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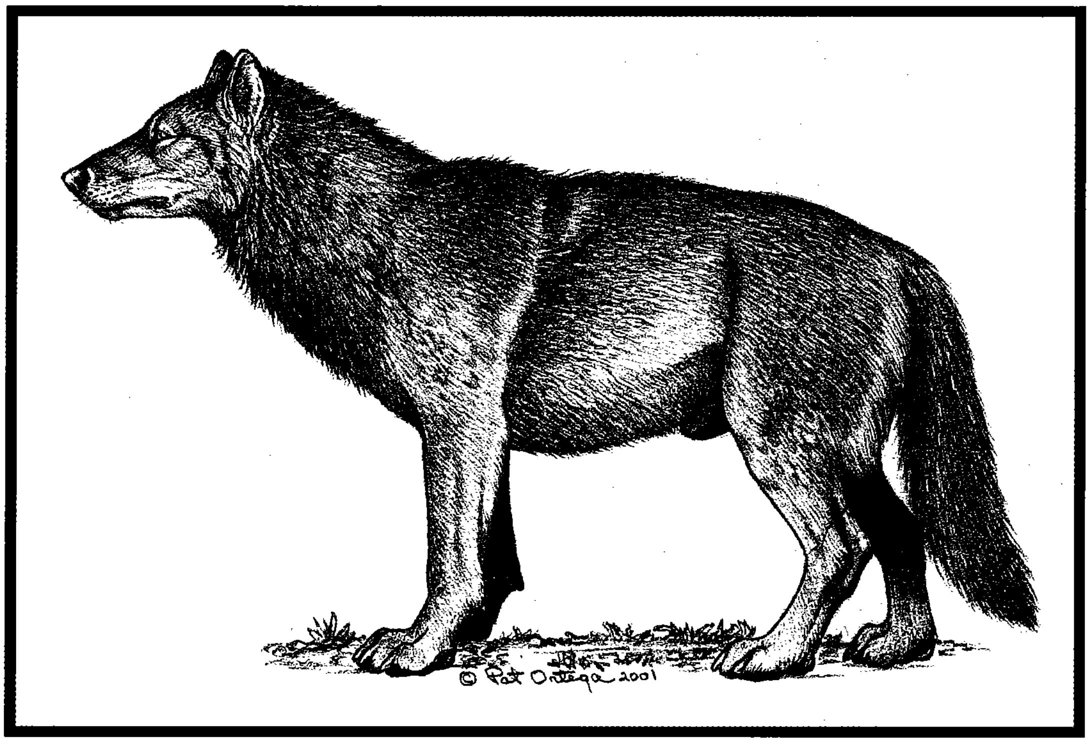

Featuring:
- Dire wolf in the Pleistocene of Oklahoma
- Oklahoma oil: past, present, and future
- Coal geology in the Western Interior Region

on the cover

Dire Wolf (*Canis dirus*) Specimen from Marlow, Oklahoma

The dire wolf (shown in the cover drawing) was one of the most common canids during the late Pleistocene (Rancholabrean land mammal age). Although it occurred from southern Canada to Peru, only two dire wolf specimens have been reported from Oklahoma. The second specimen was discovered in southwestern Oklahoma during the 1920 excavation of the new Marlow High School at Marlow, Oklahoma. The inset figure below shows a restoration of this specimen. Based on the fossil material, it appears that this dire wolf expired in its den at a very mature age. (See "Dire Wolf [*Canis dirus*] in the Pleistocene of Oklahoma," page 92, for a full description of the Marlow specimen.)

The dire wolf was similar in size to the gray wolf (*Canis lupus*), but it possessed several hyena-like characteristics, such as bone crushing carnassials (teeth with specialized shearing surfaces) and stronger, more robust limbs (especially the distal elements). Several have speculated that the dire wolf may have filled a void for hyenas in North America during the Rancholabrean. This group of canids probably went extinct at the same time as the North American megafauna ca. 8,000–10,000 years ago (Kurtén and Anderson, 1980).

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Courtesy of the George C. Page Museum, Los Angeles, California

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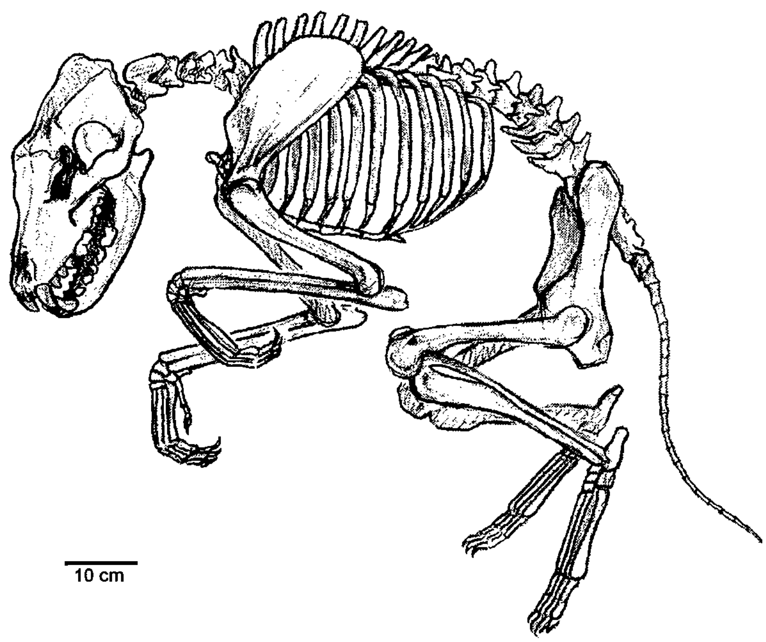

Oklahoma
Geological Survey

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OKLAHOMA GEOLOGY

Vol. 62, No. 3 **Fall 2002**

Dire Wolf (*Canis dirus*) in the Pleistocene of Oklahoma

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ABSTRACT.—The only known occurrence of the dire wolf, *Canis dirus*, from the Pleistocene of Oklahoma was collected early in the twentieth century in the town of Marlow (Stephens County). The specimen is exceptional in its completeness, including a virtually complete skull and jaws, together with much of the postcranial skeleton; thus, it ranks among the best-represented individuals of the species. Geological context cannot be established with existing data, though preservation, articulation, and relative position of the skeletal elements suggest the hypothesis that the individual represented by this specimen may have died in a den. The specimen belongs to a mature (probably aged) individual and may be referable to *C. dirus dirus*, the subspecies that is known from late Pleistocene deposits throughout the United States east of the Rocky Mountains. However, the Oklahoma specimen is unusual in several respects: it is among the largest individuals of the species in some aspects of the jaw and dentition, yet its limb elements are rather short compared to other individuals of *C. d. dirus*.

Despite relatively good representation of *Canis dirus* in a narrow interval (late Pleistocene–early Holocene) of the fossil record, this specimen is one of only a few known from the Great Plains. The significance (if any) of its unusual morphology cannot be evaluated with available data, but it is conceivable that it reflects hitherto unappreciated zoogeographic differentiation of the dire wolf in the Pleistocene of North America.

INTRODUCTION

The dire wolf, *Canis dirus* Leidy, 1858, is one of the icons of the Pleistocene of North America. It is among the largest members of the genus and is characterized by a massive skull with robust, enlarged carnassials. These features suggest that the species may have preyed on large mammals and that it may have had some bone-crushing capability, enabling it to scavenge (Merriam, 1912; Stock, 1956). However, *C. dirus* appears not to have been as strongly adapted for bone crushing as the living spotted hyaena, *Crocuta crocuta* (note Hill, 1991). The geological range of the species is not tightly constrained, though it is clear that *C. dirus* was restricted to the late Pleistocene (Rancholabrean land mammal age; see Savage and Russell, 1983) and early Holocene. The minimal age of first appearance is about 250,000 years before present. Thus far, only three somewhat suspect radiocarbon dates, ranging from 13,170 to 9,850 years before present, provide evidence on the last occurrence of the dire wolf (Dundas, 1999).

Fossils of *Canis dirus* are rather common. An enormous number of specimens have been recovered from the asphalt traps of Rancho la Brea, California. Many of the other reports are based on occurrences in caves, and an especially large sample is known from San Josecito Cave, Mexico (Kurtén and Anderson, 1980; also see Kurtén, 1984). Nonetheless, relatively complete specimens—including the skull and associated postcranial skeleton—are not common. Indeed, except for fossils from Rancho la Brea, reasonably complete skulls of the dire wolf are quite rare (Nowak, 1979).

Geographic origin of the dire wolf is highly uncertain. Nowak (1979) raised the possibility of a South American origin for *Canis dirus*, a suggestion corroborated by phylogenetic analysis (Berta, 1987, 1988). Whatever the case, *Canis dirus* was a geographically widespread species: occurrences have been reported from much of the United States, as well as from Canada (Alberta), Mexico, Bolivia, Venezuela, and Peru (Kurtén and Anderson, 1980; Dundas, 1999). A notable exception to the broad distribution and abundance of *Canis dirus* is the Great Plains of the United States, where very few specimens have been recovered (Nowak, 1979; Dundas, 1999). Herein, we report on a remarkably complete specimen of the dire wolf from southwestern Oklahoma. The completeness of the specimen is unusual, given that it is not from a cave deposit. This occurrence has been mentioned only peripherally in the literature (Nowak, 1979; Kurtén, 1984; Dundas, 1999) and, as such, was omitted from a recent compendium on the Pleistocene vertebrates of Oklahoma

(Smith and Cifelli, 2000). Locally, the specimen is of significance in that it represents the only known occurrence of the dire wolf in Oklahoma.

OCCURRENCE

The occurrence of *Canis dirus* in Oklahoma is based on USNM (formerly United States National Museum; now National Museum of Natural History, Smithsonian Institution, Washington, D.C.) 10278, a skull and associated partial skeleton. The specimen was given by Henry Higgins Lane (1878–1965) to James William Gidley (1866–1931), then a curator of fossil mammals at the USNM. At that time, Lane had just begun his brief tenure (1920–1922) as Chair of the Department of Biology at Phillips University, Enid, Oklahoma. Earlier (1906–1920), Lane had been Head of the Department of Zoology and Embryology at the University of Oklahoma (Carpenter, 1992). He subsequently took a position at the University of Kansas, where he was Head of the Department of Zoology (1922–1948), Director of the Museum of Natural History (1922–1944), and Curator of Fossil Vertebrates at that museum (1931–1944).

The only existing documentation for USNM 10278 lies in a letter from Lane to Gidley, dated July 7, 1920, and preserved with the specimen in the collection of the USNM. It is amusing to note that Gidley apparently suggested that the fossil might represent a new species and that he would name it in Lane's honor. Whether Gidley sincerely held this belief cannot be determined, but there lies the unprovable intimation that the suggestion was made mainly in the interest of securing donation of the specimen to the USNM. Because the letter is of historical interest and provides the only provenance data available for USNM 10278, the section dealing with the specimen is quoted in full:

> Dear Mr. Gidley:
>
> I am sending you today by prepaid express the remainder of that Pleistocene wolf, the skull of which I left with you about six weeks ago when I saw you in Washington. I wish that the remains were more complete. The specimen was found about a year ago at Marlow, Oklahoma, eight and one half feet below the surface of the ground, while excavating for the basement of a new school house. Aside from the fact that they were sent to me I know nothing further of their discovery.
>
> Have you had the time to determine whether this is *Canis dirus* or the new species, *C. lanei* (!), which you thought it might be upon first sight?

The geological context of USNM 10278 probably will never be known; however, the geographic origin of the specimen can be established with some confidence (Fig. 1). There can be little doubt as to the identity of the school mentioned in Lane's letter: it was the former Marlow High School (Fig. 2), occupied for nearly 50 years during the middle part of the twentieth century. Major steps toward construction of the facility began in 1919. Following recommendation of the local school board, Marlow voters passed a bond issue aimed at funding the project in a special election on December 9, 1919 (Marlow Review, 1919). A key feature of the physical plant was to be a furnace capable of heating adjacent facilities, hence the need for excavation of the basement mentioned in Lane's letter. Contracts were let early in the following year, and construction began on March 24, 1920 (Marlow Review, 1920). These dates are at variance with Lane's letter of July 7, 1920, wherein he indicates that the specimen had

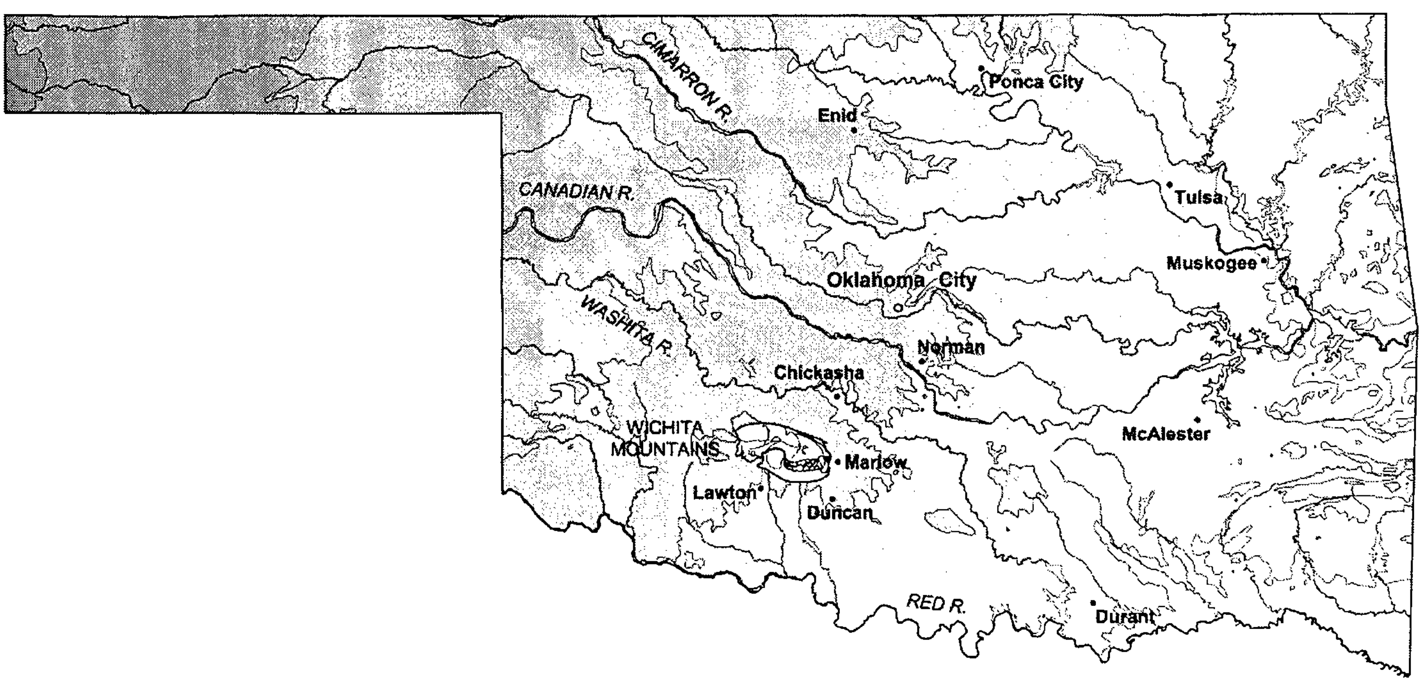

Figure 1. Occurrence of *Canis dirus* in Oklahoma. USNM 10278 was collected in 1920, during the construction of a high school building in Marlow, Stephens County. Marlow lies just east of the skull icon.

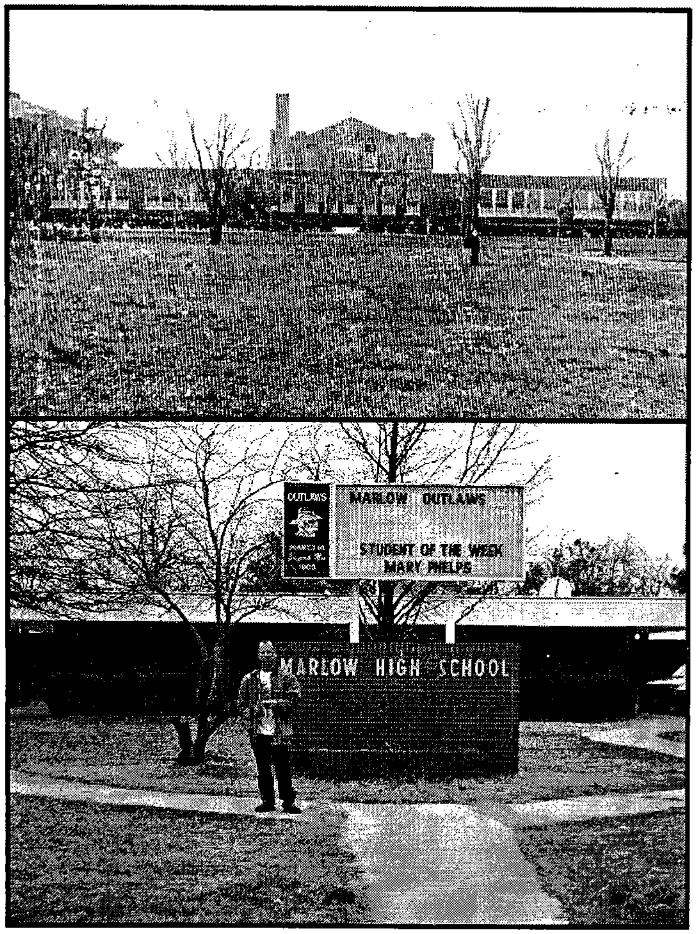

Figure 2. Locality of *Canis dirus* (USNM 10278) in Marlow, Stephens County, Oklahoma. The specimen was recovered in the course of excavation for the basement of the Marlow High School, shown (top) as it appeared just after construction was completed in 1921 (photograph courtesy of Debbie Ridley, Marlow Chamber of Commerce). The building was demolished in 1971; its basement (and hence the origin of the specimen) lay under the marker for the present Marlow High School (bottom).

been recovered "about a year ago." However, it is clear that Lane had no firsthand knowledge of the excavation and construction of the Marlow High School and that he had received only limited information when the specimen was sent to him. Hence, this minor discrepancy can be dismissed.

The high school was of brick construction and was first occupied in the fall of 1921. The building was demolished in 1971, when it was replaced by the present high school (Fig. 2). The location of the old high school, and hence the provenance of USNM 10278, was NE¼SE¼NW¼ sec. 17, T. 2 N., R. 7 W. (lat 34°38′51.5″N., long 97°57′40.4″W.).

COMMENTS ON THE SPECIMEN

USNM 10278 includes the following elements (Figure 3 shows representative cranial and postcranial elements of the specimen):

1. Skull, missing part of the left maxilla, most of the occipital, and much of the palate between the tooth rows; nearly complete mandible, missing the left coronoid and condyle (right coronoid and condyle are in a separate piece).

2. Axial column: two partial thoracic vertebrae, seven partial to nearly complete lumbar vertebrae, most of the sacrum, first caudal vertebra; five rib fragments.

3. Forelimb: fragments of both scapulae, proximal ends of both humeri and one distal humerus, both radii (one complete, the other missing the proximal end), both ulnae (one missing proximal end, the other missing the distal end), both hands (one essentially complete, the other broken through the metacarpals, with a separate piece including distal metacarpal fragments and some phalanges).

4. Hindlimb: essentially complete from the pelvis to the phalanges of the feet.

All preserved epiphyses are completely fused, and the dentition is well worn (Fig. 3D,E), which suggests that the individual was mature and, perhaps, approaching advanced age at the time of death. Dental measurements are given by Nowak (1979); some representative postcranial measurements (total lengths) for the specimen are: radius, 227 mm; femur, 255 mm; tibia, 243 mm.

The specimen has the appearance of having been fully articulated and complete at the time of burial; fresh breaks suggest that individual bones were broken and lost when the specimen was collected. Except for elements that presumably were either lost or destroyed during the excavation, specimen preservation and articulation are exceptional: individual bones are complete and are juxtaposed in correct anatomical position (even the sesamoids of the manus and pes are present and in place). The lumbar part of the vertebral column (not shown) is slightly ventroflexed, and both wrists are strongly ventroflexed (Fig. 3J,K); phalanges of all feet are also in ventroflexed position (Fig. 3I,L). Clearly, the specimen was not subject to postmortem fluvial transport, weathering, or scavenging. The preservation, articulation, and positioning of the skeletal elements suggest that the individual represented by USNM 10278 probably died in a subterranean den or burrow; extreme ventroflexion of the phalanges is likely due to postmortem drying and contraction of the flexor digitorum muscles.

We attempted to determine the geological age of USNM 10278 by radiocarbon dating of bone samples from the specimen. Unfortunately, at some point during its conservation history, the bones of USNM 10278 had been completely impregnated with a consolidant resin. Dissolving or physically removing this contaminant proved impossible, and the specimen could not be dated.

Early debate about the distinctiveness of *Canis dirus* from living *C. lupus* (see Cope and Wortman, 1884; Leidy, 1854) has been resolved (Merriam, 1912), particularly in light of detailed morphometric study (e.g., Nowak, 1979). The dire wolf is most distinctive in its relatively large, broad, robust skull, bearing large carnassials (P4, m1); see Nowak (1979) for complete diagnosis and comparisons.

