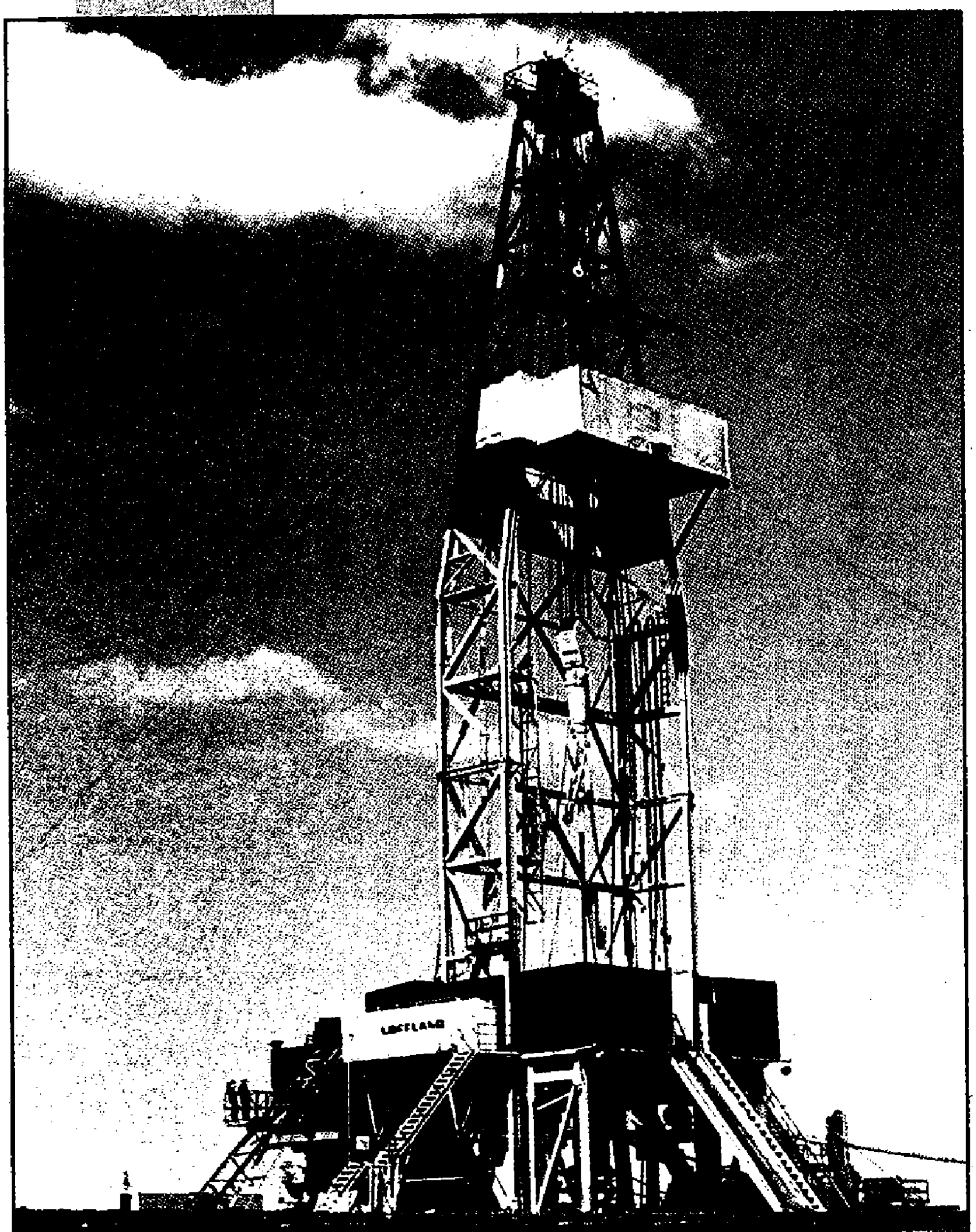
OKLAHOMA GEOLOGY



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On The Cover —

Rig Used for Drilling Deep Boreholes in Anadarko Basin in Early 1970s

The cover photograph shows Loffland Brothers Rig 32 on location during drilling of the Lone Star No. 1 Bertha Rogers well in 1974 (sec. 27, T. 10 N., R. 19 W., Washita County). Rig 32, with a total height of 172 ft, was the largest land-based rig in the world. The Bertha Rogers well reached a total depth of 31,441 ft, in the Ordovician Arbuckle Group, and is the deepest bore-hole in the world drilled for hydrocarbons. Rock cuttings from the bottom of this hole, and from the similarly deep (30,050 ft) Lone Star No. 1 Earnest Baden well, drilled about 19 mi to the west, were studied by Gerald M. Friedman and his colleagues; a summary report on evidence of low-grade metamorphism of these samples is reported by Friedman in this issue (see p. 15).

Kenneth S. Johnson

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A Basal Captorhinid Reptile from the Fort Sill Fissures, Lower Permian of Oklahoma

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Abstract

Dentigerous elements of a single-tooth-rowed reptile represent the first record of a basal captorhinid from the Lower Permian Fort Sill fissure-fill locality of southwestern Oklahoma. Although the single-tooth-rowed captorhinid from Fort Sill can be neither distinguished from nor allied to any known taxon of basal captorhinid on the basis of discrete characters in the available material, the elements clearly represent an animal larger than described basal taxa; additional materials are required to determine if these new specimens from Fort Sill represent a new species. The presence of resorption pockets and replacement gaps supports the hypothesis that there was active replacement of teeth in basal captorhinids. The presence of recurved dentition, cutting edges on the marginal teeth, and formation of a conspicuous "food trap" by the large teeth on the maxilla, dentary, and downturned premaxilla, suggest that basal captorhinids were primarily carnivorous.

Introduction

Members of the Permian reptile clade Captorhinidae occupy a prominent position in phylogenetic and morphological investigations of Paleozoic Amniota (Gauthier and others, 1988; Gaffney, 1990; Clack, 1993; Laurin and Reisz, 1995). The morphology of small captorhinids is known best from a vast amount of material collected from a Lower Permian fissure-fill locality near Fort Sill, Oklahoma (Fox and Bowman, 1966; Bolt and DeMar, 1975; Holmes, 1977; de Ricqlès and Bolt, 1983). The Fort Sill locality represents an almost exclusively terrestrial fauna, and is remarkable in that among the almost two dozen taxa that have been described, the overwhelming majority of bones are attributable to a single taxon, the multiple-tooth-rowed captorhinid *Captorhinus aguti* (Olson, 1991).

Despite more than 50 years of collecting, only five other amniote taxa are known from Fort Sill, and these are based upon limited, fragmentary materials (Vaughn, 1958; Fox, 1962; Carroll, 1968; Bolt, 1980; Reisz, 1980; Laurin and Reisz, 1989). Interestingly, *C. aguti* is the only captorhinid recognized from these fissures (Olson, 1991); accounts of other captorhinids from Fort Sill (Olson, 1967; Heaton, 1979) are regarded as misidentifications of material attributable to *C. aguti* (Bolt, 1980; Olson, 1991).

Among fossil material collected recently from the Fort Sill locality and deposited in the Oklahoma Museum of Natural History are two dentigerous elements of a small amniote with a single row of marginal teeth. These elements are unquestionably captorhinid and accordingly represent unequivocal evidence of a second

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captorhinid member of the Fort Sill fauna. The new material is described below and compared with *C. aguti* and other small captorhinids. The phylogenetic and ecomorphological implications of the new specimens are discussed briefly.

Institutional abbreviations used in this paper are MCZ, Museum of Comparative Zoology, Harvard University; OMNH, Oklahoma Museum of Natural History, The University of Oklahoma; ROM, Royal Ontario Museum, Toronto.

Description

Although disarticulated, OMNH 52366, an almost complete right maxilla, and OMNH 52367, a partial right dentary (Figs. 1–3), are attributed provisionally to the same taxon because they share a mosaic of derived and primitive characters not present in other amniotes known from the locality. It is uncertain if the two elements belong to the same individual, since they were collected from neighboring spoil heaps (William May, personal communication, 1995). Although both elements appear well ossified and are similar in size to those of the largest adult specimens of *C. aguti* from Fort Sill that were available for study (ROM 30096, ROM 30100), ontogenetic age is not determinable for either element. If the single-tooth-rowed maxilla from Fort Sill was the same relative size as those of the species of *Romeria* and *Protocaptorhinus*, then OMNH 52366 represents an animal with a skull 70–80 mm in length. (The descriptions "single-tooth-rowed" and "multiple-tooth-rowed" are hereafter abbreviated "single-rowed" and "multiple-rowed," respectively.)

The maxilla (OMNH 52366) is closely comparable in general morphology to that of other small captorhinids (Fig. 1). The prominent ventral angulation of the premaxillary process reflects the characteristic "hooking" of the captorhinid snout. The lateral surface is sculpted with shallow, vermiculate grooves and small pits in a manner strongly reminiscent of *C. aguti*. As in other captorhinids, the dorsal edge of the maxilla ascends gradually from the premaxillary process to a level immediately posterior to the caniniform tooth. The dorsal margin then descends just as gradually to the sutural surface for the jugal, which forms a distinct "step" along the posterodorsal margin of the maxilla at the 12th tooth position. In these details OMNH 52366 resembles maxillae of *C. aguti* (ROM 44627, ROM 30096). The characteristic lateral flexure of the captorhinid maxilla (Heaton, 1979) is seen clearly in ventral view (Fig. 1C); lateral flexure of 17° occurs at the 11th tooth position. The sutural surface for the lacrimal is pierced posteriorly by a prominent opening, identified by Heaton (1979) as the superior alveolar foramen (Fig. 1A). This foramen is positioned and oriented in the same manner as those present on disarticulated maxillae of *C. aguti*.

