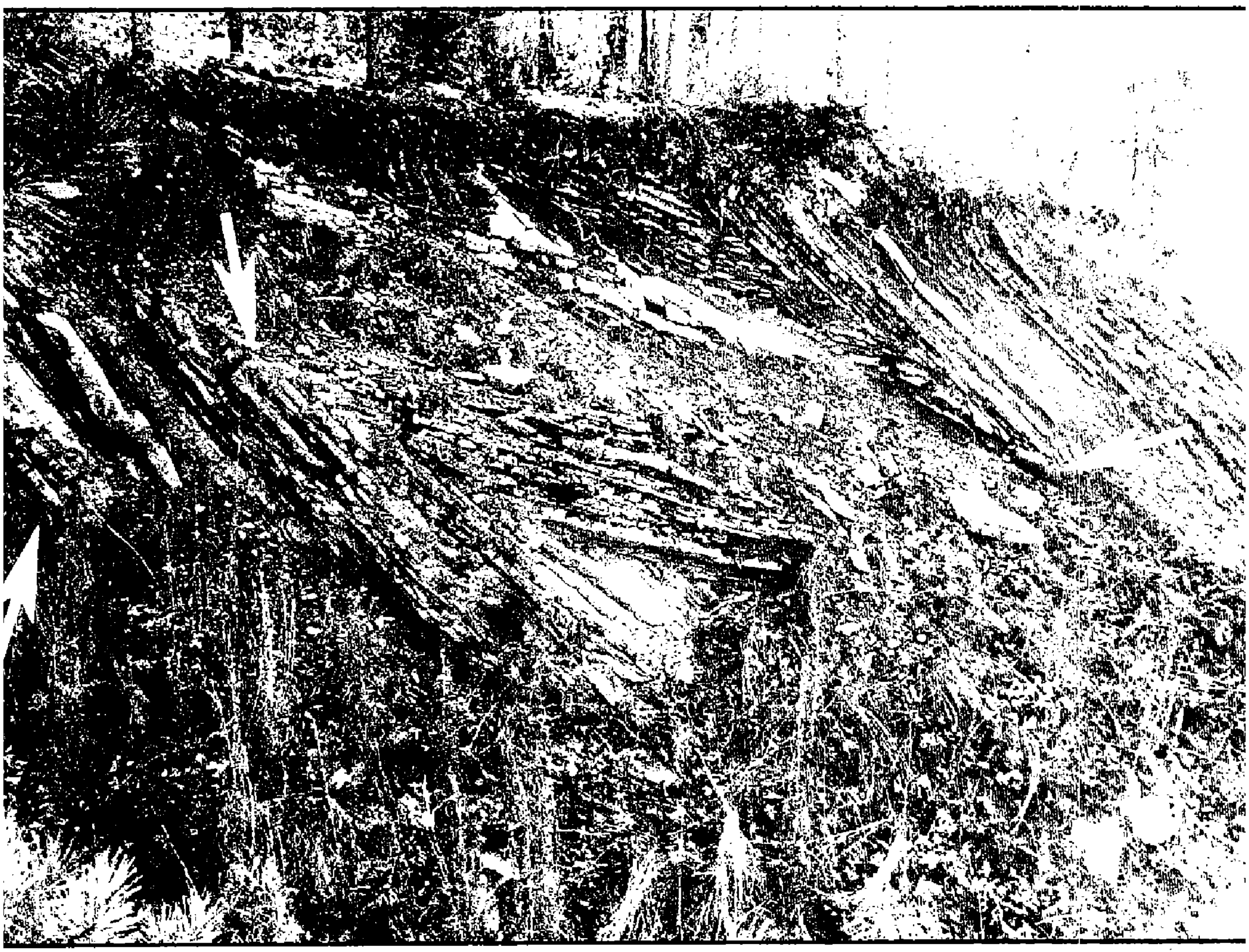
OKLAHOMA GEOLOGY



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On The Cover —

Chevron Folds in the Arkansas Novaculite, Western Potato Hills, Ouachita Mountains

The arrows on the cover photograph point to three tight, gently inclined, moderately plunging chevron folds in the Arkansas Novaculite, exposed in a road cut in the western Potato Hills (N½ NE¼ sec. 4, T. 2 N., R. 19 E.). View is to the south. The three folds are southeast-verging, as shown by an axial plane dip of 66° NW, and have an average fold-axis orientation of 30°/228°. These observations all indicate southeast-directed compression. The chevron folds are located in the hanging wall of a diverging splay from a minor back thrust, both of which strike approximately north. Both the diverging splay and the minor back thrust were intersected and offset by the South Potato Hills thrust (Allen, 1992, fig. 3). These folds developed by a combination of volumetric crowding and hanging wall rotation during the development of the minor back thrust and diverging splay.

Reference Cited

Allen, M. W., 1992, Structural analysis of the western Potato Hills, Ouachita Mountains, Oklahoma: Oklahoma Geology Notes, v. 52, p. 173–183.

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OKLAHOMA GEOLOGY

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First Notice on Mesozoic Mammals from Oklahoma

Richard L. Cifelli[1]

Abstract

Herein I report on the first Mesozoic mammals from Oklahoma, based on specimens from the Antlers Formation (Early Cretaceous: Aptian-Albian) of Atoka County; these new materials extend the known range of the Class Mammalia in the State by nearly 100 million years. Two taxa are represented. A multituberculate described as new, ?*Paracimexomys crossi*, represents the first described species of this group from below the Albian-Cenomanian boundary in the Cretaceous System of North America. The species is referable to the Cimolodonta and thus marks the first appearance on the continent of this group of morphologically advanced multituberculates, so diverse and widespread in the Late Cretaceous. The other, unnamed taxon represents a tribosphenic mammal insufficiently specialized to warrant referral to either Eutheria (which are well represented by the Early Cretaceous in penecontemporaneous rocks of Asia) or Metatheria (which make their first unambiguous appearance in the Cenomanian of North America). In several features, this mammal appears to be more advanced than described taxa from laterally equivalent rocks (Trinity Group) in Texas; it may represent a new species. Regardless, it adds to known morphological diversity among early tribosphenic mammals.

Introduction

Terrestrial rock units of all three Mesozoic systems are present, albeit not broadly exposed, in the State of Oklahoma: the Triassic Dockum Group and the Jurassic Morrison Formation in the Oklahoma Panhandle; the Cretaceous Antlers Formation in southeastern Oklahoma. Fossil vertebrates are known from each of these units, but only one labyrinthodont amphibian (Mulvany and Mulvany, 1989) and a variety of reptiles, predominantly dinosaurs (e.g., Stovall, 1938; Langston, 1974), have been discovered thus far. Mammals, of particular interest because of their conspicuous prevalence in the recent fauna, originated in the Triassic (Lucas and Luo, 1993); thus, two-thirds of the group's history occurred during the Mesozoic (e.g., Lillegraven and others, 1979). Yet Mesozoic mammals are poorly known, and the dynamics of their early radiations—critical to understanding the biogeography and relationships of living forms—remain to be adequately documented. Herein I report on mammals from the Early Cretaceous Antlers Formation, southeastern Oklahoma. The oldest previously known record of mammals from Oklahoma comes from the Laverne Formation of the Ogallala Group (Dalquest and others, 1996) and is of Clarendonian (late Miocene) age, or about 10 million years old (Tedford and others, 1987). The occurrence reported herein represents a colossal extension in range—about 100 million years—for the Class Mammalia in the State.

Early Cretaceous terrestrial vertebrates are, in general, poorly known, due to a scarcity of rock units of this age. This is especially true for mammals, which were

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generally small (thus, difficult to find as fossils) and rare constituents of a fauna dominated by large reptiles. Hence, there is a major hiatus (covering much of the interval from about 140 to 100 million years ago) between the relatively well known faunas of the Late Jurassic and Late Cretaceous (see, e.g., Clemens and others, 1979). One exception is the fauna from the Trinity Group, Texas, which includes eight described species of mammals: a triconodont (Patterson, 1951; Slaughter, 1969), a symmetrodont (Patterson, 1955, 1956), and six types of tribosphenic, or higher, mammals (Slaughter, 1971; Butler, 1978; Jacobs and others, 1989). The Trinity Group also has yielded a diverse assemblage of lower vertebrates, including fish, amphibians, and reptiles (Thurmond, 1974; Langston, 1974; Winkler and others, 1990). Most of the mammals are represented by isolated (sometimes broken) teeth, but they are of great significance: among other things, they document the presence of archaic lineages thought to have been long extinct; they include some of the earliest tribosphenic therians; and they form the basis for our current interpretation of the evolution of the mammalian molar (Patterson, 1956; Crompton, 1971; Fox, 1972, 1975; Bown and Kraus, 1979).

The Antlers Formation of Oklahoma is the lateral equivalent of the Trinity Group of central Texas (Winkler and others, 1990). Until recently, the vertebrate fauna of the Antlers Formation (summarized by Langston, 1974), included only two described taxa, both dinosaurs: an indeterminate sauropod (Larkin, 1910) and the large theropod *Acrocanthosaurus atokensis* (Stovall and Langston, 1950). Langston (1974) also noted the presence in the unit of the ornithopod *Tenontosaurus*, described from the Cloverly Formation of Wyoming and Montana (Ostrom, 1970). To this list may be added *Deinonychus antirrhopus*, a maniraptoran theropod also known from the Cloverly (Ostrom, 1969). As in the Cloverly, *Deinonychus antirrhopus* is found in association with its presumed prey, *Tenontosaurus*, in the Antlers of Oklahoma (Brinkman and others, in preparation). The age of the mammal-bearing Trinity Group of Texas, including the Twin Mountains, Glen Rose, and Paluxy Formations, is constrained through correlation of marine invertebrates. It has been determined, on the basis of interpolation, to be between 111 and 105 million years old, and is thus Aptian-Albian in age (Jacobs and others, 1991). The fossils described herein are from a locality interpreted to be in the middle part of the Antlers Formation (Brinkman and others, in preparation). It is possible that the mammalian fossils from the Antlers in Oklahoma are more or less equivalent in age to the middle part of the Trinity, but this cannot be determined without additional data. The Antlers site is notable in that it includes numerous well-preserved, and in many cases, articulated specimens of *Tenontosaurus*, together with associated remains of *Deinonychus* (Brinkman and others, in preparation). The specimens described herein were obtained from a small rock sample through underwater screenwashing and associated recovery techniques (Cifelli and others, 1996). The sample was from a presumed overbank deposit included in a mudstone ~1.5 m stratigraphically below the *Tenontosaurus* horizon.

Abbreviations for institutions cited in the text are:

- OMNH, Oklahoma Museum of Natural History (Norman, Oklahoma);
- SMU, Shuler Museum of Paleontology, Southern Methodist University (Dallas, Texas).

Measurements of the specimens, in millimeters, were taken with a Reflex microscope (MacLarnon, 1989), and follow these established conventions:

- AP, anteroposterior length, as defined for tribosphenic therians by Lillegraven and Bieber (1986) and for multituberculates by Eaton (1995);
- ANW, anterior width (Lillegraven and Bieber, 1986);
- H, crown height (Eaton, 1995);
- H:L, height divided by anteroposterior length (Eaton, 1995).

Dental terminology follows that of Eaton (1995) for multituberculates, and that of Bown and Kraus (1979) for tribosphenic mammals.

Systematics

Order Multituberculata
Suborder Cimolodonta
Family Uncertain
?*Paracimexomys crossi*, new species

Holotype

OMNH 33454, left p4.