Kurtén (1984) recognized two subspecies of *Canis dirus*: the nominate subspecies, *C. d. dirus*, distributed through North America east of the Rocky Mountains; and *C. d. guildayi*, based on fossils from California and Mexico (he did not include the South American fossils in his study). The eastern subspecies is characterized by its greater average size in general, which includes length measurements of the skull, mandible, teeth, and major limb elements. Average limb proportions are also greater: the forelimb is relatively longer and has proportionately longer radius and metapodials. Interestingly, the recent gray wolf, *C. lupus*, is proportionately similar to (though smaller than) *C. d. dirus*, and it differs in the same respects from *C. d. guildayi* (see Kurtén, 1984, fig. 1). Given the sharp morphological distinction between the two dire wolf taxa and the presumed adaptive significance (attributed by Kurtén [1984] to greater running ability in the eastern subspecies) of the differences, it is conceivable that they may warrant placement in separate species when better known.

Individual dental measurements (length of p4, m1) for USNM 10278 fall within the range of both *C. d. dirus* and *C. d. guildayi* (Kurtén, 1984, p. 224; Nowak, 1979, p. 153). Notably, however, the Oklahoma specimen has the greatest jaw depth (measured between p3 and p4) for any *C. dirus*, and it is among the largest for total length of the tooth row. To what extent these measurements reflect the advanced age of the individual cannot be determined. Most of the limb measure-

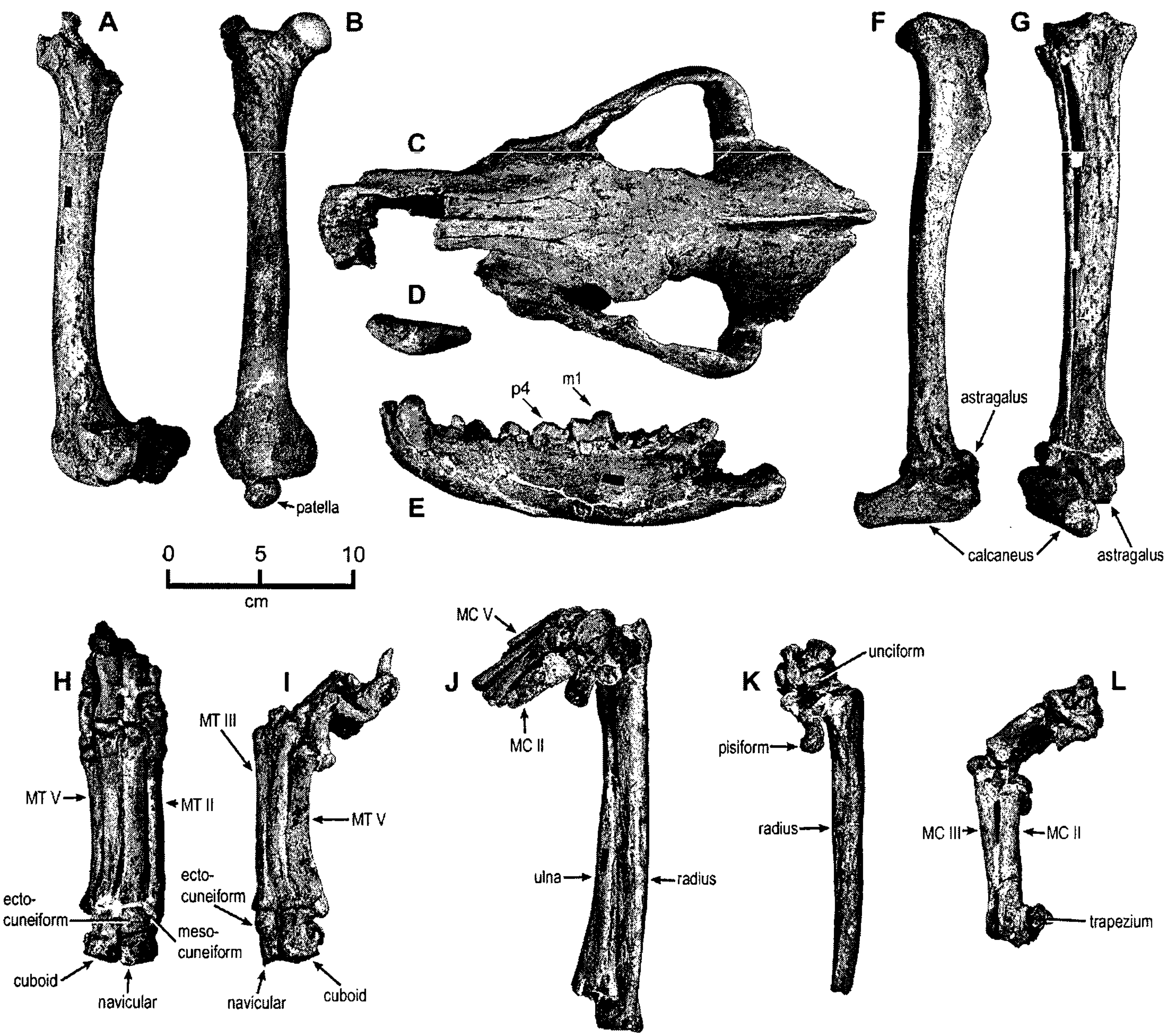

Figure 3. Representative cranial and postcranial elements of USNM 10278 (*Canis dirus*). (A) Left femur, posterolateral view. (B) Right femur, anterior view. (C) Skull, dorsal view. (D) Left upper canine, lingual view (occlusal surface is to upper left; note heavy wear). (E) Mandible, left lateral view. (F) Right tibia and proximal tarsals, lateral view. (G) Left tibia, fibula, and proximal tarsals, posterior view. (H) Left foot, dorsal view. (I) Right foot, dorsolateral view. (J) Right forearm, wrist, and metacarpals, medial view. (K) Partial left forearm and wrist, lateral view. (L) Left hand; distal carpals, metacarpals, and phalanges, medial view. Abbreviations: MC, metacarpal; MT, metatarsal.

ments for USNM 10278 exceed the means given for *C. d. guildayi* and are close to, or fall within the range of, measurements for *C. d. dirus* (Kurtén, 1984, p. 221 [ranges for *C. d. guildayi* are not given]). However, lengths for both radius and tibia are within the low end of the range, and the femur is actually shorter than any other specimen reported for *C. d. dirus* (USNM 10278 = 255 mm; range for *C. d. dirus* = 256–278 mm). Nothing can be concluded or reasonably inferred as to the significance (if any) of these differences, based on this single specimen. We point out, however, that the rather short limb elements of USNM 10278 are seemingly at odds with measurements of the jaw and dentition, some of which are at the higher end of the range for *C. dirus* as a whole.

In addition to establishing subspecies for eastern and western specimens of *Canis dirus*, Kurtén (1984) noted variation among materials referred to the eastern subspecies, *C. d. dirus*. He attributed such variation to geographic differentiation within the subspecies, differences in geological age of known specimens, or both. Either or both are plausible hypotheses to explain the peculiar proportions of USNM 10278, but neither can be tested with available data: sampling for *C. dirus* is poor in Oklahoma and surrounding areas (see Nowak, 1979; Dundas, 1999), and the geological age of USNM 10278 is unknown and cannot be determined.

Evidence in hand suggests that *Canis dirus* had a rather narrow geological range, being restricted to the latest Pleistocene and early Recent. The fossil record suggests that the dire wolf was rather successful during its short geological range: as noted above, fossils of *Canis dirus* are common in Rancholabrean faunas, and the species was geographically widespread. Despite the broad geographical range of *Canis dirus*, it is worth pointing out that the species was not ubiquitous in the late Pleistocene–early Recent of North America: for example, its distribution differs from that of living *C. lupus* in that *C. dirus* apparently did not venture far into northerly latitudes (Dundas, 1999). As well, *Canis dirus* is rare in the Rancholabrean–Holocene of the Great Plains; this scarcity is especially notable in view of the relatively good fossil record of the region. Dalquest and Schultz (1992) have suggested that the species may have largely avoided plains and prairies, in favor of more forested habitat elsewhere in North America. The occurrence of *C. dirus* in the Pleistocene of southwestern Oklahoma stands as one of few exceptions to this general pattern. The apparent morphological distinctiveness of the Oklahoma specimen, together with its geographic occurrence, suggests the possibility that zoogeographic differentiation of the species may have been more complex than previously envisaged.

ACKNOWLEDGMENTS

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Oklahoma Oil: Past, Present, and Future

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This is the first of three articles that will detail (1) Oklahoma oil, (2) Oklahoma natural gas, and (3) Oklahoma's place in the national and international energy picture. The series is geared for a non-technical audience; it will review the evolution of our petroleum industry through history and attempt broad predictions about where it's going.

INTRODUCTION

The impact of fossil-fuel–derived energy on every aspect of American life, from the economy to politics and national security, is tremendous. The success of the oil industry in providing abundant cheap energy is one of the main reasons for the unprecedented prosperity enjoyed by the United States and the rest of the developed world. However, geological and political factors have gradually forced reliance on oil from unsettled areas of the world. We can no longer satisfy petroleum demand from domestic sources, not for lack of technology, nor because we have been cheated by Mother Nature, but because exploration and exploitation of our natural resources has continued for nearly one and a half centuries. For most of that time Oklahoma—first as a Territory and then as a State—has been one of the most rewarding areas to look for petroleum.

Oil and gas are formed by alteration of microscopic organisms that have been deposited with sediment that turns into sedimentary rock. Sediments and organic remains reach maximum thickness when they accumulate in large, gradually subsiding depressions called geologic basins (Fig. 1). With increasing temperature and pressure that result from increased burial depth, organic remains are converted through millions of years into oil and natural gas. These organic compounds consist dominantly of carbon and hydrogen, and so are called hydrocarbons. As oil and gas are less dense than the water in which the original sediment was deposited, where permeable rock makes it possible they migrate upward. Movement ends where blocked or sealed by impermeable rock. The seal is a major component of any hydrocarbon trap, and its extent helps define the size of the oil or gas field that develops.

Oklahoma's prominent place in the oil industry is fortuitous, a result of encompassing the bulk of the hydrocarbon-rich Anadarko, Arkoma, and Ardmore geologic basins and their associated shelves and platforms. Figure 2 shows the approximate outline of these basins and adjacent areas, and

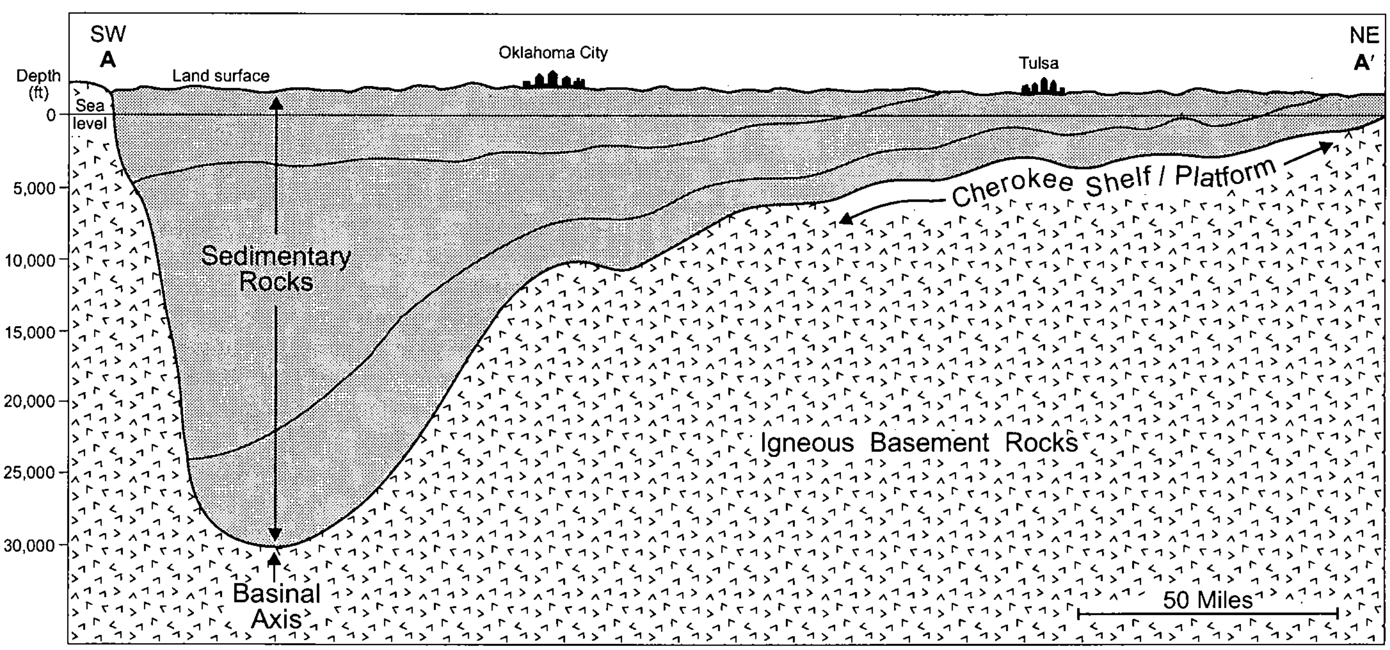

Figure 1. Cross-section of the Anadarko geologic basin. Modified from W. J. Witt and others (1971). Vertical exaggeration 14:1. See Figure 2 for base map.

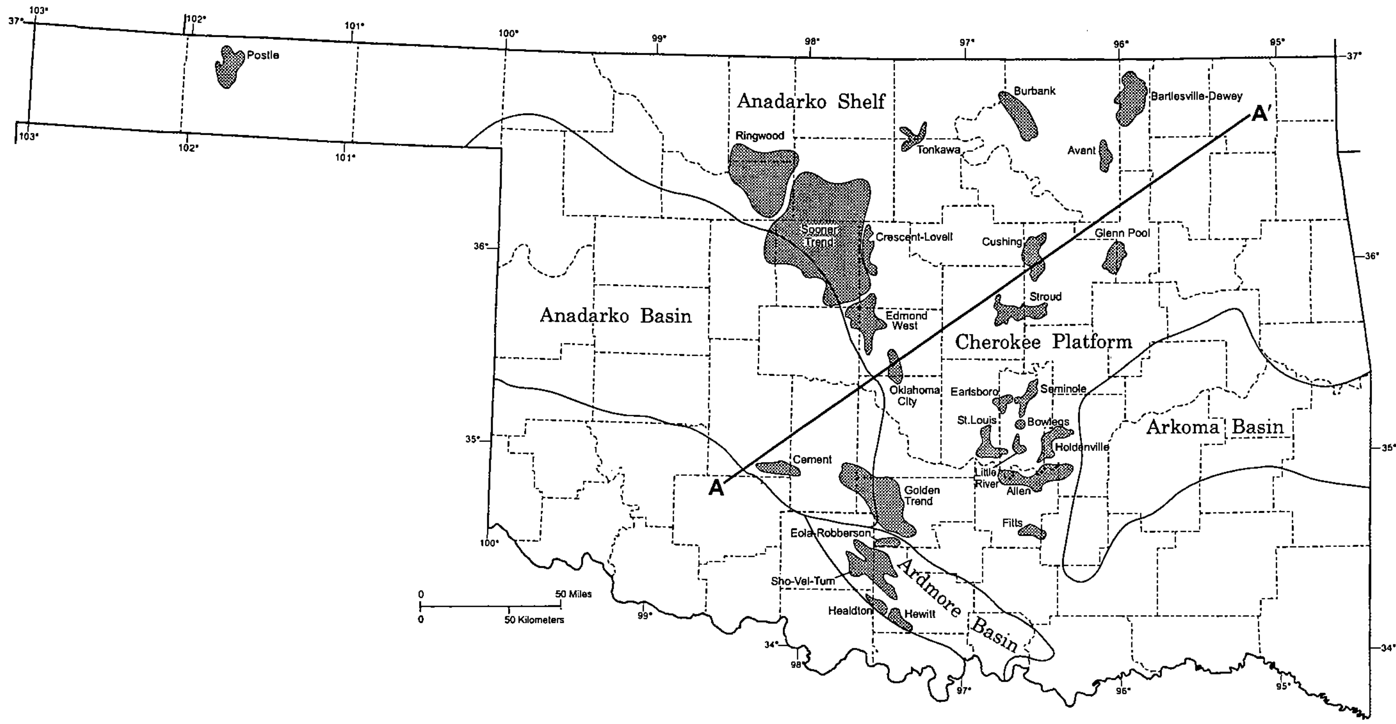

Figure 2. Petroleum provinces and major Oklahoma oil fields (>100 MMBO through January 2002). Modified from Robert A. Northcutt and Jock A. Campbell (1995) and Dan T. Boyd (in press).

also the State's major fields—those that have produced more than 100 million barrels of oil (MMBO). The sedimentary basins that have yielded the bulk of Oklahoma's oil production are mostly Pennsylvanian in age, but oil and gas reservoirs across the State range from Cambrian to Cretaceous (Fig. 3).

EARLY HISTORY

Oil seeps were recognized in Oklahoma long before the arrival of European settlers, who mined some seeps for asphalt. The first subsurface oil was recovered by accident, in 1859, in a well drilled for salt near present-day Salina (in Mayes County); its small amount of oil was sold for use in lamps. The first intentional oil find came from a well drilled in 1889 in an area of seeps near Chelsea (Rogers County); the well produced a half barrel of oil per day, used as "dip oil" to treat cattle for ticks (Franks, 1980).

The first commercial paying well, the Nellie Johnstone No. 1, was drilled in 1896 near Bartlesville (Washington County). Completed in 1897 as the discovery well for the giant Bartlesville-Dewey Field, the well ushered in the oil era for Oklahoma Territory. Production there and in other areas rose rapidly thereafter, adding much impetus towards the granting of Statehood in 1907. In the 10 years between the first discovery well and Statehood, Oklahoma became the largest oil-producing entity in the world.

After the turn of the century, discoveries were made in rapid succession in areas that would eventually encompass many of the 26 major oil fields (Fig. 4). All but five of the majors were discovered before the end of World War II; the last of them, the Postle Field, was found in Texas County in 1958 (Northcutt, 1985). Although the 26 majors constitute only about 1% of the total number of fields, they account for 59% of the total oil produced (Lay, 2001).

Until overtaken by California in 1923, Oklahoma remained the leading producing state in the U.S. (Hinton, 2001). Peak annual production of 278 million barrels (762,000 bbls/day) was reached in 1927, with several intermediate highs and lows since then. The peaks and valleys result from changes in the number of wells drilled and completed as well as from the size of the fields being found.

The historical production figures cited in Figure 5 are from the Oklahoma Corporation Commission and are based on volumes on which taxes have been paid to the State (Claxton, 2001). These volumes include condensate, but this is estimated to represent only 3% of the liquid hydrocarbons produced. Totals are believed to be accurate, but allocation of production to specific fields and reservoirs is often difficult. State records carry cumulative production by field only through 1979, forcing cumulative field-production figures to come from the International Oil Scouts Association. Also, many fields have been combined into larger fields or trends; for example, the Sooner Trend encompasses more than 100 previously defined fields.

As can be seen from well-completion history (Fig. 6), Oklahoma has had three major drilling booms. The first occurred just after Statehood; it lasted through 1930, and was most active from 1913 through 1920. That spate of drilling brought Oklahoma into the club of major oil producers. The lull that followed lasted through most of WWII, and was followed by a second boom that reached its peak in the years 1953–1956. Then drilling gradually declined, reaching postwar lows in 1971–1973.

DIVISIONS OF GEOLOGIC TIME				Age (approx.) in millions of years
Eon	Era	Period	Epoch	
Phanerozoic	Cenozoic	Quaternary	Holocene	0.010
			Pleistocene	1.6
		Tertiary	Pliocene	5
			Miocene	23
			Oligocene	35
			Eocene	57
			Paleocene	65
	Mesozoic	Cretaceous	Late	97
			Early	146
		Jurassic	Late	157
			Middle	178
			Early	208
		Triassic	Late	235
			Middle	241
			Early	245
	Paleozoic	Permian	Late	256
			Early	290
		Carboniferous: Pennsylvanian	Late	303
			Middle	311
			Early	323
		Carboniferous: Mississippian	Late	345
			Early	363
		Devonian	Late	377
			Middle	386
			Early	409
		Silurian	Late	424
			Early	439
		Ordovician	Late	464
			Middle	476
			Early	510
		Cambrian	Late	517
			Middle	536
			Early	570

Figure 3. Geologic time scale. From Harland and others (1990) and Hansen (1991).

The first drilling boom was driven by the number and size of discoveries made early in the 20th century. The second resulted from increased demand for petroleum products during conversion to a peacetime economy. (Both were caused by world and economic events that had little long-term impact on oil price.) The third and most recent boom resulted from increased oil prices arising from political tension in the Middle East (Fig. 7); however, its root cause was a gradual shift of the world's production capacity and reserves from consuming countries to less-developed areas represented by OPEC—the Organization of Petroleum Exporting Countries.