The teeth are aligned in a single row along the long axis of the jaw. There are 24 tooth positions, three of which are empty. However, the posterior tip of the maxilla is missing, and it is uncertain how many additional teeth there may have been. The teeth differ notably from those of *C. aguti* in that they are relatively longer; the basal diameter of each tooth is approximately one-half the length of the tooth (measured from base to tip) in OMNH 52366, whereas in *C. aguti* basal diameter is never less than two-thirds the length of the tooth. Beginning with the first tooth position, the teeth demonstrate a progressive increase in size that culminates with the caniniform at the sixth tooth position. Tooth size then drops markedly: the seventh tooth is approximately equal in size to the fourth precaniniform, and the

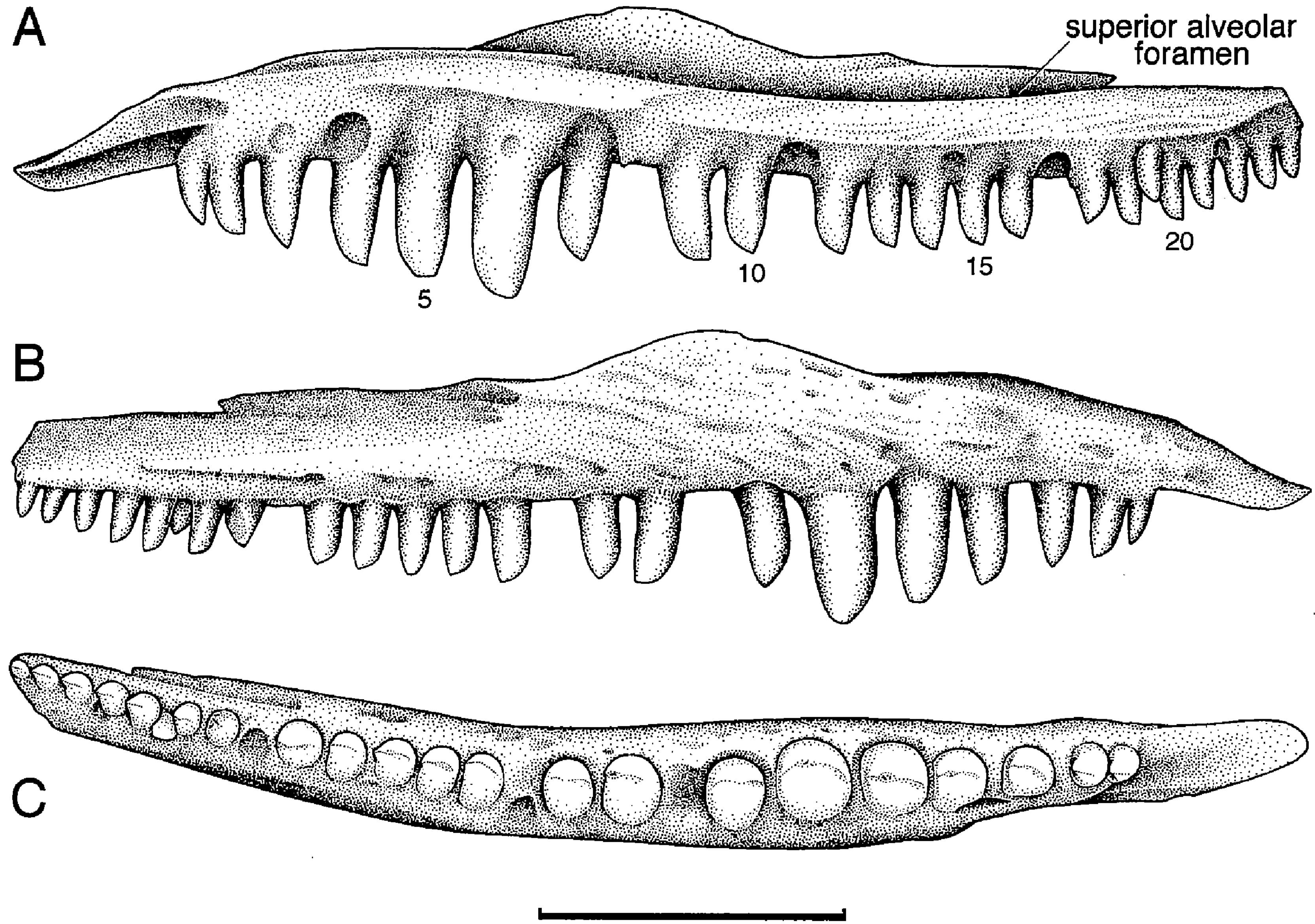

Figure 1. Captorhinidae *incertae sedis*. Right maxilla, OMNH 52366. *A*, medial view; *B*, lateral view; *C*, ventral view. Scale equals 1 cm.

succeeding cheek teeth gradually decrease in size posteriorly. This sudden change in tooth size is seen in some individuals of *Captorhinus aguti* (author's personal observation) and *Captorhinikos parvus* (Olson, 1970). However, the "stepping" of the maxillary dentition in these taxa marks the transition between the single-rowed and multiple-rowed regions of the dentition. In maxillae of other single-rowed captorhinids, the teeth decrease in size gradually, both posteriorly and anteriorly from the caniniform.

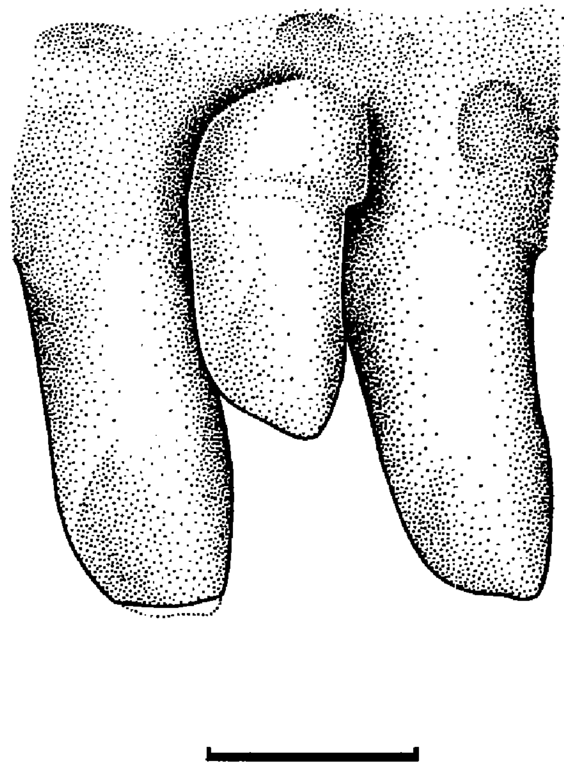

Figure 2. Captorhinidae *incertae sedis*. Three maxillary teeth in medial view, from tooth positions 19–20, OMNH 52366. Middle tooth is the presumed replacement for the tooth on the left. Anterior is to the left. Scale equals 1 mm.

The teeth are implanted in a protothecodont manner (Fraser and Shelton, 1988). The tip of each tooth is moderately recurved and possesses anterior and posterior cutting edges (Fig. 2). The cutting edges originate proximally as ridges on the lingual surface of the tooth, and are accentuated by shallow excavations of the lingual surface of the tooth. The anterior cutting edge is more conspicuous than the posterior edge, as a slight notch slightly separates the anterior edge from the tip proper. The teeth of MCZ 1963 and MCZ 1480, the holotypes of *Romeria prima* and *R. texana*, respectively, also are slightly recurved. The presence of cutting edges cannot be determined in *R. texana*; they are present in *R. prima*, but the presence of an anterior notch is indeterminable. Interestingly, cutting edges indistinguishable from those seen in OMNH 52366 are present on teeth from the single-rowed region of the maxilla of well-preserved specimens of *C. aguti* from Fort Sill (author's observation). The discovery of cutting edges in these captorhinids suggests that the presence of such edges is a captorhinid synapomorphy (shared derived characteristic). The dentition of the holotype of *Protocaptorhinus pricei* is too damaged to determine if either recurvature or cutting edges are present (S. S. Sumida, personal communication, 1995).

The alveolar shelf of OMNH 52366 bears numerous resorption pits of varying size. No replacement teeth are associated with these excavations; presumably they were lost post-mortem. In strong contrast to descriptions of other taxa (Bolt and DeMar, 1975; Heaton, 1979), there are no replacement scars associated with mature teeth. There are natural gaps in the tooth row at the 8th, 11th, and 17th tooth positions. These gaps are marked by relatively shallow scars that are too small to have housed replacement teeth (Fig. 1C). What appears to be a newly erupted tooth lies just dorso-medial to mature teeth at the 19th and 20th tooth positions (Fig. 2). This tooth is partially ankylosed to the jaw; it may have ankylosed prematurely, precluding proper replacement of the preceding tooth.

There are large resorption pits lingually at the bases of teeth at the 3rd, 4th, 14th, and 21st tooth positions (Fig. 1). There are small, incipient resorption pits on teeth at the 6th (Fig. 1) and 20th (Fig. 2) tooth positions. The position of the resorption pits with respect to the vertical axis of each tooth is slightly anterior on the precaniniforms, directly lingual on the caniniform (Fig. 1C), and posterolingual on more posterior teeth (Fig. 2). The shallow, trench-like excavations encircling their bases and the absence of associated resorption pits indicate that the 5th, 7th, and 13th teeth are the most recently ankylosed teeth. The cutting edges and associated ridges of these teeth are more sharply defined than those of teeth associated with resorption pits (Fig. 2), which suggests that the wear on the other teeth was incurred during normal feeding.

