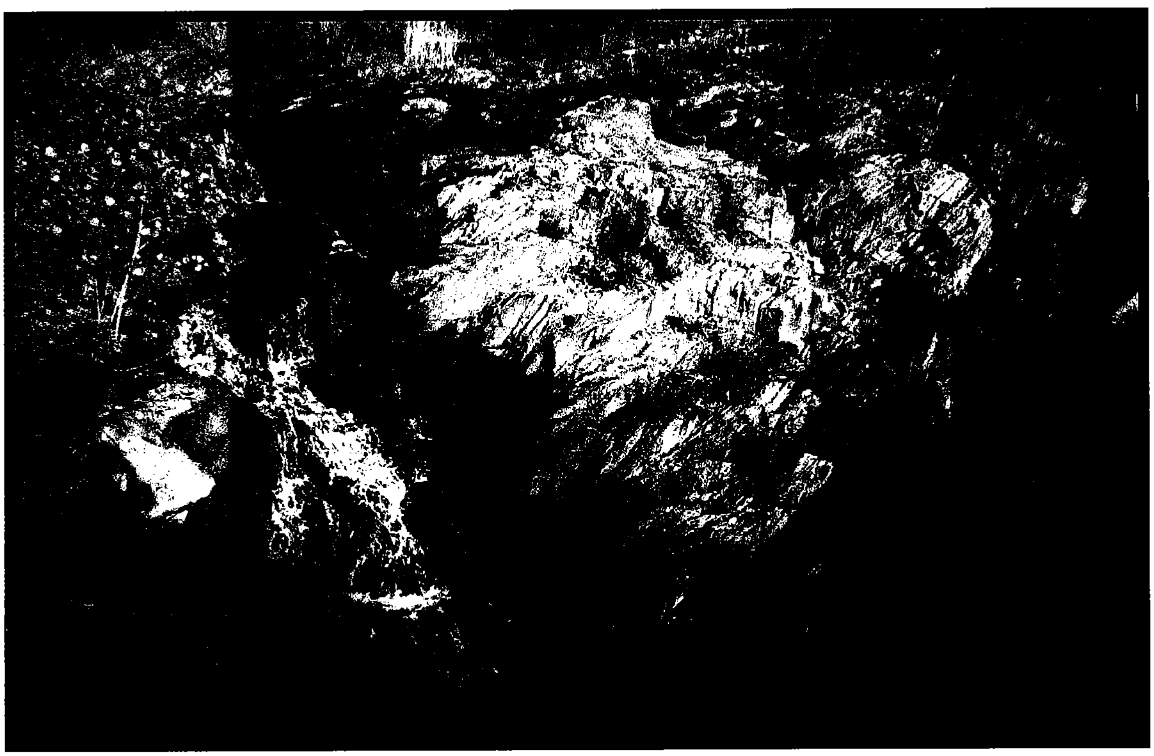
OKLAHOMA GEOLOGY

Oklahoma
Geological
Survey

Vol. 60, No. 3 Fall 2000



Featuring:

- OGS investigates mysterious leak in Bartlesville church
- Unusual crinoid from Tulsa

on the cover

Overbrook Member of the Springer Formation, City Lake spillway, Ardmore, Oklahoma

Thin-bedded, ripple-bedded, very fine grained sandstones of the Overbrook Member of the Springer Formation (Britt equivalent in the Anadarko basin) (Mississippian) are exposed in the eroded spillway channel of City Lake, Ardmore, in the NE¼NW¼ sec. 12, T. 4 S., R. 1 E., Carter County, Oklahoma. Flood waters have stripped the soil cover from bedrock in the channel below the concrete spillway, thus providing excellent three-dimensional views of the strata. The cover photograph was taken looking down from the east; younger beds are on the left. The cascading water at the left drops ~25 ft over the steeply dipping, thin-bedded rocks. The beds crop out on the southwestern flank of the Caddo anticline; they strike N. 40° W. and dip 76° SW. Petrographic analyses, abundance of trace fossils, and the relationship of the lithologic units in a coarsening-upward sequence all indicate that the sediments were deposited as a detached bar in a shallow-marine environment.

About 290 ft of the Springer Formation is exposed at this site, including 180 ft of an unnamed shale below the Overbrook Member. A section has been measured and a gamma-ray profile completed at this outcrop, which will be featured as Stop 2 in an upcoming Oklahoma Geological Survey (OGS) guidebook. The guidebook will be for a Springer field trip to be held in Spring 2001. Six other stops have been scheduled for the field trip; one of them features the Lake Ardmore Sandstone (Fig. 1). The field trip will be in conjunction with a workshop on the Springer to be presented in Norman by OGS geologist Rick Andrews.

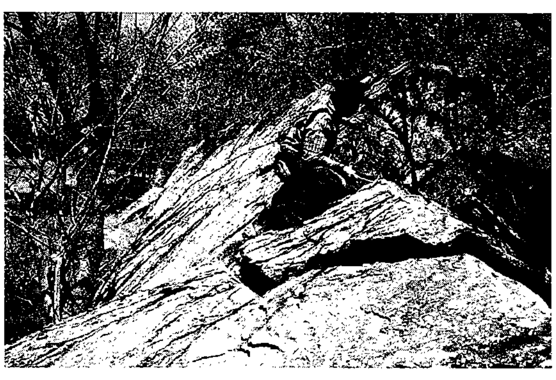


Figure 1. Exposure of the Lake Ardmore Member of the Springer Formation.

Figure 1 shows Rick Andrews examining an exposure of the Lake Ardmore Member of the Springer Formation at the MGM Ranch northwest of the city of Ardmore in the SW¼SE¼ sec. 27, T. 3 S., R. 1 E., Carter County. This outcrop is also on the southwestern flank of the Caddo anticline. The strata strike N. 25° W. and dip 65° SW (to the left in the photograph).

At this outcrop, the Lake Ardmore Member comprises two units, an 8-ft-thick unit of interbedded sandstone and shale (base covered), overlain by a 9-ft-thick unit of very fine grained, thin-bedded, ripple-bedded, burrowed sandstone with extensive boxwork concretionary structures exposed on its upper surface (Fig. 2). Iron oxide minerals form the concretionary structures, which are fracture-fillings that follow joints in the sandstone (see Hemish, 1997, p. 198, for further information on boxwork structures).

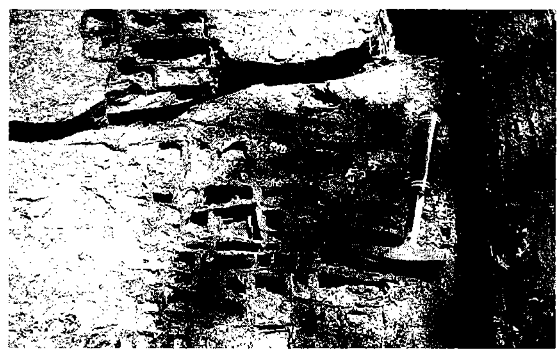


Figure 2. Sandstone with extensive boxwork concretionary structures exposed on its upper surface. Geologic pick is 1.1 ft long.

This site is one of the best three-dimensional exposures of the Lake Ardmore Member in the field-trip area. A section has been measured and a gamma-ray profile completed at the exposure, which will be featured as Stop 6A in the Springer field-trip guidebook.

Reference Cited

Hemish, L. A., 1997, Boxwork concretion from the Warner Sandstone, Pittsburg County, Oklahoma: Oklahoma Geology Notes, v. 57, p. 197–198.

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OKLAHOMA GEOLOGY NOTES, ISSN 0030-1736, is published quarterly by the Oklahoma Geological Survey. It contains short technical articles, mineral-industry and petroleum news and statistics, abstracts, notices of new publications, and announcements of general pertinence to Oklahoma geology. Single copies, $1.50; yearly subscription, $6. Send subscription orders to the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019.

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OKLAHOMA GEOLOGY

Vol. 60, No. 3 **Fall 2000**

Study of Ground-Water Problems, Good Shepherd Church Site, Bartlesville, Oklahoma

LeRoy A. Hemish
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INTRODUCTION

In its role as a public-service State agency, the Oklahoma Geological Survey (OGS) sometimes receives a request to study the geology of a specific location in Oklahoma and to assess what role the geology may play in a particular problem. In June 2000, officials of the Good Shepherd Presbyterian Church in Bartlesville asked for help in learning why water seeps into some rooms of the church. The water seeps were first noticed about 10 years ago, but construction on church property over the past year has made the water problem more apparent.

GEOLOGIC SETTING

The Good Shepherd Church (801 S.E. Washington Boulevard) is located in the NE¼NE¼NE¼, sec. 17, T. 26 N., R. 13 E., in the city of Bartlesville, Oklahoma, in Washington County (Fig. 1). It is situated on a hill ~0.5 mi east of and ~75 ft above the flood plain of the Caney River. The elevation of the church grounds is ~735 ft above sea level. Three city water tanks (Fig. 2) are located across Adams Boulevard, just to the north in the SE¼SE¼SE¼SE¼ sec. 8, T. 26 N. R. 13 E.; they stand at an elevation of ~745 ft (Fig. 1). The area around the church drains into ravines, which drop quite steeply down to the Caney River flood plain (Fig. 1).

Bartlesville is at the western edge of a geomorphic province called the Claremore Cuesta Plains by Curtis and Ham (1972, p. 3). (A cuesta is a hill or ridge with a gentle slope on one side and a steep slope on the other.) In general, resistant Pennsylvanian sandstones and limestones form cuestas between broad shale plains within this province. However, the elongate ridge that extends through the study area (Fig. 1) is not formed by a cuesta, but by the Bartlesville anticline, an uplifted structural feature (Carpenter, 1930, p. 140).

Structure

The strike of the strata of Washington County is northeast-southwest, and the dip is <1° NW. (20–25 ft per mi). Commonly, the strata incline westward, but this structure "is interrupted in places to form anticlines, terraces, and 'noses'" (Carpenter, 1930, p. 139). The church grounds and city water tanks are very near the crest of the Bartlesville anticline (Fig. 1). It is one of the most prominent structures in Washington County. It was mapped by Carpenter (1930) and again by Oakes (1940) (Fig. 1). The crest of the anticline probably extends across the hill on which the water tanks stand, and the church is just downdip on the southeast flank of the structure.

Strike and dip measurements taken on bedrock (Nellie Bly Formation) exposed by construction near the church are inconsistent, suggesting that there may be some local, minor, superimposed folds along the crest of the Bartlesville anticline (the major fold in the area). Measurements of the attitudes of the beds just west of Washington Boulevard in front of the church are: (1) strike, N. 30° E., and dip, 8° NW.; (2) strike, N. 55° E., and dip, 9° NW. Just north of the church at the edge of a small excavation, the strike is N. 70° W., and the dip is 10° SW. Although the regional dip of the strata in the area is <1° NW. and the main outcrop belt of the Nellie Bly Formation is ~2 mi to the southeast, the Nellie Bly is exposed in the vicinity of Good Shepherd Church because of uplift on the Bartlesville anticline (Fig. 1).

Stratigraphy

The sands and muds that comprise the Nellie Bly Formation were deposited in the shallow marine waters of a deltaic environment (White, 1922, p. 172; Oakes, 1952, p. 65) about 290 million years ago during the Missourian (Fig. 3). In the study area, the Nellie Bly Formation is made up of a lower unit of silty and sandy shale and an upper unit of sandstone interstratified with shale (Fig. 3). The lower part of the upper unit surrounds the church and is visible in construction areas where the sod has been removed. Mapping by Oakes (1940) shows that the Nellie Bly Formation underlies the three city water tanks. Although rocks are not exposed at the city site, it can be inferred from projection of strike and dip measurements (strike, N. 70° W.; dip, 10° SW.) taken just north of the church that the water tanks also rest on the upper sandstone unit of the Nellie Bly Formation.

