OKLAHOMA GEOLOGY

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On The Cover —

Dinosaur Trackway, Cimarron County

The dinosaur trackway shown on the cover is the most famous set of fossil footprints in Oklahoma and one of the most spectacular in the geographically widespread Morrison Formation. The Upper Jurassic Morrison Formation (~150 million years old) is named for the town of Morrison, Colorado, near the type section. The easternmost surface exposure of the Morrison is in western Cimarron County, Oklahoma. The dinosaur trackway, preserved in a creek bed, is located along a county road about 6 mi north of Kenton. Oklahoma Geological Survey geologist Ken Luza inspects the tracks in this photograph.

Dinosaur tracks are examples of trace fossils, sedimentary structures resulting from an animal's life activities (other than growth), such as moving, feeding, or resting. Unfortunately, tracks are rarely found in association with the animal that made them. This trackway is one of several preserved in sandstone of the upper part of the Morrison Formation in western Oklahoma and eastern New Mexico. It is thought to have been made by a herbivorous, semi-bipedal ornithopod, which was closely related and somewhat similar to the familiar duck-billed dinosaurs of the Late Cretaceous. Other tracks in the area have been described as belonging to small theropods (meat-eating dinosaurs) and even to pterosaurs—flying reptiles known only from the Mesozoic Era (Age of Dinosaurs).

The Morrison Formation has produced the world's best known dinosaur assemblage, including *Apatosaurus* (more widely known by the popular name *Brontosaurus*), *Brachiosaurus, Camarasaurus, Allosaurus*, and *Stegosaurus*. In the 1930s and 1940s, workers under the direction of J. Willis Stovall (of the Department of Geology, University of Oklahoma) made a significant collection of dinosaur bones from the Morrison of Cimarron County. Most of their quarries are scattered around the flanks of Black Mesa and can still be seen. The original Quarry 1, immediately north of S.H. 325, 9 mi east of Kenton, is marked by a concrete replica of a huge brontosaur thigh bone.

For directions to the dinosaur trackway, call the Boise City Chamber of Commerce, (580) 544-3344, or the Kenton Community Development office, (580) 261-7447.

Richard L. Cifelli
Photo by Neil H. Suneson

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OKLAHOMA GEOLOGY

Notes

CONTENTS

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Varanopseid Synapsid Skeletal Elements from Richards Spur, a Lower Permian Fissure Fill Near Fort Sill, Oklahoma

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Abstract

The diverse vertebrate assemblage of the Lower Permian fissure fills of Richards Spur, near Fort Sill, Oklahoma, is dominated by the skeletal remains of the captorhinid reptile *Captorhinus aguti.* Study of this terrestrial vertebrate assemblage indicates that the most frequently encountered synapsid remains belong to a small varanopseid eupelycosaur, assignable to *Mycterosaurus longiceps.* The synapsid *Basicranodon fortsillensis* is declared a junior synonym of *Mycterosaurus longiceps* because the holotype, and only known specimen of *B. fortsillensis,* is indistinguishable from *M. longiceps.*

Introduction

Richards Spur is one of the richest known sources of Permian tetrapod skeletal remains. Located in southwestern Oklahoma, near Fort Sill (Olson, 1967), the site consists of a series of fissures in Ordovician Arbuckle limestones that have been infilled with fossiliferous Lower Permian sediments. Varying concentrations of disarticulated and articulated skeletal remains are found within the soft clays and other coarser sediments that have been deposited in the fissures. The vertebrate remains in these fissure deposits are well preserved and show very little crushing or warping. Specimens are often chipped and broken; sometimes there is sufficient wear to indicate that they have been transported prior to deposition in the fissures. This locality is unique in the Early Permian because of the preservation of a predominantly terrestrial vertebrate assemblage in undistorted condition.

Much of the material collected from the Richards Spur locality is disarticulated or poorly associated, at best. In the most recent faunal review of the site, Olson (1991) recognizes 21 tetrapod taxa, 12 of which are amphibian (Bolt, 1969, 1980). The amniote component of the fauna is dominated by *Captorhinus aguti* (Fox and Bowman, 1966; Olson, 1967). Other amniote genera have been identified at Richards Spur only on the basis of incomplete or undiagnostic materials and, therefore, were afforded only limited attention (Vaughn, 1958; Fox, 1962; Reisz, 1980; Laurin and Reisz, 1989). Two of the three supposed synapsids from this locality were named and described on the basis of fragmentary maxillary and dentary remains, and their identity is uncertain (Reisz, 1986). However, the third synapsid, *Basicranodon fortsillensis* (Vaughn, 1958) was described on the basis of a para-basisphenoid complex. Reisz (1986), in the most recent consideration of *Basicranodon,* has tentatively assigned it to Varanopseidae. Although he noted the varanopseid features of *Basicranodon,* he made its assignment to varanopseids only tentative be-

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cause the parasphenoids of *Varanops* and *Varanodon* were poorly known at that time.

In addition to the holotype of *Basicranodon*, there are numerous other undescribed specimens from Richards Spur that may be attributed to a varanopseid synapsid. (Specimens in the collections of the Field Museum of Natural History, Chicago, have been noted previously [Reisz, 1986], but most of them were not available for the present study.) Several premaxillae, two maxillae, numerous vertebrae, a scapulocoracoid, two humeri, and three femora (one complete and two partial), deposited in a number of collections, are described below. They provide conclusive evidence that a small varanopseid synapsid, similar to *Mycterosaurus longiceps*, is present in the Richards Spur locality. The identification of these elements has become possible because of recent additions to our knowledge of varanopseids. Members of this family of faunivorous synapsids have a number of autapomorphic osteological features that make identification of individual skeletal elements possible (Langston and Reisz, 1981; Berman and Reisz, 1982; Reisz, 1986).

Institutional abbreviations used in this paper are FMNH, Field Museum of Natural History, Chicago; KUVP, Dyke Museum of Natural History, The University of Kansas, Lawrence; OMNH, Oklahoma Museum of Natural History, The University of Oklahoma, Norman.

Description and Comparisons

Skull Elements

The right premaxilla, KUVP 87324, is characterized by the presence of strongly recurved and mediolaterally flattened marginal dentition (Fig. 1A). In addition, the premaxilla has a massive, deep maxillary process; a broad, smooth, and gently curved dorsolateral surface on the maxillary process; and a shallow groove that extends over the lateral surface of the narial opening and terminates in a shallow, crescent-shaped, anteromedial depression. All of these features are autapomorphies of varanopseid pelycosaurs. Among premaxillae of varanopseids, this premaxilla most closely resembles that of *Mycterosaurus* in shape and size. The teeth of KUVP 87324 are strongly compressed and their anterior and posterior margins are sharply tapered, which produces a cross-sectional shape of an oval with pointed ends. The mediolateral flattening of the teeth is characteristic of varanopseids and contrasts with the tooth morphology of sphenacodontids. Characteristically, sphenacodont teeth are more robustly constructed and appear rounded or almost square in cross section, particularly at the base. The sphenacodont cutting edge is not formed by a tapering of the edges of the teeth, as in the Richards Spur specimens, but rather through the presence of anterior and posterior ridges that arise from the tip and extend only halfway along the height of the tooth.

All the premaxillary teeth in the specimens studied are strongly recurved in typical varanopseid fashion (Berman and Reisz, 1982). The teeth curve gradually throughout the distal two-thirds of their length, and the distal ends are tilted slightly inwards. These specific details of the recurvature of the teeth are comparable to the morphology of the premaxillary teeth of *Mycterosaurus*, as well as that of the larger varanopseids *Varanodon* and *Aerosaurus*.

Thrausmosaurus, another amniote with recurved teeth at Richards Spur, has been described only from maxillary and dentary fragments (Fox, 1962). *Thrausmosaurus* teeth can be distinguished from those of varanopseids by the presence of well-developed serrations on the anterior and posterior margins and by the abrupt angular curvature of the teeth. The curvature of the teeth of the *Thrausmosaurus* premaxillae is very angular; it occurs in the distal third of the tooth, and there is a distinct angle between the ascending portion of the tooth and the portion that curves posteriorly. This is dramatically different from the morphology of varanopseid teeth, in which the curvature of a tooth is gradual. The identification of a single tooth of *Thrausmosaurus* is possible on the basis of its curvature, and identification can be confirmed by microscopic examination for well-developed serrations along the cutting edges.

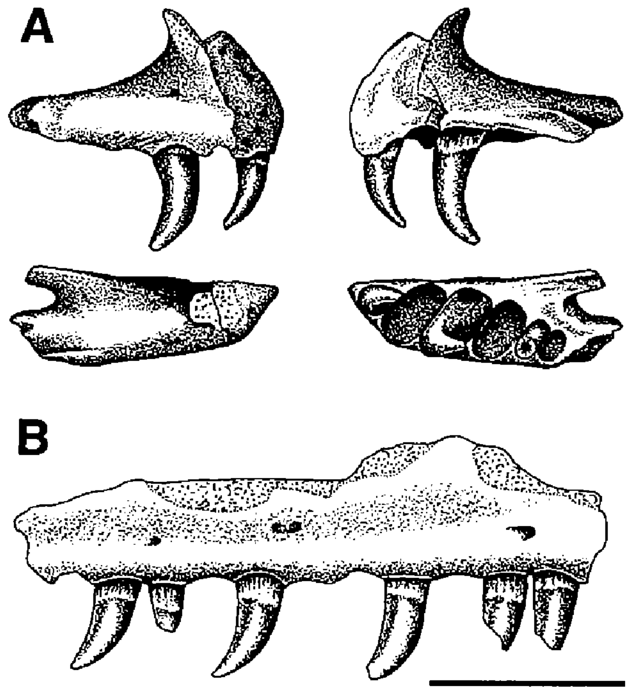

Figure 1. *Mycterosaurus*: A, right premaxilla, KUVP 87324, in lateral (upper left), medial (upper right), dorsal (lower left), and ventral (lower right) views; B, right maxilla, KUVP 8970, in lateral view. Scale equals 1 cm.

The right maxilla, KUVP 8970, compares closely with maxillae described in other varanopseids (Fig. 1B). In size and tooth morphology, it is closest to that of *Mycterosaurus* (Berman and Reisz, 1982). KUVP 8970 has six teeth (three of which are unbroken) and space for five additional teeth along the alveolar margin. The morphology of the teeth is similar to that described for teeth on the premaxilla, KUVP 87324 (Fig. 1A). Unfortunately, the distinctive morphology of the varanopseid maxillary dorsal process cannot be confirmed in this specimen because of poor preservation.

Vertebrae

Numerous vertebrae are attributable to the Richards Spur varanopseid; representative axial, cervical, and dorsal vertebrae are illustrated (Fig. 2A–C). All dorsal vertebrae are similar in size, proportion, and morphology to those of *Mycterosaurus* (Berman and Reisz, 1982). The neural spine of the dorsal vertebra, KUVP 85170, is rectangular in lateral view; its anterior and posterior margins are vertical (Fig. 2C). In transverse section, the spine is slightly thickened along its midline, tapering gently both anteriorly and posteriorly. This bladelike neural spine is similar to those of *Mycterosaurus* (Berman and Reisz, 1982) in both shape and proportions, as well as in the presence of a shallow excavation at the base of the spine. This is in contrast to the vertebral morphology of the larger varanopseids (*Aerosaurus*, *Varanops*, and *Varanodon*), where the neural spines are proportionately taller and the neural excavation is deeper than in *Mycterosaurus*. The excavation in KUVP 85170 is split into two separate, shallow fossae by a thin partition of bone, presumably present to buttress the zygapophyses. This partition is ridgelike and extends

