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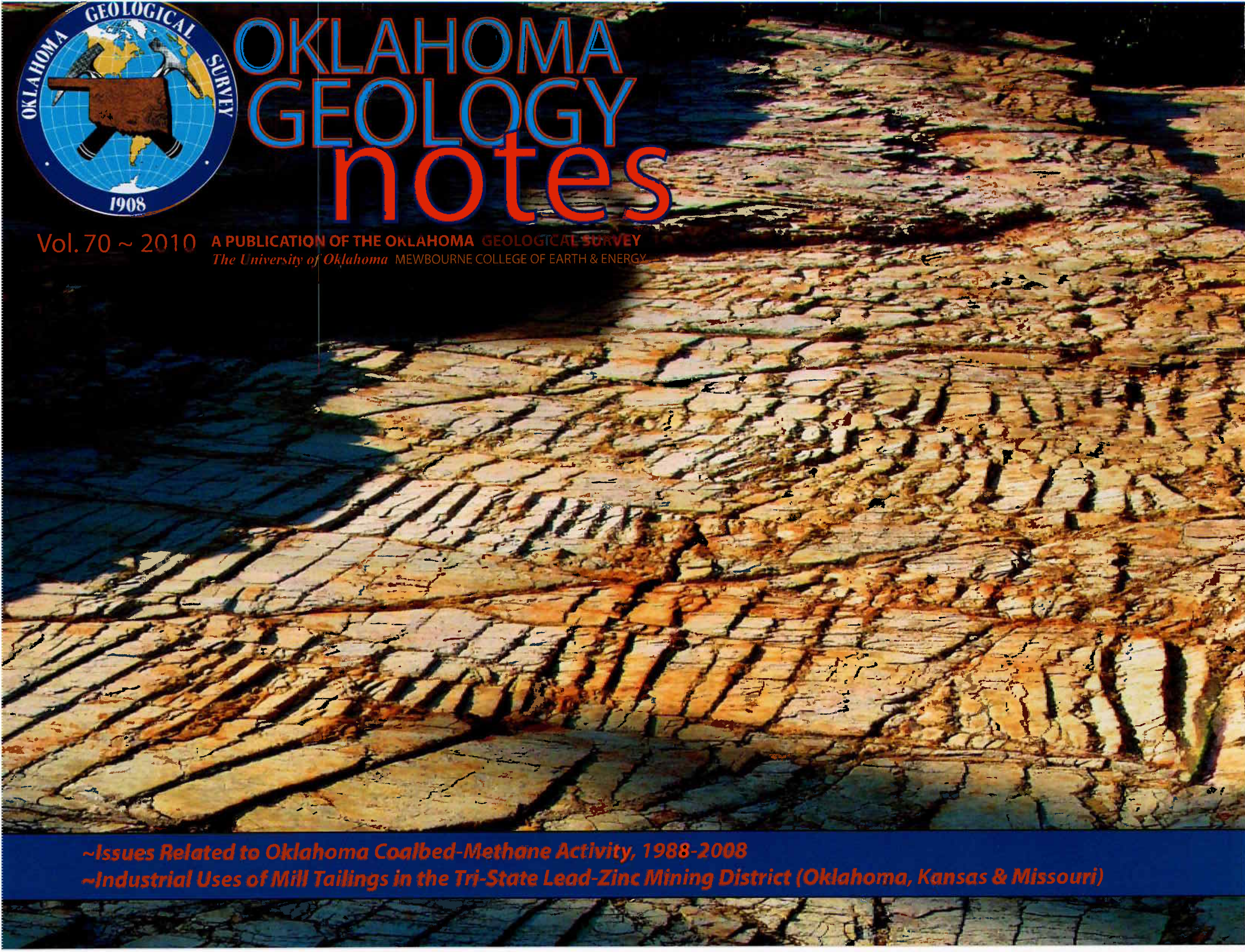

~Issues Related to Oklahoma Coalbed-Methane Activity, 1988-2008
~Industrial Uses of Mill Tailings in the Tri-State Lead-Zinc Mining District (Oklahoma, Kansas & Missouri)

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EDITORIAL MATTER: Short articles on aspects of Oklahoma geology are welcome from contributors; please direct questions or requests for general guidelines to the *NOTES* editor at the address above.

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OKLAHOMA GEOLOGY notes

Vol. 70 2010

On the cover: Close up of Woodford Shale outcrop on State Highway 77D. The sun was low in the western sky so all the details of the offset nature of the fractures are evident, including little normal faults contained within larger fault blocks. Photo by USGS Geologist Stan Paxton.