GEOLOGIC INVESTIGATION

Stratigraphy

Construction-area exposures of the Nellie Bly Formation on the church grounds show a sequence of buff, thin-bedded, wavy-bedded, very fine grained sandstones with abundant interstratified silty shales (Fig. 1, Site 1). The thickest sandstone layer is ~3 in. (Fig. 4). The highly fractured sandstones have joints aligned in three general directions (Figs. 4 and 5). Measurements taken with a Brunton compass on the joints at three different locations in the churchyard are: (location 1) N. 65° E., N. 60° W., N. 20° W.; (location 2) N. 60° E., N. 55° W., N. 32° W.; (location 3) N. 40° E., N. 52° W.,

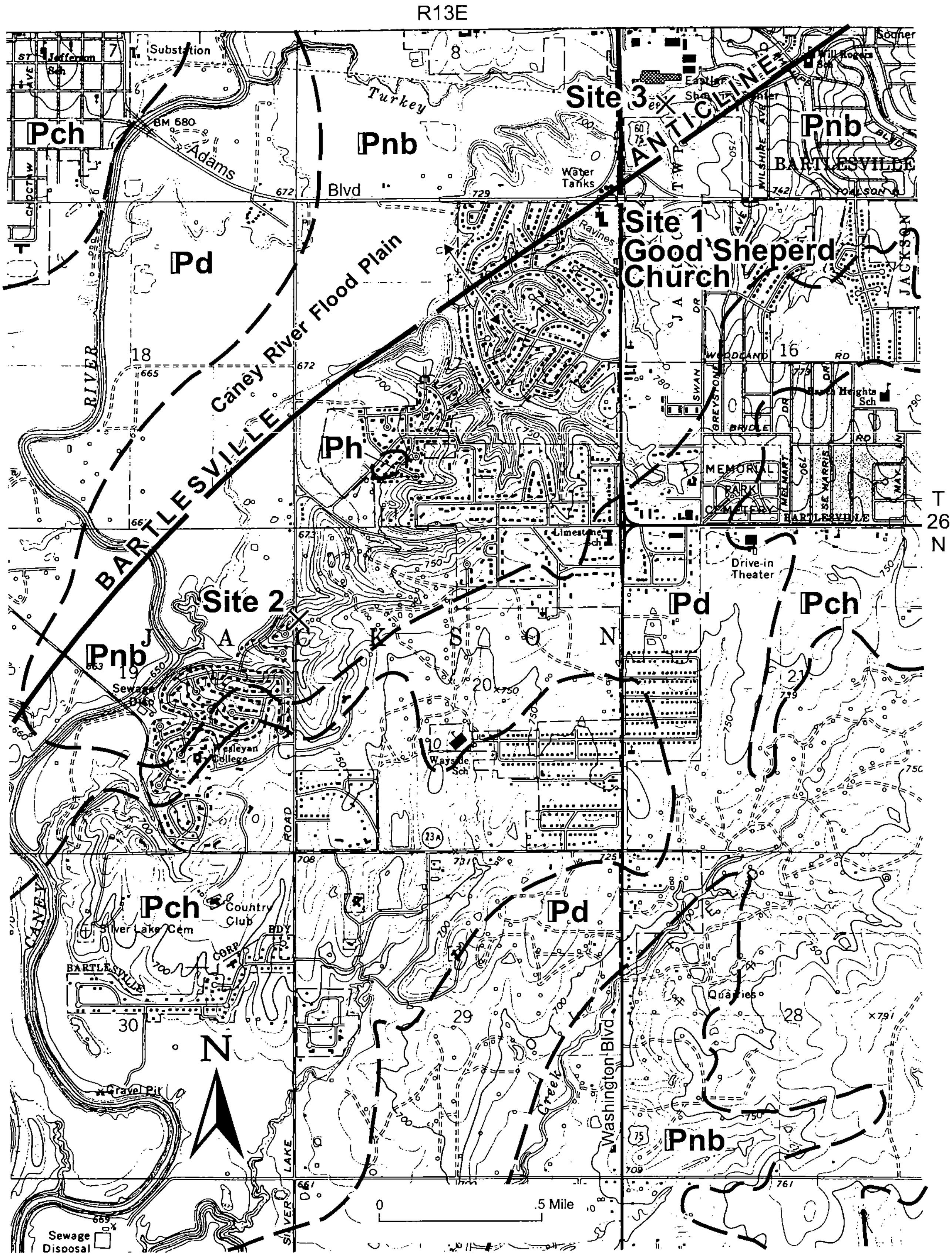

Figure 1. Geologic map showing the approximate outcrop and subcrop boundaries of Pennsylvanian strata in the vicinity of Good Shepherd Church, Bartlesville, Oklahoma. IPh = Hogshooter Formation; IPnb = Nellie Bly Formation; IPd = Dewey Formation; IPch = Chanute Formation. The upper sandstone unit of the Nellie Bly Formation is exposed at Sites 1 (Good Shepherd Church) and 2, and the contact between the lower shale and the upper sandstone units of the Nellie Bly is exposed at Site 3. Modified from Oakes (1940, fig. 10; pl.1). Base map is an excerpt from Bartlesville South, U.S. Geological Survey 7.5′ Series Quadrangle Map.

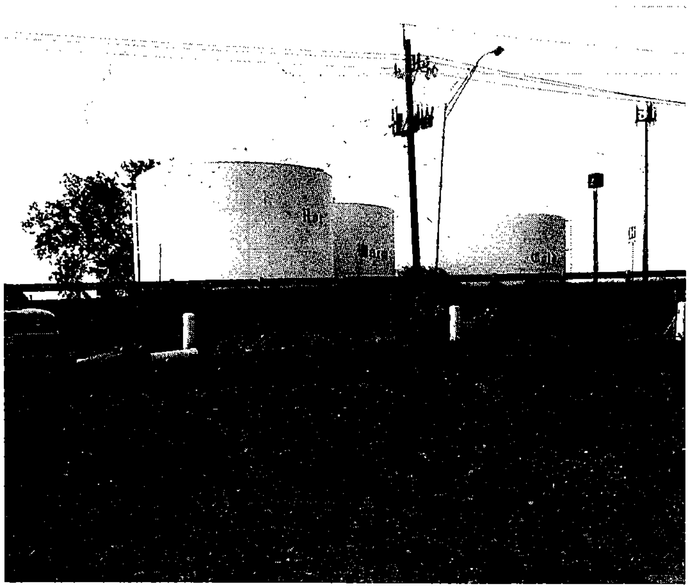

Figure 2. Three City of Bartlesville water tanks located on a knoll in the SE¼SE¼SE¼SE¼ sec. 8, T. 26 N., R. 13 E., Washington County. View is looking north from Good Shepherd Church property, located across Adams Boulevard directly south of the water tanks.

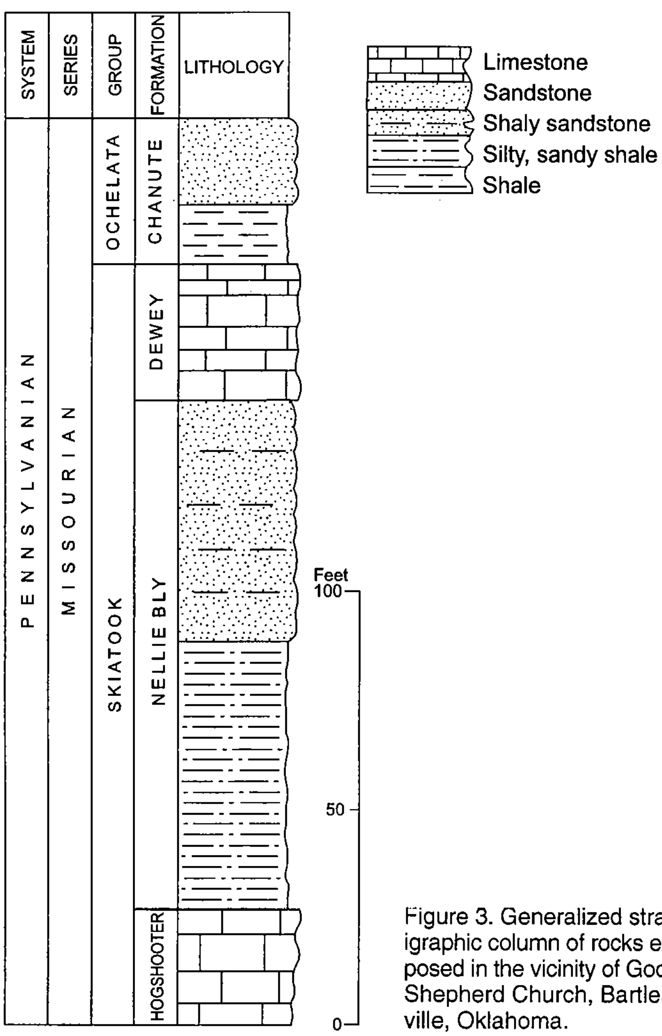

Figure 3. Generalized stratigraphic column of rocks exposed in the vicinity of Good Shepherd Church, Bartlesville, Oklahoma.

N. 24° W. The intersecting fractures produce blocks that are either triangular or shaped roughly like parallelograms, commonly with 2–9-in. sides (Fig. 6).

The upper sandstone unit of the Nellie Bly Formation (Fig. 3) is well exposed in a road cut on the east side of Silver Lake Road, NW¼NW¼SW¼NW¼ sec. 20, T. 26 N., R. 13 E., ~1.3 mi southwest of Good Shepherd Church (Fig. 1, Site 2). At this outcrop ~12 ft of mostly buff, thin- to medium-bedded sandstone with silty shale partings is exposed (Fig. 7). The sandstone is micaceous with abundant black macerated plant debris on stratification surfaces. It is wavy-bedded, ripple-marked (oscillation ripples are common), and contains wood fragments. Trace fossils, such as burrows and trails, are abundant throughout. As at Site 1, three-directional fractures cut the unit (Fig. 7).

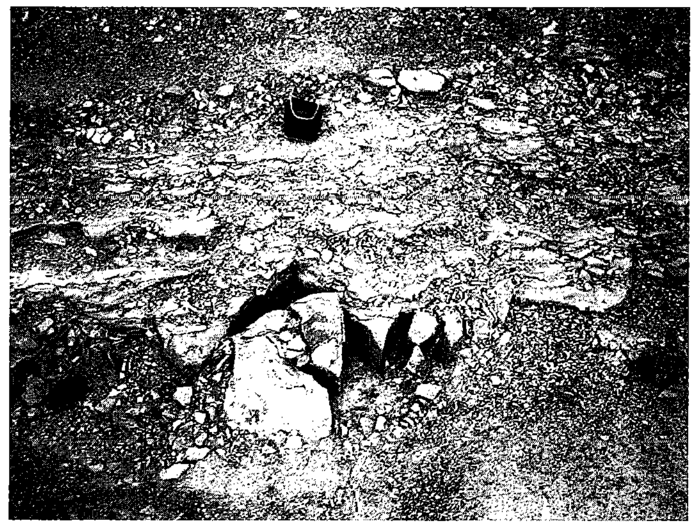

Figure 4. Exposure of the Nellie Bly Formation just west of Washington Boulevard on church property. Note the predominantly thin-, wavy-bedded character of the sandstone, and the 3-in.-thick, jointed bed ~1 ft below the camera case (3 in. × 5 in.).

Figure 5. Three-directional joint system shown in a sandstone bed of the Nellie Bly Formation. The exposure is on church property (Fig. 1, Site 1), just west of Washington Boulevard. Camera case (3 in. × 5 in.) for scale.

The contact between the lower silty, sandy, shale unit and the upper shaly sandstone unit of the Nellie Bly Formation is exposed in a shale pit, SW¼SW¼NW¼SW¼ sec. 9, T. 26 N., R. 13 E., ~0.3 mi northeast of Good Shepherd Church at the southeast side of the Eastland Shopping Center (Fig. 1, Site 3). At the base of the pit's highwall, ~15 ft of the lower shale unit (Fig. 3) crops out (Figs. 8 and 9). The interlaminated sequence of beds consists mostly of medium gray, very fine grained sandstones, siltstones, and shales. The unit is very thin bedded, wavy bedded, and micaceous, and has minor macerated plant debris on stratification surfaces. Oscillation ripples are common. The unit is extensively burrowed. Vertical burrows (diameters ≤1 in.) and horizontal burrows are abundant throughout. The unit has few fractures compared to the overlying sandstone unit (Fig. 9).

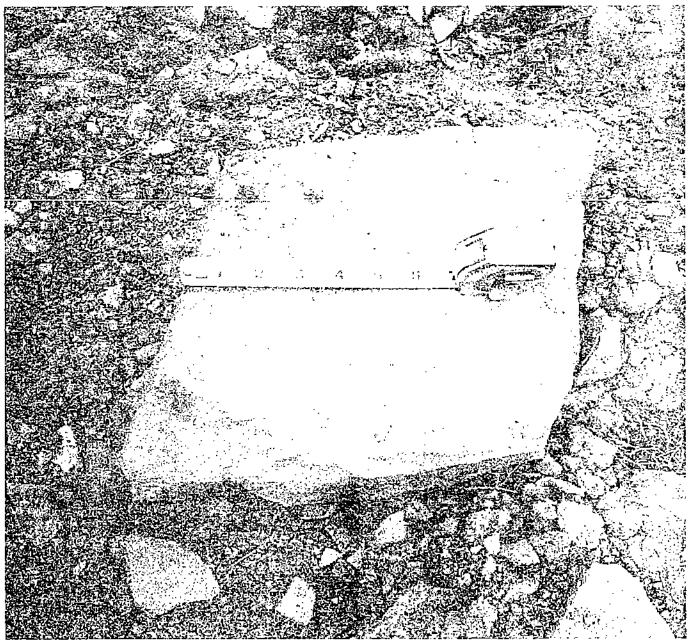

Figure 6. A block of Nellie Bly sandstone on church property (Fig. 1, Site 1), just west of Washington Boulevard. Note that the block's shape—produced by the three-directional fracture system in the area—is roughly that of a parallelogram.

Figure 7. Exposure of part of the upper unit of the Nellie Bly Formation in a road cut on the east side of Silver Lake Road, NW¼NW¼SW¼NW¼ sec. 20, T. 26 N., R. 13 E. (Fig. 1, Site 2). Note the thin- to medium-bedded, wavy-bedded character of the sandstone. Bailey Rascoe is pointing to fractures in the sandstone.

Figure 8. Exposure of the Nellie Bly Formation in the highwall of a shale pit in the SW¼SW¼NW¼SW¼ sec. 9, T. 26 N., R. 13 E. (Fig. 1, Site 3). Arrow marks the contact between the lower shale unit and the upper sandstone unit.

