Sandstone was being deposited. The stippled area shows the probable extent of the Permian sea. The Rush Springs Sandstone has been eroded east of the present-day outcrop, and the eastern margin of the sea can be located only very approximately.

extended into Oklahoma; they came only as close as the northeast corner of Kansas. However, the climate in the Rock Red Canyon area undoubtedly reflected the glacial periods. The average temperature was cooler, summers were shorter, and the amount of precipitation was greater than today.

Geologists agree that the canyon was cut by a process known as headward erosion. During the Pleistocene, streams (larger than those today) cut channels as they flowed down the south-sloping Rush Springs Sandstone. When water flowed over softer rocks, like the underlying Marlow Formation or shales within the Rush Springs, it eroded them more quickly and the stream channels steepened. A "knickpoint" formed where, during storms or other periods of high rainfall, water would rush over the southern edge of outcrops of sandstone in the Rush Springs. At first, the knickpoint probably was a short series of rapids. Over time, the relatively soft shale at the foot of the rapids eroded and the rapids developed into a waterfall. Subsequent floods continued to erode the shale at the base of the waterfall; undercutting resulted and large sections of sandstone collapsed, broke down, and eventually were carried downstream as individual sand grains. Then, the whole cycle of erosion, undercutting, and collapse started over. In this way, the waterfall migrated upstream, a process known as headward erosion. The site of the waterfall is called a box-head.

Geologists disagree, however, on exactly when canyon cutting began. Some think that it began during the first glacial period, known as the Nebraskan Stage, about 1 Ma. (The four glacial stages of the Pleistocene Epoch lasted from 1 Ma to about 10,000 years ago; each glacial stage was followed by a warm interglacial stage.) A precursor to Red Rock Canyon was cut by headward erosion, but later was filled by sediment and largely buried during the subsequent interglacial stage. The sediment that filled the canyon compacted slightly relative to the bedrock on either side of the canyon. This caused a minor depression to form over the filled canyon, setting the scene for a period of renewed canyon cutting and headward erosion during the next (Kansan) glacial stage. The canyon that was eroded during the Kansan glacial stage was at about the same site as the older Nebraskan canyon, but it was slightly deeper and longer. The Kansan canyon was filled during the subsequent interglacial, only to be re-eroded, deepened, and lengthened during the later Illinoian glacial stage. It was refilled during the next interglacial, and eroded, deepened, and lengthened during the last (and most recent) glacial stage, the Wisconsinan. Red Rock Canyon subsequently was partly filled by sediments (canyon fill); currently it is undergoing a period of mild erosion.

Other geologists are not convinced that canyon cutting began during the Nebraskan glacial stage; rather, they think that most of it occurred during the Wisconsinan, or Illinoian, at the earliest (within the last 115,000 years). Unfortunately, the process of canyon cutting, itself, removes the evidence geologists need to determine with certainty when it occurred. Thus, unless uneroded remnants of the older valley fills can be found, opinions about the geologic history of Red Rock Canyon probably will continue to differ.

Sources of Information

Much of the information presented in this brief overview of the geology of Red Rock Canyon State Park is based on the published and unpublished (mostly student theses) reports listed in the References Cited section. Four of these reports were particularly helpful and we have used them extensively: Howery (1960) and Trapnell (1961) provide excellent descriptions of the regional geology; Norris (1951) has studied the geology, particularly the Pleistocene geology, of Red Rock Canyon; and Johnson and others (1988) describe the physical setting of Oklahoma in the Permian. We have borrowed extensively from these authors. Reports on other aspects of the regional geology near Red Rock Canyon State Park include Ireland (1949), Branson and others (1962), Vining (1963), Bond (1968), and Carr and Bergman (1976).

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Glossary

alluvium—a general term for unconsolidated material (for example, silt or sand) deposited during recent geologic time by a stream or other body of running water.

Anadarko basin—a large sedimentary basin in western Oklahoma. It formed mostly during the Pennsylvanian Period (from about 330 to 290 Ma). Sedimentary rocks in the Anadarko basin are as much as 40,000 feet thick; equivalent rock strata are much thinner to the northeast and southwest outside the basin.

anhydrite—a mineral, $CaSO_4$, similar to gypsum but without water in the crystal structure. Anhydrite commonly is associated with gypsum and halite in evaporite deposits.

aquifer—a permeable rock or deposit that is water-bearing.

bedrock—a general term for the rock, usually solid, that underlies soil or other unconsolidated, superficial material.

box-head—the upper end of a steep-walled canyon that is closed upstream with a similar wall; a "dead-end" canyon.

butte—a conspicuous, usually isolated, generally flat-topped hill or small mountain that has relatively steep slopes or precipitous cliffs, and often is capped with a resistant layer or rock; it represents an erosional remnant carved from flat-lying rocks.

calcite—a common rock-forming mineral, $CaCO_3$. It is the principal constituent of limestone and commonly is the principal cement of sandstones.

cement—chemically precipitated mineral material that occurs in the spaces between the individual grains of a sedimentary rock, thereby binding the grains together. It may be derived from the sediment or its entrapped waters, or it may be brought in by solution from outside sources.

Cloud Chief Formation—a formation of Permian age, composed mostly of reddish-brown shale and minor siltstone, sandstone, dolomite, and gypsum. It underlies the Doxey Shale and overlies the Rush Springs Sandstone.

Cretaceous—the final period of the Mesozoic Era ("age of the dinosaurs"); it extended from about 140 to 67 Ma.

crop out—see *outcrop*.

cross-bedding—the internal arrangement of the layers in a sedimentary rock, usually sandstone, in which minor beds are more or less regularly inclined at various angles (typically 10°–40°) to the principal layers in the rock. Cross-bedding is produced when the sediments are deposited by a moving current of air or water.

cross section—a diagram or drawing that shows geologic features as if viewed in the vertical plane. A "cut-away" drawing of surface and subsurface features.

delta—the low, nearly flat area of land consisting of sediments deposited at or near the mouth of a river, perhaps extending beyond the general trend of the coast, and resulting from the deposition of sediment supplied by a river where it enters a larger body of water (usually a sea or lake).

dolomite—a sedimentary rock consisting mostly of the mineral dolomite, $CaMg(CO_3)_2$, formed from dolomite muds and fossil fragments or, more commonly, by alteration of limestone.

Doxey Shale—a formation of Permian age that is mostly reddish-brown shale and siltstone. It underlies the Elk City Sandstone and overlies the Cloud Chief Formation.

erosion—the natural processes of weathering, disintegration, dissolving, and removal of rock and earth material, mainly by water and wind.

evaporite—the general name for a sedimentary rock composed of minerals that precipitated out of a saline solution that became concentrated by evaporation. Evaporites often form in restricted or enclosed bodies of seawater or in salt lakes. Examples are gypsum and rock salt (halite).

feldspar—a common rock-forming mineral of the general formula $MAlSi_3O_8$, where M = K, Na, or Ca. Feldspars make up 60% of the Earth's crust.

formation—a formal unit in the classification of rocks that allows geologists to map, describe, and interpret the geology of an area. A rock unit usually is given a formation name if all the rocks in that unit are similar, contain similar fossils, or show the same repetitions of different kinds of rocks. Formations can be combined into groups or subdivided into members.

fracture—a general term for any crack or break in a rock, whether there has been movement along that break (in which case, it is called a fault) or not.

Garber Sandstone—a formation of Permian age in central Oklahoma that is mostly orangish-brown to reddish-brown sandstone and minor shale. It is a major aquifer for Oklahoma City and surrounding cities and locally contains barite rosettes (rose rocks, Oklahoma's State Rock).

geologist—a scientist who practices or participates in geology.

geology—the study of the planet Earth, including the origin of the planet; the material and morphology of the Earth; the history of the planet and its life forms; as well as the processes that acted (and act) upon the Earth to affect its historic and present landforms.

geomorphology—the science that treats the general configuration of the Earth's surface, especially the development of present landforms and their relationship to local geology.

glacial—pertaining to the presence and activities of ice or glaciers.

ground water—that part of subsurface water that is in the zone of saturation, in which all the spaces between rocks and the particles that make up the rocks are filled with water.

gypsum—a sedimentary rock consisting of the mineral gypsum, $CaSO_4 \cdot 2H_2O$, formed by chemical precipitation from evaporating seawater. The mineral gypsum forms a cement in some sandstones.

halite—a mineral, NaCl; large deposits or rock layers of halite are called salt or rock salt.

headward erosion—the lengthening and cutting back upstream of a valley or gully, caused by erosion of the upland at the head of the valley.

hematite—a common iron mineral, Fe_2O_3. It often occurs in deep red or reddish-brown earthy forms, and is the main source of red color in rocks.

Hennessey Group—several formations of Permian age in central Oklahoma that consist mostly of reddish-brown shale, siltstone, and sandstone. The Hennessey Group overlies the Garber Sandstone and underlies the Duncan Sandstone.

hydrology—the science that deals with continental water, its properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere. In recent years the scope of hydrology has been expanded to include environmental and economic aspects.

Illinoian—pertaining to the third glacial stage (of four) of the Pleistocene Epoch in North America, beginning about 115,000 years ago. It is named after excellent deposits in Illinois left by glaciers of that time period.

interglacial stage—a subdivision of a glacial epoch separating two periods of glaciation, characterized by a relatively long period of warm or mild climate.

iron oxide—a general term referring to weathered iron minerals. Hematite is a common iron oxide mineral and forms the cement of many red sandstones.

joint—a fracture in rocks along which no movement has occurred.

Kansan—pertaining to the second glacial stage (of four) of the Pleistocene Epoch in North America, beginning about 400,000 years ago. It is named after excellent deposits in Kansas left by glaciers of that time period.

knickpoint—a point of abrupt change or inflection in the profile of a stream or its valley; generally forms where a rock that is not easily eroded crops out.

Ma—abbreviation for "millions of years" or "millions of years ago."

Marlow Formation—a formation of Permian age, composed mostly of orangish-brown sandstone, siltstone, and shale, about 120 feet thick; contains two gypsum and/or dolomite beds near the top. It underlies the Rush Springs Sandstone and overlies the Dog Creek Shale.

meandering—said of a stream or river that has regular, tightly curved bends, loops, turns, and windings.

Nebraskan—pertaining to the first glacial stage (of four) of the Pleistocene Epoch in North America, beginning about 1,000,000 years ago. It is named after excellent deposits in Nebraska left by glaciers of that time period.

outcrop—that part of a geologic formation that appears at the Earth's surface. The verb to "crop out" means to appear exposed and visible at the Earth's surface.

paleogeography—the study and description of the geography of the Earth in the geologic past, such as the historical reconstruction of the Earth's surface or of a given area at a particular time in the geologic past.

Pennsylvanian—a period of the Paleozoic Era; it extended from about 330 to 290 Ma. Most of the rocks that crop out in eastern Oklahoma are Pennsylvanian in age.

permeable—said of a porous rock that easily transmits a fluid, such as water or oil. A rock can be porous but not permeable if the pore spaces between the grains are not connected.

Permian—the last period of the Paleozoic Era; it extended from about 290 to 250 Ma. Most of the rocks that crop out in western Oklahoma, especially those that are red, are Permian in age.

physiography—the description of landforms. It is similar in meaning to geomorphology, except that physiography is descriptive, whereas geomorphology is interpretative.

Pleistocene—an epoch of the Quaternary Period, which is the most recent period of the Cenozoic Era. The Pleistocene Epoch occurred from about 2 million to 10,000 years ago and is generally referred to as the "Great Ice Age"; in fact, it consisted of four glacial stages.

porous—said of a rock having numerous holes or spaces, whether connected or not. In a sandstone, the spaces occur between the individual sand grains.

quartz—a common rock-forming mineral, SiO_2. It is very hard and resistant to weathering, and it is the second most common mineral in the Earth's crust (after feldspar).