ANATOMY OF A DRILLING BOOM

The decline in Oklahoma's oil production since 1967 (Fig. 5) mirrors that of the United States as a whole. By the late 1960s, exploration in most of the prospective petroleum provinces in the country—the North Slope of Alaska and the deeper-water Gulf of Mexico being prominent exceptions—had been underway for at least 50 years, and from an exploratory standpoint most of these provinces had matured. In any area, as the number of wells increases, understanding of the many factors affecting oil accumulation increases correspondingly. Eventually, nearly all significant reservoirs and their structural and stratigraphic trapping styles (called "geologic plays") are identified. The play types are exploited through a combination of random (or trend) drilling and prospecting driven by science and technology. As the process continues, the mean pre-drilling prospect size, which is based on historic discovery sizes, becomes progressively smaller. The trend of diminishing prospect size is a natural outgrowth of increased well density, and occurs simply because it is more difficult to hide large fields in the progressively smaller areas yet to be drilled.

Most geologic plays reach a point at which the potential reward no longer justifies the risk and expense of large-scale exploration, and activity moves elsewhere. For Oklahoma as a whole, that point was reached in the late 1960s (Fig. 6). The

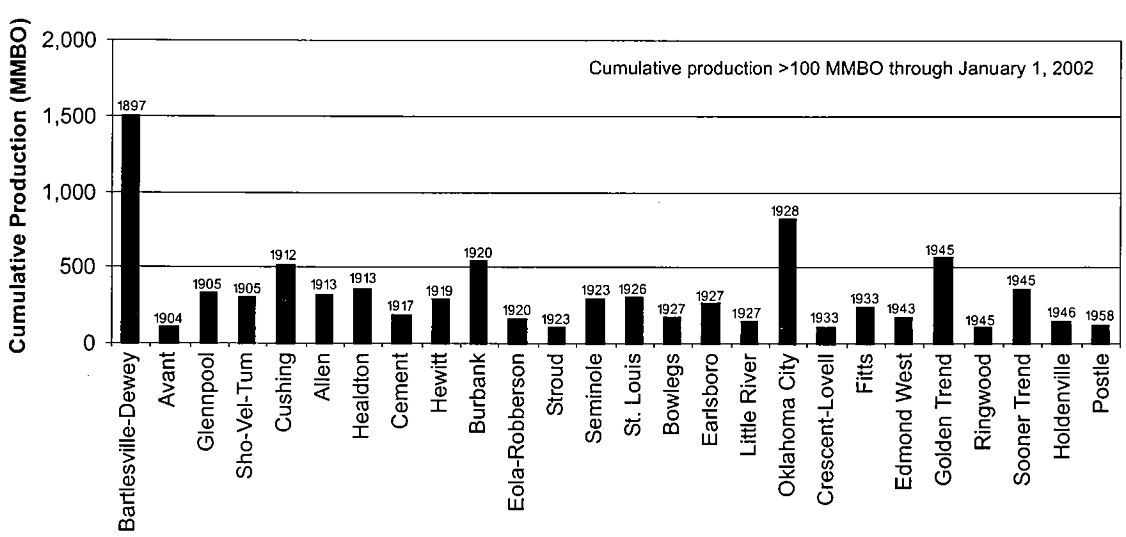

Figure 4. Major oil fields in Oklahoma; their cumulative production with discovery dates. From Lay (2001).

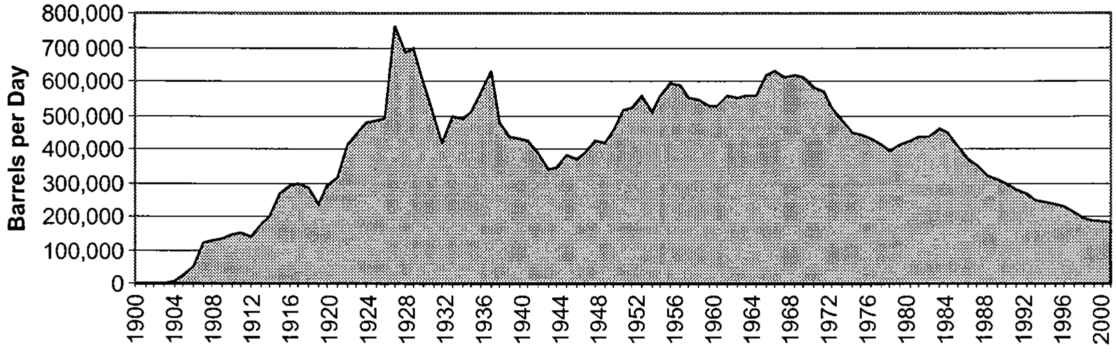

Figure 5. Historical oil and condensate production in Oklahoma. From Claxton (2001).

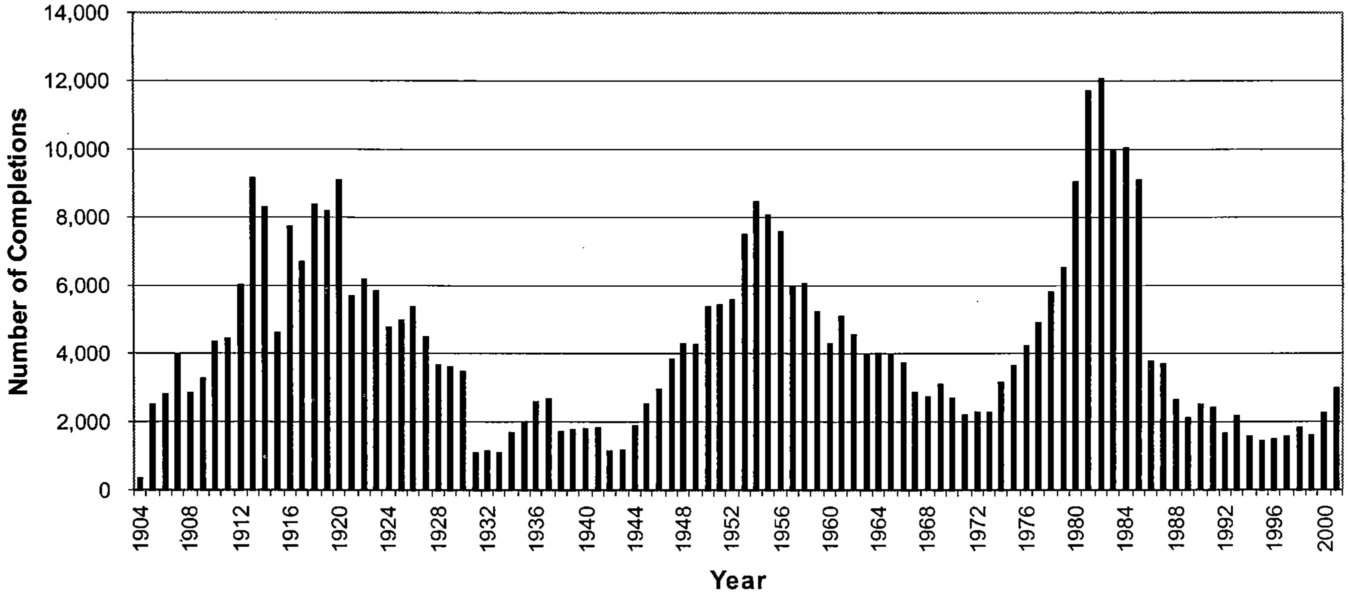

Figure 6. Oklahoma's well-completion history (producers and dry holes). From Claxton (2001).

price of crude oil had remained nearly flat for decades (Fig. 7), and discovery sizes no longer justified widespread exploration. This conclusion is inferred from the overall completion history and discovery rates, as the State did not record new-field wildcats until 1980. In 1967 oil production began a long downhill slide only briefly interrupted by the drilling boom discussed below. During the late 1960s the State's productive capacity was maintained by its older, larger, longer-lived fields. Here thousands of wells continued to produce, many in enhanced recovery projects involving water injection. Such larger fields take longer to drain, and lend themselves to recovery-enhancement techniques that usually continue for decades.

In that environment began the last major drilling boom in Oklahoma. In spite of weak drilling activity, oil production reached its second-highest peak in 1967, when about 231 MMB was produced (Claxton, 2001). A steep decline ensued between 1970 and 1975, averaging 6.1% per year (Fig. 5). Using the average number of oil completions from 1967 to 1974 (~1,250) as the pre-boom average: the drilling boom began slowly in 1975, peaked in 1981, and ended in 1987. (Figure 8 shows completions, which—because more than one oil reservoir may be stacked in a single well—only approximates actual drilling.) The jump in activity was caused not by the opening of a new geologic play, nor by a technological advance, but by a rapid increase in crude oil price beginning in 1974 (Fig. 7). From an economic standpoint the near doubling of Oklahoma crude prices—from $3.78 per barrel in 1973 to $7.18 in 1974—had the effect of doubling every oil well's production rate, as well as the value of its reserves in the ground. In one year the rise in price halved the reserves necessary for a well to make money. In addition, as the years passed and the expectation of continuing price increases was factored into economic analyses, progressively smaller well recoveries became attractive.

The State has separated oil and condensate production since 1975, which allows these statistics to apply to oil alone: after a period of steep (>6%) declines, from 1975 through

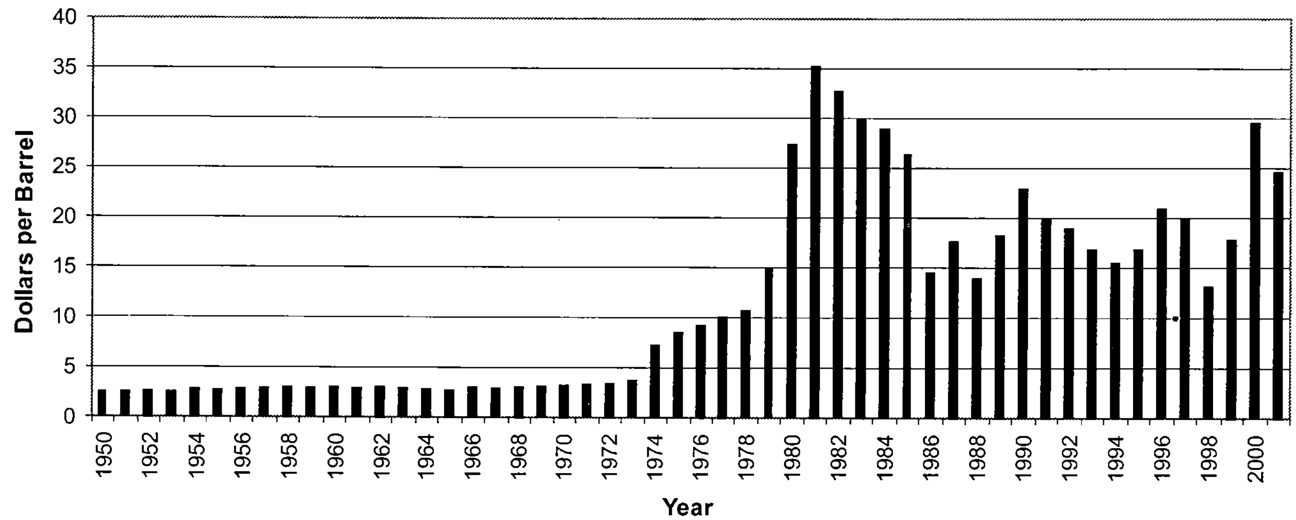

Figure 7. Average annual crude-oil price (unadjusted) in Oklahoma. From Claxton (2001).

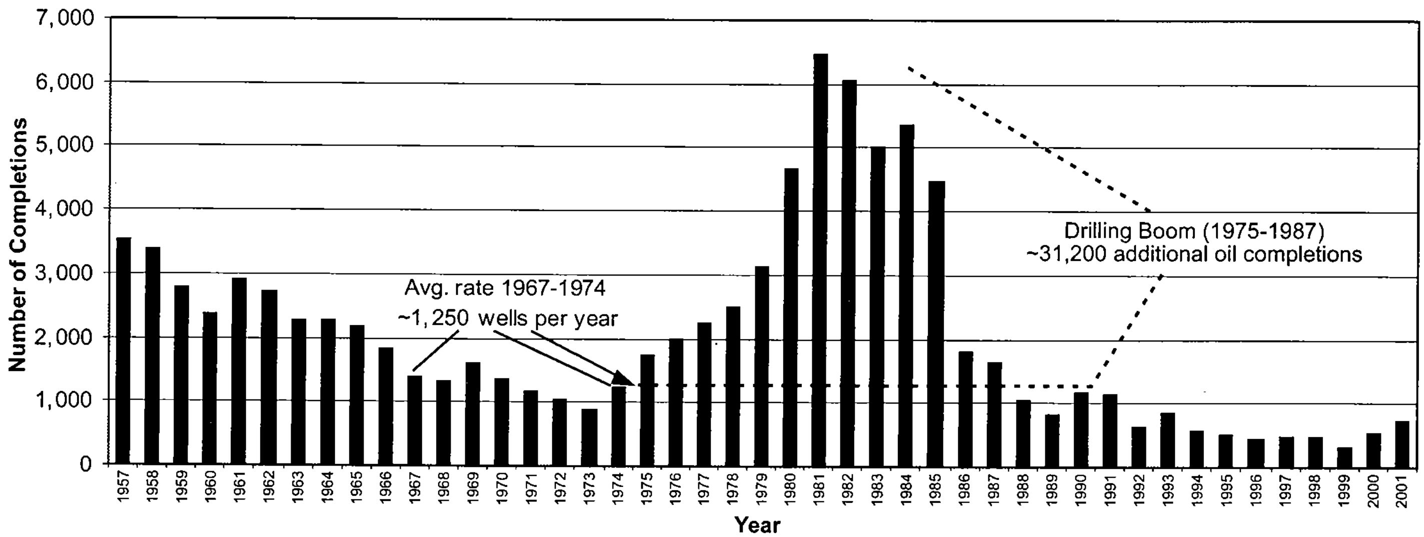

Figure 8. Historical oil-well completions in Oklahoma, showing the last major drilling boom. From Claxton (2001).

1979 the annual decline in Oklahoma's oil production averaged about 3.5%. Increased drilling during the boom inclined production from 1979 through 1984 (Fig. 9), but this 5-year rise was followed by a precipitous 6.6% annual decline from 1984 through 1990. In succeeding years the oil production curve flattened, until reaching the rather steady 3.1% average decline observed since 1993. By comparison, with large discoveries still being made in less mature areas, like the deep-water Gulf of Mexico, overall U.S. oil production for the same period (1993–2001) declined only 2.2%. Higher oil prices and the resultant increase in drilling for 2000 and 2001 have tended to flatten both the overall U.S. and Oklahoma production declines. However, with no significant new fields being added in Oklahoma, our long-term decline will probably remain significantly above the national rate.

On the Figure 9 graph, if we extend the line depicting the 3.1% decline since 1993 backwards through the boom years, it intersects the line for actual annual production in 1979. By that analysis: the area of the production curve above the artificial 3.1% decline curve (from 1979 through 1993) represents oil produced as a result of the increased drilling. This volume is 234 MMBO, and translates—with about 31,200 extra completions necessary for the increase—to 7,500 barrels per completion between 1979 and 1994. Although data are not available for determining the typical number of completions per well in Oklahoma, the average ultimate recovery for an oil well drilled during the boom is unlikely to be much more than 10,000 barrels.

Methods for calculating the volume of oil produced as a result of the drilling boom can vary, but probably not significantly from this analysis. In the six years after the end of the production boost (1993–1999) Oklahoma's oil decline averaged 4.5%. Given that this decline is significantly greater than the 3.5% before the boom, we can argue that the bulk of the 234 MMBO found was accelerated production—oil that would have eventually been produced from existing wells.

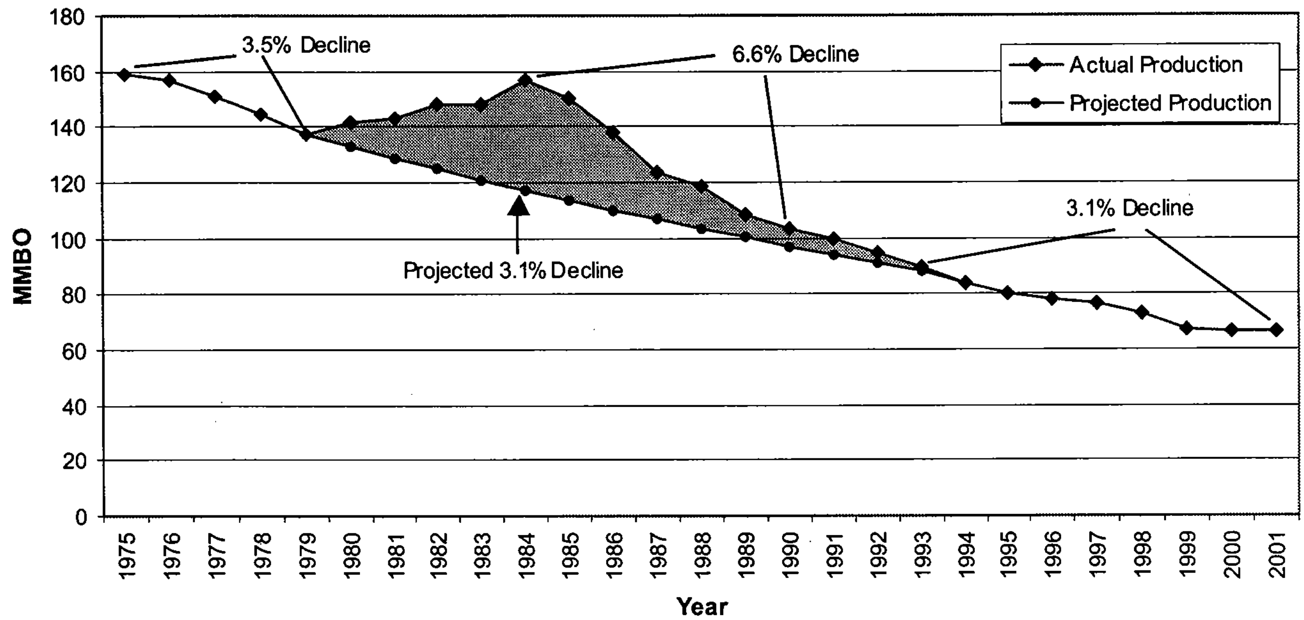

Figure 9. Annual oil production in Oklahoma, showing oil produced as a result of drilling boom. From Claxton (2001).

This contention that insubstantial new reserves were discovered is supported by the average success rate seen during the boom years of 1975 through 1987. The proportion of producers (non-dry holes) in that period has been shown by the Oklahoma Corporation Commission (Claxton, 2001) to range between 65% and 75% (Fig. 10). True wildcat success rates are far less than 65%, and the dry-hole percentage indicates that most drilling and completion activity during the boom was developmental. For the discoveries that were made, their small size is confirmed by their short-term impact on the State's production profile. Note the decreasing proportion of oil completions, relative to gas, that occurred after the drilling boom; it reflects both a percentage and an overall numeric reduction in oil-targeted drilling through time. The drilling boom nominally lasted through 1987. However, because of rapid declines and progressively less oil drilling, the divergence from the pre-boom production decline shrank dramatically after 1988, and was gone entirely by 1993—the year in which the positive effect of the drilling boom disappeared (Fig. 9).

From a Statewide perspective, except for the acceleration of tax revenues, another drilling boom has little long-term value to Oklahoma. It may be enjoyable as long as it lasts, but it would only hasten the end of meaningful oil production. Higher prices for oil would aid the State's oil industry, certainly in the short term. However, if the increased income is not used to initiate investment in enhanced recovery projects, the party will be very short. But more on this later.

WHERE DO WE STAND NOW?

State tax records show that cumulative oil (and condensate) production from Oklahoma totals about 14.5 billion barrels. The State ranks fifth in crude oil produced and accounts for 3% of national production (Hinton, 2001). That's about a quarter of the peak rate reached in 1927, and is roughly equal to that of 1913. Although the volume is less than in the past, at $25 per barrel 2001's production was still worth $1.7 billion.

Apart from the boom years, Oklahoma's oil production has, since 1967, undergone a generally continuous decline. The drilling boom in the late 1970s and early 1980s temporarily reversed the trend, but since the late 1980s the general decline has been firmly reestablished. Up-ticks in oil price and drilling in 2000 and 2001 have tended to level production, but, at this writing, 2002 seems likely to restore our long-term 3.1% decline. Because of the large number of wells in both the oil-producing and potentially oil-producing regions of the State, it is unlikely that the overall decline will change markedly as a result of new discoveries. Some sparsely drilled areas with oil potential do exist, and some may eventually prove economically viable. However, even taken together they offer no reasonable hope of markedly changing the trend.

In the early days, drilling activity rose and fell with the number and size of exploratory successes. Today, Oklahoma's oil industry is mature, and oil production nationally is at 100% of capacity, so price is the key variable that affects activity. Because the U.S. consumes more than twice as much oil as it produces, price will remain beyond our control, as will other major factors affecting the health of the oil industry in the State. The bulk of the State's oil comes from low-rate, stripper wells (<10 barrels per day), mostly in large fields that have been producing for decades. The maturity of the industry is highlighted by the average production rate for an oil well in Oklahoma—about 2.2 barrels per day. Compare that with the national average, which is about 11 barrels per day.