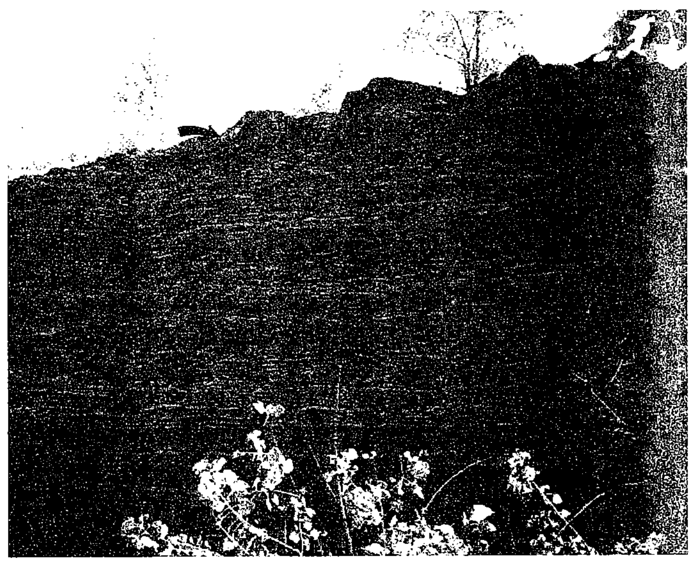

Figure 9. Close-up view of the lower sandy, silty shale unit of the Nellie Bly Formation at the same location shown in Figure 8. The arrow shows the contact with the overlying sandstone unit of the Nellie Bly. Note that the angular pattern of fractures in the sandstone does not extend downward into the shale.

About 12 ft of buff, iron-stained, very fine grained, shaly sandstone is exposed at the top of the highwall (Fig. 8). It is micaceous, has abundant black, macerated plant debris on bedding surfaces, and is ripple marked (oscillation ripples are common). Contact with the underlying shale unit is sharp and conformable where observed. The upper sandstone unit is fractured and appears to be equivalent to the beds exposed in the yard at the church (Fig. 1, Site 1).

Ground Water

Ground water occurs in the subsurface in the saturated zone, also called the ground-water zone (Jackson, 1997, p. 284) (Fig. 10). The top of this saturated zone is called the water table (Jackson, 1997, p. 709). The unsaturated zone above the water table is called the vadose zone Jackson, 1997, p. 695). The plane of the water table roughly follows the plane of the land surface. The water table shifts up and down with seasonal changes in rainfall; it is higher during a rainy season and lower during a dry season (Fig. 10). Where the water table cuts the land surface, seeps or springs occur (Fig. 10).

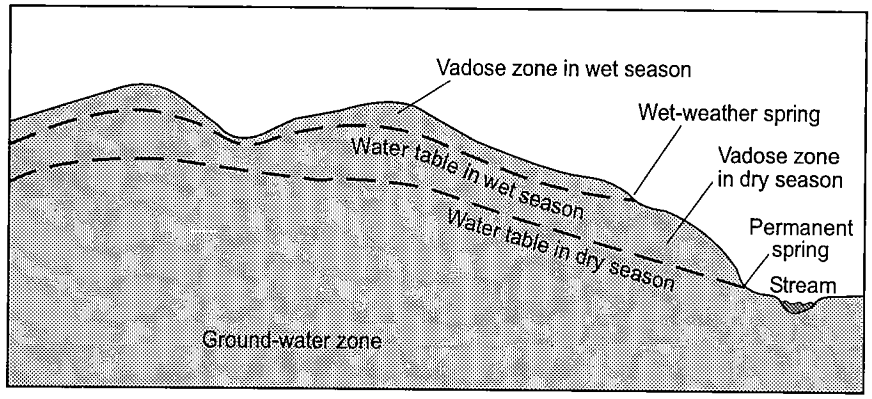

Figure 10. Diagram showing the varying positions of ground water relative to the surface and the fluctuations of the vadose zone with seasonal changes in rainfall.

Meteroic water is a common name for water (such as rain) of recent atmospheric origin (Jackson, 1997, p. 404). Factors that control the amount of meteoric water that penetrates into the ground are (1) the rate of rainfall, (2) the slope of the land surface, (3) the amount of vegetation, (4) the porosity of the surface rock, and (5) the amount of water already in the pores of the rock (Chernicoff and Venkatakrishnan, 1995, p. 420–421). Water penetrates downward by following joints and fissures in the rocks; from these openings, it works its way into cracks and pores. The penetrating water moves laterally when it encounters a satured zone, and may eventually emerge through springs and seeps (Fig. 10). How these factors relate to the area around Good Shepherd Church and the city water tanks is discussed in the "Conclusions" section of this paper.

Water circulates most rapidly in the vadose zone as it moves downward to the ground-water zone. Water moves very slowly, or not at all, in the ground-water zone. However, if rocks in the ground-water zone are highly fractured or fissured, as in the upper sandstone unit of the Nellie Bly Formation, water flows more rapidly. The rate of flow can be measured by putting an easily detected, harmless dye into the water at one location and watching for its appearance in nearby wells, springs, or seeps.

FINDINGS

It will be helpful to list the available information pertaining to the ground-water problems at Good Shepherd Church before any conclusions are drawn about a possible cause. (Mr. Bailey Rascoe, Jr., retired geologist and former church trustee, and Mr. Kenny Harris, church sexton, have monitored the water problem at the church over the past few seasons; they provided the information in points 6–13).

1. The church is built on fractured rocks (shaly sandstone) of the Nellie Bly Formation.
2. The church is on a hill ~75 ft above the flood plain of the Caney River, ~0.5 mi west.
3. The churchyard is well drained by nearby ravines, one <0.1 mi to the south and southwest of the church, and the other with its head just at the west side of the church (Fig. 1).
4. North of Good Shepherd Church property, just across Adams Boulevard, water tanks and associated water lines belonging to the City of Bartlesville are located on a hill at least 10 ft upslope.
5. Geologic mapping shows that the Nellie Bly Formation underlies the three city water tanks (Oakes, 1940), and a projection of strike and dip measurements made on outcrops of the Nellie Bly at the church site indicates that the city water tanks also are built on the fractured rocks (shaly sandstone) of the Nellie Bly Formation.
6. Water has seeped through floor tiles in the church basement. There are extensive areas of mildew in another room, close to an exterior wall on the northeast side of the church.
7. During July 1999, holes drilled for footings for playground equipment soon partially filled with water (Fig. 11). An analysis by the Bartlesville City Water Department of a water sample (collected by Mr. Rascoe) showed a chlorine content of 0.53 parts per million (ppm). Figure 12 shows the position of the playground equipment in relation to the city water tanks; Figure 13 shows the relationship of the playground equipment to the church. Note the slope of the churchyard toward the head of a ravine in back of the church and adjacent to the playground equipment. The ravine provides a natural drainageway for surface runoff during

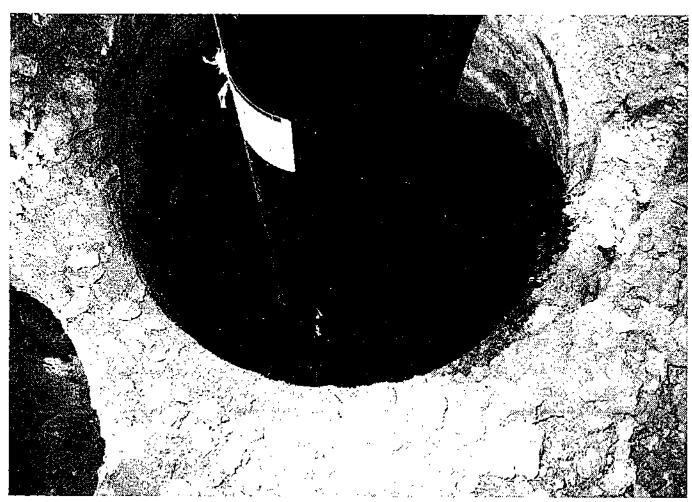

Figure 11. Water seeping into a hole drilled for footings for playground equipment being installed on church property, July 1999.

Figure 12. Position of the new playground equipment shown in Figure 11 in relation to the City of Bartlesville water tanks.

Figure 13. Position of the playground equipment shown in Figures 11 and 12 in relation to the Good Shepherd Church buildings.

times of rainfall, thus preventing water from standing in the churchyard.

8. Water seeped into a trench adjacent to the wall of a new addition on the north side of the church on May 31, 2000 (Fig. 14). An analysis of a water sample by the Bartlesville City Water Department showed a chlorine content of 1.0 ppm.

9. On May 31, 2000, Mr. Rascoe dug an 8-in.-deep hole just north of the church (Fig. 15A). Within 15 minutes, water had seeped into the hole (Fig. 15B). A water sample contained too many impurities to be analyzed properly. On the same day, Mr. Rascoe photographed a seep at the construction site on church propery (Fig. 16) and collected a water sample. This sample also was too contaminated for proper analysis. In Figure 16, note the exposure of the upper sandstone unit of the Nellie Bly Formation.

Figure 14. Water seeping into a small trench dug perpendicular to the wall of the church.

10. A gray shale was found near the bottom of an 18-in.-deep trench dug for foundation footings for an addition to the north side of the church in early 2000.

11. During the hot, dry summers of 1998 and 1999, the grass on the slope in the churchyard below the water tanks stayed lush and green without any irrigation by groundskeepers.

12. Even though little rain (<1.5 in.) was recorded at the church between June 24 and July 10, 2000, water seeped continuously into low parts of construction areas around the church.

13. The asphalt in the church parking lot (between the water tanks and the church) has deteriorated by cracking and crumbling several times since it was built in 1990 and has required repairs and resurfacing. (The parked car at the left in Figure 16 is in the parking lot.) According to Bob Steely, Oklahoma Department of Transportation (personal communication to the the author, July 2000), deterioration of the asphalt surface in the parking lot may indicate that the subgrade was excessively permeated with water. When water permeates the subgrade of an asphalt-surfaced area, it causes swelling of the subgrade material. Subsequent freeze-thaw action in the winter and drying out of the materials in the heat of the summer causes contraction and ex-

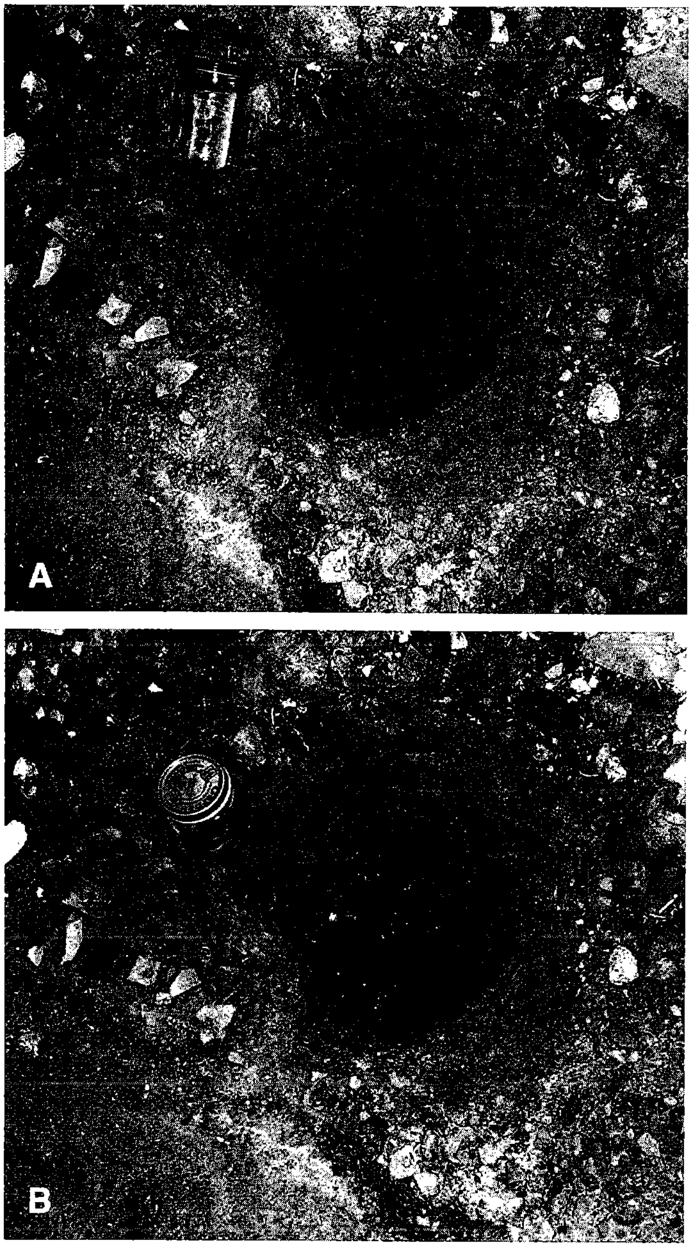

Figure 15. *A*—Small hand-dug hole (8 in. deep) in the construction area on church property, May 31, 2000. Pint jar for scale. *B*—Same hole, 15 minutes later. Note that water has seeped into the bottom of hole. Baby-food jar for scale.

