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Vol. 64, Nos. 1–4 2004

Featuring:
- *A glyptodont from northern Oklahoma*
- *Status of Oklahoma's STATEMAP Program*
- *Oklahoma earthquakes, 2003*

on the cover

Glyptodonts—Car-Sized Armadillos

Glyptodonts were relatives of the armadillos that originated in South America in the Eocene and diversified there through much of the Cenozoic. They left their home continent for the first time in the late Pliocene, around 2.5 million years ago, when they migrated to North America after the Panama land bridge became dry land. One of these heavily armored mammals, *Glyptotherium arizonae*, reached a length of about 3 meters and probably weighed at least a ton. Glyptodonts went extinct in the late Pleistocene.

Pieces of the armored shell of a glyptodont were recently found in Alfalfa County, Oklahoma, and constitute the northernmost known occurrence of these animals. The species, *G. arizonae*, is one that indicates a time range between late Pliocene to early Pleistocene for the deposit in which it occurred. Vertebrate-fossil-bearing deposits of that age are rare in Oklahoma. (See the feature article "A Glyptodont [Mammalia: Xenarthra] from Northern Oklahoma" on p. 4 of this issue.)

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Cover drawing by Brian Ford

I sincerely regret having to reduce the *Oklahoma Geology Notes* to a single issue for 2004. Problems (some unforeseen and some unnecessary) arose during the year that prevented the orderly development of the newsletter. Those matters are being addressed and the *Notes* will be prepared and distributed on time beginning with the new fiscal year (July 1).

The normal price for an annual subscription will be reduced for the 2004 calendar year to $2.00.

Please accept my sincere apology for this embarrassing situation, and thank you for bearing with us on this matter.

Sincerely,
Charles J. Mankin
Director

Oklahoma Geological Survey

CHARLES J. MANKIN
Director

OKLAHOMA GEOLOGY NOTES

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EDITORIAL MATTER: Short articles on aspects of Oklahoma geology are welcome from contributors; please direct questions or requests for general guidelines to the *NOTES* managing editor at the address above.

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OKLAHOMA GEOLOGY notes

Vol. 64, Nos. 1–4 **2004**

A Glyptodont (Mammalia: Xenarthra) from Northern Oklahoma

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ABSTRACT.—Fossil occurrences of glyptodonts in the United States are largely restricted to the southern tier of states from Arizona to South Carolina, with most occurring in the moist lowlands of the Gulf of Mexico Coastal Plain. A part of the carapace of the glyptodont *Glyptotherium arizonae* is reported from a locality in northern Oklahoma about 260 km north of the only previous state record; it is the northernmost record of a glyptodont. The occurrence probably reflects a late Pliocene–early Pleistocene (late Blancan–early Irvingtonian land-mammal age) distal expansion onto the southern Great Plains of the habitat characteristic of the lowland tropical–subtropical Gulf of Mexico Coastal Plain in which temperatures were suitable for these cold-sensitive xenarthrans.

INTRODUCTION

North American glyptodonts were heavy-bodied, extremely graviportal xenarthrans often likened to an armadillo the size of a small automobile. They lived in marshy lowlands and near permanent bodies of water. Glyptodonts are members of a South American lineage of mammals that entered North America via the Isthmus of Panama when that isthmus became a dry-land connection between the two continents in the Pliocene. They and many other terrestrial mammalian (and other vertebrate) taxa entered North America during a biogeographic event known as the Great American Biotic Interchange or simply the Great American Interchange. The range of one species, *Glyptotherium arizonae*, included the southwestern United States and Gulf of Mexico Coast, from southern Arizona to Florida (Fig. 1). I report herein the new discovery of fossils of a glyptodont in northern Oklahoma, the first to be found in the state in 75 years. (Abbreviations used in the text: Ma, mega-annum or millions of years before the present; OMNH, Sam Noble Oklahoma Museum of Natural History.)

The glyptodont specimen documented in this paper, OMNH 72109, was found by Steve Schanbacher in early September 2002, near a dry tributary of West Clay Creek and the small town of Carmen, about 15 km S of Cherokee, Alfalfa County, Oklahoma, at about 385 m elevation (OMNH locality V1342). The geology of the locality is difficult to interpret because of little topographic relief, few areal exposures of strata, and the occurrence of the fossils in a shallow gully between the ends of two erosion-control berms within a cultivated field (Fig. 2). The plow layer in the cultivated field is a mixture of material from the eroded soil surface and the subsoil from which it was derived. Soils of the area are mapped as the Quinlan–Woodward complex, which is said to have formed under a cover of tall, mid, and short grasses in material weathered from silty sandstone (Williams and Grover, 1975) of the underlying bedrock. The bedrock is mapped as the Cedar Hills Sandstone of the El Reno Group, of Permian age. The Cedar Hills consists of orange-brown to greenish-gray fine-grained sandstone and interbedded layers of siltstone, with some red-brown shale; its thickness is typically about 55 m (Morton and Fay, 1980).

The glyptodont fossil occurred in a massive fine silt—pale reddish brown, and slightly cemented by carbonate—between the Permian bedrock and the soil. Although not well exposed in the cultivated field or adjacent dry streambed, the same silt in which the glyptodont occurred is exposed in an erosional bank on the north face of a small bluff about 600 m WSW of the glyptodont site (Fig. 3). There the silt

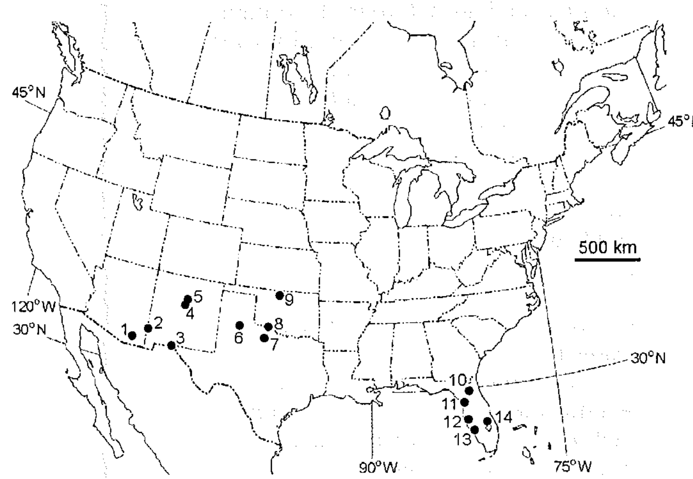

Figure 1. Localities where fossils of *Glyptotherium arizonae* have been discovered. Numbers indicate the following: 1—Curtis Ranch and California Wash, Arizona; 2—Virden local fauna, New Mexico; 3—Mesilla Basin Faunas B and C, New Mexico; 4—Tijeras Arroyo Upper, New Mexico; 5—Western Mobile gravel pit, New Mexico; 6—Rock Creek local fauna, Texas; 7—Gilliland local fauna, Texas; 8—Holloman gravel pit, Oklahoma; 9—Carmen, Oklahoma; 10—Santa Fe River sites (SF1, SF4A, and SF8A), Florida; 11—Inglis 1A, Florida; 12—Leisey Shell Pit 1A, Florida; 13—Reynolds Point, Florida; 14—Kissimmee River, Florida.

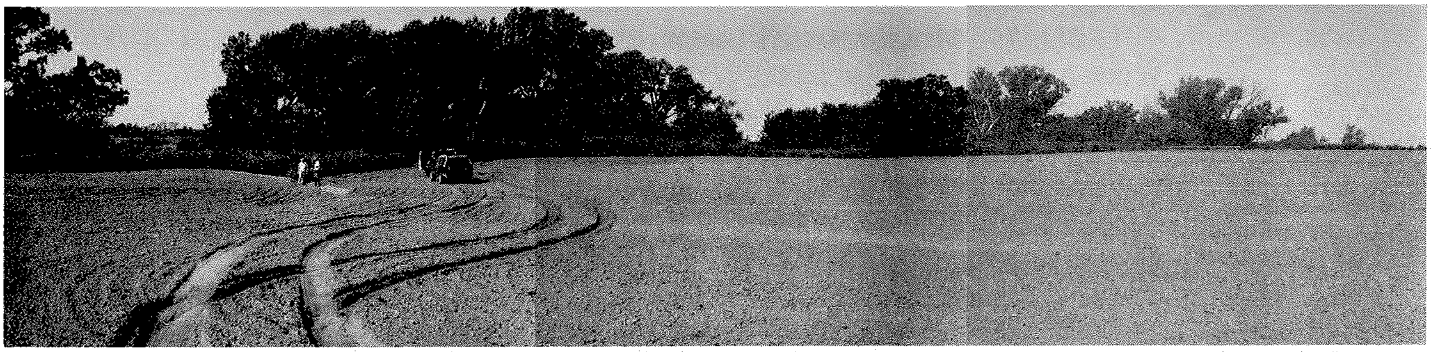

Figure 2. Panorama of the Carmen glyptodont fossil locality (OMNH loc. V1342) in a recently tilled field adjacent to a wooded dry tributary of West Clay Creek. People are standing at the location of the glyptodont osteoderms. Photos bv Donald G. Wvckoff.

forms a 1.3-m-thick unit unconformably accumulated on a flat surface of dark red Permian shale (mapped as Cedar Hills Sandstone, but here it actually resembles the Cloud Chief Formation). The underlying Permian shale is capable of producing the Plio-Pleistocene silt, although the Ogallala Formation—which once probably covered the Permian shale in this area—may also have provided an additional source for the silt. The Plio-Pleistocene silt shows no internal structure and appears to be wind-deposited (i.e., loess); it contains zones of caliche pebbles, scattered root casts, and occasional krotovinas (infilled animal burrows) having some carbonate deposition within them. Atop the silt is the modern soil horizon, 40 cm thick and dark brown in color. A tabular caliche is formed at the top of the silt layer where ground water percolating through the soil encounters the silt. The same massive silt layer is exposed in road cuts adjacent to section-line roads to the W, NW, N, and NE of the glyptodont site. As in the erosional profile described above, the silt preserving the glyptodont also contained zones of small caliche nodules as pebbles (Fig. 4).

The modern drainage system of West Clay Creek flows northward into the Great Salt Plain playa on the Salt Fork of the Arkansas River. No Quaternary deposits are presently mapped within 7 km of the fossil site in this drainage; only Permian formations including the Cedar Hills Sandstone, the overlying Flowerpot Shale, and the underlying Bison Formation are known nearby (Morton and Fay, 1980). The nearest mapped Quaternary deposits are terrace deposits 7–10 km north of the fossil site, nearer the Salt Fork. Some 25–30 km to the southwest of the fossil locality, the Cimarron River flows eastward. Broad Quaternary terrace deposits are mapped along the north side of the Cimarron River and its tributary Eagle Chief Creek to within 5 km of the glyptodont site, but these terrace deposits are on the other side of the low topographic divide separating the drainage basins of the Salt Fork of Arkansas River and the Cimarron River. The

Figure 3. This erosional profile, ca. 600 m WNW of glyptodont site (in the SW¼NW¼NW¼ sec. 29, T. 25 N., R. 11 W.), shows the areal stratigraphy.

TABLE 1.—MEASUREMENTS (IN MILLIMETERS) of Osteoderms from a Part of the Carapace plus Disarticulated Osteoderms of *Glyptotherium arizonae* (OMNH 72109) from Carmen, Oklahoma

Osteoderm position on carapace	N	Greatest diameter	Least diameter	Diameter of central figure	Number of peripheral figures
marginal (first) row	5	48.0 (39–54)	42.8 (35–48)	—	—
second row	6	41.3 (36–47)	43.7 (35–53)	37.5 (32–41)	8.0 (6–10)
interior osteoderms	75	42.0 (35–47)	38.9 (29–48)	22.3 (18–29)	8.4 (4–10)
disarticulated interior osteoderms	4	45.7 (43–48)	35.0 (30–40)	19.5 (18–21)	7.3 (7–8)

Note: Measurements are given as means, with the observed range in parentheses.

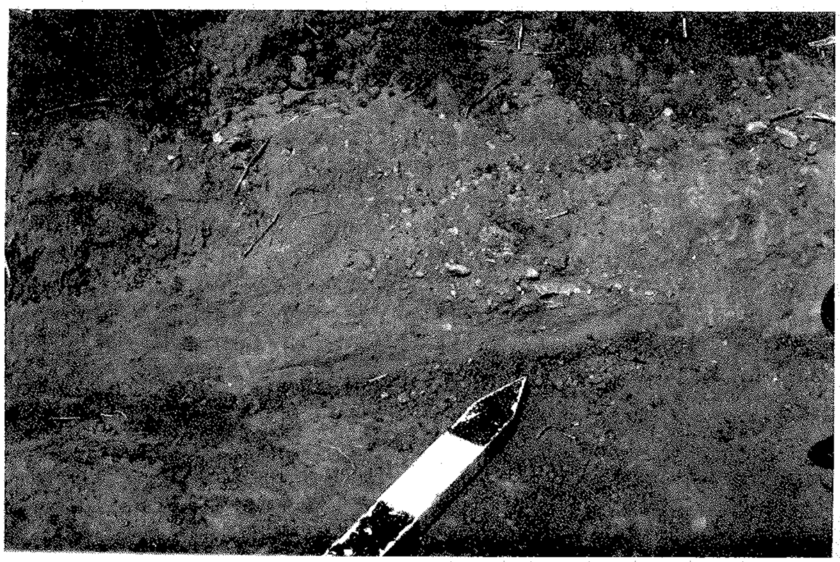

Figure 4. This detail of a horizon exposed along a gully shows caliche pebbles with glyptodont osteoderms *in situ*. Two osteoderms are actually present in this view, although only part of one is apparent in the photograph (about 10 cm beyond the tip of the arrow). The North arrow is 30 mm long, divided into decimeters. Photo by Donald G. Wyckoff.

ridge crest separating the Salt Fork and Cimarron drainages is about 2.5–3 km SW of the glyptodont locality.

Digging at the fossil locality revealed a section of the carapace and several additional osteoderms of a large glyptodont. (Osteoderms are plates of bone beneath the horny scutes or scales.) No other taxa were found. The largest piece of carapace is about 0.11 m^2 in area and is made up of 86 articulated osteoderms (Figs. 5, 6). It represents a small fraction of the posterior region of the carapace, probably near the dorsal part of the caudal aperture. It includes five border osteoderms along the aperture. This piece was flattened postmortem and after being disarticulated from the remainder of the carapace. In addition, a few other osteoderms were found nearby. Four of these were articulated with one another (Fig. 5), and the remainder were disarticulated and isolated. The patch of four are from the interior of the carapace. The internal surfaces (against the viscera) of the osteoderms in the articulated section show no evidence of roughened attachment points for the ischium, ilium, or neural ridge of the sacrum. The internal surfaces are flat to slightly concave and smooth with occasional small pits; their irregular polygonal outlines are apparent on internal view (Fig. 6B). Two of the isolated osteoderms have a conical projection of the central figure and very rugose joint surfaces situated well beneath the outwardly projecting central tubercle (Figs. 7 and 8). These two represent the second row of osteoderms, just inside the marginal row along the posteroventrolateral region of the carapace. No osteoderms were recovered from the caudal armor or cranial shield. A small piece of bone about 5 cm long and 1.3 cm wide and shaped like a flattened cylinder (i.e., oval in cross-section, but crushed) was the only non-carapacial fragment recovered, but the element is unidentifiable.

Measurements of osteoderms in the articulated piece of carapace were made approximately perpendicular to the short preserved section of margin and parallel to the margin; these amounted roughly to long and short diameters of each osteoderm as measured at the external surface. (The measurements are summarized in Table 1.) Thickness of the articulated osteoderms could not be measured, but that of several isolated osteoderms ranges from 16 to 20 mm. The central figure makes up most of the external surface of the osteoderms at the margin and in the next row or two adjacent to the margin, but diminishes quickly on osteoderms interior to these rows.

The species of glyptodonts known north of Mexico—*Glyptotherium texanum*, *G. arizonae*, and *G. floridanum*—are fairly easy to distinguish among the few nearly complete carapaces that have been found. However, isolated osteoderms are much more difficult to identify. Nevertheless, au-

Figure 5. *Glyptotherium arizonae* (OMNH 72109): a part of the carapace during collection (at left) and four other articulated osteoderms preserved internal side up (at right between the base of the North arrow and the paintbrush). The arrow is divided into decimeters. Photo by Donald G. Wyckoff.

thors often have assigned isolated osteoderms to species. To my knowledge, the variability in osteoderms across a single entire carapace of a glyptodont species has not been assessed, nor has the variability in osteoderms of complete carapaces between the species. This is due in part to the rarity of complete carapaces, but also no doubt to the complexity of osteoderms within a carapace. In their monographic review of North American glyptodonts, Gillette and Ray (1981) described some of the characters of the carapacial osteoderms that help in identification of the three species that are known north of Mexico. In terms pertinent to the features that are observable in the Carmen specimen: *G. texanum* has "border scutes not greatly enlarged; scutes small, central figures convex, larger than peripherals, frequent deep hair follicles; posterior border of carapace recurved weakly or not at all; central figures of scutes usually convex, frequently with deep medial depression . . . scutes of carapace disposed in transverse and oblique rows; posterior border scutes variable from flat to weakly conical." *Glyptotherium arizonae* has "scutes large, central figures of scutes slightly greater than half the scute diameter, always slightly larger than peripherals, flat to weakly convex . . . lateral scutes of first interior row with rounded central boss." *Glyptotherium floridanum* has "scutes small in females with marginal sculpturing at suture; scutes large for males, without marginal sculpturing at sutures; central figures of scutes approximately equal in size to peripherals, usually slightly raised and weakly concave . . . posterior border scutes of females with pointed conical bosses; posterior border scutes of males bluntly conical." Gillette and Ray (1981, p. 176) further noted for *G. arizonae* that the "Interior scutes are large and thick, averaging approximately 50 mm side-to-side diameter. As Gidley (1926) stated, the central figures are larger than the peripherals, and they measure approximately half the scute diameter. Peripheral figures are considerably smaller. . . . The number of peripheral figures varies from six to 11 or 12, with eight the most common. The central figures generally are depressed, as Gidley (1926) observed, except near the marginal areas of the carapace. The outer surfaces of the scutes are flat, rugose, and pitted."