The *Oklahoma Geology Notes* is Morphing Again

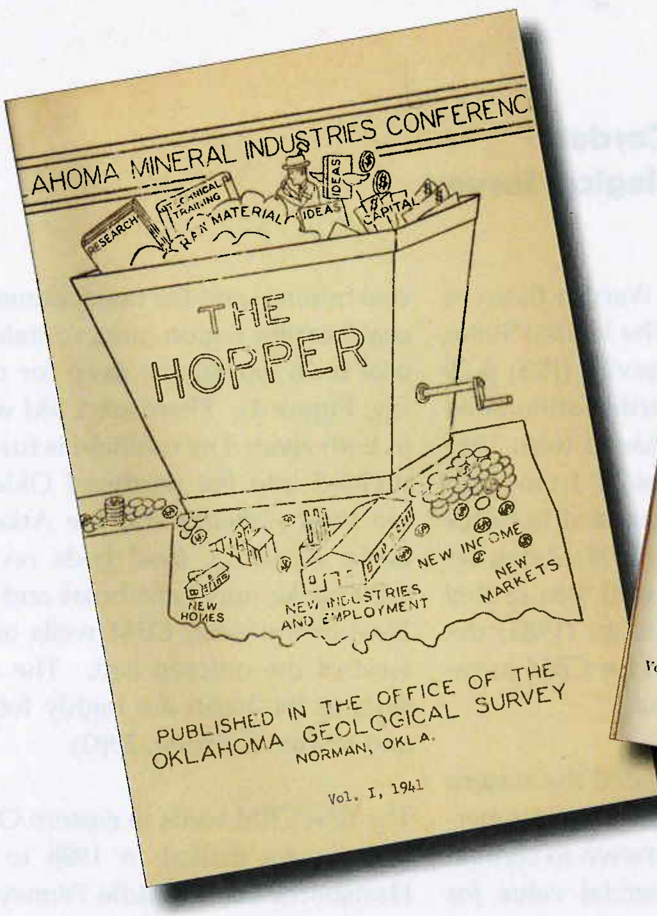
G. Randy Keller, Director
Oklahoma Geological Survey

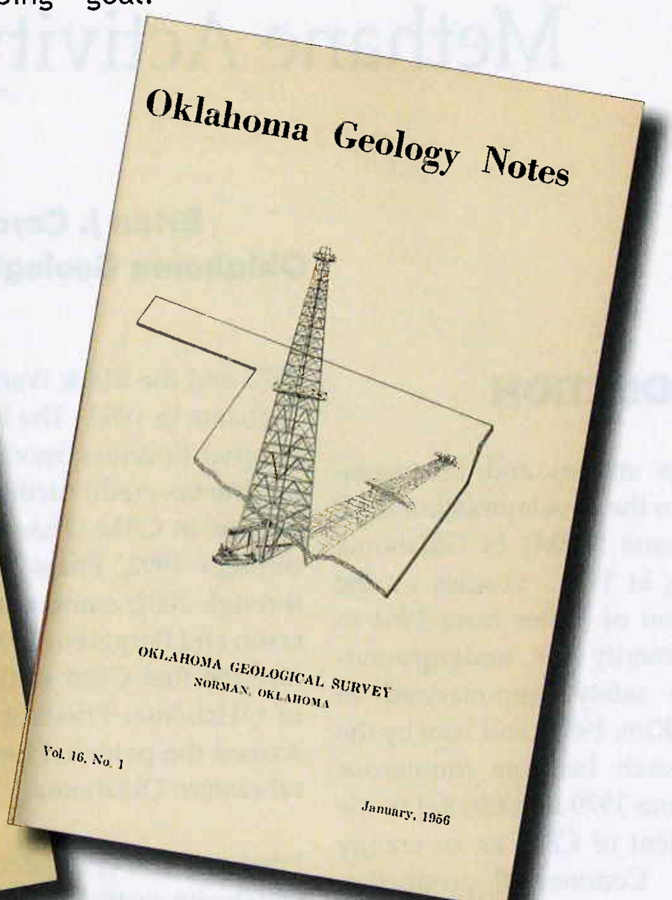
The *Notes* have changed form several times over the years. This publication series began as the *"The Hopper"* with Volume 1 in 1941. In 1956, the name of Volume 16 was changed to *Oklahoma Geology Notes*. Over the subsequent years, the physical format of the *Notes* changed and evolved into the large, colorful, and expensive format of recent years. As you know, the state budget is very tight, and we simply cannot afford to continue to publish the *Notes* in its current quarterly format. We have been preparing for a change this year, and this issue is the complete 2010 issue (Volume 70).

Beginning in 2011, we will follow many other state geological surveys and switch to a newsletter format that we will be published quarterly. This way, we can be timely in our publication while keeping costs down.

We have several other long-established publication outlets for the scientific content that has appeared in the *Notes* over the years, which include Oklahoma Geological Survey Bulletins, Guidebooks, Circulars and Special Publications, as well as the Shale Shaker published by the Oklahoma City Geological Society.

We want to emphasize timely and high quality publication of scientific articles on the geology of Oklahoma and adjacent areas, and will work with the Oklahoma City Geological Society to achieve this goal. At the same time, we want to get information about geologic developments, events, and activity in Oklahoma out in a timely manner and will use the Notes and our website to achieve this goal.