At the beginning of 2002, Oklahoma had about 84,000 active oil wells, producing about 183,000 barrels per day. Such low-rate wells are more sensitive to oil price than higher volume wells because the income generated is often not much

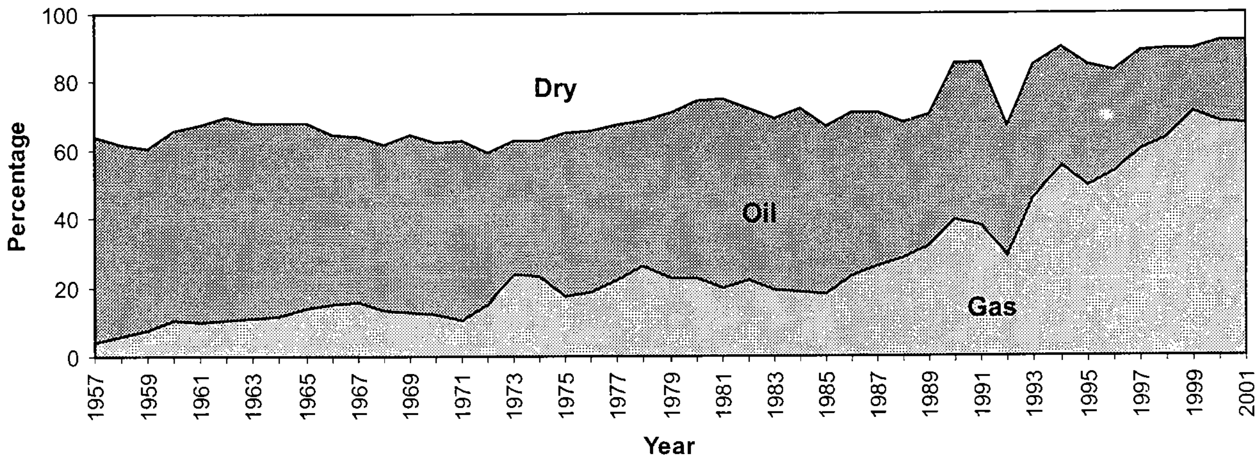

Figure 10. Oklahoma's well-completion history (all wells). From Claxton (2001).

more than the operating expense. The wells continue in production as long as maintenance is minimal and little more is required than simply collecting the oil. However, if mechanical failure requires significant expense, or if the oil price falls below an economic threshold, the well will go idle. The length of time between being shut-in and being plugged and abandoned (sometimes just abandoned) depends on the endurance of the operator and how long the price remains uneconomic. Once a well is plugged, production from its drainage area is usually lost forever. Even if the oil price rises, the prospect of another low-rate producer is likely to discourage reentry or workover of an existing well, much less drilling a new one.

Of approximately 100,000 wells producing in 1984—the last peak year of oil production—fewer than half are still producing (Claxton, 2001). This helps explain the steepness of the initial post-boom decline. It also points to the need to do as much as possible to keep stripper wells producing. In 1992 the Oklahoma Legislature created the Commission on Marginally Producing Oil and Gas Wells for the express purpose of helping operators manage marginally producing wells. The intent was to help operators weather the inevitable price dips, and keep the State production decline to a minimum. In addition, the Oklahoma Geological Survey offers low-cost, play-based workshops and a variety of other programs to aid operators. The programs help identify practical techniques and technology for finding new fields, as well as how to produce oil efficiently in existing fields.

WHAT'S LEFT?

The simplest way to markedly increase long-term oil production is to discover large, long-lived fields. The size distribution in any petroleum province is the same, with larger, easier-to-find fields making up a disproportionate share of total production and reserves. Oklahoma is no exception: its 26 major oil fields account for 59% of the oil produced. Each of the next 137 fields (in order of size) has produced at least 10 MMB of oil. Together accounting for only 5% of the total number of oil fields in the State, these 163 fields account for over 83% of production (Fig. 11).

The mean discovery date for Oklahoma's major fields is 1925, and for those that have produced more than 10 MMBO, 1934 (Lay, 2001). The last field to be discovered with recovery of more than 10 MMBO was the Wheatland Field (in Oklahoma County), discovered in 1981 (Fig. 12). A handful of fields not on this list will eventually break the 10 MMBO hurdle, but none by much. In total approximately 3,100 fields with some oil component, many already abandoned, have been found thus far. In size they are strongly skewed toward the small end of the spectrum, the fields with less than 10 MMBO of recovery averaging only 800 MBO.

These facts have not been lost on the industry, and the bulk of oil drilling continues to be directed towards infilling, extending, and adding new reservoirs to existing fields. Some areas may be under-explored, an example being the part of the Ouachita Uplift in central Atoka County and southern Pittsburg County (Campbell and Suneson, 1990). However, these are all high-risk areas, and even the greatest optimist would find it difficult to assign speculative reserves amounting to as much as 1% of past production.

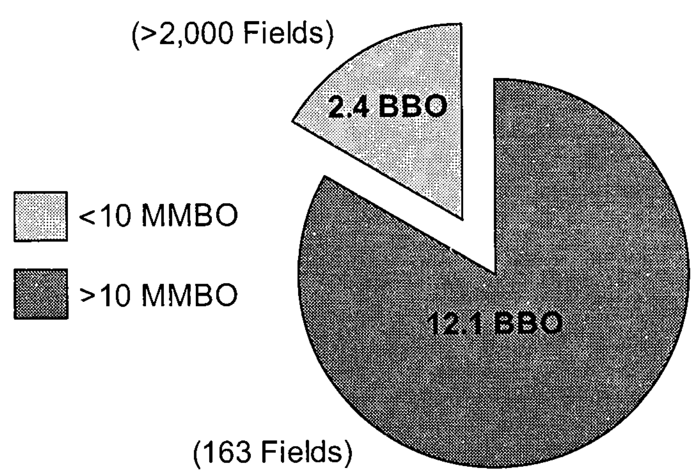

Figure 11. Oklahoma's oil (and condensate) production by field size. From Lay (2001).

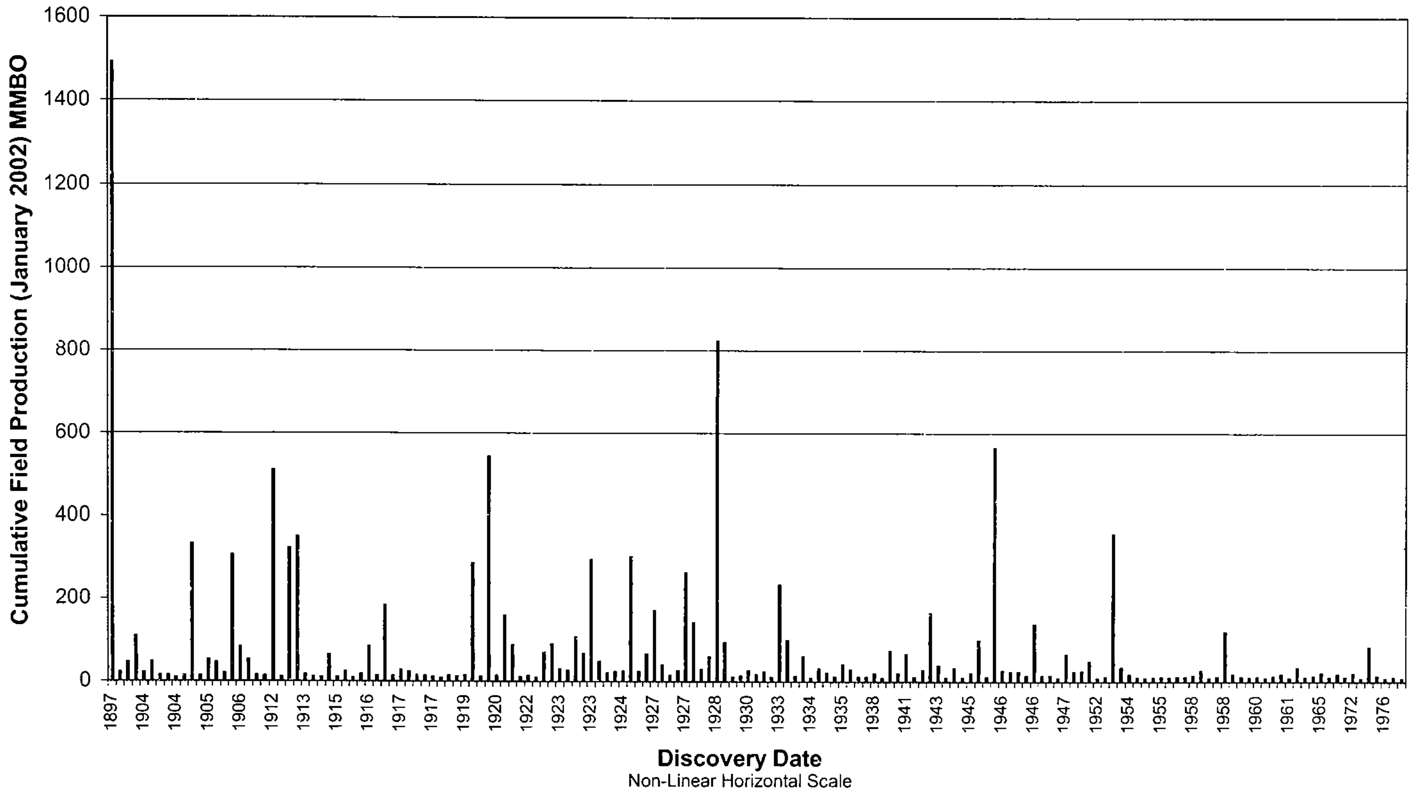

Figure 12. Oklahoma's oil-field discoveries by date (>10 MMBO cumulative recovery). From Lay (2001).

New-field wildcat numbers can be a measure of interest in exploration. In Oklahoma, fields are defined geographically, and to be declared a new-field wildcat a well must be located more than one mile from established production. Any well completed within a mile of production, whether producing from a different formation or from a disconnected reservoir compartment in the same formation, is defined as developmental. As nearly 500,000 wells have been drilled in the State, the feat of making a true discovery has become increasingly difficult. The Oklahoma Corporation Commission has kept data on the total number of wildcats drilled since 1980, shortly before the last drilling boom peaked (Fig. 13). Although these data include both oil and gas drilling, they accurately mirror the precipitous decline in overall exploratory activity through the middle and late 1980s (Fig. 8).

Because so many variables are involved, determination of remaining reserves is notoriously difficult. However, the situation in Oklahoma is somewhat more straightforward than in many other areas. Few new reservoirs are being added to the producing mix, and with 84,000 active wells scattered throughout 2,000 fields, the aggregate decline is well established. The primary source of uncertainty is, as always, the price of crude oil. A prolonged rise in price, as was seen in 2000 and 2001, can increase drilling and completions and thereby reduce the decline rate, at least in the short term. A prolonged fall in price can drop many wells beneath their economic threshold, causing large-scale abandonment and a corresponding increase in the rate of decline. For Oklahoma, changes in annual estimates of remaining reserves are based almost exclusively on accounting adjustments centered on new pricing assumptions, rather than on the addition of new reservoirs or fields.

In their last estimate at the beginning of 2000, the Energy Information Administration of the U.S. Department of Energy projected Oklahoma's proved oil reserves at 610 MMBO (Hinton, 2001). (The estimate was based on a poll of the State's thousands of operators.) Subtracting actual production through January 1, 2002, yields remaining reserves of 477 MMBO. Thus the EIA estimate leads to the conclusion that 97% of the State's ultimate oil recovery has already been produced.

Reserve estimates are meant to quantify bankable production, so they must take into account any factor that may have a negative impact on the oil actually reaching the market. Assuming that long-term oil prices remain stable—an unlikely event—the State's production decline should stay near the 3.1% rate that has prevailed for the last 9 years. If it does continue so, by 2010 the EIA reserve volume will have been produced. At this time the average well will be producing about 1.2 bbls per day, and Statewide production will still be more than 100,000 bbls per day. Economic production rates vary from area to area and well to well, but a large fraction of the State's production already comes from wells making less than 1 bbl per day. Given current trends in drilling and plugging, if the average abandonment rate for an oil well in Oklahoma is assumed to be 1 bbl per day, remaining reserves at the beginning of 2002 should be about 790 MMB. If this were reduced to 0.5 bbl per day, 1,080 MMBO would remain. Under such assumptions the good news is that (short of a pricing catastrophe) the chances are excellent that Okla-

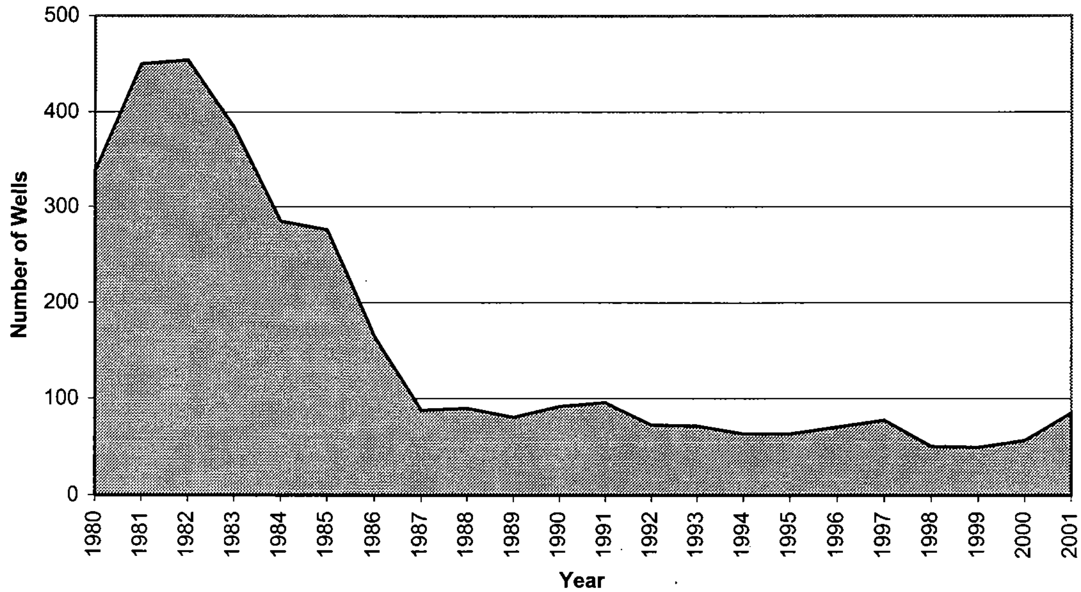

Figure 13. Historical new-field wildcat drilling in Oklahoma. From Claxton (2001).

homa will produce significantly more oil than the EIA now expects. The bad news is that the end is in sight.

The truth is that another price spike and drilling boom would bring only a short-lived respite to the long-term drop in Oklahoma's oil production. Worse, it would probably bring on an even sharper decline in succeeding years because the vast bulk of the increase would likely be in accelerated production. The likelihood of making one or more oil discoveries that would significantly change the State's long-term production curve has become vanishingly small. Therefore the only way to make a long-term, positive impact on the oil-production decline in Oklahoma is to enhance recovery in fields that have already been found.

Studies by the Oklahoma Geological Survey of fluvial-dominated deltaic reservoirs, from which a large fraction of the State's oil has come, indicate a current average recovery factor of about 15% of the original oil in place. Even if average recovery is stretched to 25%, three times as much oil as has already been produced is still in the ground. Cumulative oil recovery stands at more than 14 BBO. Regardless of how it is calculated, the volume of oil still residing in Oklahoma reservoirs is not less than 42 BBO, and could be as much as 93 BBO, and all of it has been mapped.

Even a small increase in the overall recovery percentage would yield huge rewards. The only way to markedly enhance the State's oil future is to systematically re-evaluate the means of increasing recovery in existing fields. The effort would be manpower intensive, requiring collaboration between engineers and geologists. Acquisition of data—pressure and production data especially—would take time and usually be incomplete. In spite of the State's forced unitization rules, land acquisition would be a major problem, but diverse ownership contributed to the haphazard field development that has left so much oil in the ground.

Much of the secondary and enhanced recovery work done thus far has been piecemeal. Except in the largest fields there has been little coordination between operators and undoubtedly little detailed, field-wide reservoir simulation work. A map of the waterflood unit boundaries maintained in the NRIS database (those active since 1979) shows an irregular patchwork of secondary recovery projects that overlay roughly half of the oil-producing leases in Oklahoma. Based on field studies by the OGS, many waterflood units have been subdivided into smaller areas that are operated in isolation and at cross-purposes with the management of adjacent units.

A necessity for increased oil recovery is regional mapping to show in detail the depositional environments of reservoirs. Such maps help define actual and expected reservoir geometry, and they can lead to the identification of areas with the greatest potential for undrained reservoir compartments. Combined with regional porosity and permeability trends, the maps can be used to assign provisional recovery factors for reservoirs with similar characteristics. This can then be compared with actual production to set practical recovery goals. (Such recovery factors would still be minimum values because they cannot take into account future technical improvements in drilling, completion, or recovery.) When actual recovery factors are applied to the volumetric estimates of the original oil in place, we can determine a realistic incremental recovery target using proved techniques. Analysis will not only highlight the most efficient techniques, but also reveal a practicable course of action for various types of reservoirs.

Many factors affect the capacity of a reservoir to produce oil, and their relative importance varies from place to place. Primary factors include porosity, permeability, thickness, and geometry—the reservoir's shape and connectivity. A reservoir classification scheme based on these four variables is adequate in identifying poorly drained areas and rank them by incremental oil recovery. The most attractive projects can be further evaluated based on other factors that affect recovery and economics. The additional factors include depth, well spacing, drilling and completion practice, reservoir pressure, drive mechanism, oil gravity, and gas saturation. The ranking of those projects with the greatest potential reward could be further refined on the basis of non-geologic criteria such as data availability, well condition, and ownership.

Much detailed work is necessary to determine the economic feasibility of such projects, but as most of the State's largest oil accumulations were discovered more than 70 years ago, and initial (often intermittent) waterflooding commenced 20–30 years after their discovery, there are undoubtedly many opportunities. Consider only the 163 fields that have each recovered more than 10 MMBO: every 1% of incremental recovery would add about 500 MMBO, or the equivalent of five major oil fields. With a series of long-lived, and potentially high-recovery projects, Oklahoma's oil production could actually experience a modest increase. Although an increase might be brief, the effort would certainly extend the life of the industry and the State's oil revenue for decades beyond current estimates.

We face no shortage of challenges associated with such an undertaking, but the potential rewards are great. Enhanced recovery is the only way that Oklahoma can add to its dwindling oil supply. Our biggest problem lies in forecasting the price of oil over the long term. That is especially true for projects that have substantial up-front costs and a long payout. However, once the initial investment is digested and production begins to respond, the economics for large enhanced-recovery projects usually become far more robust. A prudent strategy, in anticipation of the sustained oil price increase that must inevitably come, is to gather data and rank candidate fields now, while interest in such projects is relatively low.

ACKNOWLEDGMENTS

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Aspects of Coal Geology in the Western Interior Coal Region of the United States*

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ABSTRACT.—The Western Interior Coal Region extends across parts of six states in the Midcontinent of the United States (Arkansas, Iowa, Kansas, Missouri, Nebraska, and Oklahoma). All coal of commercial importance occurs in strata of Middle Pennsylvanian age. The coals in the region range in rank from high-volatile C bituminous to semianthracite. In general, heat values of coals in the region range from 10,000 Btu/lb to >14,000 Btu/lb on an as-received basis. Most of the coal is classified as high sulphur coal (>3% sulphur on an as-received basis). All coal currently produced in the Western Interior Coal Region is mined by surface methods, with the exception of one underground mine in Oklahoma. In the larger open pit mines, draglines are a key element used in the overburden removal process. Bulldozers, dirt-scrapers, and front-end loaders are often used in smaller surface mines to remove overburden. Coal is transported by trucks or railroad cars to destination points. Coal production in the Western Interior Coal Region has declined in the past 15 years, due largely to environmental concerns about burning high-sulphur coal. Oklahoma's production of 1,733,914 short tons led the six-state area in 1998. Missouri, Kansas, and Arkansas reported lesser production tonnages, and Iowa and Nebraska reported none. Land reclamation is an integral part of the coal surface mining process. In accordance with the Federal Surface Mining Control and Reclamation Act of 1977, mined land must be returned to its approximate original contour and revegetated. Coal operators must post bonds to ensure proper reclamation. Land reclamation has proved highly successful in the Western Interior Coal Region. About 90% of coal consumed in the United States is used by the electric power industry. Coal is by far the major source fueling electricity production, accounting for more than 55% of electricity generated by public utilities.

INTRODUCTION

The coal fields of six states located in the Midcontinent of the United States comprise the Western Interior Coal Region (Fig. 1). The region extends across parts of Arkansas, Iowa, Kansas, Missouri, Nebraska, and Oklahoma. The coals range in rank from subbituminous to semianthracite, but they are predominantly high-volatile bituminous.

Although coals (Morrowan, Atokan, Desmoinesian, Missourian, and Virgilian Series) occur throughout the Pennsylvanian System (Howes, 1990, fig. 3), all coal of commercial importance occurs in Middle Pennsylvanian strata. Figure 2 is a generalized stratigraphic column covering an area more or less centrally located in the region (Hemish, 1988). Because of differences among the states in the use of stratigraphic nomenclature, and differences in criteria for selecting formation boundaries, a generalized stratigraphic column covering the entire region is too complex for the present paper. Many of the named commercial coal beds in northeast Oklahoma correlate with beds of the same names in Kansas and Missouri, areas where non-coal markers are persistent and useful for interpretive stratigraphic work.