Hypodigm

The type only.

Etymology

For Bobby Cross, in recognition of his contributions to knowledge of the vertebrate fauna of the Antlers Formation and his help to OMNH collecting parties.

Locality

OMNH locality V706, approximately 23 km WSW of Antlers, Atoka County, Oklahoma (Fig. 1); middle Antlers Formation (Early Cretaceous: Aptian-Albian).

Diagnosis

Smallest species currently referred to *Paracimexomys*; differs from other species of the genus, and all other post-plagiaulacoid multituberculates, in having a relatively tall p4 with only 7 serrations. Differs from species of *Cimexomys* in which p4 is known by having distinct internal ridges corresponding to the last 2 serrations, by the weak, non-cuspate nature of those serrations, and by a deeper, more anteroposteriorly constricted anteroexternal lobe on p4.

Description

The type and only specimen of ?*Paracimexomys crossi* is a left p4 (AP = 2.95, W = 1.32, H = 2.09), moderately worn and lacking the posterior root (Fig. 2). In labial view (Fig. 2A), the tooth presents a relatively tall (H:L = 0.709), symmetrical, arcuate profile. The anteroexternal lobe is pendulous and anteroposteriorly constricted. Traces of three external ridges can be discerned, but the original number present cannot be determined owing to wear. The posteroexternal cusp is a low, moundlike swelling and apparently lacks the cuplike depression commonly found in Late Cretaceous multituberculates. On the anterior margin of the tooth at the base of the crown (Fig. 2B), there is a distinct, inverted V-shaped concavity, which presumably accommodated a small, peg-like preceding tooth (p3); this concavity is strongly overhung

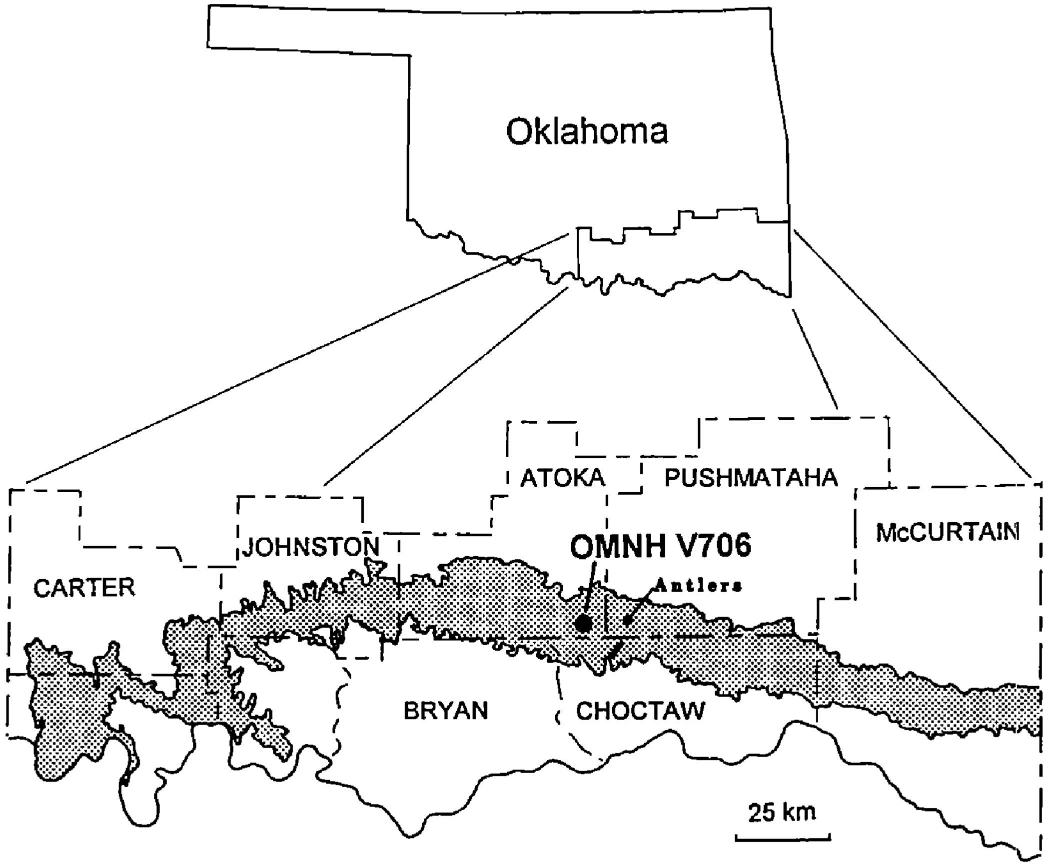

Figure 1. Map showing the distribution of the Antlers Formation (stippled area) in southern Oklahoma and the position of OMNH locality V706 (modified after Hart and Davis, 1981, fig. 7).

by the crown, and it grades downward into a broad, shallow groove on the anterior root.

On the lingual side of the tooth (Fig. 2C), there are 7 internal ridges, the posteriormost of which is very faint and does not extend fully to the dorsal crest. A low anterior serration, lacking a corresponding ridge, is distinct and is pointed dorsally. There are also 4 posterior serrations (which mark the dorsal termination of internal ridges 3–6). If one assumes that there were serrations at the anterior 2 ridges but that they have been obscured by wear, the maximum number of serrations originally present would have been 7. The apex of the tooth is at serration 4.

Comparisons and Discussion

Multituberculates are reported to be the most common mammals collected from the Trinity Group of Texas (Patterson, 1956), yet, despite announced plans for study and publication (e.g., Slaughter, 1982), they have been neither described nor illustrated. Patterson (1956) indicated the presence of at least two taxa, which he referred to the Plagiaulacidae, an archaic and primitive group known mainly from older rocks (see, e.g., Clemens and Kielan-Jaworowska, 1979). Winkler and others (1990) simply referred to the presence of an unspecified number of unidentified multituberculates from the Trinity; Krause and others (1990) mentioned the presence of at least two species, which they tentatively referred to the basal cimolo-

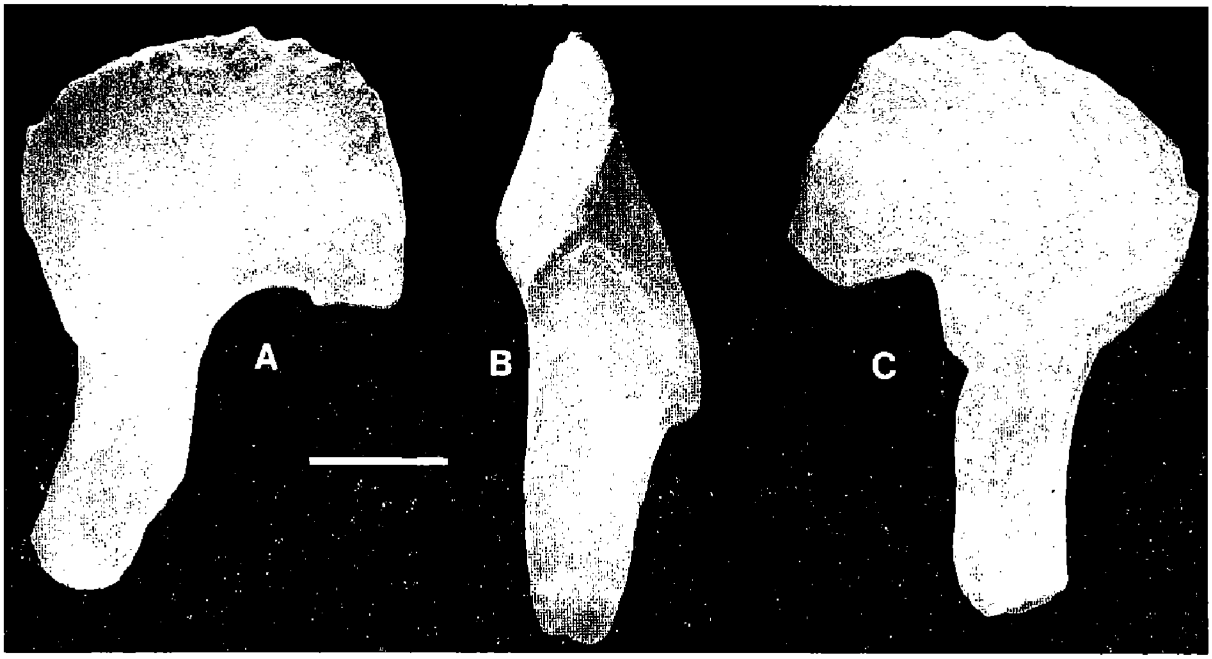

Figure 2. OMNH 33454, left p4, holotype of ?*Paracimexomys crossi*, new species, in labial (A), anterior (B), and lingual (C) views; scale bar represents 1 mm.

dontan *Paracimexomys* (see Archibald, 1982, and below), as is done for the specimen described herein. From elsewhere in North America, five taxa have been described from the upper part of the Cedar Mountain Formation, Utah (Eaton and Nelson, 1991), originally thought to be of Albian age (e.g., Tschudy and others, 1984), but now considered to lie at about the Albian-Cenomanian boundary (Kirkland and Parrish, 1995; R. L. Cifelli, unpublished data). Of these species, four were referred to *Paracimexomys* and one was described as an unidentified ptilodontoid (= Cimolodonta as used here; see definitions by Simmons, 1993). A much larger, better represented assemblage of multituberculates has been described from the slightly younger (upper Cenomanian) Dakota Formation and the Smoky Hollow Member of the Straight Cliffs Formation (Turonian) of Utah (Eaton, 1995). Hence the specimen reported herein is the first multituberculate to be described from beds of unambiguous Early Cretaceous age in North America.

Regardless of whether plagiaulacoid multituberculates are present in the Trinity Group of Texas (and, by implication, in the Antlers Formation of Oklahoma), OMNH 33454 clearly represents a more advanced taxon, referable to the Cimolodonta (see summaries by Clemens and Kielan-Jaworowska, 1979; Archibald, 1982; Simmons, 1993). This tooth has an arcuate anterior face and a deep, pendulous anteroexternal lobe, unlike the condition generally seen in plagiaulacoids[2]. The distinct, anterobasal concavity indicates that the preceding tooth, p3, had been reduced to a small peg, as in cimolodontans, in which premolars anterior to p3 have

[2]The Early Cretaceous *Arginbataar* is enigmatic in this and many other respects. Tentatively described as a plagiaulacoid (Kielan-Jaworowska and others, 1987) and considered by Simmons (1993) to represent the sister-group of Cimolodonta, this taxon has a large, arcuate p4 (with the surprisingly high number of 15–18 serrations) that displaces the anterior premolars as it erupts.

been lost (see discussion by Kielan-Jaworowska and Nessov, 1992). Nonetheless, the serration count (maximum of 7) is lower than that of any other described cimolodontan. (Archibald [1982] cites a range of 6–8 for plagiaulacoids and 8–10 for primitive ptilodontoids; Simmons [1993] lists 5–7 for plagiaulacoids and 8–10 for primitive cimolodontans.) Moreover, the anterior face of the tooth, though gently curved, is not broadly arcuate as is typical of cimolodontans, and the posterior face slopes downward to the posterior root, which lies at the very back of the tooth as is typical of plagiaulacoids; in most cimolodontans, the crown generally overhangs the posterior root to some extent.