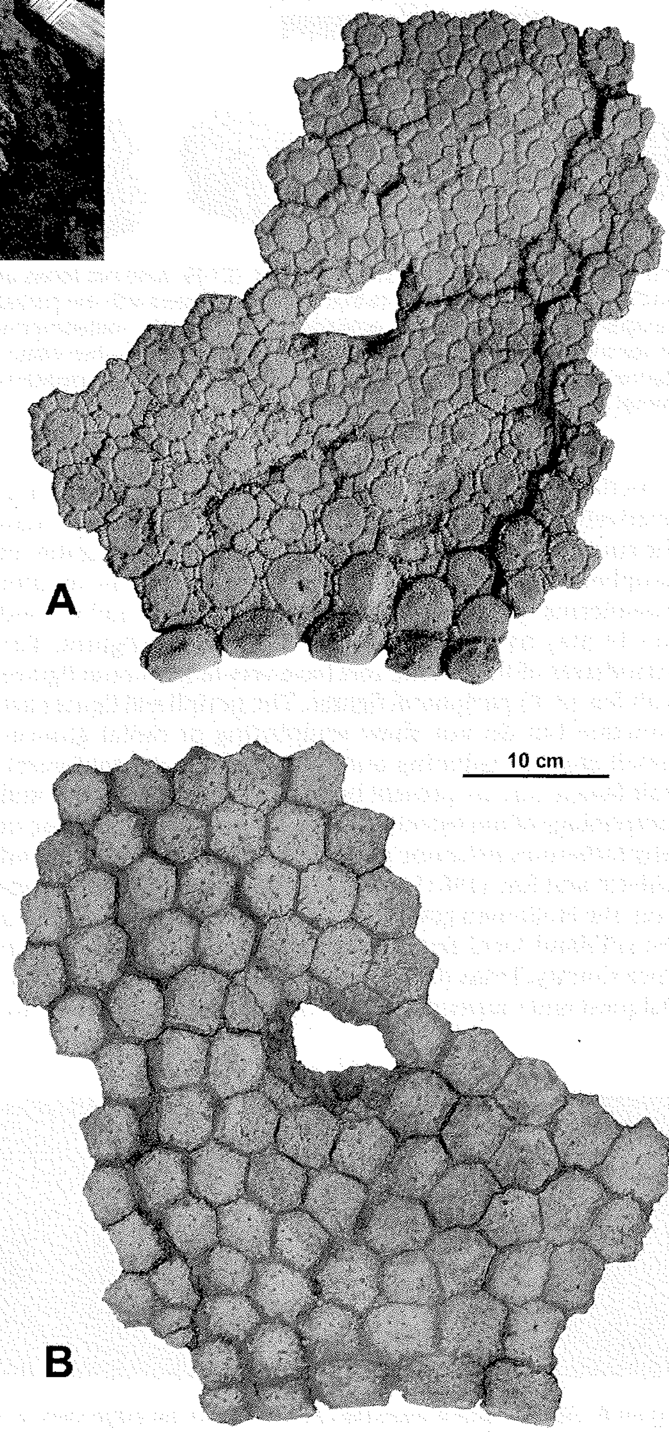

Figure 6. *Glyptotherium arizonae*, OMNH 72109. This is the same section of carapace as in Figure 5, after preparation. (A) external surface; (B) internal surface.

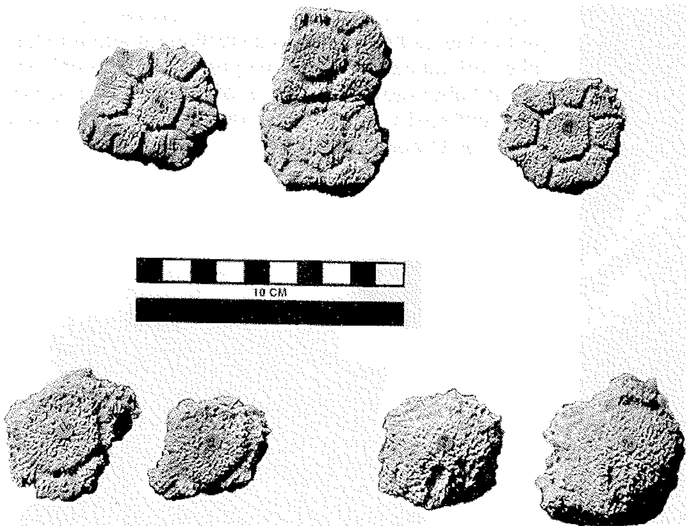

Figure 7. *Glyptotherium arizonae*, OMNH 72109: external faces of additional isolated osteoderms that were associated with the partial carapace. Top row—interior osteoderms. Lower left—osteoderms of second or third row interior to marginals. Lower right—two osteoderms from first row interior to marginals, from the posteroventrolateral area of the carapace.

In the Carmen glyptodont, the osteoderms are large and relatively thick, with the central figures flat and larger than the surrounding peripheral figures (Fig. 6A). The number of peripheral figures varies from 8 to 10 on most of the interior osteoderms, although those nearer the border and second row in may have as few as 4 or 5 peripheral figures. The osteoderms of the second row have very large central figures with few (2–6) peripheral figures. The peripheral figures are punctate but do not show sculpturing or radial grooves (small grooves radiating outward from the central figure). Hair follicle pits are present but not prominent. The size and morphology of the osteoderms from Carmen match those of *Glyptotherium arizonae* as described by Gidley (1926) and Gillette and Ray (1981) as well as specimens of *G. arizonae* from the Holloman gravel pit, Oklahoma(OMNH 2112), and the Gilliland local fauna from the Seymour Formation in Knox County, Texas (OMNH 5867; see Gillette and Ray, 1981; Dalquest and Carpenter, 1988). The Carmen osteoderms are thicker and have less obvious hair follicle pits than those of *G. texanum* from the Blancan sites at Cita Canyon, Texas (OMNH 52575), and the 111 Ranch, Arizona (OMNH 52412, 52411, 52438). They lack the marginal sculpturing and are larger with larger central figures relative to the peripheral figures than osteoderms of *G. floridanum*.

DISCUSSION

The earliest glyptodonts to appear in the fossil record in the southern United States are referable to the species *Glyptotherium texanum*. They reflect the early late Blancan land-mammal age, representing geological time from about 2.7 to 2.2 Ma and predate the slightly later species *G. arizonae*. According to Morgan and Lucas (2003), correlated biostratigraphic, magnetostratigraphic, and radioisotopic data indicate that published records of *G. arizonae* from the southern United States are late Blancan to early Irvingtonian in age, representing the interval from about 2.7 to 1.2 Ma. However, within this time span, most of the records (and all those from the western United States) are from the latest Blancan to early Irvingtonian interval (2.2–1.2 Ma). The earliest of these, in the early late Blancan (2.7–2.2 Ma), are restricted to Florida and include the localities called Santa Fe River 1, Brighton Canal, Kissimmee River, and St. Petersburg Times. The latest Blancan sites (2.2–1.8 Ma) include Curtis Ranch, Arizona (the type locality for *G. arizonae*; Gidley, 1926); Mesilla Basin Fauna B and Virden, New Mexico; and Inglis 1A, DeSoto Shell Pit, and Haile 7C, Florida. Early Irvingtonian sites (1.6–1.2 Ma) include Leisey Shell Pit, Florida; Gilliland and Rock Creek, Texas; Mesilla Basin Fauna C, New Mexico; and Holloman Gravel Pit, Oklahoma. *Glyptotherium arizonae* is unknown after the early Irvingtonian. In fact, after this time glyptodonts disappear from the fossil record in the United States until the late Rancholabrean land-mammal age (0.5 Ma) when the species *G. floridanum* reappears in late Pleistocene faunas of Florida, South Carolina, and Texas (Gillette and Ray, 1981).

The Carmen occurrence is the northernmost record of a glyptodont in North America and only the second record of a glyptodont in Oklahoma. At 36°37′ N, the Carmen locality is slightly farther north than glyptodonts from the Albuquerque Basin of New Mexico (Western Mobile gravel pit at about 35°20′ N; also Tijeras Arroyo, slightly farther south) reported by Morgan and Lucas (2000, 2003). All represent the species *G. arizonae*.

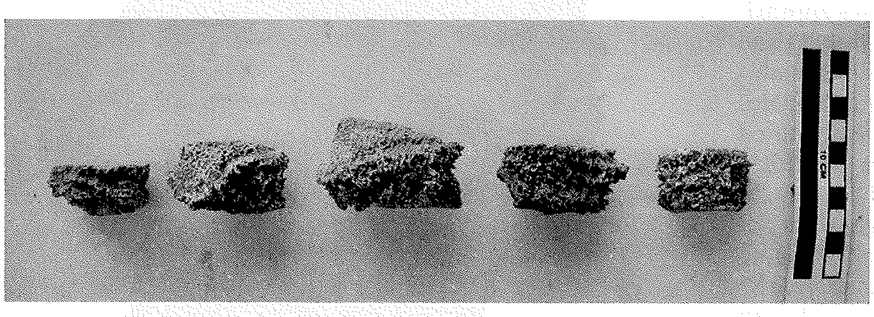

Figure 8. *Glyptotherium arizonae* OMNH 72109: an edge view of some of the same osteoderms as in Figure 7. The middle osteroderm and the second from the right belong to the first row in from marginals on the posteroventrolateral area of the carapace; others are interior carapacial osteoderms.

The only other Oklahoma record of a glyptodont is that already mentioned, *G. arizonae* from the Holloman gravel pit, near Frederick, Tillman County, about 260 km south of the Carmen locality. A partial carapace and associated large series of disarticulated osteoderms discovered at Holloman in 1927 (Gould, 1929) were donated in 1928 to the University of Oklahoma by the Oklahoma Geological Survey. These were examined by Simpson (1929), who thought they might represent an undescribed species, but other osteoderms and a lower jaw with two teeth found about the same time at the Holloman gravel pit were referred to the species *Glyptodon petaliferus* by Hay and Cook (1930). The name *Glyptodon petaliferus* is a junior synonym of *Glyptotherium arizonae* (see Gillette and Ray, 1981). The partial lower jaw and two associated marginal osteoderms mentioned by Hay and Cook (1930) were later used as the basis for the new genus and species *Xenoglyptodon fredericensis* by Meade (1953). However, the name *Xenoglyptodon fredericensis* was also later synonymized with *Glyptotherium arizonae* (Gillette and Ray, 1981). Most of the Holloman osteoderms at the University of Oklahoma were incorrectly reassembled into a "carapace" (Gillette and Ray, 1981; Smith and Cifelli, 2000) in which the individual osteoderms were laid into plaster with no regard for their original proper tight pattern of articulation; this reconstructed carapace and a few separate osteoderms remain in the OMNH collection as catalog no. 2112. The fauna from the Holloman gravel pit is considered early Irvingtonian in age (Dalquest, 1977).

The first glyptodonts reached the present-day United States in the middle of the Blancan land-mammal age, about 2.7 million years ago (Morgan, in press). In fact, the beginning of the late Blancan is defined on the first appearance in the fossil record in temperate North America of glyptodonts and other South American immigrants that participated in the Great American Biotic Interchange. Each of the three species of glyptodonts recognized in the Pliocene and Pleistocene of the United States is virtually restricted to a different North American land-mammal age: *Glyptotherium texanum* occurred in the late Blancan, *G. arizonae* is known in the latest Blancan but primarily occurs in the Irvingtonian, and *G. floridanum* occurred in the Rancholabrean. *G. arizonae* is known at fossil localities ranging from Arizona to Florida (Gillette and Ray, 1981, fig. 3). Based on biocorrelation, most of these localities, including the Holloman gravel pit, reflect the early Irvingtonian land-mammal age, although the type locality in Arizona and two sites in New Mexico are considered to represent the latest Blancan land-mammal age (Morgan and Lucas, 2000, 2003). Identification of the Carmen specimen as *G. arizonae* indicates an age from latest Blancan to early Irvingtonian (2.2 to 1.2 million years ago; ages from Morgan, in press) for the Carmen site. Without associated time-diagnostic fauna or other evidence, one cannot further constrain the age of the Carmen site.

Glyptodonts in North America are usually associated with other species of fossil vertebrates (semiaquatic birds, turtles, capybaras, ground sloths, and other shelled xenarthrans such as pampatheres and armadillos) and sedimentological conditions which suggest that they inhabited moist to wet, tropical to subtropical, flat, open lowland habitats such as swamps, marshes, seasonally flooded savannas, and pond and stream margins—reflecting their tropical origins (Webb 1978, 1991; Morgan, in press). Akersten (1972) thought that the restricted mobility of their head and neck, short stature, and ponderous body would not have predisposed them to feed on tall vegetation or live on hilly terrain. Gillette and Ray (1981) concluded that the habitat requirements of *Glyptotherium* species "were rather restrictive: proximity to standing water in a region with extensive lowland terrain; lush tropical or subtropical vegetation; a warm climate without excessive extremes of temperature; and high, relatively constant moisture (for maintaining the permanent bodies of water and the abundant vegetation)." McNab (1985) suggested that, given their large body mass, glyptodonts' southerly distribution in North America could indicate temperature sensitivity due to a low metabolic rate like that of living xenarthrans. The occurrence of the specimen near Carmen suggests that the habitat and environmental tolerances of this moist-lowland-inhabiting mammal of Neotropical ancestry—which otherwise occupied the subtropical savannas of the Gulf of Mexico Coastal Plain and low-lying parts of the present-day southwestern United States—were met far (950 km from the present Gulf of Mexico coastline) inland on the southern Plains during some period within the interval from latest Blancan to early Irvingtonian. *Glyptotherium arizonae*, which was more widely distributed than its congeners *G. texanum* and *G. floridanum*, was possibly tolerant of a broader range of variables in environment or habitat (such as cold tolerance or water-conserving capability due to its larger body size), enabling it to live farther north. Alternatively, the habitat of the Gulf Coastal Plain or moist lowland (or both) might have extended farther north during the latest Blancan–Irvingtonian interval than it did earlier in the late Blancan or later in the Rancholabrean, into the southern Great Plains in what is now northern Oklahoma and into the Rio Grande rift in what is now New Mexico. This might have occurred during a postulated warm, humid interval around 2.0–1.8 Ma (Thompson, 1991).

ACKNOWLEDGMENTS

Steve Schanbacher, the keen-sighted and conscientious farmer who found the specimen while disking his field, protected it from erosion and, together with Bobby Kildow and the Kildow family, Jeffrey W. Hickman, and Donald G. Wyckoff, notified the museum and brought the specimen to my attention. To all these folks I extend my deep appreciation. I also thank the landowners Ralph and Wanda Lou Brower for graciously donating the specimen to the OMNH. Thanks to D. G. Wyckoff for his help in field work, geological interpretation, and photographs, and to Joe Baalke and Kyle Davies for skillfully preparing the specimen in the lab. Thanks go to Gary S. Morgan for much helpful discussion of glyptodonts, and to Brian Carter for discussion of terrace, ash, and loess deposits in the area. I appreciate the critical reviews of David D. Gillette and Gary Morgan.

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Status of Oklahoma's STATEMAP Program

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ABSTRACT.—In 11 years of the STATEMAP program, the Oklahoma Geological Survey has published 35 geological maps of 7.5′ quadrangles at 1:24,000 scale and 11 sheets at 1:100,000; they are available in paper form and as digital files. The mapping program responds to land-use concerns, notably in the Oklahoma City and Tulsa metropolitan areas. In addition to detailed mapping (Project 1), STATEMAP also is doing reconnaissance field mapping (Project 2); maps generated from Project 2 will contribute to a forthcoming geological map of the State at 1:500,000. Further detailed mapping is contemplated for the Tar Creek Superfund Site in Ottawa County. Procedures for digitizing geological data to be overlaid on a standard topographic base have proved satisfactory, although problems persist.

INTRODUCTION

This year marks the eleventh anniversary of the Oklahoma Geological Survey's STATEMAP program. The OGS has published 35 detailed 7.5′ geologic maps at a scale of 1:24,000, and 11 reconnaissance geologic maps at 1:100,000; they are available both on paper and in digital form. The intent of STATEMAP is two-fold; the first is to map geology in detail at 1:24,000 scale in and around concentrated urban areas and their suburbs. Those areas need 1:24,000-scale maps that incorporate all available surface data as well as subsurface data from drill holes and geophysical surveys to help define hazards, soil types, aggregate resources, and ground-water aquifers; the maps should also help urban planners, developers, and industry managers in making land-use decisions.

Second is to publish geologic maps in modern digital form at 1:100,000 scale. The quality of previous maps ranges from good to poor; they were produced on various bases and at several scales, and now their data should be compiled, checked in the field, corrected, and digitized onto a single standard topographic base. These small-scale geologic maps should help agricultural concerns in rural areas as well as aiding planners with GIS capability where urban growth is slow. The same maps also will be used in compiling a new 1:500,000-scale geologic map of Oklahoma.

This report describes the status of the STATEMAP program—the work so far, current and future mapping projects, and pitfalls encountered in developing a digital mapping program.

OVERVIEW

Since 1985 the Oklahoma Geologic Mapping Advisory Committee (OGMAC) has aided the OGS in addressing Oklahoma's burgeoning problems in land use and resource development in urban and agricultural areas. The work involved participation in the U.S. Geological Survey's Cooperative Geologic Mapping Program (COGEOMAP), which in 1992 became the State Mapping component (STATEMAP) under the National Geologic Mapping Act. In essence, STATEMAP is a matching-fund program providing federal assistance to state geological surveys in new mapping and digital compilation of existing maps (Table 1). One result, the OGMAC recommended continued mapping at 1:24,000-scale (Project 1 mapping) along the front range of the Ouachita Mountains, particularly in the McAlester region, where emphasis is on land-use issues arising from growth of McAlester. Also being examined are energy resources and their development by the oil and gas industry in the Arkoma Basin, and stratigraphic problems in the the lower Pennsylvanian section (Suneson and others, 2001; Fig. 1).