The main body of OMNH 52367, a dentary fragment (Fig. 3), closely resembles dentaries of *C. aguti* from Fort Sill both in the pattern of sculpturing and in the organization of the areas contributing to the meckelian canal and the sutural surfaces for neighboring elements. The sculpturing, however, is relatively deeper than in *C. aguti* and in specimens of other small captorhinids that have not been overprepared (Heaton, 1979). The sutural surfaces for the splenial are organized in the manner seen in *C. aguti*, and the alveolar shelf of the dentary also features an elongate scar above the area contacting the splenial which, judging from the same area in *C. aguti*, presumably received

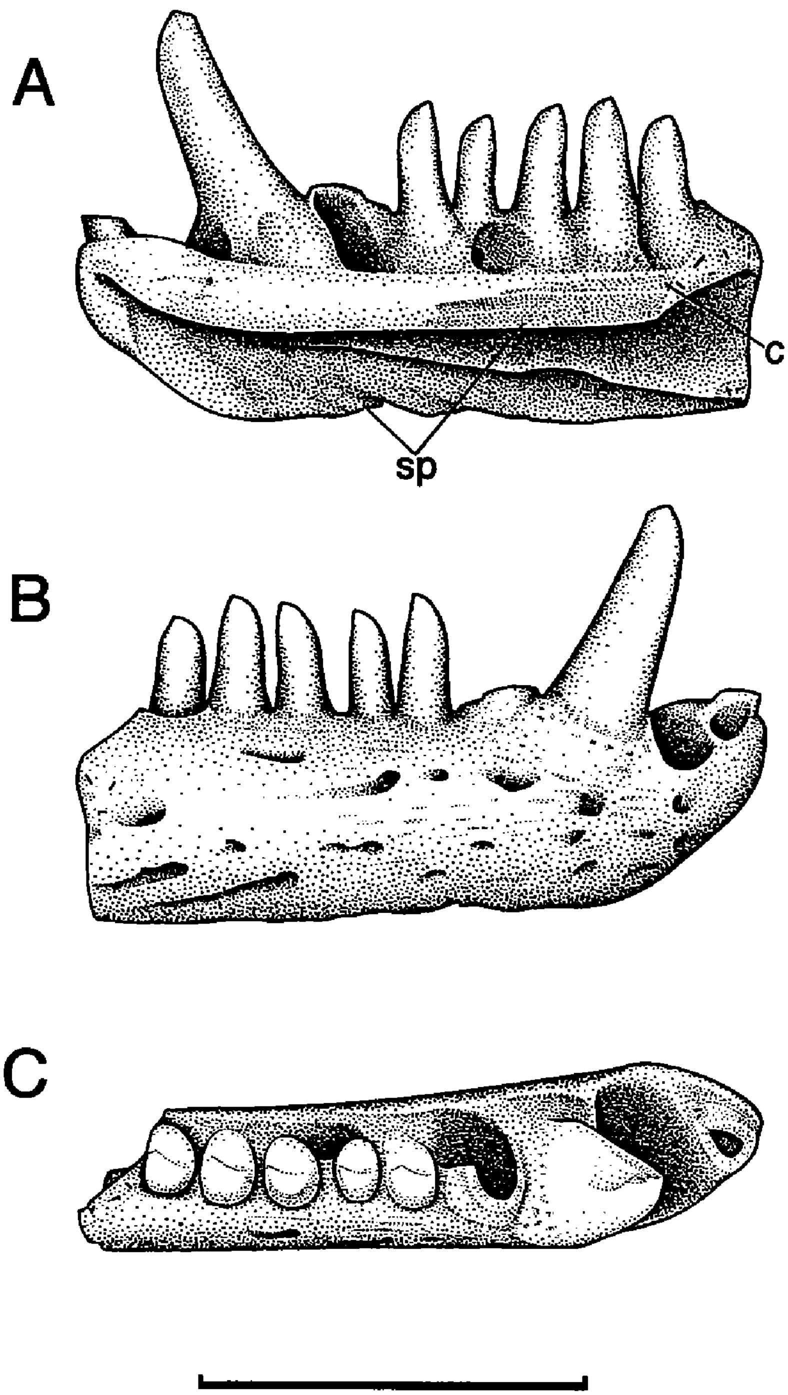

Figure 3. Captorhinidae *incertae sedis*. Right dentary, OMNH 52367. *A*, medial view; *B*, lateral view; *C*, dorsal view. Abbreviations: *c*, sutural surface for coronoid; *sp*, sutural surface for splenial. Scale equals 1 cm.

the anterior process of the coronoid (Fig. 3A); an elongate anterior process of the coronoid is also present in *Labidosaurus hamatus* and *Rhiodenticulatus heatoni* (Dodick and Modesto, 1995). The dentary teeth are relatively longer than those of *C. aguti*, as described for the teeth of the maxilla (OMNH 52366).

The postcaniniform teeth of OMNH 52367 are indistinguishable from those of OMNH 52366 except in absolute size. Except for the first tooth, the anterior dentary teeth are greatly enlarged as caniniforms, representing a captorhinid synapomorphy (Dodick and Modesto, 1995). The basal diameter of the first dentary tooth indicates that it was slightly smaller than the cheek teeth (Fig. 3B). Enough of its base is preserved to indicate that the first dentary tooth leaned only slightly anteriorly from the vertical orientation common to the cheek teeth; the first dentary tooth is conspicuously procumbent in *C. aguti* (Dodick and Modesto, 1995). The preserved caniniform tooth is approximately twice the height and basal diameter of the cheek teeth. The fourth dentary tooth is broken off at the base; what remains of its basal diameter suggests that it was intermediate in size between the caniniform and the succeeding cheek teeth. A large pit occupies the second tooth position; the replacing tooth probably had not ankylosed to the jaw and was lost post-mortem. The fourth tooth apparently was in the process of being replaced, as the lingual surface of its base bears a large resorption pit, but it is obscured by post-mortem damage. The cheek tooth implanted in the sixth tooth position appears to have been at a similar stage of replacement, and the resorption pit has exposed the pulp cavity (Fig. 3C).

Discussion

Taxonomic Affinities

The maxilla and partial dentary described here are the first incontrovertible evidence of a second captorhinid species at Fort Sill. Previous finds of dentigerous elements with single-rowed dentition feature chisel-shaped cheek teeth, but these are thought to represent polymorphic individuals of *Captorhinus aguti* rather than a single-rowed captorhinid (Bolt, 1980).

The presence of a single-rowed captorhinid at the Fort Sill locality is not the first record of single- and multiple-rowed taxa recovered from the same deposits. *Protocaptorhinus pricei* and *C. aguti* are known from the Wellington Formation of Oklahoma, although the latter taxon is collected only as occasional, fragmentary elements (Olson, 1970, 1984). The Wellington Formation has been correlated with the Petrolia Formation of north-central Texas (Olson, 1970; Heaton, 1979; stratigraphic terminology following Hentz, 1988). If that age is correct, then the single-rowed captorhinid at the Fort Sill locality, thought to be equivalent in age to the Clear Fork Group (Heaton, 1979; Olson, 1991), represents the youngest basal captorhinid of the North American Permian. The exquisite preservation of the dentigerous elements described above, and the phylogenetic information provided by tooth-bearing bones and their dentition, prompt a preliminary consideration of the taxonomic affinities of the basal captorhinid from Fort Sill.

Since the new material clearly lacks chisel-shaped cheek teeth, a synapomorphy of more recently derived captorhinids, the affinities of the single-rowed captorhinid from Fort Sill appear to lie with basal, single-rowed captorhinid taxa. Three genera of basal captorhinids are known (Clark and Carroll, 1973; Olson, 1984; Berman and Reisz, 1986). Two species are assigned to the genus *Romeria*; both

R. prima and *R. texana* are known from the Lower Permian Archer City Formation of north-central Texas. *Protocaptorhinus pricei* is known from the overlying Petrolia Formation (Clark and Carroll, 1973) and from the coeval Wellington Formation of Oklahoma (Olson, 1970, 1984). The diminutive captorhinid *Rhiodenticulatus heatoni* is known from the Lower Permian of New Mexico (Berman and Reisz, 1986). Fragmentary, poorly preserved specimens of a small, single-rowed captorhinid from the Upper Permian of Africa were assigned to the genus *Protocaptorhinus* by Gaffney and McKenna (1979). It is the most poorly known material considered here and should be regarded as Captorhinidae *incertae sedis* until it can be restudied.

A close relationship between *Rhiodenticulatus heatoni* and the single-rowed captorhinid from Fort Sill is unlikely as the former is distinguished from all other single-rowed captorhinids by its reduced number of stout, conical teeth and the presence of a relatively enormous caniniform tooth (Berman and Reisz, 1986). The teeth of *Rhiodenticulatus heatoni* also lack the cutting edges and the recurvature seen in the specimens from Fort Sill. Furthermore, lateral maxillary flexure of 5° occurs at the sixth tooth position in *R. heatoni.*

Recurvature of teeth has not been considered previously in the phylogeny of early reptiles. This character is probably plesiomorphic for captorhinids, since recurved teeth are found also in millerettids (Gow, 1972), early diapsids (Reisz, 1981; deBraga and Reisz, 1995), and other basal reptiles (Boy and Martens, 1991). Examination of MCZ 2149 confirms Price's (1937) description of the teeth of *Protorothyris archeri* as slightly recurved (in contrast to their description as simple, sharpened cones by Clark and Carroll [1973]). Even teeth in the single-rowed region of *Captorhinus aguti* show slight, but definite curvature. Among the single-rowed captorhinids, both *Romeria prima* and *R. texana* possess recurved teeth (Price, 1937); the teeth of a juvenile specimen referred to *R. texana* are damaged, yet their outlines as illustrated by Clark and Carroll (1973) reveal that they, too, curve slightly posteriorly. Unfortunately, the holotype of *Protocaptorhinus pricei* is too damaged to determine whether the teeth were recurved or not (S. S. Sumida, personal communication, 1995). Regardless, the presence of recurved dentition appears to have little bearing on the phylogenetic affinities of the basal captorhinid from Fort Sill.