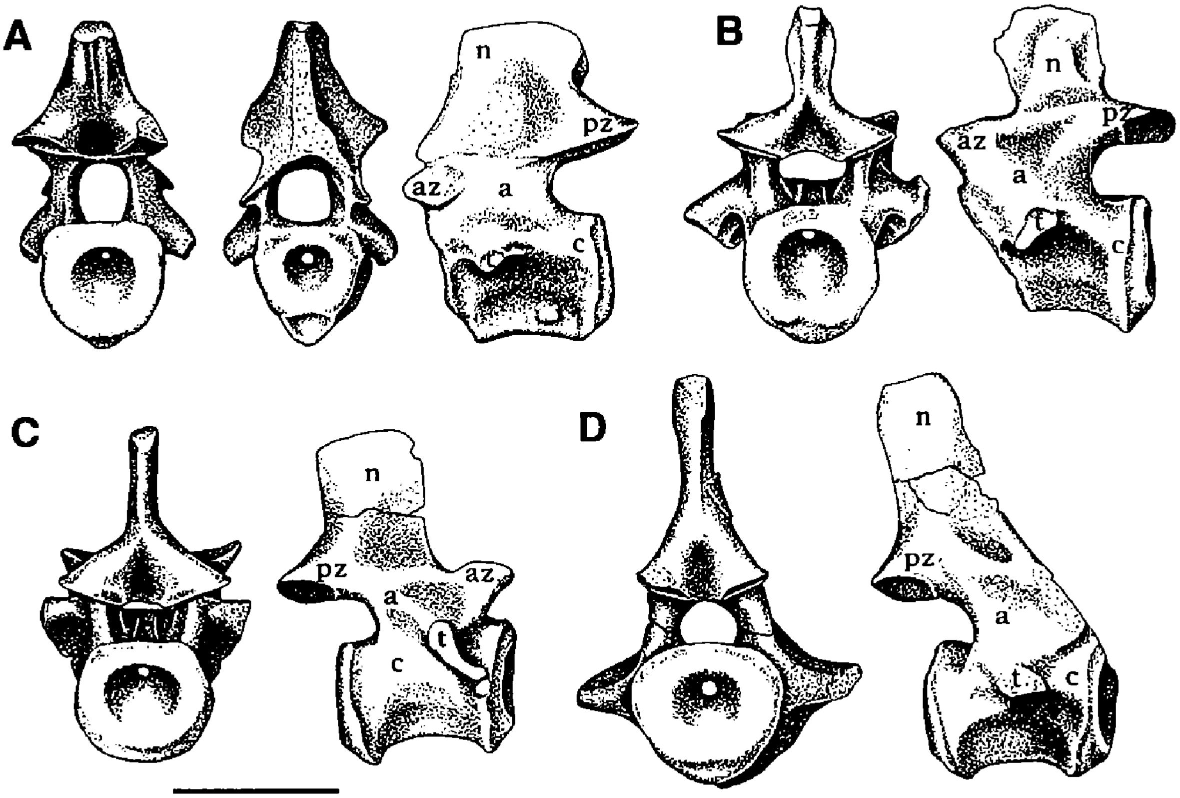

Figure 2. *Mycterosaurus* presacral vertebrae: A, axis, FMNH UR 381, in (left to right) posterior, anterior, and lateral views; B, cervical vertebra, FMNH UR 381, in posterior (left) and lateral (right) views; C, mid-dorsal vertebra, KUVP 85170, in posterior (left) and lateral (right) views; D, posterior dorsal vertebra in posterior (left) and lateral (right) views. Scale equals 1 cm. Abbreviations: a, neural arch; az, anterior zygapophysis; c, centrum; n, neural spine; pz, posterior zygapophysis; t, transverse process.

posterodorsally from the base of the anterior zygapophysis to the dorsal buttress of the posterior zygapophysis.

The posterior zygapophyses of all the presacral vertebrae (Fig. 2A–C) are separated by a deep groove that forms an inverted V when viewed from the posterior. The articular facets tilt slightly medially from the horizontal plane, as in *Mycterosaurus.* The posterior zygapophyses extend slightly beyond the lateral margin of the deeply amphicoelous centrum. Anteroventrally, there is a well-defined recess on the pleurocentrum for the intercentrum. The posterior articulating facet is similarly constructed. The centrum, only slightly elongate anteroposteriorly, is roughly square in lateral view. The lateral surface is concave below the virtually horizontal transverse process. The concavity of the centrum extends right below the transverse process, and, in ventral view, it forms a shallow pit at the base of the transverse process. Because of this fossa, the transverse process appears more substantial in lateral view than in ventral view. This concavity of the centrum accentuates the length of the transverse process. Ventrally, the centrum has a longitudinal ridge, rounded in cross section and gradually continuous with the concave lateral surfaces of the centrum. In ventral view, this ridge is slim in the center and broadens gently at both the anterior and posterior edges of the centrum to form the abutment for the intercentrum.

The axis vertebra, FMNH UR 381, is nearly complete, but there is slight damage along the anterior edge of the neural arch (Fig. 2A). Although the axis of *Mycterosaurus* is unknown, those of *Varanops* and *Aerosaurus* (which probably represent the general pattern for the family) are quite similar to the axis of the Richards Spur varanopseid, except for the height of the neural spine. Although the neural spine of FMNH UR 381 is slightly damaged, it appears to taper to a thin blade anteriorly. In dorsal view, the shape of the bladelike neural spine is a triangle, with its apex at the broken anterior edge. From a lateral perspective, the dorsal edge is straight, sloping only slightly posteriorly. The lateral surface of the neural spine is distinctly concave, especially above a well-developed horizontal ridge that extends between the anterior and posterior zygapophyses. The widened posterior edge of the spine is divided into three vertical ridges. The lateral ridges are a continuation of the lateral surface of the spine, while the median ridge forms a septum that extends farther posteriorly than the lateral ridges. This septum extends ventrally between the posterior zygapophyses to a deep, median recess located slightly above the zygapophyseal articulating surfaces. The transverse processes are small, rounded nubbins located close to the anterior margin of the neural arch. They hook slightly towards the ventral and posterior surfaces of the axis. Just above the dorsal margin of the centrum, the neural arch has two strongly tilted articular facets, with anteroventrally oriented surfaces, which would meet the atlantal centrum.

The pleurocentrum of the axis is slightly less than one-half the total height of the entire element, and it is longer anteroposteriorly than dorsoventrally. A moderately developed keel is present. From the sharp ventral edge, the lateral surface of the centrum tapers significantly in two distinct stages towards the dorsal half of the centrum; it appears concave in lateral view. The ventral keel does not run the full anteroposterior length of the centrum, but is truncated several millimeters from the edges of the vertebra by the articulating facets. These articulating facets have distinct pockets or recesses for the intercentral elements. The anterior facet is clearly recessed from the rounded pleurocentral articulating surface and is distinctly larger than the posterior facet.

Appendicular Skeleton

The left scapulocoracoid, FMNH PR 1664, is well ossified, which indicates that it probably belonged to an adult individual (Fig. 3). In the large varanopseids, the posterior coracoid typically is not preserved (Reisz, 1986). However, it is present in *Mycterosaurus* (Berman and Reisz, 1982) and in the Richards Spur varanopseid, and is co-ossified with the rest of the complex. The triceps process is small but well defined; it projects posteriorly, dorsally, and somewhat medially from the glenoid region. The glenoid region is damaged, but the supraglenoid area is intact. There is no supraglenoid foramen on the lateral surface of the scapula. The scapula is complete, and its lateral surface is significantly narrower than that of the anterior coracoid. It is, therefore, quite gracile and small, as in *Mycterosaurus*, and it does not extend as far dorsally as it does in *Varanodon* or *Varanops*. As in *Mycterosaurus* (Berman and Reisz, 1982, fig. 10A), the anterior edge of the scapula is slightly concave above the coracoid. Above this concavity, the anterior edge slopes posterodorsally to the posterior edge of the blade. In anterior view, the edge of the scapula is S-shaped along the slender anterior margin, which produces a convex shape in lateral view.

The scapulocoracoid of the Richards Spur varanopseid is closest in size and general proportions to that of *Mycterosaurus*, among all Paleozoic amniotes. The absence of the supraglenoid foramen on the supraglenoid buttress is considered to represent a derived condition (Reisz, 1986), and it is a distinctive feature of *Mycterosaurus*. The unusually gracile form of the scapula is another feature that diagnoses *Mycterosaurus*. Caseids are also reported to have no supraglenoid foramen, but the scapulocoracoid of caseids is extremely robust and much larger than that of the Richards Spur specimen.

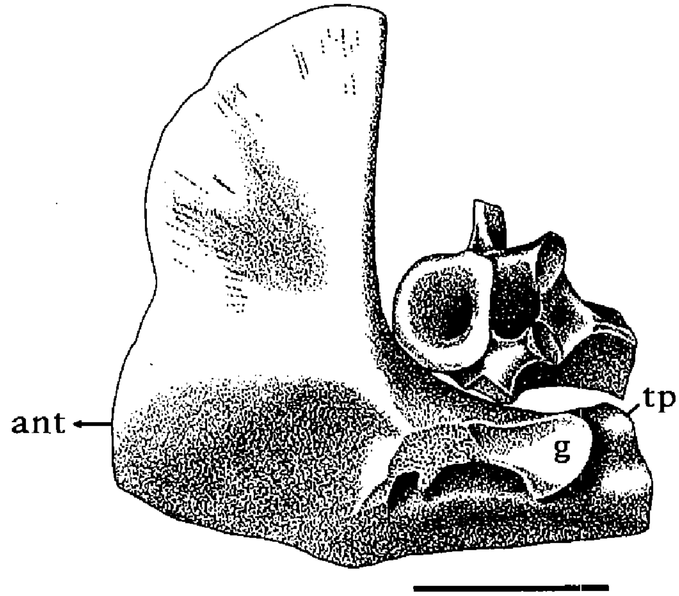

Figure 3. *Mycterosaurus* left scapulocoracoid, FMNH PR 1664, in lateral view. Scale equals 1 cm. Abbreviations: ant, anterior of skeleton; g, glenoid; tp, triceps process.

Two humeri that are attributed to the Richards Spur varanopseid are illustrated. One of the humeri, OMNH 52368, is complete (Fig. 4). In the other, OMNH 52543, the proximal and distal portions of the humerus are separated by a 5-mm hiatus in the shaft (Fig. 5). Since both fragments were found in the same collection, and they have the same size, texture, and unusual medium brown color, it is likely that they belong to the same humerus; they are treated here as a composite. These humeri closely resemble that of *Mycterosaurus* in size and proportions (Berman and Reisz, 1982, fig. 10). The most distinctive features of the Richards Spur humeri pertain to the configuration of the deltopectoral crests, proximally, and the supinator processes, distally. The deltopectoral crest of each humerus is prominent and branches into two uneven ridges, each with an extensive and rugose portion for muscle attachment. The most prominent ridge of the deltopectoral crest is oriented ventrally and proximally, and probably is for the large pectoralis muscle. The separate secondary ridge is less pronounced; it is located medially and extends towards the proximal end. This secondary ridge has been found only in varanopseid and caseid synapsids (Brinkman and Eberth, 1983; Romer, 1966). However, the overall proportions of the humeri described here are clearly similar to those of varanopseid rather than caseid synapsids. The proximal head is unusually slender, in comparison with nonvaranopseid synapsids, ~35% of the total length of the humerus. The shaft is relatively slender but not especially elongate. The distal ends of the humeri are only moderately expanded, only 46% of the total length of the humerous. In contrast, sphenacodontids, ophiacodontids, edaphosaurids, and caseids all show greater mediolateral expansion of the distal portion of the humerus. The presence of a slender, distally oriented supinator process, similar to that of *Mycterosaurus*, is a second distinctive feature of the Richards Spur humeri. This is in strong contrast to the humeri in other synapsids, including *Varanops*, in which the supinator process, if present, is strongly flared from the body of the ectepicondyle.

The femur is represented by several specimens, but only one, OMNH 52369, is illustrated (Fig 6). The shaft of the femur is slender and gracile, and there is no adductor crest visible on the ventral surface. In its overall dimensions and proportions, the Richards Spur femur is remarkably similar to that of *Mycterosaurus* (Berman and Reisz, 1982, p. 442). In anterior view, the femur has a distinctly sigmoid flexure; the proximal end is turned upward and the distal end, downward (Fig. 6A). There is also a slight anterior curvature of the femur distally. The absence of a distinct adductor crest, the absence of a fourth trochanter, and the proximal placement of the internal trochanter close to the level of the proximal articulating surface are all features of *Mycterosaurus*. Distally, the popliteal area is shallow and broad on the ventral surface of the femur (Fig. 6B), the anterior surface of the distal head is strongly concave (Fig. 6A), and the ventral intercondylar fossa is unusually broad and deep (Fig. 6C), as in *Mycterosaurus*.

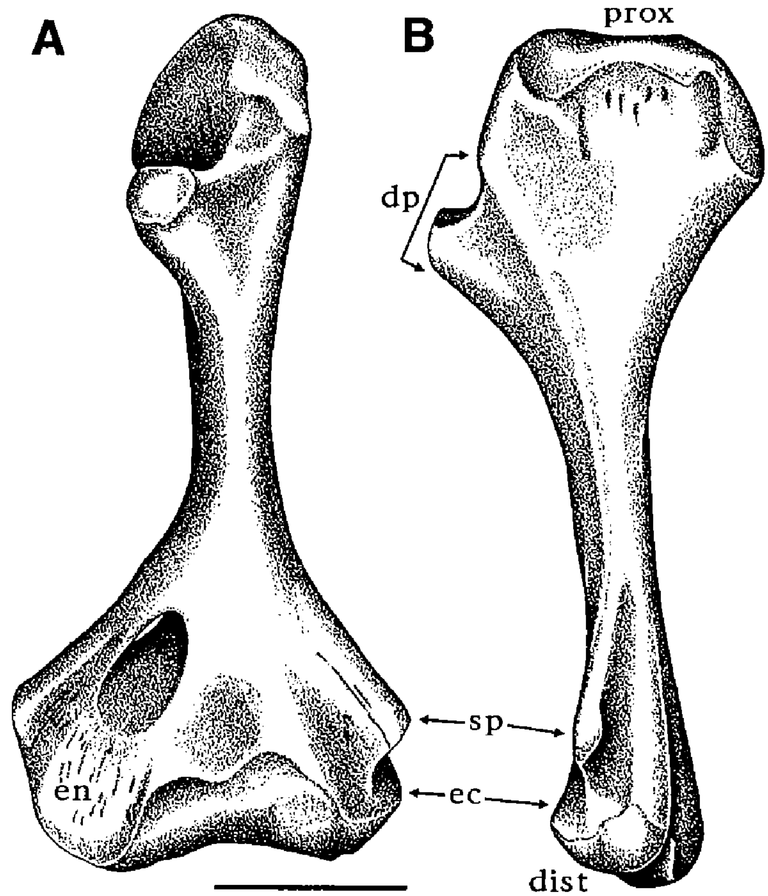

Figure 4. *Mycterosaurus* left humerus, OMNH 52368: A, distal ventral view; B, proximal dorsal view. Scale equals 1 cm. Abbreviations: dist, distal articulation of humerus with radius and ulna; dp, deltopectoral crest; ec, ectepicondyle; en, entepicondyle; prox, proximal articulation with scapulocoracoid; sp, supinator process.