Rush Springs Sandstone—a formation of Permian age, composed mostly of orangish-brown, cross-bedded sandstone with some thin dolomite and gypsum beds. It underlies the Cloud Chief Formation and overlies the Marlow Formation.

sandstone—a sedimentary rock consisting of sand grains (mostly quartz) that are cemented together.

sediment—solid fragmental material (for example, sand, gravel, mud) that originates from weathering of rocks and is transported and deposited by air, water, or ice; it forms in layers on the Earth's surface in a loose, unconsolidated form. It includes material that accumulates through other natural agents, such as chemical precipitation.

sedimentary—pertaining to or containing sediment; for example, sedimentary rock.

sedimentary basin—an area of the Earth's crust that contains an unusually thick accumulation of sedimentary rocks compared to surrounding areas. Sedimentary basins usually are downwarps in the Earth's crust that subsequently fill with sediments (for example, the Anadarko basin).

seeps—small areas where water or another liquid (such as oil) percolates slowly to the land surface.

shale—a fine-grained sedimentary rock formed by the consolidation of clay or mud. Typically, it is softer, and more easily eroded, than sandstone.

siltstone—a fine-grained sedimentary rock formed by the consolidation of silt. Silt grains are intermediate in size between clay and sand grains.

spring—a place where ground water flows naturally from a rock or the soil onto the land surface or into a body of surface water.

tectonic—said of, or pertaining to, the forces involved in shaping the broad architecture of the upper part of the Earth's crust.

terrace—any long, narrow, relatively level or gently inclined surface, bounded along one side by a descending slope and along the other by an ascending slope. A terrace commonly occurs along the margin of, and above the present level of, a body of water, and marks a former water level.

Tertiary—the first period of the Cenozoic Era; it extended from about 67 to 2 Ma.

thenardite—a relatively uncommon mineral, Na_2SO_4, that occurs as a white encrustation where water containing sodium and sulfate has evaporated.

tributary—a stream feeding, joining, or flowing into a larger stream or into a lake.

water table—the upper surface of a body of ground water.

Weatherford Bed—a layer of gypsum and/or dolomite in the Rush Springs Sandstone, about 50 feet below the top of the formation.

Wisconsinan—pertaining to the last glacial stage (of four) of the Pleistocene Epoch of North America, lasting from about 85,000 years ago until about 10,000 years ago.

A History of Lake Murray

Robert W. Allen[1]

Introduction

Lake Murray is located two miles east of U.S. Highway 77 and four miles south of Ardmore in southern Carter and northern Love Counties, Oklahoma. The major arms of the lake occupy the deep valleys of the West and East Anadarche Creeks as well as the eastern tributary of Fourche Maline Creek (Figs. 1, 2). Lake Murray's deep blue waters have none of the sediment-laden murkiness of nearby river-fed Lake Texoma. Its setting amid hills forested by blackjack and post oak provides a beautifully scenic panorama.

Ardmore is located 15 miles south of the Arbuckle Mountains, five miles south of the Caddo anticline, and five miles northeast of the Criner Hills (Fig. 1). The outcrops in these nearby, outstanding, surface geologic features range in age from Cambrian through Permian. The entire stratigraphic section of sedimentary rock units is represented in this area.

The thousands of people who enjoy Lake Murray each year should know and remember the names of Charles Weldon Tomlinson, Charles A. Milner, Jr., and W. Morris Guthrey. These men were trained geologists, whose work and efforts were responsible for creating Lake Murray. A brief biography for each of them is included at the end of this article.

History and Geology of the Lake Murray Area

The Lake Murray area was a good hunting ground for prehistoric man. Artifacts indicate that Paleo-Indians hunted the valleys now occupied by Lake Murray from 12,000 B.C. to 7000 B.C., long before the arrival of white men. Their game included such now extinct animals as the mammoth and the mastodon, as well as the larger ancestors of our present-day bison. By 6000 B.C., seasonal encampments dotted the general area; there is evidence of an increasing number of campsites from that time until about A.D. 500. In the period A.D. 500 to A.D. 1600, the area reverted to a hunting ground, and most nearby Indian campsites were along Hickory Creek (Fig. 1) to the south.

During recent historical time, hunting continued in the area, as the discovery of the occasional muzzle-loading-rifle ball has shown. Beneath the site of Tucker Tower, there was a rocky alcove (now covered deeply by water) that is said to have been used regularly by Comanche Indians to hide horses stolen in forays against settlers in northern Texas. Even as late as the 1930s, the area was so unfrequented that geologists who started mapping there found no fewer than five illegal whiskey stills in operation.

Geologically, Lake Murray is located in the Ardmore basin (Fig. 1). This is a deep sedimentary basin filled with rocks of Precambrian to Permian ages; the basin has been intensely compressed between two mountain ranges. The outcropping strata in the lake area are of Pennsylvanian age and dip at angles up to 90°; some of the

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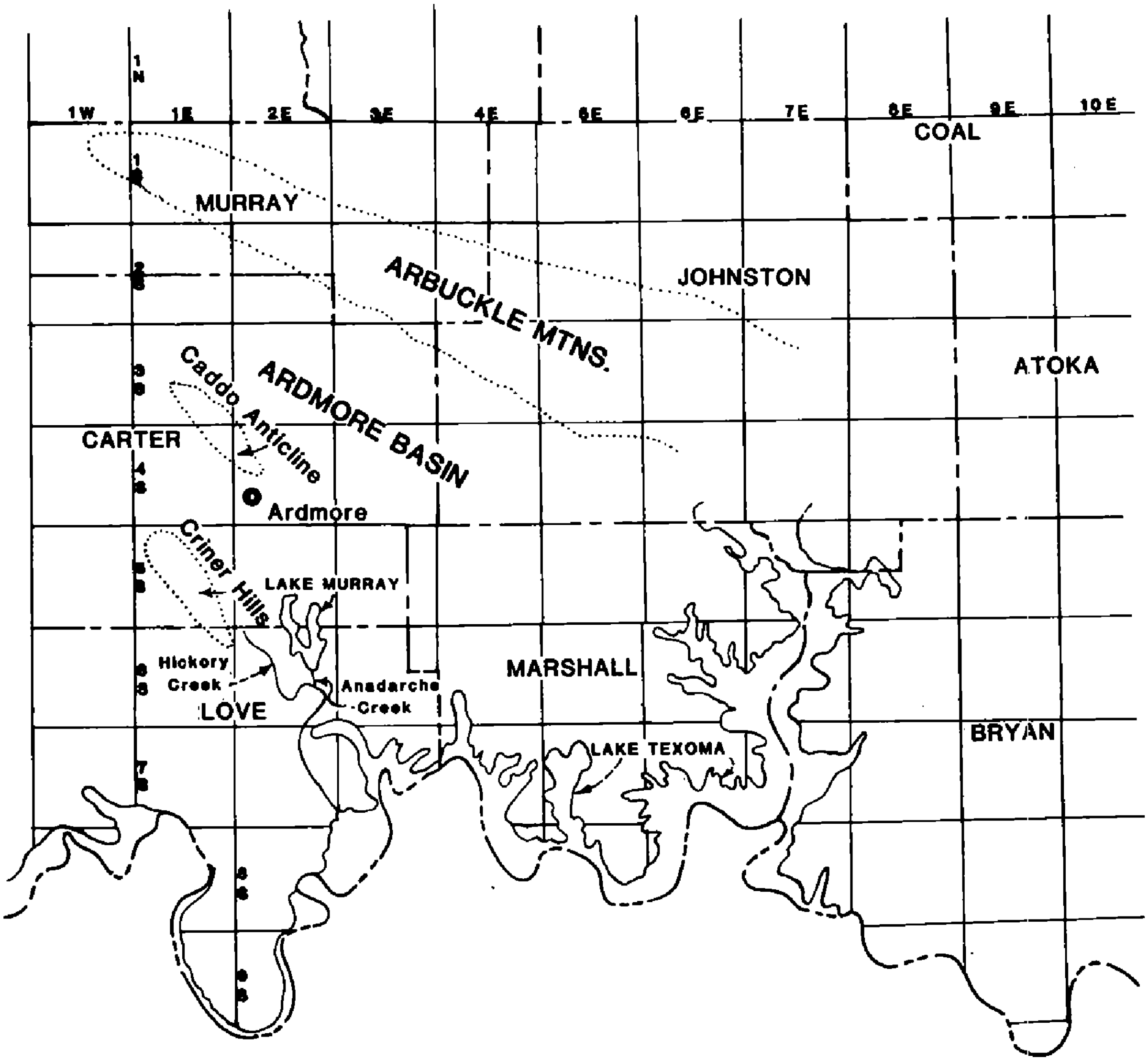


Figure 1. Generalized map of south-central Oklahoma, showing locations of Lake Murrray and its relation to principal geological features. Source: Lang and Parker (1966).

beds are overturned (Fig. 3). These strata crop out in the vicinity of Lake Murray as long, linear, forested ridges. Many of these beds produce oil just to the west of the Lake Murray area; thus, it was important geologically to correlate the outcropping rock units with those in the subsurface.

Starting in 1928, the Gypsy Oil Company (later Gulf Oil) initiated a research program directed to this problem of correlation. The program was under the direction of Dr. Maynard P. White, and the field work was done by W. Morris Guthrey and Charles A. Milner, Jr. The work of Dr. White, a micropaleontologist, focused mainly on the identification of the fusulinids (fossils shaped like grains of wheat) found in the various members of the Pennsylvanian formations. Guthrey and Milner mapped these beds by plane table and meticulously searched each bed for fusulinids. (A plane table is a surveying instrument for graphically plotting the lines of a survey directly from field observations.) This research continued in 1932 and 1933 under the supervision of Dr. C. W. Tomlinson. For the geologists involved, it was a very exciting time since some of the Lower Pennsylvanian section exposed in

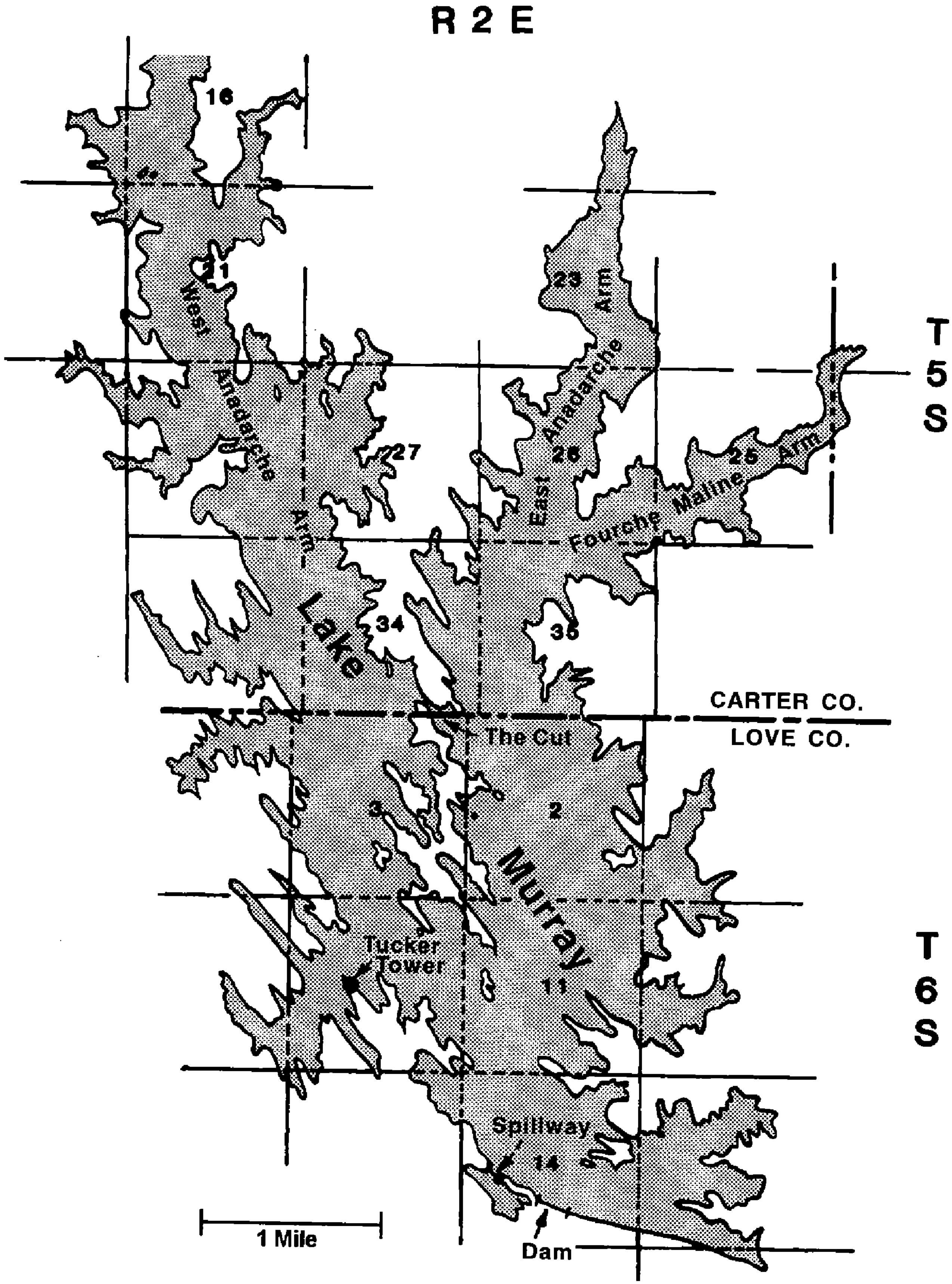


Figure 2. Map of Lake Murray in Carter and Love Counties, showing locations of dam and spillway in the south. Source: U.S. Geological Survey (1964).

the Ardmore basin crops out nowhere else in the world, and a number of hitherto unknown fossils were found. The attention of the paleontologic world was on the Ardmore basin. Such famous paleontologists as J. J. Galloway and Raymond C. Moore paid regular visits to Ardmore to study the new fossil discoveries.