Among Cretaceous multituberculates, OMNH 33454 is strongly dissimilar to *Cimolomys, Cimolodon, Mesodma,* and several other taxa typically found in the Late Cretaceous of North America. *Cimexomys,* known from the Aquilan (early Campanian) through Lancian (Maastrichtian) land-mammal ages (see Lillegraven and McKenna, 1986), differs from the Oklahoma specimen in having a somewhat lower-crowned p4 with an anteroposteriorly broader anteroexternal lobe and a greater number of serrations (8–9 in the type, *C. minor*; 9–10 in *C. hausoi*) (Sloan and Van Valen, 1965; Archibald, 1982). Furthermore, in species of *Cimexomys,* the last 2 or 3 serrations are developed as distinct cusps with internal or external ridges (Archibald, 1982), characters lacking in OMNH 33454. The fourth lower premolar of *Dakotamys,* from the Dakota Formation of Utah (Eaton, 1995), differs from OMNH 33454 in being lower crowned, in having a more arcuate anterior profile; a more distinct, cusplike last serration; a greater number of serrations (9–10) (the posteriormost of which is placed lower on the crown); a distinct lingual ridge on the last serration; and a shallower, less anteroposteriorly constricted anteroexternal lobe. *Bryceomys,* from the Smoky Hollow Member of the Straight Cliffs Formation, Utah, differs from OMNH 33454 in most of these same respects, particularly in having more serrations (9–11), the posterior ones being cusplike; in having a more broadly arcuate profile, with a more posteriorly inclined anterior margin; and in having a lower crown in general.

Comparison appears to be closest to *Paracimexomys,* originally described on the basis of three species (two referred to the genus with doubt) in addition to the type, *P. priscus,* from the Late Cretaceous (Archibald, 1982); two additional named species and two unnamed species from the upper Cedar Mountain Formation, Utah, have been referred to the genus (Eaton and Nelson, 1991), which has since been recorded from the Dakota and Straight Cliffs Formations as well (Eaton, 1995). OMNH 33454 resembles species of *Paracimexomys* for which p4 has been described (e.g., *P. bestia*; Eaton and Nelson, 1991, fig. 2) in having a lesser curvature of the anterior profile than in otherwise similar taxa, such as *Cimexomys*; non-cuspate posterior serrations, with internal ridges connected to them; and in the form of the anteroexternal lobe. However, OMNH 33454 is higher crowned than p4 of described species, has fewer serrations on that tooth (8–11 in species of *Paracimexomys*) (see Lillegraven, 1969; Fox, 1971; Eaton and Nelson, 1991), and has a more posteriorly placed posterior root. It is possible, if not likely, that the species represented by OMNH 33454 is sufficiently distinct to warrant erection of a new genus to contain it. However, in the absence of additional materials (including molars) to adequately circumscribe and diagnose the taxon, the more conservative approach of tentatively referring it to the generally similar *Paracimexomys* has been adopted. Within that genus, the species is unquestionably distinct from all other named species, so that it can be confidently regarded as new.

Tribosphenida McKenna, 1975
Family, Genus, and Species Undetermined

Referred specimen

OMNH 33455, left upper molar.

Locality

As for ?*Paracimexomys crossi*, given above.

Description

Judged by the relatively wide stylar shelf labial to the paracone and the elongate preparacrista, OMNH 33455 (Fig. 3) appears to be a penultimate tooth, M2or3, depending on whether 2 or 3 molars were present in the dentition (see Fox, 1975, for discussion). The posterolabial corner of the tooth and the metacone are missing; the tip of the protocone also is broken (Fig. 3A). Damage precludes some standard measurements; ANW is 1.96 mm; protocone width and length (as defined by Butler, 1990) are 0.64 and 0.79, respectively. Stylar cusps A and B (terminology follows Clemens, 1979) are prominent, the latter being nearly as tall as the paracone. A well-marked preprotocrista extends labially from the protocone to stylar cusp A; this crest is uninterrupted in the region of the paracone (Figs. 3A,B), much as in primitive marsupials and eutherians. By contrast, the postprotocrista extends only to the base of the metacone. Both conules are well developed and project slightly beyond the occlusal margin of the tooth. The paraconule is positioned about halfway between protocone and paracone and bears a small postparaconular crista that terminates at the base of the paracone; the metaconule is placed distinctly closer to the protocone and its internal crista is weak or lacking.

Comparisons and Discussion

In size and general morphological attributes, as well as in geographic and stratigraphic distribution, OMNH 33455 invites comparison with the Trinity therians described from Texas (Patterson, 1956; Slaughter, 1971; Turnbull, 1971; Butler, 1978). Such comparisons are hampered, however, by the fact that most described taxa are represented by isolated teeth, some of which are non-comparable (that is, they represent different molar loci or jaw), and by the fact that referral of additional specimens to these taxa has been problematic (see, e.g., Butler, 1978). Hence, reference is made to the type specimens of comparably represented taxa, unless otherwise noted.

Six taxa of tribosphenic therians have been described from beds in Texas equivalent to the Antlers Formation of Oklahoma. *Comanchea hilli*, known from a single upper molar (Jacobs and others, 1989), appears to be aberrantly specialized in having a reduced anterior stylar shelf and a stylar cusp of uncertain homology; in the former respect, it is similar to an apparently archaic group of primitive tribosphenic mammals (Cifelli, 1993a) represented by *Picopsis*, from the early Campanian of Alberta (Fox, 1980) and older deposits in Utah (Cifelli, 1993a). *Kermackia texana*, based on a type and two referred lower molars (Slaughter, 1971; Butler, 1978), cannot be compared directly with OMNH 33455. *Kermackia texana* is generally considered to be relatively primitive among tribosphenic mammals: its lower molars have a rudimentary entoconid, narrow talonid, and, especially, a cristid obliqua that attaches at the tip of the metaconid (the distal metacristid of primitive

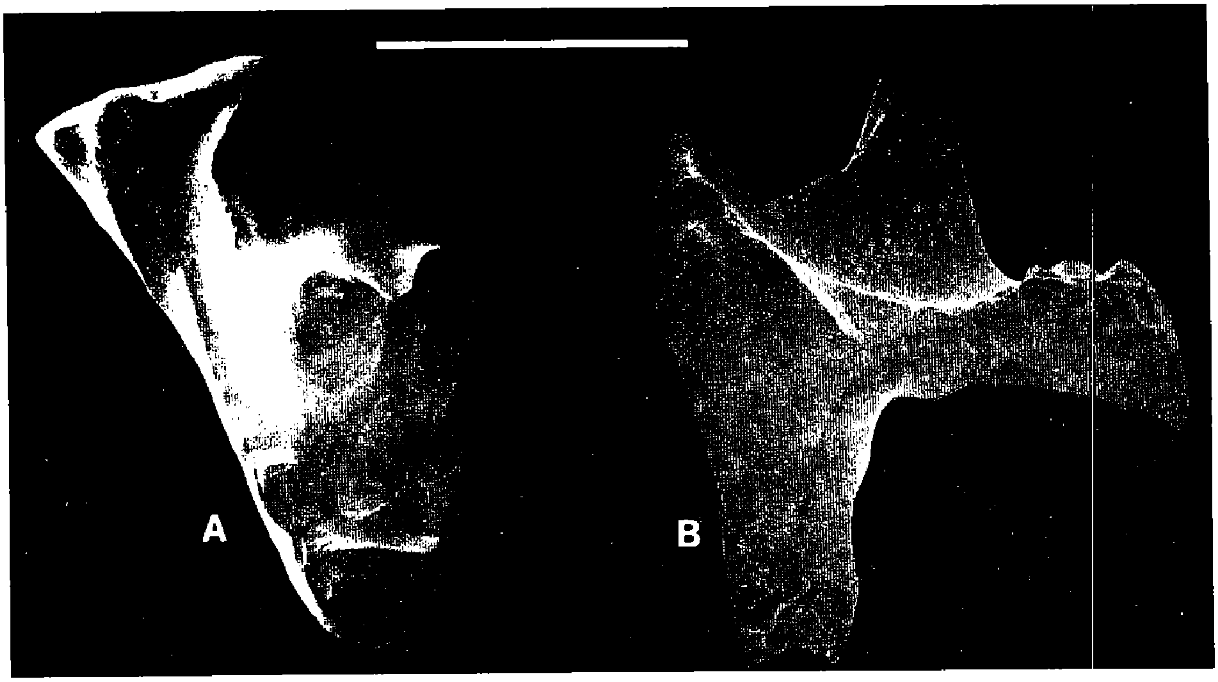

Figure 3. OMNH 33455, left M2or3, Tribosphenida, family, genus, and species undetermined, in occlusal (A) and anterior (B) views; scale bar represents 1 mm.

mammals [Fox, 1975]) indicate that full double rank or en echelon (Hiiemae and Kay, 1973) prevallum/postvallid shear had not been achieved in this taxon (Fox, 1975). The same comments apply to *Trinititherium slaughteri*, represented by a single lower molar in a jaw fragment. This taxon was grouped with *Kermackia texana* in the Kermackiidae by Butler (1978), who distinguished it on the basis of several features, including a shorter metaconid. I regard the taxa as probably synonymous, as suggested by Clemens (in Butler, 1978, p. 11); regardless, the generally primitive structure of both appears to be incompatible with occlusal relationships suggested by OMNH 33455, which indicates that the latter represents a distinctly different species. *Slaughteria eruptens* is based on a mandible (SMU 61992) including two premolariform and two molariform teeth, and is of special interest in that the type specimen presents the only evidence for tooth replacement pattern among any of the Trinity therians. This specimen was originally referred tentatively to *Pappotherium pattersoni* (see below) "on the basis of size and probable occlusal relationships" by Slaughter (1971, p. 136). He considered the mandible to include two simple anterior premolars, a molarized posteriormost premolar, and a first molar—a pattern seen in Eutheria, to which he referred the species. Butler (1978) noted that the penultimate tooth in SMU 61992 is unlikely to represent a molarized premolar because of the Early Cretaceous age of the specimen, and he considered the teeth to represent the last two premolars and the first two molars. He referred SMU 61992 to the then-new genus and species, *Slaughteria eruptens*, because of perceived differences between the molariform teeth and those which (in the same paper) he had referred to *Pappotherium pattersoni* on the basis of size. SMU 61992 is unusual in that the anterior premolariform tooth appears to be erupting, but this process is complete in the premolariform tooth succeeding it. Slaughter (1971) indicated that X-rays of the specimen did not show a replacement tooth under the anterior of the two molariform teeth. This negative evidence cannot be taken to prove that such is not the case, however; identification of different calcified tissues within the jaw depends on density differences which may or may not be apparent, owing to the nature and extent of diagenetic mineralization of the specimen in the fossilization process. Thus, a third possibility remains: that the anterior of the two molariform teeth is a decidious premolar, so that the specimen could include two premolars, the last deciduous premolar, and the first molar. Considering this, together with the general incompleteness of specimens from the Trinity Group and the small sample sizes represented in available collections (so that it is not possible to evaluate either intraspecific variability or variability which occurs as a result of tooth locus), it is presently unclear which lower molar type pertains to *Pappotherium pattersoni* and whether, in fact, *Slaughteria eruptens* is distinct from this species. The possible presence of a distal metacristid on the lower molar(s?) of SMU 61992 led Butler (1978) to tentatively group *Slaughteria* in the Kermackiidae rather than in the otherwise similar Pappotheriidae (including both *Pappotherium* and *Holoclemensia*; see below), despite the presence of a strong entoconid and a broad talonid. This situation is also open to debate because the presence of the distal metacristid in *Slaughteria* is unclear (see Fox, 1980; Cifelli, 1993a).