Discussion and Conclusions

Cranial and postcranial skeletal elements attributable to varanopseid synapsids have been recovered from Richards Spur, near Fort Sill, Oklahoma. Although these specimens are fragmentary, were compiled from a number of collections, and are the remains of several individuals, there is little doubt that these skeletal elements can be attributed to *Mycterosaurus*. Evidence for this conclusion comes from the morphology of each of the described specimens, but the most compelling evidence is provided by features of the premaxillae (Fig. 1), including the anatomy of the marginal dentition. The marginal dentition of the maxilla also is indistinguishable from that of *Mycterosaurus*. It can be readily seen that the scapulocoracoid (Fig. 3) is very similar, if not identical, to that of *Mycterosaurus*. Of particular significance are the absence of the supraglenoid foramen on the scapulocoracoid (a diagnostic

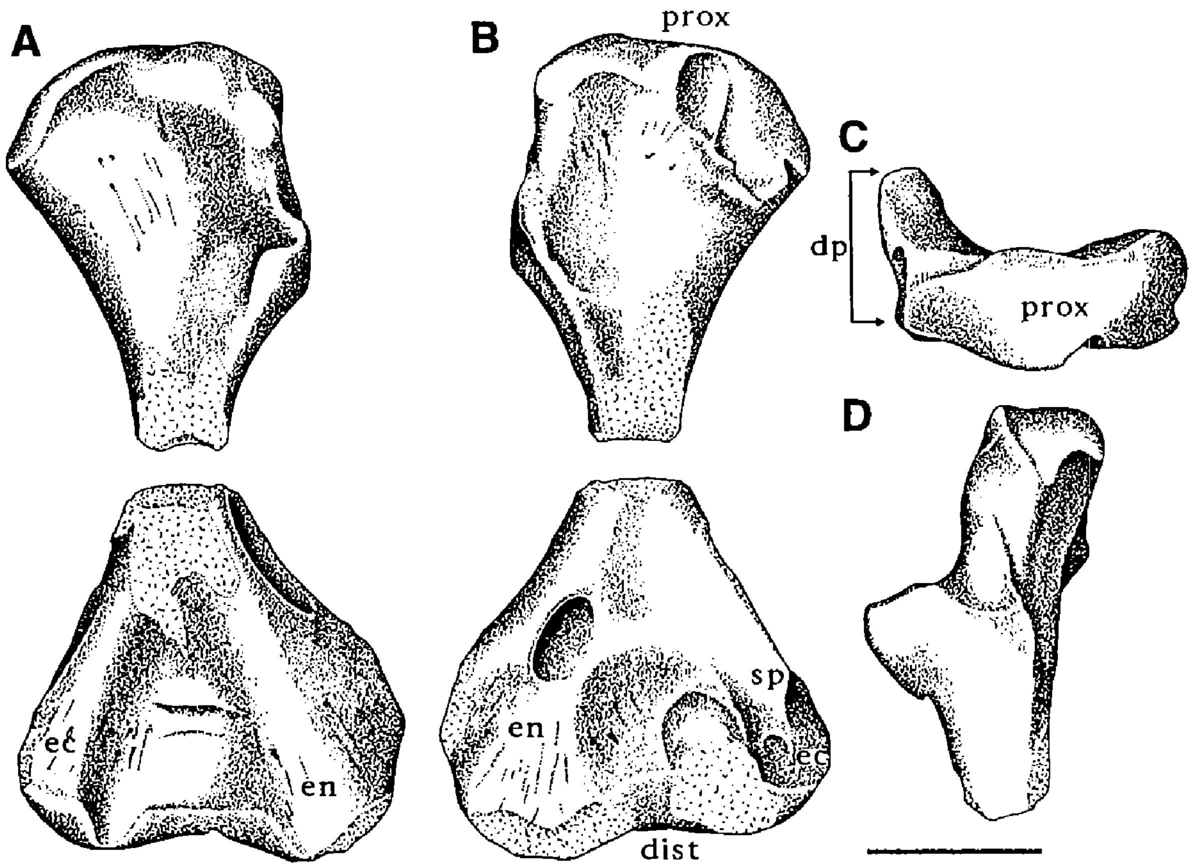

Figure 5. *Mycterosaurus* left humerus, OMNH 52543: Proximal (top) and distal (bottom) portions of humerus shown in dorsal (A) and ventral (B) views; proximal portion also shown in medial (C) and anterior (D) views. Scale equals 1 cm. Abbreviations: dist, distal articulation of humerus with radius and ulna; dp, deltopectoral crest; ec, ectepicondyle; en, entepicondyle; prox, proximal articulation with scapulocoracoid; sp, supinator process.

feature) and the distinctive morphology of the humeral supinator process. In addition, on the femur (Fig. 6), the lack of a ventral adductor crest on the shaft, the proximal position of the internal trochanter, the shape of the intercondylar fossa, and the strong concavity of the anterior surface of the tibial condyle are all features of *Mycterosaurus*. The vertebral elements (Fig. 2) can be identified as varanopseid on the basis of phenetic similarity to *Mycterosaurus* and by a process of elimination; the absence of diagnostic traits of the other synapsid groups makes it likely that the vertebrae are varanopseid.

Varanopseids are rare and unusual mammal-like reptiles. Within Synapsida, they are the sister group to all other eupelycosaurs, and they possess osteological features that indicate that they were highly specialized, gracile faunivores (Reisz, 1986). In contrast to the massive bodies of other Permian and Carboniferous synapsids, the varanopseid body appears sleek and streamlined, and skeletal elements of these enigmatic animals are recognized easily by their distinctive proportions. A nearly completed restudy of *Varanodon* has provided new insights into the anatomy of the larger varanopseids (Reisz, in preparation). It appears that the skull morphology of *Varanodon*, *Varanops*, and *Aerosaurus* has been modified greatly by

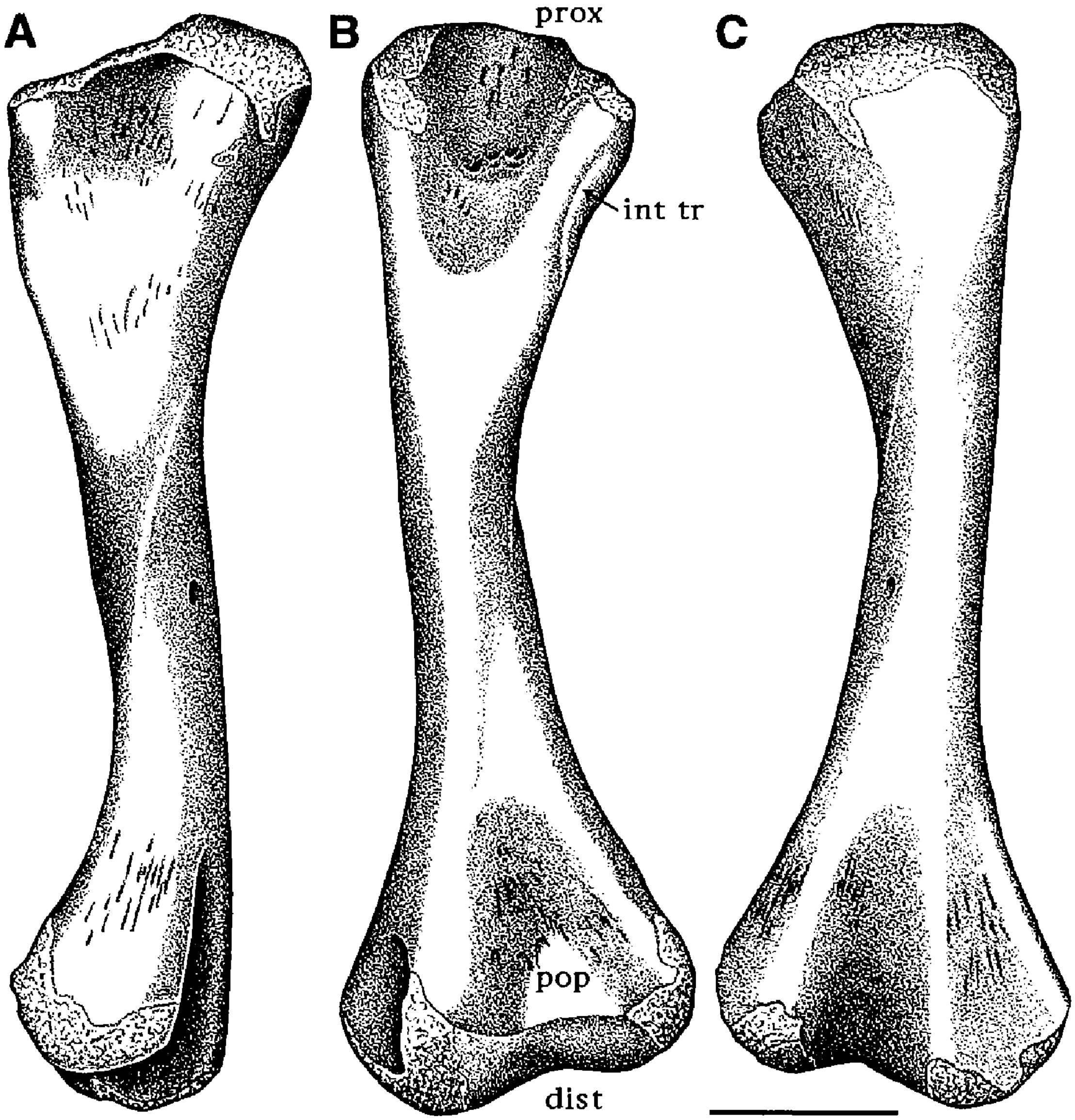

Figure 6. *Mycterosaurus* left femur, OMNH 52368, in anterior (A), dorsal (B), and ventral (C) views. Scale equals 1 cm. Abbreviations: dist, distal articulation of femur with tibia and fibula; int tr, internal trochanter; pop, popliteal area; prox, proximal articulation with pelvis.

the anteroposterior elongation of the temporal fenestra, which results in a complete reorganization of the adductor chamber, as well as of the skull roof and mandible in this area. For example, the posterior process of the postorbital has been greatly reduced, and a long anterior process of the squamosal forms the dorsal border of the temporal fenestra and contacts the dorsal process of the jugal, which excludes the postorbital from the border of the fenestra. Other work in progress also indicates that the fossil record of these groups may extend from the Late Pennsylvanian to the Late Permian (Reisz, in preparation). Despite this extended fossil record, our present knowledge of this group is based on a handful of taxa, each known from a single locality. The description of the above Richards Spur form makes *Mycterosaurus* the first varanopseid known from more than one locality. It is surprising to discover that *Mycterosaurus* is the second most common amniote in the Richards Spur assemblage, and the most common synapsid.

Reexamination of the braincase described by Vaughn (1958) as *Basicranodon* clearly indicates that this specimen is a varanopseid synapsid. More importantly, the braincase is indistinguishable from the basi-parasphenoid of *Mycterosaurus longiceps*. Although Vaughn noted that *Basicranodon* was of similar size and age to *Mycterosaurus*, he did not even consider such an assignment because the braincase of *Mycterosaurus* was unknown, and he accepted Romer's (1966) assignment of *Mycterosaurus* to Edaphosauridae. Based on the anatomy of known edaphosaurids, therefore, Vaughn (1958) did not expect that the parasphenoid of *Mycterosaurus* would look like that of *Basicranodon*. Berman and Reisz (1982) redescribed *Mycterosaurus* and assigned this synapsid to the Varanopseidae. The diagnostic features that were used to diagnose *Basicranodon* were small size, similar to *Mycterosaurus*, and the presence of parasphenoid dentition on the anterior part of the ventral plate and extending slightly anteriorly onto the cultriform process. This pattern of dentition is also found in *Mycterosaurus* (Berman and Reisz, 1982), and it is different from the pattern found in both *Varanops* (Reisz, personal observation) and *Aerosaurus* (Langston and Reisz, 1981), where an additional posterior transverse field of parasphenoid teeth is present. It is possible that the presence of the type of parasphenoid dentition found in *Mycterosaurus* represents the primitive condition for synapsids: it has been reported in caseid synapsids, as well as in some nonsynapsid amniote outgroups, such as millerosaurs, protorothyridids, and araeosceloids (Laurin and Reisz, 1995). In addition, other potential synapomorphies of *Mycterosaurus* and *Basicranodon*, such as the presence of a broad parasphenoid plate with large posterolateral wings and the acuminate shape of the large, laterally extending basisphenoid tubera, are varanopseid features and diagnose a more inclusive clade. The taxonomic status of *Basicranodon* could be resolved in two different ways. One option would be to declare *Basicranodon* a *nomen dubium* because the holotype and only referable specimen does not show any autapomorphic features. The second option is to declare *Basicranodon fortsillensis* a junior synonym of *Mycterosaurus longiceps* because the holotype of *Basicranodon* is indistinguishable from *Mycterosaurus*. We prefer the latter option because it is supported by the evidence provided in this paper, that numerous skeletal elements of *Mycterosaurus* are present in the type locality of *Basicranodon*.