By 1996, the OGMAC had also recommended a broader mapping program (Project 2 mapping) that ultimately will form the base of a new geologic map of the State. Project 2 consists of developing a series of 1:100,000-scale digital maps compiled from previous mapping data published at various scales, the work beginning in northwest Oklahoma and in the Panhandle and later sweeping to the southeast (Fig. 1). The northwest was chosen because the geology there consists of a well-studied Permian section that is regionally consistent and structurally simple (Suneson and others, 2001). Unfortunately, the initial attempt to compile previous geologic mapping directly from various sources at various scales onto a uniform topographic base met with difficulty. One problem arose from compilation methods that relied too much on office procedures and too little on field checking. The trouble was particularly evident in highly dissected terrain, where the resulting digital map depicted geology and geologic contacts radically discordant with the topographic base. The immediate remedy, to add reconnaissance field checking, helped in transferring geologic data from varied sources onto a uniform base. Of course other benefits re-

TABLE 1.—Yearly Expenditure of Federal and State Money Since Inception of the Oklahoma Geological Survey's STATEMAP Program

Federal fiscal year	Project map(s) and scale	State dollars	Federal dollars	Total project dollars
1993	• Heavener and Bates Quadrangles; Le Flore County. 1:24,000	$23,732	$20,000	$43,732
1994	• Adamson and Hartshorne Quadrangles; Pittsburg County. 1:24,000	$61,844	$50,000	$111,844
1995	• Krebs and Hartshorne SW Quadrangles; Pittsburg County. 1:24,000	$80,659	$30,000	$110,659
1996	• McAlester and Savanna Quadrangles; Pittsburg County. 1:24,000 • Watonga and Foss Reservoir sheets; Ellis, Roger Mills, Beckham, Dewey, Custer, Blaine, Kingfisher, Caddo, and Canadian Counties. 1:100,000	$69,104	$68,967	$138,071
1997	• Piedmont, Bethany NE, Edmond, and Arcadia Quadrangles; Kingfisher, Logan, Canadian, and Oklahoma Counties. 1:24,000 • Boise City sheet; Cimarron and Texas Counties. 1:100,000	$95,482	$86,433	$181,915
1998	• Bethany, Britton, Spencer, and Jones Quadrangles; Canadian and Oklahoma Counties. 1:24,000 • Guymon and Beaver sheets; Beaver and Texas Counties. 1:100,000	$113,587	$95,158	$205,745
1999	• Mustang, Oklahoma City, Midwest City, and Choctaw Quadrangles; Canadian and Oklahoma Counties. 1:24,000 • Buffalo sheet; Harper, Woods, Ellis, and Woodward Counties. 1:100,000	$70,642	$79,644	$150,286
2000	• Oklahoma City SW, Oklahoma City SE, Moore, and Franklin Quadrangles; Canadian, Cleveland, Grady, and McClain Counties. 1:24,000	$47,028	$45,966	$92,994
2001	• Blanchard, Newcastle, Norman, and Denver Quadrangles; Canadian, Cleveland, Grady, and McClain Counties. 1:24,000 • Woodward and Fairview sheets; Alfalfa, Blaine, Dewey, Ellis, Garfield, Grant, Kingfisher, Major, Woods, and Woodward Counties. 1:100,000	$167,804	$121,422	$289,226
2002	• Luther, Horseshoe Lake, Harrah, Stella, and Little Axe Quadrangles; Cleveland, Lincoln, Logan, Oklahoma, and Pottawatomie Counties. 1:24,000 • Alva and Elk City sheets; Alfalfa, Beckham, Custer, Garfield, Grant, Greer, Harmon, Kiowa, Roger Mills, Washita, Woods, and Woodward Counties. 1:100,000	$130,123	$124,494	$254,617
2003	• Claremore and Sageeyah Quadrangles; Rogers County. 1:24,000 • Anadarko, Altus, and Vernon sheets; Caddo, Canadian, Custer, Greer, Kiowa, Harmon, Jackson, Tillman, and Washita Counties. 1:100,000	$121,572	$110,789	$232,361
2004	• Collinsville and Sperry Quadrangles; Rogers and Tulsa Counties. 1:24,000 • Lawton sheet; Caddo, Comanche, Cotton, Grady, Kiowa, Stephens, and Tillman Counties. 1:100,000	$94,069	$86,231	$180,299
	TOTALS	**$1,070,017**	**$924,733**	**$1,994,749**

sulted from even cursory field checking; those benefits, and related matters, will be described later in this report.

After 1996, emphasis in the federal STATEMAP program shifted from detailed mapping that stressed development of energy resources (particularly where population growth was low) to emphasize problems of urbanization and associated use of land and water. Under this new policy, the OGMAC recommended detailed geologic mapping of the Oklahoma City metropolitan area (OCMA), and the OGS submitted a three-year plan that called for mapping four quadrangles a year starting in the northern part of the OCMA (Table 1; Fig. 2). The main purpose was to emphasize environmental and

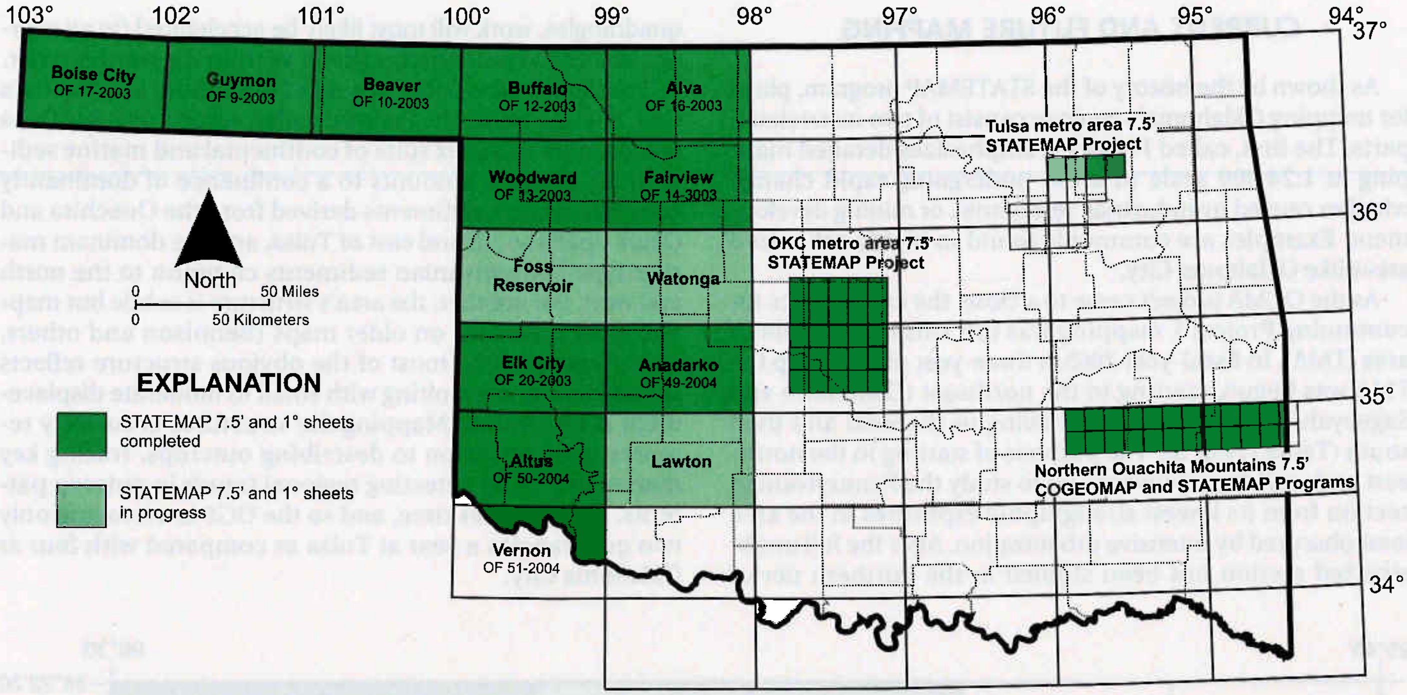
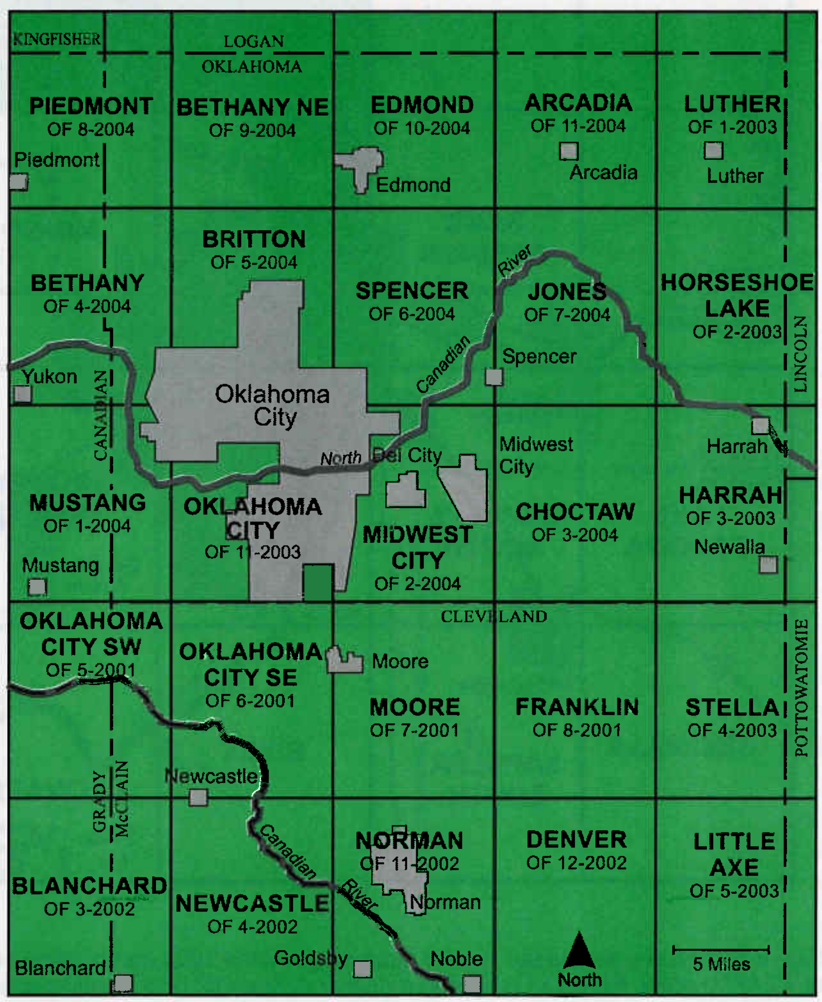


Figure 1. Geologic maps produced in the COGEOMAP and STATEMAP programs have been completed for the areas shown in dark green; areas shown in light green are in progress as of FY-2005. Below each quadrangle name is the open-file number for its color digital map (available from the Oklahoma Geological Survey's Publication Sales Office).

Figure 2 *(right)*. Color digital maps have been published for the Oklahoma City metropolitan area at 1:24,000 scale. Each map's open-file number appears under its quadrangle name.



engineering concerns caused by population growth and related housing and industrial development; the plan also aimed at solving stratigraphic problems in the Permian section.

In 1999, after success of the first plan, the OGMAC recommended (and the OGS submitted) a second three-year plan intended to complete mapping the southern tier of quadrangles in the OCMA, and to add five quadrangles along its eastern boundary (Table 1; Fig. 2). The five (Luther, Stella, Harrah, Horseshoe Lake, and Little Axe) were added because an "outer loop"—an Interstate highway bypass—had been proposed by the Oklahoma Department of Transportation. If built, the outer loop would encourage new business and residential development, and mapping would give planners, engineers, and homeowners a framework for planning development.

In federal fiscal-year 2002, mapping in the OCMA was completed and 25 1:24,000-scale bedrock geologic maps, with cross sections and detailed descriptions of mapped units, were published in printed form and also as digital files on compact disks (Fig. 2).

CURRENT AND FUTURE MAPPING

As shown by the history of the STATEMAP program, plans for mapping Oklahoma's geology consist of two interrelated parts. The first, called Project 1, emphasizes detailed mapping at 1:24,000 scale in areas undergoing rapid change whether caused by industrial, residential, or mining development. Examples are commonly found in highly urbanized areas like Oklahoma City.

As the OCMA project came to a close, the logical place for continuing Project 1 mapping was the Tulsa metropolitan area (TMA). In fiscal-year 2003, a three-year plan to map the TMA was begun, starting in the northeast (Claremore and Sageeyah quadrangles) and moving to the west and then south (Table 1; Fig. 3). The purpose of starting in the northeast and working westward was to study the Pennsylvanian section from its lowest stratigraphic exposures in the area least obscured by intensive urbanization. After the full unobstructed section has been studied in the northern tier of quadrangles, work will most likely be accelerated (to an average of three to four quadrangles a year) in the southern tier.

Problems in the Tulsa area differ from those at Oklahoma City. For one thing, the Pennsylvanian section around Tulsa is a far more complex suite of continental and marine sedimentary rocks; it amounts to a confluence of dominantly continental-type sediments derived from the Ouachita and Ozark uplifts south and east of Tulsa, and the dominant marine-type Pennsylvanian sediments common to the north and west. For another, the area's structure is subtle but mappable. As is evident on older maps (Bennison and others, 1972; Oakes, 1952), most of the obvious structure reflects broad folding, but faulting with small to moderate displacement is also found. Mapping the structures accurately requires close attention to describing outcrops, tracing key marker beds, and detecting regional trends in outcrop patterns. All that takes time, and so the OGS is averaging only two quadrangles a year at Tulsa as compared with four at Oklahoma City.

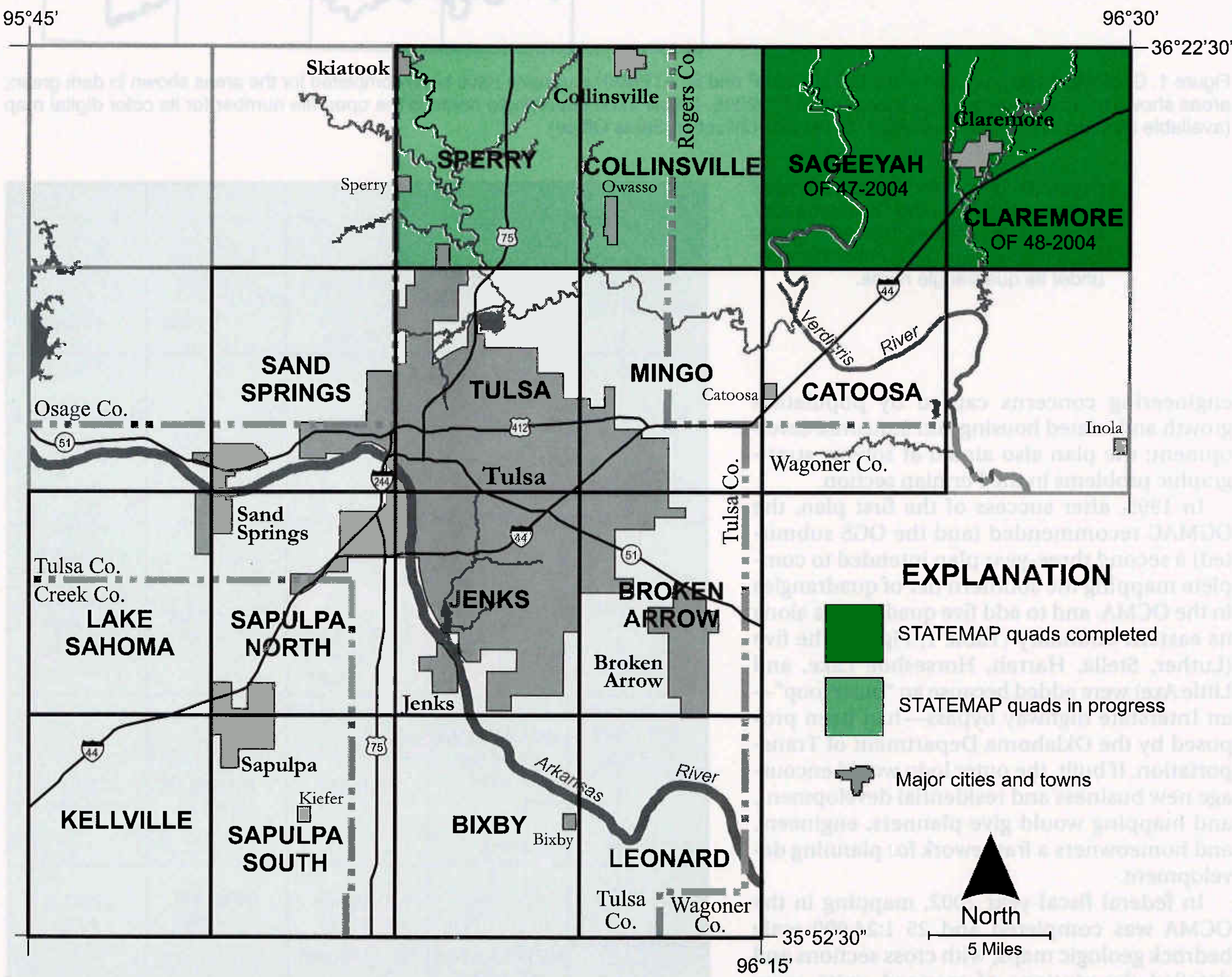


Figure 3. Light and dark green shaded quadrangles in the Tulsa metropolitan area have been mapped, or are being mapped (as shown) at 1:24,000 scale. Names of quadrangles to be proposed for later mapping appear in boldface type.

Digital-mapping terms

GIS, or Geographic Information System—A computer-based system for gathering data, turning it into digital form, and ultimately producing a digital map. The procedure may involve scanning maps, taking data from a Global Positioning System receiver, compiling tables, analyzing various combinations of attributes, and projecting data representing the 3-D Earth onto a 2-D computer screen—or assembling it for printing on flat paper.

ARC/INFO—A GIS program for exploiting information to be used in making a map. It attaches data controlling color, patterns, and symbols to points representing locations on the Earth, and enables manipulation and assembly of many individual layers into a single map.

raster file—A computer file used to store image information, often gathered by scanning paper maps or aerial photos. In a raster file, resolution is expressed as cell size and dots per inch (dpi).

TIFF, or Tagged Image File Format—It was designed as a structure for storing raster-file data (such as from a scanner) in a GIS file.

The second part of the STATEMAP program entails Project 2 reconnaissance mapping at 1:100,000 scale for eventual use in constructing the new state map at 1:500,000. The OGS has been producing reconnaissance maps since fiscal-year 1997, averaging about two maps a year and thus providing almost full digital map coverage of the western half of the State (Table 1; Fig. 1). In the current fiscal year (which began October 1, 2004) we are concentrating on the Lawton 1° sheet, which represents one of the most geologically complicated areas, structurally and stratigraphically, encountered so far in the Project 2 mapping. In later years we will continue the eastward sweep across the State.