Dr. Tomlinson, along with Mr. Milner and Mr. Guthrey, continued to map this part of the Ardmore basin. One topographic feature that met their trained geologic eyes was the Devils Kitchen Conglomerate, a massive bed of sand and chert that stands as an almost vertical wall (Fig. 3); several creeks joined and made one chan-

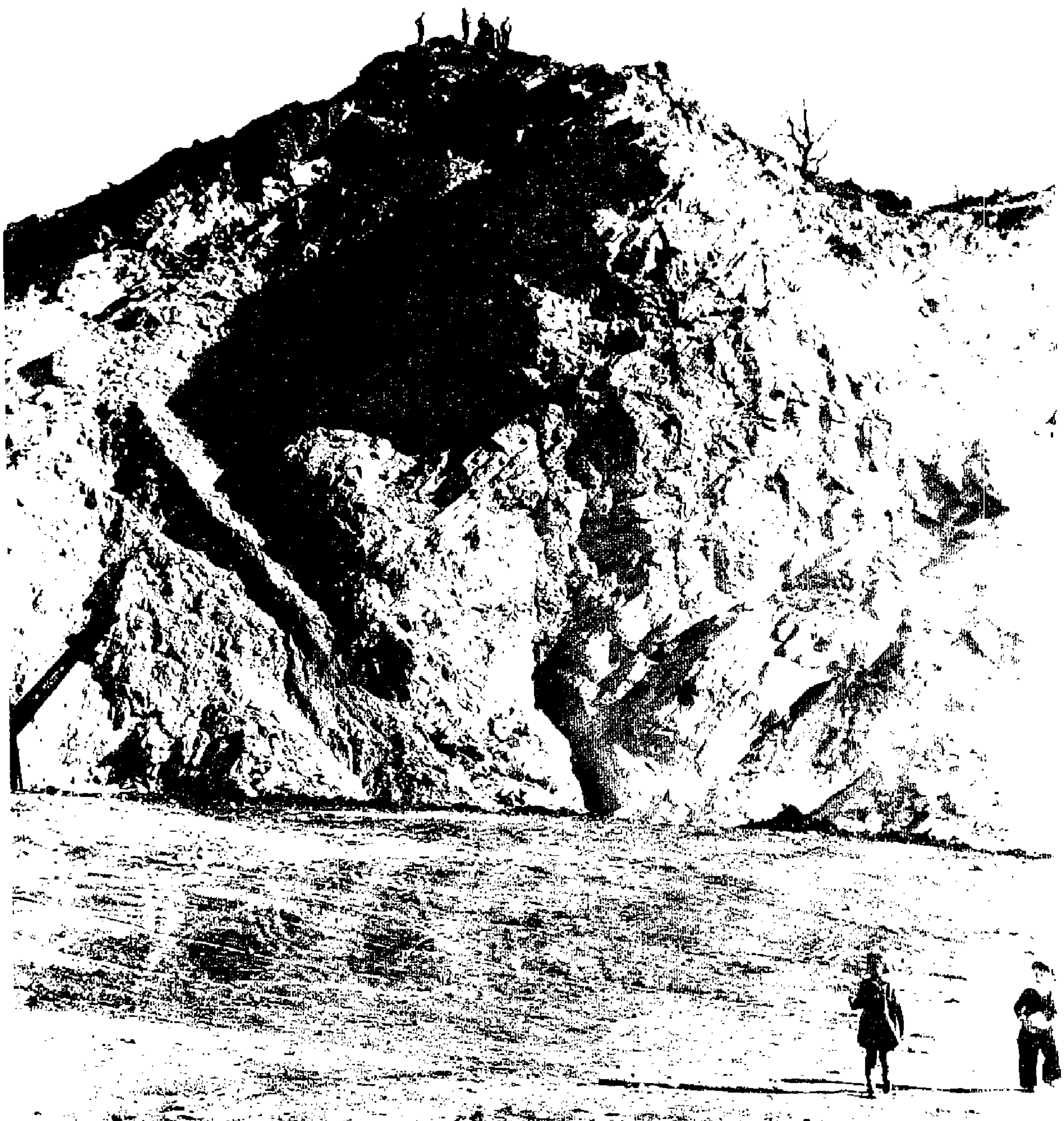


Figure 3. Layers of Devils Kitchen Conglomerate dip about 45° down to the left. Photograph taken during construction, just prior to filling of the lake. (Photograph from the collection of Alvin F. Hardison, Ardmore, Oklahoma.)

nel through this rock outcrop. They recognized that this feature could be adapted suitably for use as a dam to form a lake. Starting in 1932, these geologists put forth every effort toward getting such a dam built. It wasn't easy. No continuously flowing streams fed these valleys, and the valleys were full of trees. If a dam were built, would the deep valleys behind it fill with water? This unknown was a major obstacle for some people. Dr. Tomlinson and his professional crew insisted that there would be a lake and that it would fill with water in an estimated 10 years. They based their estimate on the average yearly rainfall in the drainage area for the potential lake, and on measurements of the volume of water that ran off the land and through the 600-foot notch in the Devils Kitchen Conglomerate. The evaporation rate of the lake water, in the hot Oklahoma summer sun, also was considered: Dr. Tomlinson made evaporation-rate measurements on several large ponds in the area in order to know how much to deduct for this evaporation. This painstaking work of making measurements continued over several years.

The dream of a lake, later to be known as Lake Murray, had been created, but it was only a dream. Dreams without follow-through are just that, dreams. Projects can remain in file folders for a lifetime, and that is all they are, just projects. Tomlinson, Milner, and Guthrey did not let this potential project remain only a dream. They got both the State and Federal governments involved, and brought them to Carter and Love Counties.

They called former State Senator (1912–20) Fred Tucker, an oil man from Ardmore, and explained the idea of the lake to him. State Senator (1933–35) Louis Fischl of Ardmore authored Senate Bill 382, which gave the State Board of Affairs authority to condemn and buy the land for Oklahoma's first state park. The bill was supported in the Oklahoma House of Representatives by Floor Leader of the 14th Legislature, Representative (1931–33) John Steel Batson, of Marietta. The bill was passed in 1933, and the land (with minerals) was purchased for $90,000. Governor (1931–35) William H. "Alfalfa Bill" Murray, a brilliant man, was not in favor of this project. Later, however, when the name was changed from Arbuckle Lake to Lake Murray, he agreed to lend his support to the construction plan.

In 1933, Franklin D. Roosevelt was elected President of the United States. The country was in a deep economic depression. Very few people had any money, and there were no jobs to be found. Bread lines literally were miles long. Dr. Tomlinson and his team agreed that something must be done to help the unemployed in Oklahoma.

The federal government had formed the CCC (Civilian Conservation Corps) and the WPA (Work Projects Administration). These government agencies employed people to perform useful work on building projects in communities. The Lake Murray project seemed ideal for these programs and was submitted for federal evaluation. Approval was granted, and work on the lake began in July 1933 (Fig. 4). Members of the CCC cleared the trees and the area; members of the WPA built the dam. There was no power equipment—only teams, wagons, and hand tools.

A total of 10,000 men, who had been on relief, shared the jobs. Each man worked five days, for $1.80 per day. The wages for one day of work provided food for a work week. The balance was enough to feed a man's family for about one month. A group of approximately 1,000 men would work for a week, and then another group would relieve them. A federal relief fund of $20,000 per month ($5,000 per month, each, from Carter, Love, Johnston, and Marshall Counties) kept 2,200 families from starving. Progress was made.

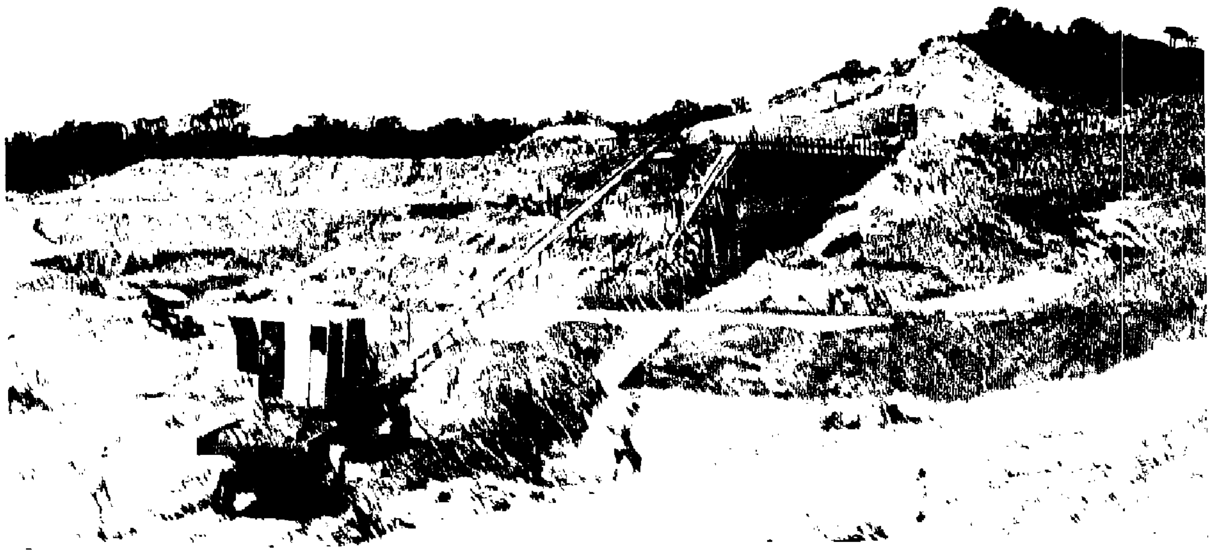


Figure 4. Construction of the dam at Lake Murray. Work began in July 1933. (Photograph from the collection of Alvin F. Hardison, Ardmore, Oklahoma.)

A dam, 600 feet long and 150 feet high, was built, but a part of that dam sloughed off before the lake filled. The locations, near the lake's shore, of the lodge and all the youth camps, had been planned before the original dam failed. When the dam was rebuilt, the lake's water level was 12 feet lower than originally planned. Thus, the lodge and the youth camps, when completed, were up the hill and away from the shoreline.

By the time World War II began on December 7, 1941, with the surprise attack on Pearl Harbor, the lake had been built and was full of water. The Armed Forces took the laborers. Progress slowed. After the war, there was a lodge to be built. But how? Prosperity was beginning to return, but there still was not enough money to build a lodge.

Lloyd Judd, President of the First National Bank and Trust Company of Ardmore, made a suggestion to State Senator (1943–47) Fred Chapman, and to State Representatives Wilson Wallace (1937–39; 1945–47), and Rhys Evans (1943–49), both of Ardmore. Mr. Judd suggested self-liquidating bonds. The bonds would be sold, and they would be paid back with money from rent derived from the property. The idea was approved by the Supreme Court of Oklahoma, and it was a first for the State of Oklahoma and a second for the entire nation. Self-liquidating bonds had been sold only once before in the U.S., for a toll road in Pennsylvania. The bonds were sold, Lake Murray Lodge was built, and the bonds were repaid. The plan was a huge success. (For years, Lake Murray supported most of the other state parks.)