Among Trinity therians, the taxa most comparable to the species represented by OMNH 33455 are *Pappotherium pattersoni* and *Holoclemensia texana*, both of which are represented by parts of the upper dentition. *Pappotherium* is based on a maxillary fragment including the last two upper molars; referral of a lower jaw (SMU 61992, mentioned above) showing diphyodonty at an anterior premolar locus led Slaughter (1971) to refer this taxon to the Eutheria. Because of a continuing lack of knowledge of premolar structure, tooth formula, and replacement pattern in *Pappotherium*, most subsequent workers have adopted a more conservative approach and consider the taxon to be simply a therian of metatherian-eutherian grade (e.g., Turnbull, 1971; Butler, 1978, 1990, 1992; Kielan-Jaworowska and others, 1979; Kielan-Jaworowska 1982; Cifelli, 1993a). Uncontested eutherians do not appear in North America until the early Campanian (Fox 1984; Cifelli, 1990a); however, the molarized premolars described from the Trinity Group (Slaughter, 1971; Butler, 1978) strongly suggest that eutherians were present on the continent much earlier—whether or not these premolars belonged to *Pappotherium*.

Placement of *Holoclemensia texana*, based on an incomplete penultimate upper molar and referred last upper molar, has been similarly controversial. The species was initially referred to the Marsupialia (Slaughter, 1968) based on the presence of a large stylar cusp C, relative size of paracone to metacone, and some features of referred lower molars (see also Slaughter, 1971). Later work has shown that the configuration of the stylar shelf in *Holoclemensia* probably is not primitive for marsupials (Fox, 1987; Cifelli, 1990b, 1993a), and most workers consider this genus as a therian of metatherian-eutherian grade (see Turnbull, 1971; Kielan-Jaworowska and others, 1979; Cifelli, 1990c, 1993a); it is sometimes grouped with *Pappotherium*, to which it is structurally similar, in the Pappotheriidae (e.g., Butler, 1978; Kielan-Jaworowska, 1982). The oldest uncontested marsupial is from the Cenomanian of Utah (Cifelli and Eaton, 1987); a somewhat older taxon, also from Utah, is in known respects at least structurally antecedent to marsupials (Cifelli, 1993b).

OMNH 33455 differs from *Pappotherium pattersoni* in that the latter has a more anteroposteriorly compressed, transversely expanded protocone; ratio of protocone width to anterior molar width (as defined by Butler, 1990, fig. 2) is 0.33, whereas it is 0.40 in *Pappotherium.* In addition, the protocone of *Pappotherium* appears to be more trenchant, although this may be owing in part to the fact that the protocone of OMNH 33455 is slightly damaged. More significantly, the development of conules differs substantially between the two: in *Pappotherium* they are faint and positioned close to the protocone (Fox, 1975), whereas in OMNH 33455 both conules are well developed and project from the occlusal margins of the tooth; the paraconule, at least, bears a distinct internal crista and is located farther from the protocone. In these respects, the Oklahoma specimen compares more favorably with marsupials, eutherians, and relatively advanced tribosphenic mammals (see Fox, 1975; Clemens and Lillegraven, 1986; Cifelli, 1993a) than does *Pappotherium,* which is apparently primitive. OMNH 33455 appears to differ further from *Pappotherium* in having a preprotocrista that extends completely to the parastylar region of the tooth, where it meets stylar cusp A, although the condition of the preprotocrista in *Pappotherium* has been the subject of debate. This crest has previously been reported to be complete in *Pappotherium* (Fox, 1975; Cifelli, 1993a), although it has a variable appearance in published illustrations[3]. On a cast of the holotype of *P. pattersoni* (SMU 61725), the crest appears to terminate near the base of the paracone in the penultimate molar (which probably represents the same locus as OMNH 33455), as it does in the last molar on that same specimen. Further cleaning and re-examination of the original specimen substantiates this conclusion (L. L. Jacobs, personal communication, 1996).

Holoclemensia texana appears to be larger than the taxon represented by OMNH 33455, although non-comparable representation precludes evaluation of standard measurements. On the type of that species (SMU 61997), which lacks the protoconal region but which probably represents the same tooth locus as OMNH 33455, the parastylar region and cusp A project much more labially than on the Oklahoma specimen. Additionally, the preparacrista is weaker and stylar cusp B less robust in *H. texana.* The paratype of the species, a last upper molar (SMU 62009), shows further differences from the taxon represented by OMNH 33455: as in *Pappotherium,* the preprotocrista does not extend labially past the paracone; it does in the Oklahoma specimen. Similarly, the conules are weakly developed in SMU 62009, as they are in *Pappotherium.* This contrasts with the condition in OMNH 33455, in which they are distinct, are placed farther from the protocone, and bear incipient cristae.

Of other taxa comparable in age and general morphology, only *Prokennalestes,* from the Aptian-Albian of Mongolia, has been comprehensively described and illustrated (Kielan-Jaworowska and Dashzeveg, 1989). The oldest uncontested eutherian, *Prokennalestes* is represented by two named species and is known from relatively complete dentitions and jaws. In known respects, OMNH 33455 is similar to upper molars referred to *Prokennalestes;* however, the conules appear to be slightly better developed in the Oklahoma specimen. On the other hand, and perhaps more significantly, upper molars of *Prokennalestes* have a postprotocrista that

[3]For example, the preprotocrista is shown to be present and complete in the region of the paracone in a drawing in Slaughter (1971, pl. 7B), but stereophotographs of the same specimen in the same paper (pl. 8E) do not bear this out: what appears to be the preprotocrista anterior to the paracone seems to be something underlying the specimen, perhaps modeling clay used to position it. The crest is shown to be incomplete in Crompton (1971, fig. 3E), but complete in Fox (1975, fig. 1).

extends labially around the base of the metacone (cf. Kielan-Jaworowska and Dashzeveg, 1989, figs. 5, 6, 8, 12), which indicates that double-rank postvallum/ prevallid shear had been attained in this taxon (Fox, 1975), as it apparently is in all metatherians and eutherians (Cifelli, 1993a).

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NEW OGS *Publications*

SPECIAL PUBLICATION 96-4. ***Techniques for Recovery and Preparation of Microvertebrate Fossils***, edited by Richard L. Cifelli. 36 pages. Price: $2.

From the editor's preface:

Most living terrestrial vertebrates are small animals. As fossils, they are important not only in constituting a major fraction of the biota but also in providing important data for biochronologic control and paleoenvironmental reconstruction. In recent years, design changes and development of new materials and approaches have permitted increased efficiency and effectiveness of microvertebrate recovery operations, provided alternatives to some of the hazardous materials commonly used, and facilitated preparation, conservation, and display of microvertebrate specimens. In addition, mechanical preparation of microscopic fossil vertebrates has become both increasingly sophisticated and more widespread, as research interests have turned to diminutive elements of paleofaunas.

The two papers contained in this volume are designed to supplement existing accounts, with particular reference to concentration and preparation techniques. The first paper ["Screenwashing and Associated Techniques for the Recovery of Microvertebrate Fossils," by Richard L. Cifelli, Scott K. Madsen, and Elizabeth M. Larsen] reviews microvertebrate recovery techniques using underwater screenwashing and associated concentration methods, emphasizing variation according to lithology and local conditions. The second paper ["Some Techniques and Procedures for Microvertebrate Preparation," by Scott K. Madsen] describes methods for manual preparation, repair, and storage of microvertebrate specimens. The main purpose of both papers is to present the various methods now available, their logistical and material requirements, and the conditions under which they are applicable.

SPECIAL PUBLICATION 96-5. ***Rockhounding and Earth-Science Activities in Oklahoma, 1995 Workshop***, edited by Kenneth S. Johnson and Neil H. Suneson. 139 pages, 17 contributions. Price: $6.

Aimed at hobbyists, scout and school groups, and others who enjoy collecting rocks, fossils, and minerals, this publication yields a wealth of information on how to collect, prepare, study, and display these items. The book contains the proceedings of a two-day workshop held in October 1995 in Oklahoma City. Cosponsored by the Oklahoma Geological Survey, gem and mineral clubs of Oklahoma, and the Omniplex Science Museum, the workshop focused on the rocks, minerals, and fossils of Oklahoma, and on earth-science activities in Oklahoma schools.

Besides featuring subjects of concern to Oklahoma collectors, the publication contains general information of use to hobbyists everywhere. Topics covered include:

- Collecting, preparing, and displaying minerals and fossils
- Geology, minerals, and fossils of Oklahoma
- Ethics in collecting minerals and fossils
- Rockhounds' rights vs. government regulations

- Experiments in geologic processes for earth science teachers
- Stimulating students' and teachers' interests in geology and rockhounding
- Topographic map-reading
- Keeping a field notebook

The book also lists rockhound organizations in Oklahoma and resources available to rockhounds from universities, museums, state and federal agencies, and private concerns in Oklahoma.

SPECIAL PUBLICATION 97-1. ***Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma: The Red Fork Play***, by Richard D. Andrews and others. 90 pages, 6 plates. Price: $6.

The fifth in a series of publications addressing fluvial-dominated deltaic (FDD) light-oil reservoirs in Oklahoma, this volume presents the material covered in the workshops on the Red Fork play held in March 1997.

In Part I of this publication, Richard D. Andrews and others explain the scope of the FDD project and describe the significant features of FDD reservoirs. Depositional environments are related to reservoir properties in order to provide a better understanding of the individual FDD reservoirs identified in the project.

In Part II, Andrews presents an overview of Red Fork FDD areas in Oklahoma. Red Fork sandstone was deposited throughout much of the State, and is one of the main producers of oil and gas in Oklahoma. Part II also contains studies of three reservoirs: the N. Carmen field in Alfalfa County, the Otoe City South field in Noble County, and the Long Branch field in Payne County. The Otoe City South field study was written by Kurt Rottman, consulting geologist.

The volume also includes a list of selected references, glossary of terms, and core descriptions, well logs, and digital images of select rock intervals for three wells. The plates feature: maps of the Red Fork sandstone play areas; maps of oil and gas wells and fields with production from the Red Fork sandstone; regional stratigraphic cross sections of the Cherokee platform and shelf areas of the Anadarko and Arkoma basins; and an index to selected references used for Red Fork sandstone mapping.

Author Richard D. Andrews is an exploration and development geologist with the University of Oklahoma's Geo Information Systems (GeoSystems) unit. Jock A. Campbell, OGS geologist, and Robert A. Northcutt, consulting geologist, Oklahoma City, are the other two lead geologists on the FDD project team. R. M. Knapp is the petroleum engineer for the FDD project and a professor in the OU School of Petroleum and Geological Engineering.

The next publication in the FDD Oil Reservoir series, to be produced for a workshop in June 1997, will be on the Tonkawa play.

OGS SP 96-4, SP 96-5, and SP 97-1 can be purchased by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; fax 405-325-7069. To mail order, add 20% to the cost for postage, with a minimum of $1 per order.