In addition to continuing detailed mapping of the TMA, the OGS will recommend to OGMAC a mapping project for fiscal-year 2005 at the Tar Creek Superfund Site, in Ottawa County. Tar Creek is important because of extreme environmental degradation from tailings and slag piles resulting from lead and zinc mining from the 1920s through the 1940s. Kenneth V. Luza of the OGS is incorporating location, texture lithology, and size of old surface and subsurface workings into GIS digital format, and we hope that converting the 1:24,000-scale geological data into a GIS format will help federal and state agencies in further studies. The area of impact lies in northern Peoria, Picher, and Miami NW quadrangles (east to west); it includes Lower Pennsylvanian (Desmoinesian) and Upper Mississippian (Chesterian and Meramecian) strata along the northwest flank of the Ozark uplift. The work proposed will most likely run for three years, starting in the Picher quadrangle.

MAPPING PROCEDURES AND PROBLEMS

One of the first problems encountered in digital transfer of previous geologic mapping data from various sources and scales onto a uniform 1:100,000-scale base was that geology on the new map often did not match the topographic base. Initially the problem was solved by transferring the old data by hand onto all the 7.5′ quadrangles in the 1° sheet, and then verifying geologic contacts by reconnaissance road mapping. The resulting 32 field sheets were then digitized onto the 1:100,000 topographic base with little conflict between geology and topography. A side benefit of field checking was refinement of the geology depicted; notably, the Quaternary System was delineated as fluvial sediments versus aeolian.

Those coarse divisions can be further subdivided based on sedimentologic texture and topographic expression to depict more accurately the history of the Quaternary since the Pleistocene. For example, wind-blown deposits can be divided into sheet sand versus dune sand, based mostly on the presence or absence of a hummocky topography; and although wind-blown sheet sands appear topographically similar to fluvial terraces, the wind-blown sediment tends to finer grains, distinct lack of gravel-size clasts, and a lighter color.

Other benefits of quick reconnaissance was re-evaluation of established formations and contacts shown on older maps, and filling in blank spots. A re-evaluation of the Permian section presently is underway.

Problems persist in producing high-quality digital color maps. One difficulty for our state survey (and most others) is lack of good digital base maps (McCraw, 1999). That is largely because the source of all topographic base maps—the USGS—either cannot supply digital maps of the quality required, or it inadvertently hinders efforts of state surveys to produce their own.

When digital mapping programs were first implemented, state surveys could generally choose from three techniques: (1) download digital base map files from the USGS—essentially a single scanned raster file of the original topographic base with culture, elevation data, hydrography, and political boundaries; (2) create its own digital base maps; (3) scan a clean flat copy of the original printed base map. At first the OGS, like most other state surveys, took the easiest course (option 1) by acquiring the digital base from the USGS. Unfortunately, the quality of the files was so poor and the resolution so low (160 to 250 dpi) that the underlying geology was obscure, and at times the maps were illegible. The problem was particularly severe in areas with thick vegetation, or with recent urban development whose patterns could not be removed without loss of useful information.

The second option worked well, but it was slow. Creating a digital base required scanning critical Mylar separates—usually those for hypsography, culture, and hydrography—at 400 dpi or more. The benefit of scanning Mylar separates was that each layer could be manipulated, such as removal of ground clutter, without disturbing other layers or themes. Separates that obscured the geology but provided no useful information (such as the one for vegetation) could be omitted. After the separates were scanned, the resulting TIFF images were registered in the ARC/INFO computer program to create a single digital base, whereupon the geology could be digitized from field sheets and placed beneath the base map. The final digital map was of exceptional quality, and rivaled conventional cartographic results in reproducibility, reproduction speed, and appearance.

However, the second method was short-lived, for the USGS stopped making the photographic composite negatives used in creating Mylar separates. Thus a state survey had only one viable option—to scan printed quadrangle maps at high resolution and convert the data into a digital file. Unfortunately, scanning preserves ground clutter that obscures geology; the clutter can be minimized but not eliminated without unduly degrading more important and informative elements on the base map.

CONCLUSIONS

The STATEMAP program at the Oklahoma Geological Survey has been a considerable success. So far, 46 new geologic maps have been published at various scales and levels of detail, focusing on many geological aspects. Mapping has followed a two-pronged approach—detailed mapping in areas with land-use problems, coupled with reconnaissance mapping where previous coverage was marginal. Detailed mapping continues in the Tulsa area, resulting in publication of at least two 7.5′ quadrangles a year, and detailed mapping is to be proposed for the Tar Creek Superfund Site.

Most problems in starting a digital map program have been solved or nearly so, and those remaining lie beyond control of the OGS. We hope the USGS will soon resume production of proper digital files for base maps, either scanned at a resolution enabling clear images, or as separate map layers that can be manipulated or even omitted to eradicate superfluous data.

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Oklahoma Earthquakes, 2003

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INTRODUCTION

More than 930,000 earthquakes occur throughout the world each year (Tarbuck and Lutgens, 1990). Approximately 95% of these earthquakes have a magnitude of <2.5 and usually are not felt by humans (Table 1). Only 20 earthquakes, on average, exceed a magnitude of 7.0 each year. An earthquake that exceeds a magnitude of 7.0 is considered to be a major earthquake and serious damage could result. (See the Catalog section, below, for a discussion of earthquake magnitude.)

Earthquakes tend to occur in belts or zones. For example, narrow belts of earthquake epicenters coincide with oceanic ridges where plates separate, such as in the mid-Atlantic and eastern Pacific Oceans. Earthquakes also occur where plates collide and/or slide past each other. Although most earthquakes originate at plate boundaries, a small percentage occurs within plates. The New Madrid (Missouri) earthquakes of 1811–12 are examples of large and destructive intraplate earthquakes in the United States.

The New Madrid earthquakes of 1811 and 1812 were probably the earliest historical earthquake tremors felt in what is now southeastern Oklahoma (then part of Arkansas Territory). Before Oklahoma became a state, the earliest documented earthquake occurred on October 22, 1882, probably near Fort Gibson, Indian Territory, although it cannot be located precisely (Ross, 1882; Indian Pioneer Papers, date unknown). The *Cherokee Advocate* newspaper reported that at Fort Gibson "the trembling and vibrating were so severe as to cause doors and window shutters to open and shut, hogs in pens to fall and squeal, poultry to run and hide, the tops of weeds to dip, [and] cattle to lowe" (Ross, 1882, p. 1). These observations indicate Modified Mercalli (MM)-VIII intensity effects. (See the section, below, on Distribution of Oklahoma Earthquakes for information about the MM earthquake-intensity scale.) The next documented earthquake in Oklahoma occurred near Jefferson, Grant County, on December 2, 1897 (Stover and others, 1981). The next known Oklahoma earthquake happened near Cushing, Payne County, in December 1900. This event was followed in April 1901 by two additional earthquakes in the same area (Wells, 1975).

The largest known Oklahoma earthquake (with the possible exception of the 1882 earthquake) occurred near El Reno, Canadian County, on April 9, 1952. This magnitude-5.5 (mb, Gutenberg-Richter) earthquake caused a 50-ft-long crack in the State Capitol Office Building in Oklahoma City. It was felt throughout Oklahoma and in parts of seven other states. The total felt area was ~362,000 km² (Docekal, 1970; Kalb, 1964; von Hake, 1976); Des Moines, Iowa, and Austin, Texas, were at the northern and southern limits. From 1897 through 2002, 1,697 earthquakes have been located in Oklahoma.

TABLE 1. — ESTIMATED NUMBER OF WORLDWIDE EARTHQUAKES PER YEAR BY MAGNITUDE
(Modified from Tarbuck and Lutgens, 1990)

Magnitude	Estimated number per year	Earthquake effects
<2.5	>900,000	Generally not felt, but recorded
2.5–5.4	30,000	*Minor to moderate earthquakes* Often felt, but only minor damage detected
5.5–6.0	500	*Moderate earthquakes* Slight damage to structures
6.1–6.9	100	*Moderate to major earthquakes* Can be destructive in populous regions
7.0–7.9	20	*Major earthquakes* Inflict serious damage if in populous regions
≥8.0	1–2	*Great earthquakes* Produce total destruction to nearby communities

INSTRUMENTATION

A statewide network of nine seismograph stations was used to locate 47 earthquakes in Oklahoma for 2003 (Fig. 1). The statewide network consists of a central station (TUL/LNO), four radio-telemetry seismograph stations (FNO, RLO, SIO, VVO), and four field stations (ACO, MEO, OCO, PCO). The U.S. Geological Survey (USGS) established a seismograph station, WMOK, 19 km southwest of the Oklahoma Geological Survey's (OGS) station at Meers (MEO). WMOK, the USGS station, does not record continuously. When triggered by moderately strong ground motion, it transmits a short segment of data to the National Earthquake Information Service in Golden, Colorado. WMOK is used mostly for distant earthquakes, although it sometimes records some of the larger Oklahoma earthquakes. Because WMOK is so near MEO, its arrival times do not improve the accuracy of location of Oklahoma earthquakes.

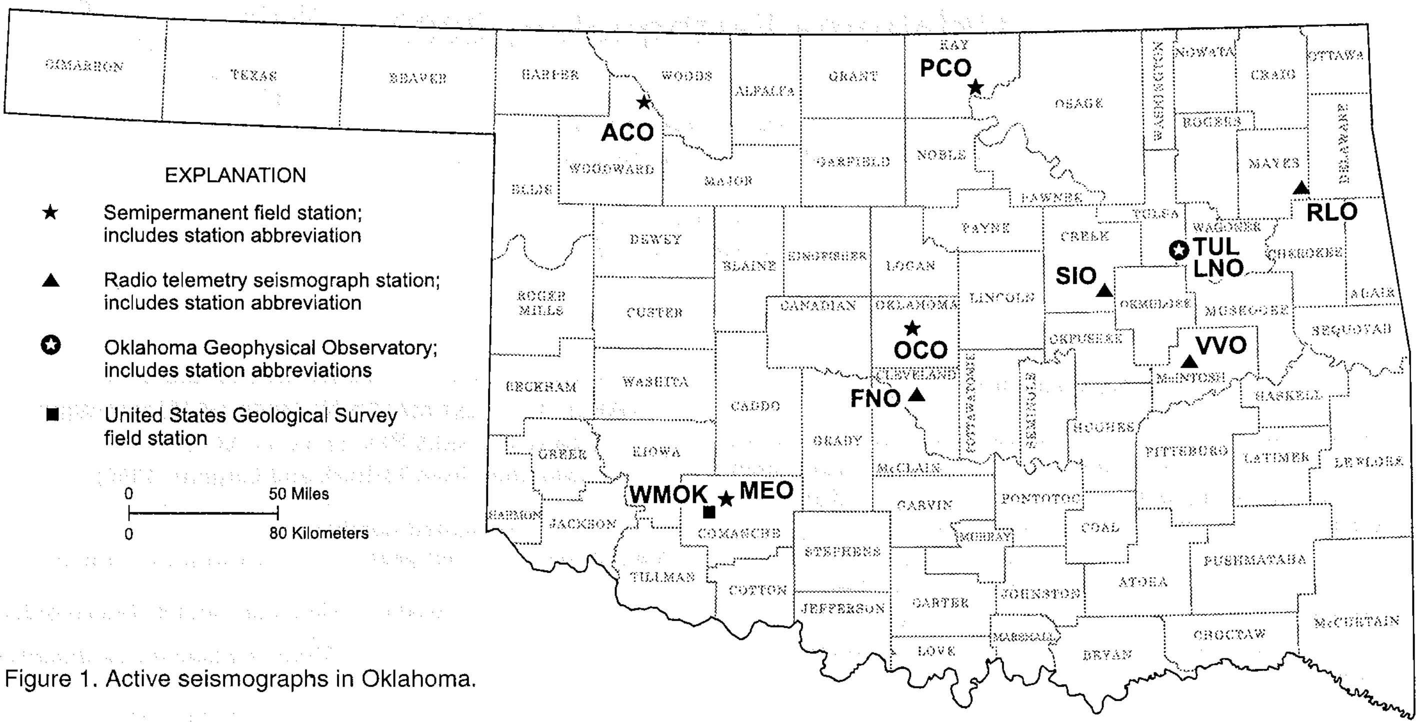

Figure 1. Active seismographs in Oklahoma.

Central Station

The OGS Observatory station, TUL/LNO, is located ~3.2 km south of Leonard, Oklahoma, in southeastern Tulsa County. At this site, digital and analog (paper) records from all stations are analyzed to detect, identify, and locate Oklahoma earthquakes. Seismometers at the central station are located on a pier in a 4-m-deep underground walk-in vault and in an 864-m-deep borehole. The vault is designated by the abbreviation, TUL, and the borehole has the international station abbreviation, LNO. In the vault, three Baby Benioff seismometers and a 3-component Guralp CMG3-TD seismometer record vertical, north-south, and east-west ground motion. Each Baby Benioff seismometer produces signals recorded on a drum recorder that uses a heat stylus and heat sensitive paper. (The original drum recorders used light beams to record on photopaper. The drum recorders were converted to ink recording in 1978 and later to more reliable recording on heat sensitive paper.)

The Guralp CMG3-TD ultra-broadband seismometer senses everything from the solid earth tides with their mHz frequencies to the high frequencies of Oklahoma earthquakes, which may approach 100 Hz. The CMG3-TD seismometer has a Global Positioning System (GPS) time receiver and digitizers in the case. The three digitizers each produce 200 samples per second. The CMG3-TD in the vault is a temporary replacement for the similar borehole seismometer, which currently is being rebuilt under warranty at the Guralp factory in the UK. When the borehole seismometer is operating again, it will provide the 200-sample-per-second signals from the central station that are used to detect and locate earthquakes in Oklahoma.

A Guralp eight-channel rack digitizer records the remote stations (RLO, VVO, and SIO) at 200 samples per second. Data are digitized and recorded by Guralp SCREAM software running on a PC. These samples are assembled into time-tagged data-compressed packets and transmitted at 38,400 bits per second to the Guralp SCREAM data acquisition software. Guralp SCREAM software, which runs on a PC, uncompresses the packets, organizes them into one-hour files on a disk, and will display one or more windows containing one or several moving traces. The windows may contain as little as one second or as much as 24 hours of ground motion. All digital data are archived on writable CD-ROMs. About two new CDs are added each week.

SCREAM sends slower packets (20 samples per second, and four samples per second) to another PC running SCREAM, and to the University of Indiana over the internet. From Indiana, the packets are sent continually or in once-per-day batches to a number of secondary schools in the United States. These slower packets lack the high frequencies characteristic of Oklahoma earthquakes but are very useful for studying teleseisms (distant earthquakes), which occur daily in the Earth's seismic belts. For distant earthquakes above magnitude 6, packages of the 20-sample-per-second, vertical, north-south, and east-west signals containing about one hour of recording are made up at the Observatory. These are sent by internet file transfer protocol to the PEPP (Princeton Earth Physics Project) data base, which is used primarily by American secondary schools.

Radio Telemetry Stations

Three radio-telemetry stations, (1) at Rose Lookout (RLO) in Mayes County, (2) at the Bald Hill Ranch near Vivian (VVO) in McIntosh County, and (3) at the Jackson Ranch near Slick (SIO) in Creek County, have Geotech S-13 seismometers in shallow tank vaults. The seismic signals are amplified and used to frequency modulate an audio tone that is transmitted to Leonard with 500-mW FM transmitters at various frequencies in the 216–220-MHz band.

Antennas on a 40-m-high tower near the OGS Observatory receive signals from the three radio-telemetry sites. These electrical signals are carried 350 m overland to the outside of the Observatory building. In a box on the outside wall, the electrical signals are converted to optical signals. The optical signals are sent through ~6 m of plastic fiber into the building, where they are converted back to electrical signals. This optical link is used to prevent wires from carrying lightning-induced surges into the building and damaging digitizers and computers.

The radio-telemetry signals are frequency-modulated audio tones. Discriminators convert the tones back into a voltage similar to the voltage produced at the field seismometer. These voltages are recorded on a 48-hour-paper-seismogram drum recorder, one recorder per station. The paper records are used mainly to backup the computer system.

The radio-telemetry signals are transmitted to three channels (one channel per station) on the Guralp rack digitizer. Each digitizer channel produces 200 samples per second. The digitizer includes a GPS (Global Positioning System) satellite receiver. The signals are assembled in memory into timed packets. The packets are transmitted to a PC running Guralp SCREAM data acquisition software.

A fourth radio-telemetry station, FNO, was installed in Norman in central Oklahoma on April 28, 1992. The seismometer, Geotech S-13, is on a concrete pad, ~7 km northeast of Sarkeys Energy Center (the building that houses the OGS main office). A discriminator converts the audio-signal frequency fluctuations to a voltage output. The voltage output is amplified and recorded by a Sprengnether MEQ-800 seismograph recorder (located in an OGS display case) at a trace speed of 60 mm/min.

Oklahoma earthquake catalogs, earthquake maps, some seismograms, and related information are on the Internet at http://www.okgeosurvey1.gov

Field Stations

Seismograms are recorded at three volunteer-operated seismographs (ACO, MEO, and PCO). Each station consists of a Geotech S-13 short-period vertical-motion-sensing seismometer in a shallow tank vault, or in an abandoned mine shaft (station MEO). The seismometer signal runs through 60–600 m of cable in surface PVC conduit to the volunteer's house or other building. The volunteer has a Sprengnether MEQ-800B timing system amplifier-filter-drum recorder, which records 24 hours of seismic trace at 1 mm/min in a spiral path around the paper on the drum. A time-signal radio receiver tuned to the National Institute of Standards and Technology and high-frequency radio station WWV is used to set the time. The volunteers mail the seismograms to the Observatory weekly (or more often, if requested). When an earthquake is felt in Oklahoma, the volunteer operators fax seismogram copies to the Observatory so that the earthquake can be located rapidly.

Station OCO, which contains equipment similar to that at the volunteer-operated stations, is at the Omniplex museum in Oklahoma City. Omniplex staff members maintain the equipment and change the seismic records daily. OGS Observatory staff help interpret the seismic data and archive the seismograms with all other Oklahoma network seismograms.