COAL RANK AND QUALITY

Table 1 presents a generalized collection of pertinent coal data from all six states in the Western Interior Coal Region. Coal beds of Pennsylvanian age range in rank from subbituminous (Iowa and Nebraska) to semianthracite (Arkansas). In general, the rank increases from north to south, with the highest rank coals occurring in the eastern part of the Arkoma Basin, a downwarped tectonic and sedimentary trough that extends from southeastern Oklahoma into central Arkansas (Fig. 1). In the eastern part of the Arkoma Basin in Arkansas, the coal is semianthracite, whereas in the western part it is low-volatile bituminous. In Iowa, far to the north, the coal is mostly high-volatile C bituminous.

Coal beds of the Western Interior Coal Region range from low- to high-ash and from low- to high-sulphur. The ash content is erratic and probably controlled by the depositional environment; the sulphur content is also variable. The lowest sulphur coal beds are invariably in localities where marine or calcite-bearing rocks are sparse or absent. Higher sulphur coal beds are commonly overlain by marine rocks. Most of

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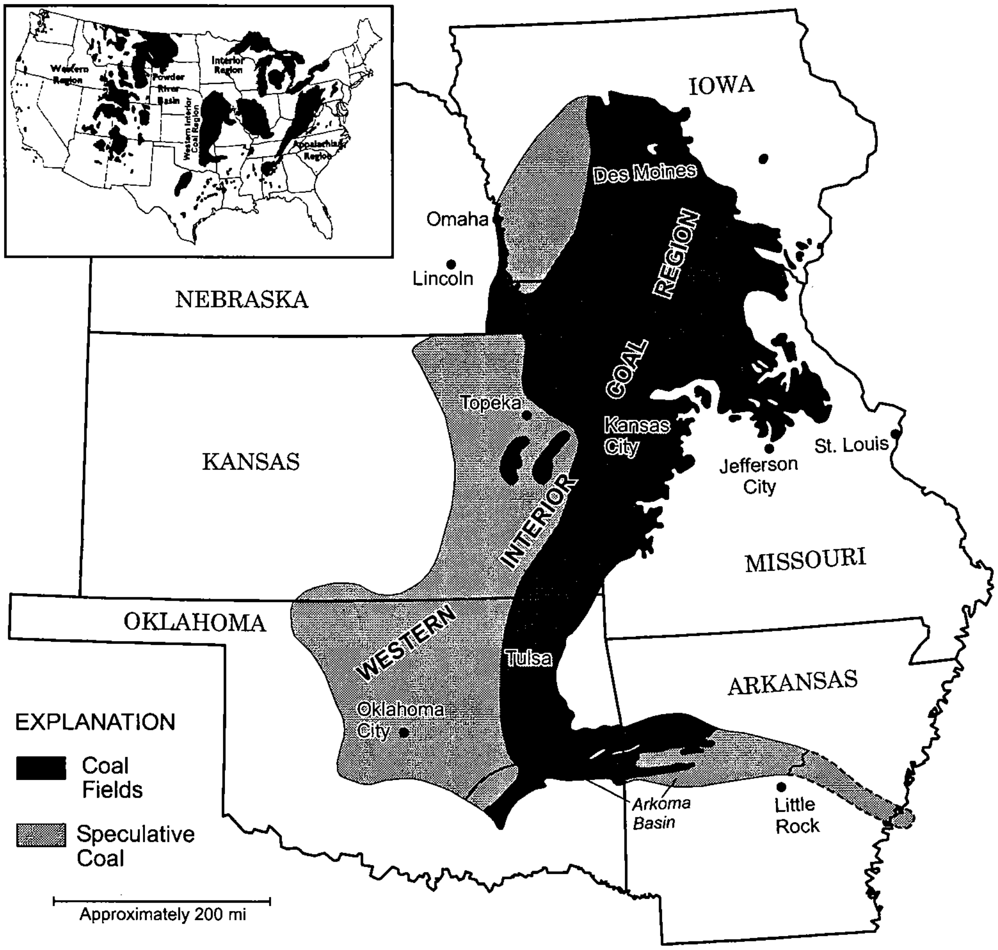

Figure 1. Map showing the location of the Western Interior Coal Region of the United States (modified from Wood and Bour, 1988).

the coal is classified as high-sulphur (>3% sulphur on an as-received basis). In general, heat values of coals in the region range from 10,000 to >14,000 Btu/lb on an as-received basis.

COAL RESOURCES

Original resources in the Western Interior Coal Region total 92,103,844,000 short tons, exclusive of the preliminary estimates of deep coal in Kansas (Table 1). Cumulative production in the region totals ~1,618,041,000 short tons. Therefore, the remaining coal resources represent more than 98% of the original resources.

COAL PRODUCTION

Only four states reported coal production in the Western Interior Coal Region during 1998. They are ranked according to production in the following list:

1. Oklahoma.—1,733,914 short tons from 12 surface mines (1,439,709 short tons) and one underground mine (294,205 short tons). The coal ranged in rank from high-volatile to low-volatile bituminous and was produced from eight coal beds by four different companies. The leading producer was Farrell-Cooper Mining Company with 948,073 short tons (B. J. Cardott, personal communication, 1999).

2. Missouri.—372,060 short tons from four surface mines. The coal was high-volatile bituminous in rank and was produced from three coal beds by four different companies. The leading producer was Midwest Coal, LLC, with 184,377 short tons (D. C. Smith, personal communication, 1999).

3. Kansas.—344,792 short tons from four surface mines. The coal was high-volatile bituminous in rank and was produced from two coal beds by two different companies. The leading producer was Continental Coal, Inc., with 340,595 short tons (L. L. Brady, personal communication, 1999).

4. Arkansas.—36,261 short tons from five surface mines. The coal was low-volatile bituminous in rank and was produced from one coal bed by five different companies. The leading producer was Russ & Sons, with 18,652 tons (W. V. Bush, personal communication, 1999).

Iowa's lack of coal production can be attributed mostly to coal quality. Iowa's reserves are lower in rank, have lower heat values and comparatively high sulphur levels. Nebraska's coal industry has been dormant for many years, primarily due to the economics of mining deeply buried, lower-rank beds. The combined total production of coal in the Western Interior Coal Region was 2,487,027 short tons in 1998, of which 2,192,822 short tons was produced by surface mining methods.

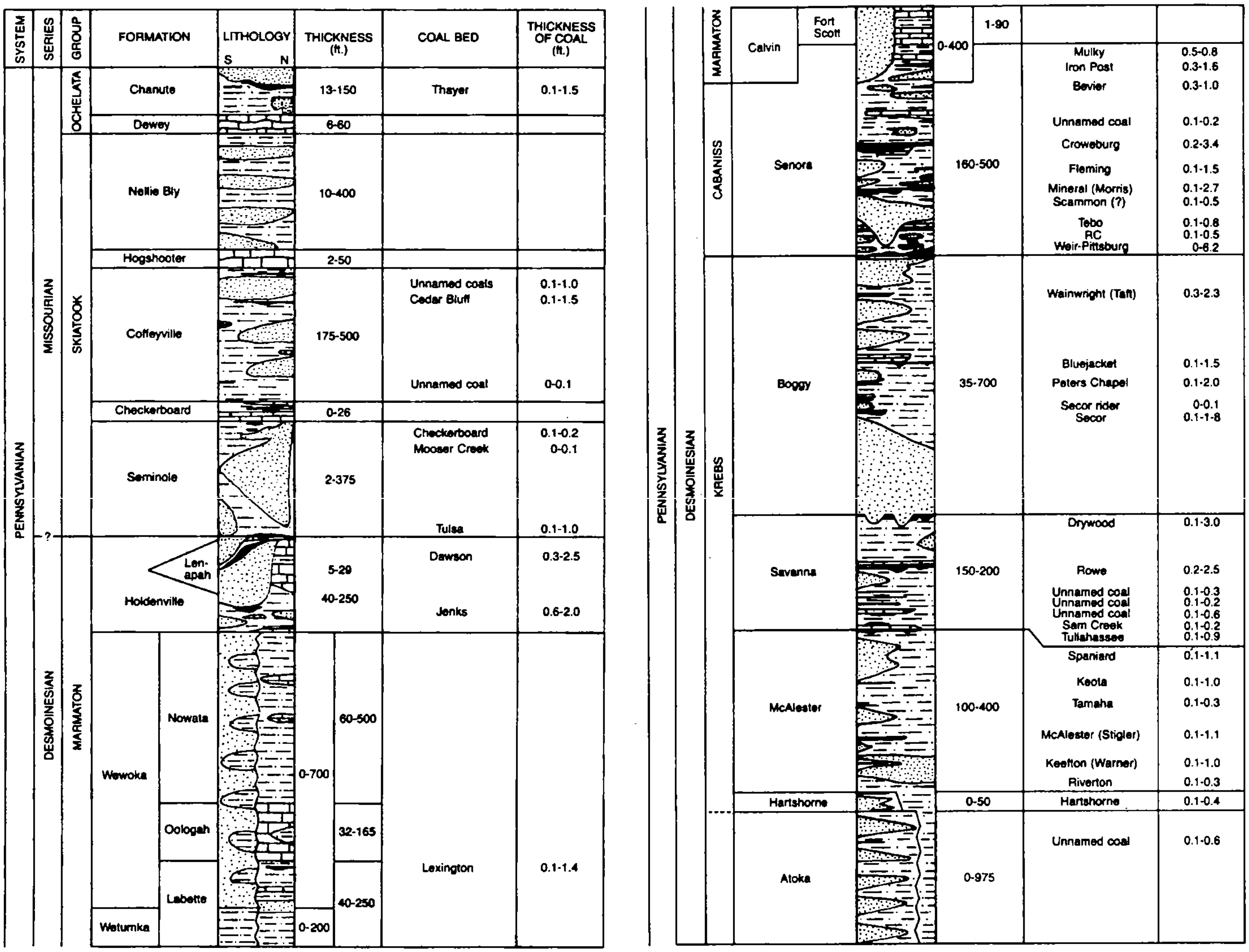

Figure 2. Generalized stratigraphic column of coal-bearing strata of the northeast Oklahoma shelf (from Hemish, 1988, fig. 6).

MINING

Coal resources are considered to be economically strippable if the thickness of overburden is <100 ft and the ratio of overburden thickness to coal thickness is <20:1. (If a coal bed has superior qualities such as low sulphur content, or coking properties, the stripping ratio is <30:1) (Hemish, 1989). If the coal is >100 ft deep, it is considered recoverable only by underground mining. The minimum thickness considered for underground mining is 14 in. (The data above are applied specifically to Oklahoma coal, but similar criteria are used in the five other states in the region.)

Several methods of overburden removal were used in stripping operations in the Midcontinent area. In general, coal beds to the north of the Arkoma Basin are particularly amenable to surface mining because of the low dip of the strata (1–2°). The type of equipment used is to a large extent dependent on the depth of mining. In larger operations electric draglines have proved to be practical and efficient when used in conjunction with smaller equipment such as bulldozers and front-end loaders. Smaller companies operate with only crawler tractors, dirt scrapers, and front-end loaders for removal of overburden and reclamation work.

LAND RECLAMATION

Land reclamation is an integral part of the coal surface-mining process. Prior to the enactment of the Federal Surface Mining Control and Reclamation Act of 1977, coal companies were not required by law to reclaim mined land (Johnson, 1974) (Fig. 3), or they were required to reclaim the land only partially (Fig. 4). Currently used reclamation practices seem to be quite successful in restoring mined land to productivity (Fig. 5). Terrain underlain by coal is variable across the region. Virgin land ranges from glaciated areas with subdued topography in the north, to mountainous terrain in the Arkoma Basin in the south. In rocky, tree- and brush-covered areas, mining and reclamation improve the value of the property by making it available for reforestation or revegetation with grasses suitable for livestock grazing. Most areas have at least a 1-ft cover of good topsoil (which is stockpiled prior to strip mining), and annual rainfall is gen-

Table 1. — Coal Data, Western Interior Coal Region, U.S.A.

Arkansas	Iowa	Kansas	Missouri	Nebraska	Oklahoma
Rank					
Low-volatile bituminous (80%) semianthracite (20%)	Subbituminous to high-volatile B bituminous (mostly high-volatile C bituminous)	High-volatile A, B, C bituminous	High-volatile A, B, C bituminous	Subbituminous to bituminous	High-volatile C bituminous to low-volatile bituminous
Original resources (short tons)					
2,225,700,000	Estimates range from 7.2 billion tons to 30 billion tons	18,700,000,000 (see "Notes" below for additional resources)	47,400,000,000	8,510,200,000	8,067,944,000
General characteristics					
Analyses (as-received basis) % moisture 1.4–3.0 % volatile matter 12.0–18.2 % fixed carbon 70.6–77.2 % ash 5.5–9.8 % sulphur 1.3–3.4 Btu/lb 13,499–14,363	Analyses (as-received basis) % ash 5–20 % sulphur 3–6 Btu/lb 9,000–11,000	Analyses (as-received basis) % moisture 3.0–17.0 % ash 5.0–34.0 % sulphur 2.0–10.0 Btu/lb (dry, ash-free basis) 13,570–15,120	Analyses (as-received basis) % moisture (avg) 11.1 % ash (avg) 11.5 % sulphur (avg) 4.27 Btu/lb (avg) 11,016	Analyses (as-received basis) % moisture (avg) 11.38 % volatile matter (avg) 43.71 % fixed carbon (avg) 40.62 % ash (avg) 4.29 (medium to high sulphur)	Analyses (as-received basis) % moisture 0.9–10.3 % volatile matter 7.8–43.6 % fixed carbon 44.3–72.3 % ash 2.6–22.6 % sulphur 0.4–6.5 Btu/lb 11,562–14,430
Production (short tons) 1998					
36,261	0	344,792	372,060	0	1,733,914
Cumulative production (short tons)					
106,227,800	375,210,000 (no production since 1994)	303,357,000	556,300,000	? (small tonnage; no mining since 1950)	276,946,000
Notes					
87% is less than 1,000 ft deep 79% is in beds 14–42 in. thick	Earliest recorded production was in 1840	Preliminary figures indicate a coal resource of ~53 billion tons for beds >14 in. thick and >100 ft deep	29.4 billion tons are >1,000 ft deep; earliest recorded production was in 1840	Only 10 million tons within 50 ft of surface; 8.5 billion tons from 1,000 to 2,300 ft deep	Commercial coal beds are 0.8–10.0 ft thick

Sources: Finkleman and others (1990); Sanda (1999).

Figure 3. Abandoned coal mine where coal was stripped in the 1950s in northeastern Oklahoma.

Figure 4. Mined land in northeastern Oklahoma, partly reclaimed in accordance with the Oklahoma Mining Lands Reclamation Act of 1968, which required leveling only the tops of spoil ridges to a width of 10 ft.

erally sufficient across the area (30–40 in.) to reestablish vegetation. Coal operators must post a bond to ensure proper reclamation.

COAL CONSUMPTION

The total production of coal in the United States was 1,090,000,000 short tons for 1997. Of that amount, 1,029,000,000 short tons was consumed in the United States (Energy Information Administration, 1998). Currently, ~90% is used by the electric power industry. Coal-burning electric-utility plants generate 55% of the electricity in the United States. The use of coal in the United States has risen almost steadily since the early 1970s. On a per capita basis, coal consumption in the 1990s was nearly 20 lbs per person per day. Virtually all of the growth has been due to the increasing amounts used to generate electricity (Energy Information Administration, 1998).

Present use of coal produced in the Western Interior Coal Region is almost totally for electric power generation and

Figure 5. Reclaimed mined land in southeastern Kansas, showing the lush growth of vegetation.

cement manufacture. Some tonnage of the higher rank Arkansas coal is used by the metallurgical industries, as well as for home heating, briquette manufacture, and for chemical sources of carbon (Haley, 1978).

CONCLUSIONS

Because of its generally high sulphur content, federal regulations requiring reduced sulphur emissions from power plants, more stringent government controls on mining, and increased competition from low-sulphur Wyoming coal, both production and consumption of Western Interior coal has steadily declined since the early 1980s. Development of fluidized bed combustion and the construction of plants designed to use this process appears to be the best answer for future use of the region's coal. Methane derived from coal beds at depths >500 ft has become an important energy source in the 1990s. Coalbed methane has grown from almost complete obscurity 20 years ago to become a commercially important, natural gas resource. In 1997, 5.9% of total U.S. domestic natural gas production was from coalbed methane (Hill and others, 1999). The abundance of deep coal in the Western Interior Coal Region (Table 1) indicates considerable potential for development of this resource. By the end of September 1999, 808 coalbed methane completions had been reported in Oklahoma alone (Cardott, 1999).

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BP America Inc. donates $5.5 million gift package to OU

BP America Inc., a global oil and gas production and refining company, has given a valuable collection of earth core samples from oil and gas wells valued at more than $2.5 million to the University of Oklahoma along with a $3 million grant to support research programs in geology and geophysics, petroleum exploration, and reservoir characterization.

"We deeply appreciate this unique gift from BP America," said OU President David L. Boren. "The impact of BP's donation goes far beyond its dollar value. The extraordinary core sample collection will enable our faculty, staff, and students to pursue several promising research opportunities and strengthen our leadership in this area."

The gift includes more than 100,000 boxes of core samples and rock cuttings totaling some 300,000 feet or around 57 miles of cores weighing in at some six million pounds. Also included are core analysis equipment and storage system components from BP's core facility in Tulsa. The University will receive the only Floroscopic core scanning system in the U.S. The technology, which can provide a 360-degree evaluation of a core sample, was originally patented by the company.

Left to right: David Maloney, vice president for University Development; John Snow, dean of the OU College of Geosciences; Tom Blackwell, BP vice president; and Charles Mankin, director of the Oklahoma Geological Survey and OU Energy Center, accept the inaugural shipment of cores from BP America Inc.

Core samples are cylindrical in shape and range in size from four to six inches in diameter. The cutting samples are ground up rock chips captured every 10 feet while a well is drilling. The core and cutting samples, taken from as deep as 20,000 feet, are used by scientists to understand the geology at great depths and increase the potential for discovering oil and natural gas.

"The diversity of the data represented by this collection is tremendous," said Tim Holt, BP Vice President, Onshore U.S. "These specimens were collected over many decades and provide a valuable history of exploration and production in this region and across the country. We are very happy to join with the University of Oklahoma to share the knowledge contained in this collection with the next generation of earth scientists."

BP's funding will support the consolidation of the materials with the extensive collections at OU and for facilities and improvements required to maintain the technical integrity of the core materials in a newly acquired research facility in Norman. OU is committing an additional $1.2 million toward the establishment of the new facility to be operated by the Oklahoma Geological Survey and which will provide much-needed additional research space.

The facility will bring together the core and samples provided by BP and the collections and petroleum-related information currently maintained at seven separate sites by the Oklahoma Geological Survey. Other participants in the Norman facility include the OU School of Geology and Geophysics in the College of Geosciences and several of the institutes within OU's Sarkeys Energy Center, including the Poromechanics Institute.

Dr. Roger Slatt, director of OU's School of Geology and Geophysics, pointed out that in addition to being a valuable new resource for future petroleum exploration in the State, the facility will "preserve rocks that record the history of the Earth and have scientific value for decades to come."

Dr. Charles Mankin, director of the Oklahoma Geological Survey and director of the OU Energy Center, noted that this first-class facility also will support exploration, development, and recovery by major companies and independent producers.

"It is the Oklahoma Geological Survey's intent to organize this new facility to make these materials easily accessible for those Oklahomans interested in exploring for oil and gas in our State," said Mankin.

BP is an international company involved in the exploration and production of crude oil and natural gas; refining and marketing, supply and transportation of hydrocarbons; and manufacturing and marketing of petrochemicals, and solar and gas-fired power generation. The company recently was listed as the number four company on Fortune's Global 500 list of the world's largest companies. BP has nearly half of its assets, resources, and people in the United States.

OGS Publication Sales Office and Log Library move to new location

New home of the OGS Publication Sales Office and Log Library showing the entrance on the northeast side of the building, located at 2020 Industrial Boulevard.

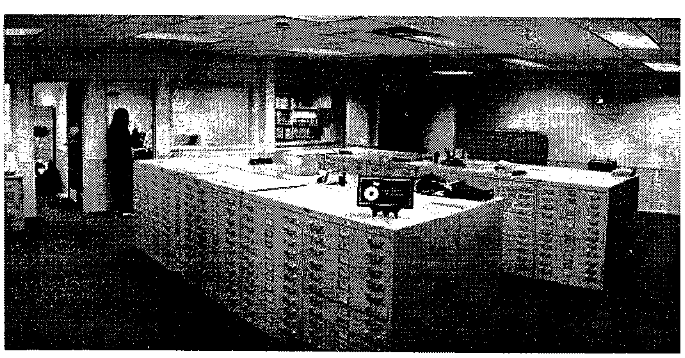
The OGS Publication Sales Office and the Log Library have moved to a new location at 2020 Industrial Boulevard in Norman. The building is the former location of SYSCO Food Services of Oklahoma, Inc.

"The new building provides easier access for the public and gives us vastly increased warehouse space for our publications, logs, and eventually for our collection of oil and gas well cores," Dr. Charles J. Mankin, OGS director and Sarkeys Energy Center director, said. "We don't have to worry about growing out of this space for a very long time."