The lateral flexure of 17° in OMNH 52366 is the greatest reported for a small, single-rowed captorhinid. This may reflect its larger absolute size when compared to the known material of other basal captorhinids; OMNH 52366 is at least one-third longer than the maxillae of *R. texana, R. prima,* and *P. pricei.* Heaton (1979) reported a lateral flexure of 5°–10° for *R. texana* and 10°–15° for *P. pricei,* but he also noted that, in general, lateral flexure increased as skull size increased. These observations suggest that maxillary flexure is of little use here for elucidating the generic identity of the basal captorhinid from Fort Sill, in light of its larger absolute size and its uncertain ontogenetic age.

As preserved, there is room for 24 teeth on the maxilla OMNH 52366, and there may have been additional teeth on the small, missing posterior portion of the bone. OMNH 52366 preserves at least one more tooth than the maxilla of *R. prima,* which possesses 23 teeth, and at least two more teeth than the maxillae of *R. texana* and *P. pricei,* each of which possesses 22 teeth (Heaton, 1979). Heaton (1979) was the only worker with a sample size sufficiently large to support investigation of the ontogenetic aspects of tooth number in a single-rowed captorhinid. Heaton (1979) noted that the number of maxillary teeth varied by one among skulls of equivalent size and that the available evidence suggested that the number of maxillary teeth increased with ontogenetic age. Because of the large size of OMNH 52366, its greater number of teeth may not be a suitable character to ally it with either *Romeria* or *Protocaptorhinus*.

Despite new information on the dentition of captorhinids, the available evidence provided by the material described above is equivocal concerning the relationships of the single-rowed captorhinid from the Fort Sill locality. Although the large size of the specimens suggests that they may represent a new species, it would be premature to erect a new taxon based on the limited samples available for this and other basal captorhinids. Therefore, the single-rowed captorhinid from Fort Sill is regarded provisionally as Captorhinidae *incertae sedis*. Additional, more complete material should permit more detailed comparisons with better known taxa.

Biological Implications

Numerous resorption pits and replacement gaps in both OMNH 52366 and OMNH 52367 are unequivocal evidence of active tooth replacement. In most specimens of basal captorhinids, the mandibles are preserved in place, precluding the determination of resorption pits, and only the presence of replacement gaps can be determined. The rarity of such gaps in available specimens of single-rowed captorhinids suggested to Heaton (1979, p. 22) that tooth replacement in adult captorhinids was rare and progressed rapidly, or was absent. If Heaton (1979) is correct, then any interpretation of tooth replacement pattern for the material described here with that described for *Captorhinus aguti* (Edmund, 1960; Bolt and DeMar, 1975; de Ricqlès and Bolt, 1983) might be inappropriate. However, Bolt and DeMar (1975) demonstrated that tooth replacement was continuous throughout life in *C. aguti*, and they believed that tooth replacement in the single-rowed region was unmodified from the (hypothesized) ancestral condition. Heaton's (1979) conclusions, therefore, might apply only to small, single-rowed captorhinids.

The conclusions of Bolt and DeMar (1975), therefore, might appear to warrant comparisons between the tooth replacement patterns seen in the new material described here and that established for *C. aguti*, despite the indeterminate ontogenetic age of the former. It remains to be established whether the tooth replacement pattern seen in both OMNH 52366 and OMNH 52367 does, indeed, represent the condition from which the pattern seen in *C. aguti* is directly derived. The problem can be examined from a phylogenetic perspective. The most recent appraisal of captorhinid interrelationships indicates that *C. aguti* forms a clade with *C. laticeps*, which in turn forms a clade with *Labidosaurus*; *Rhiodenticulatus*, *Protocaptorhinus*, and *Romeria* form successively more distant outgroups to the latter clade (Dodick and Modesto, 1995). This phylogeny indicates that a comparison of the tooth replacement patterns seen in the basal captorhinid from Fort Sill and *C. aguti* would be inappropriate if not misleading, since potentially useful information on tooth replacement from *C. laticeps* and *Labidosaurus* (which share a more recent common ancestor with *C. aguti* than either of them do with basal captorhinids) would be ignored. Accordingly, the tooth replacement patterns of both *C. laticeps* and *Labidosaurus* must be studied before the possible implications of the replacement pattern in the basal captorhinid from Fort Sill for the pattern seen in *C. aguti* can be ascertained. Tooth replacement has never been investigated in *Labidosaurus*, and restudy of this phenomenon in *C. laticeps* is necessary in light of the variance between Heaton's (1979) and Bolt and DeMar's (1975) interpretations of tooth replacement in small captorhinids.

Lastly, the morphological information provided by the new material justifies a reconsideration of the paleoecology of early captorhinids. Clark and Carroll (1973, p. 374–382) postulated that the species of *Romeria* and *Protocaptorhinus* were insectivorous, a hypothesis based upon their description of the marginal teeth as "peg-like," the observed "hooking" of the premaxilla, and the organization of large teeth on the premaxilla, dentary, and maxilla, which together form an "insect trap." Clark and Carroll (1973, p. 374) postulated that these early captorhinids inherited their adaptation to feeding upon arthropods from their immediate ancestors ("romeriids" of earlier literature), and it has been thought that early captorhinids continued a predatory way of life that was characteristic of the earliest amniotes (Carroll and Baird, 1972; Clark and Carroll, 1973). However, the information provided by the above description of OMNH 52366 and OMNH 52367, and examination of adequately preserved material of other small captorhinids, reveals that the presence of anterior and posterior cutting edges is probably synapomorphic for captorhinids. The presence of cutting edges is unexpected in small reptiles that commonly are interpreted as insectivorous.

Among contemporaneous amniotes, cutting edges also characterize the marginal dentitions of sphenacodontid (Romer and Price, 1940; Reisz, 1986) and varanopseid synapsids (R. R. Reisz, personal communication, 1995). These taxa were unquestionably carnivorous, and most were considerably larger than basal captorhinids (Reisz, 1986). Further, the jaws of sphenacodontids, like captorhinids, are modified to form a "food trap," although this feature is considerably more conspicuous in sphenacodontids than in captorhinids (Reisz, 1986). The modification of the anterior marginal teeth to form a "food trap," the presence of well-developed caniniforms, and the presence of cutting edges on all teeth, together suggest strongly that the basal captorhinids also were carnivorous, perhaps feeding primarily upon smaller tetrapods. Like many small, extant carnivorous amniotes, these carnivorous basal captorhinids may have preyed opportunistically upon arthropods.

The comparatively small body size of basal captorhinids suggests that they would have been in competition only with the youngest individuals of contemporaneous varanopseids and sphenacodontids. Together, these forms probably comprised the smallest carnivore guild among Early Permian predators. Possible prey from the known fauna of the Early Permian of both Texas and Oklahoma may have included other small amniotes, small dissorophid temnospondyls (Carroll, 1964; Bolt, 1969), and microsaurian lepospondyls (Carroll and Gaskill, 1978).

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A Note on Metamorphism in the World's Deepest Boreholes in Sedimentary Strata: Anadarko Basin, Oklahoma

Gerald M. Friedman[1]

Abstract

The world's deepest boreholes in sedimentary strata penetrate sedimentary rocks in the Anadarko basin of southwestern Oklahoma to depths >31,000 ft. Bottom-hole temperatures of ~220°C and pressures of ~2.5 kb correspond to conditions in the zone of very low grade metamorphism, but petrographic studies of bottom-hole samples of carbonate rocks and quartz sands show no evidence of the formation of metamorphic minerals. However, there is evidence of mechanical adjustment to burial pressure, and carbonate rocks have developed metamorphic textures.

Paleozoic sedimentary rocks of the Anadarko basin of southwestern Oklahoma reach a proven thickness of more than 38,000 ft (Johnson and others, 1972). The world's deepest boreholes for hydrocarbons—Lone Star Bertha Rogers (sec. 27, T. 10 N., R. 19 W., Washita County, 1974; 31,441 ft deep) and Lone Star Earnest Baden (sec. 28, T. 10 N., R. 22 W., Beckham County, 1972; 30,050 ft deep)—reach bottom in the Ordovician (Arbuckle and Viola) carbonates and quartz sandstones of the Anadarko basin at temperature and pressure conditions conducive to very low grade metamorphism (Rowland, 1974a,b,c). Petrographic studies of rock cuttings from the bottoms of these deep wells show that although the rocks have been buried at pressures of ~2.5 kb and temperatures of ~220°C since at least the Permian, there is no evidence of the development of metamorphic minerals (Friedman and others, 1981, 1984).

The boundary between diagenesis and metamorphism is gradational; it occurs in different rock types at temperature and pressure conditions that vary, depending on the criteria being used to define the onset of metamorphism. Most workers place the boundary within the 100°–200°C temperature range (Frey, 1987; Vernon, 1975; Winkler, 1976). According to Winkler (1976, p. 11), "metamorphism has begun and diagenesis has ended when a mineral assemblage is formed which cannot originate in a sedimentary environment." There are other definitions of the lower boundary of metamorphism, but they will not be discussed here. The object of this note is not to discuss the semantics of diagenesis and metamorphism, but to point out the lack of mineral changes in sedimentary rocks buried at temperature and pressure conditions that could be expected to produce such changes.