DATA PROCESSING AND ANALYSIS

Data are processed on two networked Sun UNIX workstations—a SPARC20 and a SPARC 2+. All network digital and analog short-period (frequencies > ~1 Hz) and broadband seismograms are scanned for earthquakes in and near Oklahoma. The arrival times of P and S phases are recorded on a single-page form in a loose-leaf notebook. The arrivals then are entered into the SPARC20 or the SPARC 2+ using a user-friendly flexible program written in the Nawk language. The program uses the entries to write an input file with a unique file name.

From the input files, the hypocenters are located by Johannes Schweitzer's (1997) program HYPOSAT 3.2c. A Nawk program manages the input to HYPOSAT and puts the output in a single file and writes a line in an overall catalog file.

HYPOSAT must have a velocity model of the crust and top of the mantle to calculate travel times of P and S to each station from each successive hypocenter tried in the program. The nine-layer-plus-upper-mantle Chelsea model for Oklahoma, derived by Mitchell and Landisman (1971), is used exclusively for locating Oklahoma earthquakes. This model and three other Oklahoma models are outlined on the Observatory Web site at **http://www.okgeosurvey1.gov/level2/geology/ok.crustal.models.html.**

Each hypocenter is usually run in a preliminary form using the first four or so P and/or S arrivals from about four stations. Later, after all seismograms have been read, a final location is determined. The solutions are added manually to a catalog on the Observatory Web site at **http://www.okgeosurvey1.gov/level2/okeqcat/okeqcat.2002.html.**

DISTRIBUTION OF OKLAHOMA EARTHQUAKES, 2003

All Oklahoma earthquakes recorded on seismograms from three or more stations are located. In 2003, 47 Oklahoma earthquakes were located (Fig. 2; Table 2). Nine earthquakes were reported felt (Table 3). The felt and observed effects of earthquakes generally are given values according to the Modified Mercalli Intensity scale, which assigns a Roman numeral to each of 12 levels described by effects on humans, man-made constructions, or natural features (Table 4).

On June 6, a magnitude 2.3 (mbLg) earthquake (event no. 1715) occurred in eastern Jefferson County ~10 km south of Ringling (Tables 2, 3). This earthquake was reported felt by an individual living in Ringling; it produced MM IV effects. A

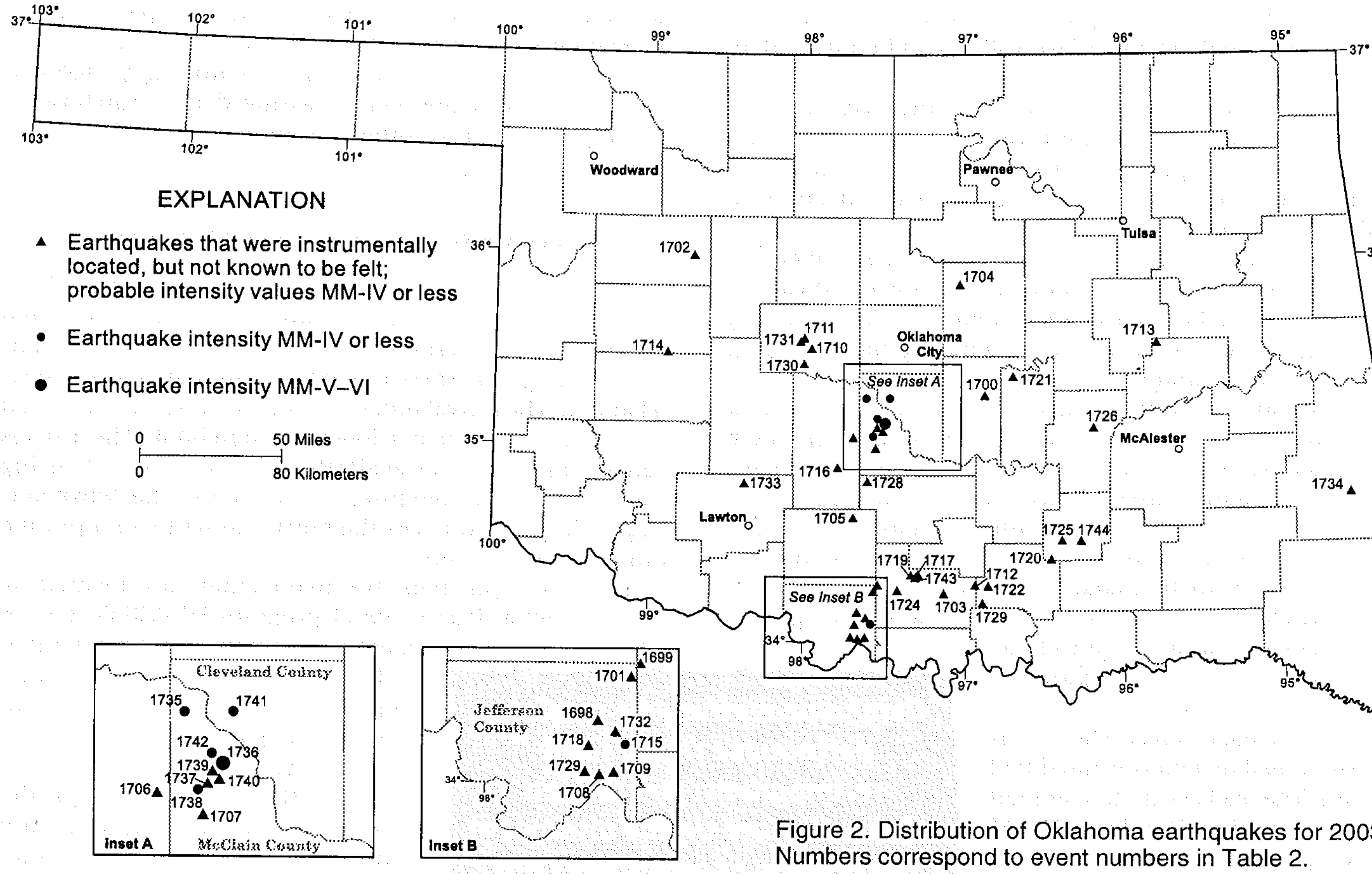

Figure 2. Distribution of Oklahoma earthquakes for 2003. Numbers correspond to event numbers in Table 2.

magnitude 2.3 (mbLg) earthquake (event no. 1723) occurred in McClain County on September 11 (Tables 2, 3). The earthquake occurred ~5 km west of Washington and was felt by a couple in Moore; it produced MM II effects. On October 31, a magnitude 1.8 (MDUR) earthquake (event no. 1730) was centered ~8 km northeast of Union City (Tables 2, 3). The earthquake was felt by residents in Union City; it produced MM IV effects. They reported hearing a rumbling sound and a chair moved side to side.

On December 8–11, nine earthquakes occurred in north-central McClain and western Cleveland Counties. (Such a series of minor earthquakes is sometimes referred to as an earthquake swarm). Six of the nine earthquakes were reported felt (Table 3). Magnitude values ranged from 1.8 (m3Hz) to 2.4 (mbLg). The December 8th earthquake (event no. 1736), which occurred at 1:18 p.m., was felt over 11,000 km^2 (Fig. 3); it produce MM V effects in Norman. Felt reports (54), of which 46 reports were from Norman, were described in Norman as: "heard a rumbling sound followed by windows rattling; we heard a loud boom; we could hear dishes rattle; building shook." The December 11th earthquake (event no. 1742) had a magnitude value of 2.4 (mbLg), about the same size as event no. 1736, and generated only nine felt reports. The felt area was considerably smaller, about 100 km^2 (Fig. 4). This earthquake was reported felt in Tuttle, Newcastle, and Norman; it produced MM IV effects in Newcastle and Norman.

In 2003, earthquake-magnitude values ranged from a low 1.1 (MDUR) in McIntosh County (event no. 1713) to a high of 2.6 (mbLg) in Garvin County (event no. 1728) (Table 2). Nine earthquakes were located in McClain County. Jefferson County experienced eight earthquakes and Carter County had seven earthquakes. Other counties that experienced multiple earthquakes include Canadian (four), Coal (three), Grady (two), and Grady (two). The first known felt earthquake located in Cleveland County occurred December 10 (event no. 1741).

CATALOG

For both preliminary and final locations, the catalog of Oklahoma earthquakes is in HTML (World Wide Web) format; one HTML page contains all of the earthquakes that occurred in one year (a single page lists earthquakes for multiple years prior to 1977). In order to assure absolute uniformity, the catalog is stored only in HTML format. One copy is on a ONENet server. (ONENet is the network of the Oklahoma Regents for Higher Education.) This server copy, at the World Wide Web address **http://www.okgeosurvey1.gov**, is used both for public distribution and for in-house reference. A second (backup) copy is on a Sun SPARC20 workstation at the Observatory in Leonard.

Each event in the catalog is sequentially numbered and arranged according to date and origin time. The numbering system is compatible with the system used by Lawson and Luza (1980–1990, 1993–2003), Lawson and others (1991,

TABLE 2. — OKLAHOMA EARTHQUAKE CATALOG FOR 2003

Event no.	Date and origin time (UTC)[a]		County	Intensity MM[b]	Magnitudes m3Hz	mbLg	MDUR	Latitude deg N[c]	Longitude deg W[c]	Depth (km)[c]
1698	Jan 12	03 57 19.52	Jefferson		1.7		1.8	34.141	97.684	5.00R C
1699	Jan 12	11 40 29.51	Carter				2.0	34.280	97.556	5.00R C
1700	Jan 20	04 38 52.59	Pottawatomie		1.4		1.8	35.260	96.873	5.00R C
1701	Feb 18	10 06 23.08	Jefferson		1.8		1.8	34.249	97.583	5.00R C
1702	Feb 21	07 55 07.01	Dewey		2.0		1.9	35.966	98.736	5.00R C
1703	Mar 10	17 36 45.97	Carter				1.5	34.238	97.139	5.00R C
1704	Mar 19	04 21 50.81	Lincoln		2.1		2.2	35.822	97.030	5.00R C
1705	Mar 19	04 28 56.94	Stephens		1.6			34.630	97.708	5.00R C
1706	Mar 20	17 28 58.83	Grady		2.2			35.042	97.709	5.00R C
1707	Mar 31	21 57 09.89	McClain				1.9	34.991	97.568	5.00R C
1708	Apr 07	10 02 13.68	Jefferson		2.2		2.4	34.004	97.676	5.00R C
1709	Apr 08	10 17 55.88	Jefferson		1.8		2.2	34.013	97.636	5.00R C
1710	Apr 26	23 05 35.14	Canadian		1.7		2.1	35.498	97.978	5.00R C
1711	Apr 27	02 59 07.49	Canadian		1.8		2.2	35.539	98.024	5.00R C
1712	May 05	16 57 52.24	Carter				1.8	34.283	96.943	5.00R C
1713	May 10	15 40 25.94	McIntosh				1.1	35.530	95.789	5.00R C
1714	May 22	09 20 13.19	Custer		1.6		1.9	35.471	98.897	5.00R C
1715	Jun 06	04 41 24.75	Jefferson	IV	2.2	2.3	2.2	34.086	97.599	5.00R C
1716	Jun 12	20 54 13.84	Grady		1.9		1.8	34.889	97.804	5.00R C
1717	Jun 19	01 35 13.77	Carter		1.8	1.8	2.0	34.342	97.302	5.00R C
1718	Jun 22	14 11 17.66	Jefferson		2.2	2.1	2.4	34.078	97.698	5.00R C
1719	Jul 16	20 51 41.37	Carter		2.3	2.2	2.0	34.333	97.324	5.00R C
1720	Jul 20	00 48 50.30	Coal		2.5		2.6	34.420	96.461	5.00R C
1721	Jul 20	15 25 07.39	Seminole		2.3		2.6	35.359	96.698	5.00R C
1722	Sep 11	01 03 41.02	Johnston				1.8	34.280	96.862	5.00R C
1723	Sep 20	15 48 48.46	McClain	II	2.3	2.3	2.4	35.074	97.527	9.69 C
1724	Sep 23	17 32 12.24	Carter		2.0		1.8	34.257	97.429	5.00R C
1725	Oct 12	22 09 40.76	Coal		2.0	1.9	2.1	34.520	96.387	5.00R C
1726	Oct 22	07 53 53.78	Hughes		1.2		1.8	35.090	96.184	5.00R C
1727	Oct 24	15 17 48.42	Johnston				2.1	34.192	96.894	5.00R C
1728	Oct 24	15 59 03.62	Garvin		2.5	2.6	2.6	34.822	97.622	5.00R C
1729	Oct 29	04 49 12.25	Jefferson		2.2		1.9	34.018	97.719	5.00R C
1730	Oct 31	20 42 28.21	Canadian	IV			1.8	35.422	98.024	5.00R C
1731	Nov 01	04 34 22.90	Canadian				2.2	35.532	98.036	5.00R C
1732	Nov 15	12 33 48.50	Jefferson		2.0		2.0	34.107	97.620	5.00R C
1733	Dec 02	13 23 39.94	Comanche		2.2		1.9	34.806	98.403	5.00R C
1734	Dec 03	18 15 10.36	Le Flore		2.1			34.762	94.588	5.00R C
1735	Dec 08	15 39 32.45	McClain	III	2.2		2.3	35.249	97.626	5.00R C
1736	Dec 08	19 18 08.04	McClain	V	2.4	2.4	2.4	35.120	97.525	5.00R C
1737	Dec 09	04 54 11.28	McClain				2.1	35.091	97.554	5.00R C
1738	Dec 09	06 08 56.06	McClain	III	1.8		2.0	35.056	97.584	5.00R C
1739	Dec 09	06 31 17.55	McClain	F	1.9		2.0	35.108	97.541	5.00R C
1740	Dec 09	21 27 43.65	McClain		1.8		2.0	35.096	97.544	5.00R C
1741	Dec 10	19 15 30.20	Cleveland	F			2.4	35.247	97.479	5.00R C
1742	Dec 11	16 35 09.09	McClain	IV	2.5	2.4	2.4	35.138	97.540	5.00R C
1743	Dec 11	18 51 30.03	Carter				1.5	34.328	97.310	5.00R C
1744	Dec 18	06 24 34.51	Coal		1.4			34.515	96.270	5.00R C

[a]UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time. The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the second. To convert to local Central Standard Time, subtract six hours.

[b]Modified Mercalli (MM) earthquake-intensity scale (see Table 4). "F" indicates earthquake was reported felt, intensity unknown, generally ≤IV.

[c]If R is preceded by a number in the latitude and/or longitude column(s), the location was restrained. 5.00R indicates that the depth was restrained to 5.00 km from the beginning of the calculation. If R is preceded by a number other than 5.00, the depth was restrained at that depth part way through the location calculations. When R does not appear, the number was an unrestrained depth, re-adjusted at every iteration during the location. C refers to the Chelsea velocity model (Mitchell and Landisman, 1971).

TABLE 3. — Earthquakes Reported Felt in Oklahoma, 2003

Event no.	Date and origin time (UTC)[a]					Nearest city	County	Intensity MM[b]
1715	Jun	06	04	41	24.75	10 km S of Ringling	Jefferson	IV
1723	Sep	20	15	48	48.46	5 km W of Washington	McClain	II
1730	Oct	31	20	42	28.21	8 km NE of Union City	Canadian	IV
1735	Dec	08	15	39	32.45	3 km W of Newcastle	McClain	III
1736	Dec	08	19	18	8.04	6 km SW of Goldsby	McClain	V
1738	Dec	09	06	08	56.06	4 km NE of Dibble	McClain	III
1739	Dec	09	06	31	17.55	8 km SW of Goldsby	McClain	F
1741	Dec	10	19	15	30.20	4 km NW of Norman	Cleveland	F
1742	Dec	11	16	35	9.09	6 km SW of Goldsby	McClain	IV

[a]UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time. The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the second. To convert to local Central Standard Time, subtract six hours.
[b]Modified Mercalli (MM) earthquake-intensity scale (see Table 4). "F" indicates earthquake was reported felt, intensity unknown, generally ≤IV.

1992), and for the *Earthquake Map of Oklahoma* (Lawson and Luza, 1995b). The sequential event number is not found on the World Wide Web catalog.

The dates and times for the cataloged earthquakes are given in UTC. UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time. The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the seconds. To convert to local Central Standard Time, subtract six hours.

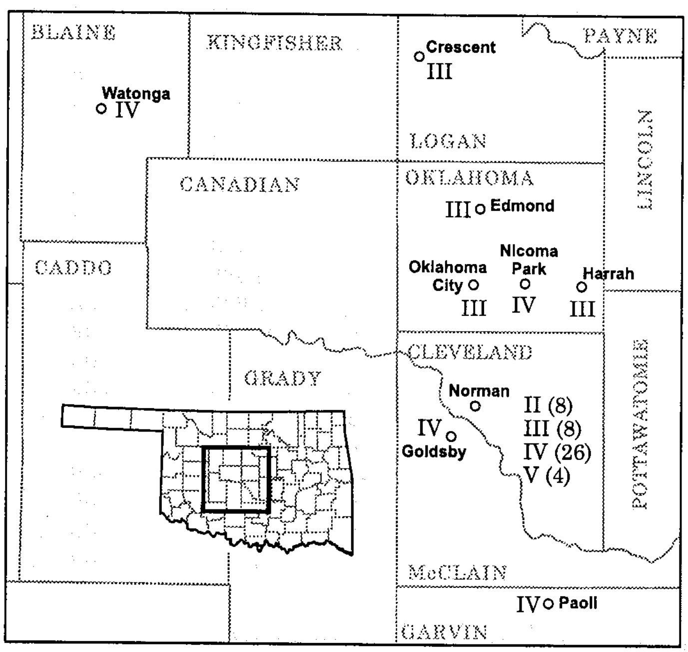

Figure 3. Modified Mercalli (MM) intensity values (Roman numerals) for the December 8 earthquake (event no. 1736) in Cleveland County (Tables 2, 3). Numbers in parentheses indicate the number of felt reports for each location. Intensity values by themselves indicate single reports.

Earthquake magnitude is a measurement of energy and is based on data from seismograph records. The magnitude of a local earthquake is determined by taking the logarithm (base 10) of the largest ground motion recorded during the arrival of a seismic-wave type and applying a standard correction for distance to the epicenter. An increase of one unit in the magnitude value corresponds to a tenfold increase in the amplitude of the earthquake waves. There are several different scales used to report magnitude. Table 2 has three magnitude scales, which are mbLg (Nuttli), m3Hz (Nuttli), and MDUR (Lawson). Each magnitude scale was established to accommodate specific criteria, such as the distance from the epicenter, as well as the availability of certain seismic data.