The lodge was dedicated in 1949. At that time, Roy J. Turner was Governor and Lloyd Judd was a member of the Oklahoma Planning and Resources Board. (Judd died on May 1, 1949.) Others involved in the offering of the self-liquidating bonds, Fred Chapman, Wilson Wallace, and Rhys Evans, were not asked to attend the dedication ceremony.

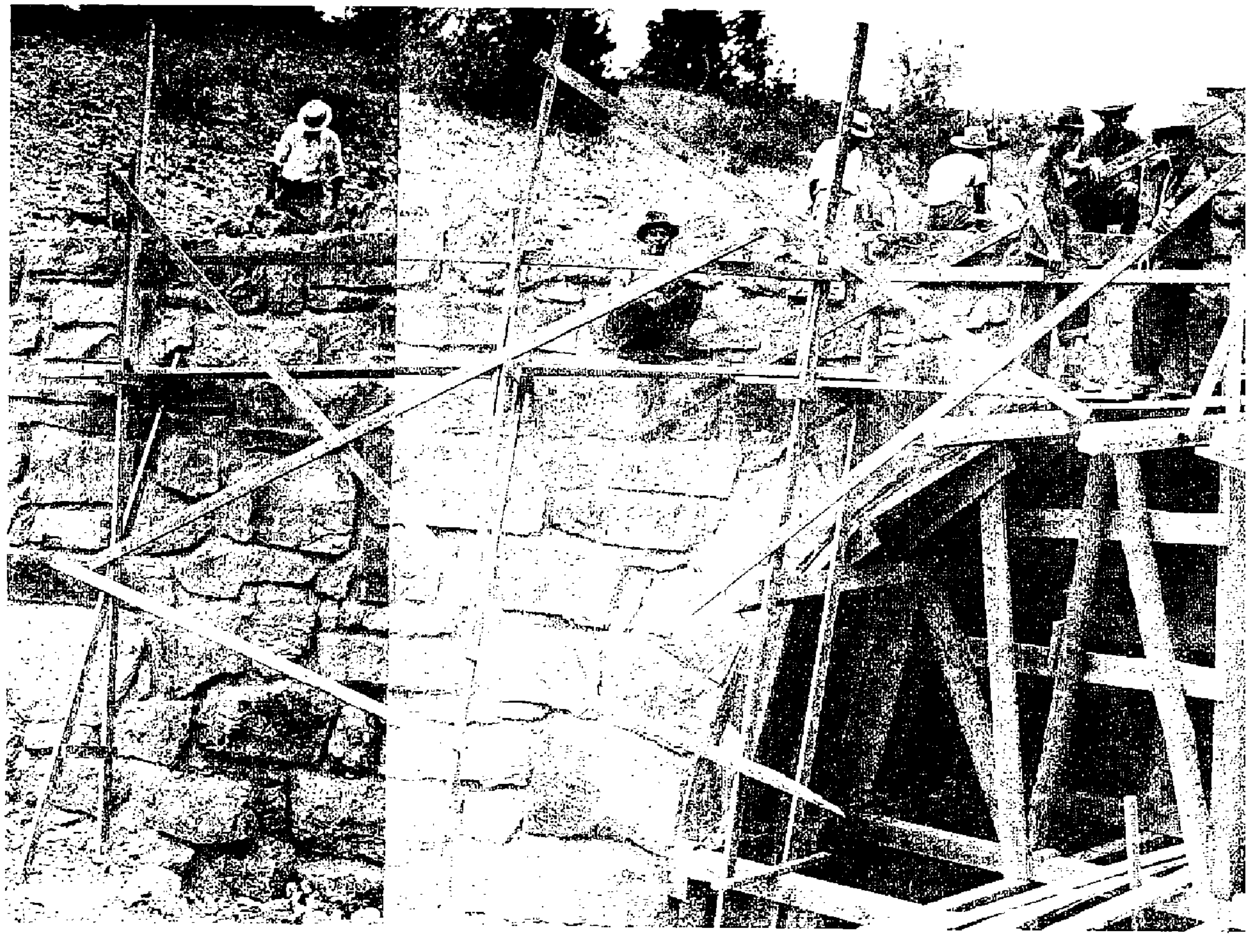


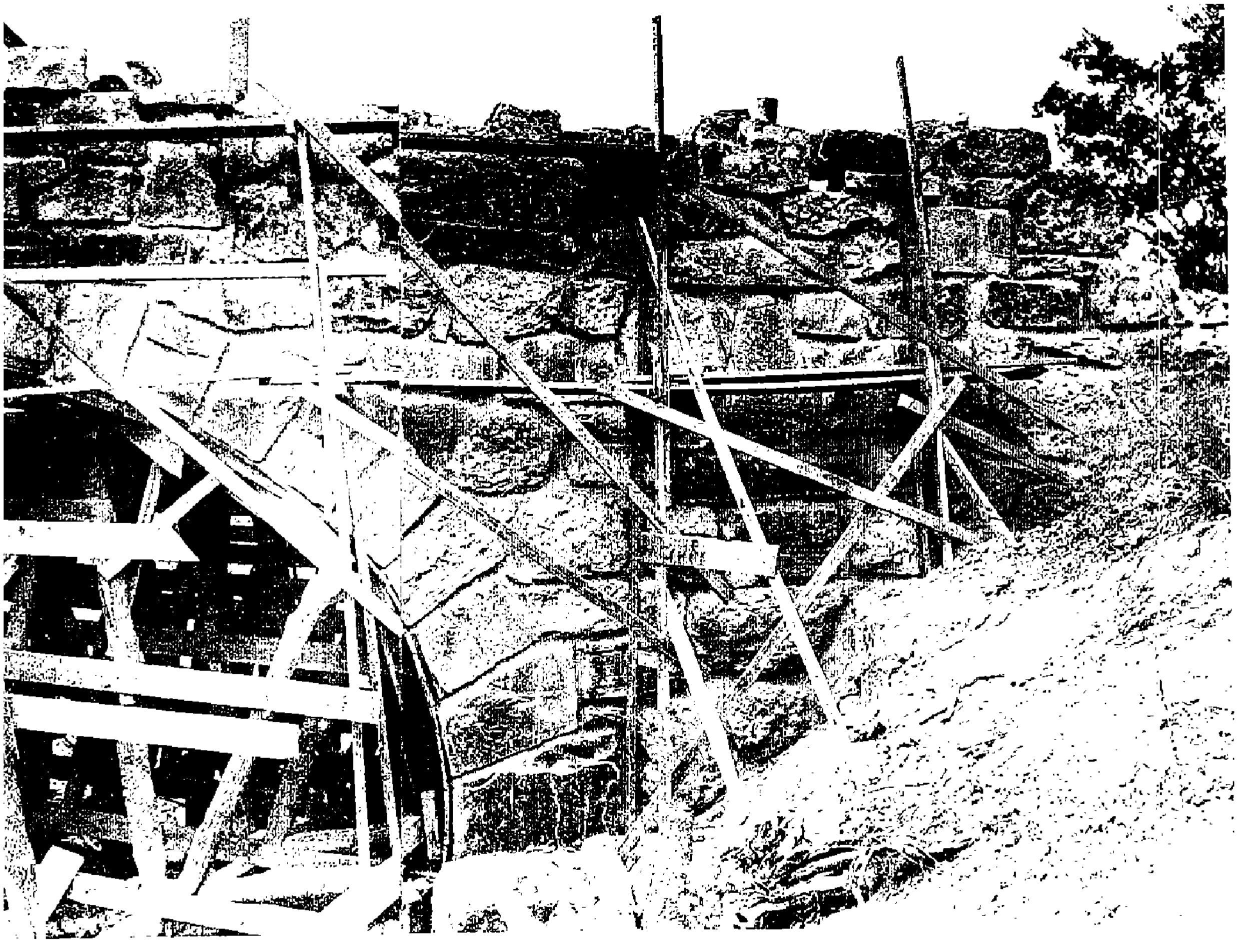
Figure 5. Construction of the foundation for Tucker Tower. (Photograph from the collection of

Not long ago (1978), another outstanding Ardmore geologist and oil man, John L. Hoard, had the oil and gas leases on Lake Murray put up for bid. The leases were sold, and more than $2,000,000 was put into the State treasury as a result of the sale. The money was spent, but it did not stay at Lake Murray. The oil industry was directly responsible for generating this $2,000,000 windfall; it was not tax-generated money.

Present Status of Lake Murray

Lake Murray is a 6,000-acre body of water; at the time it was dammed, it was the largest body of water in the State. At the man-made dam, the water is 130 feet deep; eight miles from this dam, the water depth averages 25 feet. The park includes 21,000 acres of land.

For two miles, the Devils Kitchen Conglomerate can be seen rising from the lake at a 60° angle. A boat trip along this ledge—from Tucker Tower past the lake spillway and the man-made dam, then southeast to the Marietta Landing campground—allows a good view of this enormous, natural dam of solid rock. The spillway is cut through this rock, and allows excess water to spill downstream to Hickory Creek and Lake Texoma. Halfway between the dam and the spillway, there



\lvin F. Hardison, Ardmore, Oklahoma.)

is a valve control tower. In the original design of the dam, it was to be used to drain sediment off the bottom of the lake. However, the valves rusted shut and could never be used. Lake Murray actually filled in seven years instead of in the predicted ten, and water goes over the spillway almost every year. During a period of drought in the 1950s, the lake level went down about six feet; in a few years, however, the lake was full again.

Tucker Tower (Figs. 5, 6), named for Senator Fred Tucker, originally was built as a retreat for Governor Murray. It now houses Tucker Tower Nature Center, a fine museum of natural history managed by the Lake Murray State Park. Allen Graffham of Ardmore prepared the first exhibits and was the first curator.

The lake's design is a continuing tribute to C. W. Tomlinson's ability to correctly predict the lake's performance over many years. Lake Murray will be an enjoyable recreation site, perhaps for centuries. It is fed by water from springs, runoff, and three small creeks. No rivers or major streams flow into it; thus, very little silt or fill is entering the lake. In contrast, Lake Texoma is fed by the Washita and Red Rivers. They carry much sand and silt, which rapidly are filling Lake Texoma.

Lake Murray is one of the premier tourist and sporting attractions in the State of Oklahoma, and its history, too, deserves attention. Perhaps one day there will be a monument of Oklahoma red granite at the lake to honor Charles Weldon Tomlin-

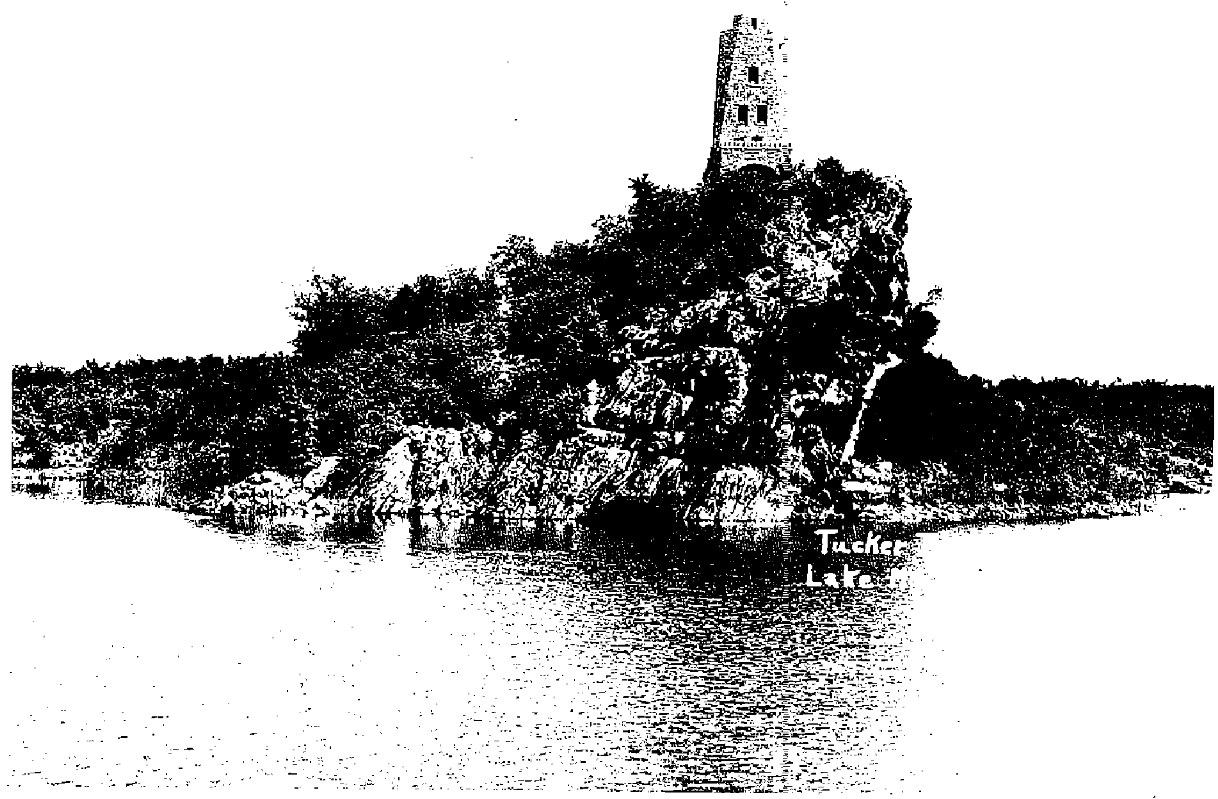


Figure 6. View of Tucker Tower overlooking Lake Murray. Tucker Tower now is the site of Tucker Tower Nature Center, a museum of natural history managed by Lake Murray State Park. (Photograph from the collection of Alvin F. Hardison, Ardmore, Oklahoma.)

son, Charles Albert Milner, Jr., and W. Morris Guthrey for their dream and for their dedicated efforts to make Lake Murray a reality.

