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OKLAHOMA GEOLOGY notes

Vol. 62, No. 2 Summer 2002

Featuring:

- *Amphibian and reptile tracks from the Hennessey Formation*
- *Vertebrate fauna of a new site in the Wellington Formation*
- *Oklahoma earthquakes*

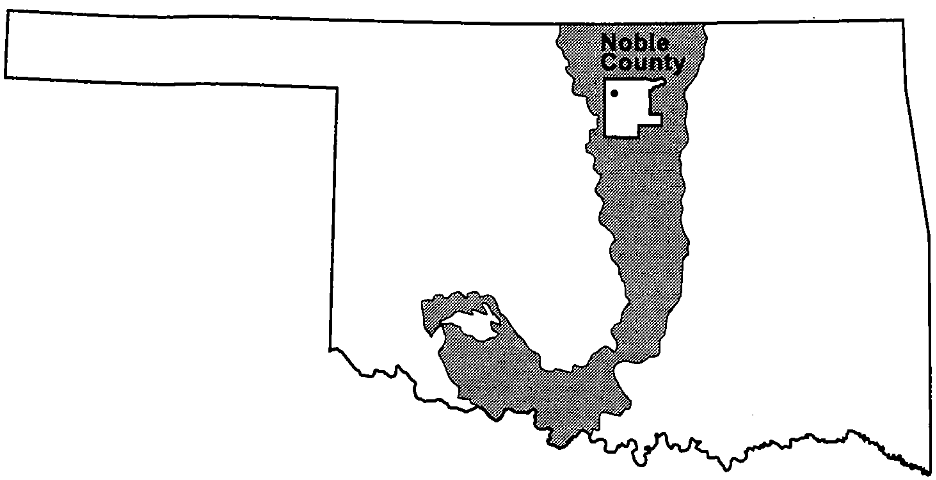
on the cover

The Billings Tracksite, Noble County, Oklahoma

Only five Permian vertebrate tracksites have been reported in Oklahoma. Raasch (1946) described three from the Wellington Formation, and Lucas and Suneson (this issue, p. 56–62) describe one from the Hennessey Formation. By far the largest and best documented of the five is the Billings site in Noble County, shown on the cover (photo from Swanson and Carlson, 2002, with permission).

The Billings tracksite is the well-exposed top (~681 ft^2) of a thin dolomite bed in the Early Permian Wellington Formation in northwestern Noble County (see location map); in that area, the Wellington consists mostly of evenly bedded gray or green shale, minor dolomite, and lenticular sandstone. These rock types represent deposition in a muddy tidal flat with interspersed channels, lakes, and ponds. Interpretation of the fauna and rock types at the site suggests that the dolomite originally was a water-saturated carbonate mud that accumulated in a lake; the water in the lake may have fluctuated between saline and fresh. When the prints were made, the mud was soft but firm enough to preserve them.

There are more than 1,400 individual amphibian and reptile footprints at the Billings tracksite. Sixteen trackways (series of tracks left by single individuals) are recognizable, 12 of which Swanson and Carlson (2002) assign to 5 morphotypes. (A morphotype is a track with a characteristic set of measurements—including width, length, and number of digits of both front and back feet—that is part of a trackway, itself with a characteristic set of measurements—for example, length of stride.) The longest trackway at the Billings site has 103 prints and extends for ~36 ft. The larger tracks at the site form impressions slightly more than 1 in. deep in the dolomite. The tracks at the Billings site were made by tetrapods that were walking, wading (on hind legs), and swimming (probably partially buoyed) (Swanson and Carlson, 2002).



Map of Oklahoma showing the general location of the Billings tracksite in northwestern Noble County and outcrop area of the Garber and Wellington Formations. The tracksite is on private property and is not open to the public.

After studying and photographing the site, Swanson and Carlson made latex molds of large parts of the exposure and collected 25 representative tracks from each trackway. The tracks and molds (specimen numbers OMNH 57012 through OMNH 57036) are in the vertebrate paleontology collections of the Sam Noble Oklahoma Museum of Natural History in Norman. Some of the molds were used to form the base of the Permian vertebrate exhibit at the museum.

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—Neil H. Suneson

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OKLAHOMA GEOLOGY notes

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Amphibian and Reptile Tracks from the Hennessey Formation (Leonardian, Permian), Oklahoma County, Oklahoma

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ABSTRACT.—Two footprints assigned to *Amphisauropus latus* Haubold and a single footprint assigned to *Dromopus* sp. were discovered in a large block of the Lower Permian Hennessey Formation (lower part) (Leonardian) in northwestern Oklahoma City during construction of the Kilpatrick Turnpike. *Amphisauropus* was probably made by a seymouriamorph amphibian and *Dromopus* by an araeoscelid reptile. These tracks are the youngest Permian vertebrate footprints yet reported in Oklahoma. This is also the youngest record of *Amphisauropus* yet reported in North America, and its identification increases the similarity of European and North American Early Permian tetrapod ichnofaunas.

INTRODUCTION

As part of the U.S. Geological Survey-sponsored STATEMAP program, the Oklahoma Geological Survey has been mapping the Oklahoma City metropolitan area since 1997. The primary purpose is to produce a series of new, detailed geologic maps at a scale of 1:24,000 that will better enable land-use planners, State and city engineers, homeowners, and others to address certain environmental concerns in this rapidly developing area. In addition, new geologic observations and data are shedding light on several aspects of Lower Permian geology in central Oklahoma, such as the depositional environments of the Garber and Hennessey Formations.

During a reconnaissance field trip in the summer of 1998, one of the authors (NHS) and Dr. Jonathan D. Price (currently at Rensselaer Polytechnic Institute) examined an outcrop of the Hennessey Formation along the alignment of the Kilpatrick Turnpike in northwestern Oklahoma City (Fig. 1). The turnpike was under construction at that time, and a new outcrop had been exposed where the turnpike was to pass under MacArthur Boulevard (southwest corner sec. 10, T. 13 N., R. 4 W., Oklahoma County). Many large blocks of unweathered Hennessey shale and siltstone covered part of the outcrop beneath and immediately east of MacArthur Blvd. One of the large blocks contained the tracks described in this paper. A search of other blocks and the adjacent outcrop uncovered no additional tracks. (The outcrop and blocks, referred to below as the MacArthur-Kilpatrick tracksite, were removed as construction progressed.)

NHS removed the tracks from the block and loaned them to Dr. William Caire, University of Central Oklahoma, for display. Caire took digital images of the tracks, sent them to NHS, who forwarded them to SGL for identification. SGL requested the tracks themselves, so NHS retrieved them and mailed them to SGL who identified them as *Amphisauropus latus* and *Dromopus* sp. SGL also recognized the significance of the tracks (see below) which are presumed to have been made by a seymouriamorph amphibian (*Amphisauropus*) and an araeoscelid reptile (*Dromopus*) and suggested that this paper be written. The specimens now are in the collections of the Sam Noble Oklahoma Museum of Natural History (OMNH).

Unfortunately, the significance of the tracks was not recognized at the time of their discovery, and the exposed section (~5 ft [1.5 m] thick) beneath MacArthur Blvd. was not described in detail. However, the sedimentary features observed in the blocks and outcrop are similar to those in nearby Hennessey Formation outcrops, and the description given in the section on the Hennessey Formation is based on Suneson and others (1999) and Suneson and Hemish (1998).

PREVIOUS REPORTS OF LOWER PERMIAN TRACKS AND SEYMOURIAMORPH AND ARAEOSCELID FOSSILS IN OKLAHOMA

The MacArthur-Kilpatrick tracksite is the fifth record of vertebrate tracks in the Lower Permian of Oklahoma. The other four sites are located in north-central Oklahoma in the Wellington Formation. Raasch (1946) located one tracksite in Noble County and two sites in Garfield County, but he identified the tracks only as having been made by vertebrates (amphibians or reptiles). Swanson and Carlson (2002) located an extensive tracksite in Noble County and documented five distinctive tracks and trackways that they

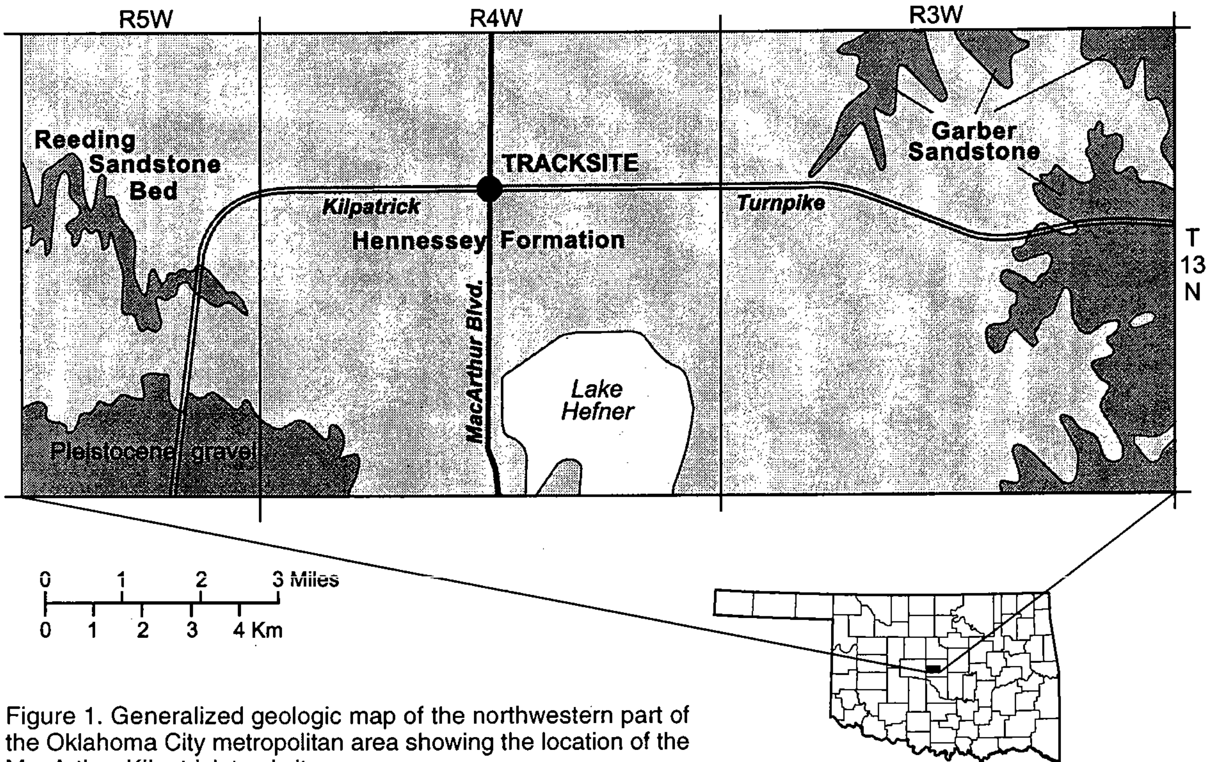

Figure 1. Generalized geologic map of the northwestern part of the Oklahoma City metropolitan area showing the location of the MacArthur-Kilpatrick tracksite.

termed morphotypes. Their Morphotype E shows an affinity with *Dromopus,* one of the ichnotaxa identified at the MacArthur-Kilpatrick site. (Raasch (1946, p. 25) noted amphibian or reptile tracks in the Garber Sandstone north of Lucien in Garfield County, but did not report an exact location.)

Olson (1965, 1967, 1970, 1979) and Simpson (1976) identified many vertebrate taxa in the Hennessey Formation, the underlying Garber Sandstone, and the overlying Duncan Sandstone in Oklahoma. Many of the vertebrate sites are in the transition zone between the Garber and Hennessey. Only one site, near Norman in Cleveland County (SW¼NW¼ sec. 13, T. 8 N., R. 2 W.), is within "the Hennessey Formation proper" (Olson, 1970, p. 395), and it is only 75–80 ft (23–24 m) above a sandstone in the uppermost part of the Garber–Hennessey transition zone.

Skeletal remains of probable seymouriamorph amphibians (genus *Seymouria*) (Fig. 2) have been identified in several Lower Permian formations in Oklahoma. Raasch (1946, p. 46) stated that the *S. baylorensis* Broili identified by Case (1915) came from the Antelope Flats Member of the Welling-

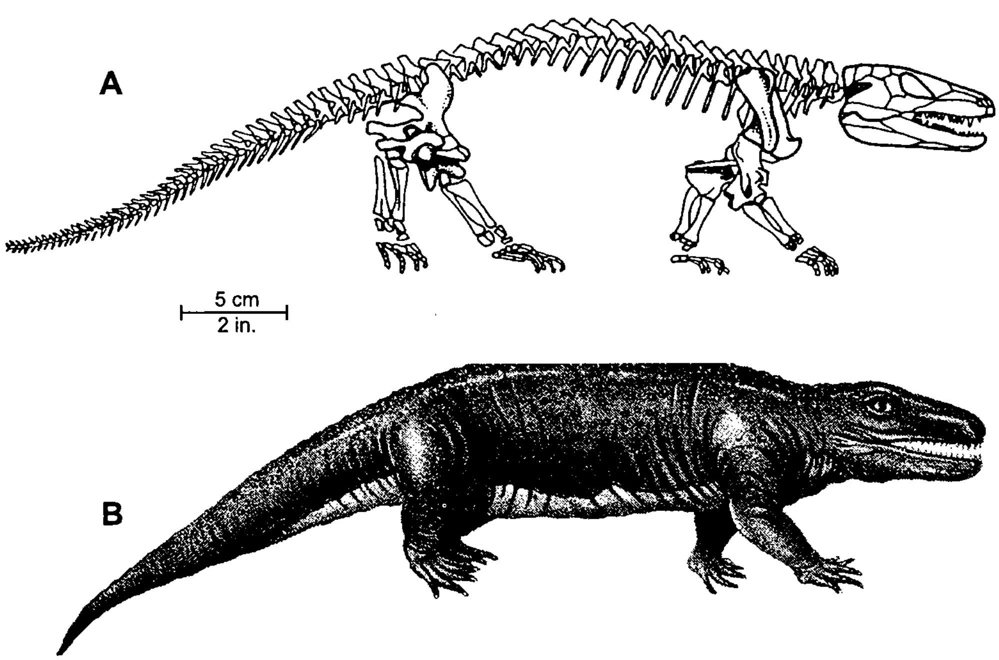

Figure 2. *A*—Skeletal reconstruction of a seymouriamorph amphibian (from White, 1939). *B*—Probable original appearance of a seymouriamorph amphibian (from Dixon and others, 1988, p. 51, with permission).

ton Formation 2 mi (3.2 km) northeast of Orlando in Noble County. Olson (1979) identified *S. grandis* in the lower part of the Fairmont Member of the Hennessey Formation. However, Olson's (1979) published location is incorrect; Oklahoma State Highway 77 should be Highway 74, and the site is ~4.4 mi (7 km) and not 6 mi (9.6 km) south of Crescent in Logan County. In addition, the most recent geologic map of the area (Bingham and Moore, 1975) shows that Olson's (1979) site probably is in the upper part of the Garber Sandstone. Olson (1980) described a small species of seymouriamorph, *S. agilis*, from the Upper Permian Chickasha Formation ~3 mi (4.8 km) north of Hitchcock in Blaine County. Most recently, Sullivan and Reisz (1999) identified *Seymouria* sp. specimens from the Lower Permian fissure-fill deposits at Richards Spur in Comanche County.

Araeoscelid reptiles (Fig. 3) also are relatively well represented in the Lower Permian fossil record of Oklahoma. The most common araeoscelid reptile is *Dictybolus tener*, described by Olson (1970) and Burkhalter (1987) from sites in the Wellington Formation ~9 mi (14.5 km) northwest of Perry in Noble County and by May and Hall (this issue, p. 63) from the Wellington Formation at the Kirby quarry in Noble County. Swanson and Carlson (2002) report the occurrence of *Dictybolus* body fossils at a site near their tracksite in the Wellington Formation in Noble County and propose *Dictybolus* as a trackmaker for their morphotype 4. Carroll (1968) found a single bone similar, and possibly related, to *Araeoscelis* at Richards Spur in Comanche County but could not confirm its identity. Simpson (1976) identified *Araeoscelis gracilis* in the Garber Formation ~6 mi (9.7 km) west of Grandfield in Tillman County. May and Hall (this issue, p. 63) identified a new araeoscelid reptile at the Kirby quarry in Noble County.