Apart from changes in clay types and crystallinity, the first metamorphic minerals that should appear at the temperature and pressure conditions of very low

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grade metamorphism (200°–325°C) include laumontite, prehnite, pumpellyite, lawsonite, and albite (Winkler, 1976), the latter two at pressures exceeding 2–2.5 kb. As temperatures increase to ~325°C, or lower according to some workers, the boundary of greenschist facies metamorphism is reached and a new mineral paragenesis develops (Winkler, 1976). Carbonate rocks and quartz sandstones from the deep Anadarko basin contain clays, glauconite, quartz, and carbonate minerals (calcite, dolomite, and ferroan calcite), which could supply the necessary elements to form some of the very low grade metamorphic minerals. The absence of these minerals raises many questions.

Do the rocks of the deep Anadarko basin contain enough impurities for the development of very low grade metamorphic minerals? Very pure limestones and quartz sandstones can remain stable mineralogically at very high temperatures and show evidence of recrystallization only. Zeolites appear to be common only in sedimentary rocks that contain large amounts of reactive material rich in cations, such as pyroclastics or volcanic fragments.

Other physical or chemical factors may alter the temperatures at which mineralogical changes would be expected. The lack of porosity in rocks at these depths may mean dry and, hence, very slow reactions. However, temperature and pressure conditions for these rocks from the deep Anadarko basin have been approximately the same since at least the Permian; thus, either the reactions are extremely slow, or time may not be an important factor. Any fluid phase present (especially within the limestones) probably contains large amounts of CO_2, which also may affect any mineralogical alterations and, perhaps, may inhibit some of the possible reactions.

Although the carbonate rocks and quartz sandstones of the deep Anadarko basin show no development of metamorphic minerals in response to the temperature and pressure conditions of prolonged deep burial, there is ample evidence of mechanical adjustment to pressure. The quartz sandstones contain abundant strained quartz grains, which increase in number with increasing burial depth (Friedman and others, 1984). In the limestones, more profound alterations occur. Twinning in calcite is common, accompanied by displacement along twin planes similar to that seen in deformed marbles (Vernon, 1981). Aggrading recrystallization of fine carbonate occurs, and granulation or cataclastic textures have developed at twin plane boundaries and around the edges of grains (Friedman and others, 1981, 1984).

Samples from the bottom of the world's deepest boreholes, in the Anadarko basin, provide some of the first in-situ material at temperature and pressure conditions near the boundary between diagenesis and metamorphism. Although the temperatures involved are within the zone of very low grade metamorphism, as defined by Winkler (1976), no mineralogical changes are evident within the rocks. Instead, adjustments to pressure have produced rock textures in the limestones similar to those seen in deformed marbles.

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OGS Educational Publication 5 can be purchased over the counter or by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031 *or* (800) 330-3996, fax 405-325-7069. A 20% discount applies to orders of 25 or more copies. To mail order, add 20% to the cost, with a minimum of $1 per order.

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Order WRI 95-4150 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 843-7570, fax 405-843-7712. A limited number of copies are available free of charge.

Environmental and Hydrologic Setting of the Ozark Plateaus Study Unit, Arkansas, Kansas, Missouri, and Oklahoma

Written by J. C. Adamski, J. C. Petersen, D. A. Freiwald, and J. V. Davis, this USGS water-resources investigations report contains 69 pages.

Order WRI 94-4022 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone (303) 236-7476. The price is $4 for microfiche and $11.25 for a paper copy; add 25% to the price for foreign shipment.

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Written by J. T. Dugan and D. A. Cox, this USGS water-resources investigations report contains 60 pages.

Order WRI 94-4157 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone (303) 236-7476. The price is $4 for microfiche and $35.75 for a paper copy; add 25% to the price for foreign shipment.

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AAPG Annual Convention
San Diego, California ⊕ May 19–22, 1996

Why go to San Diego in May? These times of industry consolidation are the most important times to attend the AAPG Annual Convention. Here we offer state-of-the-art geotechnology at the cutting edge of the industry. Where better to review new techniques and hone one's skills, to renew and revitalize your energy and become more competitive? The contacts you make here may provide opportunities for you *tomorrow.*

"Global Exploration and Geotechnology" is the theme chosen for the first-ever AAPG Annual Convention held in San Diego. We have focused on areas on the Pacific Rim and in Latin America, with exciting sessions from China, Vietnam, Australasia, Indonesia, Southeast Asia, and Latin America. A highlight of the program will be the debate series, where we will have debates on sequence stratigraphy, structural styles, and a controversial debate on global change.

Pat Abbott has worked his field trip magic and come up with a series of fantastic field trips, from Paleozoic carbonate sequence stratigraphy to neotectonics of an active continental margin. Many of the trips dovetail with and complement the technical sessions and short courses.

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San Diego in May is the perfect place for the whole family, with miles of sunny beaches, the San Diego Zoo, Tijuana and Old Mexico, and the best weather anywhere!

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General Chairman

George Pichel
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Stop by the OGS booth in the exhibits hall at the convention to see the newest OGS publications, including EP 5 (see p. 18, this issue) and Geocalendar 1996: "Oklahoma Dinosaur Days—Acrocanthosaurus."

SanDiego

Global Exploration and Geotechnology

Convention Agenda

Technical Program

Monday, May 20

Application of Sequence Stratigraphy in Exploration
Geothermics in Basin Development
Fluids, Active Tectonics, and Continental Margins
Carbonate Cyclo- and Sequence Stratigraphy
Exploration and Production in Australasia
Strike-Slip Styles
Characterization of Worldwide Gas Fields
Selected Academic Research Topics
Application of Sequence Stratigraphy in Exploration
Low-Permeability, Fractured Reservoirs
New Insights into Organic Sedimentation in Ancient and Modern Coastal Basins
Sedimentary Processes and Their Recognition in the Stratigraphic Record
Exploration and Production in Indonesia and Southeast Asia
New Concepts (and Controversies) in Exploration
Thermal Maturity and Thermochronology in Exploration
Risk Assessment and Other Regulatory Issues Related to Closure of Hydrocarbon-Contaminated Sites

Tuesday, May 21

Exploring and Modeling Complex Structural Regimes
3-D/4-D Modeling and Visualization in Exploration and Development
Research Symposium: Sequence Stratigraphy of Tectonically Active Basins
Diagenesis: Applications in Basin Analysis and Reservoir Characterization
Exploration and Production in China
Exploring in Mature Basins and Fields: Case Histories and Success Stories
Heavy Oil Enhanced Recovery
Heterogeneity, Hydraulic Properties, and Contaminant Migration
Hydrocarbon Identification and Remediation
Exploration and Production in Vietnam
Petroleum Systems of the Pacific Rim
Carbonate Reservoirs
Application of New Technologies to Enhance Oil Recovery
Application of Innovative Technologies to Site Assessment and Remediation

Wednesday, May 22

Integrated Reservoir Characterization: A Key to Global Reservoir Prediction
The Role of Sequence Stratigraphy in Field Management
Development Geophysics: Seismic Stratigraphic Analysis of Reservoirs, Case Studies of AVO Analysis, 4-D Seismic
A New Look at Exploration for and Development of Deep-Water Sands
Exploration and Production in Latin America
Structural Traps in the Gulf of Mexico and Extensional Domains

Doing Business and Managing Risk in the International Arena
Recent and Neogene Rift Basins in the Gulf of California Region
Exploring Beneath "Geophysical Basement": Subsalt/Subvolcanics
Recent Advances in Stratigraphy and Sedimentology
Geochemical Dynamics of Modern and Ancient Lake Sequences
Miocene of the Pacific Rim
Turbidite Sedimentation along Modern Continental Margins
Applied Biostratigraphy and Paleoecology
Coal, Coalbed Methane, and Alternate Energy Sources

Short Courses

Carbonate Sequence Stratigraphy—Application to Exploration and Development, *May 18–19*
Tectonics of Sedimentary Basins, *May 18–19*
Geological Prediction and Characterization: Statistical Tools and Methods, *May 18–19*
Geochemical Applications to Reservoir Assessment, *May 18–19*
Assessing Oil and Gas Resources, *May 18–19*
Beyond Bright Spots—AVO Interpretation: A Workshop, *May 18–19*
Managing Petroleum Systems, *May 18–19*
Dolomite Reservoirs: Geochemical Techniques for Evaluating Origin and Distribution, *May 18–19*
Geochemical Applications to Environmental Geology, *May 19*
Remote Sensing and CAD, GPS, GIS, and DEMs for the Petroleum Industry, *May 18*
Detection of Subtle Basement Structures and Related Hydrocarbon Plays, *May 19*
Organic Geochemistry of Sediments and Sedimentary Rocks, *May 18–19*
Climate Model Applications in Paleoenvironmental Analysis, *May 18–19*
Applications of Borehole Imaging in Sedimentary Rocks, *May 18*
Current Technology and Processes, *May 23–25*
Systematics of Fluid Inclusions in Diagenetic Minerals, *May 23–24*
Integrated Stratigraphic Analysis: Application of Sequence Stratigraphy and Biostratigraphy to Defining Basin History, *May 23–25*

Field Trips

Thick-Bedded, Coarse-Grained, Deep-Water Deposits, Cretaceous and Paleogene, Central California, *May 18–19*
Geology of the Midway-Sunset Oil Field and Adjacent Temblor Range, San Joaquin Basin, California, *May 17–19*
Tertiary Sedimentology and Depositional History of the Santa Monica Mountains of California, *May 18–19*
Neoproterozoic Carbonate Successions, Death Valley, California: Comparison and Contrast with Phanerozoic Examples, *May 16–18*
Paleokarst in Lower–Middle Ordovician Dolomites, Southern Great Basin: Evidence for Multiple Sea-Level Changes, *May 16–18*