Acknowledgments

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MINERAL INDUSTRY OF OKLAHOMA, 1996[1]

Oklahoma remained 34th in the nation in total nonfuel-mineral production value[2] in 1996, according to the U.S. Geological Survey (USGS). The estimated value for 1996 was $372 million, a 4% increase from that of 1995 (Table 1). This increase followed a 4.9% increase from 1994 to 1995 (based on final 1995 data). The State accounted for 1% of the U.S. total nonfuel-mineral-production value.

In 1996, crushed stone continued as Oklahoma's leading nonfuel mineral commodity, accounting for about 34% of the State's total nonfuel-mineral value (Table 1). The combined values of construction materials—crushed stone, portland and masonry cements, construction sand and gravel, and gypsum—accounted for 79% of the total value. The increase in mineral value in 1996 mostly resulted from increases in portland cement, iodine, fire clays, and construction sand and gravel. Compared with 1995, all nonfuel minerals increased in value in 1996 except for salt, dimension stone, feldspar, and gemstones, all of which had relatively small decreases. In 1995, increases in portland cement and crushed stone (when crushed shell and traprock are included—see Table 1) accounted for most of the year's increase in value. Tables 2–4 show, respectively, the quantity and value of crushed stone sold or used in Oklahoma by use, kind, and district; Tables 5 and 6 show, respectively, the quantity and value of construction sand and gravel sold or used in Oklahoma by major use category and district. The general distribution of Oklahoma's nonfuel mines is shown in Figure 1.

Oklahoma's mines exclusively produced industrial minerals; no metals were mined in the State in 1994–96. Based on USGS estimates of the quantities produced

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[1]From U.S. Geological Survey Minerals Yearbook, 1996, v. 2—Area reports: domestic, Oklahoma chapter. Prepared under a Memorandum of Understanding between the U.S. Bureau of Mines, U.S. Department of the Interior, and the Oklahoma Geological Survey for collecting information on all nonfuel minerals. The text, tables, and map of Oklahoma (Fig. 1) were retrieved from the USGS World Wide Web site at http://minerals.er.usgs.gov/minerals/pubs/state/ok.html#myb. The text and tables are the PDF file labeled "The Mineral Industry of Oklahoma, 1996"; the map is PDF file "Map of Principal Mineral-Producing Localities"; both files can viewed with the Adobe Acrobat Reader that can be downloaded from the same site.

[2]The terms "nonfuel-mineral production" and related "values" encompass variations in meaning, depending on the minerals or mineral products. Production may be measured by mine shipments, mineral-commodity sales, or marketable production (including consumption by producers) as is applicable to the individual mineral commodity.

Note: All 1996 USGS mineral-production data published in this article are estimates as of February 1997. For some commodities (e.g., construction sand and gravel, crushed stone, and portland cement), estimates are updated periodically. To obtain the most current information, please contact the appropriate USGS mineral commodity specialist. Call MINES FaxBack at (703) 648-4999 from a fax machine with a touch-tone handset, and request document no. 1000 for a telephone listing of all mineral commodity specialists, or call USGS information at (703) 648-4000 for the specialist's name and number. This telephone listing may also be retrieved over the Internet at http://minerals.er.usgs.gov/minerals/contacts/comdir.html

TABLE 1.—NONFUEL RAW MINERAL PRODUCTION IN OKLAHOMA[a,b]
(thousand metric tons and thousand dollars unless otherwise specified)

Mineral	1994		1995		1996[c]	
	Quantity	Value	Quantity	Value	Quantity	Value
Cement:						
Masonry	91	7,410	95	7,250	100	7,630
Portland	1,680	102,000	1,740	110,000	1,820	115,000
Clays	771	3,910	674	3,580	814	6,710
Gypsum (crude)	2,890	17,000	2,830	17,000	2,890	17,900
Iodine (crude) (metric tons)	1,630	12,800	1,210	12,500	1,170	15,800
Sand and gravel:						
Construction	8,480	27,200	7,800	25,100	8,330	27,500
Industrial	1,230	24,000	1,250	25,400	1,250	25,400
Stone:						
Crushed	29,900	125,000	31,100	125,000	29,600	126,000
Dimension (metric tons)	3,980[d]	1,250[d]	9,170[d]	2,350[d]	14,000	2,220
Combined value of feldspar, gemstones, helium (crude [1995–96]), lime, salt, stone (crushed shell and traprock [1995–96], dimension quartzite and sandstone [1995], dimension stone [1994]), and tripoli	XX	19,400	XX	28,700	XX	28,700
Total	XX	340,000	XX	357,000	XX	372,000

XX = Not applicable.

[a]Production as measured by mine shipments, sales, or marketable production (including consumption by producers).

[b]Data are rounded to three significant digits; may not add to totals shown.

[c]Preliminary.

[d]Excludes certain stones; kind and value included with "Combined value" figure.

in the 50 states during 1996, Oklahoma remained first in iodine and crude gypsum; second of four states to produce tripoli; third of three crude helium-producing states; fourth in feldspar; and ninth in industrial sand and gravel. The State was third in the production of fire clay, after having no reported production in 1995. In addition, significant quantities of crushed stone, portland and masonry cements, and common clays were produced in the State.

The following narrative information was provided by the Oklahoma Geological Survey (OGS). The OGS reported that industrial-mineral activity in the State continued to increase during 1996. Over the past several years, some of the overall trends are those of increasing production of (1) gypsum for wallboard and plasters; (2) crushed stone for aggregate, railroad ballast, and fill; (3) dimension stone for

TABLE 2.— OKLAHOMA: CRUSHED STONE[a] SOLD OR USED BY PRODUCERS IN 1995, BY USE[b]

Use	Quantity (thousand metric tons)	Value (thousands)	Unit value
Coarse aggregate (+1½ in.):			
Riprap and jetty stone	552	$3,280	$5.94
Filter stone	399	1,840	4.61
Other coarse aggregate	5	41	8.20
Coarse aggregate, graded:			
Concrete aggregate, coarse	2,610	12,300	4.71
Bituminous aggregate, coarse	1,250	5,820	4.64
Bituminous surface-treatment aggregate	554	2,830	5.11
Railroad ballast	W	W	3.34
Other graded coarse aggregate	W	W	5.47
Fine aggregate (–⅜ in.):			
Stone sand, concrete	W	W	3.54
Stone sand, bituminous mix or seal	W	W	2.68
Screening, undesignated	4,970	20,900	4.21
Other fine aggregate	W	W	5.46
Coarse and fine aggregates:			
Graded road base or subbase	1,830	6,640	3.62
Unpaved road surfacing	178	651	3.66
Crusher run or fill or waste	5,020	15,700	3.13
Other coarse and fine aggregates	347	1,390	4.79
Other construction materials[c]	2,460	8,910	3.63
Agricultural:			
Agricultural limestone	169	590	3.49
Poultry grit and mineral food	([d])	([d])	9.38
Other agricultural uses	([d])	([d])	3.69
Chemical and metallurgical:			
Cement manufacture	2,450	6,850	2.79
Flux stone	306	1,380	4.51
Special: Mine dusting or acid water treatment	([d])	([d])	8.63
Unspecified:[e]			
Actual	4,450	20,200	4.54
Estimated	3,410	14,600	4.28
Total	31,100	125,000	(average) 4.02

W = Withheld to avoid disclosing company proprietary data; included with "Other construction materials."

[a]Includes dolomite, granite, limestone, miscellaneous stone, sandstone, and slate; excludes shell and traprock, value only, from State total to avoid disclosing company proprietary data.

[b]Data are rounded to three significant digits; may not add to totals shown.

[c]Includes lightweight aggregate (slate) and roofing granules.

[d]Withheld to avoid disclosing company proprietary data; included in "Total."

[e]Includes production reported without a breakdown by end use and estimates for nonrespondents.

TABLE 3.—OKLAHOMA: CRUSHED STONE SOLD OR USED, BY KIND[a]

Kind	1994 Number of quarries	1994 Quantity (thousand metric tons)	1994 Value (thousands)	1994 Unit value	1995 Number of quarries	1995 Quantity (thousand metric tons)	1995 Value (thousands)	1995 Unit value
Limestone	43[b]	21,700[b]	$87,400[b]	$4.03[b]	47	21,800	$88,800	$4.07
Dolomite	4[b]	2,680[b]	11,400[b]	4.24[b]	4	3,740	15,700	4.20
Granite	2	W	W	5.29	3	W	W	5.21
Traprock	1	W	W	4.18	1	1,490	([c])	([c])
Sandstone	5	2,170	10,400	4.81	5	W	W	4.93
Shell	—	—	—	—	([c])	([c])	([c])	([c])
Slate	1	W	W	1.08	1	12	66	5.50
Miscellaneous stone	1	23	99	4.30	1	27	118	4.37
Total	XX	29,900	125,000	4.18	XX	31,100	125,000	4.02

Dashes indicate that no production was reported.
W = Withheld to avoid disclosing company proprietary data; included in "Total."
XX = Not applicable.
[a]Data are rounded to three significant digits; may not add to totals shown.
[b]Revised.
[c]Excludes shell and traprock, value only, from State total to avoid disclosing company proprietary data.

houses and commercial buildings; and (4) sand and gravel for a variety of construction projects. Construction activities that held steady or increased somewhat during 1996 were highway construction (mainly in the northeast and northwest), commercial and apartment building (in metropolitan areas), and airport/airbase runway projects.

Although the production of most minerals continued to increase, there were no major new operations, expansions, or technological gains during 1996. However, Global Stone Corp., an international mining company, acquired St. Clair Lime Co. The acquisition, initiated in July 1995, was finalized the following December. In 1996 Global Stone changed the name of the lime company to Global Stone St. Clair, Inc., which now operates both the underground mine in high-purity limestone near Marble City and the kiln facility in Sallisaw. Another example of industry activity was a significant increase in the number of permits for small companies to produce dimension stone in eastern Oklahoma. The thin-bedded, well-indurated sandstones are prized as a building material for homes and commercial structures.

The number of mining permits in Oklahoma has risen over the past few years. In 1996, the Oklahoma Department of Mines (ODM) issued a total of 482 mining permits covering a total of 15,753 hectares. ODM reported that the State's 1994 law on Life Expectancy Permits was well received. Under that law, a company may submit a mining plan only once to cover the mine's life expectancy, rather than undergoing a permit review every 5 years (as in the past). Of the permits now on file, ODM reported that 127 have been secured under the Life Expectancy provision.

TABLE 4.— OKLAHOMA: CRUSHED STONE[a,b] SOLD OR USED BY PRODUCERS IN 1995, BY USE AND DISTRICT[c]

(thousand metric tons and thousand dollars)

Use	District 2		District 3		District 4		District 5	
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
Construction aggregates:								
Coarse aggregate (+1½ in.)[d]	222	1,400	347	W	318	W	70	446
Coarse aggregate, graded[e]	1,550	8,870	W	W	W	W	W	W
Fine aggregate (–⅜ in.)[f]	886	2,310	W	W	W	W	755	3,240
Coarse and fine aggregate[g]	1,230	4,760	399	1,570	W	W	W	W
Other construction materials[h]	—	—	590	3,760	9,910	36,100	3,910	17,900
Agricultural[i]	([j])	([j])	111	([j])	—	—	([j])	([j])
Chemical and metallurgical[k]	([j])	([j])	([j])	([j])	([j])	([j])	([j])	([j])
Special	—	—	([j])	([j])	—	—	—	—
Unspecified[l]:								
Actual	2,690	12,700	([j])	([j])	([j])	([j])	—	—
Estimated	104	149	148	620	1,470	6,020	1,690	7,810
Total	**7,690**	**32,300**	**2,670**	**9,880**	**13,900**	**51,600**	**6,820**	**31,100**

Dashes indicate that no production was reported.

W = Withheld to avoid disclosing company proprietary data; included with "Other construction materials."

[a]No crushed stone was produced in District 1.

[b]Excludes shell and traprock, value only, from State total to avoid disclosing company proprietary data.

[c]Data are rounded to three significant digits; may not add to totals shown.

[d]Includes filter stone, macadam, riprap and jetty stone, and other coarse aggregate.

[e]Includes concrete aggregate (coarse), bituminous aggregate (coarse), bituminous surface-treatment aggregate, railroad ballast, and other graded coarse aggregate.

[f]Includes stone sand (concrete), stone sand (bituminous mix or seal), and screening (undesignated), and other fine aggregate.

[g]Includes graded road base or subbase, unpaved road surfacing, crusher run (select material or fill), and other coarse and fine aggregates.

[h]Includes lightweight aggregate (slate) and roofing granules.

[i]Includes agricultural limestone, poultry grit and mineral food, and other agricultural uses.

[j]Withheld to avoid disclosing company proprietary data; included in "Total."

[k]Includes cement manufacture and flux stone.

[l]Includes production reported without a breakdown by end use and estimates for nonrespondents.