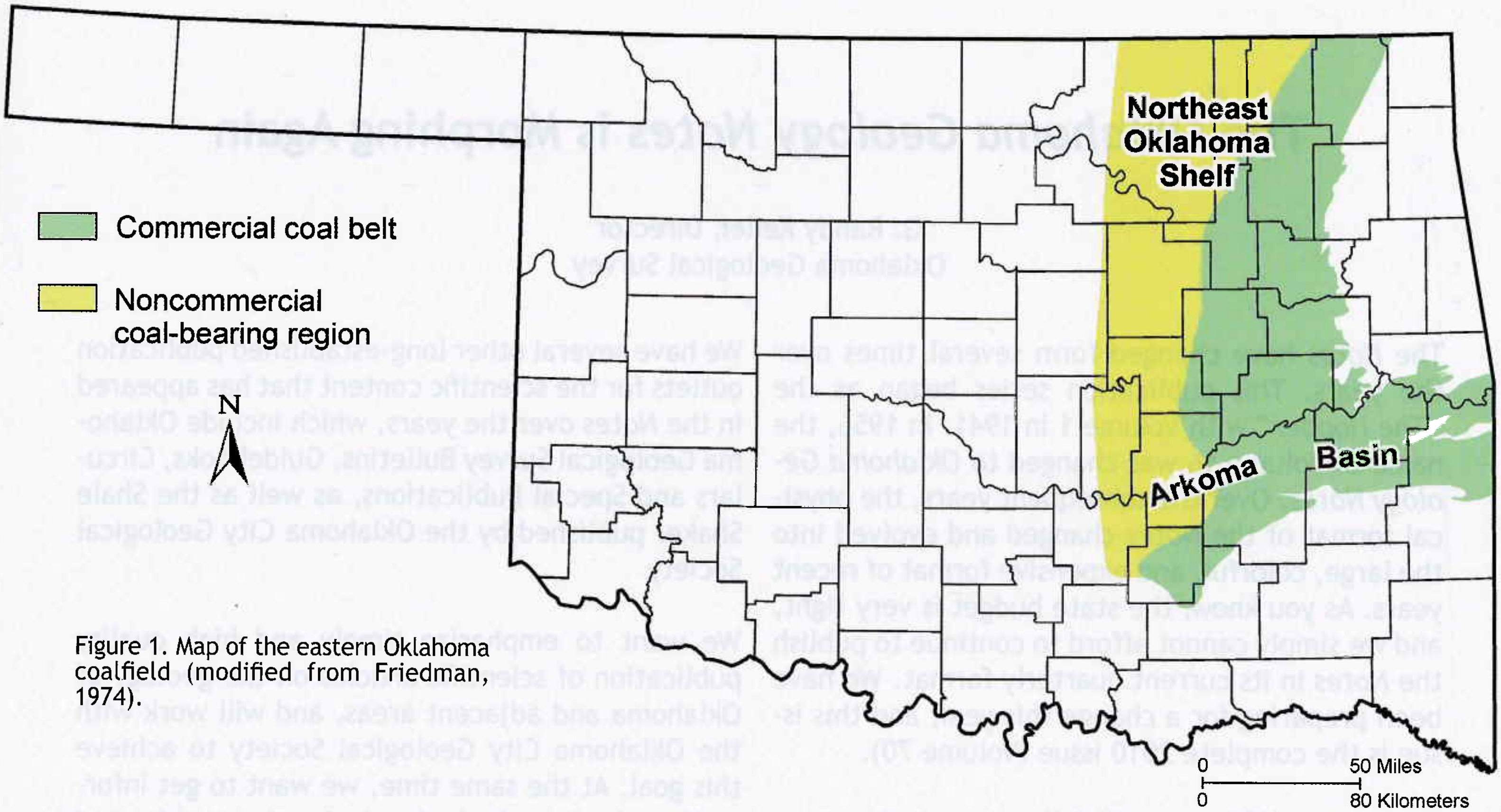


Figure 1. Map of the eastern Oklahoma coalfield (modified from Friedman, 1974).

Issues Related to Oklahoma Coalbed-Methane Activity, 1988–2008

Brian J. Cardott
Oklahoma Geological Survey

INTRODUCTION

Numerous studies and tax incentives led to the development of coalbed methane (CBM) in Oklahoma beginning in 1988. Studies by the U.S. Bureau of Mines from 1964 to 1980, primarily for underground-coal-mine safety (summarized in Deul and Kim, 1988), and later by the Gas Research Institute (numerous reports from 1979 to 2000) led to the development of CBM as an energy resource. Commercial production of CBM began in the San Juan Basin of Colorado and New Mexico in 1977 and the Black Warrior Basin of Alabama in 1980. The United States Internal Revenue Service (IRS) § 29 income tax credit further stimulated interest in CBM (Phase I from 1980 through 1992, Phase II from 1993 through 2002; summarized in Sanderson and Berggren, 1998). Long before the first CBM well was drilled in Oklahoma, Friedman (1982) described the potential for CBM in rural eastern Oklahoma.