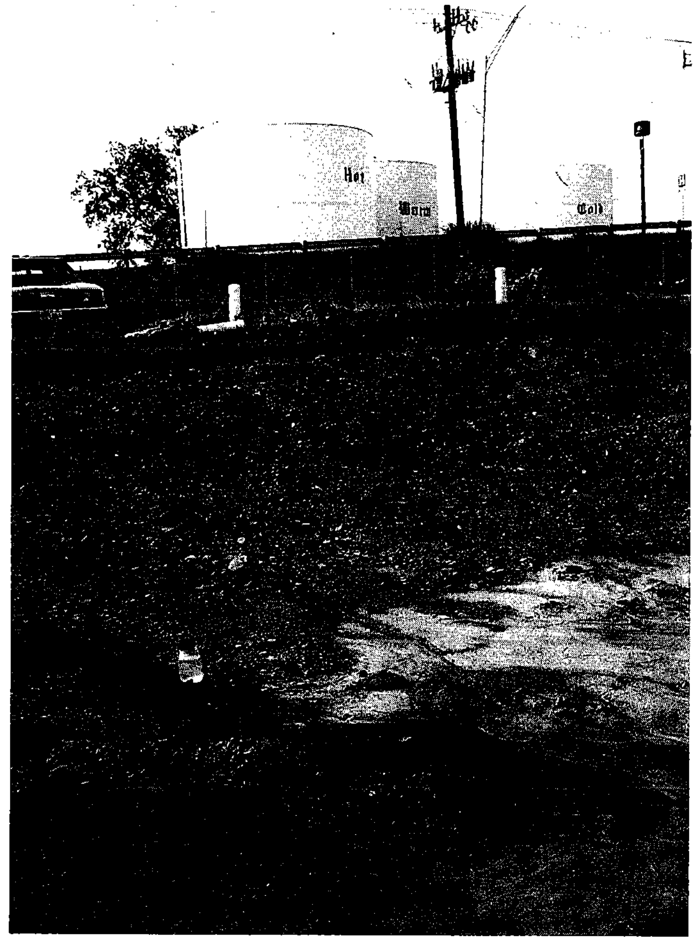

Figure 16. Water seep (dark area to left of jar) in the construction area on church property. Note the exposure of the Nellie Bly Formation between the grassy area and the jar.

pansion of the subgrade. Such fluctuations in the volulme of the subgrade material can cause the overlying asphalt to crack and crumble.

CONCLUSIONS

The findings listed above suggest that water is seeping continuously into the churchyard, and that the source of the water is leaks from the City of Bartlesville water tanks, or from water lines in their proximity (Fig. 17). There are no other sources of water in the immediate vicinity that are at a higher elevation than Good Shepherd Church. The possibility that water lines under the church might be leaking has been considered, and although this source has not been entirely eliminated, it is illogical that water would flow from a lower elevation, in an upslope direction (where, in the summer, the grass is lush and green) toward the city water tanks.

In particular, chlorine contents of 0.53 ppm and 1.0 ppm in ground-water samples suggest that the water has been treated. Chlorine does not occur naturally in ground water (Bryan Hapke, water treatment supervisor, personal communication, July 18, 2000). City of Bartlesville water is treated to bring the chlorine content to ~1.75 ppm; commonly, before the water reaches consumers, the chlorine content drops to 0.5–1.0 ppm as chlorine is lost during transport through city water lines (Staff at the City of Bartlesville water treatment plant, personal communication to Bailey Rasco, Jr., July 2000).

Normally, in dry seasons such as the summers of 1998 and 1999, the vadose zone would have expanded downward (Fig. 10), the water table in the churchyard would have dropped, and the lawn would not have remained green without irrigation. However, water leaking from the city water facilities would move downslope, continuously replenishing the ground, and, thus, eliminate most of the natural vadose zone in the churchyard. The water table in the churchyard

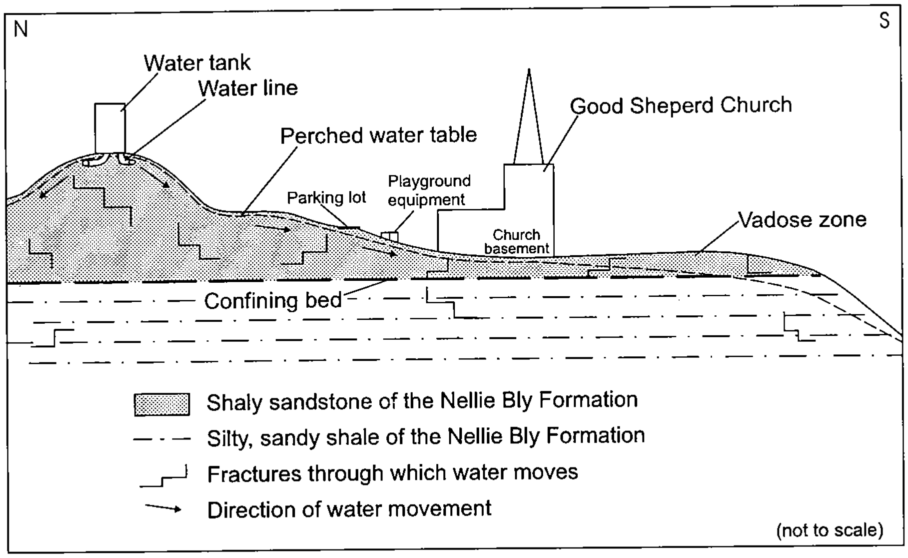

Figure 17. Schematic diagram showing a geologic interpretation of the rocks beneath Good Shepherd Church and the city water tanks. The diagram also shows how water possibly leaking from a city tank or water line would move through the fractured sandstones unit of the Nellie Bly Formation downslope toward the church.

would be high due to the pressure gradient (head) provided by the higher elevation of the water tanks. Because of the high water table, the grass would stay green without irrigation; in addition, the ground would become saturated quickly during heavy rains, and water would seep into the church.

The fractured sandstones of the Nellie Bly Formation are sufficiently permeable to provide a conduit for water. Water leaking from the city tanks or water lines would move downslope (and downdip, as the dip measurement on the north side of the church indicates) through the fractures, from the tank site toward the church. The presence of a gray shale beneath the fractured sandstones suggests that the contact between the lower and upper units of the Nellie Bly is not far below the ground surface. The lower shale unit acts as a confining bed (a body of relatively impermeable or distintinctly less permeable material stratigraphically adjacent to one or more aquifers [Jackson, 1997, p. 134]). It functions as the lower boundary for perched ground water (unconfined ground water separated from an underlying main body of ground water by an unsaturated zone [Jackson, 1997, p. 475]). Continuous replenishment by leakage of water from the city water facilities maintains a high perched water table. Therefore, during rains the ground quickly becomes saturated, and seeps develop in the church.

If leaks can be found in the city water facilities, the church's problems could be ameliorated by requesting the city to repair the leaks. Other solutions might involve installation of drainage ditches around the church that would divert excess water into the existing ravines. Tiling would serve the same purpose. Hopefully, the problems can be resolved with a minimum of expenditures.

ACKNOWLEDGMENTS

The documentation of the water problems at Good Shepherd Presbyterian Church by Bailey Rascoe, Jr., a retired geologist, and other church officials contributed significantly to the OGS study. All photographs except Figure 7 were taken by Mr. Rascoe. His personal assistance during the study was very helpful.

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A Remarkably Long Crinoid Column from the Nowata Shale (Marmaton Group, Upper Desmoinesian, Pennsylvanian), Tulsa, Oklahoma

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ABSTRACT.—A 3.3-m crinoid column is reported from the Nowata Shale (Marmaton Group, Upper Desmoinesian, Pennsylvanian) in Tulsa, Oklahoma. The column is assumed to be from a benthic crinoid; the specimen shows no evidence for an epiplanktonic habit, and epiplanktonic crinoids are not known from the Pennsylvanian. The characteristic maximum height of the column of benthic stalked crinoids is only ~1 m, thus, this specimen is remarkably tall. Specimens such as this Nowata Shale crinoid help to refine our understanding of epifaunal tiering in crinoid associations through the Phanerozoic.

INTRODUCTION

Crinoids (Phylum Echinodermata) are best known today from shallow-water, tropical forms called feather stars, which are especially common on coral reefs. Feather stars are unstalked crinoids composed principally of the arms and body, which include the feeding, digestive, reproductive, and other systems. Feather stars lack the column that is characteristic of many modern deep-water crinoids and most Paleozoic crinoids (Hess and others, 1999). Stalked crinoids attach to the sea floor (or to some object on the sea floor) and elevate the feeding apparatus (the arms) off the bottom up into higher velocity currents. Diverse crinoid associations display an ecological structure called epifaunal tiering (Bottjer and Ausich, 1986; Ausich and Bottjer, 1991), in which adults of different species are positioned to different elevations, thus minimizing feeding competition among these passive suspension feeders.

Characteristic maximum column heights for benthic stalked crinoids are ~1 m (Bottjer and Ausich, 1986; Ausich and Bottjer, 1991), so it is of special note that a benthic crinoid column of >3.0 m in length was discovered in Pennsylvanian strata in Tulsa, Oklahoma.

LOCATION AND STRATIGRAPHY

During the mid-1970s, highway construction in southeastern Tulsa, Oklahoma, temporarily exposed strata that have since become inaccessible. During this construction, Mr. Charles F. Cousins collected an intact crinoid column 3.3 m in length on the northern side of 31st Street approximately halfway between Memorial Drive and Sheridan Road. According to Richard Hedlund (retired Amoco geoscientist, personal communication, 1999), although the strata are no longer exposed, it is reasonable to assume that this crinoid was collected from the Nowata Shale (Marmaton Group, Upper Desmoinesian, Pennsylvanian) (see map 1 in Bennison, 1972). Shales of marine origin occur in the lower part of the Nowata Shale.

DESCRIPTION

The 3.3-m long Nowata Shale crinoid column is incomplete (Fig. 1). Both ends of the preserved column terminate on disarticulated facets, and the specimen has no appreciable taper from one end to the other (a diameter of 21.1 mm at the top of Fig. 1 compared to a diameter of 22.8 mm at the bottom). The cylindrical columnals are approximately 6 times wider than they are high (Fig. 2A). Each columnal is circular in outline, and the central perforation (the lumen) is pentalobate in shape (Fig. 2B). Each articular facet (Fig. 2B) contains a lumen, an areola (the depressed area surrounding the central perforation), and a crenularium (the outer region of ridges and grooves) that comprise the following percentages of the facet diameter: lumen, 29.4%; areola, 21.2%; and crenularium, 49.4%. The crenularium is composed of approximately 1.5 crenullae per millimeter, and adjacent columnals have a symplexial articulation of interlocking ridges and grooves. Cirri (short appendages) were present along the entire length of the column, as indicated on the specimen by cirri facet on the side of columnals. However, their distribution is not uniform. At some heights, they are common, at others they are rare. This remarkably long crinoid column is reposited in the Oklahoma Museum of Natural History, Norman (specimen number OU 11183).

DISCUSSION

The longest reported crinoid columns, which are >20 m long, are from the Jurassic epiplanktonic crinoid *Seirocrinus* (Seilacher and others, 1968; Ubaghs, 1978; Haude, 1980; Simms, 1986; Hess and others, 1999). These crinoids attached to floating logs and hung down into the upper portion of the water column. Attached, benthic crinoids had

shorter columns, varying in length from a few centimeters to a characteristic maximum of ~1 m. Reports of crinoid columns longer than ~1 m are rare and commonly unsubstantiated, hence the significance of the Nowata Shale crinoid column. The author has also measured an in situ Lower Mississippian crinoid column from the Muldraugh Formation of central Kentucky that is >2.1 m in length (Ausich and others, in press).

A crinoid fauna has not been described from the Nowata Shale, but large columnals have been collected from the Labette Shale, which may be a similar facies (Peter Holterhoff, Exxon geoscientist, personal communication, 2000). It is impossible to identify the species to which the crinoid column from the Nowata Shale belongs, because the column is incomplete. However, epiplanktonic crinoids, like *Seirocrinus*, are not known from the Pennsylvanian. Seilacher and others (1968), who describe morphologic distinctions between columns of *Seirocrinus* and those of the Mesozoic benthic crinoid *Encrinus*, note that various column parameters are reversed from top to bottom, which reflects the different life positions of the two species. The life position of the Nowata Shale crinoid column is not known, but there are no significant differences among the columnals along its length and, thus, no evidence for an epiplanktonic habit.

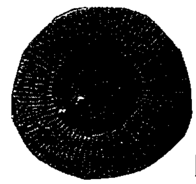
Both because epiplanktonic crinoids are not known from the Pennsylvanian and because the specimen shows no evidence for an epiplanktonic habit, it may be assumed that the Nowata Shale crinoid was benthic, with an extraordinarily long column. A benthic crinoid specimen, such as this one, with an exceedingly long column does not negate the general understanding that Paleozoic epifaunal crinoid communities had a characteristic maximum height of ~1 m; however, it does highlight the need to collect additional data in order to better establish the full range of epifaunal tiering in crinoid associations during the Phanerozoic.