Oklahoma is the only state that produces iodine, an important trace element for human development. Iodine production continued to be an important activity in Oklahoma, all domestic production coming from three companies operating in the northwest part of the State. Oklahoma's iodine production value rose in 1996, spurred on largely by the price increase from about $11 per kilogram to about $15 per kilogram over the span of 12 months. North American Brine Resources reopened its iodine-producing facility in the Woodward area in the summer of 1996. The three iodine producers in Oklahoma, IOCHEM Corp., North American Brine Chemicals, and Woodward Iodine Corp., supplied approximately 34% of the U.S. domestic demand, the remainder being imported.

TABLE 5.— OKLAHOMA: CONSTRUCTION SAND AND GRAVEL SOLD OR USED IN 1995, BY MAJOR USE CATEGORY[a]

Use	Quantity (thousand metric tons)	Value (thousands)	Value per ton
Concrete aggregate including concrete sand)	4,180	$14,300	$3.43
Plaster and gunite sands	79	230	2.91
Concrete products (blocks, bricks, pipe, decorative, etc.)	50	184	3.68
Asphaltic concrete aggregates and other bituminous mixtures	316	779	2.47
Road base and coverings	308	848	2.75
Fill	1,270	2,120	1.67
Snow and ice control	16	50	3.13
Other	38	245	6.45
Unspecified[b]:			
Actual	631	2,960	4.68
Estimated	909	3,370	3.71
Total or average	7,800	25,100	3.22

[a]Data are rounded to three significant digits; may not add to totals shown.
[b]Includes production reported without a breakdown by end use and estimates for nonrespondents.

TABLE 6.— OKLAHOMA: CONSTRUCTION SAND AND GRAVEL[a] SOLD OR USED IN 1995, BY USE AND DISTRICT[b]

(thousand metric tons and thousand dollars)

Use	District 1		District 2		District 4	
	Quantity	Value	Quantity	Value	Quantity	Value
Concrete aggregate and concrete products[c]	789	3,250	1,810	5,420	1,710	6,070
Asphaltic concrete aggregates and road base materials[d]	360	803	939	1,850	613	1,150
Other miscellaneous uses	3	39	—	—	35	206
Unspecified[e]:						
Actual	—	—	—	—	631	2,960
Estimated	117	599	541	1,630	251	1,140
Total	1,270	4,690	3,290	8,900	3,240	11,500

Dashes indicate that no production was reported.
[a]Production reported in District 3 and 5 was included with "District 4" to avoid disclosing company proprietary data.
[b]Data are rounded to three significant digits; may not add to totals shown.
[c]Includes plaster and gunite sands.
[d]Includes fill and snow and ice control.
[e]Includes production reported without a breakdown by end use and estimates for nonrespondents.

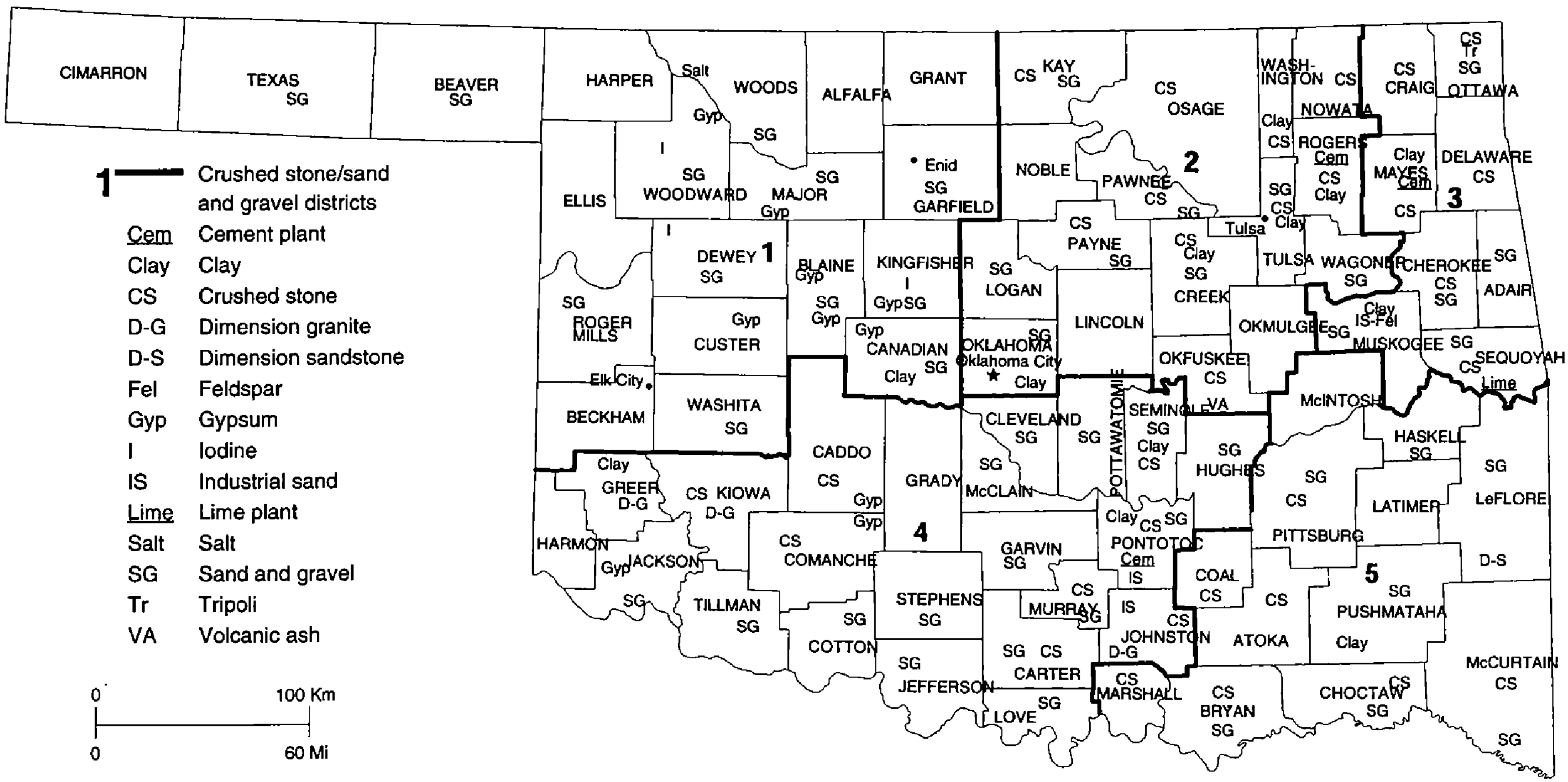

Figure 1. Principal mineral-producing localities in Oklahoma.

OGS Hires Petroleum Geologist Rick Andrews

Rick Andrews gives a presentation at a recent fluvial-dominated deltaic oil reservoirs workshop.

Richard D. Andrews has joined the staff of the Oklahoma Geological Survey as the newest petroleum geologist. Rick, who began working for the OGS in July, is known to many in the geological community through his involvement in a series of presentations at recent workshops on fluvial-dominated deltaic reservoirs, and the publications that resulted from these sessions. The workshops are sponsored by the OGS, in cooperation with the University of Oklahoma's Geo Information Systems (GeoSystems), where Rick worked since 1994. At GeoSystems, he was project geologist and primary presenter for the FDD workshops on the Morrow play, the Skinner and Prue plays, and the Red Fork play.

At the OGS, Rick will continue to work on the FDD workshop series, as well as contribute to other projects related to petroleum. As the reservoir workshops continue, he would like to incorporate seismic stratigraphy into the sessions, evaluate the relationship of depositional environments for both oil and gas reservoirs, and measure gamma-ray profiles of outcrops and relate them to subsurface electric logs.

Rick enjoys the contact with the public that working for a state agency demands, and uses insight from these encounters to help him understand what areas are most in need of study in Oklahoma. His industry experience and willingness to apply this knowledge are the perfect match for a service-oriented agency such as the OGS.

Rick received a B.S. in geological sciences in 1973, and a M.S. in 1976, both from the University of Wisconsin—Milwaukee, then added an M.S. in hydrogeology from Western Michigan University in Kalamazoo, Michigan, in 1993. He began his geologic career for Union Energy in the minerals industry in Wyoming, then moved into exploration and development for UNOCAL, working in Wyoming, Colorado, and Oklahoma from 1981 to 1992. After the closing of the UNOCAL offices, he consulted in Oklahoma City for a short period before joining the staff of GIS.

His work in the petroleum industry in Oklahoma, and his experience with the work and functions of a state geological survey through his participation in the FDD workshops, have helped Rick begin making immediate contributions to Oklahoma geology in his new role with the OGS.

—Connie Smith

UPCOMING *Meetings*

Interstate Oil and Gas Compact Commission, Annual Meeting, December 7–9, 1997, Santa Fe, New Mexico. Information: IOGCC, P.O. Box 53127, Oklahoma City, OK 73152; (405) 525-3556, fax 405-525-3592; e-mail: iogcc@oklaosf.state.ok.us.

Society of Economic Paleontologists and Mineralogists Foundation, Gulf Coast Section, Research Conference, "Shallow Marine and Nonmarine Reservoirs: Sequence Stratigraphy, Reservoir Architecture, and Production Characteristics," December 7–10, 1997, Houston, Texas. Information: GCS-SEPM Foundation, 165 Pinehurst Road, West Hartland, CT 06091; (800) 436-1424, fax 860-738-3542; e-mail: gcssepm@mail.snet.net.

Petroleum Industry Trade Fair, December 11, 1997, Enid, Oklahoma. Information: Linda Nero, Marginal Wells Commission, 1218-B W. Rock Creek Road, Norman, OK 73069; (405) 366-8688 or (800) 390-0460, fax 405-366-2882.

Tailings and Mine Waste, January 26–29, 1998, Fort Collins, Colorado. Information: L. Hinshaw, Dept. of Civil Engineering, Colorado State University, Fort Collins, CO 80523; (970) 491-6081, fax 970-491-3584; e-mail: lhinshaw@vines.colostate.edu.

34th Forum on the Geology of Industrial Minerals, May 3–7, 1998, Norman, Oklahoma. *Talk and poster ideas requested by December 1, 1997.* Information: Kenneth S. Johnson, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 or (800) 330-3996, fax 325-7069.

Oklahoma City Geological Society Elects New Officers

Officers of the Oklahoma City Geological Society for the 1997–98 term are:

President: GEORGE TROUTMAN, Troutman Geo/Logical & Associates
President Elect: WILLIAM "BILL" M. SMITH, Bracken Operating LLC
Past President: STEVEN J. BOONE, Gulf Production Corp.
Vice President: PAUL PIPES, Consultant Geologist
Treasurer: JAMES R. "DICK" HOWELL, BPB Wireline Services
Secretary: RICHARD "DICK" B. OPALKA, Consultant Geologist
Library Director: DAVID E. CARMEN, Slawson Exploration Co.
Shale Shaker Editor: CONNIE ALLEN, Independent Geologist
Social Chairman: CARROLL KINNEY, Independent Geologist
Public Relations: LAURA HOLMAN, McNic Oil & Gas Midcontinent, Inc.
AAPG Representative at Large: RALPH ESPACH, Independent Geologist
AAPG Delegate: CARROLL KINNEY, Independent Geologist

Oklahoma ABSTRACTS

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

Basin-Scale Compartments and Their Genesis

ZUHAIR AL-SHAIEB, CATHERINE PRICE, and *JIM PUCKETTE,* School of Geology, Oklahoma State University, Stillwater, OK 74078

Basin-scale compartments are areas of abnormally pressured reservoirs that are isolated from surrounding normally pressured intervals. This unique configuration evolved by the sealing of abnormally pressured intervals and the maintenance of hydrostatic conditions in the surrounding rocks.

The sealing of the overpressured interval was controlled by distinct mechanochemical processes that were coincident with basin subsidence. Within the Anadarko basin, these systematic processes resulted in the formation of seals that define the basin-scale compartment termed the mega-compartment complex (MCC). The top of the complex is relatively horizontal, cuts across stratigraphy, and is identified by the first occurrence of abnormally pressured reservoirs. The base of the complex conforms to the stratigraphy and follows the Mississippian-Devonian Woodford Shale. Seal formation was directly related to non-equilibrium diagenetic processes that occurred during the rapid subsidence phase of the Pennsylvanian Orogenic episode. The silica cement phase was the major early diagenetic event that initiated a protoseal at depths around 6000 ft (1800 m) and a temperature of 60 degrees C. With continued burial and heating, fluids migrated towards the lower pressure gradient in the southern bounding fault zone. Precipitation in the vicinity of the fault generated a lateral vertical seal. Convergence of the top and basal boundaries resulted in the complete isolation of the complex.

Normal pressure below the basin-scale compartment was maintained by hydraulic continuity between surface outcrops and subsurface reservoirs. Abnormal pore pressure generated during burial by thermal expansion or other processes was dissipated throughout the reservoir and ultimately equalized with the outcrop-connected hydrostatic regime.

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Pressure Architecture of the Anadarko Basin: Implications for Exploration and Production

JIM PUCKETTE and *ZUHAIR AL-SHAIEB,* School of Geology, Oklahoma State University, Stillwater, OK 74078

The evaluation of pressure data from the Anadarko basin indicates that the rock column is divided into three major pressure domains. (1) shallow normally pressured interval, (2) overpressured mega-compartment complex (MCC), and (3) deep normally

pressured zone. This tiered pressure system demonstrates that there is no hydraulic continuity between them.