For earthquake epicenters located 11–222 km from a seismograph station, Otto Nuttli developed the m3Hz magnitude scale (Zollweg, 1974). This magnitude is derived from the following expression:

$$m3Hz = \log(A/T) - 1.63 + 0.87 \log(\Delta),$$

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Lg waves, near 3 Hz in frequency, measured in nanometers; T is the period of the Lg waves measured in seconds; and Δ is the great-circle distance from epicenter to station measured in kilometers.

In 1979, St. Louis University (Stauder and others, 1979, p. 28) modified the formulas for m3Hz. The OGS Observatory has used this modification since January 1, 1982. The modified formulas have the advantage of extending the distance range for measurement of m3Hz out to 400 km, but they also have the disadvantage of increasing m3Hz by about 0.12 units compared to the previous formula. Their formulas

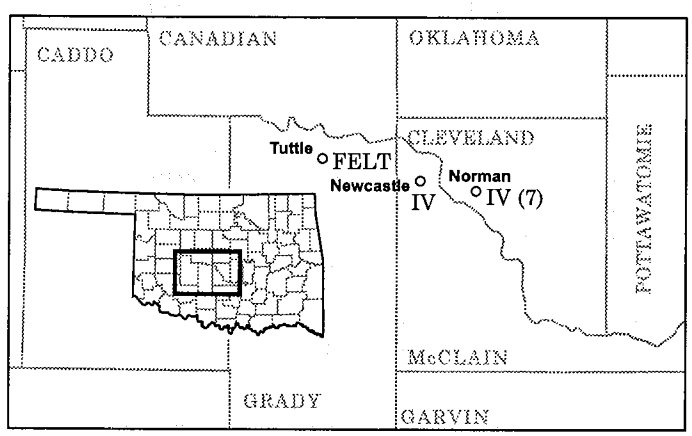

Figure 4. Modified Mercalli (MM) intensity values (Roman numerals) for the December 11 earthquake (event no. 1742) in McClain County (Tables 2, 3). Numbers in parentheses indicate the number of felt reports for each location. Intensity values by themselves indicate single reports.

TABLE 4. — MODIFIED MERCALLI (MM) EARTHQUAKE-INTENSITY SCALE
(Abridged) (Modified from Wood and Neumann, 1931)

I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings. Automobiles may rock slightly.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, doors, windows disturbed. Automobiles rocked noticeably.
V	Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction. Shock noticed by persons driving automobiles.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings; great in poorly built structures. Fall of chimneys, stacks, columns. Persons driving automobiles disturbed.
IX	Damage considerable even in specially designed structures; well-designed frame structures thrown out of plumb. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed; ground badly cracked, rails bent. Landslides and shifting of sand and mud.
XI	Few if any (masonry) structures remain standing. Broad fissures in ground.
XII	Damage total. Waves seen on ground surfaces.

were given in terms of log(A) but were restricted to wave periods of 0.2–0.5 sec. In order to use log(A/T), we assumed a period of 0.35 sec in converting the formulas for our use. The resulting equations are:

(epicenter 10–100 km from a seismograph)

$$\text{m3Hz} = \log(A/T) - 1.46 + 0.88 \log(\Delta)$$

(epicenter 100–200 km from a seismograph)

$$\text{m3Hz} = \log(A/T) - 1.82 + 1.06 \log(\Delta)$$

(epicenter 200–400 km from a seismograph)

$$\text{m3Hz} = \log(A/T) - 2.35 + 1.29 \log(\Delta).$$

Otto Nuttli's (1973) earthquake magnitude, mbLg, for seismograph stations located 55.6–445 km from the epicenter, is derived from the following equation:

$$\text{mbLg} = \log(A/T) - 1.09 + 0.90 \log(\Delta).$$

Where seismograph stations are located between 445 and 3,360 km from the epicenter, mbLg is defined as:

$$\text{mbLg} = \log(A/T) - 3.10 + 1.66 \log(\Delta),$$

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Lg waves, near 1 Hz in frequency, measured in nanometers; T is the period of Lg waves measured in seconds; and Δ is the great-circle distance from epicenter to station measured in kilometers.

The MDUR magnitude scale was developed by Lawson (1978) for earthquakes in Oklahoma and adjacent areas. It is defined as:

$$\text{MDUR} = 1.86 \log(\text{DUR}) - 1.49,$$

where DUR is the duration or difference, in seconds, between the Pg-wave arrival time and the time the final coda amplitude decreases to twice the background-noise amplitude. Before 1981, if the Pn wave was the first arrival, the interval between the earthquake-origin time and the decrease of the coda to twice the background-noise amplitude was measured instead. Since January 1, 1982, the interval from the beginning of any P wave (such as Pg, P*, and/or Pn) to the decrease of the coda to twice the background-noise amplitude has been used.

Earthquake detection and location accuracy have been greatly improved since the installation of the statewide network of seismograph stations. The frequency of earthquake events and the possible correlation of earthquakes to specific tectonic elements in Oklahoma are being studied. It is hoped that this information will provide a more complete data base that can be used to develop numerical estimates of earthquake risk that give the approximate frequency of earthquakes of any given size for various regions of Oklahoma. Numerical risk estimates could be used for better design of large-scale structures, such as dams, high-rise buildings, and power plants, as well as to provide the information necessary to evaluate insurance rates.

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James King and Amie Friend maintain the OGS Observatory at Leonard. Volunteer seismograph-station operators and landowners at various locations in Oklahoma make possible the operation of a statewide seismic network.

This work was funded directly by the Oklahoma Geological Survey. The GSE digital seismic system, provided by the Defense Advanced Research Projects Agency/Nuclear Monitoring Research Office, considerably enhanced the OGS's ability to analyze Oklahoma earthquakes. A borehole seismic system, a joint project with the Lawrence Livermore National Laboratories, was useful in recording Oklahoma earthquakes. The three-component broadband Guralp seismometer in the 864-m borehole and the Guralp data acquisition system were funded by a DARPA-DEPSCoR grant. The Observatory exists because of building and land-purchase gifts from Jersey Production Research Co. (now merged into Exxon) and the Sarkeys Foundation.

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OGS Workshop

MORROW AND SPRINGER STRATA IN THE SOUTHERN MIDCONTINENT

May 10–11, 2005 ❖ Oklahoma City

This workshop will examine contemporary and new concepts relevant to exploration and development of sandstone and carbonate reservoirs specific to Morrow- and Springer-age deposits in the southern Midcontinent. A two-day program co-sponsored by the Oklahoma Geological Survey and the U.S. Department of Energy, National Energy Technology Laboratory, Tulsa, Oklahoma, will focus on reservoir characterization, exploration and development methods, seismic modeling, depositional and facies interpretations, secondary and tertiary oil recovery, subsurface mapping, well log procurement and interpretation, and regional trend analysis. In addition to the 21 oral papers listed below, there will be poster presentations and industry exhibits.

- **Morrow and Springer Strata in the Southern Midcontinent**, by Richard D. Andrews, *Oklahoma Geological Survey, Norman, Oklahoma*
- **Controls on Porosity Origin, Presentation, Reduction, and Restoration in Two Types of Morrow Reservoirs in Western Oklahoma**, by Bruce Carpenter, *Log Experts, Edmond, Oklahoma*
- **The Springer Gas Play Development—Anadarko Basin**, by Tim O. Brown, *DrillingInfo, Inc., Austin, Texas*; and Robert A. Northcutt, *Independent, Oklahoma City, Oklahoma*
- **Depositional and Diagenetic Controls on Compartmentalization of the Cunningham and Britt Sandstones, Southeastern Anadarko Basin**, by James Puckette, *Oklahoma State University, Stillwater, Oklahoma*; and Aaron Rice, *Glenpool, Oklahoma*
- **Regional Sequence Stratigraphy and Depositional Environments of the Lower Pennsylvanian in Southwest Kansas**, by Galo A. Salcedo and Timothy R. Carr, *Kansas Geological Survey, Lawrence, Kansas*
- **Sequence Stratigraphic Control on Reservoir Quality in the Upper Morrow Sandstone, Northwestern Shelf, Anadarko Basin**, by James Puckette and Zuhair Al-Shaieb (deceased), *Oklahoma State University, Stillwater, Oklahoma*; and Erin Van Evera, *UNOCAL 76, Midland, Texas*
- **Fighting the Tide: Morrow-Springer Gas in Oklahoma**, by Dan T. Boyd, *Oklahoma Geological Survey, Norman, Oklahoma*
- **Examples of Trapping Mechanisms in the Cromwell Sandstone (Morrowan), Hughes County, Oklahoma**, by Maxwell J. Tilford, *Tilford-Pinson Exploration, Edmond, Oklahoma*
- **Cromwell Sandstone Sequence Stratigraphy and Porosity Development in Kinta Field, Haskell County, Oklahoma**, by Bryant Reasnor, *Chevron-Texaco, Midland, Texas*; and Dennis R. Kerr, *University of Tulsa, Tulsa, Oklahoma*
- **Hunting for Overlooked Pay in Midcontinent Carbonates**, by Edward A. Beaumont, *Independent, Tulsa, Oklahoma*; and Dan J. Hartmann, *Independent, Fredericksburg, Texas*
- **The Concept of Intermittent Structure and Its Influence on Morrow and Springer Deposition**, by Kurt Rottmann, *Independent, Oklahoma City, Oklahoma*
- **Morrowan to Lower Atokan Structural Evolution of the Frontal Ouachitas and Arkoma Basin, Southeastern Oklahoma**, by Ibrahim Çemen, James Puckette, Rodney Feller, Steve Hadaway, and Ata Sagnak, *Oklahoma State University, Stillwater, Oklahoma*
- **Deep-Gas Well Stimulation of the Springer in the Anadarko Basin**, by Steve Wolhart, *Pinnacle Technologies, Inc., Houston, Texas*
- **Logging Tool Deployment Methods that Insure the Acquisition of Accurate Log Data over Morrow and Springer Strata**, by Mark W. Houpe, *Precision Wireline Services, Oklahoma City, Oklahoma*
- **Imaging Thin Morrow and Springer Sands with High-Frequency 3D Seismic in the Anadarko Basin**, by Bob Springman, *Dominion Exploration and Production, Inc., Oklahoma City, Oklahoma*
- **Structural and Stratigraphic Reservoir Types in the Jackfork Group of Eastern Oklahoma**, by Roger M. Slatt, *University of Oklahoma, Norman, Oklahoma*
- **Overview of Postle Field, Morrow CO_2 Flood, Texas County, Oklahoma**, by John Southwell, *Celero Energy, Midland, Texas*
- **Geo-Engineering Modeling of Morrow/Atoka Incised-Valley Fill Deposits Using Web-Based Freeware for Incremental Field Exploitation**, by W. Lynn Watney, Saibal Bhattacharya, Alan Byrnes, John Doveton, and John Victorine, *Kansas Geological Survey, Lawrence, Kansas*; and Rick Brownrigg, *University of Kansas, Lawrence, Kansas*
- **Trends in Composition of Morrowan Gases in Southwestern Kansas**, by K. David Newell, *Kansas Geological Survey, Lawrence, Kansas*
- **Iodine Production from Morrowan Sandstones, Anadarko Basin, Northwestern Oklahoma**, by Stan Krukowski, *Oklahoma Geological Survey, Norman, Oklahoma*
- **Secondary Oil Recovery from the Upper Morrow Purdy Sandstone in Rice NE Field, Texas County, Oklahoma**, by Richard D. Andrews, *Oklahoma Geological Survey, Norman, Oklahoma*

REGISTRATION INFORMATION

The fee for advance registration (*by May 2*) is $85 and includes lunches and a copy of the proceedings; late and on-site registration is $95. Students rates are available.

For more information, contact Rick Andrews (email: rdandrews@ou.edu), Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031 *or* toll-free (800) 330-3996. For registration forms, contact Tammie Creel (tcreel@ou.edu) at the same address and phone numbers.

new OGS publications

CIRCULAR 109

• **Kenneth S. Johnson and James T. Neal, *editors***

• **353 pages**

• **Paperbound, laminated cover**

• **$20**

Evaporite Karst and Engineering/Environmental Problems in the United States

Evaporite rocks, mainly gypsum and salt, are the most soluble of the common rocks. Evaporites underlie about 35–40% of the contiguous United States, and are present in 32 of the 48 states. They dissolve readily to form caves, sinkholes, disappearing streams, drainage problems, and other karst features typically associated with carbonate rocks (limestone and dolomite). Evaporite karst (EK) is much more widespread than is commonly suspected.The most pronounced examples of problems in both gypsum karst and salt karst are in the Permian Basin of the southwestern U.S., but many other areas also have significant problems. EK can result from natural processes as well as from human activities, and is known to be be present at least locally (and sometimes quite extensively) in almost all areas underlain by evaporites. Because evaporite dissolution is so rapid, EK features can quickly produce engineering or environmental problems that are hazards to humans and property, causing great econmic hardship, disruption of lives, and even loss of life.

This volume is based on a half-day theme session on evaporite karst that was held on October 28, 2002, in Denver, Colorado, as part of the annual meeting of the Geological Society of America. The EK session was held because of the growing awareness of karst problems in evaporite rocks. Although evaporite deposits and their associated karst problems are widespread in the United States, they have received scant attention from most geologists. The 33 papers contained in this volume are grouped by geographic areas and provide insight into significant engineering and/or environmental problems related to EK.

SPECIAL PUBLICATION 2004-1

• **James R. Chaplin**

• **173 pages**

• **Paperbound, laminated cover**

• **$16**

Core Drilling and Stratigraphic Analysis of Lower Permian Rocks, Northern Oklahoma Shelf, Kay County, Oklahoma

The purpose of this investigation was to obtain information about the local bed sequence, thickness variations, stratigraphic-boundary relationships, and regional facies changes in Early Permian rocks in Kay County, Oklahoma. The new core-hole data supplemented data gathered from the examination of surface rocks for the purpose of constructing an areal geologic map of Kay County. The purpose of the new data was to evaluate the accuracy of existing interpretations of stratigraphy and structure.

Detailed descriptions of lithologic units cored in 10 holes and the description of one measured surface section, as well as stratigraphic interpretations, are presented in this report. These detailed descriptions are the first published data describing a continuous stratigraphic sequence from this interval of Early Permian rocks in central northern Oklahoma. Reevaluations of published geologic interpretations, and comparison with new core-hole data, resulted in revisions of earlier geologic mapping in Kay County.

Circular 109 and Special Publication 2004-1 can be purchased by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; fax 405-325-7069. To mail order, add 20% to the cost for postage, with a minimum of $2 per order.

All OGS publications can be purchased over the counter at the OGS Publication Sales Office, 2020 Industrial Blvd., Norman; phone (405) 360-2886, fax 405-366-2882, e-mail ogssales@ou.edu. Request the OGS *List of Available Publications* for current listing and prices.

2004 Industrial Minerals Forum Held in Indiana

The 40th Annual Forum on the Geology of Industrial Minerals attracted 200 attendees on May 2–7, 2004, in Bloomington, Indiana. The Forum is a loosely organized group of geologists, engineers, and mineral operators who meet annually to discuss the latest trends in exploration, mining, and marketing of industrial minerals. Participants come from industry, academia, and government. Industrial minerals are the non-fuel, non-metal resources that are so important to our economy, to the construction industry, and to the everyday needs of society. Industrial minerals include limestone, granite, gypsum, salt, cement, clays, iodine, and sand and gravel, and many other rock and mineral products.

The 40th Forum was chaired by Nelson R. Shaffer and hosted by the Indiana Geological Survey (IGS). The program emphasized mineral resources and developments in the Midwest, but also included many papers covering topics in the U.S. as well as overseas. A total of 56 talks and 14 posters were presented on topics including strategic minerals, dimension stone, geophysics, mining in karst, clay resources, mineral byproducts, and education and outreach. Seven field trips highlighted the diversity of industrial minerals and the challenges to mining in various parts of Indiana. The 41st Forum will be held in Istanbul, Turkey, on May 22–28, 2005.

Representing the Oklahoma Geological Survey (OGS) at the 40th Forum were Stanley T. Krukowski, industrial-minerals geologist, and Kenneth S. Johnson, emeritus geologist and former associate director. Krukowski is past chair of the Forum Steering Committee, and he co-chaired both the 35th Forum (1999) in Salt Lake City, Utah, and the 39th Forum (2003) in Reno, Nevada. Johnson chaired two earlier Forums—the 13th (1977) and the 34th (1998)—that were hosted by the OGS in Norman, Oklahoma.

At the 40th Forum in Bloomington, Johnson presented a talk and paper on "Karst Problems in Mining Salt Deposits in the United States." Papers of all the talks and posters presented in Bloomington will be published in a proceedings volume by the Indiana Geological Survey. Additional information on the 40th Forum and how to order the proceedings volume are available from the IGS at **http://igs.indiana.edu/imforum**, or email shaffern@ Indiana.edu, or phone (812) 855-7636.

The OGS published two volumes after hosting the Forums in 1977 and 1998; both publications are still available. OGS Circular 79, *Thirteenth Annual Forum on the Geology of Industrial Minerals*, was edited by Johnson and J. A. Russell. Principal themes of the 13th Forum included gypsum, silica-rich sediments, natural brines, and energy in the industrial minerals industry. OGS Circular 102, *Proceedings of the 34th Forum on the Geology of Industrial Minerals*, edited by Johnson, contains 45 papers and five abstracts that focus on industrial minerals in Oklahoma and adjacent states, as well as topics important throughout the U.S. and overseas.

Circular 79 is 107 pages and costs $7.00 (clothbound) or $5.00 (paperbound); Circular 102 is 364 pages and costs $15.00 (paperbound only). To order, contact the Oklahoma Geological Survey, Publication Sales Office, 2020 Industrial Blvd., Norman, OK 73069; phone (405) 360-2886, fax 405-366-2882, email ogssales@ou.edu, and Web site **http://www.ogs.ou.edu**. Mailing costs in the United States are an additional 20%; for international shipping costs, including Canada and Mexico, contact the Sales Office. All purchases must be by check or money order, drawn in U.S. currency.