Friedman (1974) divided the eastern Oklahoma coalfield into the commercial coal belt (area known to contain coal beds of commercial value for coal mining) and the noncommercial coal-bearing region (area containing coal beds too thin or deep for mining; **Figure 1**). There are CBM wells in both areas. The coalfield is further divided into the northeast Oklahoma shelf ("shelf") and the Arkoma Basin ("basin"). Coal beds on the shelf strike north-northeast and dip 2°–3° to the west; CBM wells occur west of the outcrop belt. The coal beds in the basin are highly folded and faulted (Cardott, 2002).

The first CBM wells in eastern Oklahoma were drilled in 1988 to the Hartshorne coal (middle Pennsylva-

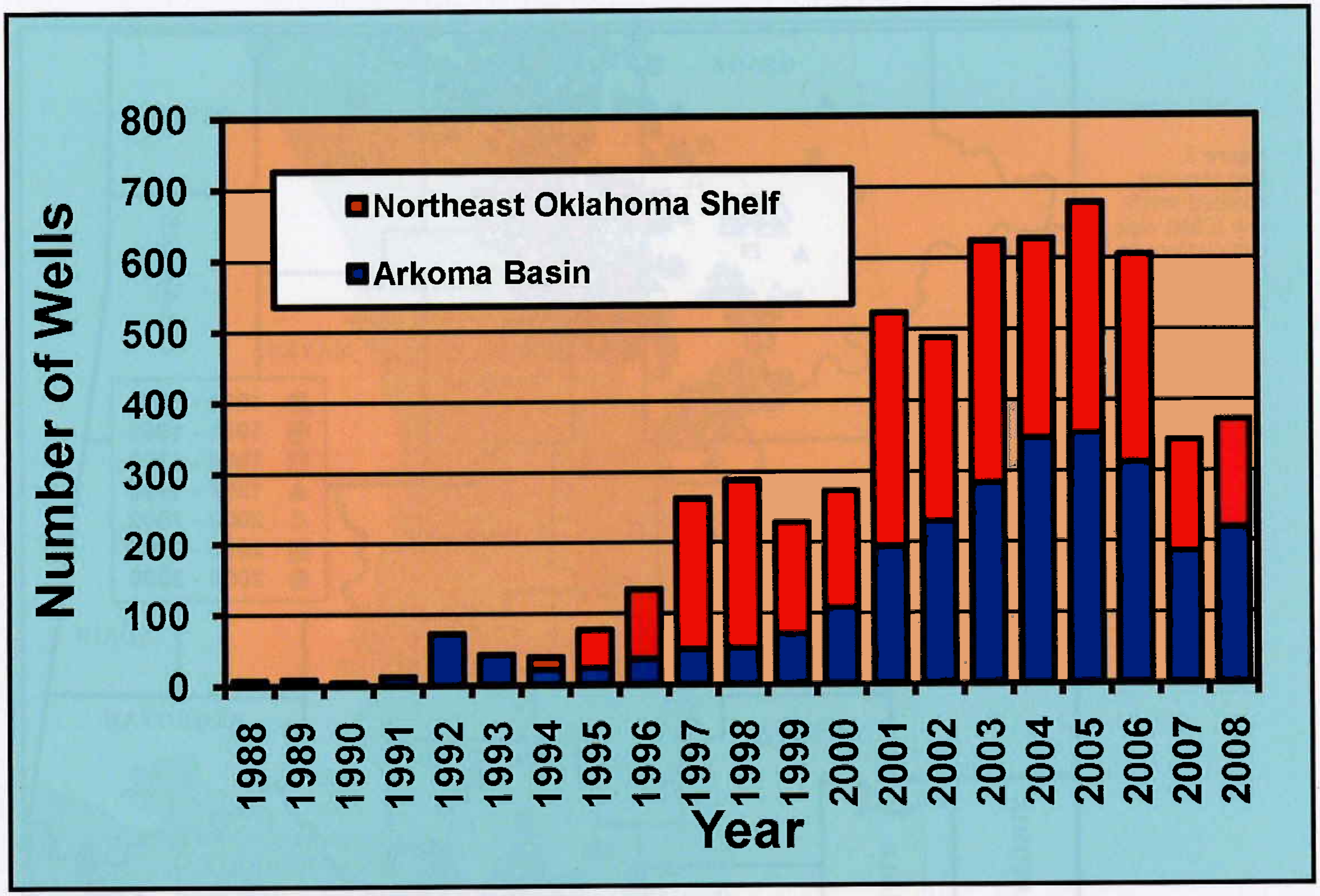


Figure 2. Histogram showing numbers of Oklahoma coalbed-methane (CBM) well completions, 1988-2008.

nian) in Haskell County. From 1988 through 2008, 5,707 gas wells were completed to coal beds in eastern Oklahoma (**Figure 2**). The peak of 73 wells drilled in the basin during 1992 occurred at the end of the first phase of the § 29 tax credit. Drilling expanded to the shelf in 1994 (**Figure 3**), in part to take advantage of the tax credit, exemplified by the large number of recompleted wells (discussed below). The highest number of CBM wells completed in Oklahoma in a single year was 678 wells in 2005.