ACKNOWLEDGMENTS

Charles F. Cousins collected, marked, and preserved this remarkable crinoid column, and without his careful work, this study would not have been possible. Also, it would have been impossible to identify the stratigraphic occurrence of this crinoid were it not for the help of Richard Hedlund and the late Patrick Sutherland. Peter Holterhoff and N. Gary Lane offered advice on this manuscript.

Figure 1 *(left)*. Very long (3.3 m) crinoid column from the Nowata Shale (Marmaton Group, Upper Desmoinesian, Pennsylvanian), Tulsa, Oklahoma (specimen number OU 11183, Oklahoma Museum of Natural History). Meter stick for scale.

A



B

Figure 2. *A*—Lateral view of a portion of the Nowata Shale crinoid column (OU 11183). Scale: ×1.0. *B*—Articular facet of a columnal from the Nowata Shale crinoid column (OU 11183). Scale: ×1.0.

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new OGS publications

CIRCULAR 101

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Platform Carbonates in the Southern Midcontinent, 1996 Symposium

Contained in this volume are papers dealing with the search for, and production of, oil and gas resources from platform carbonates of the southern Midcontinent. The research focuses on limestones and dolomites that were deposited in shallow-marine, platform (shelf) environments. Although these rocks already have produced great quantities of hydrocarbons, much remains in the ground to be explored for and produced in the future.

The 37 papers in this book concentrate on geology, depositional settings, diagenetic history, reservoir characterization, exploration, petroleum production, and enhanced oil recovery. The research originally was presented at a two-day workshop held in March 1996 in Oklahoma City, cosponsored by the OGS and the National Petroleum Technology Office of the U.S. Department of Energy. The meeting drew 275 representatives from industry, government, and academia. In describing the platform carbonates and their petroleum reservoirs, the researchers involved in this meeting increased our understanding of how the geologic history of an area can affect reservoir heterogeneity and the ability to efficiently recover hydrocarbons.

Among the reservoirs discussed are: Arbuckle Group, Viola Group, Hunton Group, Mississippi Chat, Boone Formation, Springer/Chester Groups, Union Valley Limestone, Wapanucka Formation, San Andres carbonates, Grayburg Formation, and a number of other Pennsylvanian and Permian carbonate reservoirs. As oil prices have increased recently, a greater interest in drilling in the State makes these papers a valuable resource for explorationists and operators in Oklahoma.

SPECIAL PUBLICATION 2000-2

• *by* Kurt Rottmann and others
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Hunton Play in Oklahoma (Including Northeast Texas Panhandle)

Based on an entirely new study, this volume presents information on petroleum occurrence, exploration, and development in rocks of the Hunton Group (Ordovician, Silurian, and Devonian) in Oklahoma and the Texas Panhandle. The material contained in this publication was covered in a workshop held in October 2000 by the OGS, in cooperation with the Petroleum Technology Transfer Council.

The report examines lithostratigraphic relationships of the individual formations and members that make up the Hunton Group, as well as Hunton relationships with the underlying Sylvan Shale and the overlying Woodford Shale. It includes a general overview of carbonate-reservoir basics, a history of Hunton oil and gas exploration and development, and aspects of Hunton stratigraphy such as facies, dolomitization, and karstification. The publication features field studies that represent three important Hunton parameters, including Woodford/Hunton stratigraphic relationships, Paleozoic structural trends influencing Hunton development and production, and a possible model for understanding and predicting dolomite trends. The report also discusses submersible-pump applications in Hunton reservoirs with high water cuts.

Kurt Rottmann is the principal author of this report, which is part of a continuing series that provides information and technical assistance to Oklahoma's oil and gas operators. Edward A. Beaumont, Robert A. Northcutt, Zuhair Al-Shaieb, Jim Puckette, Paul Blubaugh, and Pat Brown also contributed.

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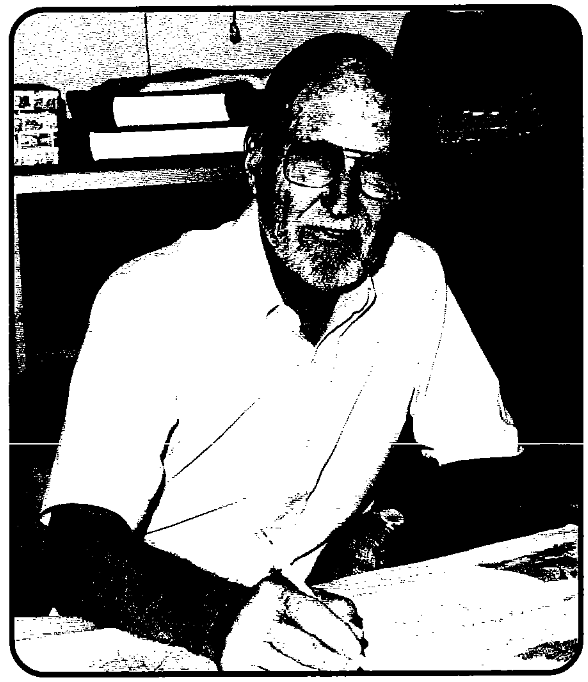
THOMAS W. AMSDEN



Tom Amsden
1915–2000

Thomas W. Amsden, an OGS geologist who was known worldwide for his writings in paleontology, died at his home in Norman on February 4. He was 85.

Tom came to the Oklahoma Geological Survey from Johns Hopkins University in 1955. He was employed "officially" by the OGS for 30 years, but he continued working part time after he retired in 1985, focusing on an evaluation of the Anadarko basin.

During his long career, Tom concentrated on the taxonomy, lithofacies, and biofacies of brachiopod faunas from Late Ordovician through Early Devonian strata in the southern Midcontinent region of the United States.

Tom received his bachelor's degree in geology in 1939 from Wichita State University in Kansas, then went on to earn his master's from the University of Iowa in 1941. By that time paleontology had hooked him. He started to pursue a doctorate at Yale University, but World War II interrupted his studies in 1943. He joined the Strategic Minerals Section of the U.S. Geological Survey, where his work focused on mapping and mineral investigations in a variety of terranes, including the slate belt of Vermont, the metasediments of the Great Smoky Mountains, and a fossiliferous Paleozoic sequence in the Little Dragoon Mountains of southern Arizona.

When the war ended, Tom returned to Yale to complete his Ph.D. studies. He then went on to teach paleontology at Johns Hopkins University for 8 years before coming to the OGS.

A prolific and internationally noted author of scores of reports and publications, Tom wrote several landmark volumes for the OGS on the geology and paleontology of the Hunton Group of rocks in the Arbuckle Mountains, the Anadarko basin, the Arkoma basin, among other Oklahoma locales. Beginning in 1960, Tom at various times received financial support from the National Science Foundation and the Oklahoma Geological Survey to collect and examine brachiopods from strata of Late Ordovician–Early Devonian age in Great Britain, Sweden, Norway, Poland, Czechoslovakia, Russia, China, and Australia. This enabled Tom to expand his detailed studies of Hunton strata to equivalent rock units in those parts of the world.

In 1989, Tom received the Paleontological Society Medal for contributions not only to paleontology but also to geology as a whole. At the award ceremony in St. Louis, J. Thomas Dutro, Jr., of the U.S. Geological Survey, noted, "Tom's monograph studies of the Anadarko and Arkoma basins, in 1975 and 1980, respectively, are models of sedimentary basin analysis. . . . Tom Amsden is a warm, generous, helpful scientist who has been both mentor and friend to younger paleontologists whom he has influenced during his long and fruitful career."

Tom Amsden's works certainly live on at the OGS. His research laid the foundation for ongoing studies into the Hunton Group and contributed significantly to the understanding of oil and gas accumulations in these strata. In their efforts to develop Hunton petroleum reservoirs, operators in Oklahoma have relied heavily on Tom's work, as reflected by the well-worn copies of his publications in their offices.

Tom Amsden was a great scientist, a dedicated employee of the Survey, and a close friend. He left large footprints that will not be erased by the passage of time.

—*Charles J. Mankin*

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.

Spillway Modification Resulting from a Hundred-Year Flood, Oologah Lake Area, Rogers County, Oklahoma

LEROY A. HEMISH, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019

In October 1986, small-scale channeled scablands and a 25-ft-deep gorge were carved in the Fort Scott Formation and upper Senora Formation (Pennsylvanian) when rapidly rising flood water was released from Oologah Lake's flood-control pool through the emergency spillway. More than 20 inches of rain had fallen during a period of five days upstream from the lake in the Verdigris River drainage basin of southern Kansas and northern Oklahoma. All grassy vegetation, trees, soil, and non-resistant bedrock were swept away by the turbulent water below the spillway floodgates, exposing the surface of the Blackjack Creek Limestone Member of the Fort Scott Formation. In the lower reaches of the 1.3-mi-long channel, rapids and a low waterfall formed as successive layers of the Blackjack Creek were plucked away, widening and extending back upstream a small gorge just above the confluence with the Verdigris River. Now, 13 years later, the erosional scar remains on the landscape—little changed.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-14.

Induced Thermoluminescence of Ozark Cherts: Paleothermometry and Implications for Migration of Ore-Forming Fluids

PAUL H. BENOIT and *D. GLEN AKRIDGE,* Dept. of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701

Chert is common in various stratigraphic units of the Oklahoma-Arkansas-Missouri Ouachita and Ozark mountains and was commonly used by native Americans of the region for tools. We have performed induced thermoluminescence (TL) and cathodoluminscence (CL) measurements on chert samples from a variety of localities. We find that CL intensity and features generally reflect the presence of carbonate inclusions and fossils. The induced TL of cherts exhibits a very broad range of properties. "Novaculite" from central Arkansas exhibits very high TL sensitivity with glow curves similar to quartz.

Ozark cherts, however, exhibit no induced TL, or exhibit quartz glow curves or a broad peak with very low TL sensitivity. We have found that the TL sensitivity of Ozark chert correlates with the degree of crystallinity, as indicated by bulk X-ray diffraction (Murata and Norman, 1976, Am. J. Sci. 276, 1120).

We suggest that the TL sensitivity and glow curve properties of chert reflect thermal alteration. Novaculites in central Arkansas experienced temperatures ~700°C (Keller et al., 1985, GSA Bull. 96, 1353). Heating experiments indicate that the TL sensitivity of Ozark cherts can be increased by heating at ~380°C for a few weeks. Most Ozark cherts exhibit little or no induced TL, suggesting that they have not experienced heating. However, we find a regional grouping of cherts in the NW Arkansas–SW Missouri area from the Reed Springs and adjacent formations that exhibit TL levels suggestive of thermal alteration. Cherts from above and below this portion of the stratigraphic column have not been altered. We suggest that this portion of the stratigraphic column may have been the conduit for the migration of hot saline fluids from the Arkoma basin during the Ouachita orogeny, which produced lead-zinc deposits in the Upper Mississippi Valley (e.g., Leach et al., 1984, GSA Abs. with Programs, 572).

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-3.

Compositional and Depositional Analysis of Atokan Sandstones (Middle Pennsylvanian), Southern Ozarks, Northern Arkansas

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The Atoka Formation (Middle Pennsylvanian), the youngest lithostratigraphic unit in the southern Ozarks, comprises nearly 3,000 feet (1,000 m) in capping the Boston Mountains Plateau as it passes into the Arkoma basin. There, the Atoka Formation becomes the major natural gas reservoir. The formation consists essentially of black shales punctuated by persistent quartz sandstones. Lower, middle, and upper members are recognized informally in the Arkoma basin by reference to specific sandstone reservoir units that are designated by industrial names. The Atokan members and their component reservoir sandstones can be correlated from the subsurface into a series of road cuts constructed for Interstate 540 in northwestern Arkansas. These road cuts expose an essentially complete section of the Atoka Formation and provide data on compositional changes in the sandstones that are not available from wells in the basin.

The Atokan Formation exposed in the road cuts comprises a single third-order Vail cycle with well-developed fourth-order tidal flat and tidally influenced depositional sequences. Lower member sandstones are mature quartz arenites reworking quartz from Morrowan and older sources. Many of these sandstones contain marine fossils and exhibit low-angle cross stratification probably representing upper shelf bar systems. Fully marine horizons become rare in the middle and upper member sandstones, which are typically churned through bioturbation and also ripple laminated. Compositionally, these sandstones are sublitharenites with contributions by metamorphic rock fragments (MRFs), angular quartz, plagioclase feldspar, muscovite and chert. MRFs dominate the non-quartz fraction in these rocks and their sudden occurrence appears to mark the lower-middle member contact regionally. Source of the MRFs remains uncertain, but they may be derived from the southern Appalachians as the proto-Atlantic closed northward.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-6.

Glauconitic(?) Pellets in the Insoluble Residue of the Boone Formation (Mississippian–Osagean), Northwestern Arkansas, and the Color of the Boone Regolith

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The Lower Mississippian Boone Formation is a thick, chert-bearing carbonate that forms the Springfield Plateau across the southern Ozarks. Pleistocene weathering in response to glacially driven climatic cycles produced an extensive regolith derived from the Boone Formation that mantles the plateau in the conterminous Arkansas-Oklahoma-Missouri region. The regolith is dominated by chert gravel with subordinate sand and clay fractions. It represents the insoluble component of the Boone Formation, but a contribution by eluvial material, including volcanic ash, is also present. Except for the white gravel-size component, the regolith has a distinctive, characteristic, bright to dark red color that has been assumed to represent iron oxide released by the weathering of pyrite in the Boone limestones. Examination of the insoluble residue of the Boone from samples taken in northwestern Arkansas reveals no pyrite in its upper portion. Both the sand and silt size insoluble fractions contain small, rod-shaped, composite pellets with polished surfaces that may be of fecal origin. The pellets are distinctly green and appear to be composed of glauconite. They comprise nearly half of the insoluble residue in some samples. Weathering of these pellets appears to be the likely source of the iron that colors the Boone regolith in the tri-state area of the southern midcontinent.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-7.