—*Kenneth S. Johnson*

Annual Meetings of the Forum on the Geology of Industrial Minerals

1st	1965	Columbus, Ohio
2nd	1966	Bloomington, Indiana
3rd	1967	Lawrence, Kansas
4th	1968	Austin, Texas
5th	1969	Harrisburg, Pennsylvania
6th	1970	Ann Arbor, Michigan
7th	1971	Tampa, Florida
8th	1972	Iowa City, Iowa
9th	1973	Paducah, Kentucky
10th	1974	Columbus, Ohio
11th	1975	Kalispell, Montana
12th	1976	Atlanta, Georgia
13th	1977	Norman, Oklahoma
14th	1978	Albany, New York
15th	1979	Golden, Colorado
16th	1980	St. Louis, Missouri
17th	1981	Albuquerque, New Mexico
18th	1982	Bloomington, Indiana
19th	1983	Toronto, Ontario, Canada
20th	1984	Baltimore, Maryland
21st	1985	Tucson, Arizona
22nd	1986	Little Rock, Arkansas
23rd	1987	North Aurora, Illinois
24th	1988	Greenville, South Carolina
25th	1989	Portland, Oregon
26th	1990	Charlottesville, Virginia
27th	1991	Banff, Alberta, Canada
28th	1992	Martinsburg, West Virginia
29th	1993	Long Beach, California
30th	1994	Fredericton, New Brunswick/ Halifax, Nova Scotia, Canada
31st	1995	El Paso, Texas
32nd	1996	Laramie, Wyoming
33rd	1997	Quebec City, Quebec, Canada
34th	1998	Norman, Oklahoma
35th	1999	Salt Lake City, Utah
36th	2000	Bath, England
37th	2001	Victoria, British Columbia, Canada
38th	2002	St. Louis, Missouri
39th	2003	Reno, Nevada
40th	2004	Bloomington, Indiana
41st	2005	Istanbul, Turkey

OGS and OU Participate in OERB Educators' Retreat

The Oklahoma Energy Resources Board (OERB) conducted an educators' retreat on August 9–10, 2004, in Oklahoma City and Norman for more than 88 science teachers from throughout the State, representing 53 school sites and 49 school districts. The retreat acquainted the teachers with OERB energy curricula such as "Fossils to Fuel," a hands-on six-week program for elementary school students to learn about energy basics. Another six-week program, "Petro Active," is for middle school students; it provides information about the formation and recovery of petroleum and natural gas. The newest OERB program, "Core Energy," is for high school students. The courses also include exercises about energy that can be performed in the classroom or laboratory. OERB is located on the Web at **http://www.oerb.com**.

On the first day of the retreat, teachers visited an operating drill rig and natural gas well to observe energy resource recovery methods. On the second day, they toured the Oklahoma Geological Survey's Oklahoma Petroleum Information Center (OPIC), which opened in 2002 and soon will be the largest petroleum information center in the country. This facility integrates an impressive petroleum and geological collection, housing drill cores and samples, well logs, and other well data from Oklahoma and other petroleum producing states. The Survey's core collection has expanded with contributions from BP America; Ardmore Sample Cut and Library; ChevronTexaco of New Orleans; Amoco, Denver (Shawnee Sample Cut); Samson Resources Company; Vintage Petroleum; Devon Energy; and several individuals who have contributed private collections. These cores are now available for research and analysis by students and companies. OPIC sells OGS publications and U.S. Geological Survey (USGS) topographic maps. OPIC also offers core imaging, preparation, and viewing services. After an introduction by OERB Executive Director Mike Terry, Dr. Charles J. Mankin, Director of the OGS and the University of Oklahoma Sarkeys Energy Center, served as host and tour leader during the stop; he was assisted by OPIC Acting Manager Gene Kuhllmann.

Later in the day at Sarkeys Energy Center on the OU campus, two workshops were conducted by OGS staff geologists. Galen Miller provided a first-hand look at digital mapping in a presentation titled "Geologic Mapping in Oklahoma: STATEMAP and Mapping You Can Use." Miller showed how to map underground gypsum caves and how to apply the results—in one case, showing how mapping aids the Oklahoma Department of Transportation in recognizing potential geological hazards in highway construction. A second exercise showed teachers how to use the Internet, air photos, and topographic maps to locate their schools; this was made possible by the USGS's contribution of topographic map indices for all the teachers.

In a second presentation, "Industrial Minerals: The Everyday Minerals in Our Lives," Stan Krukowski showed the practical side of Oklahoma's mining industry, and he

OGS geologist Stan Krukowski presented examples of various industrial minerals produced in Oklahoma and explained how they are used in home building and ordinary household items.

demonstrated the value of industrial minerals to the economy of Oklahoma. Examples of various minerals produced in the State were shown to the teachers, and it was illustrated how the minerals are used in home building and ordinary household items.

OGS provided a packet of literature on the petroleum and mining industries, as well as information on the geology of Oklahoma. Additional educational materials included minerals and mapping Web-site locations, earth science teaching resources, and information on careers in earth sciences. For each teacher, OGS contributed a pair of barite roses, Oklahoma's official State rock, and OERB added a copy of the laminated poster *Oklahoma Generalized Geologic Time Scale* (OGS Educational Publication 6). The Interstate Oil and Gas Compact Commission contributed the booklet *The Petroleum Pros* to the packet.

Caterpillar provided copies of *Modern Mining and You*, which includes the videos "Common Ground," "Promoting Good Science in the Classroom," "Education Works! Kids Talk About Mining," and the companion "Teaching Aids"—a teacher's guide with classroom exercises. Copies of Caterpillar's new hot-off-the-press compact disc *Adventures in Mineral Education: Classroom Activities for K–12* also were distributed to the group and demonstrated after the OGS presentations. Caterpillar furnished a canvas tote bag to contain the information packets.

In a drawing immediately following the OGS presentations, two lucky teachers received copies of the USGS wall poster *Mineral Resources: Out of the Ground...Into Our Daily Lives*, and a third teacher won an OGS golf shirt. Copies of the wall poster can be downloaded at **http://geopubs.wr.usgs.gov/open-file/of01-360/**. Lunch was provided by OERB and served in the east atrium of Sarkeys Energy Center. After lunch, teachers had the opportunity to visit booths representing various OU earth science departments in the College of Geosciences.

—*Stanley T. Krukowski*

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.

Improving Bedrock Geological Mapping Through the Use of Digital Soil Maps and Surveys

MARISSA D. RAGLIN and *STANLEY T. PAXTON*, School of Geology, Oklahoma State University, 105 Noble Research Center, Stillwater, OK 74078; and *BRIAN J. CARTER*, Dept. of Plant and Soil Sciences, Oklahoma State University, 368 Agriculture Hall, Stillwater, OK 74078

Most soil scientists and geologists know that the character of residual soil is closely linked to the nature of the underlying bedrock. For this reason, use of soil surveys to facilitate mapping of bedrock geology is deemed common practice. In the past era of paper maps, however, geologists became quickly overwhelmed by the reams of detailed data available from county soil surveys for incorporation into their geological mapping programs. Consequently, soil surveys have probably not been utilized to the fullest extent possible in some bedrock mapping efforts. With the advent and availability of digital data sets via GIS, however, soil surveys can now be easily incorporated in geological mapping efforts. The digital soil maps are particularly valuable in unglaciated settings where bedrock exposures are limited (areas with subtle topographic relief).

For the state of Oklahoma, we used available digital soil maps as well as soil surveys for each of the counties to create a new bedrock geology map. Using the MIADS soil data, we mapped the bedrock based on the parent material information of the soils gleaned from the soil surveys. This exercise required the consolidation of 2406 soil mapping units. One of the challenges encountered during this step of the process was that descriptions from the soils surveys and other resources were sometimes vague or incomplete. To remedy this situation, we evaluated the geographically associated soils and their bedrock descriptions providing us with a better idea of the bedrock in question. The consolidation of the mapping units produced sixteen general categories of bedrock lithologies. These bedrock lithologies were further subdivided into about ten mapping classes of geologic time as defined by the soil surveys.

The resulting map is a representation of the bedrock geology based on the soils. This approach has the potential to improve detailed bedrock geological mapping for use in resource assessment, civil engineering, agriculture, and land preservation.

Reprinted as published in the Geological Society of America *2004 Abstracts with Programs*, v. 36, no. 5, p. 581.

New Geologic Mapping in the Tulsa Metro Area, Northeast Oklahoma

THOMAS M. STANLEY and *GALEN W. MILLER*, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019

The first round of detailed mapping of the Tulsa Metro Area, with the completion of the Claremore and Sageeyah 7.5′ Quadrangles, highlights a number of subtle lithologic and structural characteristics overlooked in previous studies of these areas, as well as providing a better understanding of the overall stratigraphic framework of the Desmoinesian section in northeast Oklahoma.

Of the lithologic changes, there are extensive Quaternary terrace deposits along the Verdigris River that were previously unreported in the Sageeyah Quad. There are also new occurrences of the Bluejacket Sandstone Member, an important subsurface marker horizon, and the underlying Savanna Formation in the Claremore Quad.

Structually, there are several broad anticlines and synclines that trend roughly northwest-southeast. These folds are best found by careful attention to outcrop pattern and noting subtle changes in bedding dip and dip direction in relation to contour of key marker horizons. Subsurface correlation of wire-line logs provides independent verification that these structures are present. Several northeast-southwest trending faults also occur. These faults appear to be normal, have displacements ranging from 15 to 50 feet, and the extension of fracture zones related to one fault may have locally influenced the course of the Verdigris River.

Some discrepancies in the overall Desmoinesian section are present. Currently, several small-scale maps of this area have erroneously placed the Boggy-Senora contact at the base of the Chelsea Sandstone, at the Tiawah Limestone, or at the top of the Upper Taft Sandstone; however, in order to conform more closely to regional stratigraphic precedence, this contact was moved down to the base of the Weir-Pittsburg coal. Further up the Desmoinesian section, some reports have placed the Sageeyah Limestone at the base of the Oologah Limestone instead of at the top of the Labette Shale. Field characteristics of the Sageeyah Limestone consisting of textural, bedding, and color differences, coupled with a sharp, irregular upper contact suggestive of an unconformity, implies it is depositionally unrelated to the overlying Oologah Limestone.

Reprinted as published in the Geological Society of America *2004 Abstracts with Programs*, v. 36, no. 5, p. 584.

The Seismic Hazard from Major Earthquakes in the Central and Eastern United States

JOHN E. EBEL, Weston Observatory, Dept. of Geology and Geophysics, Boston College, 381 Concord Road, Weston, MA 02493; and *MARTITIA P. TUTTLE*, M. Tuttle & Associates, 128 Tibbets Lane, Bay Point Road, Georgetown, ME 04548

While earthquake hazard arises from all earthquakes above about magnitude 5, major earthquakes (those of magnitude 7 or above) contribute the most to the hazard since their effects can be so devastating. In the Central and Eastern US (CEUS), it is difficult to ascertain where and how often major earthquakes are likely to occur because of their low rates of occurrence and

our poor understanding of seismogenic structures. Evidence is accumulating that major earthquakes might be generated more frequently and on more geologic structures or faults in the CEUS and nearby Canada than previously believed. Several major earthquake sequences in the New Madrid seismic zone over the past two millenia and recurrent M7 earthquakes near Charleston, SC have been documented. Less widely recognized but nevertheless significant earthquakes took place at Charlevoix, Quebec, in 1663 and perhaps in central New Hampshire in 1638. Geologic evidence has been uncovered of major prehistoric earthquakes in Holocene time on the Meers Fault in Oklahoma, in the Wabash Valley region, and in the St. Louis area. Given the past earthquake history, people in the CEUS should not discount the possibility of one or more M7+ earthquakes affecting the CEUS sometime during the 21st century.

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Final Movements Associated with Late Ancestral Rockies Deformation

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The easternmost Ancestral Rockies (AR), the Wichita Mountains and the Arbuckle Mountains of southern Oklahoma, contain an interesting paleogeomorphic and stratigraphic record documenting amount and style of tectonism near the end of the AR series of events. For example, in the Wichita Mountains area there is reasonable evidence that ~1000 m of vertical uplift, and then subsidence, occurred in the Early Permian (Wolfcampian and Leonardian). Perhaps 3× that amount of horizontal displacement is possible based on work of Donovan. These offsets are distinct from the larger and earlier Pennsylvanian uplifts of 5–7 km which formed the AR. It suggests that the tectonism responsible for the AR was episodic and probably far-field. The subsidence is even more striking than the uplift: (1) it shows that movement was concentrated locally along existing faults and did not affect the adjacent Oklahoma Permian basin; (2) it documents a relaxation (extensional) event not long after the earlier compressive event.

These conclusions are based on an understanding of the Permian paleotopography of the Wichita Mountains and of the origin of the Permian Post Oak Conglomerate (POC). The character of this locally derived unit (POC) implies a pre-existing low-relief plain. Regional Permian stratigraphy shows that this plain was near sea level. All relief related to the initial Pennsylvanian uplift had been worn away, implying some substantial time between uplift (tectonism) and formation of the plain on the uplifted block. Thus the Permian tectonism is distinct in time from the Pennsylvanian tectonism. Detailed correlations need to be made with events farther west, and east, to potentially tie this Permian event to larger regional ones.

Gilbert (2004) has argued that crustal thickening of the paleorift, the Cambrian Southern Oklahoma Aulacogen, occurred during the Pennsylvanian compression related to the formation of these Ancestral Rockies. It is not clear how this later event, the Early Permian one, is related, if at all, to this thickening process. However, because the Permian offsets seem to be specific to those existing faults bounding the paleorift, one could argue for whole crust involvement.

Reprinted as published in the Geological Society of America *2004 Abstracts with Programs*, v. 36, no. 5, p. 509.

Fracture Characterization Across a Complex Structure: Arbuckle Anticline, Oklahoma

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Detailed mapping of fractures was conducted within the Lower Paleozoic of the asymmetric Arbuckle anticline, Oklahoma. Outcrop mapping of fractures in an active petroleum system can improve prediction of hydraulically conductive fracture sets in the subsurface. Outcrops along I-35 define a north-south transect across the anticline. Fracture characterization included orientation, spacing, length, width, and timing. Fracture sets in carbonate, shale and sandstone units are related to the Pennsylvanian age Ouachita-Marathon Orogeny. The results show the dominant fracture sets on the back-limb of the fold trend NNE to NE with steep SE and NW dip. The NNE set form a common through-going set of fractures that are most likely hydraulically significant. A wide range of secondary fractures oriented E-ESE and SE with moderate N and NE dips are also observed in outcrop, but are less systematic. No persistent set of strike-parallel faults is observed across the shallow dipping limb. The fracture character is a function of the lithology, bed forms and thickness. Limestone units with thinly bedded chart layers had the greatest number of fractures with massive limestone units the least. Additional analysis focused on the density of fractures versus lithologic type and on the relationship of fractures to faults and minor folds within the basin. Fractures in the overturned forelimb show a well-developed set of strike-parallel faults. The NE trending fracture sets mapped on the shallow dipping limb are absent. The mapped fracture sets cannot be predicted from simple curvature analysis, but are most likely related to the hinge migration and folding of the layers.

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A Detailed New Look at Structures in the Ardmore Basin, Southern Oklahoma, USA

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This is a detailed, highly constrained example of the relationship between mechanical stratigraphy, pre-existing fold geometry, and subsequent fold initiation. It also illustrates potentially surprising opportunities that may hide in the core of some compressional structures. The Milroy and Velma structures in the Ardmore Basin of Oklahoma are disharmonic with three scales of structuring. First order morphology is from basement thrusting that verges northeasterly ahead of the Wichita Mountain Front, a major tectonic feature in the basin. Second order morphology is from backthrusting in the 4500-ft thick Arbuckle Lime above the basement, and synchronous forelimb rabbit ears in the shale-rich Simpson as it accommodated stain within the core of the structure. Third order is from detachments in the shallower Caney-Goddard shales which carried rock up both limbs, inducing folding above convex inflections below. Later Arbuckle orogenic reactivation further deformed the structures, and produced breakthrough of faulting from the Arbuckle Lime.

Mechanical stratigraphy influenced fold morphology. Thick shales focused fault-fold initiation in the Simpson and Goddard. Thick limestone constrained faulting in the Simpson shales below the Viola Lime. Simpson rabbit ears form map-scale substructures causing the main structures to commonly have two or more Simpson closures their core.

The fold morphologies at Velma and Milroy are inconsistent with a strike-slip origin. The causal fault and the resulting fold are coincident rather than oblique. Divergent and convergent bend related features are missing. The only observed translation is where ~2500 ft of translation occurs at a localized tear zone at Velma.

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Vertical Zonation in the Mount Sheridan Gabbro, Wichita Mountains, Oklahoma

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The Mt. Sheridan Roosevelt Gabbro of the Southern Oklahoma Aulacogen displays evidence of multiple impulses of new magma into the chamber, resulting in mineralogical layering within the crystallizing magma chamber. Twenty-eight samples were collected along the southern part of "little" Mt. Sheridan, encompassing 714 vertical feet. Modal mineralogical analysis and petrographic observations document changes in the size, shape, alteration, and zonation of plagioclase crystals throughout the vertical section. In addition, abundance of granophyric textures and presence of olivine in select slides helps to define two distinct zones within the chamber. The chamber itself appears to be stacked, with a large, layered lower zone, and a homogenous upper zone. The lower zone coarsens upward in grain size and displays repetitions in the modal abundance of plagioclase. Plagioclase in the lower chamber grade from unaltered to heavily altered and display zonation that changes from poorly developed, patchy zones to sharp, oscillatory zones. These gradations in plagioclases are repeated at least three times in the lower chamber. Felsic dikes and "blobs" are common in the lower chamber, while they are extremely rare in the upper chamber. Sericitic alteration is more abundant in the lower zone. Alteration rims on oxides occur in the lower zone as well. These alteration tendencies may indicate that the magma "stewed in its own juices" before crystallization was complete, resulting in the deuteric alteration seen throughout the lower chamber. The upper chamber is a homogenous gabbro that increases in the modal abundance of plagioclase as the top of the chamber is approached.

The presence of two zones in the single magma chamber indicates that there were two different conditions of crystallization occurring within the chamber, one producing layers, and the other producing a homogenous zone. It is possible that the lower chamber was formed by several impulses of magma, with time enough between each impulse to allow crystallization and accumulation from gravity settling to take place before the next impulse occurred. The large upper zone of the chamber may have formed from either a final large volume impulse of magma into the chamber or by homogenization of new magma and melts filter pressed from the lower cumulate pile by convection.