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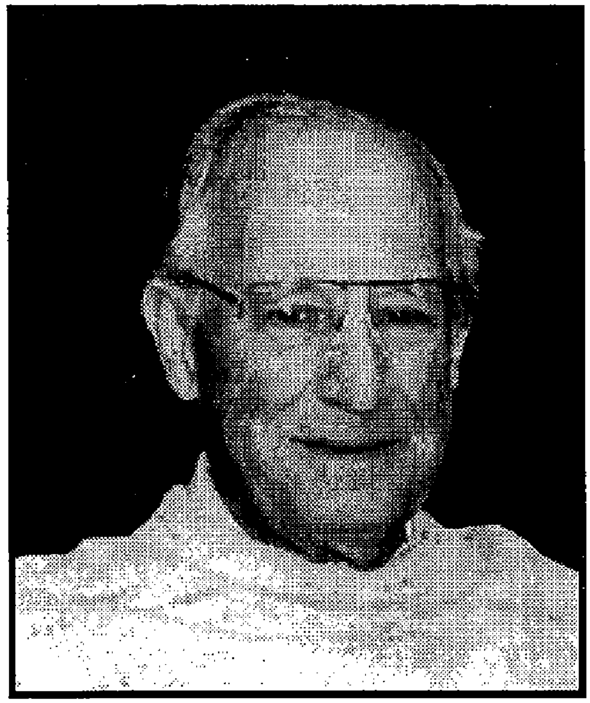


Robert Arndt
(1918–1996)

In Memoriam

Robert H. Arndt

Retired OGS Geologist

Robert H. Arndt, a member of the Oklahoma Geological Survey staff from 1980 to 1990, died at home November 7, 1996, following an extended illness. Bob is survived by his wife, Marjorie, daughter Geri Calderon and her husband Joe of Redlands, California, two grandchildren, and two great-grandchildren.

When Bob joined the OGS staff in 1980, he also served as director of the Oklahoma Mining and Mineral Resources Research Institute, which provided research grants to graduate students and faculty to improve information and technology for the State's minerals industries. His work for the Survey centered on industrial minerals, where he contributed much to the State's understanding of this important resource. He compiled the first directory of mineral producers in Oklahoma and contributed annually to the U.S. Bureau of Mines report on mineral production in the State. Although Bob officially retired from the OGS in 1990, he continued to work part time until 1994.

Bob was born May 19, 1918, in Milwaukee, Wisconsin. His interest in the Earth and science led him to major in geology at Lawrence College in Appleton, Wisconsin, where he received a B.A. in 1940. In 1942, he received an A.M. in geology from Harvard, then was employed by Shell Oil Company as a petroleum geologist in Centralia, Illinois, where he worked the Illinois basin from 1942 to 1945. On July 7, 1943, he married Marjorie

Herrmann, whom he had met at Lawrence College.

In 1945, Bob enrolled in the Ph.D. program at Harvard, then in 1946 received a teaching fellowship in geology at Hamilton College in Clinton, New York, where he taught until 1948. He then returned to Harvard for one year to complete his course work, and began work on his dissertation while doing field work in the White Mountains of New Hampshire.

In 1949, he began teaching geology at the University of Arkansas, and continued there until 1954. While there, he taught a wide range of undergraduate and graduate courses, including mineralogy, petrology, optical mineralogy, and structural geology. In 1955, he joined the faculty of the University of Tulsa, where he served until 1962. During this time, he also worked part time with Carter Oil Company at the Jersey Production Research Facility in Tulsa.

Bob's particular interest in industrial minerals dates back to 1962–63, when he worked for Alpha Mineral Company in Houston, before joining the U.S. Bureau of Mines in Bartlesville as an industrial minerals specialist in 1963. During his tenure with the Bureau, he also served as a liaison officer for Oklahoma and eventually the five-state region of Kansas, Oklahoma, Missouri, Nebraska, and New Mexico. He moved from Bartlesville to Oklahoma City in 1970, when he became the liaison officer for Oklahoma, then in 1979 moved to Colorado to assume the responsibility for the five-state region.

Outside of his work, Bob had many interests, including remote-controlled model airplanes, woodworking, rug-making, and music. His father was a classical pianist, and Bob grew up in a home filled with music. His younger sister, Ellen, studied piano and violin, and became a professional clarinetist with the Milwaukee Symphony and the Albuquerque Philharmonic Orchestra, from which she now is retired. Bob played both the tuba and guitar, and was drum major of his high school band. He sang with the Select Chapel Choir while at Harvard, was in the glee club at Lawrence College, and sang in productions of *Carmen* and the *Marriage of Figaro* at the University of Arkansas. A favorite pastime was listening to symphonic music and attending performances of the Oklahoma City Philharmonic.

Shortly before his retirement, Bob began work on a large, round hooked rug bearing the seal of the Oklahoma Geological Survey. He greatly enlarged the seal, transferred it to canvas, and selected and cut the yarn for the project. He donated the rug to the office to cheer up those of us who work on the lower floor, deprived of sunlight and an outside view, and to let visitors enjoy the piece as well. This beautiful, vibrant artwork now also serves to remind us of the man who also demonstrated these qualities throughout his life, and was both a colleague and dear friend to all of us.

—*Connie Smith*

AAPG Annual Convention
Dallas, Texas ★ April 6–9, 1997

The theme for the 1997 convention is "Future Legends." Our industry was created by legendary oil finders, legendary discoveries, and legendary technology. As we approach the 21st century, and in keeping with the theme, we will focus not only on past legends and the lessons they hold for our future, but also the new exploratory, developmental and technological concepts that have the potential to become our "Legends of the Future."

Technical program emphasis will be on modern structural geology, syn-sedimentary tectonics, emerging worldwide exploration/development plays, and emerging exploration/development technology and concepts applied to the finding and developing of oil and gas reserves in a professional and environmentally protective manner. To complement the technical program, a wide array of short courses and field trips has been scheduled. Additional highlights of the technical program will be the debates and special lecture sessions. These will include a panel of great explorationists discussing legendary and successful exploration methods and concepts and technology required for future successes, debates on such timely topics as deep-water sedimentation and 3-D coherency cubes, and NASA space scientists discussing the geology and life of the universe.

A new and innovative aspect of the 1997 convention will be the International Corporate Forum, which will be a direct communication link between the oil and gas ministries and international exploration companies.

The Dallas Geological Society, hosting this event for the 11th time during the past 81 years, and the Coordinating Committee cordially invite y'all to come to "Big D" for the AAPG Annual Convention, where you will discover future technology, enjoy unique entertainment, renew old acquaintances, and network and establish new contacts. Come join us and become a part of the Legend!

Tom Mairs
General Chairman

Mark Rainer
General Vice Chairman

Stop by the OGS booth (no. 681) in the exhibits hall at the convention to see the newest OGS publications!

1997 AAPG ANNUAL MEETING
APRIL 6-9, 1997 · DALLAS, TEXAS
FUTURE LEGENDS

Convention Agenda

Technical Program

Monday, April 7

Basin Modeling, Petroleum Generation, and Migration
Research Symposium: Application of Sequence Stratigraphy to Carbonate Reservoirs and Outcrops
Coupled Sedimentation and Tectonics
New Technology in the Exploration and the Exploitation of Fractured Reservoirs
Source Rocks: Controls, Predictive Models, and Identification
Selected Academic Research Topics
Stratigraphy and Reservoir Characterization of Incised Valley Fills
Emerging Plays/Development in Africa/Middle East
Geometry and Interpretation of Compressional and Strike-Slip Structures
Compartmentalization: Basin and Reservoir Scale
Climatic and Biologic Signals in Sequence Stratigraphy
Science vs. Junk Science, How Bad Geology Makes Bad Law; The Role of the Geologist
Predictive Diagenesis: Application and Case Histories

Tuesday, April 8

New Concepts in Deep-Water Reservoir Sand Development
Emerging Plays/Development in North America
Sequence Stratigraphy of Marine and Lacustrine Rift Basins
Petroleum Geochemistry as an Exploration Tool
The 21st Century Domestic Independent—Strategies and Techniques for Success
Coals into the 21st Century
Geometry and Interpretation of Extensional and Diapiric Structures
Emerging Plays/Development in Latin America
Geochemical Methods in Field/Reservoir Management
Redeveloping Old Fields
Transgressive Traps
Geometry and Interpretation of Reactivated Structures

Wednesday, April 9

High-Resolution Sequence Stratigraphy
Emerging Exploration Technologies
Carbonate Reservoirs and Carbonate Field Analogs of the CIS
GIS and Resource Exploration and Development
Environmental Considerations in Exploration and Production
Numerical and Physical Modeling

Diagenetic Minerals as Recorders of Basin History and Hydrocarbon Migration
Environment Characterization and Remediation of Oil Field Sites
Subsalt Exploration/Development
Surface Exploration Technologies
Carbonate Depositional Systems and Diagenetic Processes
Emerging Plays and Development in Asia
Organic/Inorganic Interaction in Sedimentary Basins
New Development in Formation Evaluation: Techniques and Technology
3-D Basin Simulation and Visualization
4-D Seismic Application to Field Development

Short Courses

The Internet Guide for the Petroleum Professional, *April 3, April 4, or April 5*
Advanced Surface Geochemical Methods and Interpretation Integrated with Geologic and Geophysical Case Histories, *April 4*
Applied Oil and Gas Property Evaluation, *April 4–5*
Sequence Stratigraphy and Characterization of Carbonate Reservoirs, *April 4–6*
3-D Seismic Time-Lapse Monitoring, *April 5*
International Exploration in the 21st Century: What Will Your Company Be Doing?, *April 5*
Geochemical Tools to Enhance the Exploration/Development of Petroleum, *April 5–6*
Geological Application of Borehole Imaging, *April 5*
Oilfield Environmental Litigation Technical Data Base Development and Presentation Using Geographic Information Systems, *April 5*
The Origins of Stratigraphic Sequences, *April 5–6*
Petroleum Geology of Venezuela, *April 5–6*
New High-Resolution Satellite Imagery Applied to Exploration and Development Programs: Computer Processing, Data Integration, and GIS Strategies, *April 5–6*
Allocyclic Controls on the Occurrence and Quality of Fossil Fuels, *April 5–6*
Petroleum Geology of Turbidite Systems, *April 5–6*
The Stratigraphic Organization of Incised-Valley Systems: Implications to Hydrocarbon Exploration and Production, *April 5–6*
The Interpretation Problem, *April 5–6*
Geostatistics in Petroleum Geology, *April 6*
GIS—An Introduction to the Technology, Its Application, and Its Future, *April 6*
There Are Many Ways to Make Money in the Oil and Gas Business, *April 6*
Experimental Modeling of Tectonic Processes, *April 6*
Applications of Produced Water Geochemistry to Reservoir Evaluation, *April 10*
Current Technology and Processes, *April 10–12*

Field Trips

Classic Mississippian to Permian Reefal Carbonates: Deposition, Diagenesis, and Reservoir Geology, *March 31–April 5*

Sedimentation and Diagenesis of Middle Cretaceous Platform Margins, East Central Mexico, *April 2–6*

Surface Geology of the Keechi and Palestine Salt Domes, Anderson County, Texas, *April 5*

Structure and Stratigraphy of the Arbuckle Mountains, Ardmore Basin, and Criner Hills, Southern Oklahoma (restricted to students and faculty advisors), *April 5*

Petroleum Systems, Ardmore Basin and Arbuckle Mountains, *April 5–6*

Dinosaur Tracks in the Cretaceous Glen Rose Formation of Central Texas, *April 6*

Sequence Stratigraphy and Cyclicity of Lower Austin/Upper Eagle Ford Outcrops (Turonian-Coniacian), Dallas County, Texas, *April 6*

Structure and Stratigraphy of the Arbuckle Mountains and the Slick Hills, Southern and Southwestern Oklahoma, *April 9–11*

Interwell-Scale Architecture, Heterogeneity, and Pore-Network Development in Paleocave Reservoirs, *April 9–11*

Sand Bodies in Muddy Environments, Geologic Framework and Sedimentary Processes of the Chenier Plain in Southwestern Louisiana, *April 9–11*

Structure and Stratigraphy of Trans-Pecos Texas, *April 9–13*

Sequence Stratigraphy and Sedimentation, Shelf to Basin Transition Brushy Canyon–San Andres Formations, Brokeoff and Guadalupe Mountains, New Mexico, *April 9–13*

Fluvial Point Bar Analysis: Surface Morphology Compared to Downhole Image Interpretation, *April 10*

Holocene Coastal and Inner Shelf Deposits of East Texas, *April 10–11*

Fine-Grained Submarine Fan Architecture and Turbidite Nomenclature, Jackfork Group, Arkansas, *April 10–12*

Structure, Stratigraphy and Paleontology of Late Cretaceous–Early Tertiary Parras–La Popa Foreland Basin near Monterrey, Northeast Mexico, *April 10–13*

For more information about the annual meeting, contact AAPG Convention Dept., P.O. Box 979, Tulsa, OK 74101-0979; phone (918) 560-2679, fax 918-560-2684; E-mail: dkeim@aapg.org.