HENNESSEY FORMATION

Description and Depositional Environment

The Hennessey Formation, which is part of the Permian red-bed sequence of central Oklahoma, extends from the Kansas border in the north to the Texas border in the south. The Hennessey is underlain by the Garber Sandstone, the principal aquifer for much of the Oklahoma City area; it is overlain in the Oklahoma City area by the Duncan Sandstone (Fig. 4). The rank of the Hennessey in Oklahoma is controversial. Some authors (e.g., Bingham and Moore, 1975) elevate the Hennessey to group status and subdivide it into four formations: (from bottom to top) the Fairmont Shale, the Kingman Siltstone, the Salt Plains Formation, and the Bison Formation. However, Suneson and Hemish (1998) and Suneson and others (1999) did not identify those four formations as mappable units. Instead, they subdivide the Hennessey Formation into three parts: (from bottom to top) the lower part of the Hennessey Formation, the Reeding Sandstone Bed, and the Cedar Hills Member. Where the Reeding Sandstone Bed pinches out (~3 mi [4.8 km] south–southwest of the MacArthur-Kilpatrick tracksite), the lower part of the Hennessey Formation and the Cedar Hills Member of the Hennessey Formation are undivided.

The tracksite occurs in the Hennessey Formation (lower part) (Fig. 4) of Suneson and others (1999) ~180 ft (55 m) above its base. The Hennessey Formation (lower part) in the area of the tracksite is ~450 ft (135 m) thick and consists of poorly exposed, mostly moderate reddish brown (10R4/6) to light brown (5YR5/6) muddy siltstone, silty shale, and minor very fine grained sandstone. (Rock-color terms are those shown on the rock-color chart (Rock-color Chart Committee, 1991).) The shale typically is unstratified and highly frac-

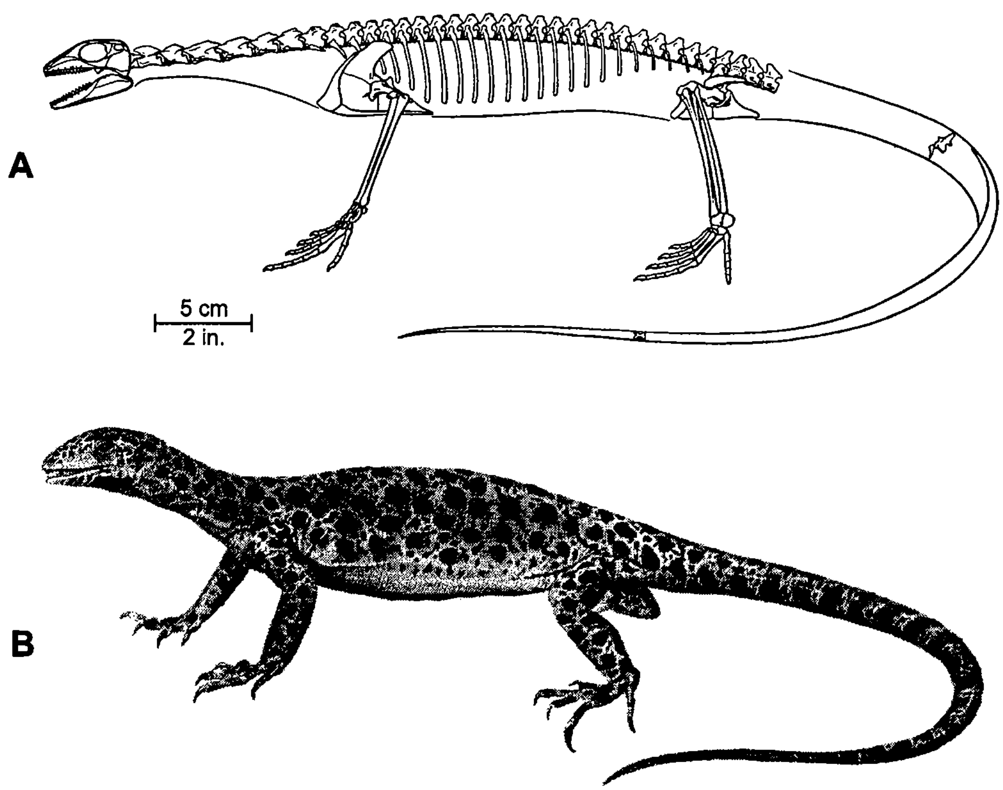

Figure 3. *A*—Skeletal reconstruction of an araeoscelid reptile (from Vaughn, 1955, fig. 15). *B*—Probable original appearance of an araeoscelid reptile (from Dixon and others, 1988, p. 82, with permission).

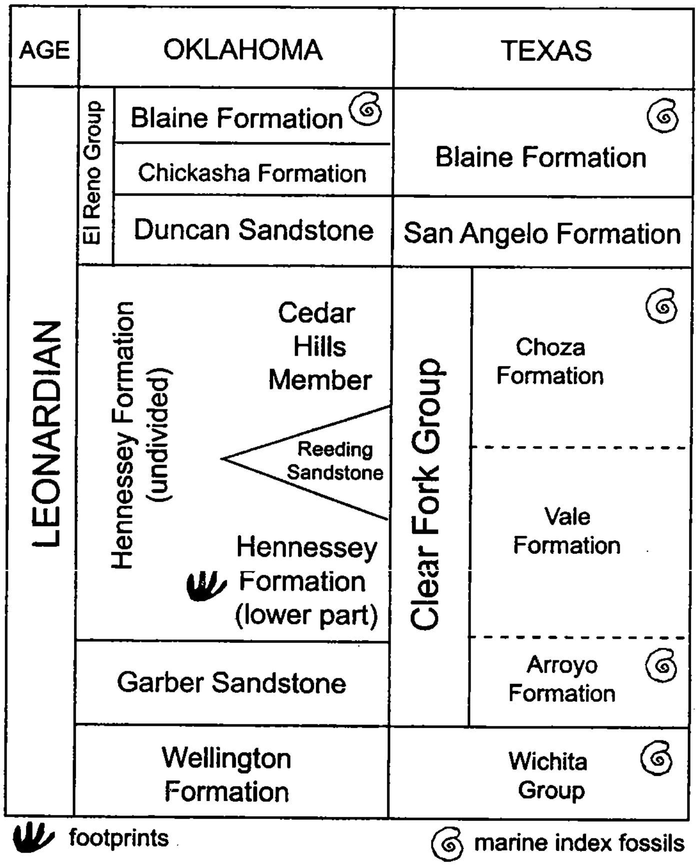

Figure 4. Stratigraphic column of Permian units in central Oklahoma referred to in the text. The MacArthur-Kilpatrick tracksite is located in the Hennessey Formation (lower part) above the Garber Sandstone and below the Reeding Sandstone Bed. The El Reno Group is shown as Leonardian based on Lucas (in review, "A global hiatus in the middle Permian tetrapod fossil record"). Correlation of pre–El Reno Group strata is based on Mankin (1987). Correlation of the El Reno Group is based on Hills and Kottlowski (1983).

tured to fissile; rare pedogenic slickensides are evidence of local paleosol development. Siltstone beds are moderately to well stratified. Sandstones locally are cross-stratified and/or ripple-marked; channelform deposits are rare. The block that contained the tracks consisted of interbedded siltstone and cross-stratified very fine grained sandstone.

In addition to fine-grained clastic material, the Hennessey Formation also contains thin gypsum beds. Gypsum beds do not occur in outcrop but have been identified in several groundwater-monitoring wells at the Will Rogers World Airport, ~15 mi (24 km) south of the MacArthur-Kilpatrick tracksite in secs. 23, 24, 25, 33, 34, and 35, T. 11 N., R. 4 W. (Well records are available from the Oklahoma Water Resources Board.)

No studies have systematically addressed the depositional environment of the Hennessey Formation. Olson (1967, p. 79) noted that "part of the formation is nonmarine, part near-shore marine, and part probably was deposited under fully marine conditions. A thorough study of the beds encompassed under this formational name is needed and many questions concerning the nature of its deposition . . . remain to be answered." Olson's statement is still true 35 years later. The dominantly fine-grained character of the Hennessey sediments, the rarity of channels, and the presence of paleosol horizons and thin gypsum beds are evidence that much of the Hennessey Formation in the Oklahoma City area was deposited in a supratidal, possibly sabkha-like environment.

In contrast to the Hennessey, the depositional environment of the underlying Garber Sandstone has been studied extensively, and some geologists suggest that it was deposited in a fluvial-deltaic environment (e.g., Johnson and others, 1988; Simpson and others, 1999).

Age

The Leonardian age of the Hennessey Formation is based primarily on its correlation with most of the Clear Fork Group (Vale and Choza Formations) in Texas (e.g., Dunbar and others, 1960; Simpson, 1973; Mankin, 1987) (Fig. 4). The Hennessey–Clear Fork correlation is based on physical stratigraphy. The Clear Fork in northern Texas can be traced into the Hennessey Formation of Oklahoma (e.g., Simpson, 1973). However, the Hennessey lacks marine fossils by which its age can be directly determined, so the age of the Hennessey must be established by the age of the laterally equivalent Clear Fork Group. The Clear Fork Group has been recognized as Leonardian since the series was established (Adams and others, 1939; Dunbar, 1940; Dott, 1941). Ammonoids and fusulinids in marine intervals of the Clear Fork Group confirm its Leonardian age (see below).

The Clear Fork Group is 1,200–1,500 ft (365–457 m) thick, and its outcrop zone extends from the Red River of Texas southwestward to Tom Green County. In that part of Texas, the oldest Leonardian strata are assigned to the Clyde Formation of the upper part of the Wichita Group. The Clyde Formation contains earliest Leonardian ammonoids (*Medlicottia copei* assemblage of Plummer and Scott, 1937; also see Miller and Furnish, 1940) and fusulinids (*Schwagerina crassitectoria* Dunbar and Skinner, see Myers, 1968).

The lowest formation of the Clear Fork Group, the Arroyo Formation, contains a marine limestone near its top that yields Leonardian ammonoids of the *Perrinites kempae* Zone (Plummer and Scott, 1937; Miller and Furnish, 1940). Ammonoids from 59 ft (18 m) below the top of the Choza Formation on the Colorado River in Runels County, Texas, belong to the *Medlicottia chozaensis* Zone (Sellards and others, 1932; Plummer and Scott, 1937) and are also of Leonardian age. The Blaine Formation of the Double Mountain Group, which is younger than the Choza Formation (Fig. 4), contains ammonoids that include *Perrinites hilli* and is widely considered to be of latest Leonardian age (e.g., Miller and Furnish, 1940; King, 1942; Clifton, 1942; Tharalson, 1984), although a few authors have suggested that it may be of earliest Guadalupian (Roadian) age (e.g., Ross, 1987). The correlation of the Blaine to the latest Leonardian seems most likely, as it and the underlying San Angelo Formation are equivalent to (represent the same transgression as) the Glorieta Sandstone and lower San Andres Formation of West Texas and southeastern New Mexico, strata of well established latest Leonardian age (King, 1942).

These ammonoids and regional stratigraphic relationships indicate that the Clear Fork Group is a correlative of parts of the marine Skinner Ranch, Hess, and Cathedral Mountain Formations in west Texas and therefore is of Leonardian age (e.g., Dunbar and others, 1960; Ross, 1987). Correlation of the Hennessey Formation to much of the Clear Fork Group (Vale and Choza Formations) indicates a Leonardian age as well, and the MacArthur-Kilpatrick tracksite in the Hennessey Formation (lower part) thus is of early Leonardian age (Fig. 4).

PALEOICHNOLOGY OF THE MACARTHUR-KILPATRICK TRACKSITE

Identification

The best preserved footprints from the MacArthur-Kilpatrick tracksite are two nearly complete, concave impressions (Figs. 5, 6) that can be assigned to *Amphisauropus latus* Haubold, 1970, the presumed track of a seymouriamorph. The width of these prints (~2.75 in. [70 mm]) is noticeably larger than the length (~2.2 in. [55 mm]), and the estimated divarication between digits I and V is ~30°. Digit IV is longest, and these plantigrade tracks superficially appear to be tetradactyl. Close examination, however, reveals a faint impression of a small digit V on one of the footprints (Fig. 5); the digit V of the other (Fig. 6) is broken off at the edge of the slab. Commonly, digit tips of *Amphisauropus* are rounded, but many extramorphological variants show the pointed digits that are seen in these two prints (Haubold, 1971, fig. 14; Mossman and Place, 1989, fig. 6; Lucas and others, 2001, figs. 2, 3).

A second, much smaller ichnotaxon is poorly represented at the MacArthur-Kilpatrick tracksite. This track (Fig. 7), also a concave impression, has three, relatively long, thin, pointed, slightly curved digits that increase dramatically in length from digit to digit. This track is longer than wide (length, ≤1.2 in. [30 mm]; width, ≤1.0 in. [25 mm]). All characters suggest assignment to *Dromopus*, the presumed track of an araeoscelid reptile (Haubold, 1971, fig. 18). We thus refer this track to aff. *Dromopus* sp., noting that it is not well enough preserved for certain identification.

Significance

Dromopus is one of the most common and characteristic Permian tetrapod footprint ichnotaxa (Haubold, 2000), so its probable presence in the Leonardian Hennessey Formation

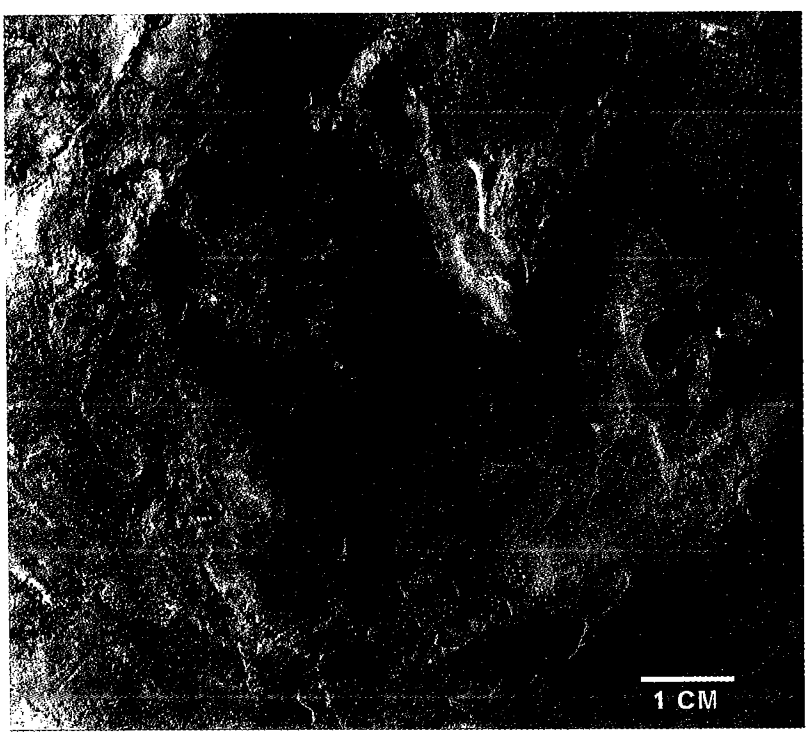

Figure 5. *Amphisauropus latus* Haubold, presumed track of a seymouriamorph amphibian, Hennessey Formation (Leonardian) from the MacArthur-Kilpatrick tracksite (OMNH no. 71041). Digit V is barely visible in the lower left part of the photograph.

Figure 6. *Amphisauropus latus* Haubold, presumed track of a seymouriamorph amphibian, Hennessey Formation (Leonardian) from the MacArthur-Kilpatrick tracksite (OMNH no. 71042).