Lithostratigraphic Correlation of a Lateral Facies Change Within the Cane Hill Member (Pennsylvanian–Morrowan), Hale Formation of Northwest Arkansas

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Exposures in the Davidson area of northwestern Arkansas allow resolution of the nature of lithic changes near the base of the Cane Hill Member, Hale Formation. Morrowan deposition in northwestern Arkansas reflects a gently south-sloping platform dominated by noncalcareous sandstone and shale, alternating with calcareous units, in response to the fluctuation of sea level during the early Pennsylvanian period. Uplift of the Ozark Dome during the late Paleozoic encouraged stream incision that produced the Boston Mountains as erosional remnants of the Upper Mississippian and Lower Pennsylvanian sequence and exposed section for study.

The Cane Hill Member rests unconformably on the Pitkin Limestone (Upper Mississippian) and lies below the upper division of the Hale Formation, the Prairie Grove Member. The Cane Hill is a noncalcareous unit of thinly bedded siltstone, shale, and fine-grained sandstone. Westward into Oklahoma. the lithologic characteristics of the Cane Hill are quickly lost. The lithology of the basal Pennsylvanian section to the west is quartz-rich in the lower third portion, containing alternating carbonates and shales above. This is more consistent with the lithology of the Prairie Grove Member, although the interval has been referred to the Braggs Member, Sausbee Formation in Oklahoma.

A petrographic study using standard thin-section analysis of field samples, in the Davidson, Arkansas, area documents the lithologic changes for the section overlying the Pitkin Limestone. Suggesting that the area west of the type Cane Hill should be referred to the Prairie Grove as a duration of the Sausbee Formation.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-6–A-7.

Sequence Stratigraphy of the Middle Pennsylvanian Bartlesville Sandstone, Northeastern Oklahoma: A Case of an Underfilled Incised Valley

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The Middle Pennsylvanian Bartlesville sandstone, a prominent oil producer in Oklahoma over the past 90 yr, is evaluated in terms of its sequence stratigrahic architecture over its occurrence in northeastern Oklahoma. The Bartlesville sandstone is interpreted to be a fluvial-dominated incised-valley fill deposited mainly during rising stages of relative sea level.

The incised paleovalley, as defined by relief along the sub-Bartlesville type 1 sequence boundary, extends for over 140 mi (225 km) in a north-south direction through Oklahoma, and exhibits widths ranging from 6 mi (9.7 km) in the north to 60 mi (96.5 km) in the south. Thickness of the Bartlesvile sandstone ranges from 140–280 ft (42.7–85.3 m) within the paleovalley to less than 20 ft (6.1 m) outside the paleovalley. The lower Bartlesville sandstone represents the lowstand systems tract and consists of braided-fluvial deposits. The upper Bartlesville sandstone represents the transgressive systems tract and is dominated by meandering fluvial facies that transition down the paleovalley and stratigraphically upward to estuarine facies. The regionally extensive Inola Limestone Member marker, capping the Bartlsville sandstone, is equivalent to a condensed section representing maximum flooding. The Bartlesville sandstone is regarded as representing an underfilled incised valley when compared to the early sequence stratigraphy paradigm as both the lowstand and transgressive systems tracts are filled within the valley.

Original oil in place (OOIP) and reservoir quality are incorporated into the sequence stratigraphic architecture. The lowstand systems tract, which contains about two-thirds of the OOIP for many of the Bartlesville sandstone fields and reservoirs, has been the primary target of development over the past century and is nearly depleted. The transgressive systems tract, much more heterogeneous and less developed by comparison, offers the main potential for future development.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 84, p. 1185, August 2000.

Early Ordovician Facies Development on the Laurentian Craton: A Comparison Between Northwest Scotland and Southern Oklahoma

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During the Upper Cambrian and Lower Ordovician, a major transgression took place across the Laurentian craton which was centered astride the equator between latitudes 30° N and 30° S. "Oklahoma" was located between latitudes 8–10° S, at the western margin of the continent. This part of the craton was subject to a maritime equatorial climate; more specifically it was on the leeside of the continent with respect to southeast trade winds. "Northwest Scotland" was located at a similar latitude but on the eastern, windward, margin of the continent. This study will compare the petrology and petrography of sequences from the Kindblade Formation in the Upper Arbuckle Group (Oklahoma) to Sangomore and Balnakeil Formations of the Durness Group (Scotland).

The Arbuckle and Durness Groups were deposited on one of the largest carbonate platforms that has ever existed. There is an ongoing debate as to the reality and cause of the meter-scale cyclic motifs recognized by some authors in these sequences. By examining in detail two sequences of similar age but from geographically disparate areas, it is hoped to add a further dimension to this debate.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 82, p. 2159, November 1998.

The Cambrian–Ordovician New Mexico Aulacogen: Westward Continuation of Rifting of the Southern Margin of Laurentia

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Cambrian and Ordovician alkaline and carbonatitic igneous rocks throughout New Mexico and southern Colorado document magmatism that was probably related to lithospheric extension in a failed rift. Syenite and carbonatite intrusions consistently crosscut Proterozoic foliations and are nonconformably overlain by Lower Paleozoic sedimentary rocks. Suites with reliable age determinations include the Florida Mountains K-feldspar granite in southern New Mexico at 503±10 and 514+3 Ma (Evans and Clemons, 1988; Matheny et al., 1988), the Lemitar carbonatites in central New Mexico at 449±16 Ma, volcanic rock from a depth of about 2800 m in an oil test well near Tularosa at 541±21 Ma (Loring and Armstrong, 1980), and the Lobo Hill alkaline complex near Moriarty in central New Mexico at 518±5.7 Ma.

Syenites of this suite vary broadly in major and trace element composition and include quartz-normative and nepheline-normative samples. Most of the samples are metaluminous, but the suite ranges from peraluminous to peralkaline. Interpretation of major and trace element data is complicated by K-metasomatism in some locales, which mobilized K, Na, Rb, Sr, and Ba. However, metasomatized and non-metasomatized samples from each locale have similar concentrations of Y, Nb, and Zr, suggesting that immobile elements can be used to assess igneous processes. Concentrations of immobile trace elements are highly variable from site to site (i.e., 0–1400 ppm Zr, 0–400 ppm Nb, 0–650 ppm Y), reflecting the heterogeneity of the source region.

Recognition of the New Mexico aulacogen has significant implications. The region has previously been considered to be a simple passive margin because Cambrian syn-rift sediments are absent beneath the passive margin sequence. The identification of the New Mexico aulacogen extending into the continent from the western end of Laurentia's southern rifted margin demands a reassessment of this hypothesis. The New Mexico aulacogen also constrains the position and evolution of the rifted margin in the SW U.S. and Mexico. Magmatism occurred somewhat later in the New Mexico aulacogen than in the Southern Oklahoma Aulacogen or than syn-rift deposition in the Reelfoot rift, suggesting that extension proceeded from east to west during Cambrian time.

Reprinted as published in the Geological Society of America *1999 Abstracts with Programs*, v. 31, no. 7, p. A-475.

Geochemistry of Diabase Dikes, Eastern Arbuckle Mountains, Oklahoma

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A swarm of diabase dikes intrude the 1400–1365 Ma granitoids of the eastern Arbuckles. The dikes strike predominantly N60°W, parallel to the rifted margin of the southern Oklahoma aulacogen. Most diabases are related to Cambrian opening of that structure. An unknown but probably small number of the diabase dikes are near the age of the host granitoids. These, along with a suite of highly silicic northwest-trending microgranite porphyry dikes, record a Mesoproterozoic structural grain that influenced Paleozoic structure. Dikes from the two diabase suites cannot be easily distinguished, and the present geochemical database shows no compelling evidence of a bi-modal distribution of major or trace elements.

The diabases are olivine-hypersthene-normative to hypersthene-quartz normative and consist mainly of basalt with minor basaltic andesite and andesite. Their tholeiitic character is further indicated by low TiO_2 and P_2O_5 contents, low Nb/Y ratio, and variable Zr/P_2O_5 ratio. Mg numbers of 62-38 are indicative of derivative basaltic liquids which are consistent with the fine grained, equigranular mineral assemblage of plagioclase + augite + Fe-Ti oxides + olivine of most diabases. Normative compositions suggest that the diabases were emplaced at shallow depth along a plagioclase + olivine cotectic. Trace elements indicate that the diabases are similar to many continental flood basalts. They display a generally smooth convex-up pattern of incompatible elements when normalized to chondrites, essentially no depletion in the high field strength elements Nb and Ta, and moderate enrichment in light rare earth elements (LREE) (CeN/YbN = 2-6). The diabases are closely similar to E-MORB in Zr/Nb and La/Nb ratio and in LREE abundances, but contain an additional incompatible element crustal or sub-continental enrichment component as expressed, for example, in Th/Yb, Ta/Yb, and Ce/Yb ratio. They are comparable to the later sequences of Keweenawan flood basalts exposed at Lake Superior in the Midcontinent rift system.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-34.

Identifying Paleoproterozoic and Mesoproterozoic Crustal Domains Within the Southern Granite and Rhyolite Province Using Sm-Nd Isotopes

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In the Mesoproterozoic Southern Granite-Rhyolite province (SGRP) of the south-central midcontinent region, North America, most Precambrian basement rocks are restricted to the subsurface. The exceptions include exposures in the Arbuckle Mtns., SE Oklahoma. Felsic igneous rocks of the SGRP have published U-Pb ages of 1.40 to 1.34 Ga and Sm-Nd crustal residence ages (TDM) of 1.98 to 1.49 Ga. New SGRP subsurface samples were selected from drill core and cuttings from Kansas, Missouri, Oklahoma, Texas, and New Mexico. In addition, 11 outcrop samples were collected from the Arbuckle Mtns. All samples were analyzed for whole-rock Sm-Nd to determine their TDM and E(t) values (t = 1.37 Ga). E(t) within the SGRP range from –1.2 to +4.5, with corresponding TDM of 1.95 to 1.34 Ga. This suggests variable contamination by older crustal material that was added to a presumably juvenile magma (epsilon = +4.5). Domains underlain by Paleoproterozoic crust related to the southern margin of pre-1.55 Ga Laurentia are defined by older TDM (1.9–1.6 Ga) and generally lower E(t) (–1.2–2.0). Conversely, domains underlain by Mesoproterozoic crust have younger TDM (1.5–1.3 Ga), which are close to the age of crystallization, and higher E(t) (2.0–4.5). Using these data, the southern limit of Paleoproterozoic crust at 1.37 Ga extends from northwest Arkansas to the southeast corner of New Mexico.

Reprinted as published in the Geological Society of America *1999 Abstracts with Programs,* v. 31, no. 7, p. A-260.

Evaluation of Bed-Thickness Analysis Techniques as Applied to the Viola Springs Formation (Ordovician), Southern Oklahoma

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Bed thickness-frequency analysis has become one of the cornerstones of modern quantitative stratigraphy. Over the past five years various researchers have directed efforts towards the application of several analytical techniques including log-normal, Poisson, gamma, and exceedence probability analysis. In order to evaluate fully these techniques of analytical stratigraphy each has been applied to a single set of 859 bed thickness measurements from the Ordovician Viola Springs Formation of southern Oklahoma. Through the use of these multiple analytical procedures, the thickness data of the Viola Springs Formation are found to be well characterized by an exponential thickness-frequency distribution over the range of 30 to 300 millimeters. Beds thinner or thicker than this range deviate significantly from the negative exponential model trend. Poisson and gamma-style analysis of binned thickness-frequency data highlight deviations in thin beds while the exceedence probability technique seems to be more applicable for the discovery of deviations at larger stratigraphic thicknesses. As such, the method chosen for statistical analysis can strongly influence the quality and utility of stratigraphic interpretations drawn from the data. Perhaps only through the application of multiple analytical techniques can the nature of the bed thickness-frequency distribution present within a stratigraphic section be fully characterized.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs,* v. 30, no. 7, p. A-145.

Paired Granites: Further Evidence from the Wichita Mountains, Oklahoma

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Recent investigation has further refined the term "paired granites" to mean two or more distinct granite bodies that are contiguous, coeval, and consanguineous. Paired granites are individual bodies emplaced at the same crustal level, indicative of near simultaneous intrusion and magmatic interaction. They express subtle, relatable differences in mineral and chemical composition. Sheet granites emplaced in extensional terranes should be reviewed for possible paired granite relationships.