Brief Biographies of Tomlinson, Milner, and Guthrey

These three men not only were trained geologists, whose professional vision sparked the creation of Lake Murray, but they also were citizens of Oklahoma and of Ardmore who gave of themselves to their human community.

Charles Weldon Tomlinson

Charles Weldon Tomlinson (1892–1960) was born in Detroit, Michigan. He received a B.A. degree from the University of Wisconsin in 1913 and a Ph.D. in geology from the University of Chicago in 1916. Dr. Tomlinson taught at Mississippi State College and at the University of Illinois before he went to work for the Gypsy Oil Company (Gulf). He moved to Ardmore in 1920 to work for J. B. Schermerhorn of Minneapolis, Minnesota. Ardmore became Dr. Tomlinson's home, and he was a real asset to the city and to the State. The signs along U.S. Highway 77 describing the geological formations in the Arbuckle Mountains are among his many contributions. He also served with the Ardmore Community Chest, the Ardmore Chamber of Commerce, the Southern Oklahoma Osteopathic Hospital, and many other organizations. The St. Philip's Episcopal Church played an important role in his life. He published 25 scientific papers and served as President of the American Association of Petroleum Geologists in 1949. The Ardmore City Library has a room for Dr. Tomlinson's books and papers.

Charles Albert Milner, Jr.

Charles Albert Milner, Jr. (1900–1971) was born in Ardmore, Indian Territory, November 15, 1900. In 1923, he received a B.S. degree in geology from the University of Oklahoma. Mr. Milner was active at O.U. both in geology and in music, and these two interests became his life's works. Following graduation from O.U., he worked for oil companies in Kansas and in Texas before he returned to Ardmore in 1927 as a consultant geologist. Charles Milner also was active in many Ardmore activities, including those of the St. Philip's Episcopal Church.

W. Morris Guthrey

W. Morris Guthrey was born in Hico, Texas, in 1901. He died in Tulsa in December 1994. Mr. Guthrey received his B.S. degree from the University of Chicago in 1926. He was first employed as a geologist by Gypsy Oil Company (Gulf). Later, he worked for Dr. Tomlinson, and then he joined Texaco and became district geologist for the Texas Company at Ardmore (1935–1941). In 1941, he was transferred to Wichita, Kansas, where he was district geologist until 1946. He moved to Texaco's main office in Tulsa in 1946. Mr. Guthrey resigned from Texaco in 1950, but he continued to do consultant geological work until his retirement in 1965.

Acknowledgments

This history was written after I had an opportunity to visit, and/or correspond, with many people. The information and ideas that they shared with me contributed significantly to this article. I gratefully acknowledge W. Morris Guthrey (Geologist), C. E. ("Ed") Hannum (Geologist), Dr. Kenneth S. Johnson (Oklahoma Geological Survey), Mrs. Waylan D. Morris, George H. Ramsey (Petroleum Engineer), and R. P. Wilkinson (Petroleum Geologist).

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Wilson Wallace videotape, July 27, 1993. On file at the Greater Southwest History Museum, 35 Sunset Dr., Ardmore, Oklahoma 73401; phone (405) 226-3857.

NEW OGS *Publications*

SPECIAL PUBLICATION 96-2. ***Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma: The Skinner and Prue Plays,*** by Richard D. Andrews and others. 106 pages, 9 plates. Price: $6.

The fourth in a series of publications addressing fluvial-dominated deltaic (FDD) light-oil reservoirs in Oklahoma, this volume presents the material covered in the workshops on the Prue and Skinner plays held in June 1996.

In Part I of this publication, Richard D. Andrews and others explain the scope of the FDD project and describe the significant features of FDD reservoirs. Depositional environments are related to reservoir properties in order to provide a better understanding of the individual FDD reservoirs identified in the project.

In Part II, Andrews presents an overview of Skinner and Prue FDD areas in Oklahoma. Deposition of Skinner sandstone occurred throughout much of the State, while Prue sandstone is confined to the Cherokee platform and shallow shelf areas of the Anadarko basin. Part II also contains studies of four reservoirs, including three within the Skinner: the Perry S.E. Skinner Sand Unit in Noble County, by Kurt Rottmann; the Salt Fork North field in Grant County, by Andrews; and the Guthrie S.W. field area in Logan County, by Rottmann. One reservoir study, by Andrews, features a Prue oil pool in Long Branch field, Payne County. Included in these reservoir studies are stratigraphy, structural and isopach mapping, reservoir characteristics, and oil and gas production.

In Part III of this volume, one Skinner reservoir study and one Prue reservoir study are developed into reservoir simulations. The simulation of the Skinner reservoir in Salt Fork North field, by Z. N. Bhatti and R. M. Knapp, includes forecasts of production results of current waterflooding operations and of an expanded waterflooding strategy, an immiscible gas injection strategy, and a strategy of alternating gas with water injection. The simulation of the Prue reservoir in Long Branch field, by X. H. Yang, R. M. Knapp, and R. P. Simpson, included a forecast of production results for the current production strategy and for a well recompletion strategy and an infill drilling strategy as part of a waterflood simulation.

The volume also includes a list of selected references and a glossary of terms. The plates feature: maps of the upper Skinner sandstone play area, the lower and middle Skinner and lower Senora sandstone play areas, and the Prue and Calvin sandstone play areas; production maps of the Skinner and lower Senora sandstones and of the Prue and Calvin sandstones; stratigraphic cross sections of the Cherokee platform and shelf areas of the Anadarko and Arkoma basins; and an index to selected references used for Prue, Calvin, Skinner, and lower Senora mapping.

Author Richard D. Andrews is an exploration and development geologist with the University of Oklahoma's Geo Information Systems (GeoSystems) unit. Jock A. Campbell, OGS geologist, and Robert A. Northcutt, consulting geologist, Oklahoma City, are the other two lead geologists on the FDD project team. R. M. Knapp is the petroleum engineer for the FDD project and a professor in the OU School of Petroleum and Geological Engineering. Z. N. Bhatti, X. H. Yang, and R. P. Simpson are graduate students in the OU School of Petroleum and Geological Engineering.

The next publication in the FDD series is scheduled for release in October 1996; it will be on the Cleveland and Peru plays.

GEOLOGIC MAP OF THE KREBS QUADRANGLE, PITTSBURG COUNTY, OKLAHOMA. One sheet, scale 1:24,000. Xerox copy. Price: $6, rolled in tube.

The Ouachita STATEMAP project, which began in 1993, is a joint effort of the Oklahoma Geological Survey and the U.S. Geological Survey to prepare new 1:24,000 geologic maps of the Ouachita Mountains and Arkoma basin in Oklahoma. STATEMAP is part of the National Cooperative Geologic Mapping Program and replaces the successful COGEOMAP program, which began in 1984. Under COGEOMAP, the OGS completed and published 15 7.5¢ geologic quadrangle maps along the northern part of the Ouachita Mountains frontal belt and southern part of the Arkoma basin.

During the first year of STATEMAP, in early 1994, the Oklahoma Geologic Mapping Advisory Committee, chaired by OGS associate director Kenneth S. Johnson, was established to recommend mapping priorities for the State. The committee recommended Pittsburg County, especially near McAlester, as an important area for OGS efforts. The committee chose the McAlester area for several reasons: (1) Coal has been a major resource in the area, and substantial reserves still are present. (2) A number of natural-gas fields have been discovered recently and others are being developed in this part of the Arkoma basin, and the giant Wilburton deep gas field was discovered in 1987 immediately east of the area. (3) Environmental problems resulting from open mine shafts, undocumented underground mines, and poor reclamation practices in the past may impact urban development near McAlester, as well as rural development throughout the region. (4) Several type localities of Arkoma basin formations are in the area, but are unmeasured or otherwise poorly documented.

The Krebs Quadrangle, by LeRoy A. Hemish, is the third in a series of STATEMAP geologic maps of Pittsburg County. It is now available as a black-and-white, author-prepared xerox copy, comprising geologic map, cross sections, description and correlation of units, and a list of gas wells. This map is an important addition to the series of previously mapped quadrangles because of its proximity to the expanding urban area of McAlester. Planners for new highway construction, building construction, and abandoned coal-mine reclamation will find the map useful in addressing environmental concerns. Further economic assets of the area include gas reservoirs and documented coal reserves in several of Oklahoma's principal coal beds.

COGEOMAP and STATEMAP maps also are available for the Higgins, Damon, Baker Mountain, Panola, Wilburton, Red Oak, Leflore, Talihina, Leflore Southeast, Blackjack Ridge, Gowen, Summerfield, Hodgen, Hontubby/Loving, Wister, Heavener/Bates, Adamson, and Hartshorne Quadrangles.

SP 96-2 and COGEOMAP/STATEMAP geologic quadrangle maps can be purchased by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019. For SP 96-2, add 20% to the cost for mail orders, with a minimum of $1 per order. For mail orders of 1–10 maps, add $2; for 11–25 maps, add $3.

All OGS publications can be purchased over the counter at the OGS Publication Sales Office's new location at 1218-B W. Rock Creek Road, Norman; phone (405) 360-2886; fax 405-366-2882. Parking is free and readily available.

UPCOMING *Meetings*

International Conference on Ground Control in Mining, August 13–15, 1996, Golden, Colorado. Information: Colorado School of Mines, Office of Special Programs and Continuing Education, Golden, CO 80401; (800) 446-9488, ext. 3321 *or* (303) 273-3321, fax 303-273-3314.

13th Annual International Pittsburgh Coal Conference, September 3–7, 1996, Pittsburgh, Pennsylvania. Information: Adrian DiNardo, Pittsburgh Coal Conference Office, University of Pittsburgh, 1140 Benedum Hall, Pittsburgh, PA 15261; (412) 624-7440, fax 412-624-1480.

AAPG/SVG International Congress and Exhibition, September 8–11, 1996, Caracas, Venezuela. Information: American Association of Petroleum Geologists, Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 560-2679, fax 918-560-2684.

MINExpo International '96 Conference (sponsored by National Mining Association), September 9–12, 1996, Las Vegas, Nevada. Information: MINExpo, 5420 LBJ Freeway, Suite 410, Dallas, TX 75240; (800) 693-3216, fax 214-702-1042.

Deep Seismic Profiling of the Continents, International Symposium, September 15–20, 1996, Asilomar, California. Information: Simon Klemperer, Dept. of Geophysics, Mitchell Bldg., Stanford University, Stanford, CA 94305; (415) 723-8214, fax 415-725-7344.