Stratigraphy of a Marine Rift Basin: Neogene Imperial Formation, Salton Trough, California, *May 17–19*

Neogene Detachment Faulting in the Salton Trough Region: Extensional Geometries and Their Influence on Strike-Slip Faulting, *May 16–18*

Early Rift Sedimentation and Structure along the Northeastern Margin of Baja California, *May 16–18*

Old Oil Fields and New Life: A Visit to the Giants of the Los Angeles Basin, *May 18–19*

Quaternary, Neogene, and Cretaceous Stratigraphy, Coastal Baja California Norte, Mexico, *May 18*

Monterey Formation Fractured Reservoir and Source Rock, *May 22–24*

Structure and Hydrocarbon Exploration in the Transpressive Basins of Southern California, *May 23–24*

Sequence Stratigraphy along a Tectonically Active Margin, Paleogene of Southern California, *May 23–25*

Cycle and Sequence Stratigraphy of Middle Cambrian Bonanza King Carbonates, Southern Great Basin, *May 22–24*

Stratigraphic and Tectonic Evolution of Early Miocene Extensional Basins, Central Mojave Desert, California, *May 23–25*

Tectonic Effects on the High-Resolution Sequence Stratigraphic Framework of Upper Cretaceous–Paleocene Nonmarine to Deep-Marine Forearc Basin Deposits, Baja California, Mexico, *May 23–25*

Geology and Culture of Northern Baja California, Mexico, *May 23–24*

Coastal Wetlands in Southern California: Geological, Hydrological, and Ecological Bases for Their Management, *May 23–24*

The San Andreas Fault System: Identification of Wrench-Fault Assemblages and Their Associated Hydrocarbon Traps, *May 22–24*

Sedimentary Facies and Biostratigraphy of an Upper Cretaceous Submarine Fan, La Jolla and Point Loma, California, *May 23*

Rifting, Transpression, and Neotectonics of the Salton Trough, Southern California, *May 22–24*

> For further information about the annual meeting, contact AAPG Convention Dept., P.O. Box 979, Tulsa, OK 74101-0979; phone (918) 560-2659, fax 918-560-2694; E-mail: vbeighle@aapg.org. The preregistration deadline is *April 10, 1996.*

UPCOMING *Meetings*

Geological Society of America, South-Central Section Annual Meeting, March 11–13, 1996, Austin, Texas. Information: Mark Cloos, University of Texas, Dept. of Geological Sciences, Austin, TX 78712; (512) 471-4170, fax (512) 471-9425.

Platform Carbonates in the Southern Midcontinent, March 26–27, 1996, Norman, Oklahoma. Information: Kenneth S. Johnson, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 *or* (800) 330-3996, fax 405-325-7069.

National Fossil Exposition, April 12–14, 1996, Macomb, Illinois. Information: Gilbert Norris, 2623 34th Ave. Court, Rock Island, IL 61201; (309) 786-6505.

GEO 96—The Middle East Geosciences Conference and Exhibition, April 15–17, 1996, Awali, Bahrain. Information: Jalil Al-Samahiji, General Chairman, Geo 96 Headquarters, P.O. Box 25510, Awali, Bahrain; telephone 973 753475, fax 973 753421.

Hydrology and Hydrogeology of Urban Areas, Annual Meeting, April 21–26, 1996, Boston, Massachusetts. Information: Helen Klose, American Institute of Hydrology, 3416 University Ave. S.E., Minneapolis, MN 55414; (612) 379-1030, fax 612-379-0169.

21st Annual Southwest Geotechnical Engineers Conference, April 22–25, 1996, Tulsa, Oklahoma. Information: Jim Nevels, Oklahoma Dept. of Transportation, Materials and Research Division, 200 N.E. 21st St., Oklahoma City, OK 73105; (405) 521-2677.

Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 28–May 1, 1996, Keystone Resort, Colorado. Information: Mark Cramer, Environmental and Engineering Geophysical Society, P.O. Box 4475, Englewood, CO 80155; (303) 771-6101, fax 303-843-6232.

Research Symposium—Geomicrobiology: From Basic Science to Implications for Bioremediation, May 2–3, 1996, Ames, Iowa. Information: Blythe L. Hoyle, Dept. of Geological and Atmospheric Sciences, Iowa State University, Ames, IA 50011; (515) 294-6583.

Offshore Technology Conference, May 6–9, 1996, Houston, Texas. Information: American Association of Petroleum Geologists, Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 584-2555.

32nd Forum on the Geology of Industrial Minerals, May 19–21, 1996, Laramie, Wyoming. Information: Ray E. Harris, Wyoming State Geological Survey, P.O. Box 3008, University Station, Laramie, WY 82071; (307) 766-2286.

North American Paleontology Meeting, June 9–12, 1996, Washington, DC. Information: NAPC-VI, c/o Dept. of Paleobiology, Mail Stop 121, National Museum of Natural History, Washington, DC 20560.

3rd International Symposium on Environmental Technology, June 10–12, 1996, San Diego, California. Information: Eleanor Nothelfer, Fritz Engineering Lab, Lehigh University, Bethlehem, PA 18015; (610) 758-3549, fax 610-758-4522.

Clay Minerals Society, Annual Meeting, June 15–20, 1996, Gatlinburg, Tennessee. Information: Patricia Jo Eberl, Clay Minerals Society, P.O. Box 4416, Boulder, CO 80306; (303) 444-6405, fax 303-444-2260.

Society of Professional Well Log Analysts, Annual Conference, June 16–19, 1996, New Orleans, Louisiana. Information: American Association of Petroleum Geologists, Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 584-2555.

North American Rock Mechanics Symposium, June 19–21, 1996, Montréal, Québec. Information: Michel Aubertin, Conference Chair, École Polytechnique, Dept. of Mineral Engineering, CP 6079, Succ. Centre-ville, Montréal, Québec, Canada, (514) 340-4046, fax 514-340-4477.

SEPM/IAS Research Conference, "Carbonates and Global Change," June 22–27, 1996, Wildhaus, Switzerland. Information: Judy Tarpley, Society for Sedimentary Geology, 1731 E. 71st St., Tulsa, OK 74136; (918) 493-3361, ext. 22.

International Airborne Remote Sensing, Meeting and Exhibit, June 24–27, 1996, San Francisco, California. Information: Robert Rogers, ERIM, Box 134001, Ann Arbor, MI 48113; (313) 994-1200, ext. 3234, fax 313-994-5123.

Soil and Water Conservation Society, Annual Conference, July 7–10, 1996, Keystone Resort, Colorado. Information: Nancy Herselius, SWCS, 7515 N.E. Ankeny Road, Ankeny, IA 50021; (800) 843-7645, ext. 18.

AAPG/EAPG International Research Symposium, "Conpartmentalized Reservoirs: Their Detection, Characterization, and Management," October 20–23, 1996, Houston, Texas. *Abstracts due April 5, 1996.* Information: Education Dept., American Association of Petroleum Geologists, P.O. Box 979, Tulsa, OK 74101; (918) 560-2621, fax 918-560-2684; E-mail: educate@aapg.org.

AAPG Southwest Section Convention
El Paso, Texas March 10–12, 1996

The El Paso Geological Society will host the Southwest Section meeting of the American Association of Petroleum Geologists. The theme of this year's meeting is "Energy, Minerals, and the Environment—A Pan American Perspective."

A program is planned that mixes papers on traditional topics and recent developments in oil and gas exploration and production with papers on energy minerals, alternate energy sources, mineral deposits, environmental geoscience, and regional geology. Field trips include "Copper Canyon, Mexico," and "Paleozoic Stratigraphy of the Franklin Mountains." An additional field trip, "The Brushy Canyon Play in Outcrop and Subsurface: Concepts and Examples," is offered by the Permian Basin Section SEPM.

For further information about the meeting, contact Robin L. Hoffer or Mick Whitelaw, General Co-Chairmen, Dept. of Geological Sciences, University of Texas at El Paso, El Paso, TX 79968; (915) 747-5101 or 747-5440, fax 915-747-5073.

Oklahoma ABSTRACTS

The following abstracts were presented as part of the Geology Section program at the Oklahoma Academy of Science 84th annual technical meeting, Northwestern Oklahoma State University, Alva, Oklahoma, November 3, 1995.

Recognition, Stratigraphic Distribution, and Significance of Paleosols in the Geologic Record

JAMES R. CHAPLIN, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019

The recognition and interpretation of paleosols (fossil soils), paleoweathering surfaces, and surfaces of subaerial erosion is extremely critical in any stratigraphic analysis. Some diagnostic field features used to identify significant paleosol intervals include: (1) evidence of root traces in their place of growth, (2) truncation of root traces and other trace fossils by an erosional surface, (3) antiformal/synformal sets of slickensided peds, (4) striated/grooved manganese oxide-coated slickensided peds, (5) mottling and gleying of blocky weathering mudstones, (6) desiccation features, (7) in-place brecciation of micritic carbonate nodules, (8) pedogenic color changes vertically, (9) blocky and columnar peds, (10) pedogenic carbonate (caliche), (11) subtle horizonation, (12) filled veinlets (root traces, soil cracks, burrows) with illuviated sediment from overlying horizon, (13) microkarsting, and (14) subhorizontal (dipping up to 40°) mudstone-filled fractures.

Although examples of paleosols are represented in each of the geologic eras, their stratigraphic distribution is not particularly even, either temporally or geographically. Three Paleozoic paleosols described in this paper are from the western part of the Appalachian basin; one focuses on an Ordovician estuarine/tidal flat red-bed sequence, another on a Mississippian subtidal/tidal channel/sandbelt facies, and a third on a Mississippian mixed siliciclastic/carbonate system. In addition, two paleosols described from the Midcontinent provide an interesting comparison between Pennsylvanian and Permian paleosols developed on carbonate/siliciclastic rocks.