Two members of the Cambrian Wichita Granite Group, the Mount Scott Granite and the Rush Lake granite (formerly Unit B granite), are paired granites. These two granites result from related magmas intruding the same level of the crust at nearly the same time. Continuous contacts between these two units are observed: the westernmost exposures of the Rush Lake granite are found directly beneath the Mount Scott Granite, and eastern exposures have both granites at the same elevation, sharing near-vertical contacts. Contacts are gradational in places, sharp in others, and the sharp boundaries are commonly intimate, convoluted and swirled, indicating that both were simultaneously molten and not separated by much time. Both are alkali-feldspar granites that are porphyritic and contain variable amounts of granophyre, but there are significant differences: feldspar phenocrysts within the Mount Scott Granite are gray and ovoid, and exhibit rapakivi texture, while those within the Rush Lake granite are largely euhedral. The Mount Scott Granite also contains a higher percentage of hornblende and biotite, and it alone has magmatic plagioclase. These variations, and the corresponding differences in chemical composition, result from minor amounts of fractionation of the precursor Mount Scott Granite magma to produce the related Rush Lake granite. Major-element modeling indicates that the Rush Lake Granite is produced through crystallization of amphibole, plagioclase, and titanite from a magma of Mount Scott Granite composition. Trace element ratios, particularly Y/La and Ba/Sr, show variation with Rb consistent with the major-element model.

In this case, differentiation occurred at a crystal magma trap, when the parental magma ponded, crystallized and separated the fractionated phases, produced the magma that gave rise to the Rush Lake Granite. Differentiation may have been enhanced through ascent. The rise and intrusion of the Rush Lake granite provided a heated pathway for the slightly later rise of the Mount Scott Granite, resulting in the development of rapakivi texture within the latter.

Reprinted as published in the Geological Society of America *1998 Abstracts with Programs*, v. 30, no. 7, p. A-378.

Experimental Study of Titanite-Fluorite Equilibria in the A-Type Mount Scott Granite: Implications for Assessing F Contents of Felsic Magma

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Titanite and fluorite stability in melt were experimentally evaluated at 850°C, 200 MPa, $f(O_2)$ nearly equal to NNO (nickel-nickel oxide oxygen buffer) as functions of total F and H_2O content. Experiments employed the metaluminous Mount Scott Granite of the Wichita igneous province, Oklahoma. Over a large range of added H_2O (~1–7 wt%), melts containing <1 wt% F precipitated titanite without fluorite, whereas melts containing >1 wt% F precipitated fluorite without titanite. In addition, at high F (greater than or equal to 1.2 wt%) plagioclase and hornblende reacted to form biotite. Thus, an increase in F during crystallization may explain the observed higher modal abundance of plagioclase and hornblende in titanite-dominant samples vs. higher modal biotite in fluorite-dominant samples within the Mount Scott Granite pluton. Coexistence of magmatic titanite and fluorite in the Mount Scott Granite pluton implies Fm of ~1 wt% at the point in its crystallization history where these minerals coprecipitated. We suggest that the presence of primary fluorite within high-temperature, shallowly emplaced, moderate $f(O_2)$, subaluminous felsic rocks indicates high magmatic fluorine, whereas titanite without fluorite in such rocks indicates low initial fluorine.

Reprinted as published in *Geology*, v. 27, p. 951, October 1999.

The Quanah Granite: An Alkalic Member of the A-Type Wichita Granite Group from the Cambrian Southern Oklahoma Aulacogen Suite

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The Wichita Granite Group of SW Oklahoma is distinctive for its classic sheet form, A-Type granites. These are part of the upper veneer of the igneous section filling the Cambrian rift called the Southern Oklahoma Aulacogen. All of these granites were intruded relatively shallowly along a crustal magma trap formed where the Carlton Rhyolite rested on the eroded top of a gabbroic section. Most granites are metaluminous, except the Quanah, which has alkaline characteristics. The Quanah was early delimited from the Group because of topographic expression and mafic mineralogy of sodic amphiboles and pyroxenes, and in places, cm-sized zircons. The Quanah crops out as a 20- × 3-km body abutting the Glen Mountains Layered Complex, Mount Scott Granite, Cache Granite, and Carlton Rhyolite with field relations showing it is the youngest. Topographically, the Quanah has the largest bare-rock surfaces of any Wichita Granite, has low relief over its finer facies, and high relief over its coarser facies with well-recognizable tors.

The mafic mineralogy is the most unusual of Wichita Granites in that it has (1) facies reported to carry fayalite; (2) facies with coexisting calcic and sodic amphiboles where the sodic is classic riebeckite-arfvedsonite; (3) nearly pure acmite; (4) very annite-rich biotite; and (5) veins and "pegmatites" with these minerals, commonly accompanied by large, strongly metamictic zircons. The Quanah has less than 20 ppm Sr, about 500 ppm Zr, strong depletion in Eu(Eu/Eu* = 0.16), Ce(n)/Yb(n) = 3.0, showing less relative enrichment in LREE compared to other Wichita granites, all indicating this is one of the most evolved. Biotite chemistry (on 22O) reflects the evolved state: Ti >0.4; low Al(IV) <1.5; very high Fe(2+) >5.0, and F ~1.0.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-11.

Permeability Structure of a North Texas Permian Fluvial and Quaternary Terrace System Delimited by Saline Plumes

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Ground-water flow in a Permian bedrock–Quaternary terrace system is documented by the distribution of historically introduced brine. We used a multidisciplinary approach to describe the geometry of the saline plume and its relationship to host sediments, including airborne conductivity mapping, ground-based conductivity transects, time-domain electromagnetic soundings, core sampling, downhole conductivity logging, hydraulic-head mapping, and ground-water geochemical analyses.

The study area consists of a historic and still-active oil field on a basement uplift of the Wichita Uplift–Muenster Arch trend. Brine co-produced with oil and released to the subsurface from unlined pits more than 30 years ago moved into fluvial channel sandstones and conglomerates in weathered Permian bedrock. High permeability allowed saltwater to move laterally and down hydrologic gradient away from recharge points. Saltwater moved laterally from Permian bedrock uplands across the incised paleovalley wall and into Quaternary terrace deposits of the Red River. The saltwater plume shown by airborne conductivity mapping helps us to infer the geometry of buried channel deposits observed in core in the terrace. Heterogeneous permeability distribution in fluvial sands and gravels is reflected by differences between plume velocity calculated by using aquifer test results and those calculated by using observed plume length. Fine-grained overbank deposits form local barriers to vertical flow beneath the terrace and affect near-surface freshwater recharge and saltwater dilution.

Reprinted as published in the American Association of Petroleum Geologists *1999 Annual Convention Official Program*, v. 8, p. A63.

Seismic Modeling as a Tool for Interpreting Complex Subsurface Structures: An Example from the Wichita Mountain Front, Southern Oklahoma

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The Wichita Mountain Front is part of the linear trend in southern Oklahoma that extends from the Arbuckle Mountains in south-central Oklahoma through the Wichita Mountains to the buried Amarillo Mountains in the Texas Panhandle. Oil and gas well data document intense subsurface deformation along the Wichita Mountain Front, including steeply dipping to overturned bedding, faulted-folds, and granitic basement thrust over Paleozoic sedimentary rocks. Dipmeter data indicate 180° changes in dip direction. High resolution 2D seismic data are unable to clearly image the subsurface structures because of their complexity. Correct time and depth migrations of the seismic data are vital to accurate interpretations. Accurate interpretations are a prerequisite to improving exploration successes.

A synthetic seismic data set can be created with ray-tracing software by building a cross section using all available data, including well data, seismic and aeromagnetic data. X,Z coordinates and layer velocities are specified as are ray propagation parameters (such as attenuation, and shear or compressional waves). The resulting synthetic data set can be migrated with the exact velocity grid used to create the data. This allows us to verify the accuracy (or lack of accuracy) of the migration techniques for complex models. Finally, the synthetic data set and resulting migrations can be compared to an actual seismic line, allowing structures and seismic events to be verified or discounted. Several iterations of this process may be needed before correspondence is seen between the synthetic and real data sets. Insights from this modeling may provide information (such as improved acquisition and processing parameters) that will help produce enhanced seismic images of complex subsurface structures.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-8.

Carlton Rhyolite at Bally Mountain, Southwest Oklahoma: Evidence for Extensive A-Type Cambrian Felsic Flows in the Southern Oklahoma Aulacogen

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The A-type Carlton Rhyolite Group (CRG) makes up an important part of the magmatic assemblage formed during Cambrian rifting in the Southern Oklahoma aulacogen. Although widespread in the subsurface, the rhyolites crop out only in limited areas in the Wichita and Arbuckle Mountains. Bally Mountain in the Wichitas exposes perhaps the thickest and best preserved section of the CRG. Here we revise the classic description of this section by W. Ham and R. Denison (in Ham et al., 1964, Okla. Geol. Surv. Bull. 95). An apparently unbroken rhyolite sequence greater than 1 km thick underlies Bally Mountain and adjacent hills; an additional 700 m is poorly exposed to the west but may reflect structural duplication. The sequence consists of a series of lava flows up to 400 m thick showing variably developed flow banding; flow breccias or lithophysal zones occur in the upper parts of some units. Contacts between flows in places are defined by bedded tuffaceous deposits or channelized, nonwelded ignimbrite. Peperite consisting of angular to fluidal rhyolite clasts set within a disrupted tuff matrix occurs at the bases of some flows and formed when lava overrode thin interflow sequences of wet sediment. Bases and tops of flows exhibit quenched, originally glassy, perlitic margins that grade inward into nonvesicular, homogeneous, lithoidal rhyolite. The groundmass in flow interiors consists of feldspar microlites intergrown with acicular, spherulitic to randomly arranged quartz paramorphs after cristobalite or tridymite. Groundmass phases typically show a progressive size increase inwards, implying that even the thickest flows acted as single cooling units during primary crystallization or high-T devitrification. This simple textural zonation is unlike that typically shown by small rhyolite domes and suggests that the cooling units formed from laterally extensive, large-volume flows similar to those described from other A-type felsic provinces. Work is in progress to determine whether the Bally Mountain flows are true "flood rhyolites" or thoroughly homogenized rheomorphic ignimbrites.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-39.

Structural Geology of the Ouachita Mountains Reexamined

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The rocks exposed in the Ouachita Mountains of Arkansas and Oklahoma are part of a late Paleozoic thrust belt that traces a series of sharp bends mostly beneath the Mesozoic Gulf Coastal Plain from central Mississippi to southwestern Texas. The corners of nearly right-angle bends convex to the north and west (structural salients) are located in the Ouachita Mountains and Marathon uplift. The Ouachita allochthon consists of deep-water off-shelf facies that have been thrust onto passive-margin shelf facies along the margin of continental crust, clearly indicating thrust translation toward the craton. Palinspastic restorations of published cross sections constructed perpendicular to thrust-belt strike overlap within the concave bend of the Ouachita structural salient, implying a large apparent volume surplus if translation is assumed perpendicular to strike of the thrust belt.

A set of ten cross sections constructed roughly perpendicular to strike across the Ouachita Mountains is based on surface geology, several deep wells, and seismic profiles. The strike-perpendicular cross sections define the three-dimensional structural geometry, but a kinematically and volumetrically balanced reconstruction requires translation oblique to thrust-belt strike. Oblique translation is consistent with along-strike changes in structural style. For example, the central Benton and Broken Bow uplifts have an en echelon arrangement. In the western Ouachitas (north and west of the Broken Bow uplift), a wide belt of numerous, relatively coherent, imbricate thrust sheets contrasts with a more narrow belt of less coherent, smaller-scale structures to the east (north of the Benton

uplift). South-vergent delaminating backthrusts (passive-roof duplexes with disharmonically deformed roofs) bound the Ouachita frontal zone on the east along the Y-City fault and the southern boundary of the "Jackfork belt." The Benton uplift may be a deformed mega-scale triangle zone, the apex of which is along the Cossatot Mountains; and the Broken Bow uplift plunges eastward beneath imbricate thrust sheets south of the Benton uplift. The cross sections demonstrate several detachment horizons which have varying amounts of translation in different places. Kinematic restoration using translation oblique to the pre-orogenic continental margin achieves volume balance.

Reprinted as published in the Geological Society of America *1999 Abstracts with Programs*, v. 31, no. 7, p. A125.

Structural Geometry and Evolution of Thrust Faulting in the Frontal Ouachitas–Arkoma Basin Transition Zone, Southeastern Oklahoma

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A well-developed triangle zone is present between the Arkoma basin and frontal Ouachitas fold-thrust belt in the Wilburton gas field area. It is floored by the Lower Atokan Detachment (LAD) and flanked by the Choctaw fault to the south and the Carbon fault to the north. Below the triangle zone is a well-developed duplex structure, which was formed by hinterland dipping imbricate thrust faults splaying from a floor thrust and joining to the LAD in the Atoka Formation. The LAD continues northward and displaces the Red Oak sandstone before reaching a shallower depth and forming the Carbon fault as a north dipping backthrust below the San Bois syncline. East of the Wilburton field, the Carbon fault is not present in the surface. However, the fault can be observed in the seismic reflection profiles. It makes a lateral ramp to the east and becomes a blind backthrust. This geometry shortens the width of the triangle zone by about 50%. The Wilburton triangle zone, however, continues eastward as far east as the Wister Lake area. Below the triangle zone, the duplex structure is also present. The number of horses within the duplex structure lessens eastward as the north-south width of the triangle zone also decreases. When restored to their position at the time of the Spiro deposition by using the key-bed restoration method, the cross-sections indicate about 60% shortening in the Wilburton area but about 40% shortening in the Wister Lake area.