The overpressured interval is typically encountered in the upper Desmoinesian (around 8,000 to 10,000 ft) and extends to the Mississippian-Devonian Woodford Shale. The overpressured basin-scale compartment (MCC) is dominated by siliciclastic rocks with the textural variability and mineralogic diversity conducive to seal formation. Normally pressured reservoirs below the Woodford Shale are predominantly carbonates and sandstones in the Hunton, Simpson and Arbuckle Groups. These rocks have great lateral continuity and remain normally pressured over most of the basin. Therefore, abnormal pore pressure generated by various processes was not maintained as a result of the hydraulic continuity between outcrops and the subsurface reservoirs.

The basin-scale overpressured domain is highly compartmentalized. Most gas accumulations are independent of structural position and often require particular facies to be productive. Other compartments contain separate gas and brine columns or brine only. Normally pressured reservoirs below the basin-scale compartment have active water drives and gas accumulations occur primarily in anticlinal traps.

The productive potential for the MCC is high across the basin. However, it decreases in the vicinity of the Wichita fault zone. On the other hand, the deep normally pressured rocks remain viable exploration targets up to and within the fault zone.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 81, p. 1353, August 1997.

Sequence Stratigraphy and Reservoir Evolution in the Hunton Group, Anadarko Basin

ZUHAIR AL-SHAIEB and *JIM PUCKETTE*, School of Geology, Oklahoma State University, Stilllwater, OK 74078

The Late Ordovician–Devonian-age Hunton Group is a major oil and gas reservoir in the Anadarko basin. The Hunton carbonates were deposited on a gentle ramp in an epeiric sea. Supratidal, intertidal and subtidal facies can be recognized in core and outcrop and are distributed subparallel to bathymetric contours.

Sequence-stratigraphy concepts are directly applicable to the exploration for oil and gas in the two types of Hunton reservoirs. The first type (Type 1) forms during shallowing (progradational phase) associated with the highstand systems tract of the Henryhouse-Haragan/Bois d'Arc sequence. The second (Type 2) is associated with the intra-Hunton sequence boundary at the top of the Chimneyhill Subgroup and the pre-Woodford sequence boundary.

Type 1 reservoirs are common in the Henryhouse Formation where grain-rich intertidal facies were burrowed and dolomitized. Burrowing generated a pore fluid network in the sediments. Dolomitizing fluids permeated the carbonate and preserved porosity and permeability. Subsequent dissolution removed nondolomitized fossils, creating moldic porosity. Type 2 reservoirs were impacted by meteoric diagenesis associated with sequence boundaries. In this case, the spatial relationship of the reservoir to the unconformity and flow regime were critical. Diffuse flow dissolution generated moldic porosity in grain-rich intertidal facies. Typical karst features usually developed in areas where focused flow occurred along fractures in relatively impermeable rocks.

By integrating a precise understanding of the sequence stratigraphy with facies analysis and distribution, it is possible to predict the anticipated reservoir types in a prospective area and improve reserve estimates.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 81, p. 1346, August 1997.

Advances in Regional Geology: A Regional Stratigraphic Correlation and Production Allocation Project Within the Anadarko Basin and Shelf of Oklahoma with Emphasis on the "Washes"

WALTER J. HENDRICKSON, PAUL W. SMITH, CRAIG M. WILLIAMS, and *RONALD J. WOODS,* Dwight's Energydata, 4350 Will Rogers Pkwy., Oklahoma City, OK 73108

As part of a regional study, the logs from every producing well in the majority of the Anadarko Basin and Shelf of Oklahoma were reviewed to verify the actual producing reservoir and assign a consistent nomenclature. Both detail and regional cross-sections were constructed and used to determine stratigraphic relationships and develop a stratigraphic nomenclature system that could be used across the area with accuracy, detail, and consistency. Correlations were made from the Heebner Shale (Cisco, Upper Pennsylvanian) to the deepest zones penetrated. Allocation of the production within the study area was made based on these correlations and the associated nomenclature system.

Some of the end products of this study have been greater definition and accuracy in the production data. One example of this is seen in the production from the mountain front "washes" found in the southwestern portion of the Anadarko Basin. Previously, in many instances, thousands of feet of washes had reservoir nomenclature indicated as "Granite Wash" or "Atoka Wash." Analysis indicated that often the reservoir rocks were neither granite wash (being chert or carbonate washes) nor Atokan (being either younger or older). With the regional correlations as indicated by cross-sections, it was possible to subdivide the washes and assign more accurate and definitive nomenclature.

Cross-sections and other pertinent data will be presented that will demonstrate the regional correlations and the methodology used to arrive at them.

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Effects of Depth on Reservoir Characteristics and Production in Morrow and Springer Well Completions in the Anadarko Basin

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A recently published report by the Gas Research Institute entitled "Gas Well Recovery -vs- Depth in the Anadarko Basin of Western Oklahoma" (GRI Report # 96/0196) suggests that the observed increase in gas well recovery with increased depth is more influenced by increased reservoir volume than by increased pressure. The GRI conclusions are based upon the physical volumes at depth required to contain the produced gas. The study did not include an investigation into the physical reservoir parameters (i.e., thickness or porosity). Trends in well recovery (and required reservoir volumes) versus depth resulting from the GRI study will be presented.

Independent of the GRI study, detailed reservoir characteristic studies for numerous fields producing from Morrowan and Springeran have been conducted. Approximately 300 wells producing from Springeran Sandstones and 375 wells producing from Morrowan Sandstones were evaluated. The distribution of wells represents a wide spectrum of depth ranges. The results of the reservoir characterization studies will be presented to include trends in reservoir thickness, reservoir porosity, water saturation, and well

spacing. These factors can be used to determine the reservoir volume and demonstrate trends in physical reservoir volume with depth. Using original bottom hole pressure and temperatures, one can then derive an expansion coefficient for each completion. This method can be used to make estimates of original gas in place for each completion. The original gas in place for each well was calculated using the perforated porosity and perforated thickness; the same was done using saturated thickness and saturated porosity. An interesting set of plots and data resulted. These can be used to expedite exploration strategies, exploitation strategies, and/or acquisition strategies. Guidelines for estimating the productivity of the specific reservoirs resulting from the reservoir characterization studies were generated and will be presented.

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A Regional Stratigraphic Correlation, Reservoir Characterization and Production Allocation Project Within the Anadarko Basin and Shelf of Oklahoma with Emphasis on the Springer Group

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As part of a regional study, the logs from every producing well in the majority of the Anadarko Basin and Shelf of Oklahoma were reviewed to verify the actual producing reservoir and assign a consistent nomenclature. Both detail and regional cross-sections were constructed and used to determine stratigraphic relationships and develop a stratigraphic nomenclature system that could be used across the area with accuracy, detail, and consistency. Correlations were made from the Heebner Shale (Cisco, Upper Pennsylvanian) to the deepest zones penetrated. Allocation of the production within the study area was made based on these correlations and the associated nomenclature system.

Some of the end products of this study have been greater definition and accuracy in the production data.

The Springer Group consists of the Boatwright, Britt and Cunningham, in ascending order. While the Cunningham was always found to be a sandstone, extensive correlations indicated that the Boatwright and Britt, which are sandstones in the southeastern portion of the basin, develop an equivalent carbonate facies to the northwest. Facies and production maps are presented for the individual members of the Springer Group as well as a comparative analysis of the reservoirs.

Cross-sections and other pertinent data will be presented that will demonstrate the regional correlations and the methodology used to arrive at them.

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Anatomy and Oil Recovery from Fluvial Deltaic Reservoirs in the Cottage Grove Sandstone, Lake Blackwell Field, Central Oklahoma

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Channel-fill and crevasse-splay or crevasse-channel sandstones form four separate oil reservoirs (zones A, B, C, and D), in the Cottage Grove Sandstone (Osage-Layton sand), section 14, T. 19 N., R. 1 E., western Payne County. Net reservoir sandstones

range in thickness from 16 ft to 6 ft having ten or more percent log porosity. Hydrocarbon-saturated thickness is commonly ten or fewer feet of sandstone. Entrapment is structural/stratigraphic; the reservoirs are located on a westerly-plunging anticline.

The discovery well was drilled to test the "Wilcox" sand, but was completed in the Osage-Layton sand in 1987, for 20 BOPD (43° API) and 7 BWPD, at 3,300 ft. Twelve development wells were drilled and completed in the four reservoirs between mid-1990 and mid-1993. Eleven were completed in zone A, two with no initial water and three with minor production of gas. Three other reservoirs (zones B, C, and D) produce from one well each. Two of the twelve wells penetrated reservoirs below oil-water contacts and one well completed in zones A and C has been abandoned because of high water cut. The more continuous reservoirs (A, B, and C)) appear to benefit from a weak natural water drive. At least three structurally high wells flowed oil from zone A prior to the installation of pumps.

The four reservoirs had produced nearly 320,000 BO from ten wells by September 1995. We estimate that total recovery from the four reservoirs will be 421,000 BO by 12/31/2005, with no change in well status (base case). Reservoir simulation studies indicate that two options for management that will maximize oil recovery, using the same date (12/31/2005) for comparison. Recompletion of 7 wells, 6 of them in zone B, will improve oil recovery to an estimated 940,000 BO, or 223% of the base case. In addition, the drilling of four development wells, one to be completed in each of the four reservoirs, would provide for the recovery of an additional estimated 126,000 BO, or an additional 30%, compared to the base case.

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The Effect of Water Flooding on Produced Oil Composition from Bartlesville Reservoir, Prairie Gem Field, Central Oklahoma

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Water flooding is a commonly applied operation in many petroleum fields to increase oil production. The heterogeneities in the oil composition as well as in reservoir are two main factors impeding the sweep efficiency of water flooding and causing unexpected field problems. The present study integrates geochemical characterization of oils collected before and after water flooding and production information of the studied field.

The oils are characterized by a number of geochemical parameters indicative for source rock type, maturity and mobility determined by GC and GC-MS. Prior to water flooding, the results suggest a uniform oil composition regarding the source and maturity of the oils within the reservoir. The oil produced from a group of wells in the SE part of the field, however, is distinguished by higher values of a very sensitive geochemical migration parameter, i.e., the ratio of C_{16} n-alkane and aromatic 2-methylphenanthrene. The comparison with the oils produced after the water flooding indicates smoothing of these differences. Observed distinctions in mobility parameter of the oils are related to higher recovery factor for the NW part compared to the SE part of the field, demonstrated by volumetric calculations. Further, significant changes in the ratio of hydrocarbon (saturate and aromatic) to non-hydrocarbon (resins and asphaltenes) fractions are found in oils produced from SE part of the field before and after water flooding, mainly due to prominent variations in asphaltene content of the oils. These changes in oil composition are discussed in relation to production as causing short-distance migration of the oil within the reservoir and the heterogeneities in reservoir permeability.

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Geochemical Study of Potential Source Rocks and Crude Oils in the Anadarko Basin, Oklahoma

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Paleozoic source rocks and crude oils from the Anadarko basin, Oklahoma, have been characterized by means of a variety of organic geochemical techniques. The potential source rocks investigated include the Viola Group, Sylvan Shale, Lower Mississippian limestone, Chester group, Springer Formation, and Morrow group. The Woodford Shale, which is an important source rock in the basin and has been discussed extensively in the literature, was used as a laboratory standard in this study. The crude oils examined in this study were obtained from reservoir formations of various ages from throughout the basin.

The source rock screening analysis indicates that the lower and middle subfacies of the Viola, especially from the southeastern part of the basin, have substantial oil-generation potential. The Sylvan is not a source rock, although the black shales in the Springer and Morrow have substantial oil- and especially gas-generation potential. The results of this study support the proposal for multiple sources of oil and gas generation in the Anadarko basin.

Selected source rock and oil samples were characterized in more detail, and the distributions and concentrations (both relative and absolute concentrations) of biomarkers in different source rocks and oils were determined. The biomarker characteristics were combined with other geochemical and geological data to interpret the sources, depositional environments, diagenesis and catagenesis processes, migration, and weathering. Oil-source rock correlations were made between source rocks and a number of crude oils based on quantitative and qualitative biomarker distributions.

Petrographic descriptions and graptolite reflectance measurements were used to evaluate petrographic properties of source rocks and maturity levels of the Viola rock. There was a reasonable correlation between measured graptolite and predicted vitrinite reflectance values.

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Ancient and Modern Deltas: Some Perspectives and Stratigraphic Implications

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Fluvial-deltaic deposits are the Mid-Continent's most important hydrocarbon reservoirs. Deltaic facies show enormous lithic variability with multiple opportunities for facies changes in short time and space intervals.