Mineral Dusts—Their Characterization and Toxicology Symposium, September 19–20, 1996, Washington, D.C. Information: Meetings Dept., Society for Mining, Metallurgy, and Exploration, P.O. Box 625002, Littleton, CO 80162; (800) 763-3132 *or* (303) 973-9550, fax 303-979-3461.

GIS and Water Resources Conference, September 22–26, 1996, Fort Lauderdale, Florida. Information: American Water Resources Association, 950 Herndon Pkwy., Suite 300, Herndon, VA 22070; (703) 904-1225, fax 703-904-1228.

Association of Engineering Geologists, Annual Meeting, September 24–29, 1996, New Brunswick, New Jersey. Information: Joseph Torlucci, Environmental Compliance Inc., 101 Mount Bethel Road, Warren, NJ 07059; (908) 754-1700, fax 908-754-1866.

27th Binghampton Geomorphology Symposium: "Scientific Nature of Geomorphology," September 27–29, 1996, Urbana-Champaign, Illinois. Information: Bruce L. Rhoads or Colin E. Thorn, Dept. of Geography, University of Illinois, Urbana, IL 61801; (217) 333-1880, fax 217-244-1785.

International Surveying and Mapping Users Conference and Exposition, October 2–4, 1996, San Jose, California. Information: Lea Ann McNabb, Trimble Navigation Ltd., 645 N. Mary Ave., P.O. Box 3642, Sunnyvale, CA 94088; (408) 481-7808.

American Association of Petroleum Geologists, Gulf Coast Section Meeting, October 2–5, 1996, San Antonio, Texas. Information: AAPG, Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 560-2679, fax 918-560-2684.

Geological Society of America, Annual Meeting, October 28–31, 1996, Denver, Colorado. *Abstracts due July 9.* Information: Becky Martin, GSA Meetings Dept., Box 9140, Boulder, CO 80301; (800) 472-1988 *or* (303) 447-2020, ext. 164, fax 303-447-1133.

Watershed Boundaries and Digital Elevation Model of Oklahoma Derived from 1:100,000-Scale Digital Topographic Maps (CD-ROM)

Watershed boundaries for Oklahoma and a digital elevation model (DEM) are included in this USGS open-file report, by Joel R. Cederstrand and Alan Rea, released on CD-ROM. The USGS developed the data sets in cooperation with the State of Oklahoma, Office of the Secretary of Environment, and the Oklahoma Water Resources Board. The data sets were designed especially for use with Geographic Information Systems (GIS) for computerized mapping and spatial analysis. Additional data sets include flow-direction, flow accumulation, and shaded-relief grids, all derived from the DEM, and the hydrography data set used in producing the DEM. The CD-ROM can be used with UNIX, MS-DOS, Macintosh, and VAX operating systems. Each data set is provided in a public-domain format and ARC/INFO (Version 7.0.2) format. Graphic images of the data sets also are provided in Graphics Interchange Format (GIF) files.

Order OF 95-727 from: U.S. Geological Survey, Earth Science Information Center, Open-File Reports Section, Box 25286, Denver, CO 80225; (303) 202-4200. The price is $32. A limited number of copies may still be available free of charge from the USGS Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 843-7570, fax 405-843-7712. The data sets also were released on the Internet at the following URL: http://www.seic.okstate.edu/gis/usgs/okdem/okdem.html

Ordovician Odyssey: Short Papers for the Seventh International Symposium on the Ordovician System

Ordovician Odyssey is a proceedings volume for a 1995 symposium held in Las Vegas, Nevada. The 498-page book contains 120 short papers covering topics on every aspect of research on rocks of the Ordovician System, including chronostratigraphy, paleogeography, paleoclimatology, paleooceanography, sea-level changes and sequence stratigraphy, volcanism, paleoecology, and biostratigraphy. Published by the Pacific Section SEPM, the volume was edited by J. D. Cooper, M. L. Droser, and S. C. Finney.

Four papers in particular relate to Oklahoma geology: (1) "An Affirmation of the Jeffersonian Stage (Ibexian) of North America and a Proposed Boundary Stratotype," by J. D. Loch; (2) "Simpson Paleogeography, Southern Midcontinent U.S.A.," by R. W. Suhm; (3) "Lower Ordovician Reefs of Hubei, China, and the Western United States," by J. K. Rigby and others; and (4) "The Chickasaw Bryozoan Reef in the Middle Ordovician of South-Central Oklahoma," by C. A. Cuffey and R. J. Cuffey.

Order Book 77 from: J. D. Cooper, Managing Editor, Pacific Section SEPM, Dept. of Geological Sciences, California State University, Fullerton, CA 92634; fax (714) 449-7266; e-mail: jcooper@fullerton.edu. The price is $40; add 10% to the price for foreign shipment.

A related publication, *Ordovician of the Great Basin: Field Trip Guidebook for the Seventh International Symposium on the Ordovician System* (Book 78), also is available. Edited by J. D. Cooper, this 151-page volume presents five field trips that examined Ordovician strata in Nevada and adjacent Utah and California. If purchased alone, this book costs $15 and can be ordered from the address above. If purchased together, the cost for both Book 77 and Book 78 is $50; add 10% to the price for foreign shipment. Make checks payable to: Pacific Section SEPM.

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.

Oklahoma Geological Survey Educational-Outreach Activities

NEIL H. SUNESON, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019

The Oklahoma Geological Survey (OGS) is a research and public-service agency whose charter is "to investigate the land, water, mineral, and energy resources of our state and to disseminate the results of these investigations to encourage the wise use of our natural resources." A vital part of the OGS mission is to translate technical information into layman's language for the public and, in particular, earth-science teachers and students.

OGS educational-outreach activities take many forms. Rock, mineral, and fossil sets are available for loan and teaching specimens may be picked up. Staff members make presentations to school groups; lead field trips; participate in professional organizations (e.g., Paleontological Society, AIPG, Oklahoma Academy of Science) that publish educational materials, make awards, and fund educational activities; and attend educational functions (e.g., science fairs, teacher workshops). Many inexpensive OGS publications are written for educators.

Recently, the OGS published *Guide to Resources for Earth Science Information in Oklahoma* [Educational Publication 5]. The book is divided into three sections: "places" that are a resource; "people" that are a resource; and "continuing education." Of particular interest to educators are extensive and annotated lists of (1) museums with earth science exhibits; (2) state parks that feature geology; (3) active quarries and mines that permit school field trips; (4) college and university faculty and oil and gas company geologists that enjoy working with educators and children; (5) professional and amateur organizations that are a resource for earth science information; (6) continuing-education courses (evening, weekend, and summer); (7) popular articles and books about Oklahoma geology and rocks, minerals, and fossils (mostly from rockhound magazines); and (8) sources for earth science educational materials available from private and government agencies and foundations.

Reprinted as published in the Geological Society of America *1996 Abstracts with Programs*, v. 28, no. 1, p. 65–66.

Mapping of Karst Terranes in Oklahoma to Identify Potential Environmental and Hydrologic Problems

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

The Oklahoma Geological Survey (OGS) is mapping the distribution of karst features in the State in order to understand their potential threats to life, health, and property. Wherever highly soluble rocks, such as limestone, dolomite, gypsum, or salt, are at or

near the land surface, karst develops in response to dissolution by circulating ground water. The sinkholes and caverns thus formed are potential hazards because of possible settlement or collapse of the land surface and because ground-water contaminants can travel rapidly without significant attenuation of their noxious qualities. Principal areas in Oklahoma where karst features are present in limestone and dolomite are in the Ozark Mountains in the northeast and the Arbuckle Mountains in the south. Karst terranes are present in many areas of western Oklahoma where gypsum and shallow salt deposits are common.

Areas where relatively water-soluble rocks crop out, or are in the shallow subsurface, are being identified as part of the OGS program of mapping the surface geology in all counties of the State. In most areas the mapping is done through a coordinated study by stereoscopic photo interpretation and field examination. This is a long-term program, with separate reports being released as mapping is completed for each county or area: most maps are being published at a scale of 1:62,500 or 1:63,360. In the interim, we will compile available data onto a 1:500,000-scale map to show areas in the State that may be subject to the consequences of karst development.

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Early Ordovician Echinoderms from Southern Oklahoma and West Texas

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Small echinoderm faunas have recently been collected from several parts of the Lower Ordovician (Ibexian) upper Arbuckle Group in southern Oklahoma and from the similar-aged upper El Paso Group in west Texas. Both of these regions were located on the southwestern tropical margin of Laurentia during the Early Ordovician as part of an extensive carbonate platform made up of thick, light-colored, cyclic limestone and dolomite units. Neither of these echinoderm faunas is as diverse as those occurring further northwest in western Utah and central Nevada where the Lower Ordovician sections contain abundant clastics and more varied lithologies. Most of these new echinoderms were members of the Paleozoic Evolutionary Fauna that was radiating to a dominant position at this time.

Arbuckle Group echinoderms have come from several levels in the West Spring Creek Formation (trilobite Zones H–J) and from the underlying upper Kindblade Formation (top of trilobite Zone G-2) in the Arbuckle Mountains of southern Oklahoma. Only three genera of disparid and cladid inadunate crinoids have been found in thin carbonate mudstone units (some with flat pebbles) that probably represent individual storm deposits in a very shallow nearshore setting. About 10 small iocrinid disparids have been collected from several beds in the West Spring Creek, along with two small cladids from near the top of the Kindblade, and a single large anomalocrinid disparid calyx from the lower West Spring Creek.

New upper El Paso Group echinoderms (beyond the rhombiferan, eocrinoid, and cladid inadunate crinoid described in 1994) have come from the Florida Mountains Formation (trilobite Zone J) or the Scenic Drive Formation (trilobite Zone I). These include another specimen of the rhombiferan *Cuniculocystis* and a specimen of another new rhombiferan genus having numerous radiating ridges on all the thecal plates from the Florida Mountains, and two small iocrinid disparids from the Scenic Drive similar to those found in Oklahoma.

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Simpson-Arbuckle Contact Revisited in Northwest Oklahoma County, Oklahoma

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The Joins Formation, the lowermost formation of the Simpson Group, is traditionally the least studied or understood of the Simpson formations. The Joins, not known to produce hydrocarbons in central Oklahoma, is frequently overlooked by those more interested in the productive Simpson formations above and the Arbuckle carbonates below.

In a study of the lower Simpson to upper Arbuckle interval in northwestern Oklahoma County, Oklahoma, the Joins Formation was found to be present. The formation in this area varies from 65 to 195 feet in thickness, which is considerably thicker than most published literature for the area; some of which state that the formation is absent.

Lithologically, the Joins Formation in central Oklahoma closely resembles the Arbuckle Mountain type section. The central Oklahoma section consists of interbedded gray, olive gray and green splintery moderately waxy shale, cream to light gray homogeneous microcrystalline dolomite, and micorystalline to fine crystalline fossiliferous slightly glauconitic limestone. In the lower half of the formation fine to medium grain slightly conglomeratic and glauconitic well cemented sandstones are also noted. The entire Joins Formation is moderately to very fossiliferous; primarily consisting of crinoids, ostracods, brachiopods, and trilobites. The ostracod fauna closely resembles and correlates with the Arbuckle Mountain section, which has been extensively studied over the years by such authors as Taff, Ulrich and Harris. Beneath the Joins in this area is a normal section of Arbuckle dolomites.

Due to the absence of a basal sand in the Joins the separation of the Joins and Arbuckle, utilizing electric logs only, is frequently tenuous. In comparison with the Arbuckle, the Joins tends to have higher gamma ray and SP values. Other tools, such as resistivity, bulk density and photoelectric (PE), are frequently inconclusive. The newest of the above tools, the photoelectric that was primarily designed as a lithology identification tool, is particularly ineffective due to the very thin bedded nature of the Joins and the two feet minimum resolution limits of the PE tool during normal logging.

For geologists studying the Simpson-Arbuckle contact in central Oklahoma, the presence or absence of the Joins Formation is best determined through conventional lithologic and paleontologic sample identification techniques. Once this has been done, correlation of electric logs with this type log is possible for the local area. Care must be taken not to extend these correlations too far from the type well, primarily due to the frequent inconclusive nature of electric logs over the Joins interval.