Southwest of Wilburton, the Choctaw fault forms a splay, which is named here as the Northern Choctaw fault. The Spiro is well exposed on the hanging wall of the Main Choctaw. The absence of the Spiro sandstone in the fault wedge between the Main Choctaw and Northern Choctaw faults indicates that the Northern Choctaw fault is formed after the deposition of the Spiro formation and is younger than the Main Choctaw fault. This suggests a break-forward thrusting between the two faults and implies that the imbricate thrusts on the hanging wall of the Main Choctaw fault were developed by a break-forward sequence of thrusting.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-5–A-6.

The Atokan Series Represents a Single Vail Sequence in Its Type Region, Arkoma Basin, Arkansas and Oklahoma

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Although controversy surrounds the duration of the Atokan Series, Pennsylvanian System, most recent absolute age assignments fall between 3 and 4 million years. A short duration for the Atokan Series is supported further by the recognition that it represents a single Vail sequence in its type region, although its thickness may reach as much as 6,000 feet in the central Arkoma basin. The Atoka Formation is bounded by well-documented type 1 erosional unconformities. The lower Atoka represents a transgressive systems tract succeeding Morrowan or older strata across the southern midcontinent. The shale-dominated middle Atoka Formation represents maximum flooding and highstand conditions, while the upper Atoka highstand systems tracts are followed by regression and basin-fill as the subsidence rate of the Arkoma basin increased in response to Ouachita tectonics. The Atoka is succeeded by the Hartshorne Sandstone of Desmoinesian age (Middle Pennsylvanian).

At least 15 fourth-order cycles that reflect orbital forcing (eccentricity and precession) can be recognized in the shale-sandstone alternations that characterize the entire Atokan shelf succession. Where seen in outcrop, these shales and sandstones exhibit remarkably similar lithologies that suggest stable upper shelf and perhaps estuary conditions, in contrast to deltaic and deeper water settings along the basin axis to the south. The shelf shales are typically black, but have low TOC, lack marine fossils, and represent paralic palynofacies. The sandstones are composed of very fine to fine quartz sand that is highly bioturbated with ripple bed forms and may contain intervals with flaser and lenticular bedding. Some lower Atokan sandstones contain marine fossils, but they have not been found from higher units. Individual sandstone intervals represent tidal or tidally influenced settings that can be traced continuously for miles in outcrop. Sandstone development reflects sediment supply and interrupts what is otherwise a shale sequence deposited on a mud-dominated upper shelf that forms most of the present outcrop belt. The similarity of the lithologic succession that characterizes Atokan deposition in this shallow shelf setting further supports the interpretation that it represents a single Vail sequence and not much time on an absolute basis.

Reprinted as published in the Geological Society of America *1999 Abstracts with Programs*, v. 31, no. 7, p. A-62.

Sedimentation Patterns along Southern Margin of North America from Combined Neodymium/Graptolite Stratigraphy of Ordovician Shales, Ouachita and Southern Appalachian Mountains

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A new integrated approach combining neodymium whole rock analysis with high-resolution graptolite biostratigraphy has been applied to Ordovician shales along the southern margin of North America as a correlation tool for investigating changes in sediment sources across a broad region during this period. The data clearly reveal time-diachronous shifts in sediment sources between the Appalachian and Ouachita regions, beginning with onset of the Blountian phase of the Taconic orogeny in the southern Appalachian Mountains. The overall regional shift, recorded in neodymium isotopes, shows a westward progression beginning in the Appalachians with deposition of Blountian clastics at about 480 Ma, and migrating westward into the Ouachita region by about 460 Ma. This coincides in time with an Ordovician sea-level highstand and the emergence of the Appalachian orogenic belt as the primary source of sediment for the North American continent. A well sampled section in the westernmost part of the Ouachita fold belt, at Black Knob Ridge, Oklahoma, shows fluctuating sources over a several million year period before a primarily Appalachian-derived isotopic signature becomes locked in by about 455 Ma. At the Black Knob Ridge section, we see that, superimposed on the general westward shift in sediment sources with time, there are more complicated localized effects that reflect multiple sources of sediment persisting for some time after the Appalachian-derived flux first arrives. By 450 Ma, the entire southern margin of North America (and the seafloor south of it) was being supplied apparently by sediment from a single, homogeneous source, the Appalachian orogen.

Reprinted as published in the Geological Society of America *1999 Abstracts with Programs*, v. 31, no. 7, p. A373–A374.

Nature and Regional Significance of Unconformities Associated with the Middle Ordovician Hagan K-Bentonite Complex in the North American Midcontinent

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Stratal patterns of the Middle Ordovician Hagan K-bentonite complex and associated rocks show that the Black River–Trenton unconformity in the North American midcontinent formed through the complex interplay of eustasy, sediment accumulation rates, siliciclastic influx, bathymetry, seawater chemistry, and perhaps local tectonic uplift. The unconformity is diachronous and is an amalgamated surface that resulted from local late Turinian lowstand exposure followed by regional early Chatfieldian transgressive drowning and sediment starvation. The duration of the unconformity is greatest in southern Wisconsin, northern Illinois, and northern Indiana, where the Deicke and Millbrig K-bentonite beds converge at the unconformity. On the basis of published isotopic ages for the Deicke and Millbrig beds, it is possible that in these regions erosion and nondeposition spanned a period of as much as 3.2 m.y.

Two broad coeval depositional settings are recognized within the North American midcontinent during early Chatfieldian time. (1) An inner shelf, subtidal facies of fossiliferous shale (Spechts Ferry Shale Member and Ion Shale Member of the Decorah Formation) and argillaceous lime mudstone and skeletal wackestone (Guttenberg and Kings Lake Limestone Members) extended from the Canadian shield and Transcontinental arch southeastward through Minnesota, Wisconsin, Iowa, and Missouri. (2) A seaward, relatively deep subtidal, sediment-starved, middle shelf extended eastward from the Mississippi Valley region to the Taconian foreland basins in the central and southern Appalachians and southward through the pericratonic Arkoma and Black Warrior basins. In the inner shelf region, the Black River–Trenton unconformity is a composite of at least two prominent hardground omission surfaces, one at the top of the Castlewood and Carimona Limestone Members and the other at the top of the Guttenberg and Kings Lake Limestone Members, both merging to a single surface in the middle shelf region. The inner and middle shelves redeveloped later in approximately the same regions during Devonian and Mississippian time.

Reprinted as published in the Geological Society of America *Bulletin*, v. 110, p. 723, June 1998.

The Potato Hills Revisited: Exploration Potential Aided by Mesoscale Structural Studies

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The Potato Hills are a roughly elliptical exposure of Ordovician to Mississippian rocks in the Central Ouachita Mountains of southeastern Oklahoma. The Potato Hills have been variously interpreted, both as a structural window through an upper folded thrust sheet and as pop-up block between oppositely vergent thrusts (i.e, forethrust and backthrust). Ongoing exploration interests in the Ouachita Mountains, and particularly deeper structures in the Potato Hills, suggests that a better understanding of the complex deformation history is needed. This study focuses on a detailed mesoscale analysis and 1:24,000 scale geologic mapping of the Potato Hills with the goal of clarifying the structural interpretation and integrating this into the overall tectonic development of the Ouachitas.

Preliminary field mapping confirms the presence of numerous upright to steeply inclined, subhorizontal, tight to isoclinal folds that span a range of scales (from a few meters to hundreds of meters). Many folds display straight limbs and small angular hinges (kink folds) that are parasitic with respect to larger folds. The structural fabric is nearly east-west (strike varies from 075° to 080°), although local variations exist, particularly near the western edge of the Potato Hills where the structures plunge more steeply to the west. Although the overall structural interpretation (window vs. pop-up) is still unclear, the strongly plunging folds near the western edge of the Potato Hills, lends support to the window interpretation.

Reprinted as published in the American Association of Petroleum Geologists *2000 Annual Convention Official Program, v. 9, p. A99.*

Structural Interpretation and Exploration Potential of the Potato Hills: Surface Mapping Aided by New Well Data

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The Potato Hills, a roughly elliptical exposure of Ordovician to Mississippian rocks in the Central Ouachita Mountains of southeastern Oklahoma, have been variously interpreted, both as a structural window through an upper folded thrust sheet and as pop-up block between oppositely vergent thrusts (i.e., forethrust and backthrust). Ongoing hydrocarbon exploration has led to questions about the deeper structures beneath the surface exposures, and suggests that further study of the complex deformation history in the Potato Hills and its relationship to Ouachita tectonics is warranted.

Field mapping in the western Potato Hills at a scale of 1:24,000 confirms the presence of upright to steeply inclined, subhorizontal, tight to isoclinal folds that strike nearly east-west (075° to 080°) and plunge toward the west. Many mesoscale folds exhibit straight limbs and angular hinges that are consistent with larger (map-scale) folds. Although the overall structural interpretation (window vs. pop-up) is still unclear, the strongly plunging folds near the western edge of the Potato Hills and the shallow subsurface structure observed in exploration wells, lends support to the window interpretation.

A difficulty in the Potato Hills is distinguishing the Early Ordovician Womble shale that underlies the Big Fork Chert (a ridge-former) from the Late Ordovician Polk Creek shale that overlies the Big Fork. Similar lithology and gradational contacts with the Big Fork chert make field identification difficult. New and previously unavailable well data provides a possible means for identifying these units in the field. The well logs clearly show a significant difference in the character of the gamma ray profiles. By combining standard mapping techniques with a portable gamma ray detector, it is possible to distinguish between these units, thereby facilitating the surface interpretation.

Reprinted as published in the Geological Society of America *2000 Abstracts with Programs*, v. 32, no. 3, p. A-36.

Beyond Whole-Rock Geochemistry of Shales: The Importance of Assessing Mineralogic Controls for Revealing Tectonic Discriminants of Multiple Sediment Sources for the Ouachita Mountain Flysch Deposits

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The origin of the Ouachita Mountains has been the focus of significant debate for decades. Considerable confusion also exists concerning the provenance of the Carboniferous flysch of the Ouachitas.

Trace-element geochemistry of shales from the Stanley Group delineates the provenance of the sediments and provides clues to the plate tectonic evolution of the southern continental margin during Mississippian time. Th/Sc and Cr/Th ratios indicate a cratonic source for the majority of the Stanley Group sedimentary rocks. However, in several samples, low Th/Sc ratios and high Cr/Th ratios suggest a contribution from a mafic source. Using element ratio diagrams, all of the samples plot along a curve consistent with a two-component mixing model, consisting of a dominant felsic and a subordinate mafic source.

The heavy-mineral fraction of these shales sequester many of the trace elements used in whole-rock studies. Monazite is ubiquitous in trace amounts and is the probable site for much of the rare earth elements in the whole rock. The occurrence of monazite almost exclusively in sialic igneous rocks implies that Sm/Nd isotopic signatures are not sensitive to sediment input from more mafic sources. In some Stanley shale samples, chromite and Mn oxides were identified and positively identify an oceanic crustal component as a source of Stanley Group sediment. The results of this study emphasize the importance of determining the mineralogic sites of trace elements, and realization of specific mineralogic contributions from mafic or sialic tectonic provenances.

Reprinted as published in the Geological Society of America *Bulletin*, v. 112, p. 1012, July 2000.

Oxygen Isotope Systematics Between Veins and Host Rocks: Implications for Fluid Flow Regimes During Deformation

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Over 75 new determinations of oxygen isotopic compositions of veins and their coexisting host rocks from the Appalachians (Valley and Ridge Province) and Saih Hatat (Oman) complement data sets from the Lachlan fold belt (SE Australia), the Otago Schist (New Zealand), and the Ouachita Mountains. Plots of $\delta^{18}O$ values of host rocks (vertical axis) against coexisting veins (horizontal axis) are diagnostic of the style of fluid rock interaction and the scale of exchange. Vertical arrays transform to arrays smeared along the slope 1 line as the style of deformation changes from folding accompanied by cleavage development to strongly deformed rocks with transposition layering and multiple foliations. Veins from the former regions commonly exhibit a much narrower range of $\delta^{18}O$ values than the coexisting rocks (e.g., the Lachlan, Appalachia, Ouachitas). The distribution of $\delta^{18}O$ values in veins is uniform (± per mil) over large distances (>> km^3) whereas coexisting host rocks preserve several per mil ^{18}O heterogeneities. In more strongly deformed rocks, veins exhibit the same ^{18}O heterogeneity as the local host rocks with buffering of vein assemblage ^{18}O on a much smaller scale (e.g., Otago Schist). Because quartz concentrates ^{18}O and most host rocks are not pure quartz, quartz veins tend to be enriched relative to the volume of solid rock with which the fluid interacts. Fractionations between veins and bulk rocks tend to be positive and decrease as the host rocks become more quartz rich. Modeling of this type of fluid rock interaction indicates that this outcome is obtained when the fluid phase averages inputs from multiple sources of ^{18}O and the fluid flux rate is low relative to the reaction rate with the rocks.

Reprinted as published in the Geological Society of America *1999 Abstracts with Programs*, v. 31, no. 7, p. A-95.