Some important observations to note in the recognition and interpretation of deltaic facies include the following: (1) There is a lack of type well logs tied into subsurface ref-

erence sections and into updip reference surface sections. (2) Earlier workers were less successful in describing deltaic facies, because they used a low-density data base of primarily electric log not core descriptions or outcrop information. (3) Log patterns are representative of major deltaic depositional facies, but in no way do they indicate all of the possible facies variations. (4) It is significant to understand not only the physical processes of delta formation, but also the gross sedimentology of the sand bodies. (5) There is a lack of regional chronostratigraphic correlations of deltaic sandstones to convincingly demonstrate if the deltaic facies are temporally equivalent to the reservoir sandstones. (6) Existing modern deltas do not convincingly describe the environments of deposition of ancient counterparts. (7) Classifications of delta systems by earlier workers may not always be applicable because the study area is too small to allow for the determination of such criteria as the overall shape of the inferred delta. *8) Analysis of most major deltaic hydrocarbon-producing sandstone reservoirs in the Mid-Continent has not yet been conducted within a rigorous sequence stratigraphic framework. (9) Some significant channelized bodies are marine bodies resulting from the extension of delta systems into offshore areas during sea-level lowstands. (10) Different stratigraphic correlations yield different interpretations; correlations based on lithologies do not give the same sandstone-body geometries or interpretations as those based on boundary discontinuities.

An understanding of all of these complex stratigraphic relationships is absolutely necessary in predicting reservoir occurrence and quality in deltaic facies, particularly in less explored parts of foreland basins.

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Characterization of Lower Permian, Cyclic Carbonate Reservoirs (Chase Group) in the Midcontinent Based on Outcrop Model-Analogs

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95% of the original 80 TCFG reserves in the midcontinent is from the Chase Group in Hugoton-Guymon fields. Outcrops in Kansas, Nebraska and Oklahoma are model-analogs of the occurrence and complex reservoir architecture in these fields. The rocks compose a glacio-eustatic and tectonically-forced section of 7 depositional sequences and component higher frequency transgressive-regressive cycles deposited on a broad ramp. Principal reservoir-analog facies are distal-ramp, subtidal lime sands and proximal-ramp, peritidal dolomudstones that compose the regressive systems tract within sequences. Multiple pore types characterize these facies, which are laterally and vertically heterogeneous in terms of porosity and permeability distribution. Bryozoan reef facies, present in outcrops, have not been reported as a reservoir facies in the subsurface.

Architecture of porous facies was predictably controlled by the nature of hierarchal cyclicity and history of accommodation. Subtidal sands are the dominant reservoir-analogs in the lower Chase Group because of deposition during a time of relatively high-magnitude eustatic fluctuations that precluded peritidal deposition. Most of these reservoirs are associated with type-1 unconformities and forced regressive systems. In contrast, progradational peritidal facies of more extensive areal extent progressively replaced carbonate sands as reservoir-analog facies in the upper Chase Group. The normal regressive systems within which this facies occurs were deposited during a time of decreasing marine accommodation and lower-magnitude eustatic fluctuations.

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Stewart Field, Finney County, Kansas: Seismic Definition of Thin Channel Reservoirs

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Fluvial channel sandstones of Early Pennsylvanian (Morrowan) age comprise regional reservoirs in parts of Colorado, Kansas, Texas, and Oklahoma. In southwestern Kansas, these reservoirs commonly exist at depths of 4000–5000 ft (1200–1500 m) and have reserves of 150,000–200,000 bbl of oil per well, making them highly economical. Reservoir sandstones form part of transgressive valley-fill sequences deposited within channels incised into underlying Mississippian carbonates. Thickness of the fill varies up to 60 ft (~8 m), is commonly 10–30 ft (3–9 m), and displays rapid changes along channel length. As a result, detailed mapping of channel trends is difficult. Stewart field, located in Finney County, Kansas, is a good example of this type of reservoir. Maximum reservoir quality exists in very fine to fine-grained fluvial sandstones reworked by tidal action. Early attempts to extend the field to the east failed because existing two-dimensional seismic and well data did not help workers properly resolve channel orientation. A three-dimensional (3-D) seismic survey, shot prior to initiation of waterflood operations, helped (1) locate the channel between existing dry holes and (2) identify prospective locations that were then successfully drilled. Further extrapolation of the 3-D data resulted in a dry hole that established the limits of interpretation in this area. Stewart field thus provides an important case study regarding the capabilities and limitations of 3-D data in exploring the interwell frontier.

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Use of the Photoelectric Absorption Cross Section Index (Pe) as a Qualitative Permeability Indicator in Deep, Overpressured Reservoirs—Anadarko Basin, Oklahoma

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During open hole logging of wells where mud weights exceed 11.5 lb./gal. and/or a barite pill is spotted just prior to logging operations, many logging company engineers will not display the photoelectric absorption cross section index (Pe) data due to the sensitivity of Pe to mud weight. This is because heavy mud in general and barite in particular make the data unreliable. While the primary function of Pe is lithology determination, the data recorded can also be used as a "pseudo-microlog" to detect permeability in sandstones when enough barite (Pe = 267) is present in the mud system to be detected by the tool following invasion of a permeable sandstone (Pe = 2).

We present evidence from recent deep Springer Formation wells in the Anadarko Basin, Oklahoma, that demonstrate how Pe data can be used to detect permeability in heterogeneous, tight sandstones at 17,000 to 19,000 feet and mud weights up to 16.5 lb./gal. The Pe has been used to identify "sweet spots" of reservoir productivity and has aided the design of perforation and stimulation programs. The recording and displaying of the Pe data in these tight, overpressured Springer sandstones has precluded the need to run micrologs and can be run in slim holes too small to run conventional micrologs.

The use of Pe data as a permeability indicator in overpressured sandstones should have direct application in other geologic provinces.

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Three Dimensional Basin Reaction-Transport-Mechanical Modeling: A Comprehensive, Fully Coupled Computational Approach

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A three dimensional basin model has been developed that accounts for the coupled diagenetic reaction-transport-mechanical processes believed to be key to the evolution of a sedimentary basin. These include grain growth/dissolution/nucleation, pressure solution, fracturing, continuous irreversible rock deformation, and single- and multiphase fluid reactions and transport. The model is a fully coupled, finite element/difference, three dimensional implementation.

Our model is used to predict the evolution of porosity, permeability, fluid composition, and phase across the basin over the 100 million year time frame. Example studies of the Anadarko, Piceance and Midland basins will be reviewed in the light of contemporary thought on compartmentation and fractured reservoirs.

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Late Paleozoic Deformation of Interior North America: The Greater Ancestral Rocky Mountains

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Late Paleozoic deformation within interior North America has produced a series of north-northwest to northwest-trending elongate basins that cover much of Oklahoma, Texas, New Mexico, Colorado, and Utah. Each basin thickens asymmetrically toward an adjacent region of coeval basement uplift from which it is separated by synsedimentary faults with great vertical relief. The remarkable coincidence in timing, geometry, and apparent structural style throughout the region of late Paleozoic deformation strongly suggests that these paired regions of basin subsidence and basement uplift form a unified system of regional deformation, the greater Ancestral Rocky Mountains. Over this region, basin subsidence and basement uplift were approximately synchronous, beginning in the Chesterian-Morrowan, continuing through the Pennsylvanian, and ending in the Wolfcampian (although minor post-Wolfcampian deformation occurs locally). The basement uplifts show evidence for folding and faulting in the Pennsylvanian and Early Permian. Reverse faults and thrust faults have been drilled over many of the uplifts, but only in the Anadarko region has thrusting of the basement uplifts over the adjacent basin been clearly documented. Extensive basement-involved thrusting also occurs along the margins of the Delaware and Midland basins, and suggests that the entire greater Ancestral Rocky Mountains region probably formed as the result of northeast-southwest-directed-intraplate shortening.

Deformation within the greater Ancestral Rocky Mountains was coeval with late Paleozoic subduction along much of the North American plate margin, and has traditionally been related to emplacement of thrust sheets within the Ouachita-Marathon orogenic belt. The nature, timing, and orientation of events along the Ouachita-Marathon belt make it difficult to drive the deformation of the greater Ancestral Rocky Mountains by emplacement of the Ouachita-Marathon belt along the southern margin of North America. We speculate the deformation was driven instead by events within a late Paleozoic Andean margin along the southwestern margin of North America. Evidence for the existence of this previously unrecognized Andean margin comes from east-central Mexico, where a Pennsylvanian and Permian volcanic arc indicates that a northeast-dipping subduction boundary lay to the south and west. The interpretation that deformation throughout the greater Ancestral Rocky Mountains occurs by basement-involved overthrusting on gently to moderately dipping thrust faults suggests that potential hydrocarbon reserves beneath crystalline thrust sheets may be much greater than is generally supposed.

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Application of Dipmeter Data to Structurally Complex Areas in the Mid-Continent

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Dipmeter tools provide a practical method to determine the true strike and dip of strata within a single borehole. In a vertical borehole structural dips have to approach 20 degrees before they are recognized by stratigraphic expansion. If the borehole deviates in an updip direction, then the dips can approach 30 degrees before they produce observable stratigraphic expansion. By using dipmeter calculations with a reducing copy machine, expanded stratigraphic intervals can be corrected to a normal section even when the dips exceed 60 degrees. The corrected intervals can aid in stratigraphic correlations, identify fault blocks, and quantify the internal geometry of complex folds. "Stick plots" which can be generated from dipmeter data integrate effectively with other subsurface tools, especially seismic data. Various examples of dipmeter applications, types of data output, and factors that influence data quality will be presented. Even though dipmeters for the Mid-Continent area have been available for almost fifty years, they are still underutilized on many exploration projects.

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Correlation of Upper Carboniferous and Lower Permian (Desmoinesian-Wolfcampian) 4th Order (Milankovitch Band) Depositional Sequences from the Midcontinent to the Eastern Shelf of the Midland Basin: A New Approach to High Resolution Stratigraphy

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Upper Carboniferous and Lower Permian (Desmoinesian, Missourian, Virgilian, and Wolfcampian) strata from the Northern Shelf of the Anadarko Basin and Eastern Shelf of the Midland Basin as well as coeval strata throughout the world consist of numerous alternations of marine and non-marine strata that constitute fourth-order cyclothemic-scale depositional sequences. These fourth-order depositional sequences can be grouped into composite third-order depositional sequences based on the observed

stacking patterns of the depositional sequences. Sea-level fluctuation curves derived from analysis of these depositional sequences and composite depositional sequences are presented from both of these geographically isolated basins in order to test whether the pattern of successive sea-level events can be utilized for high resolution interbasinal and interprovincial correlation. Multitaxial (conodonts, ammonoids, and fusulinaceans) biostratigraphic tie points are utilized in order to calibrate the sea-level curves developed from each basin. The results presented herein demonstrate that the pattern of sea-level fluctuations in the two basins is virtually identical with 100 percent of the major and intermediate scale eustatic events being recognized in each basin. The same pattern is discernible regardless of whether the depositional sequences are carbonate-dominated or primarily siliciclastic influenced. The composite depositional sequences that constitute the third order depositional sequences are also present in each basin.

These results demonstrate that high resolution correlation of depositional sequences on an interbasinal and perhaps even interprovincial basis is plausible using biostratigraphically calibrated patterns of successive sea-level eustatic events. This method has distinct advantages over traditional biostratigraphy due to provincialism as well as ecologic restriction of biostratigraphically useful taxa in many of the individual depositional sequences.

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Plutonic Relationships Within the Eastern Wichita Mountains, Oklahoma

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Recent detailed mapping of the Eastern Wichita Mountains of southwestern Oklahoma has focused on the contact relationships between the Cambrian Mount Scott Granite (MSG), an areally extensive sheet pluton, and the felsic units it contacts. Two units, Unit F and Unit B, have emerged that are likely floor material for the MSG. Although these units were previously recognized, their origin and relationship to the MSG is problematic.

Unit F is a recrystallized silicic volcanic; metamorphism most likely resulted from intrusion by MSG or Unit B. Contacts with both units are sharp, and MSG appears chilled adjacent to Unit F. Unit F is a fine-grained (matrix 0.1 mm), porphyroblastic hornfels rock that is pale-pink to light orange in outcrop. The rock is 40% quartz, 58% feldspar, 2% opaques. The matrix is comprised of small, equigranular crystals; many of the matrix quartz crystals are optically continuous on the order of 1 mm^2. Porphyroblasts are comprised of ~equant clusters of rounded, larger (0.3 mm) grains of alkali feldspar. Trace amounts of altered biotite occur as larger (0.3 mm) isolated grains. There are many voids within the rock, most of which are angular, possibly indicating dissolution of some mafic grains. Zircon occurs in trace amounts; grains are large (0.08 mm) and typically are subhedral.

Unit B is a granite similar to the MSG that intrudes Unit F and is intruded by MSG. Contacts with the latter unit are limited, and are irregular and intimate where visible. Like the MSG, Unit B is dark pink to red, medium-grained, contains variable amounts of granophyre texture; it is predominantly comprised of alkali feldspar and quartz, with small amounts of primary plagioclase. Unit B lacks the ovoid alkali-feldspar phenocrysts characteristic to the MSG, and contains a smaller amount (1% *vs.* 4%) of mafic minerals. Mafic minerals are largely comprised of altered biotite, commonly in small glomerocrysts, and many are spatially associated with secondary plagioclase.

The following sequence has emerged from the available evidence: Unit F was erupted and then buried by the subsequent eruptions of Carlton Rhyolite. Intrusion of Unit B and MSG followed. The intimate contacts observed between these units suggest that both were still magmas at the time of intrusion.