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Structures in Outcropping Permian Rocks of Western Oklahoma Indicate Deep-Seated Structures

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Permian outcrops in southwestern Oklahoma mantle deep-seated structures that were developed mainly during Pennsylvanian tectonic activity. Surface mapping of the Blaine Formation and associated Permian strata shows that a number of faults, flexures, and folds, with vertical displacement of less than several hundred feet, overlie similar deep-seated structures with several thousand feet of relief. Structures in outcropping

Permian strata result from late-stage tectonic adjustments along preexisting (Pennsylvanian) structures, and/or from differential compaction of thick-versus-thin sequences of sediments on either side of deep-seated faults or basement highs.

The three major structural provinces of southwestern Oklahoma are, from north to south: the Anadarko basin, which contains up to 40,000 ft of Paleozoic sediments; the west–northwest-trending Wichita uplift, which is covered by about 1,000–3,000 ft of latest Pennsylvanian and Early Permian sediments in the study area; and the Hollis basin, which typically has 6,000–12,000 ft of Paleozoic sediments. The veneer of outcropping Permian strata responded passively to forces deeper in the crust and within the mantle. Stresses on these strata were mostly vertical, because block faulting and broad folding are the only results observed, and at no place do the structures contain evidence of compression.

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Geologic Provinces of Oklahoma

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The geologic provinces of Oklahoma are mainly the product of tectonics and attendant sedimentation of Pennsylvanian age. Most boundaries are structural; thus, the provinces map is a generalized tectonic map. Permian and post-Paleozoic strata tend to mask those structures, but most of those strata have been removed by erosion, except in the Anadarko Basin and the Wichita Uplift provinces. The location of most of Oklahoma's oil and gas resources are either influenced by, or are the direct result of, Pennsylvanian tectonics and sedimentation patterns. Therefore, the present study also defines provinces in the subsurface on the basis of geological criteria. The authors have attempted to use the originally published names for the recognized provinces. However, we have also used the most *geologically* correct names, i.e., Nemaha Uplift, Nemaha Fault Zone, and Central Oklahoma Fault, in lieu of Nemaha "Ridge."

Oklahoma is separated into five major uplifts and five major basins. Most of these have subprovinces, which sum to 20 additional identified geologic units. The Gulf Coastal Plain is not included in this study because it is a veneer of Cretaceous cover that masks significant structures. Faults are the most common boundary element. Although their precise age commonly is known only approximately, their geographic location is less controversial, except in detail. Stratigraphic/structural boundaries are based on less precise geological information. Such boundaries interpreted at the surface are influenced by both geology and geomorphology, and are therefore strongly influenced by the present level of erosion. The major example of a surface stratigraphic/structural boundary is the southwestern limit of the Ozark Uplift in eastern Oklahoma. Stratigraphic/structural boundaries in the subsurface are commonly based on structural or isopachous contours from well or geophysical data, or on a structural trend, as well as the experience of the authors. Basement structure is preferred. An example is the boundary that separates the Marietta Basin from adjacent geologic elements.

Important subsurface boundaries in the Anadardko and Arkoma Basins have been neglected in previous studies: The Anadarko Basin/Shelf boundary is placed near the 700-ft isochore of the Atokan and Desmoinesian Series (Rascoe, 1962), at which there is a marked rate of change of thickening southward into the basin. The northern limit of the Arkoma Basin seems to merge imperceptibly into the southern part of the Cherokee Platform, and has been variously drawn by a number of authors. For the purpose of this study the boundary is modified from the "hinge line" of the Atokan Series (Weirich, 1953). This boundary approximates the striking rate of change of thickness of Atokan strata southward into the Arkoma Basin.

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The Anadarko: Two Basins, Not One

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Located at the core of the Sooner Trend on the northeast shelf of the Anadarko Basin is the Enid Embayment. Using regional mapping and production trends it is possible to expand the idea of an Enid Embayment to a concept of two basins, a northern shallow basin and the main basin to the south. From a terminology point of view, it would also be appropriate to map a single basin with a northwest trending arch cutting across the shelf of that basin.

The evidence for this concept is most pronounced in the Pennsylvanian producing trends but can also be inferred as early as Siluro-Devonian Hunton time. There also clearly exists the presence of a through going linear on the Landsat interpreted data suggesting the existence of a deep seated, basement fault or fault system underlying the arch which separates the two basin axes.

Shoreline trends in the northern basin are very pronounced because the basin was very shallow, and the shelf edges were very low dip. Therefore, small changes in sea level caused large movements in shoreline locations. The mapping of shoreline location through time in the shallow basin can produce a better understanding of shoreline deposits in the deep basin and assist in the understanding of producing fairways and their potential extensions.

Although the concept is not new, the recognition and interpretation of a two basin concept can be of assistance in exploring for, and finding, the more elusive fields that remain in this mature area.

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Regional Correlations and Reservoir Characterization Studies of the Morrow Group in the Anadarko Basin Area of Western Oklahoma

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Reservoir characterization studies of numerous fields within the Anadarko Basin area have demonstrated nomenclature problems regarding Morrowan age reservoirs. The Morrow can be overlaid by strata as young as basal Des Moinesian and underlaid by strata that is Springeran to Chesterian in age. This problem has led to Morrow production being erroneously called as young as Red Fork (Des Moinesian) and as old as Chester. To further complicate nomenclature, a correlative and equivalent formation may be called various names from one region of the basin to another and/or may be known by local names from one field to another. Misallocated Morrow production is carried incorrectly throughout the production history of the well. Further, this misallocated production is then used by various state and federal agencies to model reserves and to create energy policies. To date, few detailed regional cross-sections have been available (or even exist outside proprietary studies) showing the most up-to-date logs correlated throughout the basin. By using regional cross-sections the stratigraphic relationships between the Morrow and overlying and underlying formations are clearly demonstrated.

Reservoir characterization occurs after cross-section grids have established that all log correlations tie intra-field as well as inter-field. Production was allocated by comparing the perforated interval to the log which was correlated to the correct reservoir. Characterization of the reservoirs was conducted to include geologic and engineering data such as depths, thicknesses, porosities, permeabilities, pressures, water saturations, area, spacings, and heterogeneities along with a correlated reservoir specific type log. The results of those studies are presented.

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Regional Correlations and Reservoir Characterization Studies of the Springer Group in the Anadarko Basin Area of Western Oklahoma

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The nomenclature used within the Anadarko Basin and encompassing shelf areas is typically erratic. A productive horizon may be incorrectly called several various names within the same field. The Springer Group, Upper Mississippian and Lower Pennsylvanian, is often misnamed as the abovelying Pennsylvanian Morrow or the underlying Mississippian Chester. Generally, the Springer Group consists of the Boatwright, Britt, and Cunningham in ascending order. A correlative and equivalent formation may be called by various names by geologists familiar with the nomenclature of one region of the basin. Further complicating the understanding of the Anadarko Basin's geology, few detailed regional cross-sections are available (or even exist outside proprietary studies) showing the most up-to-date logs correlated throughout the basin. By using regional cross-sections, the stratigraphic relationships existing within the Springer Group are demonstrated as well as the contacts of the Springer/Chester and the Springer/Morrow identified. The lateral facies change of the Springer Group from a clastic facies into a carbonate dominated facies is illustrated by the log cross-section.

Wells accounting for approximately 25% of the production attributed to the Springer Group in the Anadarko Basin have been evaluated. The perforated interval was compared to the logs and the correct (Springer) reservoir was identified. Detailed reservoir characterization of the reservoirs was conducted to include geologic and engineering data such as depths, thicknesses, porosities, permeabilities, pressures, water saturations, area, spacings, and heterogeneities along with a correlated "field-specific" reservoir type log. Log analysis was conducted on the producing interval, saturated interval, and gross interval. The results of the studies are presented.

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Regional Correlations and Reservoir Characterization Studies of the Pennsylvanian System in the Anadarko Basin Area of Western Oklahoma and the Panhandle of Texas

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Correlation problems have long existed between the Pennsylvanian marine clastics of the northeastern half of the Anadarko Basin and Shelf and the Pennsylvanian terrig-

enous washes of the extreme southwestern portion of the Anadarko Basin. These correlation problems have created nomenclature problems resulting in thousands of feet of washes often referred to on completion reports and production records as "granite wash" or "Atoka Wash" when much greater accuracy and specificity is both needed and possible.

Few detailed cross-sections are available. Regional and field scale cross-sections were constructed which have been correlated well by well and field by field using nearly every deep well drilled in the basin. This process has provided for a high degree of consistency. These cross-sections have greatly diminished the correlation and nomenclature problems within the Anadarko Basin.

Certain markers proved to be regionally persistent from the marine clastics into the terrigenous washes making the subdivision of thousands of feet of washes possible. Those of greatest importance were the top of the Marmaton, the Cherokee Marker, the Pink "Limestone" Interval, the top of the Atoka and the top of the Morrow. Once these and other subdivisions were made, production was allocated on a much more definitive basis. Additionally, detailed reservoir characterization of the reservoirs was conducted to include geologic and engineering data. Finally, a "field-specific" reservoir type log was chosen.

A series of regional cross-sections will be presented along with the results of reservoir characterization studies conducted on reservoirs within the fields located along the cross-sections. A type log for each reservoir will also be illustrated.

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Compartmentation in the Anadarko Basin: Implications for Exploration and Production

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Integrated pressure, potentiometric, and geologic data demonstrate the existence of a basin-wide, completely sealed overpressured compartment in the Anadarko basin. All reservoirs within this complex exhibit pressure gradients ranging from 0.6 to 0.98 psi/ft, which exceed the normal gradient of 0.465 psi/ft. These reservoirs have produced large quantities of natural gas, particularly from the Pennsylvanian Red Fork and Morrowan sandstones.

This mega compartment complex is enclosed by top, bottom, and lateral seals. The top seal, which is located between 8,500 and 11,000 ft below the surface, is relatively horizontal, dips slightly to the southwest, and appears to cut across stratigraphy. However, the basal seal is stratigraphically controlled and seems to coincide with the Devonian Woodford Shale. The complex is laterally sealed to the south by an intense cementation zone associated with the Wichita uplift frontal fault zone and by the convergence of the top and basal seals along the eastern, northern, and western boundaries.

Nested within this complex is a myriad of smaller compartments with their own distinct pressure gradients. In addition, local overpressured compartments are present outside the mega compartment complex in normal and near-normal pressured regions.

Due to their hydraulically isolated nature, nested pressure compartments may provide drilling prospects that are not constrained by structural position or proximity to existing reservoirs. Predicting the compartment and seal geometries and internal reservoir quality should improve drilling success ratios and diminish hazards associated with drilling abnormally pressured rock sequences.

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Preliminary Fluid Inclusion Evidence for the Mechanism of Dolomitization in the Lower Permian Chase Group, Hugoton Embayment, Southwest Kansas

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Primary fluid inclusions in dolomite from the lower Krider Limestone of the Mobil Nix #1 Unit #3 well and the base of the Winfield Limestone of the Mobil Clair Curry Unit #3 well in southwestern Kansas were analyzed to determine the salinity, temperature, major ions, and gas content of fluids responsible for dolomitization.

Dolomite rhombs show growth zonation with inclusion-rich cores and clear, inclusion-free rims. Both one-phase and two-phase aqueous fluid inclusions are present in the inclusion-rich cores. Melting temperatures of ice range from –17.5°C to –22.8°C (20.6 to 24.2 weight % NaCl equivalent). Homogenization temperatures range from 56.9°C to 128°C, with 85% between 75°C and 95°C. Eutectic melting temperatures were observed at –57°C for the Nix well and –52°C for the Clair Curry well indicating model compositions of Na-Ca-Mg-Cl–rich and Na-Ca-Cl–rich fluids, respectively. Intermediate melting temperatures between about –42°C and –38°C were observed but were not interpretable. Crushing runs reveal the vapor phase contains an exsolved gas of unknown composition at pressures between 5 to 35 bars at room temperature.

Cathodoluminescence petrography reveals three growth zones that are especially well developed in dolomite of the Clair Curry well. Zone 1 (inclusion-rich core) is dull but contains some bright areas suggestive of recrystallization of an originally dull rhomb. Zone 2 (inner zone of clear rim) is bright and exhibits polyhedral crystal growth. Zone 3 (outer zone of clear rim) is dull and rhombic. The presence of one-phase and two-phase inclusions within the cores of dolomite crystals suggests that highly saline fluids were entrapped below about 50°C and subsequently re-equilibrated (by leakage and refilling or by recrystallization). A possible model responsible for the dolomitization involves refluxing of brines followed by re-equilibration of inclusions by warm brines migrating cratonward from the Anadarko Basin.