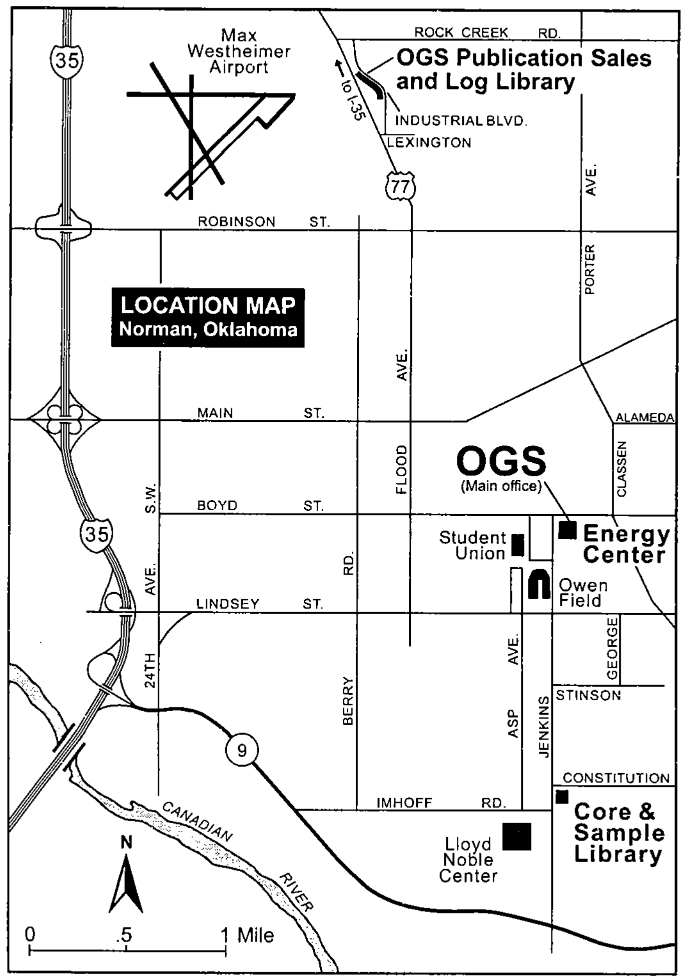
The OGS Log Library contains the State's official files of 5″-scale logs from more than 367,000 wells. Current additions of well logs, completion cards, and 1002A forms also are available to the public for examination.

The Oklahoma Geological Survey's main office will remain at the Sarkeys Energy Center on the University of Oklahoma's Norman campus.

For further information on publications, contact the Sales Office at (405) 360-2886 or e-mail <ogssales@ou.edu>. To contact the Log Library, phone (405) 447-3118.



OGS Publication Sales Office.



Location map.

new OGS publications

OPEN-FILE REPORT 9-2002

- **Brian J. Cardott, *compiler***
- **170 pages**
- **Three-ring binder**
- **$10**

Fourth Annual Oklahoma Coalbed-Methane Workshop

Prepared for a workshop held in October 2002, this manual presents an overview of coal as a gas source rock and reservoir, and it contains papers that examine factors affecting coalbed-methane (CBM) producibility, Oklahoma coal geology, Oklahoma CBM activity, Oklahoma CBM economic potential and completion practices, gas content measurement, and electric-log interpretation. The manual also includes three bibliographies on Oklahoma coal, Oklahoma CBM, and selected CBM references.

SPECIAL PUBLICATION 2002-2

- **LeRoy A. Hemish**
- **22 pages**
- **Paperbound, laminated cover**
- **$5**

Surface to Subsurface Correlation of Methane-Producing Coal Beds, Northeast Oklahoma Shelf

In this report, coalbed-methane production from 10 named Pennsylvanian (Desmoinesian) coals in the northeast Oklahoma shelf area give insight into the stratigraphic relationship of methane-producing coal beds in that area.

Six cross sections were constructed from specific logs to provide a subsurface stratigraphic framework throughout the area. Sixty-one well logs (gamma ray and bulk density or neutron) were selected from more than 200 logs examined at the Oklahoma Geological Survey's (OGS) Log Library. This report formed the basis of a workshop given in September 2002 by the OGS.

This correlation of named coals from previous surface studies with those identified in this subsurface study will provide a much-needed basis for accurate recognition of the 10 methane-producing coals in the shelf area. Deflections in the log curves suggest that many of the beds are probably not more than 1 foot thick, with a few exceptions where the coal may be as thick as 4 feet.

CIRCULAR 107

- **Brian J. Cardott, *editor***
- **183 pages**
- **Paperbound, laminated cover**
- **$12**

Revisiting Old and Assessing New Petroleum Plays in the Southern Midcontinent, 2001 Symposium

Sedimentary basins in the Southern Midcontinent, an area that includes Oklahoma, are major sources of oil and gas in this region, and increasingly are targets for petroleum exploration and enhanced recovery efforts using advanced technologies. Because exploration and development decisions are made based on technical information and data, it is important that new ideas and approaches be discussed and exchanged.

The 20 papers and abstracts in this book focus on the application of new technologies and new interpretations of existing data to finding new petroleum deposits. The research originally was presented at a two-day workshop held in May 2001 in Oklahoma City, cosponsored by the Oklahoma Geological Survey and the National Petroleum Technology Office of the U.S. Department of Energy. The meeting drew about 150 representatives from industry, government, and academia. The symposium covered a wide range of topics, including seismic and well-log analysis, computer modeling, petroleum engineering, seal formation and timing, surface geochemistry, remote sensing, coalbed methane, and enhanced oil recovery.

Research reported upon in this volume includes an overview of petroleum developments in the Southern Midcontinent; petroleum charge to the Mill Creek Syncline and adjacent areas; computer modeling of a small-scale inversion feature; finding producible sandstones with 3-D seismic data; remote sensing of geologic structures in highly vegetated areas; Arkoma Basin coalbed methane potential and practices; finding new pays in old plays; interpreting seismic data from the Wichita frontal fault zone with the help of ray-trace modeling; size-frequency effects and reservoir structure; regional Chimneyhill correlations and their impact on reservoir predictability; bypassed gas production; AVO analysis in a high-impedance Atoka Sandstone; seal characterization and fluid-inclusion stratigraphy of the Anadarko Basin; influence of fracturing-fluid rheology on the productivity of stimulated oil and gas reservoirs; and enhanced oil recovery with downhole-vibration stimulation.

Open-File Report 9-2002, Special Publication 2002-2, and Circular 107 can be purchased by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; fax 405-325-7069. To mail order, add 20% to the cost for postage, with a minimum of $2 per order.

All OGS publications can be purchased over the counter at the OGS Publication Sales Office, 2020 Industrial Blvd., Norman; phone (405) 360-2886; fax 405-366-2882; e-mail ogssales@ou.edu.

Request the OGS *List of Available Publications* for current listings and prices.

upcoming meetings

MARCH

American Association of Petroleum Geologists, Southwest Section, Annual Meeting, March 1–4, 2003, Fort Worth, Texas. Information: George A. Hillis, Bass Enterprises Production Co., 201 Main St., Fort Worth, TX 76102; (817) 390-8661; fax 817-390-8626; e-mail: ghillis@basspet.com. Web site: http://www.aapg.org/.

Geologic Field Trip in the Oklahoma City and Edmond Area for Earth Science Teachers, March 8, 2003, co-sponsored by Oklahoma City Geological Society and Oklahoma Geological Survey. Information: Jim Chaplin, OGS, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031; fax 405-325-7069; e-mail: jchaplin@ou.edu.

GIS Day at the Capitol, March 11, 2003, Oklahoma City, Oklahoma. Information: Shellie Willoughby, Oklahoma Conservation Commission, 2800 N. Lincoln Blvd., Suite 160, Oklahoma City, OK 73105; (405) 521-4828; fax 405-521-6686; e-mail: shelliew@okcc.state.ok.us.

AAPG/SEG Spring Student Expo, March 14–16, 2003, hosted by the University of Oklahoma School of Geology and Geophysics, Oklahoma Geological Survey, and Sarkeys Energy Center, Norman, Oklahoma. Information: Sue Crites, OU School of Geology and Geophysics, 100 E. Boyd, Suite 810, Norman, OK 73019; (405) 325-8971; e-mail: scrites@ou.edu.

National Earth Science Teachers Association, Annual Meeting, March 27–30, 2003, Philadelphia, Pennsylvania. Information: NESTA, 2000 Florida Ave., N.W., Washington, DC 20009; (202) 462-6910; fax 202-328-0566; e-mail: fireton@kosmos.agu.org.

Geologic Field Trip to the Arbuckle Mountains for Earth Science Teachers, March 29, 2003, co-sponsored by Oklahoma City Geological Society and Oklahoma Geological Survey. Information: Jim Chaplin, OGS, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031; fax 405-325-7069; e-mail: jchaplin@ou.edu.

APRIL

Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP 2003), April 6–10, 2003, San Antonio, Texas. Information: EEGS, 720 S. Colorado Blvd., Suite 960-S, Denver, CO 80246; (303) 756-3143; fax 303-691-9490; e-mail: eegs@neha.org. Web site: http://www.eegs.org.

Geologic Field Trip to the Wichita Mountains for Earth Science Teachers, April 12, 2003, co-sponsored by Oklahoma City Geological Society and Oklahoma Geological Survey. Information: Jim Chaplin, OGS, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031; fax 405-325-7069; e-mail: jchaplin@ou.edu.

MAY

Marginal Well Trade Fair, May 8, 2003, Oklahoma City, Oklahoma. Information: Commission on Marginally Producing Oil and Gas Wells, 3535 N.W. 58th St., Suite 870, Oklahoma City, OK 73112; (405) 604-0460 or (800) 390-0460; fax 405-604-0461; e-mail: mwc@marginal.state.ok.us. Web site: http://www.marginal.state.ok.us.

South Midcontinent Region
of the Petroleum Technology Transfer Council
and Oklahoma Geological Survey
Workshop

PRODUCED WATER AND ASSOCIATED ISSUES

Through the PUMP (Preferred Upstream Management Practices) program, operators in the South Midcontinent Region have identified produced water as a major constraint in the production of hydrocarbons. A manual has been developed to assist the independent operator in dealing with produced water and related problems encountered throughout the life of a well. These workshops focus on the proven practices and technologies discussed in that manual.

The following workshops are listed by sponsoring organization, date, and location:

The Oklahoma Commission on Marginally Producing Oil and Gas Wells

January 21, 2003 — Enid, Oklahoma
9:30 a.m.–3:30 p.m.

January 22, 2003 — Pawhuska, Oklahoma
9:30 a.m.–3:30 p.m.

February 18, 2003 — Ardmore, Oklahoma
9:30 a.m.–3:30 p.m.

February 19, 2003 — Okmulgee, Oklahoma
9:30 a.m.–3:30 p.m.

Cost: $15

Contact: Tawnia Wise, (800) 390-0460 *or* (405) 604-0460; fax 405-604-0461; e-mail: twise@marginal.state.ok.us

Oklahoma Geological Survey

March 2003 — Smackover, Arkansas

Cost: $15

Contact: Michelle Summers, (800) 330-3996 *or* (405) 325-3031; fax 405-325-7069; e-mail: mjsummers@ou.edu

Society of Petroleum Engineers

February 20, 2003 — Oklahoma City, Oklahoma
8:00–11:00 a.m.

Cost: Member $25; Non-Member $35

Contact: Tia Johnson, (405) 720-5527; fax 405-720-5686; e-mail: tsjohnson@marathonoil.com

March 20, 2003 — Tulsa, Oklahoma
1:00–4:00 p.m.

Cost: Workshop $10–$20
Luncheon $15 (11:30 a.m.–1:00 p.m.)

Contact: Rodney Tate, (918) 588-7715; fax 918-588-7773; e-mail: rtate@oneok.com

THE GEOLOGICAL SOCIETY OF AMERICA

Geological Society of America

South-Central and Southeastern Sections Joint Annual Meeting

March 12–14, 2003 • Memphis, Tennessee

Located along the Mississippi River and the boundary between the South-Central and Southeastern Sections, Memphis, Tennessee, is the perfect site for a joint meeting. Centered in the Mississippi Embayment, the Memphis area has many field locations pertinent to Quaternary geology, neotectonic processes, geologic hazards, and fluvial geomorphology. Field trip destinations in the Ouachita Mountains, Ozark Plateau, St. Francis Mountains, and central Tennessee are all within a few hours by car. The meeting will be held at the University of Memphis Conference Center, located on the northwest side of the campus area. The following agenda is planned:

Symposia

History of Geologic Investigation of Crystalline Rocks of Alabama, with Emphasis on the Past 40 Years: How We Saw It Then; How We See It Now

A 21st Century Look at the Cretaceous Coon Creek Formation

Cenozoic Paleodrainage in the Southeastern United States

Environmental Research and Remediation at the Department of Energy's Savannah River Site

Theme Sessions

Petrotectonic History of the Blue Ridge Belt: Faults, Fault Blocks, Terrains, and Ophiolites

Post-Mesozoic Tectonics of the Southern Midcontinent

Seismicity and Neotectonics in the Southern United States

Connections and Timing in the Appalachian-Ouachita Orogen

Late Paleozoic Intraplate Deformation of Central North America

Oh Southern Stars! Planetary Geology in the South

Earth Science and Earthquake Education Resources for K–12 Science Teachers in the Central and Eastern United States

Innovative Initiatives in Geoscience Education

Geologic Maps and Digital Geologic Maps (Posters)

Coastal Plain Stratigraphy of the Southeastern United States

Hydrostratigraphy and Hydrology of Cenozoic Aquifer Systems of the Southeastern Coastal Plain, Gulf Coast, and Mississippi Embayment

The Role of Fieldwork in the Study of Carbonate Rock Aquifer/Landscape Systems

Recharge Mechanisms and Estimation

Groundwater–Surface Water Interactions

Water Rock Life: Interactions Between Hydrology and Biology

Advances in Environmental Biogeochemistry

Radioisotopes as Tracers of Sedimentary and Pore-Water Processes in the Coastal Zone

Geomorphology, Sedimentation, and Environmental Geology of the Loess Region of the South-Central United States

Geoscience Innovation: Fostering the Achievement of Students with Disabilities

Advances in Gulf Coast Paleoecology

Workshops

Introduction to ArcGIS with Geohydrology Applications (ESRI's ArcGIS 8.2), *March 15*

Three-Dimensional Geological Visualization and Volumetrics: A Hands-On Short Course Using RockWorks2002, *March 12*

New Satellite Data for the Field Geologist, *March 15*

Roy J. Shlemon Mentor Program in Applied Geoscience, *March 13* and *March 14*

Field Trips

Cretaceous to Late Tertiary Gravel Deposits in the Western Tennessee River Valley, *March 11–12*

Late Paleozoic Tectonics of the Southern Ozark Dome, *March 11–12*

Mississippian–Pennsylvanian Deep Water Depositional Systems and Related Structure of the Ouachita Orogen, *March 9–12*

Sedimentology, Stratigraphy, Paleontology, and History of Cretaceous Coon Creek Formation of Western Tennessee, *March 14–15*

Hands-On Earth Science at the Coon Creek Science Center, *March 14–15*

Waulsortian-like Bioherms of the Maury and Fort Payne Formations, Tennessee, *March 14–16*

Basement-Cover Tectonic Relationships in Southeastern Missouri, *March 14–16*

Loess in the Northern Mississippi Embayment, *March 15*

The New Madrid Seismic Zone, *March 16*

Paleoenvironment, Depositional Setting, and Plant Fossil Diversity Found in the Claiborne Formation (Middle Eocene) Clay Deposits of Western Tennessee, *March 16*

For more information about the meeting, contact:

GSA, Meetings Dept., P.O. Box 9140, Boulder, CO 80301
Phone: (303) 447-2020 or toll-free 1-888-443-4472
Fax: (303) 357-1070
E-mail: member@geosociety.org
Web site: http://www.geosociety.org

Additional information or suggestions should be addressed to the meeting chairman: Dan Larsen, (901) 678-4358, dlarsen@memphis.edu, or visit www.geosociety.org/sectdiv/southc/03sc-semtg.htm

Preregistration deadline: *February 7, 2003*

notes on new publications

Guidebook for Geological Field Trips in South-Central Oklahoma

The geology of south-central Oklahoma is described in this volume, along with the locations of mineral- and fossil-collecting sites in the 11-county region of Cleveland, Seminole, Hughes, Garvin, Pontotoc, Coal, Murray, Carter, Johnston, Love, and Marshall Counties.

Authors Robert L. Neman, Douglas Schulte, and Donald Johnston have organized 85 sites into 19 separate field trips, each designed to last between several hours and an entire day. Each trip is based on a common theme—for example, field trip 3 is "Paleozoic stops along U.S. Highway 377."

The 140-page, wire-spiral–bound book includes such key features as exact location, access, stratigraphic unit, geology, owner/permission, and references. Site correlation charts, identification aids to common rock types, a glossary, and a simplified paleontological taxonomy also are included. The book contains detailed maps to the sites and the fossils that are found at some of the sites.

Order from: Dr. R. L. Neman, Arbuckle Geosciences, P.O. Box 641, Ada, OK 74820. Cost is $30 plus $2.50 shipping and handling.

Are We Running Out of Oil?

USGS Open-File Report 00-0320

L. B. Magoon answers the question "Are we running out of oil?" and explains how the "Big Rollover" (the time when the demand for oil outstrips the capacity to produce it—predicted to happen sometime between the years 2003 and 2020) will effect future prices and how new technological solutions will be required to meet our energy needs. This publication is presented as a poster measuring approximately 33 inches wide by 17 inches high.

USGS Open-File Report 00-0320 is available only on the Web at **http://geopubs.wr.usgs.gov/open-file/of00-320/**.

USGS Toxic Substances Hydrology Program: Proceedings

USGS Water-Resources Investigations Report 99-4018-C

Edited by D. W. Morganwalp and H. T. Buxton, this USGS water-resources investigations report contains papers presented at the seventh Technical Meeting of the U.S. Geological Survey Toxic Substances Hydrology Program, held in 1999 in Charleston, South Carolina. Volume 3 (345 pages) contains papers on subsurface contamination from point sources.

The papers in this volume relating to Oklahoma are: "Identifying ground-water and evaporated surface-water interactions near a landfill using deuterium, ^{18}oxygen, and chloride, Norman, Oklahoma," "Biogeochemical processes in a contaminant plume downgradient from a landfill, Norman, Oklahoma," "Evidence for natural attenuation of volatile organic compounds in the leachate plume of a municipal landfill near Norman, Oklahoma," "Aquifer heterogeneity at the Norman, Oklahoma, landfill and its effect on observations of biodegradation processes," "Mapping the Norman, Oklahoma, landfill contaminant plume using electrical geophysics," and "Shallow-depth seismic refraction studies near the Norman, Oklahoma, landfill.

Order WRI 99-4018-C from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone 1-888-275-8747. The cost is $4, plus $5 per order for handling. More information on the Toxic Substances Hydrology Program, including a searchable bibliography of publications and selected on-line publications, is available on the Web at **http://toxics.usgs.gov/toxics/**.

Hydrology and Leachate Plume Delineation at a Closed Municipal Landfill, Norman, Oklahoma

USGS Water-Resources Investigations Report 01-4168

In this report, author C. J. Becker describes the hydrogeologic features at the City of Norman, Oklahoma, closed landfill, including the topography of the bedrock and water-level changes in the alluvial aquifer, and delineates the leachate plume using specific conductance data. Data used in the 36-page report include drilling information, shallow seismic data, continuous ground-water level measurements in six wells, continuous surface-water measurements in the slough, daily precipitation, potentiometric head measurements near the water table and at the base of the alluvial aquifer in 15 wells, and specific conductance of ground water from October 1995 to November 1997.

Order WRI 01-4168 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.

Regional Stratigraphic Cross Sections of Cretaceous Rocks from East-Central Arizona to the Oklahoma Panhandle

USGS Miscellaneous Field Studies Map MF-2382

Three color sheets show sedimentary rocks of Cretaceous age in eastern Arizona, northern New Mexico, southern Colorado, and western Oklahoma. The rocks and unconformities are depicted on two lithostratigraphic cross sections—one extending from the Mogollon Rim in eastern Arizona to Pagosa Springs, Colorado, and the other from Pagosa Springs to Kenton, Oklahoma. The same rocks and unconformities also are represented on a chronostratigraphic profile sheet, which was prepared mainly from surface and subsurface data shown on the lithostratigraphic cross sections.

This compilation, by C. M. Molenaar, W. A. Cobban, E. A. Merewether, C. L. Pillmore, D. G. Wolfe, and J. M. Holbrook, is the third in a series that was prepared for the Western Interior Cretaceous Project of the Global Sedimentary Geology Program, established by the International Union of Geological Sciences.

Order MF-2382 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone 1-888-275-8747. Cost for print-on-demand, high-resolution plots is $60, plus $5 per order for handling. A PDF version of this report also is available free on the Web at **http://greenwood.cr.usgs.gov/pub/mf-maps/mf-2382/**.