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What's New in Oklahoma's Old Basement

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Ham, Denison and Merritt (1964) laid the groundwork for trying to understand the importance and control of the basement in the development of subsequent stratigraphy and structure of the Mid-Continent. The map of the Geologic Provinces of Oklahoma produced by Northcutt and Campbell (1996) prompts a new look at the character of the basement. What are the cover rock-basement relationships? Can we read something about the basement from the Geologic Province Map? Can we "predict" Paleozoic structure and stratigraphy from a knowledge of the basement?

It is clear that basement features are involved in definitions of the major provinces, the most profound being the contact between the younger basement of the Southern Oklahoma Aulacogen and the older basement of the northern Arbuckles. This boundary, well-defined on the north of the SOA, splits the Arbuckle Uplift in two and separates the Wichita Uplift and Anadarko Basin. New dating of this younger basement reveals a compressed time interval for its formation (~525–540 Ma), and implies substantial erosion before deposition of the Upper Cambrian Timbered Hills Group and the Arbuckle Group. The extent of the dense fin of new rock defines the core of the SOA and determined the positions of some of the major Pennsylvanian thrust faults. Some are presumably reactivated Cambrian normal faults.

There is evidence from gravity that the Anadarko Basin lies across an extension of the older Mid-continent Rift (1.1 Ga). This may have a relation to the largest overhang or the Mountain View Fault, and the placement of the Cyril Basin, Cement Fault, etc.

Puzzling questions remaining are: Why the Nemaha Uplift?, and Where is the other half of the Arbuckle basement?

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Evidence for Regional Cenozoic Denudation of the Ouachita Trend and Southern High Plains Based on Apatite Fission-Track Thermochronology

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A growing database of apatite fission-track (AFT) thermochronology results from the Ouachita trend and the Southern High Plains can be used to infer that 1 to 2 km of denudation has occurred in these areas since the middle Cenozoic. AFT data from the Anadarko Basin, Oklahoma, suggest that ~1.5 km of denudation has occurred since 40 to 50 Ma. AFT analysis of samples from the Arbuckle, Llano, and Marathon uplifts (Corrigan et al., 1997) and Wichita Mountains (Winkler, 1996) indicates that ~1 km of late Cretaceous to early Cenozoic sedimentary rock has been eroded from these uplifts since 25 to 50 Ma. This timing is roughly coincident with the development of the Rocky

Mountain erosion surface in Colorado and Wyoming and the widespread mid-Cenozoic unconformity on the northern Great Plains. AFT data from the High Plains–Southern Rocky Mountain boundary of New Mexico indicate that denudation was in progress during late Oligocene to early Miocene time, resulting in removal of at least 2 km of section in eastern New Mexico. Possible mechanisms causing regional denudation include a drop in eustatic sea level, as well as climatic and tectonic factors. Elevated temperatures during burial prior to denudation has had an important affect on the level of thermal maturity attained in hydrocarbon-producing areas in the southern mid-continent. In addition, denudation may have altered the pressure and fluid flow regimes in basins of the southern mid-continent.

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Fold-Thrust Deformation along Portions of the Arbuckle Thrust System and Frontal Wichitas, Southern Oklahoma

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The Arbuckle Anticline is a basement-involved foreland structure. Near its central portion, where the greatest shortening has occurred, the Arbuckle Anticline is a complex fault-bend fold. However, as it plunges to the southeast and northwest and progressively loses slip, the Arbuckle Anticline exhibits fold-thrust style deformation. Timing of the formation of synclinal crowd features is constrained by their relationship to preserved synorogenic sediments. Along the southeastern plunge, early stages of folding resulted in the formation of subsidiary structures up the steep flank and shallow flank of the fore-limb syncline. Thrusts along the steep flank created a paleo-topographic high which ponded synorogenic sediments of the Collings Ranch Conglomerate as they were being shed from the Arbuckle Anticline. Subsequent shortening occurred as slip along the Arbuckle Thrust and imbricates resulting in the gentle folding and dissection of the Collings Ranch basin. An apparent normal fault visible in surface exposure is an overturned thrust fault on the overturned fore-limb of the Arbuckle Anticline. Along the northwestern flank of the Arbuckle Anticline an overturned footwall syncline developed. Crowding from northeast-directed shortening along the Arbuckle Thrust and southwest-directed shortening along the oppositely verging Mill Creek Fault System created the Eola Anticline. Similar relationships between structural position and structural style are observed and documented in the frontal zone of the Wichita Uplift.

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Structural Inversion in Southern Oklahoma by Late Paleozoic Transpression, a Working Hypothesis

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The tectonic history of southern Oklahoma, guided by Precambrian structural trends, includes massive rifting accompanied by a thick accumulation (about 6 miles or 10 km) of early to middle Cambrian mafic igneous rocks and associated clastic sediment overlain by a 1 mile (1.6 km) thickness of late Cambrian rhyolite. Early Paleozoic thermal subsidence allowed deposition of a 3 mile (5 km) thickness of preorogenic sediment.

Late Paleozoic transpression across rifted and subsided Precambrian basement blocks in southern Oklahoma (during the assembly of Pangaea) accounts for dominant structural styles along the Wichita-Marietta block, the Ardmore basin block, and several blocks of the Arbuckle Mountains. Although complex in detail, the various structures and their mechanical linkages find common explanation in context of east-west to northeast-southwest compression and reactivation of northwest trending basement faults. This fault reactivation and associated basin inversion resulted in structural relief of at least 6 miles (10 km) and accumulation of a 3 mile (5 km) thickness of synorogenic sediment, extensive thrusting, and left-slip faulting. Dip-slip shortening of the preorogenic rocks amounts to about 9 miles (15 km) whereas net left-slip displacement exceeds 18 miles (30 km).

Dynamic interplay among basement blocks under transpression inverted igneous filled graben and formed several types of mechanically linked structures in the overlying sedimentary sequences. (1) Northwesterly trending, left-reverse, oblique-slip faults vary in attitude depending on the attitude of basement block interfaces with greater structural relief and imbricate faulting at confining bends in the basement block pattern, for examples, the Wichita uplift–Cyril basin pair and the Criner Hills–Ardmore deep pair. (2) Northeasterly trending basement fractures apparently provided antithetic adjustment to the dominant northwest trending en echelon folds and faults, influenced the plunge of folds, and caused confining bends during slippage along basement block boundaries. (3) Flower structures formed at several scales including the complex Cumberland anticline and faulting above the Criner, Tishomingo, and Wichita-Marietta basement blocks.

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Gravity Anomaly Indications of the Cambrian Rift Geometry in Southern Oklahoma

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Listric normal faults associated with rifling can act to influence the distribution of intrusives around a rift zone by creating effective conduits along the footwalls of the faults. As the intrusives migrate into the shallower sections of the footwall, lacoliths and/or sills form in the shallow footwall sections of the major rift faults. As a result, shallow intrusive bodies associated with a rift event may sometimes be indicative of where the footwalls of major rift faults were located. If the intrusives are more dense than the crust into which they are injected, the intrusives will show up as gravity anomalies which can be used to locate the footwalls of the major rift faults.

In southern Oklahoma, the recognition of the original Cambrian rift faults is difficult because of the subsequent tectonic overprint during the Pennsylvanian. However, two gravity anomalies in southern Oklahoma are interpreted to be the results of major intrusions guided by rift faulting during the Cambrian rifting. One of the gravity anomalies is interpreted to be the basalt zone along the southern rim of the Wichita mountains. The second anomaly is just north of the Arbuckle uplift. The implication is that the Anadarko and the Ardmore-Marietta basins were the sites of two opposing half-grabens formed by major rift faults. The grabens acted to confine and control the extent of extrusives while the fault geometry affected the distribution of intrusives into the footwall. Later, the rift geometry ultimately influenced the Pennsylvanian tectonics and mountain building in southern Oklahoma.

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Gravity Anomalies Associated with Rift Faulting in Southern Oklahoma

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Faulting during rifting can act to control the flow of intrusives into the shallow crust. As the intrusives migrate into the shallower sections of the footwall, laccoliths and/or sills can form in the shallow footwall sections of major rift faults. As a result, shallow intrusive bodies associated with a rift event may sometimes be indicative of where the footwalls of major rift faults were located. If the intrusives are more dense than the crust into which they are injected, the intrusives will show up as gravity anomalies which can be used to locate the footwalls of the major rift faults.

The normal faults associated with the rifting that took place in southern Oklahoma during the Cambrian are difficult to identify because of tectonic overprinting. However, two gravity anomalies in southern Oklahoma are interpreted to be the results of major intrusions guided by rift faulting during the Cambrian rifting. One of the gravity anomalies is associated with a basalt zone along the southern rim of the Wichita mountains. The second anomaly is just north of the Arbuckle uplift. The implication is that the Anadarko and the Ardmore-Marietta basins were the sites of two opposing half-grabens formed by major rift faults. The grabens acted to confine and control the extent of extrusives while the fault geometry affected the distribution of intrusives into the footwall. Later, the rift geometry ultimately influenced the Pennsylvanian tectonics and mountain building in southern Oklahoma.

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Geochemistry of Late Ordovician Viola Limestone, Oklahoma: Implications for Marine Carbonate Mineralogy and Isotopic Compositions

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Late Ordovician (Caradocian) age Viola limestones from the Arbuckle Mountains, Oklahoma, have Sr concentrations from 216 ppm to 3720 ppm (average 1600 ppm), $\delta^{18}O$ values from –5.1‰ to –3.1‰ (PDB), and $^{87}Sr/^{86}Sr$ ratios from 0.70775 to 0.70793. Although textural and chemical evidence indicates that these limestones suffered diagenetic alteration, the elemental and isotopic compositions still reveal important information about the primary marine mineralogy and seawater compositions during Late Ordovician time. First, the high Sr concentrations suggest that original Viola sediments were composed mainly of aragonite. Second, the highest $\delta^{18}O$ value (–3.1‰) of the limestones, which is interpreted to be the least altered, constrains the $\delta^{18}O$ values of seawater to >–1‰ (SMOW), assuming that ocean temperatures were 27° ± 5°C. Third, the $^{87}Sr/^{86}Sr$ ratios of Viola limestones probably better represent the $^{87}Sr/^{86}Sr$ ratios of coeval seawater because the ratios from these Sr-rich limestones show less scatter than those of similar-aged samples previously published.

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Multiple Stratigraphic Indicators of Major Strike-Slip Along the Eola Fault, Subsurface Arbuckle Mountains, Oklahoma

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The Eola fault bisects the deep portion of the Eola oil field (T. 1 N., R. 2 and 3 W., Garvin County, OK). At least 9 wells cut the fault and more than 200 wells within a mile of the fault define local stratigraphic relationships on either side. Within the eight miles of control in the Eola field, the fault is a linear steeply southwest dipping fault that trends N75°–80°W with 1500 feet of normal separation to the east and 2000 feet of reverse separation to the west. Juxtaposition of markedly different stratigraphy across the fault cannot be explained by pure dip-slip deformation, but are consistent with left-lateral displacement. More specifically offset of contour lines across the fault on isochore maps of units in the Sycamore, Hunton, and Tulip Creek Formations (based on a 650 well study) all indicate a left-lateral strike-slip motion of 16 miles.

Data presented here indicates that the Eola fault has 16 miles of left-lateral strike-slip and plunges 3° to the west, with less than 0.5 mile of either reverse or normal displacement, all of which makes interpretation of the fault consistent with a wrench fault model. Other fault models may also explain the large strike-slip component of displacement, but any model that fails to account for a large strike-slip component will automatically be inconsistent with the well constrained data from the Eola field.

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Examples of Scale-Independent Structural Models from the Arbuckle Mountains as Examples for Subsurface Interpretations

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Outcrop exposures of structural features in the Arbuckle Mountains are often used as "examples" for subsurface interpretations. If such examples are to be true *models*, it is critical to establish that such features are scale-independent. By recognition of scale independence, a structural geometry that is readily observed at one scale, may be applied across several orders of magnitude.

A variety of fault and fold geometries which can be demonstrated to be scale independent and are thus useful models for subsurface interpretations include the following: (1) Ramp and Flat geometry of thrust faults, (2) Lateral Ramps of major thrusts, (3) Berg's Fold-thrust model, (4) Fault-Propagation folding, (5) Conical termination of folds.

Outcrop photographs as well as surface map analysis will be presented as techniques for interpretations of these and other features.

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Is the Washita Valley Fault a Strike-Slip Fault or a Thrust Fault, and Who Cares?

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The Washita Valley fault has been considered by many scholars to be a strike-slip fault with a left lateral movement of approximately 36 miles. A regional view of the subsurface evidence, however, seems to indicate that the Washita Valley fault may be composed of one or more thrust faults. If this is true, then the sub-thrust zone beneath the Washita Valley fault may contain hidden structural traps in a very prolific oil producing environment.

The prolific nature of the sub-thrust objectives is demonstrated by the production history of two fields that are located on each end of the Washita Valley fault zone. The Eola Field is located on the west end, and the Cumberland Field is located on the east end of the fault zone. Each of these oil fields have now produced more than 800,000 barrels of oil per well.

Re-thinking the structural nature of the Washita Valley fault may lead to the discovery of several more prolific oil fields. A seventy-mile prospective trend located between two giant oil fields should get serious consideration from any visionary exploration geologist.

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