Geographic Information Systems (GIS) Day at the Capitol, April 23, 1997, Oklahoma City, Oklahoma. Information: Bob Springer, Oklahoma Conservation Commission, 2800 N. Lincoln Blvd., Suite 160, Oklahoma City, OK 73105; (405) 521-4831, fax 405-521-6686.

Geological Society of America Penrose Conference, "Paleocene-Eocene Boundary Events in Time and Space," April 24–30, 1997, Albuquerque, New Mexico. Information: Spencer Lucas, New Mexico Museum of Natural History, 1801 Mountain Road N.W., Albuquerque, NM 87104; (505) 841-2873, fax 505-841-2866; e-mail: lucas@darwin.nmmnh-abq.mus.nm.us.

48th Highway Geology Symposium, May 8–10, 1997, Knoxville, Tennessee. Information: Harry Moore, Tennessee Dept. of Transportation, Geotechnical Section, P.O. Box 58, Knoxville, TN 37901; (423) 594-9436, fax 423-594-9310.

Marginal Oil and Gas Well Commission of Oklahoma Trade Fair, May 15, 1997, Tulsa, Oklahoma. Information: Marginal Oil and Gas Well Commission of Oklahoma, 1218-B W. Rock Creek Road, Norman, OK 73069; (800) 390-0460 *or* (405) 366-8688 (Oklahoma City area).

Prospect to Pipeline Conference, May 18–21, 1997, Casper, Wyoming, sponsored by Wyoming Section of Society of Petroleum Engineers and others. Information: Michael T. Borah, program chairman, (307) 472-1985.

Society for Sedimentary Geology and Canadian Society of Petroleum Geologists, Joint Convention, "Sedimentary Events and Hydrocarbon Systems," June 1–6, 1997, Calgary, Alberta. Information: CSPG Office #505, 206 Seventh Ave. S.W., Calgary, Alberta, T2P OW7, Canada; (403) 264-5610, fax 403-264-5898; e-mail: cspg@cspg.org.

14th International Conference on Basement Tectonics, June 2–6, 1997, Blacksburg, Virginia. Information: A. K. Sinha, Dept. of Geological Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061; (540) 231-5580, fax 540-231-3386; e-mail: searches@vtvm1.cc.vt.edu.

American Association of Petroleum Geologists, Southwest Section, Annual Meeting, June 4–5, 1997, San Angelo, Texas. Information: AAPG Convention Dept., Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

Interstate Oil and Gas Compact Commission Mid-Year Meeting, June 8–10, 1997, Oklahoma City, Oklahoma. Information: IOGCC, P.O. Box 53127, Oklahoma City, OK 73152; (405) 525-3556, fax 405-525-3592; e-mail: iogcc@oklaosf.state.ok.us.

11th International Clay Conference, June 15–21, 1997, Ottawa, Ontario. Information: Jeanne Percival, Geological Survey of Canada, 601 Booth St., Ottawa, Ontario K1A 0E8, Canada; (613) 992-4496, fax 613-943-1287; e-mail: ICC97@gsc.emr.ca.

American Association of Petroleum Geologists, Mid-Continent Section, Annual Meeting, "New Techniques for an Old Frontier," September 13–17, 1997, Oklahoma City, Oklahoma. Information: Bill Boyd, 1408 N.W. 148 St., Edmond, OK 73013; (405) 749-0188, fax 405-236-8085.

USGS Miscellaneous Field Studies Map: Midcontinent

Compiled by W. P. Pratt and C. J. Wandrey, these three color maps show thickness and limestone-dolostone ratios of selected Paleozoic carbonate units in the northern Midcontinent for latitudes 36°–46° N. and longitudes 88°–100° W. The USGS and state geological surveys from Arkansas, Illinois, Iowa, Kansas, Minnesota, Missouri, Nebraska, Oklahoma, and Wisconsin have been compiling data on the area bounded by these latitudes under the Midcontinent Strategic and Critical Minerals Project. The maps in this publication were prepared as an aid to regional appraisal and prospecting for Mississippi Valley–type (MVT) lead-zinc sulfide deposits in the region. Scale is 1:1,000,000 (1 in. = about 16 mi). Each sheet measures 42 × 56 in.; a 10-page text accompanies the maps.

Order MF 1835-I from: U.S. Geological Survey, Information Services, Box 25286, Denver Federal Center, Denver, CO 80225; for information, call 1-800-HELP-MAP. Cost is $4, plus $3.50 per order for handling.

Bouguer and Isostatic Residual Gravity Anomaly and Derivative Maps of the Lawton Area, Southwestern Oklahoma

Prepared by Meridee Jones-Cecil and S. L. Robbins, this USGS geophysical investigations map is on two sheets, both in color. Sheet 1 shows latitude 34°30′ to 35°05′, longitude 98°00′ to 99°15′; sheet 2 shows latitude 34°30′ to 35°05′, longitude 98°22′30″ to 99°15′. Scale is 1:100,000 (1 in. = about 1.6 mi). Sheet 1 measures 58 × 41 in.; sheet 2 is 34 × 57 in.

Order GP 0998-B from: U.S. Geological Survey, Information Services, Box 25286, Denver Federal Center, Denver, CO 80225; for information, call 1-800-HELP-MAP. Cost is $4, plus $3.50 per order for handling.

Changes in Flow in the Beaver–North Canadian River Basin Upstream from Canton Lake, Western Oklahoma

The results of an evaluation of hydrologic data for the Beaver–North Canadian River basin upstream from Canton Lake are released in this 58-page water-resources investigations report by Kenneth L. Wahl and Robert L. Tortorelli. The primary use of surface water in the North Canadian River and its tributaries is public water supply. Flow in the Beaver–North Canadian River in the Oklahoma Panhandle has decreased substantially since the mid-1960s, although precipitation and use of surface water were unchanged. The Beaver–North Canadian River and the High Plains aquifer are hydrologically connected where the water table is shallow. The High Plains aquifer has been subject to large-scale pumping for irrigation since the late 1960s, resulting in widespread water-level declines in the Central High Plains and Southern High Plains in Colorado, Kansas, Oklahoma, and Texas. About 30% of the ground water used in the United States is pumped from the aquifer.

Order WRI 96-4304 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116, phone (405) 843-7570. A limited number of copies are available free of charge.

Oklahoma ABSTRACTS

The following abstracts were presented as part of the Geology Section program at the Oklahoma Academy of Science 85th annual technical meeting, Oklahoma State University, Oklahoma City Campus, November 8, 1996.

Thermal Conductivity of U.S. Coals

J. MATTHEW HERRIN and *DAVID DEMING*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Coal samples in the form of randomly oriented aggregates were obtained from the Pennsylvania State University Coal Bank for the purpose of thermal conductivity measurements. Samples represented 55 locations from throughout the United States and included 6 lignites, 10 subbituminous coals, 36 bituminous coals, and 3 anthracite samples. Matrix thermal conductivities measured at 22°C in the laboratory ranged from 0.22 to 0.55 W/m°K, with an arithmetic mean of 0.33 W/m°K and a standard deviation of 0.07 W/m°K. The thermal conductivity of lignites, subbituminous, and bituminous coals is controlled by composition and can be predicted by a three-component (moisture, ash, and carbon + volatiles) geometric mean model with an rms residual of 6.1%. The thermal conductivity of bituminous and anthracite samples was found to be positively correlated with matrix density. With the exception of three anthracite samples, rank was not correlated with thermal conductivity nor was the ratio of carbon to volatiles. The relatively high thermal conductivity of three anthracite samples (mean of 0.49 W/m°K) may have been related to graphitization.

A Heat Flow Map of Oklahoma

CONSTANTIN CRANGANU and *DAVID DEMING*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

We need to know and to understand the magnitude and the variation of terrestrial heat flow on the continents because:

- Temperature strongly affects seismic waves velocity, the rheology of the Earth materials, maturation of hydrocarbons.
- Temperature and heat flow are sensitive tracers for ground-water flow in the upper crust.
- We may better understand some important geologic processes, such as: sedimentary diagenesis, the genesis of hydrothermal ore deposits, the resetting of paleomagnetic poles, and hydrocarbon migration.
- We can constrain climate changes due to the enhanced greenhouse effect.

A heat flow study in Oklahoma is necessary because the thermal state of the southern Midcontinent is a key to understanding several important problems: Paleozoic fluid migrations and thermal anomalies, thermal evolution of sedimentary basins, and climatic changes.

This first version of the heat flow map of Oklahoma is based on 57 heat flow values distributed throughout all of the State of Oklahoma. Out of the 57 values, 20 are reported for the first time in this paper. In order to constrain our map, we used 101 heat flow values from neighboring states.

The 20 new heat flow values have been obtained by using a set of equilibrium temperature logs in idle oil wells made in the late 1920s by the American Petroleum Institute. These temperature data are generally regarded as being high quality, accurate estimates of rock temperature and they cover the entire central part of Oklahoma. In order to determine the thermal conductivities, we made almost 1,500 measurements on drill cuttings utilizing a divided bar apparatus. Each conductivity value was corrected for anisotropy, temperature, and porosity in situ using porosity logs. For each site with the temperature well, we constructed a facies map to correct the data for stratigraphic offset. The average error for heat flow values was ±20%.

The map exhibits an area of minimum heat flow (~30 mW/m^2) near the Wichita Mountains and an area of maximum heat flow (~80 mW/m^2) in the central eastern part of the State. The trend of increasing heat flow values is from SSW to NNE, in good concordance with the increase of geothermal gradients in the same direction (from 14°C/km in SSW to 43°C/km in NNE). The thermal conductivities range from 1.1 to 2.2 W/m°K.

The variation in heat flow could be indicative of a change related to variations in the concentration of radioactive heat-producing elements in the crust or heat transport by one or more regional ground-water systems. There is a good correlation between the variation of heat flow and thermal gradients. We are proceeding to reduce ambiguity in interpretation by estimating heat production from available gamma-ray logs which penetrated basement rocks.

Heat Flow in the Anadarko Basin, Southwestern Oklahoma: Implications for Hydrocarbon Generation and Overpressuring

YOUNGMIN LEE and *DAVID DEMING*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The Anadarko Basin is the deepest sedimentary basin on the North American Craton; total sediment thickness is greater than 11 km. Although it has been tectonically quiescent for more than 100 million years, the Anadarko is known to have extensive areas of overpressuring. We are investigating the thermal regime of the basin in part to evaluate the efficacy of hydrocarbon generation as an overpressuring mechanism.