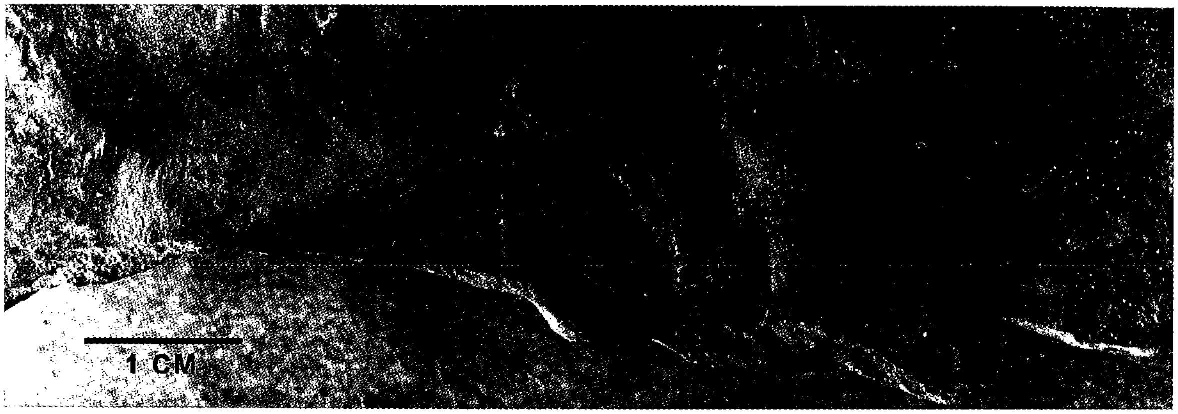

Figure 7. *Dromopus* sp., presumed track of an araeoscelid reptile, Hennessey Formation (Leonardian) from the MacArthur-Kilpatrick tracksite (OMNH no. 71044).

is not surprising. However, *Amphisauropus*, although common in the European Lower Permian (Haubold, 1971), has been reported from North America only twice previously—from Prince Edward Island in Canada (Mossman and Place, 1989) and from central New Mexico (Lucas and others, 2001). Both of those records are of Wolfcampian age. Thus, the Hennessey record of *Amphisauropus* is only its third report from North America and its youngest record on the continent.

Hunt and Lucas (1998), Lucas and others (1999), and Haubold and Lucas (2001) have argued that there is a globally uniform tetrapod footprint ichnofauna in red-bed facies of Early Permian age. This is to be expected because the global Early Permian tetrapod fauna, as now understood from body fossils, is relatively uniform, forming one paleobiogeographic province across equatorial Pangea (e.g., Milner, 1993). The Hennessey footprints support this concept by further documenting the presence of *Amphisauropus* in North America and by extending its stratigraphic range on the continent into the Leonardian, thus increasing the similarity of European and North American Early Permian tetrapod ichnofaunas.

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Geology and Vertebrate Fauna of a New Site in the Wellington Formation (Lower Permian) of Northern Oklahoma

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ABSTRACT.—Remains of terrestrial vertebrates have been discovered in the Wellington Formation (Lower Permian) in Noble County, Oklahoma. The site, designated "The Kirby Quarry," is named for the owner of the fossiliferous exposure. It has yielded a diverse vertebrate assemblage of three-dimensional remains of fish, amphibians, and reptiles. The Kirby Quarry is the first reported site from the Wellington Formation, Oklahoma, in which the hybodont shark *Hybodus* is known to occur; it is also only the third known site for the araeosceloid reptile *Dictyobolus tener.*

INTRODUCTION

The Kirby Quarry—site OMNH 1220, Oklahoma Museum of Natural History—is in Noble County, north-central Oklahoma. The quarry opens into a west-facing road cut with rock exposures extending east into a pasture. Site data, on file in the Museum's Department of Vertebrate Paleontology, are available to qualified investigators.

Several vertebrate-bearing sites are known in the Wellington Formation of northern Oklahoma. Among them, the Kirby Quarry is remarkable because its vertebrate material occurs in highly packed, concentrated pockets within curved depressions in the gray shales. Masses of bones and scales are cemented together by reddish siltstone. The majority of the vertebrate fossils consist of scales, skull pieces, and rib fragments of small palaeoniscoids and the larger platysomid fish. Remains of several different amphibians and reptiles also have been recovered there. The site has yielded specimens of a new araeosceloid reptile whose description awaits recovery of additional material.

Two seasons have been devoted to field studies at the site, resulting in a modest collection of fossils now deposited in the OMNH vertebrate paleontology collection. All the bones are three-dimensional with very little crushing. They are disarticulated and fragmentary, so that most are inadequate for species-level identification. All the fossil elements are small, although a few larger bones are represented as fragments. Plant fossils occur in the uppermost meter of Unit 9 and in Unit 10, but the remains are either carbonized film or barite replacement; identification is impossible.

GEOLOGY AND ENVIRONMENTAL INTERPRETATION

The area around the quarry has been mapped by Shelton (1979). The basal sandstone is easily recognized as his Pwu (upper key bed of the Wellington Formation). The capping sandstone is about 6 m (~20 ft) above the basal sandstone and therefore likely Pwu-620—in the Billings Pool Member of the Wellington Formation.

Stratigraphic Column
(see Fig. 1)

Unit 10 (Pwu-620) consists of a fine-grained subarkosic sandstone (Shelton, 1979), reddish brown (10R 4/6), cross bedded with climbing ripples and de-watering structures. It includes rare, moderately well-preserved fossil plant trunks ranging from 2.5 to 5 cm in thickness, and cuts sharply into Unit 9.

Unit 9 is a blocky to fissile shale, pale olive (10Y 6/2) with reddish brown intervals. It contains vertebrate and plant fossils, most of which are rare and are concentrated in the uppermost 114 cm. Malachite, cuprite, hematite, and limonite weather from the unit in the form of lenticular concentrations about 2–3 mm across.

Unit 8 is a reddish brown sandstone. Its lithology and thickness vary within the locality; to the north, it is a fine-grained siltstone about 8 cm thick; to the south it grades into a dense, cross-bedded, heavily burrowed sandstone about 61 cm thick. Farther south the unit thins to about 12 cm, with casts of vertebrate tracks on the underside of the unit and pelecypod fossils on the top surface. Overlying this sandstone is a lens of carbonate about 3.5 m wide and 15 cm thick in the middle; it does not persist laterally.

Unit 7 is a pale olive, blocky shale and claystone about 46 cm thick; it grades into a reddish brown, well-laminated siltstone in the uppermost 7 cm.

Unit 6 is a pale olive dolomitized carbonate mudstone that varies in thickness from 14 to 30 cm. To the north it pinches out into a claystone; to the south the unit approaches 30 cm in thickness.

Unit 5 is a blocky reddish brown and pale olive mottled shale approximately 45.7 cm thick with two distinctive carbonate intervals, each 1–2 cm thick.

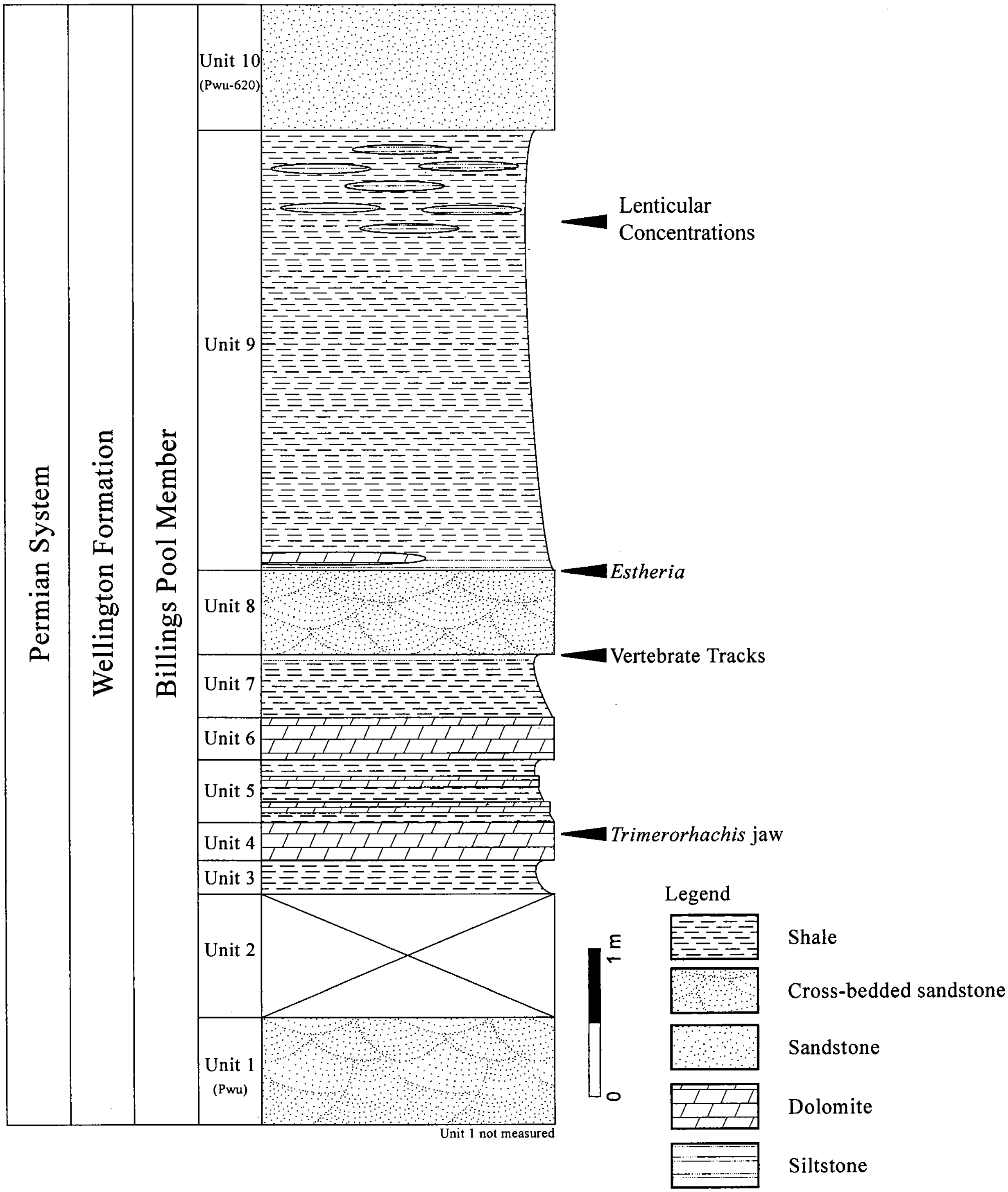

Figure 1. This stratigraphic column for the Kirby Quarry shows the geology and the fossil-producing layers.

Unit 4 is a pale olive dolomitized carbonate mudstone about 23 cm thick in which a jaw section of a *Trimerorhachis* was found. To the north, the unit forms large disconnected nodules; to the south it pinches out.

Unit 3 is a pale olive to reddish brown mottled blocky shale about 60 cm thick.

Unit 2 is covered, but may be a red shale.

Unit 1 is a fine-grained, subarkosic reddish brown (10R 4/6), cross-bedded sandstone. (This is the Pwu of Shelton, 1979.) The base of the sandstone is not exposed here.

Given the occurrence of freshwater fauna, carbonized plant material, and de-watering structures in the upper sandstone, these sediments appear to represent a lacustrine environment. Concentrations of bone and plant material can be found in lenticular concentrations, possibly formed by oscillating current directions. The dolomitized carbonate mudstones may have resulted from dolomitization within the vadose zone post-depositionally—or they could be dolomitized freshwater carbonate lenses that formed in lacustrine water. Further study of these dolomitized carbonates could lead to a better understanding of the environment and timing of dolomitization of these lenses, which are horizontally inconsistent.

FAUNA

The fauna at this site are mainly aquatic. Most of the identifiable remains are palaeoniscoid fish, represented by scales and skull fragments, and four types of freshwater sharks. The most important of the sharks, *Hybodus*, is represented by fin spines. In Oklahoma, *Hybodus* remains have been recovered in younger strata at three sites (Simpson, 1974, 1976, 1979; Zidek, 1976)—all in the upper Garber Formation of southwestern Oklahoma. At the Kirby Quarry, all the recovered *Hybodus* fin spines (OMNH 58220, 58221, and 58444 through 58448) are small fragments, about 3 mm to 5.5 mm long. No *Hybodus* teeth have yet been found in the Wellington Formation of Oklahoma.

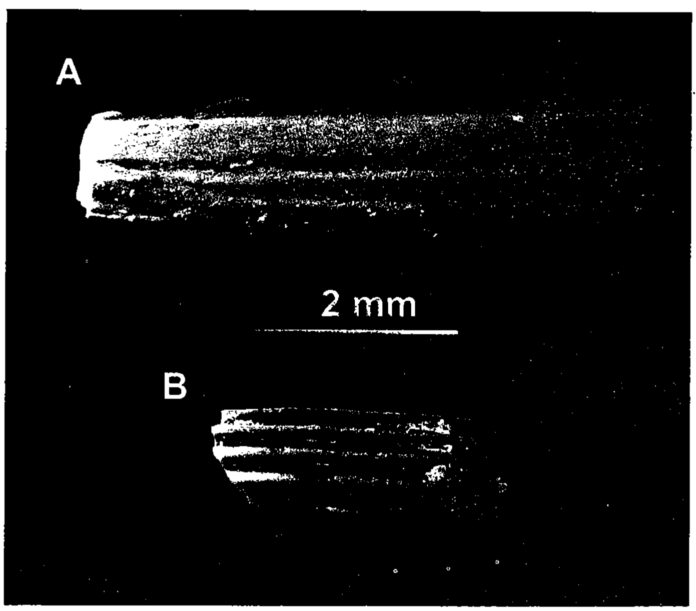

Figure 2. *Hybodus* shark fin spines at the Kirby Quarry occur as two different types. *A*—OMNH 58220 is type "A"; *B*—OMNH 58221 is type "B".

TABLE 1. — Faunal List from Unit 9, the Kirby Quarry

Invertebrata
- Conchostraca
  - *Estheria*

Vertebrata
- Chondrichthyes
  - *Hybodus* sp.
  - *Orthacanthus platypternus*
  - Orthacanthus texensis
  - *Xenacanthus luederensis*
- Osteichthyes
  - *Sphaerolepis arctata*
  - Platysomus parvus
  - *Palaeoniscoidea*, spp. indet.
- Amphibia
  - *Archeria* sp.
  - *Diplocaulus* sp.
  - *Trimerorhachis* sp.
- Reptilia
  - *Dimetrodon* sp.
  - *Dictyobolus tener*
  - *Ophiacodon* sp.
  - ?*Captorhinus* sp.
  - *Araeosceloidea*, indet.

Two distinct types of *Hybodus* spines have been found at this site (Fig. 2). Type "A" (OMNH 58220, 58445 through 58448) is represented by fragments of five fin spines. Morphology of two fragments indicates that they are almost complete distal ends; the three others represent more proximal ends.

On fin spines referred to as *Hybodus* type "A", the entire surface is ornamented, with seven parallel longitudinal ridges running the entire length, one of which forms the anterior keel of the spine. Ridges and grooves are smooth, and approximately equal in width. The ridge walls are slightly rounded proximally and extremely rounded distally. The grooves narrow toward the distal end to about one-half the width of the ridges. The height of the ridges also decreases toward the distal end. The shape of the denticles changes from a sharp edge with a downward pointed tip toward the proximal end, to a gently arch-shaped denticle ridge with a center high apex distally. The three ridges and grooves on each side are almost centered with a flat surface, both anterior and posterior to the ridges and grooves series. The anterior flat surface is approximately the width of four to five ridges, and the posterior flat surface is about two ridges wide. On both of the flat surfaces are three longitudinal lines of pits. In OMNH 58220 are four denticles along the posterior face; they are in a single series. The distal tip is slightly displaced, alternating from right to left of the base of the preceding denticle. The denticles are smooth, and longer than wide. There is very little space between denticles; they almost touch. OMNH 58220 is 5.63 mm long, 1.22 mm wide distally, and 1.98 mm proximally. The widest spine fragment measures 2.76 mm.

Type "B" is represented by two fragments (OMNH 58221 and 58444) that show characteristics of a distal position on the spine. The entire surface of the spine is ornamented with 11 parallel longitudinal ridges, running the entire length. One ridge forms the keel of the spine. Ridges and grooves are smooth and approximately equal in width. The ridge walls are slightly rounded, and the grooves are deep. On either side of the single row of denticles are three rows of longitudinal pits. On OMNH 58221 are two partial denticles. The lower denticle shows that the surface was smooth. The distal tip is slightly offset to the right. The distal tip of the second denticle is missing, so it is unknown if the distal tips alternate from right to left as in the type "A" spines. The denticles are longer than wide and between them is a space approximately three-fourths the length of a denticle. OMNH 58221 is 2.86 mm long and 1.24 mm wide.