Ground-Water Quality in the Central High Plains Aquifer, Colorado, Kansas, New Mexico, Oklahoma, and Texas, 1999

USGS Water-Resources Investigations Report 02-4112

The ground-water quality of the central High Plains aquifer in parts of Colorado, Kansas, New Mexico, Oklahoma, and Texas is described in this 63-page report, written by Mark F. Becker, Breton W. Bruce, Larry M. Pope, and William J. Andrews. Water samples collected in 1999 from 74 randomly distributed domestic water-supply wells in the aquifer were analyzed to evaluate ground-water quality. Water samples from each well were analyzed for 186 constituents, many of which are regulated in public drinking-water supplies by the U.S. Environmental Protection Agency under the Safe Water Drinking Act. The study area extended from about Goodland, Kansas, south to Amarillo, Texas.

Order WRI 02-4112 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.

HPBEDROCK: Bedrock Formations Underlying the High Plains Aquifer

USGS Open-File Report 99-0214

This geospatial data set consists of the bedrock formations of the High Plains aquifer, which underlies parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. This data set was created to assist in the regional analysis of water quality in the High Plains aquifer as part of the National Water-Quality Assessment (NAWQA) program–High Plains Region study unit.

Open-File Report 93-0643 is available on the Web at **http://water.usgs.gov/GIS/metadata/usgswrd/ofr99-214_hpbedrock.html**.

Hydrology and Water Quality near Bromide Pavilion in Chickasaw National Recreation Area, Murray County, Oklahoma, 2000

USGS Water-Resources Investigations Report 01-4250

Historically, the Bromide Pavilion in Chickasaw National Recreation Area was an attraction to many thousands of people who visited each summer to drink the mineral-rich waters piped from nearby Bromide and Medicine Springs. Periodic detection of fecal coliform bacteria in water piped to the pavilion from the springs, low yields of the springs, or flooding by adjacent Rock Creek spurred National Park Service officials to discontinue piping of the springs to the pavilion in the 1970s. Park officials would like to resume piping mineralized spring water to the pavilion to restore it as a visitor attraction, but they are concerned about the ability of the springs to provide sufficient quantities of potable water.

In this 31-page report, authors William J. Andrews and Steven P. Burrough describe the quantities and quality of water that may be obtainable from Bromide and Medicine Springs, as measured by water properties and the occurrence of selected disease-causing microorganisms in water samples collected in 2000.

Order WRI 01-4250 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.

Oklahoma abstracts

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

Two Previously Unreported Sauropod Dinosaurs from the Upper Jurassic Morrison Formation of Oklahoma

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Between 1935 and 1942, J. Willis Stovall directed the excavation of thousands of dinosaurs bones from quarries in the Morrison Formation of the Oklahoma panhandle, near the town of Kenton. Sauropods previously reported in this material are *Apatosaurus*, *Camarasaurus*, and *Diplodocus*. *Apatosaurus* material from the Kenton quarries has traditionally been regarded as *A. excelsus*, following Stovall's referral of the material to *Brontosaurus excelsus*. To date, no characters have been cited that support the referral of this material to either *A. excelsus* or *A. louisae*. OMNH 01368 is a disarticulated cervical rib of a large sauropod from Kenton Pit 1. The specimen lacks an anterior projection and is therefore referrable to *A. louisae*, a species previously unrecognized from Oklahoma. This and other specimens from the quarry pertain to one or more individuals at least 35% larger than CM 3018, the holotype of *A. louisae*. Furthermore, the capitular and tubercular synchondroses of OMNH 01368 are unfused, indicating that the animal was not skeletally mature, and that the range of body size at maturity in *Apatosaurus* was very large.

OMNH 01138, also from Kenton Pit 1, is a sauropod metacarpal II that was previously catalogued as *Camarasaurus*. The specimen is proportionally and absolutely longer than any metacarpals that can be reliably referred to *Camarasaurus*. It is more similar in morphology and proportions to the elongate metacarpals of *Brachiosaurus*, a second sauropod taxon that has not been previously reported from Oklahoma. The vertebrate fossils from the Kenton quarries have never received a thorough analysis and description, and represent an underutilized record of morphological and taxic diversity.

Reprinted as published in *Journal of Vertebrate Paleontology*, v. 22, supplement to no. 3, September 2002, p. 118A.

A Description of the Anatomy of a Digitally Constructed *Acrocanthosaurus atokensis* (Theropoda: Allosauroidea) Endocast and Its Uses

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Acrocanthosaurus atokensis, a large allosauroid theropod, is known from several specimens collected in the 1990s, as well as the two original specimens collected in the 1940s. The holotype, O.M.N.H. 8-O-S9, contains a well-preserved and complete braincase. This braincase was scanned at the High Resolution X-ray Computed Tomography (CT) Facility at The University of Texas at Austin by Richard Ketcham on January 12, 1999.

The resulting images were manipulated using graphics and volume rendering programs to produce a digital endocast of the endocranial cavity. Due to the preservation of the braincase, and the large density difference between the bone and the matrix, a very complete endocast was obtained. Just a cursory glance at the images revealed most of the cranial nerves. Those readily visible include the olfactory bulb and tract (CN I), the optic nerve (CN II), the trigeminal nerve (CN V), the abducens nerve (CN VI), the facial nerve (CN VII), and several branches representing the glossopharyngeal, vagus, accessory, and hypoglossal nerves (CN s IX-XII). Also easily visible are the pituitary fossa, the foramen ovale, the entrance of the internal carotid, and all three semicircular canals. Other structures which may be present but are harder to verify include the oculomotor nerve (CN III), the trochlear nerve (CN IV), and several smaller arteries and veins.

This complete endocast not only allows the description of a previously undescribed endocranial cavity to be done, but it also allows for several different types of comparisons. The volume rendering program used to create the endocast calculates a volume for it once it is constructed, permitting volume comparisons to be made with other digital, natural, and plaster endocasts. The shape of the endocast also permits comparisons with others, and, as might be expected, it is similar to the closely related taxa *Allosaurus* and *Carcharodontosaurus*. It is these types of comparisons that are vital in answering the question of how the modern avian brain evolved.

Reprinted as published in *Journal of Vertebrate Paleontology*, v. 22, supplement to no. 3, September 2002, p. 55A.

Cranial Structure and Affinities of the Lower Permian Captorhinid Reptile *Captorhinikos parvus* (Reptilia, Captorhinidae)

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The cranial morphology of the Lower Permian captorhinid reptile *Captorhinikos parvus* (Reptilia, Captorhinidae) is re-interpreted. Re-examination and further preparation of 7 specimens from the original study characterizing the species, as well as preparation and examination of 16 new specimens, all from the Hennessy Formation of Central Oklahoma provide significant new information bearing on the characterization of *C. parvus*. This study shows it to be a valid and distinct taxon based on very small adults with multiple maxillary and mandibular tooth rows. This determination supports Olson's original characterization in the broadest sense, but significant revision and additions to cranial morphology and relationships can now be offered. Fine scale preparation of these excellently preserved specimens has yielded one of the most complete pictures of cranial structure in a basal reptile, including the morphology

and interrelationships of palatal as well as braincase, and stapedial elements. Three single rows of small palatal teeth radiate anteriorly, anterolaterally, and laterally from the medial edge of the transverse flange. In addition, the suture connecting the vomer and palatine bones bisects the facet marking the contact between the palate and the maxilla anterior-posteriorly. Visualization of individual braincase elements, including opisthotic, basioccipital, and stapes bones allows for a much more complete braincase reconstruction. Preliminary phylogenetic analysis reinforces the validity of the taxon and hints at possible affinities with the small, single rowed captorhinid reptile *Saurorictus australis.* Confirmation that *C. parvus* is indeed based on adult specimens also invites speculation that the taxon represents an example of miniaturization within the Captorhinidae.

Reprinted as published in *Journal of Vertebrate Paleontology*, v. 22, supplement to no. 3, September 2002, p. 31A.

Captorhinus magnus, a New Captorhinid (Amniota: Eureptilia) from the Lower Permian of Oklahoma, with New Evidence on the Homology of the Astragalus

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The new species of single tooth-rowed captorhinid reptile *Captorhinus magnus* n. sp. from the Lower Permian fissure fillings at Richards Spur, Oklahoma differs from *Captorhinus aguti* in body size and dental and femoral morphology. Linear measurements of fully mature *C. magnus* elements range in size from 1.5 to 2.3 times as great as those of *C. aguti*, and the proximal articular surface of the femur, which is convex in *C. aguti*, is concave throughout ontogeny. *C. magnus* possesses ogival cheek teeth aligned in a single row, indicating that ogival dentition can no longer be considered unique to *C. aguti*. A phylogenetic analysis of captorhinid interrelationships indicates that *C. aguti* and *C. magnus* form a clade that possesses a sister-group relationship with *Captorhinus laticeps*. Incompletely ossified astragali referred to *C. magnus* provide unequivocal evidence that the astragalus of *Captorhinus* formed through the fusion of three, originally separate ossifications, the tibiale, intermedium, and proximal centrale, rather than from a single ossification center. At the Richards Spur locality, *C. magnus* is the most abundant *Captorhinus* species produced from the deeper, stratigraphically lower sediments of the quarry. It is rare, however, in the uppermost, presumably younger deposits, where *C. aguti* represents the most numerous Richards Spur captorhinid.

Reprinted as published in *Canadian Journal of Earth Sciences*, v. 39, no. 9, September 2002, p. 1363.

Lower Permian Fissure Deposits in the Slick Hills, Oklahoma, the Oldest Known Fossiliferous Paleokarst

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Caves and fissures that formed in the geological past, and were preserved through burial, are referred to as paleokarst or fossil karst. Sediments filling such structures often contain large concentrations of vertebrate bone: particularly well-studied examples include the australopithecine-bearing caves of southern Africa and the Triassic and Jurassic sites of southwest Britain, but paleokarst sites of Mesozoic and especially Cenozoic age are widely distributed. Known Paleozoic occurrences, by contrast, are presently limited to an Upper Permian site near Korbach, Germany, and at least two Lower Permian fissure systems in the Slick Hills of Oklahoma. The latter preserve an anomalous fauna of highly terrestrial Early Permian tetrapods, and also represent the oldest example of fossiliferous paleokarst in the terrestrial geological record.

Although the Bally Mountain site is the better studied of the two Slick Hills localities geologically, the still active Dolese Brothers limestone quarry near Richards Spur has yielded a much richer faunal assemblage. It is dominated in numerical terms by a single species, the early reptile *Captorhinus aguti*, but nearly 30 other terrestrial and relatively small (up to about a meter in length) amniotes and anamniotes occur in much lesser numbers.

We contend that the Richards Spur locality can be identified as a definite example of paleokarst and a probable subterranean cave system, and that comparison to Mesozoic and Cenozoic equivalents is likely to yield significant taphonomic insights. Recent work on blocks of fossiliferous clay from the site (as opposed to sieved samples) has shown that individuals of *C. aguti* are not only numerous but also extremely well preserved, often in nearly full articulation, without signs of either weathering or predator activity. These taphonomic characteristics suggest that this species was actually resident within the caves, either permanently or seasonally. Most other species, however, are represented by much less abundant material of widely varying completeness and preservational quality, indicating that they were probably transported in from outside.

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Tetrapod Footprints from the Lower Permian Hennessey Formation, Oklahoma City, Oklahoma

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During construction of the Kilpatrick Turnpike in Oklahoma City, a large block of the lower part (about 55 m above the base) of the Lower Permian Hennessey Formation was uncovered that contained tetrapod tracks. The dominantly fine-grained character of the Hennessey sediments, rarity of channels, and the presence of paleosol horizons and thin gypsum beds are evidence that in the Oklahoma City area much of it was deposited in a supratidal, possibly sabhka-like environment. Correlation of the Hennessey Formation to much of the Texas Clear Fork Group indicates a Leonardian age, and the tracksite in the lower Hennessey thus is of early Leonardian age.

The best preserved footprints are two, nearly complete concave impressions that can be assigned to *Amphisaurapus latus* Haubold, 1970, the presumed track of a seymouriamorph. These prints are noticeably wider than long: width is ~70 mm, length is ~55 mm, and the estimated divarication between digits I and V is ~130°. Digit IV is longest, and these plantigrade tracks superficially appear to be tetradactyl, but close examination indicates a faint impression of a small digit V on one, and the digit V of the other is broken off at the slab edge. Usually, digit tips of *Amphisauropus* are rounded, but many extramorphological variants show the pointed digits seen in these two prints.

A second, much smaller ichnotaxon is poorly represented. The best preserved track, also a concave impression, has three, relatively long, thin, pointed, slightly curved digits that increase dramatically in length from digit to digit. This track is longer than wide (width is <25 mm, length is <30 mm). All characters suggest assignment to *Dromopus*, the presumed track of an araeoscelid reptile, and we refer this track to aff. *Dromopus* sp. because it is not completely or well enough preserved for certain identification. These tracks are the youngest Permian vertebrate footprints in Oklahoma. This is the youngest report of *Amphisauropus* in North Amenca, and its identification increases the similarity of European and North American Early Permian tetrapod ichnofaunas.

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A Tetrapod Ichnofauna from the Middle Pennsylvanian (Desmoinesian) McAlester Formation (Krebs Group), Haskell County, Oklahoma

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New Mexico Museum of Natural History locality 4399, in the Middle Pennsylvanian (Desmoinesian) Keota Sandstone Member, McAlester Formation (Krebs Group) of Haskell County, Oklahoma, yields an extensive tetrapod ichnofauna. Well-preserved trackways occur in a 0.8–1.5-m-thick unit of thinly laminated sandstone at the base of the Keota Sandstone Member. These deposits represent a lagoonal setting in a deltaic paleoenvironment. The tetrapod tracks are assigned to two ichnogenera: *Pseudobradypus* Matthew and *Notalacerta* Butts. Tracks of *Pseudobradypus* are pentadactyl plantigrade prints of a quadruped in which the manus is distinctly smaller than the pes, and digits III–IV are the longest. Tracks of *Notalacerta* are pentadactyl lacertoid prints of a quadruped that lack sole impressions and in which digit IV is the longest. This is the first record of *Pseudobradypus* in western North America, and the second of *Notalacerta*. Both ichnotaxa are also known from the Pennsylvanian of eastern North America. *Pseudobradypus* tracks at the Oklahoma site outnumber those of *Notalacerta* by a ratio of 5:1 (N=400); providing insight into the relationship within this facies between temnospondyl amphibians and protorothyridid captorhinomorphs, the presumed respective trackmakers.

There is also a diverse invertebrate ichnofauna at locality 4399 that includes arthropod tracks, resting traces and feeding trails. We record the second occurrence of *Tonganoxichnus buildexensis* Mangano, Buatois, Maples & Lanier, previously known only from the lower Virgilian Tonganoxie Sandstone Member (Stranger Formation) of eastern Kansas. *Paleohelcura tridactyla* Gilmore is present, extending the North American stratigraphic range of this ichnospecies from the Lower Permian to the Middle Pennsylvanian. A single body impression of a rare arachnid belonging to the order Palaeoricinulei is also known from this site.

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Invertebrate Ichnofauna from the Middle Pennsylvanian (Desmoinesian) McAlester Formation (Krebs Group), Haskell County, Oklahoma

ALLAN J. LERNER and *SPENCER G. LUCAS*, New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, NM 87104; *MONTGOMERY BRUNER* and *PAUL SHIPMAN*, Dept. of Zoology, Oklahoma State University, Stillwater, OK 74078

New Mexico Museum of Natural History locality 4399, in the Middle Pennsylvanian (Desmoinesian) Keota Sandstone Member, McAlester Formation (Krebs Group) of Haskell County, Oklahoma, yields a diverse invertebrate ichnofauna that includes arthropod tracks, resting traces and feeding trails. The ichnofauna occurs in a 0.8–1.5-m-thick unit of thinly laminated sandstone at the base of the Keota Sandstone Member. These deposits represent a lagoonal setting in a deltaic paleoenvironment. We record the second occurrence of *Tonganoxichnus buildexensis* Mangano, Buatois, Maples & Lanier, previously known only from the lower Virgilian Tonganoxie Sandstone Member (Stranger Formation) of eastern Kansas. *Paleohelcura tridactyla* Gilmore is present, extending the North American stratigraphic range of this ichnospecies from the Lower Permian to the Middle Pennsylvanian. *Diplichnites gouldi* occurs, making this only the second record from the Middle Pennsylvanian. Other ichnotaxa include *Diplodichnus biformis*, *Treptichnus bifurcus*, *Gordia* sp. and *Helminthoida* sp. There is also an extensive ichnofauna at locality 4399 consisting of tetrapod tracks assigned to two ichnogenera: *Pseudobradypus* Matthew and *Notalacerta* Butts. This is the first record of *Pseudobradypus* in western North America, and the second of *Notalacerta*. Both ichnotaxa are also known from the Pennsylvanian of eastern North America. A single body impression of an arachnid possibly belonging to the order Palaeoricinulei is also known from this site.

Reprinted as published in the Geological Society of America *2002 Abstracts with Programs*, v. 34, no. 6, p. 358.

Paleoecology of Trilobites from the Viola Group of Oklahoma: Implications for Changes in Ordovician Marine Communities

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The Viola Group (Mohawkian–Cincinnatian) of south-central Oklahoma is a nearly pure carbonate sequence that was deposited on a carbonate ramp along a passive margin. This setting differs from siliciclastic-dominated environments forming in the Taconic Foreland Basin region during the same interval. The Viola Group, which consists of the lower Viola Springs and the upper Welling formations, contains four distinct lithofacies deposited along a lateral depth gradient. Each lithofacies represents a depositional environment ranging from deep subtidal to shallow shoal and preserves a unique trilobite assemblage.

Laminated to bioturbated carbonate mudstone was deposited below storm wave base in the deep subtidal environment of the distal ramp. The trilobites *Cyptolithus*, *Pugilator* and *Ampyxina* were the only benthic organisms preserved. *Cryp*-

tolithus persisted as deposits shallowed and coarsened upward into an intermediate-depth subtidal environment, and *Anataphrus, Isotelus* and *Flexicalymene* were added to the assemblage. Shallow subtidal deposits formed in an area of intermediate energy on the proximal ramp where abundant carbonate mud was preserved between shell-rich, storm-winnowed beds. The trilobite assemblage found in this facies contains the highest diversity (approx. 20 species) and is dominated by *Calyptaulax* and an illaenid. High-energy shoal deposits on the ramp margins in the Viola Springs Formation are lithologically similar to shallow carbonate platform deposits of the Welling Formation and consist mainly of cross-bedded, well-washed mudstone. These environments supported slightly lower levels of diversity than the shallow subtidal habitat. *Bumastoides, Thaleops* and *Ceraurus* were dominant in shoal deposits of the Viola Springs, while large isotelines including *Anataphrus, Isotelus* and *Ectenaspis* were the most common elements in the younger Welling Formation.

The results of our study confirm that trilobites remained important and diverse components of paleocommunities at multiple depths in the Late Ordovician of southern Laurentia. Any argument postulating the displacement of trilobites by members of the Paleozoic Evolutionary Fauna must account for this persistence of trilobite diversity and abundance in shallow carbonate environments.

Reprinted as published in the Geological Society of America *2002 Abstracts with Programs*, v. 34, no. 6, p. 463.

Evidence for Elevated Regional Heat Flow During Late Oligocene Time on the Southern High Plains

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Apatite fission-track (AFT) analysis of core samples from seven deep oil wells in Oklahoma, Texas, and northeastern New Mexico indicates that the base of a middle Cenozoic apatite partial annealing zone (PAZ) is preserved in the subsurface. The base of the PAZ, which approximately corresponds to the 110°C paleoisotherm, is at a subsurface depth of ~3,000 m in the Anadarko Basin, at ~825 m at the NM-TX stateline and emerges from the subsurface, projecting into the air, near the Pecos River in eastern New Mexico. The AFT cooling age just beneath the base of the PAZ is ~27 Ma in northeastem New Mexico and ~38 Ma in the Anadarko Basin. Triassic sandstones exposed at the surface between Santa Rosa, NM, in the Pecos River valley and Albuquerque, NM, on the western margin of the Rio Grande rift yield AFT ages of 25 to 30 Ma. Thermal modeling combined with AFT data from the Hagan embayment northeast of Albuquerque indicates that a heat flow >84 mW/m^2 and at least 2 km of denudation are needed to explain the distribution of AFT ages. In addition, modeling of AFT age and length data from the south end of the Wet Mountains, Colorado, suggests that paleotemperatures were ~95°C at the base of the range at ~25 Ma. This data, when linked with the preservation of the Rocky Mountain erosion surface beneath 33 Ma andesite flows on Greenhorn Mountain, can be used to calculate a middle Cenozoic paleogeothermal gradient of ~47°C/km for this area.

Reprinted as published in the Geological Society of America *2002 Abstracts with Programs*, v. 34, no. 6, p. 322.