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Sequence Stratigraphy and Depositional Facies in the Chase Group (Permian, Wolfcampian), South-Central Kansas

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Chase Group strata in south-central Kansas consist of 400 ft of cyclic carbonate and siliciclastic strata. The fundamental stratigraphic unit recognized is the cyclothem (sensu Heckel), defined as a transgressive-regressive package of genetically related strata. Component shallowing-upward cycles within the transgressive and regressive phases of cyclothems are the highest-frequency genetic units in the section. Single cyclothems, or groups of two cyclothems, are included within six depositional sequences, which are bounded by terrestrial red shales interpreted as representing periods of maximum lowstand emergence.

The six depositional sequences recognized in the section, and most of their component cyclothems, are regionally correlated from southeastern Nebraska, through Kansas, and into northeastern Oklahoma. Evidence of Southern Hemisphere glaciation and characteristic stacking patterns of cyclothems and component cycles suggest fundamental glacio-eustatic control on deposition. However, some cyclothems and component high-frequency cycles in the section do not extend regionally, cyclothem and cycle thicknesses deviate from those expected in eustatic-controlled accommodation events, and in many cases, cycles cannot be correlated regionally. Furthermore, dramatic thickness changes occur within some cyclothems, particularly in areas of longlived tectonism. In these cases, cycle and cyclothem development apparently were controlled largely by accommodation changes related to local tectonism. Chase Group strata therefore represent a complex mosaic of eustatically and tectonically controlled cyclic deposits.

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Holocene Siliciclastic-Carbonate Facies Mosaics, Northern Belize: Exploration Analog to Some Midcontinent Pennsylvanian (Morrowan) Reservoirs

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Midwinter Lagoon is a large, shallow coastal lagoon, bordered on its seaward side by a barrier bar, along the mainland coast of northern Belize. As much as 19 ft of Holocene sediments, deposited on karsted Tertiary limestones during the Flandrian transgression, consist of a complex mosaic of mixed siliciclastic and carbonate facies. Basal transgressive marine, intra-lagoonal facies are variously siliciclastic-rich carbonates to carbonate-rich siliciclastics, locally with layers of shoreline mangrove peat. These facies shallow-upward to either siliciclastic or carbonate-dominated sands or muds. Lagoonal facies were deposited within a broad topographic low, locally punctuated by bedrock highs, on the underlying limestone. The seaward edge of the barrier bar complex, which was deposited on a linear topographic high, consists mostly of quartz sands, whereas the lagoonal side is a mixture of quartzose and carbonate sediments (sands and muds). The barrier bar appears to have accreted southward in response to southerly longshore drift as a tidal inlet-spit complex; quartz sands are being transported into the lagoon from its seaward side.

In terms of geometry, modern and buried, intra-lagoonal carbonate sands occur as lobes deposited proximal to extant and older tidal inlets. Either carbonate or siliciclastic sands variously occur as erratically distributed, anastomosing beach deposits around small mangrove islands and along the irregular mainland coast. In contrast, siliciclastic sands on the seaward side of the barrier bar define a narrow but areally persistent linear trend. Similar complex facies associations and geometries are typical of many Pennsylvanian (Morrowan) reservoirs in the midcontinent U.S.

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Interbasinal Correlation of Late Pennsylvanian 4th Order (10^5-Year) Depositional Sequences from North-Central Texas to Illinois Basin: A Test for Eustasy and Relative Shelf Elevation

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Sea-level fluctuation curves derived from analysis of early Late Pennsylvanian (Missourian) 4th order depositional sequences (cyclothems) for the north Texas (Eastern) Shelf of the Midland Basin, the broad Northern Midcontinent Shelf of the Anadarko

Basin, and the northern part of the Illinois Basin were compared to see if the patterns of successive transgressions and regressions are consistent across a significant part of the North American Craton. Our data demonstrate that the vertical patterns of Missourian sea-level rises and falls are remarkably similar in the three basins, but there are fewer minor cycles on the north Texas shelf and particularly in the northern Illinois Basin.

As an independent test of the sea-level fluctuation curves for the three basins, conodont faunas were examined from marine condensed sections (dark phosphatic shales and carbonates) within each depositional sequence in the three basins. Specifically, rapidly evolving morphotypic species of *Idiognathodus* and *Streptognathodus* were utilized in correlating the sequences. Every major marine transgression, including the Hertha (Mound City), Swope (Hushpuckney), Dennis (Stark), Dewey (Quivira), Iola (Muncie Creek), and Stanton (Eudora) of the Midcontinent have been identified in the other basins by their distinctive conodont faunas. Additionally, two intermediate transgessions, the Cherryvale and Wyandotte (Quindaro), have been identified in all three basins. Thus far, the Exline, Plattsburg (Hickory Creek), and South Bend intermediate transgressions have been identified only in the Midcontinent and north-central Texas. The absence of some of the lesser transgressions to the northern part of the Illinois Basin probably reflects its Pennsylvanian position at a higher elevation on the cratonic shelf above the level of these lesser highstands.

The combination approach of comparing calibrated sea-level curves with biostratigraphic correlation demonstates the pervasive glacial-eustatic control of Pennsylvanian 4th order depositional sequences, provides a way to estimate relative Pennsylvanian shelf elevation, and should also provide testable working hypotheses for high resolution interbasinal and ultimately intercontinental correlations.

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Recognition of Sequence Boundaries in Pennsylvanian Outcrops of the Midcontinent

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Subaerial exposure surfaces and associated features are important and common components of shallow-marine Paleozoic sequences in the Midcontinent. Recognition and mapping of such surfaces are of economic importance because the distribution of reservoir facies is closely associated with subaerial exposure. The absence of strong evidence of subareal exposure in these sequences (e.g., unambiguous petrographic and isotopic data) creates problems in stratigraphic correlation at both the reservoir and regional scales. However, exposure surfaces and associated paleo-water tables can be recognized by variations in the concentration of the three most commonly occurring radioactive elements (i.e., uranium, potassium, and thorium). These variations in the concentration are readily detected in both the surface and subsurface using the spectral gamma-ray log.

Detailed field description, petrographic examination, and geochemical analysis were used to understand the relationship between the concentration of radioactive elements, and the style of alteration associated with subaerial exposure at the overlying sequence boundary in selected Pennsylvanian carbonate sequences. In several sequences distinctive change in uranium concentration is observed at the contact of the vadose and phreatic zones. On the basis of detailed examination, the uranium anomalies cut across primary sedimentary structures, and are proposed to be the result of selective inclusion of uranium in micrite cements and associated clays concentrated at the contact between the vadose and phreatic environments. Development of criteria to recognize this distinctive signature in both the surface and subsurface may assist in correlation of individual sequences and will aid in understanding genetic mechanisms that control reservoir development in similar shallow-marine Midcontinent reservoirs.

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Comparison of Conventional (100%), Two-Dimensional (2D), and Three-Dimensional (3D) Seismic Data: Case Histories from the Midcontinent

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The principal objective of seismic exploration is to determine three geologic parameters, the structural top, the bottom, and the lateral extent of an oil and gas reservoir. Conventional (100%) data is very efficient in locating the structural top and bottom of reservoirs. Two-dimensional (2D) common depth point (CDP) seismic data provides an immense improvement in seismic data quality over conventional (100%) data. This improvement enables the explorer to better visualize and map the reservoir in each direction of the seismic line. Three-dimensional (3D) seismic technology provides even more mappable data and capability. The explorer may visualize every imaginable direction and subtlety of a reservoir. This talk compares conventional (100%), two-dimensional (2D), and three-dimensional (3D) seismic data from the Midcontinent. Case histories of the Douglas (Upper Pennsylvanian) in Texas, the Morrow (Lower Pennsylvanian) in Colorado, the "Chat" (Mississippian) and the Hunton (Silurian–Devonian) in Oklahoma, and the Simpson (Ordovician) in Kansas will be discussed. Major and independent operators can maximize their exploration efforts by integrating existing data with three-dimensional (3D) technology and a solid geologic interpretation.

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Does Sequence Stratigraphy Need Biostratigraphy?

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The sequence stratigraphy methodology integrates diverse geophysical and geological data sets, which has revitalized both geoscience disciplines. Biostratigraphic data has become essential to the geological interpretation of seismic record sections. Quantitative analyses of fossil abundances, diversities and ranges provide important data for the definition and constraint of hypotheses of sequence stratigraphy. Within carbonate platforms sequence boundaries may separate similar facies and so be difficult to recognize. For example, regional unconformities within skeletal limestones of the Silurian–Devonian Hunton Group in Oklahoma were first clearly defined by means of the biofacies and extinctions. Within mixed siliciclastic and carbonate facies successions the subtle changes in biotic associations define the stacking pattern. Quantitative biotic analyses of the Midcontinent Pennsylvanian cyclothems constrain the depth limits of the cyclothem members. The timing of sea level changes and their correlation within and between basins is essential for distinguishing the relative effects of basinal tectonics and eustasy. Mid-Cretaceous transgressive and regressive depositional cycles in the Denver Basin can be correlated precisely with shoaling-deepening cycles in the East Texas Basin. The consistent delineation of depositional or seismic sequences depends upon the successful integration of biostratigraphic, geochemical and petrographic data with well log and seismic data.

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Will Environmentally Acceptable Mid-Continent Coal Reserves be Adequate for Electric Power Generation in the 21st Century?

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In 1993, 2.9 million tons of medium- to high-sulfur bituminous coal was produced mostly at surface mines, while about 80 million tons of mostly low-sulfur subbituminous coal was consumed at 150 electric-power generators that produced 34,000 megawatts per hour (MW/hr) in 5 Midcontinent states (Arkansas, Iowa, Kansas, Missouri, and Oklahoma). These 5 states contain 98 billion tons of identified bituminous coal resources of which 41 billion tons are recoverable reserves documented by state geological surveys) and 11 billion tons are included in the Demonstrated Reserve Base of the U.S. Department of Energy.

Bituminous coal reserves are available in these Midcontinent states to produce at least 34,000 MW/hr of electricity. However, the technology of most of these states' power plants, coupled with increasingly restrictive, federally mandated air-pollution regulations, has resulted in economics-driven decisions by the electric power utilities to use "compliance," low-sulfur, subbituminous coal from Wyoming.

Only one million tons of Oklahoma high-sulfur bituminous coal is used in a state-of-the-art fluidized-bed combustion, cogeneration, 320 MW/hr power plant.

I believe 110 large (300 MW/hr) FBC plants, whose technology removes air-polluting sulfur, ash, and trace elements (at a temperature 500 degrees cooler than conventional plants) would have to be on-line, before the medium- to high-sulfur bituminous coal reserves could be burned and meet federal and state clean air standards in these 5 states. Otherwise these states' large bituminous coal reserves will not be adequate to generate the required electric power now or far into the 21st century.

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Midcontinent U.S. Fault and Fold Zones: A Legacy of Proterozoic Intracratonic Extensional Tectonism?

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The U.S. continental interior (midcontinent) contains numerous fault and fold zones. Seismic and drilling data indicate that some of these zones first formed as Proterozoic-Eocambrian rift faults, but the origin of most remains enigmatic. We propose that the enigmatic fault and fold zones also began as Proterozoic-Eocambrian normal faults. We base our hypothesis on the following: (1) enigmatic zones parallel known rifts, (2) the structural style of enigmatic zones mirrors the structural style of known rifts, (3) the map pattern of some enigmatic zones (e.g., the La Salle deformation belt of Illinois) resembles the map pattern of contemporary rifts, and (4) it is easier to rupture an intact craton by normal fauting than by reverse or strike-slip faulting. These zones, along with known rifts, represent the legacy of widespread extensional tectonism that brittlely broke up the craton into fault-bounded blocks prior to deposition of Phanerozoic platform cover. Once formed, midcontinent fault and fold zones remained weak, allowing cratonic blocks to jostle relative to one another during the Phanerozoic, thereby inverting faults (and creating transpressional or transtensional structural assemblages), localizing seismicity, and channeling (or releasing) ore-generating fluids.

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