Paleosols are significant stratigraphic tools and provide clues to: (1) time-significant surfaces, (2) emergent exposure surfaces, (3) sea-level lowstands (sequence-bounding unconformities), (4) karsting events, (5) basinward shift of paleoshoreline, (6) locating the position of sand bodies within a fluvial system, (7) defining correlation surfaces, (8) identifying the level of a marine flooding surface above, (9) paleoclimate, (10) diagenetic traps in sub-unconformity sandstones, and (11) recognizing different levels of stratigraphic compartmentation in hydrocarbon-producing reservoirs.

The Thermal Conductivity of Coal

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The extremely low thermal conductivity of coal and carbonaceous sediments may contribute to elevated temperatures and unusually high thermal maturities in certain

sedimentary basins containing these rock types as overburden. While much is known about the thermal conductivity of common lithologies such as sandstone, limestone, and shale, little is known about the thermal properties of coal and carbonaceous sediments. In an effort to fill the gaps of thermal conductivity data in the literature 60 coal samples, representing all the major U.S. coal provinces, were collected for conductivity measurements. A total of 225 measurements were made using the divided bar technique. Conductivity values ranged from 0.219 W/m-K to 0.55 W/m-K, which are an order of magnitude lower than values for the more common lithologies. There appears to be no correlation between coal thermal conductivity and rank, however the data do show a direct relationship between ash content and conductivity. Since thermal conductivity is of first order importance in determining heat flow, and because all coals exhibit low conductivity values, even thin coal seams in sedimentary basins should be accounted for when estimating heat flow.

Designation of a Neostratotype for the Savanna Formation in Its Type Area, Pittsburg County, Oklahoma

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A 1,714.1-ft section measured and described in the south limb of the Sans Bois syncline just northwest of the town of Adamson (Adamson 7.5′ topographic quadrangle) is designated as the principal reference section for the Savanna Formation (Pennsylvanian). Although the Savanna Formation is a long- and well-established stratigraphic unit, a formal type section never was specified. The Adamson section has been selected as the neostratotype for the Savanna on the basis of (1) accessibility of rocks in place; (2) excellent exposures, including both the upper and lower contacts as well as lithologic units immediately above and below the contacts; (3) geographic location within the type area (central Pittsburg County); and (4) close adherence to the original sense in which the Savanna Formation was defined by its nomenclator.

The 1,714.1-ft measured section includes 122.5 ft of the upper part of the McAlester Formation (predominantly silty shale containing ironstone concretions); 1,449.1 ft of the Savanna Formation; and 142.5 ft of the lower part of the Boggy Formation (sandstones and shales of the Bluejacket Sandstone Member).

Lithologically, the Savanna Formation comprises sandstones (~16%) and shales, and includes one 2-ft-thick fossiliferous, sandy limestone. The sandstones are variable in character. Soft-sediment deformation features such as convolute bedding, flow rolls, and large, rolled sandstone masses are common. Seven sandstone "groups" (based on topographic expression) are mappable in the area of the principal reference section, as well as throughout much of the Arkoma basin in southeastern Oklahoma.

Structural Geometry of the Thrust Faulting in the Wilburton Gas Field Area, Southeastern Oklahoma

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The Arkoma basin, located in southern Oklahoma and western Arkansas, has long been recognized as a foreland basin of the Ouachita fold and thrust belt. It is mainly a gas producing basin and is believed to contain more than 3 trillion cubic feet of gas re-

serves. The Choctaw thrust fault is the structural boundary between the basin and the frontal Ouachita Mountains. The Wilburton gas field, located to the south–southwest of the town of Wilburton, mainly produces from the overthrusted Pennsylvanian (Atokan) Spiro sandstone reservoirs as well as the Arbuckle Group in the footwall (lower) block of Choctaw fault zone. This investigation was concerned with providing a better understanding of the geometry of the thrust faulting in the area between the towns of Wilburton and Hartshorne (Latimer and Pittsburg Counties). The study is a part of an OCAST (Oklahoma Center for Advancement in Science and Technology) project that was aimed at developing an exploration module for oil and gas companies exploring in the Spiro sandstone reservoirs in the Wilburton area.

Many balanced structural cross-sections were constructed to determine the structural geometry of the thrusting in the area between Wilburton and Hartshorne. The cross-sections were based on the updated surface geological maps of the Oklahoma Geological Survey, wire-line well log data, and our interpretations of seismic profiles donated by Exxon. When restored to their original position, the cross-sections suggest about 60% shortening in the Wilburton area. The hanging wall (upper) block of the Choctaw fault contains many south-dipping imbricate thrusts that are mostly exposed at the surface. In the footwall block, well-developed duplex structures are present. The duplexes contain hinterland dipping imbricate thrusts splaying from a detachment surface, usually referred to as the Springer detachment. The imbricate thrusts join to a roof thrust named as the Lower Atokan detachment. The roof thrust is believed to continue in the Atoka Formation. It displaces the Red Oak sandstone and forms the Carbon fault as the north-dipping backthrust in the northern part of the Wilburton area.

Thermal Modeling of Diabase Dike Emplacement at Elmer Thomas Dam, Wichita Mountains, Oklahoma

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The Cambrian igneous rocks of the Wichita Mountains, southwestern Oklahoma, resulted from rift-associated bimodal magmatism. The youngest products are tholeiitic diabase, occurring in thin (<2 m thick) dikes that crosscut older granite, gabbro, and rhyolite. Most surface exposures are weathered into loose, saprolitic soils.

Adjacent to the dam at Lake Elmer Thomas, a small quarry has excavated three diabase dikes within the Mount Scott Granite. The largest of these is a 0.7–1.2-m-thick, N15W-trending, 96°E-dipping dike comprised of two separate stringers. These are separated by a ~0.4-m zone of partially melted granite, resulting from dike intrusion, with included blocks of unmelted granite. The dike's west stringer is ~0.3 m wide. Its westernmost contact is sharp and linear, with a 0.05–0.75-m chilled margin. Its east contact is sharp but irregular, with a 0.04–0.05-m chilled margin. The east stringers width varies from 0.4 m, in the south, to 0.9 m, in the north. Its west contact is irregular and broken by fractures filled with partially melted granite; many of these fractures completely cut the stringer. This contact has a 0.03–0.05-m chilled margin. The east contact is sharp, linear, with a 0.05–0.07-m chilled margin. The dike's chemical composition suggests a solidus above 1000°C, and a conductivity of 1.7–2.5 W m^{-1} K^{-1}. The density of the diabase is 2.9 g/cm^3. Based on CIPW normative calculations, the dike has a heat capacity of 1.1 kJ kg^{-1} K^{-1} and a latent heat of fusion of –453 kJ $mole^{-1}$ at 1200°C.

The intruded rock, Mount Scott Granite (MSG), was emplaced as a shallow (<2 km), tabular pluton, 55 km long and 0.5 km thick. This sheet granite was emplaced along a contact between the older Glen Mountains Layered Complex and the penecontemporaneous Carlton rhyolite. Minimal, poorly constrained evidence of hornfels metamorphism is found contacting the pluton. Previous work places the MSG "dry" solidus just below 850°C. The density of the MSG is 2.6 g/cm^3, and the conductivity falls within a range from 2.4 to 3.8 W m^{-1} K^{-1}. Based on CIPW normative calculation, the dike has a heat capacity of 1.2 kJ kg^{-1} K^{-1} and a latent heat of fusion of –194 kJ mole^{-1} at 850°C.

Thermal modeling (1D) of the dike calculated a 2.8-day solidification period, a reasonable time-frame for chilled-margin development. The half-space model assumed instantaneous emplacment at 1200°C, vapor-undersaturated magma, and simple conduction heat transfer. The wall-rock temperature was constrained by the presence of partial melt, since the model requires an initial temperature excessive of 275°C (~100°C above the inferred geothermal gradient) to obtain interface temperatures above the granite solidus (850°C). An MSG temperature ~350°C provides a better fit when considering the extent of melting observed adjacent to the dike. This wall-rock temperature implies diking into a still-cooling MSG pluton.

Half-space modeling of the MSG employed the same assumptions and used an inferred geothermal gradient of ~100°C for the wall-rock temperature. The model calculated a 87-year hypersolidus period. Thermal modeling of subsolidus cooling history proved inconclusive, resulting in an unreasonable (35 m.y.) time span to cool to 275°C. Further evaluation of the subsolidus cooling history is required to constrain the timing of dike emplacement.