Several issues over the years have influenced the development and reporting of CBM wells in Oklahoma. These issues, discussed below, impacted what wells to include in a CBM completions database (available on the Oklahoma Geological Survey website, http://www.ogs.ou.edu/coaldb.php) and how to compare and evaluate them.

ISSUES IN OKLAHOMA CBM

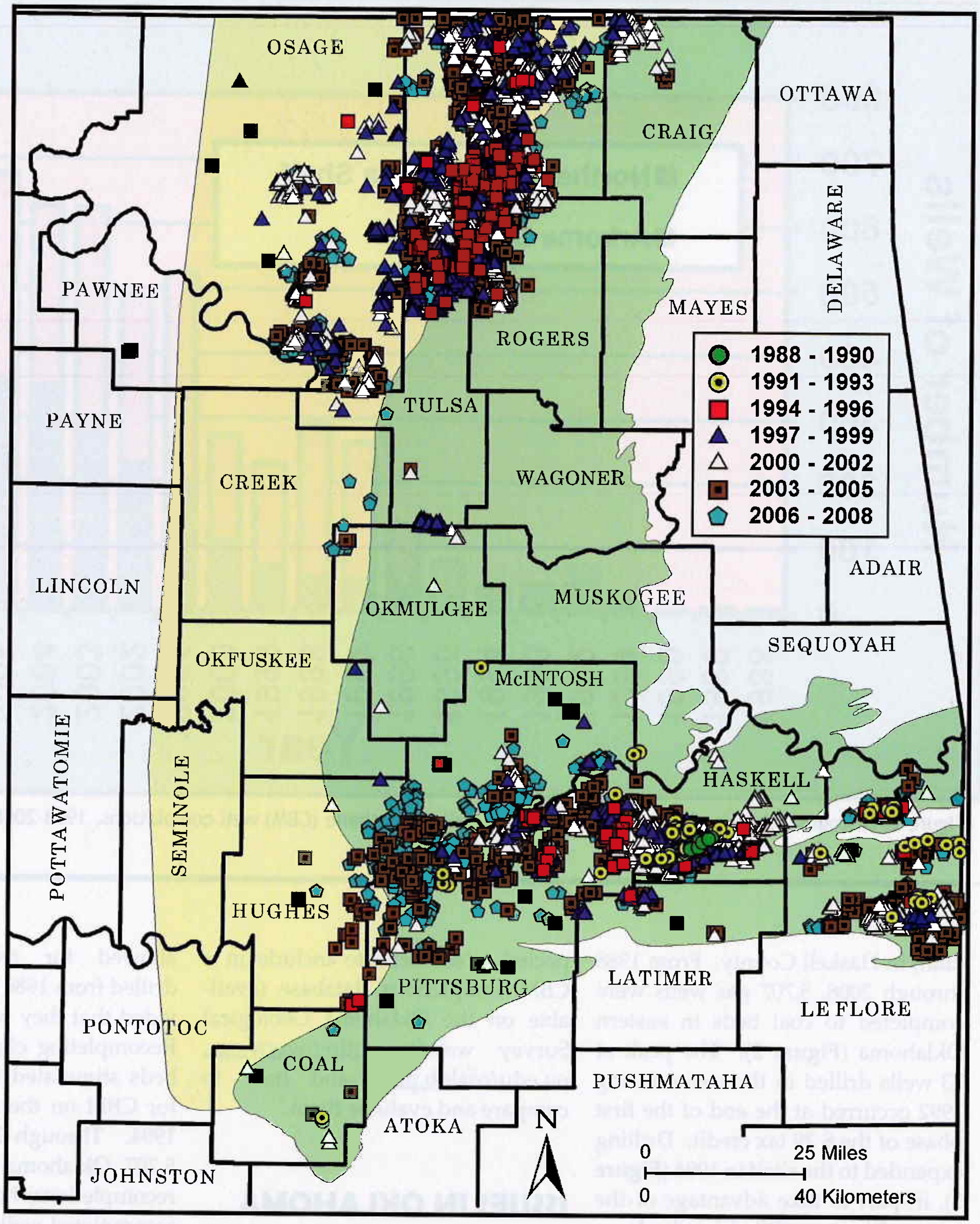
Recompletions

Beginning in 1991, several pre-existing petroleum wells in the basin were recompleted as CBM wells. Recompleting wells was a pivotal part of the second phase of the § 29 tax credit (1993–2002). This phase allowed for recompleting wells drilled from 1980 through 1992, provided that they were not deepened. Recompleting eligible wells to coal beds stimulated interest in drilling for CBM on the shelf beginning in 1994. Through 2008, 738 (13%) of 5,707 Oklahoma CBM wells were recompletions; however, most (687) recompleted wells were on the shelf (**Figure 4**).