The type "A" and "B" fin spines above were compared with the three types described by Simpson (1974, 1976, 1979) and Zidek (1976), all in the collection of the OMNH and from the upper Garber Formation of southwestern Oklahoma; they differ morphologically. Because these specimens are fragmented and small, we believe that type "A" and "B" are both from immature sharks.

The Kirby Quarry is only the third recorded site for the araeosceloid reptile *Dictybolus tener*; the others are Perry 6 (Olson, 1967, 1970) and Perry 7 (Burkhalter, 1987)—both 2 mi west of the Kirby Quarry. *Dictyobolus tener* has been described by Olson (1970), who suggested that it was piscivorous. Such a dietary preference would explain the presence of *Dictyobolus tener* in the highly aquatic fauna of this site.

A new araeosceloid reptile was also found. Two vertebrae, one caudal (OMNH 58183) and one dorsal (OMNH 58183), have the same general structure and size as *Dictyobolus tener*, but they lack the heavy pitting on the surface. These new vertebrae are similar to specimens being studied by Keith Carlson (personal communication, 1993) of Gustavus Adolphus College (Saint Peter, Minnesota) from a site about 4 mi northwest of the Kirby Quarry; he has recovered multiple coiled strings of articulated vertebrae. A complete faunal list for the site is given in Table 1.

ACKNOWLEDGMENTS

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Oklahoma Earthquakes, 2001

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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 km^2 (Docekal, 1970; Kalb, 1964; von Hake, 1976); Des Moines, Iowa, and Austin, Texas, were at the northern and southern limits. From 1897 through 2001, 1,655 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 10 seismograph stations was used to locate 30 earthquakes in Oklahoma for 2001 (Fig. 1). The statewide network consists of a central station (TUL/LNO), four radio-telemetry seismograph stations (FNO, RLO, SIO, VVO), and four volunteer-operated field stations (ACO, CCOK, MEO, PCO, OCO). These stations (except OCO) are operated and maintained by the Oklahoma Geological Survey (OGS). Station OCO, which contains equipment similar to the volunteer-operated stations, is at the Omniplex museum in Oklahoma City. Omniplex staff members change the seismic records daily as well as maintain the equipment. OGS Observatory staff help interpret the seismic data and archive the seismograms with all other Oklahoma network seismograms. The U.S. Geological Survey (USGS) established a seismograph station, WMOK, 19 km southwest of the OGS station at Meers (MEO). WMOK, the USGS station, does not record

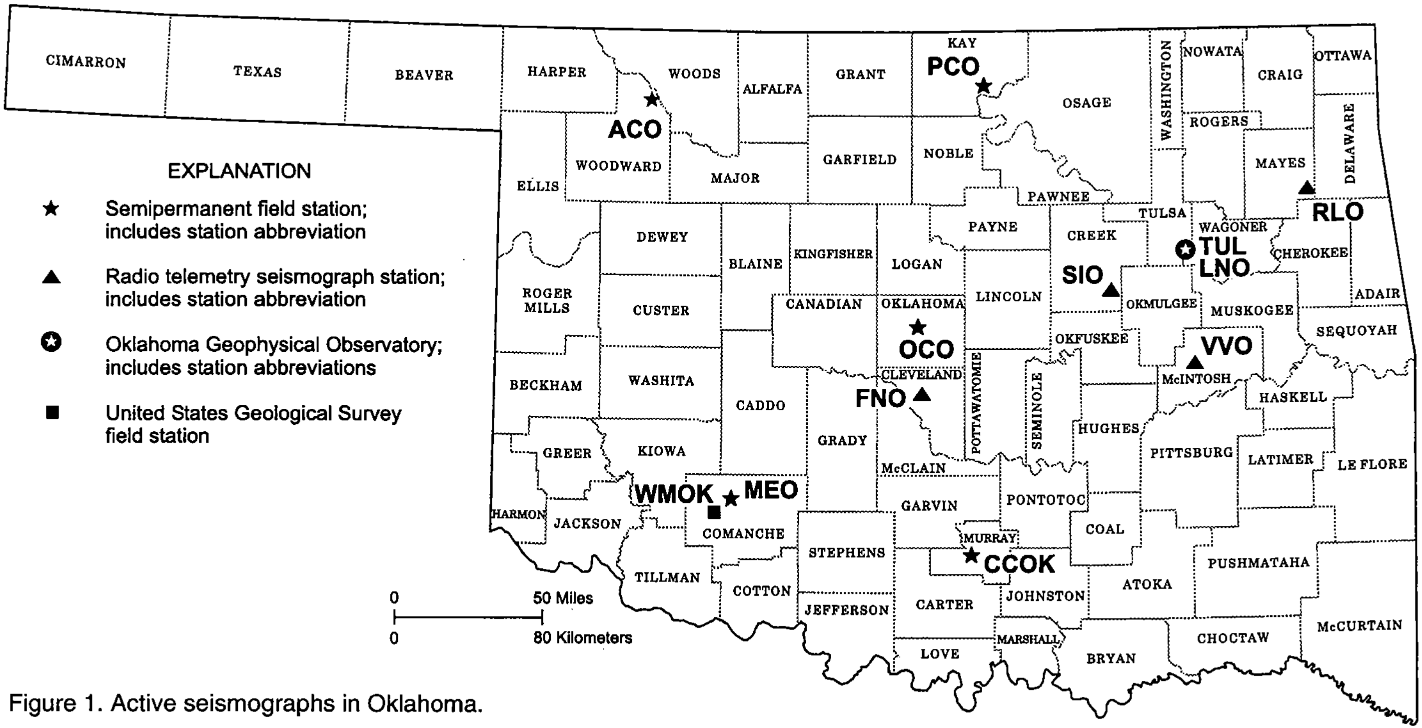

Figure 1. Active seismographs in Oklahoma.

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.

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 μHz 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 four volunteer-operated seismographs (ACO, CCOK, 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.2001.html.

DISTRIBUTION OF OKLAHOMA EARTHQUAKES, 2001

All Oklahoma earthquakes recorded on seismograms from three or more stations are located. In 2001, 30 Oklahoma earthquakes were located (Fig. 2; Table 2). Two 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).

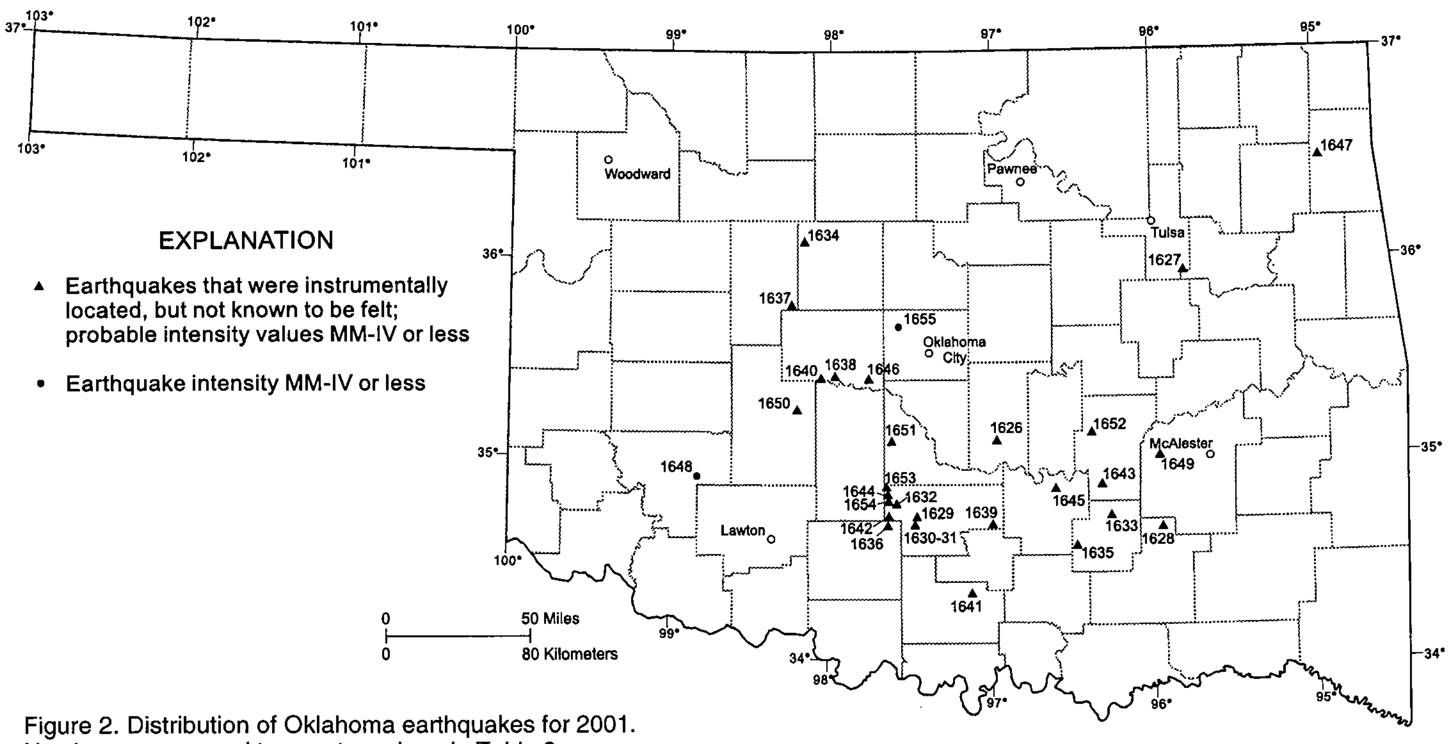

Figure 2. Distribution of Oklahoma earthquakes for 2001. Numbers correspond to event numbers in Table 2.

A magnitude 2.6 (mbLg) earthquake was reported felt in east-central Kiowa County on September 2, 2001. The epicenter was 10 km southwest of Sedan, where people felt vibrations from the earthquake, and 8 km east of Cooperton. Two people in Sedan felt the earthquake and reported that it sounded like thunder and/or a sonic boom. No damage was reported. The felt area for the Cooperton/Sedan earthquake probably was restricted to a few tens of square kilometers away from the epicenter. This earthquake was the fifth known to have occurred in Kiowa County.

On December 16, a magnitude 2.1 (mbLg) earthquake occurred in northwestern Oklahoma County ~9 km west of Edmond. The earthquake was felt in Edmond, Oklahoma City, Warr Acres, and southern Logan County. This earthquake produced MM IV effects near the epicenter. Felt reports (29) ranged from "very sudden loud boom followed by the rattling of kitchen windows" in Warr Acres to "entire house shook, moving some items on the book shelf" in northern Edmond. The felt area for the Edmond earthquake was ~525 km^2. Prior to this earthquake, six earthquakes were known to have occurred in Oklahoma County.

In 2001, earthquake-magnitude values ranged from a low of 1.1 (m3Hz) in Pottawatomie County to a high of 2.9 (mbLg) in Garvin County. Most of the earthquakes occurred in central Oklahoma. Nine earthquakes were located in Garvin County; Canadian County experienced three; and Coal and Hughes Counties each had two.

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, 1993–2001), Lawson and others (1991, 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.

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

TABLE 2. — Oklahoma Earthquake Catalog for 2001

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]
1626	Jan 02	02 34 38.61	Pottawatomie		1.1		1.6	35.0774	96.9628	4.99 C
1627	Jan 02	02 50 25.42	Tulsa				1.8	35.9084	95.7954	0.10 C
1628	Jan 27	00 57 54.28	Atoka		2.3	2.1	2.0	34.6404	95.9524	15.19 C
1629	Feb 21	02 26 25.26	Garvin		1.6			34.6963	97.4551	5.31R C
1630	Feb 21	02 59 52.52	Garvin		1.7			34.6628R	97.4748R	5.31R C
1631	Feb 21	03 39 23.70	Garvin		2.5	2.4	1.9	34.6628	97.4748	5.31 C
1632	Feb 21	03 41 12.57	Garvin		2.4	2.1		34.7598	97.5827	4.01 C
1633	Apr 27	23 48 39.04	Coal		1.6		1.7	34.6975	96.2606	5.00R C
1634	Jun 14	02 30 34.20	Kingfisher		2.1	2.2	1.8	36.0651	98.1631	5.00R C
1635	Jun 29	01 52 24.53	Coal				1.5	34.5542	96.4784	5.00R C
1636	Jul 12	03 16 50.79	Stephens		2.3	2.1	1.7	34.6558	97.6473	5.00R C
1637	Jul 15	13 42 46.37	Blaine		1.8		1.9	35.7388	98.2416	5.00R C
1638	Jul 18	01 28 59.68	Canadian		2.0	2.0	2.1	35.4026	97.9677	5.00R C
1639	Jul 18	06 09 10.59	Garvin		1.7		1.9	34.6427	96.9984	5.00R C
1640	Jul 18	17 14 04.53	Canadian		2.1	2.1	1.9	35.3867	98.0606	5.00R C
1641	Jul 18	18 01 05.60	Carter				1.6	34.3209	97.1244	5.00R C
1642	Jul 18	19 25 12.40	Garvin		2.5	2.5	2.1	34.7030	97.6340	5.00R C
1643	Jul 22	07 48 50.73	Hughes		1.8		1.8	34.8529	96.3140	5.00R C
1644	Jul 22	11 49 22.61	Garvin		2.3	2.4	2.1	34.7953	97.6453	5.00R C
1645	Aug 06	06 38 33.73	Pontotoc		1.5		1.6	34.8320	96.5979	5.00R C
1646	Aug 11	01 12 38.11	Canadian		2.2	2.1	2.0	35.3856	97.7555	5.00R C
1647	Aug 15	04 15 55.80	Delaware				1.9	36.4632	94.9477	5.00R C
1648	Sep 02	22 48 42.34	Kiowa	F	2.7	2.6	2.4	34.8976	98.8181	5.00R C
1649	Sep 17	22 19 34.52	Pittsburg		1.7	1.8	1.9	34.9993	95.9636	7.69 C
1650	Sep 22	15 32 55.74	Caddo				1.7	35.2264	98.2151	5.72 C
1651	Oct 04	04 29 17.64	McClain				1.7	35.0771	97.6197	5.00R C
1652	Oct 25	02 41 00.17	Hughes				1.7	35.1119	96.3776	4.36 C
1653	Nov 09	16 16 17.89	Garvin		2.2		2.2	34.8431	97.6527	5.00R C
1654	Nov 09	22 04 03.04	Garvin		2.7	2.9		34.7809	97.6400	5.00R C
1655	Dec 16	08 21 42.4	Oklahoma	IV	2.2	2.1	2.2	35.6428	97.5706	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).

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:

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

TABLE 3. — Earthquakes Reported Felt in Oklahoma, 2001

Event no.	Date and origin time (UTC)[a]		Nearest city	County	Intensity MM[b]
1648	Sep 02	22 48 42.34	Cooperton/Sedan	Kiowa	F
1655	Dec 16	08 21 42.4	9 km west of Edmond	Oklahoma	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.

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.

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 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. After 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 is 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 necessary information to evaluate insurance rates.

ACKNOWLEDGMENTS

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 Na-

tional 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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Digital Data Sets of Depth-Duration Frequency of Precipitation for Oklahoma

Prepared in cooperation with the Oklahoma Department of Transportation, this USGS open-file report provides digital geospatial data sets produced as part of a regional precipitation frequency analysis. Precipitation depths for various durations and frequencies, referred to as depth-duration frequency of precipitation in this report, have many uses. A common use of depth-duration frequency of precipitation is for the design of drainage structures that control and route localized runoff—such as parking lots, storm drains, and culverts. Another use of this data is for compilation of rainfall-runoff river-flow models, which incorporate precipitation characteristics. Accurate depth-duration frequency of precipitation estimates are important for economical and safe structural designs at stream crossings and for developing reliable flood prediction models. Written by Alan Rea and Robert L. Tortorelli, this report provides updated digital estimates of depth-duration frequency of precipitation for any location in Oklahoma.

USGS Open-File Report 99-463 is available on the Web at http://water.usgs.gov/pubs/of/ofr99-463/.