Reprinted as published in the Geological Society of America *2004 Abstracts with Programs*, v. 36, no. 3, p. 42.

Significance of Layering in the Mount Sheridan Gabbro, Oklahoma

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The Cambrian Mt. Sheridan Roosevelt Gabbro of the Southern Oklahoma Aulacogen exhibits repetitive phase layering and cryptic layering interpreted to form as a result of multiple replenishment of new magma into the chamber during crystallization. Samples were collected along a traverse spanning 714 vertical feet up the side of "little" Mt. Sheridan towards the contact with Mount Scott Granite. Petrographic observations document changes in modal abundance, size, shape, alteration, and zonation of plagioclase crystals throughout the vertical section. Variation in abundance of granophyre and particularly olivine aids in recognition of two distinct zones within the pluton: a large, multiply layered, lower zone overlain by a homogenous upper zone. Layers in the lower zone coarsen upward and display repetition in the modal abundance of olivine and plagioclase. Plagioclase in the lower chamber grade from unaltered to heavily altered and display zonation that changes from poorly developed, patchy zones to sharp, oscillatory zones. These gradations in plagioclases are repeated at least three times in the lower chamber. Felsic pegmatitic dikes and "blobs" are common to locally abundant in the lower chamber, and rare in the upper chamber. Sericitic alteration of plagioclase and alteration rims on oxides is more abundant in the lower zone. This may indicate that the magma "stewed in its own juices" before crystallization was complete, resulting in the deuteric alteration seen throughout the lower chamber. The upper chamber is a homogenous gabbro that increases in the modal abundance of plagioclase as the contact with the overlying granite is approached. The presence of two zones in the single magma chamber indicates that there were two different conditions of crystallization occurring within the chamber, one producing multiple cumulate layers, and the other producing homogenous gabbro. It is possible that the lower chamber was formed by several impulses of magma, with time enough between each impulse to allow crystallization and accumulation from gravity settling to take place before the next impulse occurred. The large upper zone of the chamber may have formed from either a final large volume impulse of magma into the chamber or by homogenization through mixing of new magma and melts filter pressed from the lower cumulate pile.

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Relict Tertiary Pediment Surfaces in the Wichita Mountains, Southwest Oklahoma

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Digital Elevation Models (DEMs) were used to identify and characterize sub-horizontal topographic surfaces found at high elevations in the Wichita Mountains, Oklahoma. The extent and form of these topographic surfaces correlate well with the bedrock geology. In the eastern Wichita Mountains, surfaces on the medium-grain Mount Scott Granite are typically gently sloping and have an interior topographic high. Surfaces on the adjacent coarse-grain Quanah Granite are typically horizontal, cover a larger area, and lack interior topographic highs. These surfaces are common at ~2200 ft (approaching that of the highest peaks) and are currently being dissected. To the west of the Wichita Mountains is the Southern High Plains, a pediment surface underlain by Tertiary sediments of the Ogallala Formation which extended from the Rocky Mountains to the Gulf of Mexico. NAD 27 UTM coordinates and corresponding elevations of the Southern High Plains were extracted from DEMs on 60 meter spacing. Recent topographic surfaces (e.g., sinkholes, streams) were excluded from this data set. The extracted data brackets the Wichita Mountains between the 3833970, and 3863070 northings. The data was blocked into one kilometer wide strips and plotted on an east-west projection. Logarithmic trend lines were generated for each data set with all R^2 values exceeding 0.95. Projection of the logarithmic trend lines into the western Wichita Mountains reproduced the elevations of these high surfaces within 10–30 feet of actual elevations. Extension of the model to the eastern Wichita Mountains reproduced the elevations of these surfaces 20–60 feet of expected elevations. Logarithmic slopes and intercepts from this set of equations were plotted verses the midpoint of their Y range. Then logarithmic regressions were used to combine these equations into a single equation describing the 3D Tertiary erosional surface, Z=[–108107*ln(Y)+1637269]*ln(X)+1352187*ln(Y) –20475324 (Z feet X&Y UTM coordinates). Evaluating the equation using coordinates from the Wichita Mountains generated values within 60 feet of actual values. The results of this study suggest sub horizontal surfaces at high elevations in the western and eastern Wichita Mountains are remnants of the paleo-erosional pediment surface developed during Tertiary time.

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Crystal Size Distribution Analysis of a Rhyolite Dike, Wichita Mountains, Oklahoma

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Crystal Size Distribution (CSD) analysis is being applied to a "rhyolite dike" from the Wichita Mountains, Oklahoma to reveal its magmatic history. This dike is unique in that, texturally, it has the appearance of rhyolite, but field relationships clearly show that it is intrusive into the Mt. Scott Granite. The porphyritic rhyolite dike consists of quartz (25%) and alkali feldspar (75%) phenocrysts, which constitute 19% of the rock. Embayed quartz phenocrysts (subhedral with 2–3 euhedral sides) are 0–1 mm in size. Euhedral tabular K-feldspar phenocrysts are 0–7 mm long. Both minerals occur as individual phenocrysts and as glomerocrysts. Vesicles (1%), which indicate volatile saturation at the time of emplacement, are present and are 2–3 mm in diameter. The other 80% is a fine grain matrix of quartz and feldspar. Comparison with the Q-AB-Or-H_2O ternary indicates the melt composition coincides with 1.0 kb and 730°C, corresponding to a depth of 3.5 km. The rhyolitic texture indicates a near surface emplacement for the dike. The magma underwent a period of crystallization at depth, ascended, and quenched. CSD analysis (in progress) is being applied to quantify the early textural development of this magma. Application of CSD consists of mapping individual crystals in a computer drawing program. This image is exported as a binary image and the area and length of individual crystals within a population is determined with image analysis software. CSD Corrections (Higgins 2002) is then used to analyze this data and determine the frequency distribution of the area number density of these populations and fit a logarithmic-normal curve to the results. Growth histories of crystals can be inferred from the shape and slopes of these curves. Linear correlations indicate uniform nucleation and growth. For the rhyolite dike we expect clustering of quartz and feldspar will produce spikes in the data and skew the frequency distribution. We also expect a kink in the quartz data corresponding to resorption of quartz crystals in response to decompression during magma ascent. The nature of the CSD curve for the rhyolite dike should help to define its magmatic history and potentially provide insight into the nascent stages of development of "granitic" textures.

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Crystallization History of a Rhyolite Dike: Insights from Crystal Size Distribution Analysis

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Crystal Size Distribution (CSD) analysis of a porphyritic rhyolite dike from the Wichita Mountains, Oklahoma is being used to constrain the magmatic history and textural development of felsic igneous rocks. This dike has the textural appearance of rhyolite, but field relationships indicate intrusive relationships with Mt. Scott Granite. Phenocrysts constitute 19% of the rock and consist of quartz (25%) and alkali feldspar (75%) crystals set in a fine grain matrix (80%) of quartz and feldspar. Quartz phenocrysts are typically 0–1 mm in size subhedral to euhedral and can be embayed. K-feldspar phenocrysts are 0–7 mm long, euhedral and tabular. Both types of phenocrysts occur as individual crystals and as glomerocrysts. Vesicles (1%) are 2–3 mm in size and occur throughout the rock. Comparison with the Q-AB-Or-H_2O ternary indicates "equilibrium" crystallization conditions of 1.0 kb and 730°C, corresponding to a depth of 3.5 km. Outlines of quartz and feldspar phenocrysts were traced from multiple scanned images approximately 900 mm^2. These "maps" were exported as greyscale images and converted to binary images. The individual crystals were fitted to an ellipse and the minor and major axis lengths were determined. Length data was analyzed using CSD Corrections (Higgins, 2002) to determine the frequency distribution of the area number density of the quartz and feldspar crystal populations and to fit a logarithmic-normal curve to the results. 1042 feldspar and 899 quartz crystals within a total area of 11016 mm^2 were analyzed. Both populations yield inverted "S" shaped curves. Regression of the total straight lines segments yielded a slope of –0.429 and an intercept of –3.57 (R^2 = 0.53) for feldspar and a slope of –1.20 and an intercept of –0.72 (R^2 = 0.80) for quartz. Linear correla-

tions indicate uniform nucleation and growth. Convex tails indicated under representation of smaller crystals sizes and concave tails indicated over representation of larger crystals sizes and indicate a deviation from uniform nucleation and growth. Under representation of small crystals may reflect dissolution in response to decompression during magma ascent. Over representation of larger crystals is attributed to the presence of glomerocrysts formed as a result of either synneusis or resorption during crystallization.

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The Southern Oklahoma and Dniepr-Donets Aulacogens: A Comparative Analysis

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The classic failed continental rift or aulacogen is one that intersects a rifted continental margin at a high angle. Based on recent geological and geophysical studies, we have revisited a classic analogy that was drawn between two major intracratonic rifts, the Southern Oklahoma aulacogen in the southern portion of Laurentia and the Dniepr-Donets basin in the southern portion of Baltica. The Southern Oklahoma aulacogen (SOA), also known as the Wichita aulacogen, consists of a linear alignment of extensively inverted rift structures that begins at the rifted margin of Laurentia in northeast Texas and extends northwestward to New Mexico. Deep seismic profiles have revealed the upper crustal structure of this feature, and gravity data provide a regional context for interpreting these results. Velocities low enough to indicate the presence of sedimentary rocks extend to a depth of ~15 km, and the deepest of these sedimentary layers has been interpreted as rift fill. In addition, the Wichita uplift is underlain by very high velocity and density mafic material even at upper crustal depths of <10 km. The Dniepr-Donets Basin (DDB) has been cited as a type example of an aulacogen and is clearly a "failed rift" in the sense that it did not itself lead to continental break-up and ocean crust formation. The main feature of the DDB is a Late Devonian rift basin overlain by a substantial (but variable) post-rift sedimentary sequence that records several extensional or transtensional and at least one moderate compressional reactivation. The width of the rift zone varies from 150 km in the Pripyat Trough, 60–70 in the Dniepr, and 140–160 km in the southeastern segment. Recent deep seismic surveys in the Donets segment of the basin resolve the geometry of the sedimentary basin, indicating an asymmetric form with a steeper basement surface in the south than in the north and a total sedimentary thickness of about 20 km. A thick (>10-km) high velocity (>6.9 km/s) lower crustal body lies beneath the rift basin itself and is offset slightly to the north compared to the main basin depocenter. The Moho displays only slight topography around a depth of 40-km along the profile. Thus, the major differences between these two major rifts are the degree of inversion and the nature of the magmatic modification of the crust.

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Lithofacies and Trilobite Biofacies on a Late Ordovician Carbonate Ramp: Bromide Formation, Southern Oklahoma

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The Late Ordovician Bromide Formation of southern Oklahoma records a spectrum of lithofacies along a carbonate ramp associated with the southern Oklahoma aulacogen. Above a basal sandstone unit, the Mountain Lake Member is composed of deep subtidal parasequences that grade upward from lime mudstone and shale to bioclastic wackestone and packstone. Low diversity trilobite assemblages dominated by isotelines, *Failleana* and *Remopleurides* occur as thin (cm-thick) bioclastic packstone to rudstone horizons, and are joined by bryozoa and brachiopods in the shallower, upper portions of parasequences. With shallowing towards the top of the member, some parasequences are capped by rippled, echinoderm-rich packstone and grainstone. Deepening at the base of the overlying Pooleville Member is recorded by the appearance of poorly fossiliferous lime mudstone and a shift to blanketing as the dominant depositional process. Monospecific horizons of articulated exoskeletons of the isoteline trilobite *Vogdesia* are interpreted as reproductive aggregations. Shallowing in the upper Pooleville is indicated by the occurrence of thin, storm-winnowed, bioclastic rudstone that yields a diverse trilobite fauna dominated by "*Encrinuroides*", *Lonchodomas*, and *Calyptaulax*. Brachiopods, bryozoa and echinoderm debris are also conspicuous components of the rudstone. Along the margins of the aulacogen, the Pooleville is capped by peritidal carbonate, although subtidal deposition continued in the basin center. Abrupt deepening at the base of the overlying Viola Springs Formation led to regional extirpation of the Pooleville trilobite fauna. However, most genera reappear as shallow subtidal conditions became established in the Viola. As with other recent studies, our work demonstrates that trilobites remained significant, diverse components of shallow subtidal paleocommunities, even during the height of the Ordovician Radiation.

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A Revision of "*Climacograptus*" *caudatus* (Lapworth) Based on Isolated Three-Dimensional Material from the Viola Springs Formation of Central Oklahoma, USA

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The Late Ordovician Viola Group of the Arbuckle Mountains in Oklahoma is well known for containing three-dimensionally preserved specimens of graptolites. One horizon, 5 meters above the base of the Viola Springs Formation at the Mountain Lake section (Alberstadt, 1973, section I) yielded well-preserved specimens of *Diplacanthograptus* (previously *Climacograptus*) *caudatus* (Lapworth). *Diplacanthograptus caudatus* is an abundant and widespread taxon that has always been recognized by a characteristic long virgella and well developed parasicula. Its distinctive morphology and global distribution have made it an

excellent index fossil for early Late Ordovician (post-*Climacograptus bicornis* Zone) strata. Although it has been recorded from many important graptolite successions around the world, no specimens have ever been described from isolated material, and hence, the details of the proximal end remained unknown.

The new isolated material includes numerous growth stages that allow for a new and surprising revision of the morphology and taxonomy of this species. The most conspicuous feature of *D. caudatus*, which has always been assumed to be an elongate virgella is actually a theca 1^1 spine. A very short, dorsally deflected virgella is also present, hidden by the large parasicula. The overall proximal end morphology is extremely similar to *D. lanceolatus* and *D. spiniferus* indicating a close phylogenetic relationship with these two taxa. In this paper we provide a revised systematic description and scanning electron microscope photographs of *D. caudatus*.

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The Black Knob Ridge Section, Southeastern Oklahoma, USA: A Possible Global Stratotype-Section and Point (GSSP) for the Base of the *Diplacanthograptus caudatus* Biozone and the Middle Stage of the Upper Ordovician Series

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At the 2003 meeting of the International Symposium on the Ordovician System in San Juan, Argentina, the Ordovician Subcommission recommended that the base of the second (middle) stage of the Upper Ordovician Series be placed at the first appearance datum (FAD) of the graptolite species *Diplacanthograptus caudatus*. *D. caudatus* is an easily recognizable, cosmopolitan taxon with a consistent FAD within a succession of first appearances of several other graptolite taxa. The rapid succession of FADs provides a secure basis for identification of the *D. caudatus* Zone and for its global chronostratigraphic correlation. Additionally, the FAD of *D. caudatus* is in close proximity to several important marker horizons—just above the Millbrig and Kinnekulle K-bentonite complexes in Eastern North America and Scandinavia, respectively; just below the base of the *Plectodina tenuis* conodont zone; and just below the beginning of the Upper Ordovician Guttenberg 13C excursion (GICE). These event and chemostratigraphic marker horizons provide an independent test on the global synchroneity of the FAD of *D. caudatus*, and greatly increase our confidence in the usefulness of that zone for chronostratigraphic correlation. An excellent Global Stratotype-Section and Point (GSSP) for the base of the *D. caudatus* Zone is an exposure along Black Knob Ridge at the western end of the Ouachita Mountains, Atoka County, southeastern Oklahoma. This exposure extends for several hundred meters, is readily accessible, contains a continuous graptolite succession across the *C. bicornis–D. caudatus* zonal boundary, and yields biostratigraphically important conodonts and chitinozoans. The boundary interval is abundantly fossiliferous and the FAD of *D. caudatus* is precisely located at 4 meters above the base of the Bigfork Chert. Additionally, the shale above and below the graptolite zonal boundary contains biostratigraphically important conodonts. These conodonts can be correlated with nearby sections of the Viola Springs Fm. that contain a more complete conodont zonation, and are part of Sweet's (1984, 1995) graphic correlation framework. Thus, the biostratigraphic level of the FAD of *D. caudatus*, and hence the base of the middle Upper Ordovician Stage, can be precisely correlated into both graptolitic shale and shallower platform sections.

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An Edrioasteroid-Acrothoracic Barnacle-Dominated Community Attached to Pennsylvanian Extraformational Conglomerate Clasts

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Although extraformational conglomerates occur throughout Earth history, these hard substrates are rarely preserved with associated biota. A locality from the Lower Pennsylvanian (Morrowan) Golf Course Formation in south-central Oklahoma is interpreted to be a marine, synorogenic conglomerate deposited in a shallow lagoonal setting with bored and encrusted clasts eroded from many of the Lower and Middle Paleozoic units during the Criner Uplift. The low-diversity fauna is dominated by hard-substrate taxa including four genera of edrioasteroids (highly unusual for the Pennsylvanian: *Neoisorophusella, Ulrichidiscus, Postibulla,* and *Parapostibulla*), acrothoracic barnacle borings, serpulid tube worms, and fewer solitary rugose and alloporid corals, ramose and encrusting bryozoans, and several species of pediculate brachiopods. Associated soft-substrate fauna includes the stemless crinoid *Paragassizocrinus tarri*, several species of ostracodes and conodonts, isolated crinoid, holothuroid, and echinoid ossicles, and a single rostroconch mollusk. The hard-substrate fauna attached to some of the isolated clasts at the locality shows several types of preserved interactions. Even though a single clast, typically large pebble to small cobble in size, can have an edrioasteroid concentration of over 4,000 individuals per square meter, edrioasteroids are never preserved overgrowing members of their own species but rather become polygonal in crowded conditions. However, the edrioasteroids *Ulrichidiscus* and *Parapostibulla* are preserved overgrowing other elements of the fauna including serpulid worms, corals, bryozoans, and the edrioasteroid *Neoisorophusella*. Also, very small serpulids are preserved overgrowing *Neoisorophusella* but not the other three edrioasteroids. Edrioasteroid colonization shows little preference for clast size, shape, or lithology. Acrothoracic barnacles prefer carbonate clasts and to a lesser degree siltstone and sandstone. Although they have no clast size preference, acrothoracic barnacles tend to bore into the edges of subangular clasts and show preference for softer lithologies in larger clasts. Some clasts have been rolled and bored or encrusted on both sides.

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