CBM Wells with Noncoal Contributions

Nelson and Pratt (2001) recognized that hydrocarbon-source-rock shales, with densities >1.75 g/cm^3, can contribute significant amounts of methane to CBM wells. Without

Figure 3. Map showing coalbed-methane (CBM) well completions in Oklahoma by year.



restrictions such as those imposed for the tax credit or state limitations (e.g., sharing allowable, separate sources of supply), operators are permitted to produce as much methane from a well as possible with no requirement to limit the production strictly to CBM. Beginning in 1992, some Oklahoma CBM wells included perforations of noncoal lithologies, including sandstone (e.g., Bartlesville, Burgess, Cleveland, Peru, Red Fork, Skinner, and Tucker/Cushing), limestone (e.g., Big Lime, Oswego, Pink Lime, and Verdigris), and shale (e.g., Little Osage, Nuyaka, Oakley, and Summit). Only wells with noncoal perforations as a minor component were included in the CBM completions database. CBM wells with perforations in thin noncoal lithologies represent 330 (6%) of a total 5,707 (**Figure 5**).

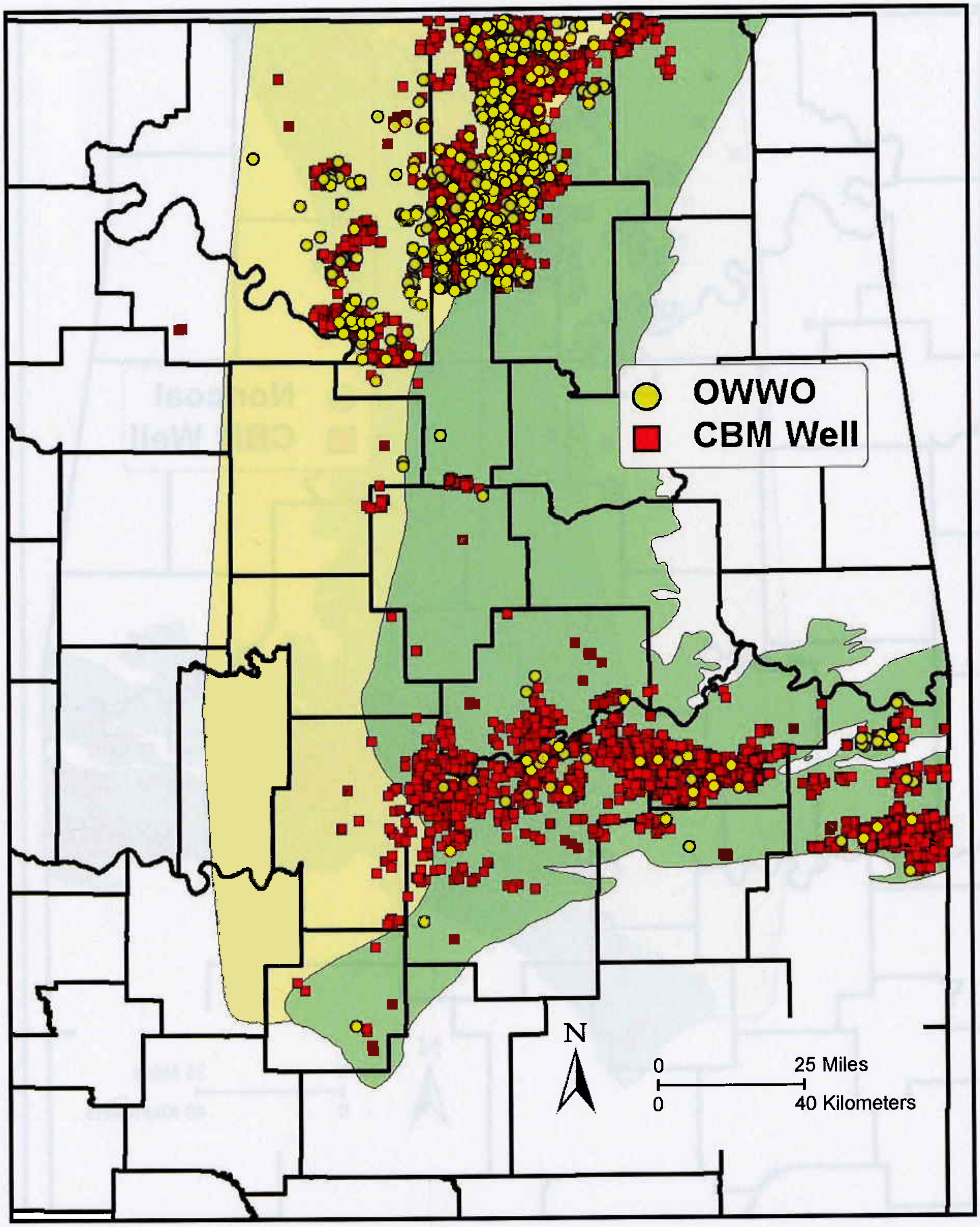
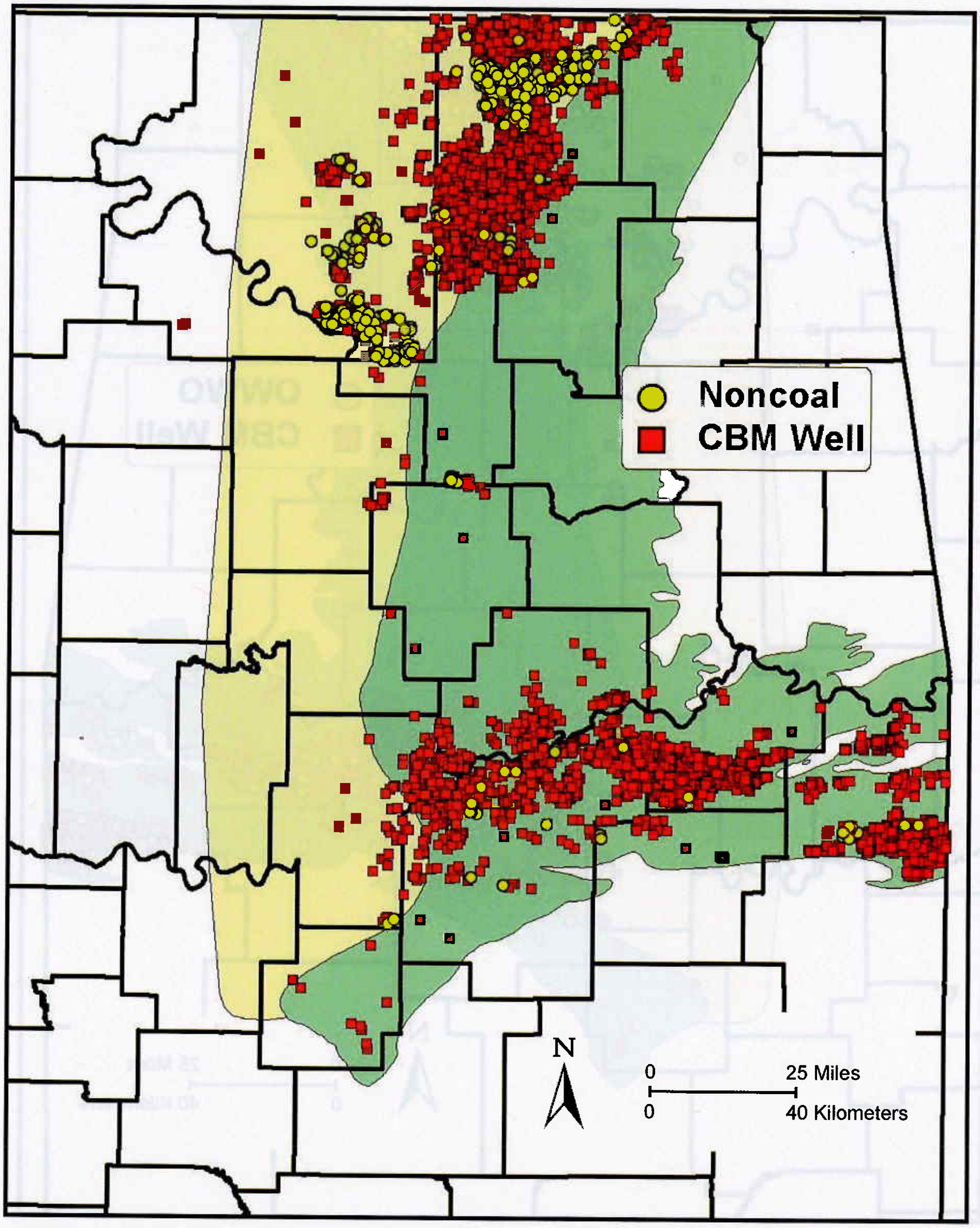