Rapid Recharge of Parts of the High Plains Aquifer Indicated by a Reconnaissance Study in Oklahoma, 1999

The High Plains aquifer underlies about 174,000 mi^2 in parts of eight states, including about 7,100 mi^2 in northwestern Oklahoma. This aquifer consists of the saturated part of the Ogallala Formation and saturated materials of Quaternary age that are hydraulically connected to the Ogallala. The High Plains aquifer in northwestern Oklahoma is the primary source of water to an important agricultural region. Historically, water from precipitation was thought to take hundreds or thousands of years to reach the water table because the depth of the water table is >100 ft over most of the aquifer and the low-permeability beds in the Ogallala would impede downward flow. It also was thought that land uses would take a similar period of time to affect water quality in the aquifer. This 4-page USGS fact sheet was written by William J. Andrews, Noel I. Osborn, and Richard R. Luckey.

Order Fact Sheet 137-00 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone 1-888-275-8747. Fact sheets are available at no cost. This fact sheet also is available on the Web at http://water.usgs.gov/pubs/FS/FS-137-00/.

Digital Map of Aquifer Boundary for the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming

Compiled by Joel R. Cederstrand and Mark F. Becker, this USGS report contains digital data and accompanying documentation for aquifer boundaries for the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. This digital data set was compiled from a digital coverage that was created for publication of paper maps in USGS Water-Resources Investigations Report 93-4088 (McGrath and Dugan, 1993).

USGS Open-File Report 99-267 is available on the Web at http://pubs.water.usgs.gov/ofr99-267/.

Digital Map of Water-Level Changes in the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, 1980 to 1997

In the area underlain by the High Plains aquifer, the total number of acres irrigated with ground water expanded rapidly after 1940. Water-level declines appeared in the High Plains aquifer soon after extensive ground-water irrigation development began. By 1980, water levels in the High Plains aquifer in parts of Texas, Oklahoma, and Kansas had declined >100 ft. In response to these declines, the U.S. Geological Survey, in cooperation with numerous water-resource agencies, began a ground-water monitoring program in 1988 to assess annual water-level change in the aquifer using water-level measurements from >7,000 wells. This USGS report was written by B. C. Fischer, K. M. Kollasch, and V. L. McGuire.

USGS Open-File Report 00-96 is available on the Web at http://pubs.water.usgs.gov/ofr00-96/.

Digital Map of Water Levels in 1980 for the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming

Digital data and accompanying documentation for contours for 1980 water-level elevations for the High Plains aquifer in parts of eight states are contained in this USGS open-file report, written by Joel R. Cederstrand and Mark F. Becker. This digital data set was created by digitizing the 1980 water-level elevation contours from a 1:1,000,000-scale base map created by the U.S. Geological Survey High Plains Regional Aquifer-System Analysis (RASA) project.

USGS Open-File Report 99-263 is available on the Web at http://pubs.water.usgs.gov/ofr99-263/.

Digital Map of Predevelopment Water Levels for the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming

Digital data and accompanying documentation for aquifer boundaries of contours for predevelopment water-level elevations for the High Plains aquifer in parts of eight states are contained in this USGS report by Joel R. Cederstrand and Mark F. Becker. This digital data set was created by digitizing the contours for predevelopment water-level elevations from a 1:1,000,000-scale base map created by the U.S. Geological Survey High Plains RASA project.

USGS Open-File Report 99-264 is available on the Web at http://pubs.water.usgs.gov/ofr99-264/.

Digital Map of Changes in Water Levels from Predevelopment to 1980 for the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming

This report by Joel R. Cederstrand and Mark F. Becker contains digital data and accompanying documentation for contours of predevelopment to 1980 water-level elevation changes for the High Plains aquifer in parts of eight states. This digital data set was created by digitizing the contours for predevelopment to 1980 water-level elevation change from a 1:1,000,000-scale base map created by the U.S. Geological Survey High Plains RASA project.

USGS Open-File Report 99-265 is available on the Web at http://pubs.water.usgs.gov/ofr99-265/.

Digital Map of Saturated Thickness in the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, 1996 to 1997

The High Plains aquifer underlies one of the major agricultural regions in the world. A saturated-thickness map of the High Plains aquifer was prepared by superimposing a 1996–97 water-table map over a map of the elevation of the base of the aquifer and contouring the elevation difference. Authors B. C. Fischer, K. M. Kollasch, and V. L. McGuire report that saturated thickness in 1996–97 ranged from generally 0 at the boundary of the aquifer to >1,000 ft in west-central Nebraska.

USGS Open-File Report 00-300 is available on the Web at http://water.usgs.gov/pubs/of/ofr00-300/.

Digital Map of Areas of Little or No Saturated Thickness for the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming

This USGS report contains digital data and accompanying documentation for boundaries of areas of little or no saturated thickness within the High Plains aquifer in parts of eight states. Compiled by Joel R. Cederstrand and Mark F. Becker, this digital data set was from a digital coverage that was created for publication of paper maps in USGS Water-Resources Investigations Report 93-4088 (McGrath and Dugan, 1993).

USGS Open-File Report 99-266 is available on the Web at http://pubs.water.usgs.gov/ofr99-266/.

Digital Map of Geologic Faults for the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming

This report by Joel R. Cederstrand and Mark F. Becker contains digital data and accompanying documentation for faults of the High Plains aquifer in parts of eight states. This digital data set was created by digitizing the faults from a 1:1,000,000-scale base map created by the U.S. Geological Survey High Plains Regional Aquifer-System Analysis (RASA) project.

USGS Open-File Report 99-261 is available on the Web at http://pubs.water.usgs.gov/ofr99-261/.

upcoming meetings

OCTOBER

Society of Exploration Geophysicists, Annual Meeting and Exhibition, October 6–11, 2002, Salt Lake City, Utah. Information: SEG, P.O. Box 702740, Tulsa, OK 74170; (918) 497-5500; fax 918-497-5557; E-mail: meeting@seg.org. Web: http://www.seg.org/.

Oklahoma Geological Survey, Coalbed-Methane Workshop, October 10, 2002, Norman, Oklahoma. Information: Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 *or* (800) 330-3996; fax 405-325-7069; E-mail: tcreel@ou.edu. Web: http://www.ou.edu/special/ogs-pttc/.

American Institute of Hydrology, "Hydrologic Extremes: Challenges for Science and Management," October 13–17, 2002, Portland, Oregon. Information: Helen Klose, 2499 Rice St., Suite 135, St. Paul, MN 55113; (651) 484-8169; E-mail: AIHydro@aol.com. Web: http://www.aihydro.org.

Annual International Conference on Contaminated Soils, Sediments, and Water, October 21–24, 2002, Amherst, Massachusetts. Information: Denise Leonard, Environmental Health Sciences, N344 Morrill Science Center, University of Massachusetts, Amherst, MA 01003; (413) 545-1239; E-mail: info@UMassSoils.com. Web: http://www.umasssoils.com/.

Geological Society of America, Annual Meeting, October 27–30, 2002, Denver, Colorado. Information: GSA Meetings, Box 9140, Boulder, CO 80301; (303) 447-2020 *or* (800) 472-1988; fax 303-447-1133; E-mail: meetings@geosociety.org. Web: http://www.geosociety.org.

American Association of Petroleum Geologists, International Conference and Exhibition, "Ancient Oil—New Energy," October 27–30, 2002, Cairo, Egypt. Information: AAPG, P.O. Box 979, Tulsa, OK 74101; (918) 560-2679 *or* (800) 364-2274; fax 918-560-2684 *or* 800-281-2283; E-mail: convene@aapg.org. Web: http://www.aapg.org/meetings/cairo/index.html.

Gulf Coast Association of Geologic Societies, Annual Convention, October 30–November 1, 2002, Austin, Texas. Information: Doug Ratcliff, General Chairman, Bureau of Economic Geology, University of Texas, University Station, Box X, Austin, TX 78713; (512) 471-5117; fax 512-471-0140; E-mail: doug.ratcliff@beg.utexas.edu. Web: http://www.beg.utexas.edu/gcags2002/info.htm.

NOVEMBER

Oklahoma Geological Survey/Oklahoma City Geological Society, Hunton Field Trip, November 6, 2002, Ada, Oklahoma. Information: Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 *or* (800) 330-3996; fax 405-325-7069; E-mail: tcreel@ou.edu. Web: http://www.ou.edu/special/ogs-pttc/.

DECEMBER

Interstate Oil and Gas Compact Commission, Annual Meeting, December 15–17, 2002, Little Rock, Arkansas. Information: IOGCC, P.O. Box 53127, Oklahoma City, OK 73152; (405) 525-3556; fax 405-525-3592; E-mail: iogcc@iogcc.state.ok.us. Web site: http://www.iogcc.state.ok.us/.

OGS Workshop

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

TULSA, September 18 and 19
NORMAN, September 24

The Tulsa Geological Society (TGS), the Oklahoma Geological Survey, and the Petroleum Technology Transfer Council (PTTC) South Midcontinent Region will co-host a half-day workshop on the stratigraphic relationship of methane-producing coal beds in the northeast Oklahoma shelf. The workshop will be held at the Geophysical Resource Center in Tulsa on Wednesday, September 18, 1–5 p.m.; it will be repeated at the same location on Thursday, September 19. The workshop also will be held at the Moore Norman Technology Center in Norman on Tuesday, September 24, co-hosted by the Oklahoma City Geological Society, OGS, and PTTC.

The workshop will provide information on Oklahoma coal geology with emphasis on the surface-to-subsurface correlation of methane-producing coal beds in an area of the State where more than 1,100 wells have been completed for coalbed methane. Interest in further development of the coalbed-methane industry is high.

The meeting is designed to aid geologists, engineers, and operators in identification and correlation of methane-producing intervals through the use of geophysical logs. Hands-on laboratory exercises using copies of actual logs from the study area, with supervision and assistance by two OGS geologists—Rick Andrews and LeRoy Hemish—are scheduled for part of the workshop.

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

Society of Vertebrate Paleontology
62nd Annual Meeting

October 9–12, 2002
Norman, Oklahoma

This year's meeting will be held for the first time ever in Oklahoma. We plan to make the meeting pleasurable and memorable for all. The meeting will be held at the new National Center for Employee Development, and special events will be hosted by the Sam Noble Oklahoma Museum of Natural History. Come see the beautiful new museum!

The Division of Vertebrate Paleontology at the Sam Noble Oklahoma Museum of Natural History has a long history beginning in 1899. The early years were difficult; fires destroyed much of the collection twice in the early 20th century. What survived the fires was moved to different buildings at least eight times by the end of the century. Today, for the first time in our history, all the museum collections, departments, and exhibits are under one roof.

The new museum, which opened in 2000, includes 60,000 square feet of collections storage and 50,000 square feet of exhibits. Permanent exhibit galleries include the Hall of Ancient Life, the Hall of Natural Wonders, and the Hall of the People of Oklahoma. A visit to the museum's vertebrate paleontology collection area is offered during the meeting (by prior appointment; requests for appointments must be received by September 10).

The Host Committee for the 62nd Annual Meeting looks forward to seeing you in Norman. We think you will find your experience here memorable and enjoyable.

—NICHOLAS J. CZAPLEWSKI
Host Committee Chair

Symposia

Recent Advances in the Origin and Early Radiation of the Vertebrates: A Symposium Honoring Hans-Peter Schultze

200 Years of Vertebrate Paleoichnology

Preparators' Symposium

The Continental Permian

Recent Advances in Lepidosaurian Evolution and Systematics

Origin, Timing, and Relationships of Major Extant Placental Clades: A Symposium Honoring the Centennial of George Gaylord Simpson's Birth

Workshops

Preparators' Workshop: Forum on Cyanoacrylate and Its Place in the Continuum of Other Adhesives and Consolidants Used in Fossil Preparation, *Oct. 9*

Teachers' Workshop: Learning from the Fossil Record, *Oct. 12*

Field Trips

Tracking Dinosaurs in No Man's Land, *Oct. 6–8*

Cretaceous of Southeast Oklahoma, Southwest Arkansas, and Northeast Texas, *Oct. 6–8*

Late Cenozoic Verebrate Paleontology of the Texas and Oklahoma Panhandles, *Oct. 6–8*

Early Permian Vertebrates of Southwestern Oklahoma and Northern Texas, *Oct. 13–15*

Information

For general questions regarding the 62nd Annual Meeting of the Society of Vertebrate Paleontology, contact the SVP Business Office. The Business Office will coordinate registration and exhibits.

SVP Business Office
60 Revere Drive, Suite 500
Northbrook, IL 60062

Phone: (847) 480-9095
Fax: 847-480-9282
E-mail: svp@vertpaleo.org
Web: http://www.vertpaleo.org

SVP 62nd Annual Meeting logo: Drawing of the *Diplocaulus* is provided by Coral McCallister, illustrator for the Department of Zoology, University of Oklahoma.

GSA Annual Meeting and Exposition
October 27–30, 2002 • Denver, Colorado

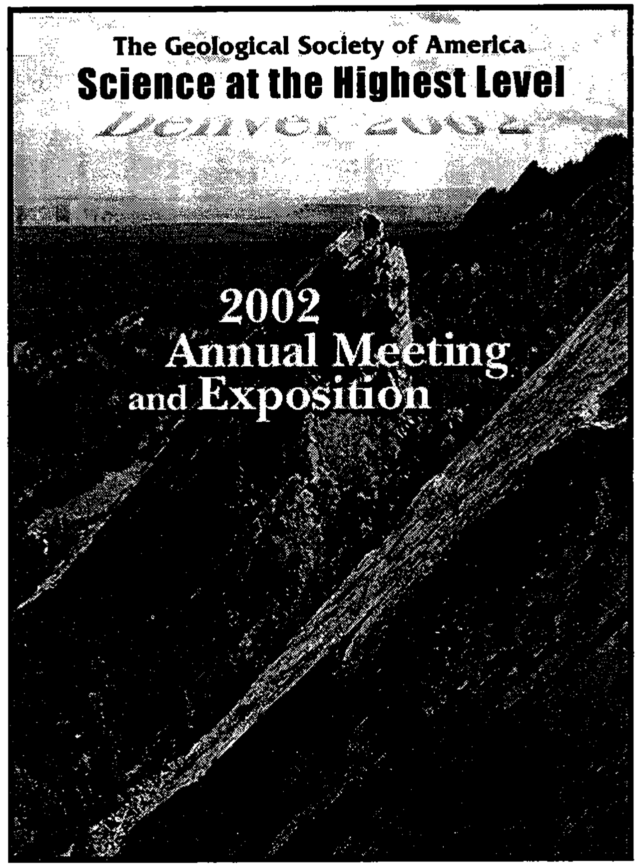
Greetings!

We return to Denver for the GSA 2002 Annual Meeting with the hope of making this meeting an even greater success than its predecessor in 1999, when more than 6,300 geoscientists attended.

The theme for the 2002 meeting—Science at the Highest Level—emphasizes the quality of vibrant and current research presented at GSA annual meetings. The meeting's Pardee Keynote Symposia and topical sessions represent an extreme diversity of geoscience and highlight the interdisciplinary nature of many, if not most, facets of our science. We strongly encourage you to participate in the Denver meeting. Strengthen the quality and diversity of *Denver 2002: Science at the Highest Level* by submitting an abstract. Remind your colleagues to do so! As always, quality field trips and short courses, informative and/or controversial hot topics, and an array of exhibitors form an integral part of the meeting.

With its ever-changing and vibrant downtown and its wide range of cultural attractions, dining, and nightlife, Denver is as close to a perfect venue for a GSA annual meeting as you'll find. The geologic surroundings are magnificent; plan to participate in a field trip to prove it to yourself.

— John W. Geissman
Technical Program Chair



Flatirons in Boulder, Colorado. Photo by John Karachewski.