Subsurface Temperature and Overpressure in the Anadarko Basin, Southwestern Oklahoma

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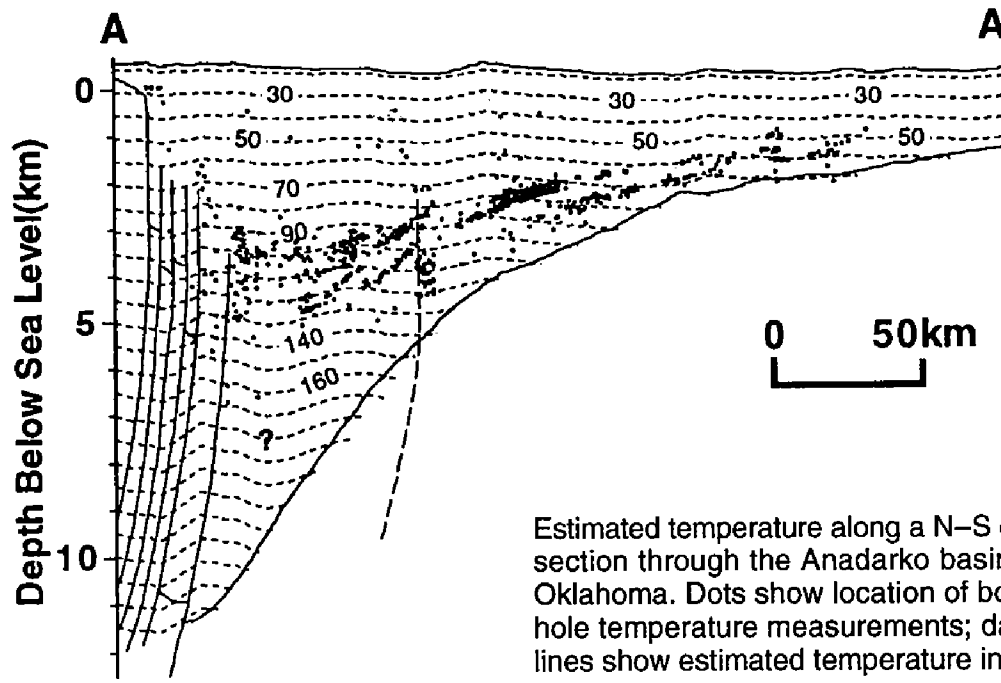
The Anadarko basin in southwestern Oklahoma is known to have areas of extensive overpressure. However, the basin has not experienced significant sedimentation for more than 200 million years, and has undergone uplift and erosion for the last 100 mil-



Estimated temperature along a N–S cross-section through the Anadarko basin, SW Oklahoma. Dots show location of bottom-hole temperature measurements; dashed lines show estimated temperature in °C.

lion years. The origin of overpressure in older basins such as Anadarko, which have not undergone active subsidence for tens or hundreds of millions of years, is not well understood. One hypothesis is that overpressures are being actively generated through an ongoing process of hydrocarbon generation. The rate of hydrocarbon generation is exponentially dependent upon temperature; therefore, understanding the present day temperature field within the Anadarko basin is a starting point for evaluating hydrocarbon generation as a viable mechanism for the creation and maintenance of overpressures.

We corrected 895 bottom-hole temperatures (BHTs) from log headers of 589 oil and gas wells located on a N–S cross-section through the Anadarko basin. Thirty-eight sets of multiple time-temperature measurements were corrected by means of a Horner plot. The remaining 818 BHTs were corrected by an average depth-time correction. A total of 856 corrected BHTs was used to estimate equilibrium formation temperatures in the Anadarko basin. The method of variable bias (Deming and others, 1990, Geophysical Research Letters, v. 17, p. 1949–1952) was used to estimate lateral temperature variation along the N–S cross-section.

The average geothermal gradient calculated from our data is 21°C/km. We also estimated fluid pressure along the same cross section from 1,442 records of drilling mud density and 1,328 records of bottom-hole pressure. We found that fluid pressure estimated from mud weights increases from a hydrostatic regime to overpressures at a depth of ~3 km at temperatures of ~80°C. We are now proceeding to refine our estimates of temperature and fluid pressure, as well as evaluate hypotheses of overpressure generation through hydrocarbon maturation.

Recent Seismicity in North-Central Oklahoma

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Prior to the installation of a Statewide network of seismograph stations in 1977, over half the known Oklahoma earthquakes occurred in Canadian County. The earliest documented Oklahoma earthquake occurred near Jefferson, Grant County, on December 2, 1897. The largest known earthquake in Oklahoma occurred near El Reno, Canadian County, on April 9, 1952. This magnitude-5.5 (Gutenberg-Richter) earthquake was felt in Austin, Texas, as well as Des Moines, Iowa, and covered a felt area of 362,000 km^2.

The recent earthquake epicentral locations define a 40-km-wide by 145-km-long earthquake zone that extends northeastward from El Reno toward Perry (Noble County). Most of the earthquakes have occurred in the vicinity of the El Reno–Mustang area, the site of numerous earthquakes since 1908. The El Reno–Perry trend appears to cut diagonally across the Nemaha uplift structures at about 30° angle.

The first known felt earthquake in Woods County was recorded at 7:31 p.m. local time, September 14, 1995. This magnitude 3.8 (mbLg) earthquake produced Modified Mercalli (MM) intensity effects in Alva, Oklahoma, and Kiowa, Kansas. Residents of Alabaster Caverns, Alva, Cherokee, Enid, northwest Oklahoma City, and several places in southern Kansas reported feeling the event. A preliminary epicentral determination placed the earthquake location about 35 km (22 mi) south of Alva. However, subsequent data relocates the eipcenter 10 km (6 mi) northwest of Alva. Only four instrumentally located earthquakes are known to have occurred in Woods County prior to the September 1995 earthquake. The events were recorded in 1980, 1981, and two in 1992.

Many of the earthquake-generating structures are buried 5 to 10 km below the surface. Apparently, periodic readjustments along some north-central Oklahoma faults produce small magnitude (2.0–3.5) earthquakes.

Heat Flow and Hydrocarbon Generation in the Transylvanian Basin, Romania

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The Transylvanian Basin in central Romania is a Neogene depression superimposed on the Cretaceous nappe system of the Carpathian Mountains. The basin contains the main gas reserves of Romania, and is one of the most important gas producing areas of continental Europe; since 1902, gas has been produced from more than 60 fields.

Surface heat flow in the Transylvanian Basin as estimated in other studies ranges from 26 to 58 mW/m^2, with a mean value of 38 mW/m^2, relatively low compared to surrounding areas. The effect of sedimentation on heat flow and temperature in the Transylvanian Basin was estimated with a numerical model that solved the heat equation in one dimension. Because both sediment thickness and heat flow vary widely throughout the Transylvanian Basin, a wide range of model variables were used to bracket the range of possibilities. Three different burial histories were considered (thin, average, and thick), along with three different values of background heat flow (low, average, and high). Altogether, nine different model permutations were studied.

Modeling results show that average heat flow in the Transylvanian Basin was depressed ~16% during rapid Miocene sedimentation while present day heat flow remains depressed, on average, ~17% below equilibrium values. This result suggests that low heat flow in the Transylvanian Basin is at least in part a lingering effect of Miocene sedimentation.

Source-rock maturation and the timing of hydrocarbon generation was estimated by applying Lopatin's method. Potential source rocks in the Transylvanian Basin are Oligo–Miocene, Cretaceous, and Jurassic black shales. Results show that potential source rocks entered the oil window no earlier than ~13 Ma, at depths between ~4,200 and 8,800 m. Most simulations encompassing a realistic range of sediment thicknesses and background heat flows show that potential source rocks presently are in the oil window. However, no oil has ever been discovered or produced in the Transylvanian Basin. Model simulations of the thermal history of the Transylvanian Basin show that in most scenarios potential source rocks are too cold for significant gas generation. Only simulations with average or high heat flow and average to high sediment thicknesses yield predictions of significant gas generation. There is a correlation between heat flow and gas occurrence in the Transylvanian Basin, but gas fields are also likely to be found in areas with relatively thin sedimentary cover.

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Environmental Geophysics at Aberdeen Proving Ground, Maryland

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Geophysical data collected at several sites in the Edgewood Area, Aberdeen Proving Ground (APG), Maryland, were used in the characterization of the natural hydrogeologic framework of APG and in the identification of buried disturbances (trenches and other evidences of contamination). Studies included magnetic surveys using an E G & G Geometrics cesium-vapor magnetometer, electrical conductivity using Geonics EM-31, EM-34, and EM-61 meters, electrical resistivity using an ABEM Terrameter instrument, ground-penetrating rader (GPR) using GSSI SIR-2 and SIR-3 acquisition systems, seismic reflection and refraction using an E G & G 24-channel seismograph, and metallic debris detection using a Schonstedt magnetic gradiometer and cable locator.

At the Beach Point Peninsula site, located in the Bush River estuary environment, the studies were used to determine thickness variations in the clay overburden (based on GPR and conductivity data), possible DNAPL contamination plumes (suspected from resistivity and conductivity profiles), suspected contaminant disposal pits (from GPR and conductivity data), and locations of underground storage tanks (USTs) and other buried metal (identified by high values in magnetic and conductivity maps). GPR imaging provided detailed displays of reflectors to a depth of 30 ft showing depositional contacts in Atlantic Coastal Plain strata separating surface clays from underlying sands and gravels. The strata consist of the Pleistocene Talbot Formation overlying the Cretaceous-age Potomic Group. A correlation was observed between surficial emergence of these GPR reflections with decreased electrical conductivity, observed using the EM-31 meter, allowing the EM-31 to be used as an initial indicator of where surficial clays were thin. Seismic reflection data showed the elastic wave response to a succession of fluvial terraces, believed to be representative of episodic and constructive channel filling of alluvium during the Pleistocene-age sea-level rise. Underlying the coastal-lain sediments, an angular unconformity of Pleistocene age overlying gently dipping strata belonging to the Potomic Group was imaged at 50–100 ft. Deeper seismic reflection and refraction indicated a depth of 500–600 ft for the Precambrian basement.

A possible contaminant plume was suggested by the unusual noncontinuous appearance of a low-resistivity (high conductivity) lens near a monitoring well located in DNAPL-contaminated ground water. However, low-conductivity values resulting from a DNAPL-contaminated plume at depth are difficult to identify, and the anomaly might be caused by nearer-surface variations in soil or water conditions.

Conductivity and GPR profiles were particularly useful in identifying the locations of USTs. While most such tanks were suspected based ventilation pipes and other surface observations, at least one UST was imaged without any visible surface indications.