The average geothermal gradient along an N-S cross section through the Anadarko Basin is 21°C/km as estimated from analysis of 895 bottom-hole temperatures from oil and gas wells. To estimate the magnitude and spatial variation of heat flow in the Anadarko Basin, we made 918 thermal conductivity measurements on drill cuttings from 17 oil and gas wells along the same cross section. All measurements were corrected for effects of anisotropy, temperature, and porosity. Matrix conductivities perpendicular to bedding at 22°C range from 1.9 W/m°K for Permian age units to 3.0 W/m°K for Ordovician–Upper Cambrian age units. Estimated heat flow (±20%) ranges from 32 mW/m^2 to 44 mW/m^2; average heat flow along the N-S cross section is 39 mW/m^2. These results are similar to seven heat flow estimates for the Anadarko Basin reported by D. Blackwell and his students at SMU in Dallas. However, Blackwell and other's estimates show that heat flow increases from about 40 mW/m^2 in the deep Anadarko Basin to the south, to about 60 mW/m^2 on the Oklahoma Platform to the north. In contrast, our estimates show that heat flow is essentially a constant 40 mW/m² from south to north. At the present time, we do not know if these contrasting results are due to geographic variations in heat flow between sites, or if they can be attributed to inherent errors.

Fault-Associated Cementation: The Lateral Seal of the MCC in the Anadarko Basin

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

Gas well productivity patterns in the Anadarko basin indicate that the overpressured reservoirs proximal to the Wichita Mountain fault zone are tightly cemented in some areas. Production profiles from the western basin reveal that sandstone/conglomerate-dominated rock units within the overpressured interval, or mega-compartment complex (MCC), are cemented and non- to poorly productive adjacent to the fault. On the other hand, distal overpressured and normally pressured clastic and carbonate reservoirs both above and below the MCC are relatively unaffected by this cementing.

Basin evolution modeling indicates sandstone/conglomerate-dominated sequences within the MCC entered the seal window concurrent with displacement along the fault zone. Hydrostatic conditions within the faults were maintained by continuing movement. Reduced pore fluid pressure in the fault vicinity facilitated fluid flow from the overpressured sediment column toward the fault. As a result, solute precipitation and augmented compaction may have occurred.

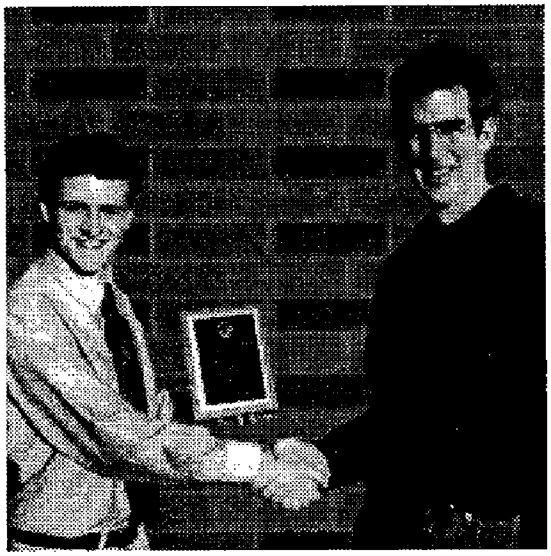
Core data reveal the increased cementation within the overpressured interval near the fault zone reflects framework grain mineralogy. Chert-rich rocks are predominantly silica cemented, while carbonate-rich rocks are dominated by carbonate cements. Strata above and below the MCC contain intergranular and vuggy porosity, while fracture porosity is of secondary importance. These intervals maintained near-normal pressures and were unaffected by cementation as no pressure differential existed to drive fluid migration.

The cemented interval along the Wichita frontal fault zone forms a low-porosity fairway that functions as the southern lateral seal of the MCC. This seal isolated the highly overpressured chert conglomerate reservoirs in the fields to the north and prevented their equalizing with the hydrostatic pressure of the fault zone.

Near Surface Granite Weathering of Mount Scott Granite

JON M. MOLLISON, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The results from a detailed investigation of the top 100 feet of a recovered Mount Scott Granite core are reported on. The following changes in the core take place as a function of increasing depth: (1) the magnetic susceptibility increases from 1.8×10^{-4} to 9×10^{-3} (SI m), (2) the specific gravity increases by 4.4×10^{-2}, (3) the amount of hematite staining increases, (4) porosity decreases, and (5) there is a decrease in the amount of balsalm, clay, and fractures. The possible correlation between fracture density and degradation of the primary igneous mineralogy as a result of weathering suggest fluid-rock interactions were controlled by fracturing.

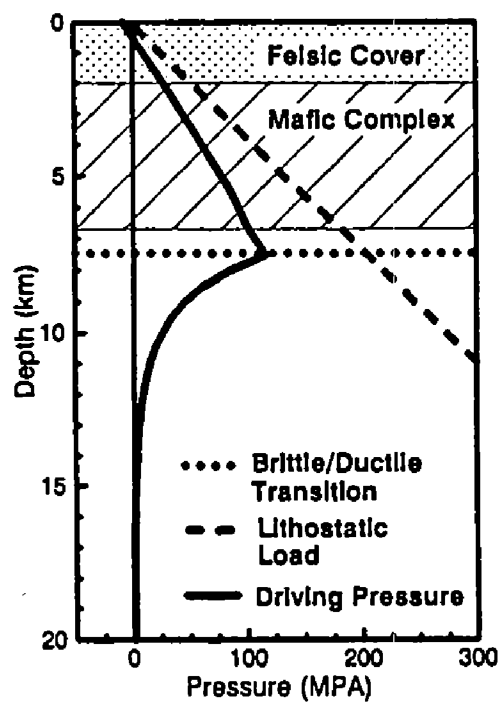


Jon Mollison (left) accepts the Oklahoma Junior Academy of Science award for best student paper (Geology Section) at the 1996 Fall Technical Meeting of the Oklahoma Academy of Sciences. (*Abstract appears on facing page.*) Jon is a senior in the School of Geology and Geophysics at the University of Oklahoma and plans to attend graduate school this fall. Presenting the award as chair of the geology section is Dr. John P. Hogan. The Academy extends its gratitude to James Chaplin of the Oklahoma Geological Survey for lending his expertise in judging all of the student presentations in this section.

Catching Gabbro Plutons in a Crustal Magma Trap

J. D. PRICE, J. P. HOGAN, and *M. C. GILBERT,* School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Igneous rocks of the Southern Oklahoma Aulacogen (SOA) are stratified into a voluminous volcanic felsic cover that overlies an older layered mafic substrate. This contact served as a Crustal Magma Trap (CMT) for slightly later felsic magmas, which formed sheet granites with high aspect ratios (e.g., 55:0.5) (Hogan and Gilbert, 1995). These sheet granites themselves may have become a CMT impeding the rise of younger mafic liquids, suggesting that CMTs play an important role in compositional stratification of rift products.



Younger mafic liquids include biotite-bearing gabbroic plutons (Roosevelt Gabbro) that intrude the layered mafic complex. These have enigmatic contacts with the overlying felsic rocks. Recent geochronologic studies indicate that these gabbroic plutons may be younger than the granites. Field and geophysical investigations show that these bodies are much smaller plutons (<20 km^2) than the granites. They have generally steep walled contacts extending for depths >0.5 km, although some shallow spreading is observed near the tops of these bodies.

Magmastatic calculations (see figure) indicate sufficient driving pressure for Roosevelt Gabbro magmas to have been emplaced within the felsic cover. However, their consistent occurrence along the felsic cover–layered complex contact indicate that this boundary acted as a CMT which impeded further ascent of these magmas.

Although the Roosevelt Gabbro magmas formed plutons of lower aspect ratio, it is still likely that small amounts of spreading occurred along the contact with the CMT. However, magmastatic calculations, using typical rift values for horizontal stress, suggest that the driving pressure was insufficient to lift the overburden at this depth, and space must have been made by mechanisms such as stoping rather than simply lifting the overburden. In order to create space by lifting the overburden, the driving pressure must have exceeded the lithostatic load at the depth of the CMT. Such an increase in the driving pressure could arise from a decrease in horizontal stress by an increased amount of diking and/or extension, which implies episodic periods of high magma supply rates during rifting.

The geologic setting and the magmastatic calculations can explain the lack of mafic extrusives and the presence of small gabbroic plutons and diabase dikes. It also suggests that high density magmas can be emplaced at shallow crustal levels, casting doubt on the importance of "mid-crustal density filters" in explaining bimodal magmatism within rift settings.

Reference Cited

Hogan, J. P.; and Gilbert, M. C., 1995, The A-type Mount Scott Granite sheet: importance of Crustal Magma Traps: Journal of Geophysical Research, v. 100, p. 15,779–15,792.

Structural Geometry of Thrust Faulting in the Baker Mountain and Panola Quadrangles, Southeastern Oklahoma

JUSTIN EVANS and *IBRAHIM CEMEN*, School of Geology, Oklahoma State University, Stillwater, OK 74078

The Arkoma Basin of southeastern Oklahoma is recognized as a foreland basin of the Ouachita Mountain fold and thrust belt. The Choctaw Fault, the leading edge thrust of the fold and thrust belt, separates the frontal Ouachitas from the Arkoma basin, which contains relatively gentle anticlines and synclines. This study is aimed at a better understanding of the Late Paleozoic thrust faulting in the Baker Mountain and Panola quadrangles of southeastern Oklahoma. The Spiro Sandstone is a major producing unit in the Wilburton gas field to the west as well as in the Red Oak gas field to the east. Cambrian-Ordovician Arbuckle Group members are minor producers in these fields.

Several balanced structural cross-sections are under construction to determine the geometry of Late Paleozoic thrusting in the area which is responsible for the overpressured Spiro Sandstone reservoirs. Seismic lines donated by Amoco and Exxon are being used as well as data from the Oklahoma City and Tulsa log libraries and geological maps of the Oklahoma Geological Survey to prepare the structural cross-sections. After the cross-sections are constructed, they will be restored using the key bed method (based on the Spiro) to determine the shortening.

Our preliminary interpretations suggest that the hanging wall block of the Choctaw Fault contains thrust faults forming an emergent imbricate fan structure. The footwall shows a major detachment surface named as the Woodford Detachment to the south which ramps upward to become the Springer Detachment to the north. Also present in the footwall are the duplex structures between the Woodford Detachment (floor thrust) and the Lower Atokan Detachment (roof thrust).

Geologic Mapping by the Oklahoma Geological Survey in Southeastern Oklahoma

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

Since 1984 the Oklahoma Geological Survey (OGS) has been involved in a project designed to carry out geologic mapping under a 50:50 matching (Federal-to-State) funded program. The program originated as the Cooperative Geologic Mapping Program (COGEOMAP), and involved the U.S. Geological Survey (USGS) as well as the Arkansas Geological Commission (AGC). The major OGS goal was preparation of a series of new 1:24,000-scale geologic maps (plotted on 7.5-minute topographic quadrangle maps) of the Ouachita Mountains and adjacent parts of the Arkoma basin, and their release as black-and-white open-file maps. COGEOMAP was discontinued in 1992, but mapping continued under the new STATEMAP program (also under 50:50 matching funding). Sixteen maps were completed under COGEOMAP, and to-date, four maps have been completed under STATEMAP, with two others in preparation.

Geologic maps show the distribution of rock units and other geologically related information. They are useful in construction and engineering projects, city and county planning and in a variety of environmental activities. They can be used to evaluate and predict the consequences of natural and human activities.

The first step in constructing a geologic map is assembling the existing data—aerial photographs, measured stratigraphic sections, borehole records, water-well information, soil surveys, and literature—to assist in field work and interpretation.