GSA Annual Meeting Agenda

PARDEE KEYNOTE SYMPOSIA

Earth Sciences Challenges in the National Problem of High-Level Radioactive Waste Disposal
Evolution of the Early Atmosphere, Hydrosphere, and Biosphere: Constraints from Ore Deposits
Flood Hazard on Dynamic Rivers: Human Modification, Climate Change, and the Challenge of Non-Stationary Hydrology
Geologic and Ecologic Responses to Landscape Disturbances
The Role of the Earth Sciences in Fostering Global Equity and Stability
There and Back Again: Terrestrial Approaches to Extraterrestrial Problems
Toward a Better Understanding of the Complicated Earth: Insights from Geologic Research, Education, and Cognitive Science

TOPICAL SESSIONS

Application of GIS and Remote Sensing to Archaeological Geology
Nature, Effects, and Control of Groundwater at Archaeological Sites
Obsidian Sources and the Distribution of Archaeological Sites from These Sources
Coal Resource and Utilization Issues
Wetlands Paleoecology Through Time
Chemostratigraphy: An Emphasis on Metal-Rich Black Shale Deposits
Diverse Origins of Sedimentary Rock-Hosted Disseminated Gold Deposits: A Global Perspective
Evolution of the Early Atmosphere, Hydrosphere, and Biosphere: Constraints from Ore Deposits
Mining in the Twenty-First Century: Meeting the Environmental Challenges
Role of Mafic Magmas in the Generation of Porphyry Copper Deposits
SEG Special Session: The Global Tectonic Setting of Ore Deposits—Present Understanding and New Advances
The Changing Vision of Marine Minerals
Case Studies in Landslide Problem Solving, Landslide Monitoring, and Alarm Methodology: In Honor of David J. Varnes
Integrated Studies of the Effects of Abandoned Mines on the Environment
Decay and Conservation of Stone Buildings and Monuments
Evaporite Karst and Engineering and Environmental Problems in the United States
Bentonitic Claystone—Geologic Hazards, Engineering Properties, and Land-Use Issues
Geohazards and Transportation Routes
Groundwater and Hardrock Mining
Humans as a Geologic Agent: In Honor of George Kiersch
Remote Sensing and Geographic Information Systems in the New Millennium: Their Use in Environmental and Engineering Geology
Rumbling in Below the Radar: Earthquake Hazards in Areas Where Seismic Potential is Underrecognized
Working with Geological Chaos: Characterization, Design, and Construction Problems of Fault Rocks, Mélanges, Saprolites, and Other Block-in-Matrix Rocks (Bimrocks)
Human Health Sciences and Geosciences: Bridging the Gap
Modern and Ancient Tidal Flats Reflecting Environmental and Climate Changes for Past and Future
From Geochemistry of the Geosphere, Atmosphere, and Cosmos to Forensic Environmental Geochemistry: A Tribute to Ian Kaplan
Geochemical and Mineralogical Records from Ancient Lake Sediments
Sources, Transport, Fate, and Toxicology of Trace Elements in the Environment: A Tribute to Gunter Faure
Micropaleontological Applications to Problems of Urbanization

Microbial Sulfur Transformations Throughout Earth's History: Development, Changes, and Future of the Biogeochemical Sulfur Cycle
Magnetic Mapping of North American Geology
New Views of Extensional Basins and Related Volcanic Fields Using Geophysics and Remote Sensing
The Anisotropy of Magnetic Susceptibility of Granitic Rocks: New Methodological Developments, Interpretations, and Challenges
Design and Assessment of Computer-Based Instructional Materials for the Geosciences
Digital Libraries as Vehicles for Systemic Educational Change
Educational Issues in Teaching and Research at Two-Year Colleges
Geology in the National Parks: Research, Mapping, Education, and Interpretation
Geoscience Research Partnerships as a Strategy for Engaging K–16 Students and Teachers in Inquiry-Based Learning
Special Session in Honor of John C. Butler: Water Where the Grass Is Greener—Emerging Uses of Technology in Geoscience Education
Special Session in Honor of John C. Butler: Multimedia in Earth Science Education—Creation, Use, and Limitations
Undergraduate Research in the Geosciences: Faculty and Student Perspectives
Urbanizing Geoscience Education
New Heights in Geoscience Information: Access and Technology
Implementing Geoinformatics for Knowledge Integration and Decision Management
Contributions of American Geologists to Theoretical Tectonics on the Basis of Research Done West of the 100th W Meridian in the Latter Half of the 19th Century
Advances in Karst Modeling
Application of Biological and Hydrochemical Tracers in Groundwater Quality Investigations
Artificial Recharge: Hydrologic, Hydrogeochemical, and Microbiologic Aspects
Characterizing Geochemical Processes: When Is There Sufficient Information?
Delineation of Contributing Areas for Wells in Challenging Hydrogeologic Settings: Methods, Uncertainty, and Verification
Denver Basin Bedrock Aquifers—Past, Present, and Future
Experimental, Field, and Modeling Studies of Geological Carbon Sequestration
Flow and Transport in Fractured Aquifers—From Field Characterization to Model Construction
Geophysical Evaluation of Aquifer Properties
Groundwater Depletion and Overexploitation: A Global Problem
Hydrogeologic Framework and Basin Hydrology of the Desert Southwestern United States
Hydrogeology and Water Resources of the High Plains Aquifer: Issues for Public Policy Over the Next 50 Years
Mass and Energy Transport in Groundwater: In Memory of Patrick Domenico
Rivers in Karst: Processes and Applications
The Platte River Basin of Colorado, Nebraska, and Wyoming: Where Geology, Hydrology, Endangered Species, People, and Politics Attempt to Coexist
The Role of Analytic Elements in Groundwater Modeling
The Terrestrial-Aqueous Interface: Multidisciplinary Research and Opportunities
The What, When, Why, and How Much of Chemical (Nutrient) Supplements for Bioremediation
Characterization, Attenuation, and Remediation of Subsurface Organic Contaminants in Heterogeneous Chemical or Physical Settings
Fate, Transport, and Treatment of Pollutants from Municipal Solid Waste Landfills
Watershed Processes Within Tropical Montane Catchments
Yucca Mountain Update: Recent Advances from Scientific Investigations of the Unsaturated Zone
Phosphates: Geochemical, Geobiological, and Materials Importance
Antarctica During the Neogene
Feedback in Earth Systems—Determining System Response to Perturbation Through Observations and Modeling
Geologic Records of Paleoelevation
Global Biogeochemical Change During PETM Events
Isotopic and Elemental Tracers of Late Quaternary Climate Change
Paleosols and Phanerozoic Climate: Geochemistry to Trace Fossils
Three Billion Years of Reef Systems
Advances in the Fossil Record of Insects and Terrestrial Arthropods
Developing Perspectives on the Ecological Context of Biological Evolution Across the Neoproterozoic-Cambrian Transition
Evolutionary Paleobiology and Paleoecology of the Bivalvia
New Frontiers in the Fossil Record of Insects and Terrestrial Arthropods
Paleobiogeography: Integrating Plate Tectonics and Evolution
Paleontology in National Parks: Sharing the Fossil Record with Managers and the Public
Phenotypic Variation: Discriminating Between Evolution and Environment
Seafood Through Time—The Ecologic Context of the History of Life: In Honor of Richard K. Bambach
Microprobe Monazite Geochronology: New Developments and Applications
Chesapeake Bay Impact Structure: Geology, Geophysics, and Geohydrology of America's Largest Crater
Drilling into Impact Structures: Petrology, Geochemistry, and Geophysics
Early Mars
Impact Stratigraphy
Terrestrial Approaches to Extraterrestrial Problems and Vice Versa
A-Type Plutons and Convergent Margins: Orogenic Links to Anorogenic Magmatism?
Effective Communication and/or Partnership Among Geoscientists, the Public, and Policy Makers: Case Studies
Hydrogeology in Developing Countries: Opportunities and Challenges
Injecting Geoscience Into Public Policy: Strategies That Work
Whetting the Appetite of Politicians: Water Issues in the American West
Workforce and Education: Exploring the Industry-Academia Connection Toward Developing a Capable and Sufficient Science and Technology Labor Pool
Geoecology—The Emergence of an Old Concept to Solve Problems in the 21st Century
Geological and Ecological Responses to Landscape Disturbances
Geology, Biogeochemistry, and Ecology: A New Synthesis for Arid Landscape Processes
Geomorphic Impacts of Wildfire
Interdisciplinary Approaches to Understanding Soil and Vadose Zone Hydrology of Saprolite: Integration of Hydrogeology, Sedimentology, Geomorphology, Pedology, and Biology
Post-Laramide Uplift and Erosion of the Rocky Mountains and Colorado Plateau
Quaternary Sciences from Land to Sea: In Honor of John T. Andrews
Quaternary Stratigraphy and the Glacial Environment: In Honor of Ernest H. Muller
Response of Dryland Geomorphic Systems to Climate Change and Variability
Remotely Sensed Data for Geologic and Environmental Studies
New Perspectives on Chert, Its Origin, Diagenesis, and Economic Significance
The Green River Formation Revisited: Crucible for New Concepts and Advances in Paleoclimatology, Tectonics, Chronostratigraphy, Sequence Stratigraphy, Isotope Geochemistry, and Paleontology
Deltas—Old and New
Tectonics, Climate Change, and the Late Cenozoic Evolution of the Rocky Mountains, Colorado Plateau, and Western Great Plains
EarthScope Town Hall Meeting

Detrital Thermochronology—Dating of Exhumation and Landscape Evolution in Mountain Belts

Extensional Tectonics in the Southern Basins and Ranges, United States, and in Western Turkey

Forward Modeling in Tectonics and Structural Geology

Geometry, Kinematics, and Vorticity of High-Strain Zones

Kinematics of the Himalayan-Tibetan Orogen—Comparing the Present with the Past

Lithospheric Structure and Evolution of Rocky Mountain Region, from Deep Mantle to Mountain Tops

New Constraints on Mesoproterozoic–Early Neoproterozoic Supercontinent Assembly and Dispersal

Nonconventional Fold-Thrust Belts: Assessing the Spectrum of Variation in a Structural Style

Structure and Tectonics of the Midcontinent, North America

Tackling Transpression and Transtension in Orogenesis: Tools of Structural Geology from Microfabric to Tectonic Reconstruction

Tectonic Evolution of the Middle East and Adjacent Regions: The Confluence of the Alpine and Himalayan Orogenic Systems and a Window into Processes of Continental Dynamics

Tectonic Modeling Applied to the Characterization and Evaluation of Yucca Mountain as a National Nuclear Waste Repository Site: Concepts, Methods, and Hazard Analyses at Local and Regional Scales

Thermal and Mechanical Significance of Gneiss Domes in the Evolution of Orogens

Thrust Belt Curvature: Integrating Paleomagnetic and Structural Analyses

Reconstructing the Cambrian World: Temporal and Spatial Changes in Physical and Biotic Environments

The Role of the Earth Sciences in Fostering Global Equity and Stability

SHORT COURSES & WORKSHOPS

Anisotropy of Magnetic Susceptibility and Applications to Granitic Rocks, *Oct. 25–26*

Managing Environmental Projects, *Oct. 25–26*

Abrupt Climate Changes, *Oct. 26*

Estimating Rates of Groundwater Recharge, *Oct. 26*

Laser Ablation ICP-MS: Fundamentals and Applications to Environmental and Biological Samples, *Oct. 26*

Practical Methods in Applied Contaminant Geochemistry: From Characterization to Remediation, *Oct. 26*

Sequence Stratigraphy for Graduate Students, *Oct. 25–26*

Phosphates: Geochemical, Geobiological, and Materials Importance, *Oct. 26–27*

The Art of Technical Writing: Improving Your Technical Reports, *Oct. 26*

The Fossil Record of Predation, *Oct. 26*

Professional Licensing for Geologists: How Does It Affect You?, *Oct. 26*

Digital Forum, *Oct. 29*

Job Hunting in the Geosciences, *Oct. 29*

Rational Science for Rational Policy: Geology in Service of Society Through Communications with Government and Media, *Oct. 28*

Exploring Plate Tectonics: A Hands-On Approach, *Oct. 27*

Earthquakes—A One-Day Workshop for College Faculty, *Oct. 27*

GIS for Earth Science Educators, *Oct. 26*

Writing K–14 Grant Proposals to the National Science Foundation—A Workshop, *Oct. 26*

The Science of Rock Climbing: Geology and Physics, *Oct. 26*

Learning from the Fossil Record, *Oct. 26*

Proposal Writing Strategies for Faculty at Primarily Undergraduate Institutions, *Oct. 27*

An NAGT Workshop for Graduate Students: Preparing for Teaching and Academic Careers, *Oct. 26*

Online and Interactive But Not Inefficient: Creating Low-Maintenance Interactive Web Resources, *Oct. 27*

FIELD TRIPS

Paleontology and Geology of the Green River Formation, Utah and Wyoming, *Oct. 22–25*

Middle and Late Jurassic Dinosaur Fossil-Bearing Horizons: Depositional Settings and Implications for Dinosaur Paleoecology, Northeastern Bighorn Basin, Wyoming, *Oct. 23–26*

Cleanup at Summitville—The Superfund Mine Site that Changed Colorado, *Oct. 24–26*

High Plains to Rio Grande Rift: Late Cenozoic Evolution of Central Colorado, *Oct. 24–26*

Key Rocks and Seminal Thinkers: Classic Rocky Mountain Localities That Influenced Tectonic Thought, *Oct. 24–26*

Active Incision-Driven Evaporite Tectonism, Glenwood Springs, Colorado, *Oct. 25–26*

Formation, Reactivation, and Evolution of Proterozoic Shear Zones in the Colorado Rocky Mountains: From Continental Assembly to Intracontinental Orogeny, *Oct. 25–26*

Neotectonics of the Rio Grande Rift in Colorado, *Oct. 25–26*

Structure and Stratigraphy of the Southern Colorado Front Range–Cañon City Syncline, Colorado, *Oct. 25–26*

Borehole Image Logging in Geology and Hydrogeology, *Oct. 26*

Debris Flows Along the I-70 Corridor, Floyd Hill to the Eisenhower Tunnel, *Oct. 26*

Eco-Geo Hike Along the Dakota Hogback North of Boulder, Colorado, *Oct. 26*

Environmental and Engineering Geology of the I-70 Corridor Denver–Eisenhower Tunnel, *Oct. 26*

Geoarchaeology of South Park: A Prairie Ecosystem in the Rocky Mountains, *Oct. 26*

Geologic Reconnaissance of the Denver Front Range and Dinosaur Ridge, *Oct. 26*

Laramide Structure and Synorogenic Sedimentation of the Colorado Front Range, *Oct. 26*

Modern-Day Consequences of Historic Coal Mining in the Foothills and Boulder and Weld Counties, Colorado, *Oct. 26*

Tepee Buttes: Fossilized Methane-Seep Ecosystems, *Oct. 26*

Tour of U.S. Geological Survey Mapping and Geologic Facilities, Denver Federal Center, *Oct. 29*

Permian-Triassic Depositional Systems, Paleogeography, Paleoclimate, and Hydrocarbon Resources in Canyonlands and Monument Valley, Utah, *Oct. 31–Nov. 4*

Approaches to Characterizing Complex Geology for Watershed Investigations in Fractured Crystalline Bedrock: The Idealized and the Reality, *Oct. 31*

Consequences of Living with Geology: A Model Field Trip for the General Public, *Oct. 31*

Field Trip to Glenwood Caverns–Fairy Cave, Glenwood Springs, Colorado: An Introduction to CO_2 and H_2S Speleogenesis, *Oct. 31*

Structural Geometry and Thermal History of Pseudotachylyte from the Homestake Shear Zone, Sawatch Range, Colorado, *Oct. 31*

Geological Reconnaissance of Dinosaur Ridge and Vicinity, *Oct. 26*

Cleanup of the Rocky Flats Environmental Technology Site, *Oct. 26*

Cripple Creek Gold Mining District, *Oct. 25*

Field Workshop: Interpretation of Leached Cappings and Evaluation of Copper Deposits for Solvent Extraction and Electrowinning Copper Production, *Oct. 31–Nov. 2*

For more information, contact Geological Society of America, 2002 Annual Meeting, P.O. Box 9140, Boulder, CO 80301 • (303) 447-2020 • Fax: 303-357-1070 • e-mail: meetings@geosociety.org • World Wide Web: http://www.geosociety.org.

The preregistration deadline is September 20.

Oklahoma abstracts

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

The Reptile *Macroleter*: First Vertebrate Evidence for Correlation of Upper Permian Continental Strata of North America and Russia

ROBERT R. REISZ, Dept. of Zoology, Erindale Campus, University of Toronto, Mississauga, Ontario L5L 1C6, Canada; and *MICHEL LAURIN*, Institut für Palaontologie, Naturhistorisches Forschungsinstitut, Museum für Naturkunde, Zentralinstitut der Humboldt-Universitat zu Berlin, Invalidenstrasse 43, D-10115 Berlin, Germany

The spectacular evolutionary history of terrestrial vertebrates is uncharacteristically poorly documented between the Paleozoic subequatorial exposures of the Permo–Carboniferous of North America and Europe, and the much higher latitude, Upper Permian deposits of central Russia and southern Africa. We report here that the discovery of the reptile *Macroleter* in Oklahoma provides the first direct vertebrate evidence of biochronological correlation between continental sediments from the Upper Permian of North America and Russia. The presence of the reptile *Macroleter*, a member of a major group of Upper Permian amniotes known previously only from central Russia, in North America improves dramatically our understanding of this early phase of amniote evolution, and also provides evidence of terrestrial tetrapod faunal interchange between North America and Russia in Late Permian time.