The Interstate Oil and Gas Compact Commission: A Partnership Involving Geoscientists and Policy Makers

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The Interstate Oil and Gas Compact Commission (IOGCC) was founded in 1935 to ensure the efficient recovery of domestic petroleum resources while protecting health, safety and the environment. The Commission today represents the Governors of 30 oil and gas producing states; an additional 7 states are affiliate members. The IOGCC is a venue in which geoscientists can work with governors and state agencies to have an impact on public policy. In 2001, IOGCC published the report "Human Resources: The Missing Piece of the Energy Puzzle" by William L. Fisher and Sarah Seals, highlighting education and workforce needs for the petroleum industry. Subsequently, the incoming Chairman of IOGCC, Governor John Hoeven of North Dakota, convened a Blue Ribbon Petroleum Professionals Task Force to address IOGCC's concerns about future shortages of technically trained, environmentally responsible personnel for the domestic oil and gas industry workforce. As a result, IOGCC has started new initiatives to increase advocacy for federal oil and gas research funding, and to become more involved with professional societies to enhance educational and career services for the next generation of geologists, geophysicists, and engineers who will be employed by the U.S. oil and gas industry. In 2002 IOGCC created the Geosciences Electronic Resource Center website **http://www.iogcc.state.ok.us/GEOSGIENCE/index.htm**, linked to the IOGCC home page at **http://www.iogcc.state.ok.us**. The website will serve students and professionals by providing education and career services such as links to internship programs with state agencies and industry; information on academic scholarship opportunities at universities and colleges; and links to education and outreach websites of professional societies. The IOGCC welcomes suggestions from users for making the Center more effective. Gov. Hoeven is also convening a meeting of industry leaders to identify solutions developed at individual company levels which can be shared and encouraged in other companies. Through the IOGCC, the petroleum-producing states will become more directly involved with this issue, and state employees will be encouraged to work cooperatively with industry organizations. State employment agencies will be urged to develop outreach efforts.

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Research and Development for the Domestic Petroleum Industry

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Two major changes have taken place within the domestic petroleum industry. First, the major oil companies have reduced their internal R&D activities significantly. Second, these companies also have essentially abandoned onshore exploration and development in the continental U.S. These actions have left future development of this region largely to the smaller companies and independents.

Historically, small companies and independents obtained their new science and technology largely through the "trickle-down" process from the majors and larger service companies. With these sources rapidly disappearing, new sources of science and technology are needed.

Some universities and state geological surveys are attempting to fill this void. These efforts are being accomplished through the development of consortia with these industries, through directed studies in cooperation with local geological and engineering societies, and organizations such as the Petroleum Technology Transfer Council.

Examples include petroleum play-based studies to identify new reservoirs and other by-passed production in mature areas, simplified processes for reservoir delineation and characterization, and a host of other needs identified by domestic operators and consultants.

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Technology Transfer for the Domestic Petroleum Industry

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A second phase of the highly successful Technology Transfer to the Domestic Petroleum Industry began in early 2001. The current Phase 2 effort consists of:

Regulator "Train-the-Trainer" Workshops: Six workshops will be conducted during Phase 2 to provide "train the trainer" instruction and materials.

Pilot Producer Workshops: Phase 2 will include six pilot workshops for petroleum producers in Oklahoma and Arkansas.

Technology Transfer Centers: Phase 2 will include the establishment of IPEC Technology Transfer Centers at public libraries in Oklahoma and Arkansas.

Videotapes: Five videotapes will be produced and distributed, covering topics from the list: bioremediation primer; remediation of small oil spills; remediation of brine spills; remediation of combined spills of oil and brine; first response to spills of oil, brine, and oil + brine; prevention—new ideas; new technologies developed by IPEC researchers (a single video of all research).

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Oklahoma Energy Resources Board Environmental Program Update

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The Oklahoma Energy Resources Board (OERB) has enjoyed a successful environmental program in the restoration of orphaned and abandoned exploration and production sites throughout Oklahoma. With awareness of environmental issues constantly before the public, the OERB developed a program to enhance the public perception of prudent operators by restoring sites as turned in by the Oklahoma Corporation Commission (OCC). The restoration of over 2,600 impacted sites associated with oil and gas production has had a profound impact on the public image of our industry. Issues have typically included produced oil and formation brine spills, abandoned equipment, junk and debris, and open or improperly closed pits. Projects are scattered literally from border to border as work has been completed in 55 counties. By addressing these issues, the OERB has influenced landowners statewide, aided OCC working relations with landowners and provided an example to other states.

As with any statewide program, economy of scale has enabled the environmental contractor to develop procedures that recognize the repetitive nature of project issues and to utilize oil field contractors for actual on-site construction. The two primary areas of soil impact that require different approaches for restoration are brine impacted sites with little or no erosion to severe erosion and soil with varying degrees of hydrocarbon impact. Other areas that compound restoration efforts include the presence of concrete structures and other junk and debris issues. As the program has matured, the obvious historical sites have been addressed as they have been turned in by the OCC. With continued support of the OCC, the OERB and the environmental contractor look at progressively more complicated projects that are historical in age and still meet the orphaned and abandoned criteria. As these new projects are turned in, more of them are in closer proximity to active operations, which requires careful records review and special considerations to avoid interrupting production. Applicable state and federal regulations are included in the project planning process as well as meeting landowner interests. As with any oil and gas project, economics are considered as an integral part in reviewing options for restoration. Site examples from the OERB program will be used to illustrate site types with before and after photo review.

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How the Oklahoma Corporation Commission's New Water Quality Standards Implementation Plan Applies to Site Remediation and RBCA

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Oklahoma Senate Bill 549, passed in 1999, required all of Oklahoma's environmental agencies to write and by July 1, 2001, implement a Water Quality Standards Implementation Plan (WQSIP) specifying how the State's water quality standards will be applied within each agency's areas of environmental jurisdiction. The Oklahoma Corporation Commission's Oil and Gas Division has jurisdiction over many areas, from pipelines to oil and gas exploration and production to spill remediation, that are addressed by the Division's newly adopted WQSIP. Included are (1) how the WQSIP applies in each jurisdictional area, (2) the water quality standards to be met when a spill affects or potentially affects surface or ground water, (3) where (regulatory point of compliance) these standards must be met, and (4) how the remediation/cleanup standards (numerical table or RBCA derived) at the problem's source will be set.

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Oil and Brine Spill Remediation Tools for Small Independent Producers

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There are over 3,500 independent oil producers in Oklahoma and Arkansas. Most of these are very small companies, the "mom and pop" operations whose business is run from the pickup truck and the kitchen table. These small producers have no in-house expertise to advise them on the latest production techniques to minimize costs; how to prevent spills and the accompanying clean-up costs; or how to comply with state and federal regulations to avoid fines and costly loss of production. And small producers simply cannot afford private sector services of this kind.

The Integrated Petroleum Environmental Consortium (IPEC) is an EPA Research Center whose mission is to increase the competitiveness of the domestic petroleum industry through a reduction in the cost of compliance to U.S. environmental regulations. The IPEC member institutions are the University of Tulsa, the University of Oklahoma, Oklahoma State University, and the University of Arkansas. Through a variety of mechanisms, IPEC's technology transfer program works to deliver useful tools to small independent producers to help them reduce operating costs and improve their bottom line. This paper will describe recent efforts to produce simplified guidelines for oil and brine remediation and easy-to-use field kits to monitor remediation of brine spills.

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Development of an Environmentally Friendly Process for Plugging Abandoned Wells

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The primary importance of plugging to abandon a well is to prevent contamination of groundwater aquifers by surface water, oil or gas seepage, or brine formations below the groundwater aquifers. Cement grout is the present material used in plugging. Fly ash is known to have properties very similar to cement and can be produced with strength similar to cement. Presently, only about half of the fly ash produced by the various coal-fired power plants is used and the rest must be treated as a waste product and disposed of in landfill. Much of this fly ash is the higher lime content, more cementitious, Class C fly ash.

The present research is funded by Integrated Petroleum Environmental Consortium (IPEC). This research reveals Class C fly ash can be retarded like cement when slurried and it can be pumped and placed like cement with coiled tubing instead of employing a rig. To ensure a comprehensive understanding of fly ash grout characteristics as a cement material, extensive experiments were performed. These involved chemical compositions, size distribution, compressive strength, thickening time, durability, and rheology of fly ash slurry. Effects of the various additives on the characteristics of fly ash slurries were investigated by extensive experiments. Frictional pressure loss tests were also performed with field size equipment in order to apply coiled tubing technology in placing fly ash slurry to the downhole of wellbores. This paper specifically describes a process developed by the Well Construction Technology Center at the University of Oklahoma to formulate the best fly ash grout. These research results provide a more environmentally friendly, economical material of plugging wells.

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Pay-For-Performance Remediation at Hydrocarbon-Impacted Sites

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The State of Oklahoma implemented Pay-For-Performance (PFP) remediation at hydrocarbon-impacted sites since October 1997. The purpose of this paper is to present several case studies that are representative of the State approved PFP site remediation. In each case study, PFP performance is presented in terms of average reduction of benzene concentrations in selected key monitoring wells. Remedial technologies evaluated include air sparge and soil vapor extraction, high-vacuum liquid-ring pump system, and enhanced bioremediation. Benzene was used as the only Chemical of Concem (CoC) for PFP performance evaluation as other CoCs such as toluene, ethylbenzene, xylenes, and naphthalene were less than the established cleanup levels in these case studies. Key limitations affecting PFP performance were identified in each case study. Recommendations were made for future implementation of like PFP projects.

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Assessment of Downstream Impact of Low-Cost Remediation Practices on Recent Brine Spills: Tallgrass Prairie Preserve, Oklahoma

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In this paper, we present the results of ongoing research into the impact of remediation efforts on a brine spill that occurred in the Tallgrass Prairie Preserve in the summer of 1999. The spill originated from an accidental release of brine due to failure of a wastewater disposal line. The purpose of the current research is to assess the efficacy of the remediation practice by continuing the already established sampling program and to further determine the impact of the remediation on the downstream hydrologic system. Surface water samples were collected in January 2001 and March 2001 to determine if runoff from the site had an impact on the conductivity of surface waters downstream from the site. In addition, soil samples were collected and extracts analyzed for salinity and sodicity.

After the 1999 spill, the site was sampled, and hay and gypsum tilled into the soil. Six sampling sites were used, and composite samples collected from each. The site was sampled in November 1999, April 2000, July 2000, and March 2001. Soil extracts were analyzed for changes in salinity and sodicity. The data were plotted and analyzed using the ArcView GIS package. The results of this analysis show that the remediation program is reducing the total brine concentration in the soils, with the greatest impact seen in the topographically higher areas of the spill. The conductivity of the soils in these areas decreased by roughly ⅓ over the time frame of measurements. Areas of the spill that are topographically low, and thus serve to collect contaminated run-off show significant temporal variation in conductivity. Sample site 4, the lowest topographically, initially rose from a conductivity of 12,000 µmhos to 41,000 µmhos. The latest conductivity measured at sample site 4 was 20,000 µmhos. The results clearly show that brine components are being leached from the contaminated soils.

The second part of the research is aimed at determining the downstream impact of the remediation program. Surface water samples were collected both above and below the spill site on two different occasions. The first sampling took place under low flow conditions. The second took place during a peak flow event. During low flow conditions, the surface waters immediately downstream show significantly high conductivity (7,800 µmho). During the peak flow event, the same location had a conductivity of 250 µmho (within the range of normal tap water). These results suggest the leaching of contaminated soil that occurs during rainfall events may not generate a significant pulse of salinity downstream of recent brine spills of modest size. Instead, run-off from adjacent uncontaminated areas can dilute the brine components to near background levels.

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Remediation of Brine-Impacted Soil with a Leachate Collection System with Evaluation of Several Performance Enhancements

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Brine-impacted soil poses several environmental problems. High salinity in soil inhibits plant growth, resulting in erosion. The secondary contamination of surface and ground waters by surface runoff and leaching is also a major concern. Currently, many brine-impacted soil remediation techniques exacerbate secondary contamination as they increase the hydraulic conductivity of soils. These methods rely on leaching of salt deeper into the soil instead of its removal. The leachate collection system collects the leachate for disposal and ultimate removal of salt from the soil. Several potential performance enhancements were investigated on a field scale in a historic and contemporary brine scar in northern Oklahoma for approximately one year. These modifications included installation of collection system piping in gravel filled trenches to increase the collection rate of the leachate, a drained limestone gravel layer to protect a fresh imported topsoil layer, enhancement of sodium ion exchange on the clay soil particles by using limestone gravel, and enhancement of the dissolution of limestone by biostimulation with elemental sulfur. Effectiveness of the enhancements was evaluated by analysis of salt concentration in soils, leachate, and bacterial plate counts.

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PLFA Analysis for Total Microbial Biomass in Oilfield Brine-Impacted Soil

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The high salinity and sodicity of soil contaminated with oilfield brine inhibits plant growth. To prevent the subsequent loss of topsoil through erosion, it is imperative that the salt be leached from the soil as rapidly as possible. The use of organic matter to stimulate "surface leaching" to run-off during rainfall events is being considered in this project. It has been hypothesized that the organic matter stimulates microorganisms in the soil to produce polymeric substances capable of enhancing the aggregation of soil particles. This in turn should increase the hydraulic conductivity of the soil and thus the rate of leaching. Phospholipid fatty acid (PLFA) analysis is being used to track changes in total microbial biomass resulting from prairie hay that has been applied to field demonstration sites in the Tallgrass Prairie Preserve.

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Mitigating the Effects of a Brine Spill by Harvesting Surface Vegetation

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A ruptured valve resulted in a spray of produced fluids at a marginal well in December 2000 in the Tallgrass Prairie Preserve. The well produces about 1–2 bbl/day of oil and about ten times that much brine. Most of the released fluid was brine, therefore, but the oil made it easy to identify affected vegetation, which was dormant and 2–3 ft high at the time. Near the well both the vegetation and the soil were soaked with brine and oil. However, an area of about 10,000 ft^2 received sufficient spray to blacken the vegetation but there was no visible oil on the ground. In order to protect the soil from salt contamination which could result from a rainfall on the contaminated vegetation, all of the blacken vegetation was harvested by cutting at about the three inch level and the vegetation disposed of off site. The following spring the area where vegetation was harvested showed low salt concentrations in the soil and regrowth of native vegetation.

Harvesting and disposal of the vegetation was conducted by the current lease operator and there was no opportunity to test the harvested grasses for salt contamination. However, a laboratory simulation suggests that the dead vegetation would have retained salt from the brine spray and released that salt during a subsequent rain event.

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The Use of Hay in the Remediation of Oilfield Brine-Impacted Soil

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The high salinity and sodicity of soil contaminated with oilfield brine inhibits plant growth. To prevent the subsequent loss of topsoil through erosion, it is imperative that the salt be leached from the soil as rapidly as possible. The use of hay to enhance "surface leaching" to run-off during rainfall events is being considered in this project. It has been hypothesized that the hay affects surface leaching in three different ways: (a) by augmenting the physical structure of the soil, (b) by adding cation exchange capacity capable of drawing sodium ions away from the clays, and (c) by stimulating microorganisms to produce polymeric compounds capable of causing soil particle aggregation. While microorganisms play an explicit role in the last process, they should also significantly affect the first two processes. The impact of these processes is being assessed through determination of changes in brine component concentrations' the cation exchange capacity, the permeability and the wet aggregate stability of the soil. Phospholipid fatty acid (PLFA) analysis is being employed to quantify the total microbial biomass. The effect of hay is being studied in a field demonstration involving two recently contaminated sites and an adjacent uncontaminated area in the Tallgrass Prairie Preserve, and in microcosms being conducted under more controlled conditions in the laboratory.

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Revegetation of Crude Oil Contaminated and Uncontaminated Prairie Sites Disturbed by Tilling and Earth Moving

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The rupture of a crude oil pipeline in 1992 in the Tallgrass Prairie Preserve resulted in the release of crude oil over an area of about 12 m by 40 m. At the time of the spill a vacuum truck was used to recover pooled oil but contamination remained that could not be recovered. The site was covered with hay and left alone. A site assessment in early 1996 showed that the crude oil had migrated downward to a depth of one meter with TPH (IR) concentrations in the 0–1 m interval ranging from 6,000 to 33,000 mg/kg. The downward migration of the oil was stopped by a clay layer at about one meter.

Nearby the spill was an old tank battery. All of the tanks had long since been removed but the original containment berm was still in place. The soil in the berm was free of hydrocarbon or salt contamination. In May 1996 the contaminated soil was excavated and replaced with soil from the berm. The excavated soil was land treated within the confines of the old tank battery using standard methods with the addition of hay and N-P-K fertilizers. After 46 days of treatment average TPH levels were reduced to about 7,000 mg/kg on average. The most recent TPH measurements showed residual concentrations ranging from 2,000 to 9,800 mg/kg.

Both the site of the old land treatment cell and the excavation site have at least partially revegetated since active intervention ceased. This paper will compare the current status of the two sites relative to unimpacted prairie in terms of above ground biomass of grasses and forbs and species diversity.

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A Comparison of Remediation Methods at Three Sites Contaminated with Crude Oil and Brine in the Tallgrass Prairie Preserve

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The fragile ecosystem of the Tallgrass Prairie Preserve located in Osage County, Oklahoma, contains over 100 producing wells. The average well generates 1–2 bbl/day of crude oil and 10 times that volume of brine. With aging equipment, spills of produced fluids sometimes occur. One particular pipeline in the Preserve, containing oil and brine, leaked in three closely spaced hillside areas. Different types of remediation methods for both the oil and brine were implemented on the three areas to compare remediation techniques on combination spills.

The first area was treated with fertilizer amendments to help with the bioremediation of hydrocarbons. Hay was also tilled into the area to help build soil structure to increase oxygen transport in the soil and leaching of brine components. The hay also helped stop soil erosion. An interception ditch was also installed at the end of the spill area to catch saltwater leachate and transport it directly to the natural drainage area, avoiding contamination of the prairie down slope. In the second area, an interception ditch was installed and the soil was tilled but no amendments or hay were added. The third area was treated with fertilizer and hay but no interception ditch was installed. This paper will compare the results of these treatments for both brine and oil remediation at these sites during the first year of treatment.

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Development of Relevant Ecological Screening Criteria (RESC) for Petroleum Hydrocarbon-Contaminated Soil at Exploration and Production Sites

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Faced with the task of assessing clean-up options based on ecological risk-based criteria at thousands of small upstream sites, oil and gas producers are in need of a streamlined rationale for assessing ecotoxicological risk at these sites. The development of a risk based corrective action (RBCA) approach for the protection of ecological resources provides a mechanism for site-specific ecological risk assessment. Crude oil-contaminated soil containing a gradient of oil contamination was collected from the Tall Grass Prairie Preserve, Pawhuska, OK. Laboratory-based toxicity tests with microbes, soil invertebrates, and plants were conducted to determine hydrocarbon toxicity. Total petroleum hydrocarbons (TPH) levels in the soil as detemmined by standard techniques (IR and GC/MS) ranged from below detection limits to 13,243 mg/kg. Exposure, as determined using solid-phase microextraction (SPME) techniques for measuring bioavailable petroleum hydrocarbon (BPH) will be compared to TPH values. Toxicity tests have been conducted with soil invertebrates (earthworm *Eisenia fetida*, potworm *Enchytraeus albidus*, and springtail *Folsomia candida*), plant species (*Lactuca sativa, Brassica rapa*, Little Bluestem, Big Bluestem), and soil microbial assessments. The approach for the development of a relevant ecological screening criterion (RESC) using the results from these toxicity tests will be presented.

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Salty Soil Remediation Update at the Tallgrass Prairie

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Produced water spills to land and the detrimental consequences of these releases are a continuing E&P site restoration and regulatory issue. The Nature Conservancy has a number of historical brine scars at the Tallgrass Prairie Preserve in Oklahoma. These brine scars are of unknown source and occurrence. However, they are persistent, and have not naturally remediated over an approximate 60-year period. One brine scar on the Tallgrass Prairie Preserve was chosen as a test site to evaluate selected promising remediation techniques including traditional chemical amendments (gypsum and hay mulch), proprietary chemical amendments, and two phytoremediation approaches, with and without mycorrhizal fungi.

The objectives of this project include: (1) quantitative assessment of the performance of three chemical amendments under field conditions; (2) quantitative assessment of two phytoremediation approaches; (3) develop approach to eliminate unnecessary "trial and error" pilot studies of multiple products; (4) cost/benefit analyses of the alternative treatment schemes; (5) share learnings; and (6) identification of best practices.

The project background, startup, and initial treatments were presented at the 2000 IPEC. This paper presents the results of on-going monitoring, modifications to improve surface water management, and treatment during the second year of the project.

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Characterization of Humic and Fulvic Acids Isolated from Pristine, Petroleum-Contaminated, and Bioremediated Mollisols

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Humic and fulvic acids (HA&FA) were isolated from three soil sets collected from a 4-year-old petroleum-contaminated site at the Tallgrass Prairie Preserve in Pawhuska, OK: a pristine, a petroleum-contaminated, and a set of four petroleum-contaminated mollisols that were bioremedited using one of three nitrogen fertilizers (ammonium nitrate, ammonium sulfate, urea). Using elemental analysis, 13-C NMR, and tetramethylammonium hydroxide thermochemolysis (TMAH), only minor differences were observed in the HA&FA composition and in the percent soil organic matter as a function of petroleum contamination. However, greater differences were observed in the bioremediated HA&FAs relative to the pristine and petroleum-contaminated HA&FAs, as well as between the three nitrogen fertilizer-amended HA&FAs. This demonstrates that addition of bulking agents and the type of nitrogen amendment used influences soil HA&FA composition to a greater extent than does petroleum contamination. These results imply that in the long-term, minor differences in simple bioremediation techniques may change soil HA&FA, thereby altering the physical and chemical properties of the soil.

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