Field data (acquired mostly by walking the outcrops and measuring strikes and dips) are recorded on 7.5-minute topographic quadrangle base maps. Formation contacts and structural features are plotted on the base maps. Finalized versions of field maps result from data and inference. Because outcrops may be a mile or more apart, and bedrock may be covered by soil and vegetation, geologists must use their training and experience to put all the "clues" together to solve the geologic puzzle. Completed geologic maps graphically show the distribution, rock type, age, and horizontal distribution of bedrock near the Earth's surface.

Structural Geometry of Thrust Faulting in the Wister Lake Area of the Frontal Ouachitas, Arkoma Basin, SE Oklahoma

JEFF RONCK and *IBRAHIM CEMEN,* School of Geology, Oklahoma State University, Stillwater, OK 74078

The Ouachita Mountains and the Arkoma Basin were formed during the Ouachita orogeny in the Late Paleozoic. The basin consists of relatively gentle synclines and anticlines, and is considered a foreland basin of the Ouachitas. It is separated from the frontal Ouachitas by the Choctaw fault, which serves as the leading edge thrust.

This study is restricted to the Wister Lake area in the Blackjack Ridge and LeFlore quadrangles, and includes the Red Oak gas field, which mainly produces from the overthrusted Spiro Sandstone and the Red Oak Sandstone, as well as minor production from the Cambro-Ordovician Arbuckle Group. The purpose of this study is to construct structural balanced cross-sections throughout the area in order to determine the structural geometry of the Late Paleozoic thrust system, which is responsible for the overpressured Spiro Sandstone. Surface geological maps from the Oklahoma Geological Survey, wire-line well logs, scout tickets, and seismic profiles donated by Amoco Oil

Company are used to prepare the cross-sections. After completion of these cross-sections, restoration will be performed, using the key-bed method, to estimate the percentage of shortening in the area.

Our preliminary interpretations suggest that the hanging wall block of the Choctaw fault is dominated by south-dipping imbricate fans, joining the Choctaw Detachment at depth. The footwall block contains the Springer Detachment, which becomes the Woodford Detachment as it ramps to the stratigraphically higher, Woodford Shale. Several duplex structures are present between the Woodford Detachment (floor thrust), and the Lower Atokan Detachment (roof thrust). Seismic interpretation of one seismic profile suggests that the Lower Atokan Detachment contains a northerly dipping back-thrust, just beneath the Cavanal Syncline in the northern part of the area.

Storm-Generated Disturbances Within an Early Pennsylvanian (Atokan) Muddy Epeiric Sea: Arkoma Basin, Oklahoma

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Approximately 886 ft (270 m) of the upper part of the Atoka Formation (Pennsylvanian) is exposed in the southern part of the Arkoma Basin at Wister Lake Spillway, Le Flore County, Oklahoma. Many sandstones of uncertain stratigraphic position and continuity occur in the subsurface within the Atoka Formation. This is the first study to document that some of these outcropping sandstones can be correlated into the subsurface stratigraphically.

The lower 207 ft (63 m) of the succession (less distal shelf) is mud-dominated, but it is more sand-rich, has higher sand/shale ratios, and shows more frequent indications of oscillatory flow and of sedimentary features recording deposition by less distal processes than the upper part. The upper 679 ft (207 m) of the succession (more distal shelf) is mud-dominated, but has lower sand/shale ratios, and shows less frequent evidence of oscillatory flow than the lower part. The upper part records deposition by more distal processes as evidenced by the dominance of finer-grained sediments and paucity of shallow-water bedforms. The upper part contains rare isolated sand lithofacies, which suggests only localized transportation of sand.

The textures, vertical successions of facies, and sedimentary structures suggest variable energy conditions that produced a range of features: (1) suspension fallout features (mudstone/shale; laminated and rippled mudstone); (2) low-flow regime features (climbing ripples; straight-crested current ripples; ripples at top of planar cross-bedded sets); (3) transitional-flow regime features (undulatory small-current ripples; trough cross-stratification); and (4) relatively high-flow regime features (linguoid current ripples; horizontal, parallel, continuous laminations; hummocky cross-stratification). Episodic rapid depositional events (e.g., storms) are indicated by sharp-based hummocks, syndepositionally deformed beds, laminated sandstone lenses in mud-rich intervals, and starved ripples. Wave-generated/influenced bed forms consist dominately of symmetrical and asymmetrical wave ripples, hummocky cross-stratification, opposed ripple foreset directions within a single ripple horizon, and laminations out-of-phase with ripple forms.

The textures, vertical succession of facies, and sedimentary structures, considered together, suggest that the upper part of the Atoka Formation, at least at this stratigraphic level and geographic setting, is part of a thick, fining-upward transgressive shale sequence that contains thin, coarsening-upward regressive sandstone sequences deposited on a storm-influenced, mud-dominated shelf. This interpretation suggests that new and varied exploration plays may exist in the Atoka Formation.

Thermoelastic Mechanism of Pulsations in Hydrothermal Venting

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We had suggested (Germanovich and Lowell, 1992) that thermoelastic closure of cracks in the upflow zone of a ridge crest hydrothermal system could result in oscillations in the power output of a black smoker vent field. For example, suppose that thermoelastic stresses in a fault-controlled hydrothermal upflow zone decrease the interconnectivity of the crack network. The flow then slows down and the upflow area will cool by thermal conduction from the cooler areas outside the fault zone. In time, the cracks will reopen and hot fluid may once again flow through the fault. This constitutes the problem of pulsations of hydrothermal fluid in upflow zones. We have begun to test this idea by developing a simple model of an upflow zone (see Fig. 1) in which the permeability and porosity of the rock is temperature and pressure dependent.

We consider the case where an influx of magma results in an increased heat flux to a system in which the temperature, T, initially increases linearly with depth, z, while the temperature at the surface is maintained at $\partial T/\partial z + hT = 0$. We derived the dependence $h = a/(vL^2)$ on flow velocity, v, leading to reasonable limiting cases for low and high fluid

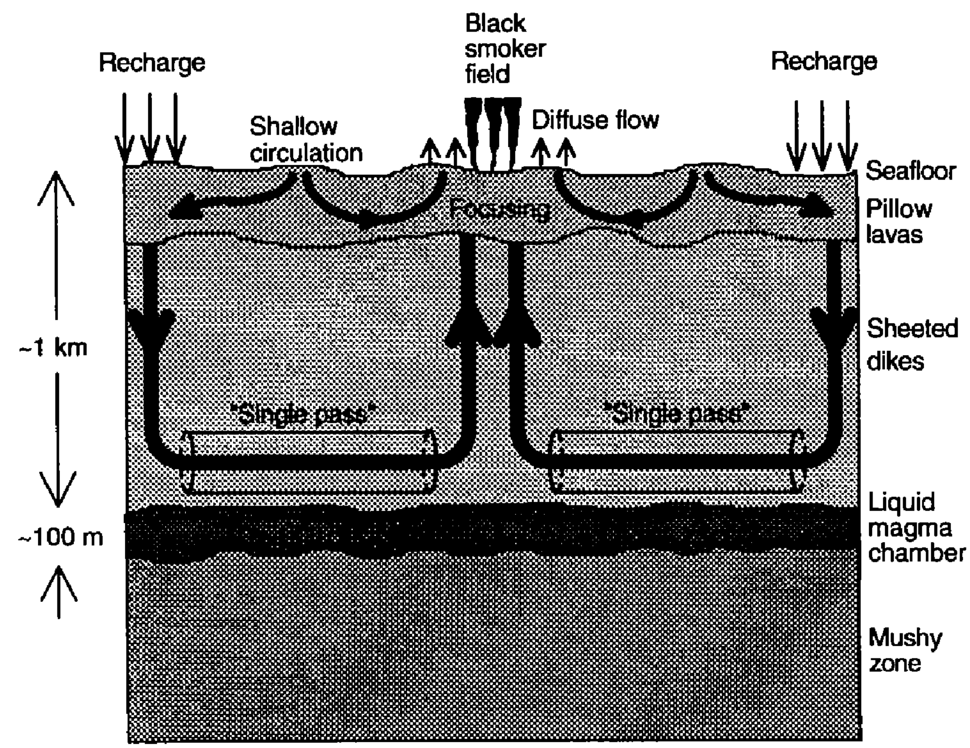

Figure 1. Cartoon of single-pass hydrothermal circulation model at an ocean ridge crest. The "single pass" segment refers to the zone at the base of the sheeted dikes where chemical reactions and heat uptake from the magma chamber occur. The focused, high temperature flow is thought to occur in the main single-pass limb. Diffuse flow may occur as a result of mixing of the deep circulation with a more shallow circulation in the pillow basalts.

fluxes in hydrothermal system; that is T= 0 and $\partial T/\partial z = 0$, respectively. Here a is the rock thermal diffusivity and L is the internal rock structure scale defining the mixing of fluid at the ocean floor (e.g., L could be a typical rock block size). The permeability, k, is assumed to result from cracks randomly distributed along the dike margins so that $k = k_0[1-\Delta T\alpha/\phi]^3$, where k_0 is the initial permeability (before the magma influx), α is the rock coefficient of thermal expansion, and ΔT is the temperature change with respect to the initial temperature gradient.

Our preliminary numerical results indicate that flow oscillations resulting from temperature dependent permeability and thermoelastic effects may occur for only a narrow range of parameters and their typical period is in the decade time scale. Typical example of the temperature dependence on time is shown in Figure 2.

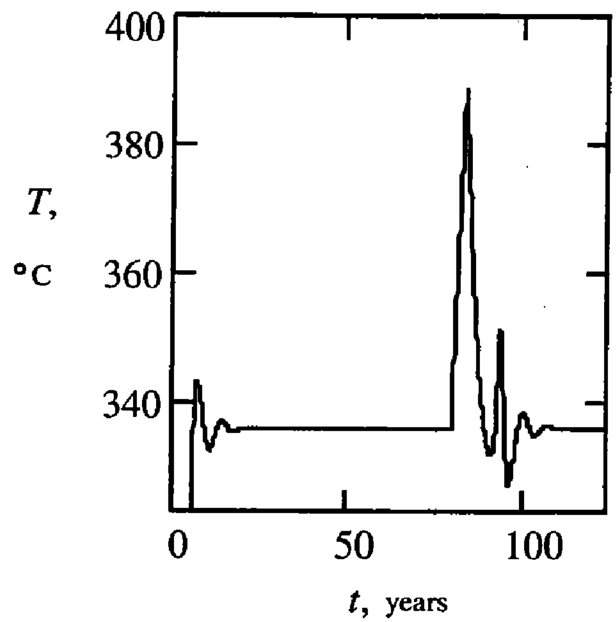

Figure 2. Temperature at the top of upflow zone time variations.

This result needs to be checked for different boundary conditions and more realistic models accounting, in particular, for more than just upflow zone, shallow circulation and tidal effects. If the preliminary results hold though, short-term (~years and smaller) fluctuations in black smoker output may not be related solely to thermoelastic processes. Chemical precipitation coupled with thermoelastic effects may induce more pronounced long term oscillations. Thermoelastic closure leads to quite distinguished permeability contrast so that in the lower part of the upflow zone the permeability is appreciably higher compared to the upper part. Under such conditions, the real 2-phase fluid flow is unstable which may also induce short term oscillations (~years).

Reference Cited

Germanovich, L. N.; and Lowell, R. P., 1992, Percolation theory, thermoelasticity, and discrete hydrothermal venting in the Earth's crust: Science, v. 255, p. 1564–1567.