Reprinted as published in the Geological Society of America *Bulletin*, v. 113, September 2001, p. 1229.

Sampling at the Species Level: Impact of Spatial Biases on Diversity Gradients

STEPHEN R. WESTROP, Oklahoma Museum of Natural History and School of Geology and Geophysics, University of Oklahoma, Norman, OK 73072; and *JONATHAN M. ADRAIN*, Dept. of Geoscience, University of Iowa, Iowa City, IA 52242

Sample bias is a fundamental issue in analyses of diversity. The adequacy of the fossil record continues to be questioned, especially at fine taxonomic and spatial scales. Here we evaluate the impact of variability in sampling intensity on diversity patterns of Late Cambrian trilobite faunas of Laurentian North America across a spectrum of five shelf environments. The data set consists of nearly 2000 samples from the published literature and 55 field collections that provide an independent estimate of diversity in each environment. Collections from the literature are distributed unevenly among environmental groupings; shallow subtidal carbonates account for almost half of the total. [Oklahoma is among the localities that yielded collections for literature-based compilation of species diversity.] However, despite the strong sampling bias, raw counts of species from the literature reproduce the general shape of the diversity gradient established from field collections, including low species richness in nearshore environments and peak diversity in carbonate buildups. Rarefaction of species records confirmed the overall shape of the gradient, although the rank order of some facies was obscured by sampling problems. The results suggest that the adequacy of the published fossil record depends upon the level of analysis. Gross diversity patterns retrieved in this study appear to be robust, but resolution of fine detail is influenced by sampling issues.

Reprinted as published in *Geology*, v. 29, October 2001, p. 903.

Pleistocene Incision Rates in the Western United States Calibrated Using Lava Creek B Tephra

DAVID P. DETHIER, Dept. of Geosciences, Williams College, Williamstown, MA 01267

The Lava Creek B ash bed, erupted from the Yellowstone caldera ca. 0.64 Ma, provides a datum for measuring long-term fluvial incision west of the Mississippi River [study area includes Oklahoma]. The ash is widely preserved due to its substantial volume, broad initial dispersal, and the aggrading environment into which the ash fell. Drainages incised soon after Lava Creek B deposition, isolating the ash from fluvial erosion and preserving it in fill terraces. Calculated rates of incision since ca. 0.60 Ma range from $\leq$2 to ~30 cm k.y.$^{-1}$. Rates are high in most areas near the Rocky Mountains and downstream along rivers draining mountainous terrain, and are lowest east of the High Plains and along the Snake River. Incision rates along many rivers decrease downstream. Rates of downcutting increased in the late Pleistocene along several major rivers, indicating that climate change altered sediment budgets. Regional and temporal data suggest that fluvial incision records increased middle and late Pleistocene runoff from the southern Rocky Mountains, rather than epeirogenic uplift, but regional rock uplift cannot be excluded as a significant factor.

Reprinted as published in *Geology*, v. 29, September 2001, p. 783.

Ancient Hydrocarbon Emission Sites, North America Western Interior Cretaceous Basin Cold-Seep Mounds (Tepee Buttes)—Geographic, Stratigraphic, and Age Distribution

CHERYL L. METZ, Texas A&M University, Houston,TX

Western Interior Cretaceous (WIK) basin cold-seep mounds or tepee buttes, which are anomalous carbonate bodies within basinal shales, are reported to be sites of hydrocarhon emissions (methane) during the Late Cretaceous. Stratigraphic sleuthing has revealed WIK cold-seep mounds to be narrowly restricted in their geographic, stratigraphic, and age distributions. The geographic distribution ranges from the northern Black Hills southward to the Texas-Mexican border, in a narrow band east

of the front-range of the Rocky Mountains, roughly between 101′ 30″ W and 105′ 30″ W longitude. The age distribution of cold-seep formation in the WIK basin consist of five discrete intervals during a time span of approximately 14 million years, from the basal Campanian through the Early Maastrichtian.

The earliest and most southern WIK cold-seeps are reported from the upper Ojinaga Formation, West Texas, within basal Campanian Gulf Coast biozone *Submortoniceras tequesquitense*. Later cold-seep mounds are reported from the central WIK basin (Black Hills to Colorado/New Mexico border) within the Pierre Shale. These occurrences are distributed within four intervals from the Middle Campanian through Early Maastrichtian within the WIK ammonite biozones of: (1) *Baculites perplexus* and *B. gregoryensis*, (2) *B. scotti* through *Didymoceras cheyennense*, (3) *B. reesidei* through *B. eliasi*, and (4) *B. grandis* and possibly *B. clinolobatus*. Comparisons in the geographic and temporal distribution of central WIK basin cold-seep mounds to subsurface structures, basinal subsidence patterns, and strandline position, suggest an association between cold-seep formation and changes in basin tectonics, western strandline migration, and the possible delineation of the forebulge region.

Reprinted as published in the American Association of Petroleum Geologists *2002 Annual Convention Official Program*, v. 11, p. A120.

Sequence Stratigraphic and Paleoecologic Lowstand Model of Ephemeral Connections in Epeiric Seaways, U.S. Western Interior Cretaceous

JOHN HOLBROOK, Dept. of Geosciences, Southeast Missouri State University, Cape Girardeau, MO 63701; *ROBERT W. SCOTT*, Precision Stratigraphic Associates, Cleveland, OK; *FRANCA OBOH-IKUENOBE*, Dept. of Geology and Geophysics, University of Missouri, Rolla, MO 65409; *MICHAEL EVETTS*, Evetts Consulting, Longmont, CO; and *STAVENA AKINS*, Dept. of Geosciences, Southeast Missouri State University, Cape Girardeau, MO 63701

High-resolution sequence stratigraphy of mid-Cretaceous (Albian-Cenomanian) strata in the U.S. Western Interior between Wyoming and Texas reveal that rocks generally attributed to transgression during the early part of the Greenhorn third-order cycle record three thin sequences of unusually large regional extent deposited during three lower-order marine cycles. The three sequences are best exposed in the Oklahoma Panhandle section of the Dakota Formation.

Each sequence records biofacies shifts of over 200 km within vertical sections of less than 20 m that mark ephemeral connections between Boreal and Tethyan realms across eastern Colorado. In each sequence, basal fluvial-estuarine sandstone with non-marine fossil assemblages passes vertically into a section of marine-influenced shale and sandstone. Biofacies in marine-influenced units show a progressive loss of marine influence up dip. Marine palynomorphs and a diverse Skolithos ichnofacies dominate coastal plain strata up dip of marine shoreface and shelf deposits. Marine fossils become progressively depauperate up dip until only brackish-tolerant ichnofauna and non-marine palynomorphs remain. The shift from coastal marine to near terrestrial fossil assemblages spans a distance of over 200 km. The sequence boundaries separating these thin sequences are unique mappable surfaces over the length of this transition. The depauperate fauna record intervals when ephemeral biotic connections allowed limited and selective exchange of Tethyan and Boreal fauna.

These strata illustrate that transference of marine biota and integrity of sequence boundaries may extend for very long distances up dip on low gradient systems. Likewise, even ephemeral connections between oceans may permit limited exchange of biota having paleoenvironmental and biostratigraphic significance.

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Stable Isotopic Variability in Travertine-Depositing Streams: Implications for Paleoclimate Interpretations

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Suites of water samples (spring-mouth) collected through a 4-year period from Gorman Creek, central Texas, exhibit well-defined trends toward higher isotopic values downflow. Increases downflow of $\delta^{18}O$ values are less than 1 permil and $\delta^{13}C$ values average 2 permil. Water temperature at the spring averages 22°C and changes downflow in response to seasonal and diurnal air temperature.

Calcite precipitates exhibit isotopic variability laterally (along flow) and vertically (within the water-column at individual stations). The isotopic values of precipitates are higher downflow (vs. upstream) as well as near the water surface (calcite rafts) compared to those formed on submerged substrates.

Similar trends of higher isotopic values downflow (and near the top of the water column) are known for other travertine-depositing systems, both ambient temperature (Tx, NY, Va, Okla, and NM) and thermal waters (Ariz, Mont, Co, Ca, and Italy). The precipitates in these systems are disequilibrium deposits. Equilibrium oxygen values calculated for theoretical carbonates on the basis of water temperature, in general, are lower than the measured values and this difference is greater for the thermal deposits than the ambient precipitates.

Stable isotopic values in waters and precipitates from central Texas and 14 other travertine systems clearly show variability depending on lateral and vertical positions within each system. On the basis of these trends caution is strongly suggested for paleoclimate interpretations based on ancient travertine deposits. Single sampling sites will not identify the lateral and vertical isotopic variability inherent in these systems.

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Lower and Middle Pennsylvanian Conodont Zonation for Midcontinent North America

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Most of the important advances in Pennsylvanian conodont biostratigraphy since the early work of Lane and colleagues is dispersed among papers that address limited biostratigraphic or taxonomic issues, often on limited geographic and stratigraphic scales. A summary of these advances is now appropriate. The early work provided a detailed zonation for the Morrowan Stage that is widely accepted. However, a combination of stratigraphic and taxonomic problems has hindered development of a reliable conodont zonation for the Atokan and Desmoinesian stages.

Most conodont specialists currently rely on species of *Neognathodus* to zone Middle Pennsylvanian strata. We believe that *Neognathodus* is just as useful in Morrowan strata, but is probably less useful than generally believed for subdividing the Desmoinesian. *Idiognathodus* remains underutilized, but should eventually provide the best biostratigraphic resolution once its complex taxonomic relationships are worked out. *Gondolella* is useful in lithologies where it reliably occurs. Additional taxonomic revision of these three genera is needed, but enough useful taxa are now described and illustrated that we propose the following zonation:

Zones based on species of *Neognathodus* for the Morrowan through Desmoinesian are [ascending order]: *higginsi, symmetricus, bassleri*; a zone based on an unnamed species (spans the Morrowan-Atokan boundary), *atokaensis, colombiensis, caudatus* (base coincides with the Atokan-Desmoinesian boundary), *asymmetricus, roundyi* (*sensu lato*). We recognize the following very preliminary zones based on idiognathodids for the Atokan and Desmoinesian [ascending order]: *incurvus* (base approximates the Morrowan-Atokan boundary), *incurvus* descendents (informal zone for a succession bearing features derived from *incurvus*), *amplificus* (base coincides with the Atokan-Desmoinesian boundary), *amplificus* descendents (informal, like above), *Idiognathodus* sp. 3 (of Swade 1985), new genus 'S'. 'Naked' gondolellids and mesogondolellids are commonly encountered as acme zones in the lower and middle Atokan respectively. Noncrenulated *Gondolella* species such as *G. pohli* characterize the middle Desmoinesian, followed by rare crenulated gondolellids, and ultimately *G. magna* in the upper Desmoinesian.

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Conodonts from the Middle Ordovician Oil Creek Formation, South-Central Oklahoma

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The Oil Creek Formation consists of more than 190 m of carbonate and siliciclastic rocks in outcrops in the western Arbuckle Mountains, south-central Oklahoma. The formation represents a transgressive-regressive cycle produced in a shallow, tropical sea that covered the eastern Midcontinent during the Middle Ordovician (Whiterockian Series). Sixty-four samples taken at approximately 3-m intervals from the Oil Creek yielded a collection of over 45,000 conodont elements. These elements are assigned to at least 25 species, 3 of which represent new species.

The Oil Creek conodont fauna is dominated (over 80%) by *Neomultioistodus compressus* Harris and Harris, *Trigonodus sinuosus* (Mound), and *Drepanoistodus angulensis* (Harris). *N. compressus* is joined by a new species of *Neomultioistodus* in the upper Oil Creek. Other notable species represented in the collection include *Ansella jemtlandica* (Lofgren), *Chosonodina rigbyi* Ethington and Clark, *Dischidognathus primus* Ethington and Clark, *Fahraeusodus marathonensis* (Bradshaw), *Oistodus multicorrugatus* Harris, *Oistodus cristatus* Ethington and Clark, *Oistodus* n.sp., *Parapanderodus striatus* (Graves and Ellison), *Paraprioniodus costatus* (Mound), *Paraprioniodus* n.sp., *Protopanderodus gradatus* Serpagli, *Pteracontiodus cryptodens* (Mound), *Pteracontiodus gracilis* Ethington and Clark, and four species of *Histiodella*.

The large collections of *Histiodella* from the Oil Creek offer a unique perspective on the evolution of this biostratigraphically important genus. *Histiodella* is characterized by a skeletal apparatus composed of geniculate coniform, ramiform, and carminate pectiniform elements. *Histiodella serrata* Harris, *H. sinuosa* (Graves and Ellison), *H.* n.sp., and *H. holodentata* Ethington and Clark are represented in the Oil Creek. Species assignment is based on characteristics of the carminate pectiniform elements. Other elements in the apparatus show modification but are rare and tend to be more conservative. In addition to modification of individual elements, the *Histiodella* lineage shows a trend toward decreasing relative abundance of ramiform and geniculate coniform elements. Collections of *Histiodella* n.sp. and *H. holodentata* from the middle to uppermost Oil Creek contain no ramiform elements and few geniculate coniform elements.

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On Five Ordovician Carbonate Facies—Depositional Setting and Diagenesis of Limestones in the Topmost Pooleville Member (Simpson Group) and Basal Viola Springs (Viola Group): I-35 Road Cuts, Arbuckle Mountains, Southern Oklahoma

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Five distinctive carbonate lithologies are juxtaposed on the I-35 road cuts on the south flank of the Arbuckle anticline. The lowest unit, a dense, sparsely fossiliferous micritic limestone with bioturbation, is interpreted as a low energy peritidal facies. The succeeding sequence of bioclastic and micritic limestones is punctuated by numerous erosional hardgrounds with relief of up to 15 cm. Bioclastic accumulations of current- and wave-sorted shell hash, dominated by brachiopods, and bryozoans, fill the relief. The micrite layers display both burrowing and boring. This facies is interpreted as an intertidal facies, responding to short term fluctuations in sea level. The third unit, a dense bioturbated micritic limestone that is locally highly fossiliferous, is interpreted as a peritidal deposit. The lower three units are placed in the Pooleville member, Bromide Formation, Simpson Group. Patchy ferroan dolosparite precipitation in all three units was controlled by burrows, brings and some bed boundaries. Contact with the overlying Viola is sharp but not erosional at outcrop scale. It appears that the Pooleville was completely lithified prior to Viola basin development. The lowermost Viola Springs unit is a cross laminated alternation of lime mud and ostracod-bearing non-ferroan sparry limestone that contains chert nodules and graptolites. The top of this unit is a hiatus marked by pyrite and an impersistent bed of granule sized phosphatic and carbonate grains, overlying which is the fifth facies, a black carbonate-rich shale containing abundant graptolites and cut by bedded radiolarian cherts. The basal Viola is traditionally interpreted as deep water deposits; the distinctive nature of the lowermost unit suggest the definition of the Viola depocenter was a two step process.

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Continental Growth Along the Southern Margin of Laurentia During the Late Paleoproterozoic and Early Mesoproterozoic

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The Southern Granite-Rhyolite (SGR) province, in the southern midcontinent of North America, represents a major pulse of crustal formation during the Mesoproterozoic. Basement rock units of this province are primarily restricted to the subsurface with the exception of exposures in the Arbuckle Mountains and in Mayes County, Oklahoma. Felsic igneous rocks characterize the SGR province with published U-Pb ages ranging from 1400 to 1340 Ma. In addition to the crystallization ages, crustal residence ages of 1.98 to 1.49 Ga have been determined by previous Sm-Nd isotopic studies. Information presented in this study includes Sm-Nd isotopic data for 71 whole-rock samples. Whole-rock samples from drill cores, drill cuttings, and surface exposures were analyzed for Sm-Nd isotopes to determine the crustal residence age with respect to the depleted mantle model curve (TDM) and the eNd(t) values. Values of eNd(t) within the SGR province ranged from –1.2 to +4.5 with corresponding crustal residence ages of 1.95 to 1.34 Ga. This range of Sm-Nd data suggests variable contamination by the melting of older lithospheric material that was added to a presumably juvenile magma (epsilon = +4.5). Tectonic interpretations of previous and new isotopic data along with geochemical data within the province, focus on the development of the southern margin of the continent. These interpretations suggest episodes of crustal growth along an Andean-type continental margin to the south followed by felsic igneous activity possibly in a back-arc extensional setting.