Figure 4. Map showing recompletions (old-well work-over, OWWO) as coalbed-methane (CBM) wells in Oklahoma (1991–2008).

Mulky Coal

Hemish (1986) reported a thin (<10 in.) coal above the Breezy Hill Limestone as the Mulky coal (top of the Senora Formation) in northwest Craig County (T. 28 N., R. 19 E.; chemistry is not available to verify coal grade). Hemish (2002, p. 11) used a "Mulky marker" to indicate the Mulky coal interval, stating that, "If present, the Mulky coal occurs at the base of the Excello Shale, but it cannot be identified separately on the geophysical logs." A cross section from Crawford County, Kansas, to Craig County, Oklahoma, in Hemish (1986, figure 13) illustrated the Mulky coal pinching out to the south. **Figure 6** is a photograph of a coal-mine highwall in Nowata County (Sec. 32, T. 25 N., R. 17 E.) showing the Excello Shale in contact

Figure 5. Map showing coalbed-methane (CBM) wells with perforations in noncoal lithologies (1992-2008).



with the Breezy Hill Limestone with the Mulky coal absent.

Cassidy (1968, Figure 1) showed the Excello Shale outcrop striking north-northeast in northeast Oklahoma and the approximate southern limit of the shale in southern Tulsa County. The 506 Mulky-only wells (1994–2008) in **Figure 7**, extending to the southern limit of the Excello Shale, are more likely perforated in and producing gas from the Excello Shale.