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How High Were the Permian Wichita Mountains of Oklahoma?

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The Wichita Mountains of southwestern Oklahoma consist of Lower Cambrian igneous rocks, exposed basement of the Southern Oklahoma Aulacogen (SOA), and of Lower Paleozoic carbonates (Slick Hills area) that were deposited on the igneous rocks. As current denudation proceeds, the more resistant igneous rocks and carbonates form the rugged topography while the softer Lenardian siltstones (Hennessey Group and interfingering Post Oak Conglomerate (POC)) form the surrounding plains. The protruding older rocks represent a Perrnian topography that is being uncovered. Some interesting observations follow:

(1) 4–5 km of Upper Cambrian to Mississippian strata were removed from SOA basement during Pennsylvanian uplift. (2) ~750 m (average) of Permian encased this paleotopography. (3) The POC sits about midway in this ~750-m section and contains clasts of granite that attained their shape from spheroidal weathering before local transport. (4) Such weathering implies a previous very low relief landscape (weathering rates greater than erosion rates). (5) ~300–350 m of uplift and relief is needed to release these weathered boulders and to deposit the POC (erosion rates greater than weathering rates). This event is the last recorded Permian tectonism in this area. (6) ~2000 m of Permian on SOA basement occurs in a few places. Whether this could represent topography is debatable.

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Overpressures in the Anadarko basin, Southwestern Oklahoma: Static or Dynamic?

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Fluid pressures were estimated from mud weights and wellhead shut-in pressures along a north-south linear trend through the Anadarko basin in southwest Oklahoma. Fluid pressures above hydrostatic start at a depth of about 2.5 km. On a normalized scale where hydrostatic pressure equals 0 and lithostatic pressure equals 1, estimates of fluid pressures were found to range from 0.4 to 0.8 over a depth range of 4–7 km.

Using scale analyses and a simple numerical model, we evaluated two end-member hypotheses (compaction disequilibrium and hydrocarbon generation) as possible causes of overpressuring in the Anadarko basin. If compaction disequilibrium is the primary cause of present-day overpressures in the Anadarko basin, the Anadarko basin is required to have an average permeability of 10^{-23} m^2 (10^{-8} md) or lower. If geopressures in the Anadarko basin result from hydrocarbon generation, average basin permeabilities can be as high as 10^{-21} m^2 (10^{-6} md). Scaling these average permeabilities down to thicknesses of 100 m or less implies permeabilities lower than 10^{-25} m^2 (10^{-10} md) are required in the most optimistic scenario. The lowest permeabilities ever measured on sedimentary rocks are in the neighborhood of 10^{-22}–10^{-23} m^2 (10^{-7}–10^{-8} md). Thus it is not possible to reconcile the existence of overpressures in the Anadarko basin with classic hydrodynamic theories that maintain that aquicludes do not exist. Either some unknown process is generating excess fluid pressures, or the Anadarko basin contains pressure seals.

Geopressure models that invoke compaction disequilibrium and are commonly applied to Cenozoic basins undergoing rapid sedimentation (e.g., the Gulf Coast basin of the southeastern United States) do not appear to apply to the Anadarko basin. The Anadarko basin belongs to a group of cratonic basins that are tectonically quiescent and characterized by the association of abnormal pressures with natural gas.

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Shallow Gas Systems in Tight Reservoirs on Basin Margins

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Shallow gas accumulations in tight reservoirs on basin margins fall into three distinct systems: early generation biogenic, late generation biogenic, and nonassociated thermogenic. Fields tend to be large (50–100 sq mi), shallow (<2000–3000 ft) and have relatively low cumulative production (1–2 BCF/sq mi). Each system has a representative archetype with distinctive attributes and characteristic gas compositions.

The southeastern margin of the Alberta basin has early generation biogenic gas in Cretaceous, marine clastic reservoirs. Reservoirs and source rocks are interbedded; gas has not migrated significantly since generation shortly after deposition. Gas is methane-rich with microbial isotopic signatures. Fields tend to be underpressured and have little co-produced water.

The northern margin of the Michigan basin has late generation biogenic methane in fractured Antrim Shale (Devonian). The marine black shale acts as both reservoir and source rock; gas migration is minimal. The gas was generated in the recent geologic past and is in relatively young water that is flowing down the basin margin, away from subcrops beneath glacial drift. Fields are usually near hydrostatic pressure and large quantities of water are co-produced.

The northwestern margin of the Anadarko basin has nonassociated thermogenic gas produced from heterogeneous Permian rocks in the Hugoton embayment. Reservoirs on the basin margin are widely separated from the areas of thermogenesis in the deeper basin. Gas has migrated substantial distances up the basin margin and contains the heavier hydrocarbons characteristic of thermogenic gas. In addition, the gas has significant amounts of nitrogen that may be an indication of ground water transport. There is, however, essentially no coproduced water with the gas.

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Variable Redox Signals Recorded by Rare-Earth Elements in Carboniferous Phosphatic Black Shale from Kansas, Oklahoma, and Arkansas and the Influence of Authigenic Phosphate on Provenance Analysis

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Shale-normalized rare-earth element (REE) patterns record variable redox conditions in coprolitic phosphorite concretions and their host shales. Patterns enriched in middle REE (MREE) developed under reducing conditions in pore waters of organic-rich marine muds. Rare and weak negative cerium depletions in both reworked and unreworked phosphorite concretions suggests exposure to oxygenated waters. Positive europium anomalies in thick phosphorite coatings on coprolitic phosphorite concretion cores suggests extreme reduction during lithification of the phosphorite coating.

Phosphate diagenesis can affect the trace element chemistry of black shales enough to alter provenance signals. Flat REE patterns in black and gray shales that host the phosphorite concretions as well as some phosphorite concretions probably reflect detrital influence. Host shales depleted in MREE suggest mobility of REE from early diagenetic pore waters to REE- and MREE-enriched phosphorite concretions. The effect of REE mobility on geochemical provenance information is illustrated in La-Th-Sc relationships. Typical La-Th-Sc distribution in host shale results when P_2O_5 values are below 0.5%. High La abundance substantially skews the La-Th-Sc distribution when P_2O_5 is above 5.0%, but when P_2O_5 is between 0.5% and 5.0%, the extent of the effect is unclear. Detrital influence and relative proximity to the shoreline is suggested by phosphorite concretions that have both flat REE patterns and elevated values of $Al_2O_3/(Al_2O_3 + Fe_2O_3)$.

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The Red River Delta, Lake Texoma: A Remote Sensing Study of Delta

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The Red River is a classic braided stream, and carries a very high sediment load. Because the river is mostly uncontrolled, this high sediment load is deposited where the Red River flows into Lake Texoma, forming a rapidly changing delta. This delta has grown since the Denison Dam was completed in 1944.

We used ASTER and Landsat satellite imagery to study the highly dynamic growth of this delta. It has a classic river-dominated "bird foot" type morphology, with sub-lobes formed due to protrusion of terminal distributary channels into Lake. Delta morphology has changed with growth. Satellite images collected from 1984 to 2001, show the Red River delta prograded into Lake Texoma more than 8 km.

Study of turbidity in front of the delta suggests that the river outflow is hyperpycnal at discharges less than 1000 ft^3/s but homopycnal at discharges more than 1000 ft^3/s. For calculation of suspended concentrations in the water, we used bands 1, 2 and 3 Landsat TM data and band 2 and 3 ASTER data. Transformation of digital numbers yielded estimates of suspended sediment concentrations between 0 and 800 mg/l, but the method has some limitation for concentrations higher than 600 mg/l. The remote sensing data sets we used were obtained during relative low discharge of the Red River, but for a discharge of 3500 ft^3/s (July 2nd 1997) suspended sediments are visible as far as 8 km away from the delta front.

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Downstream Fining of Sediment in a Modern Fluvial System: Lessons from the Canadian River Drainage, Oklahoma, USA, and Implications for Regional Reservoir Performance

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Developments in regional reservoir-quality technology suggest that prediction of porosity/permeability in ancient clastic deposits requires better pre-drill estimates of sandstone composition and texture. Toward this end, we are evaluating a series of topographic analysis tools for describing the character of modern fluvial systems for input to reservoir models. Our intent is to demonstrate for the Canadian River drainage that texture and composition of sand varies predictably as functions of (1) distance of sediment transport, (2) bedrock lithology, and (3) changes in stream gradient.

Our results indicate that downstream fining occurs in the Canadian River (1,027 km along-channel-length). However, the fining is best recognized in sediments obtained from positions high on the sand bars. These samples correspond to high discharge events when most particle size attrition occurs. Samples obtained at lower (intermediate) positions on the sand bars also show a downstream decrease in grain size, though this along-river change is less pronounced. Samples from the main channel (mean low-flow channel) do not show a change in grain size with distance.

Another finding of this work for exploration is that sediment size varies strongly with bedrock lithology. This relationship suggests that changes in bedrock character beneath an incisement can influence the permeability of the immediately overlying valley fill.

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Shallow-Depth Seismic Refraction Studies Near the Norman, Oklahoma, Landfill

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Seismic refraction surveys were performed near the Norman, Oklahoma, landfill to determine the depth to bedrock between the landfill and the Canadian River. For two lines, one short and one longer, both compressional wave data and shear wave data were acquired. Because the compressional wave velocities are strongly influenced by the variable saturation of sand, clay, and gravel in the unconsolidated sediments, and shear wave velocities are not influenced by these features, the shear wave data lead to much more accurate models of the bedrock interface.

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Aquifer Heterogeneity at the Norman, Oklahoma, Landfill and Its Effect on Observations of Biodegradation Processes

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Biodegradation processes in the leachate plume at Norman landfill probably vary among the distinct hydrologic and chemical environments at the site. These environments include zones of mixing with surface water, rainfall recharge or background ground water, and areas of varying permeability in the part of the aquifer occupied by the contaminant plume. The alluvial aquifer at the Norman landfill site consists of sediments ranging from mud to pebbly sand, which, except for the mud layers, have a range of measured hydraulic conductivity from 2.4×10^{-7} to 2.8×10^{-4} m/s. Core descriptions from the site indicate that average aquifer composition is 75% sand (fine, medium and coarse), 10% silt and clay in discrete layers, 10% medium-grained sand matrix with pebbles or mud clasts, and 5% coarse sand with pebbles. A numerical model (BIOMOC) was used to explore how permeability might affect observed biodegradation processes and rates. Results of the simulation suggest that low-permeability areas in the aquifer may be relatively uncontaminated, and act as reservoirs of electron acceptors to the surrounding leachate-contaminated areas. A moderate permeability area in the model had relatively low contaminant concentrations and biodegradation appeared to be most efficient in that area. In the highest-permeability areas, the simulation results suggested that preferential electron acceptors are depleted very quickly, leading to higher contaminant concentrations due to less efficient degradation processes and high rates of transport.

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Evidence for Natural Attenuation of Volatile Organic Compounds in the Leachate Plume of a Municipal Landfill near Norman, Oklahoma

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Samples of ground water collected downgradient from the Norman Landfill in 1995 and 1996 were analyzed for volatile organic compounds (VOCs) by purge-and-trap gas chromatography/mass spectrometry. More than 70 individual compounds were identified. The VOCs originate from a wide variety of natural and anthropogenic sources. This is consistent with the heterogeneous mixture of materials likely to have been buried at the site. Concentrations of VOCs are low when compared with published data for other landfills, and the dominant class (monoaromatic hydrocarbons) accounts for less than 0.1% of the total dissolved organic carbon. The low concentrations likely reflect the age of the landfill and the character of the wastes. Spatial distributions of the VOCs in ground water are variable, but concentrations of all compounds are near or below detection limits within 200 meters of the landfill. Meanwhile, the distribution of chloride ion, a putative conservative tracer, shows little dilution over the same distance. Thus, natural attentuation processes are effectively limiting migration of the VOC plume. Large differences in the spatial distribution of isomeric alkylbenzenes suggest that biodegradation is a significant, if not dominant, process contributing to the observed attenuation.

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Identifying Ground-Water and Evaporated Surface-Water Interactions near a Landfill Using Deuterium, ^{18}Oxygen, and Chloride, Norman, Oklahoma

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The composition of water discharging to a small wetland (the slough) downgradient from a closed municipal landfill was investigated using chloride concentration and enrichment in deuterium and ^{18}oxygen to determine the source waters for the slough. Potential source waters include native alluvial ground water, shallow recent recharge to the alluvium from precipitation, and leachate-contaminated ground water. Effects of evaporation from the slough on those potential source waters were calculated to determine source waters for the slough.

Deuterium and chloride are enriched in the landfill leachate relative to the native ground water. Deuterium and ^{18}oxygen have a great range and chloride concentration is low in recent recharge relative to native ground water. The initial water isotopic composition of the slough was estimated based on the range of temperature and humidity conditions under which the water was evaporated. The amount of evaporation of the potential source waters was then estimated by the change in deuterium, ^{18}oxygen, and chloride values of the slough from those in potential source waters. Results of calculating evaporation of potential source waters suggest the slough receives primarily uncontaminated native ground water but also some landfill leachate and the contribution from these sources varies over time. One of three slough samples had a suggested initial composition of leachate-contaminated water, which was diluted approximately 70 percent by recent recharge prior to entering the slough. Suggested initial compositions of other two samples included native ground water only.

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Biogeochemical Processes in a Contaminant Plume Downgradient from a Landfill, Norman, Oklahoma

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Studies of an alluvial aquifer contaminated with landfill leachate, at Norman, Oklahoma, indicate that the non-uniform distribution of electron acceptors and biogeochemical reactions in anoxic ground water result in steep chemical gradients and the formation of distinct reaction zones. A combined geochemical and microbiological approach was used to delineate different biogeochemical zones along a transect parallel to regional ground-water flow downgradient from the landfill. The important microbially mediated reactions in the anoxic plume are iron reduction, sulfate reduction, and methanogenesis. Dissolved H_2 measurements in ground water at several depth intervals at one location near the edge of the landfill indicate that sulfate reduction is a dominant respiratory process, but near-saturation levels of methane were detected in some intervals. Cycling of sulfur was apparent in a thin interval at the water table where the highest rates of sulfate reduction (13.2 micromoles per day [μM/day]) and sulfate concentrations well above background levels (up to 4.6 millimolar [mM]) were measured. In this zone, sulfur isotope analyses indicate that the sulfate is enriched in ^{34}S ($\delta^{34}S$ of SO_4^{2-} was 67–69 per mil). Elevated concentrations of sulfate near the water table appear to result from the oxidation of sulfides as oxygenated recharge water mixes with anoxic plume water during recharge events. Sulfate availability in this vertically thin zone near the water table appears to control the high sulfate reduction rates measured in the zone. Iron reduction occurred at the edges of the sulfate-depleted plume, whereas methanogenesis was detected only in the center of the plume. This study underscores the importance of examining the availability of electron acceptors in contaminated environments and using a combined geochemical and microbiological approach to elucidate the spatial distribution of biogeochemical processes.

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Mapping the Norman, Oklahoma, Landfill Contaminant Plume Using Electrical Geophysics

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The lateral extent of the electrically conductive portion of the contaminant plume emanating from the Norman Landfill was mapped using electrical geophysical measurements. EM induction and DC resistivity methods measured the apparent electrical resistivity of the subsurface. Both methods show an area of low resistivity indicating poor ground water quality in the alluvium, presumably due to leachate from the Norman Landfill. This area extends from the southwest side of the main landfill mound toward the Canadian River for no more than about 200 meters. Cross section and depth-slice maps made from the interpretation of the DC resistivity soundings and maps of measured resistivity from the EM measurements illustrate the lateral extent of the landfill contamination and show that the contaminate plume, which is about 9 m thick, does not appear to extend into the bedrock. The EM induction method proved to be an easy and efficient procedure for rapidly determining the lateral extent of the leachate plume. The DC resistivity method, although more time consuming, provided better vertical resolution of the resistivity distribution.

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