Commingled Coals

There are more than 40 named and unnamed coal beds in the northeast Oklahoma shelf (Hemish, 1988). Most coal beds are <2 ft thick. The 15 middle Pennsylvanian coal beds

Figure 6. Photograph of Excello Shale (above) and Breezy Hill Limestone contact (white line) in surface coal-mine highwall in Nowata County.

in CBM wells on the shelf are, from oldest to youngest: Riverton, Rowe, Drywood, Bluejacket, Wainwright, Weir-Pittsburg, Tebo, Mineral, Fleming, Croweburg, Bevier, Iron Post, Mulky, Lexington, and Dawson. From 1995 through 2008, 824 CBM wells on the shelf commingled 2 to 9 coal beds per well. Only the shallowest coal bed represents the location of a commingled well plotted in **Figure 8**, which shows all CBM wells on the shelf.

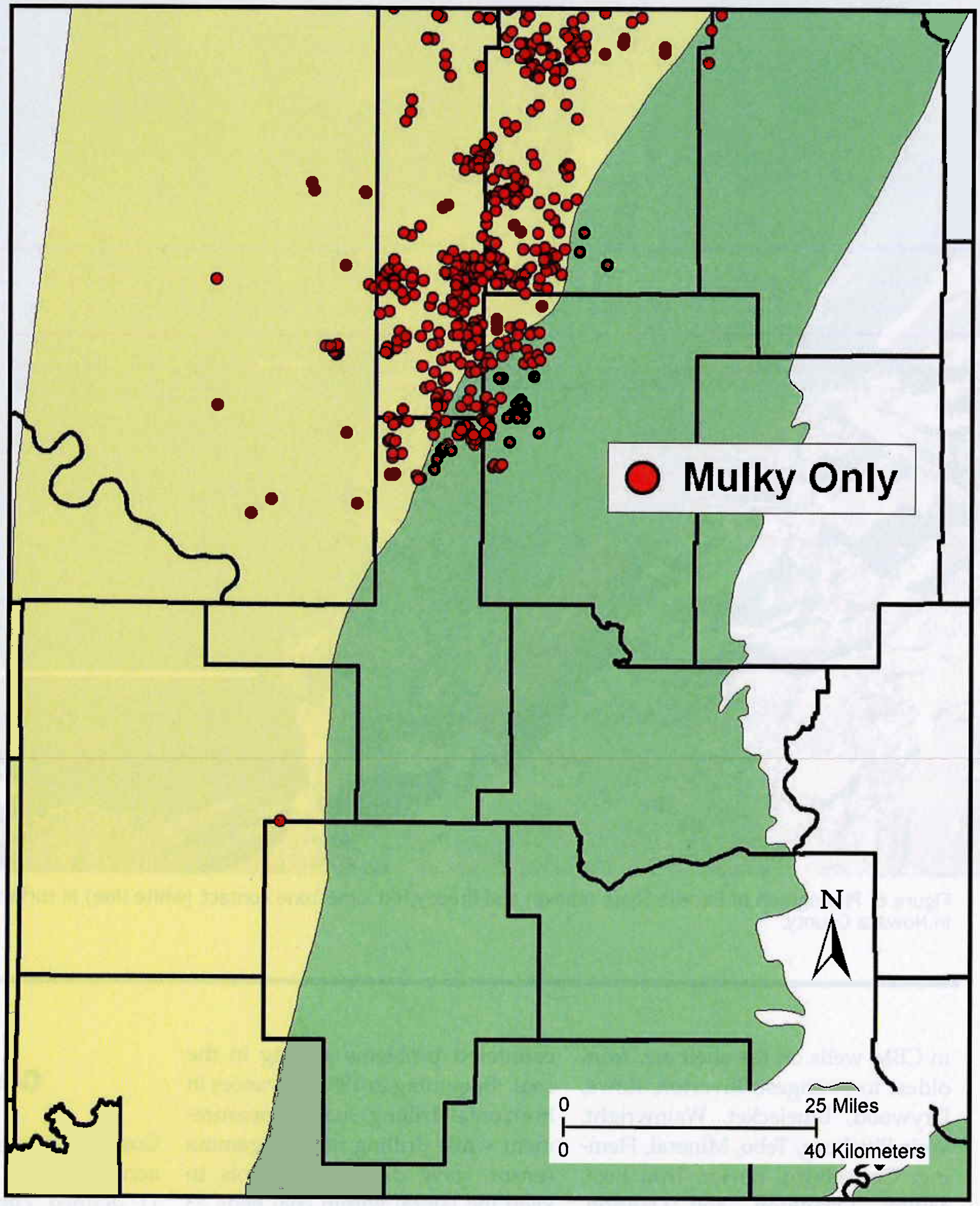
Horizontal CBM

Some of the 6 horizontal CBM wells in the basin drilled during 1998 encountered problems staying in the coal. Beginning in 1999, advances in horizontal drilling, such as measurement while drilling using a gamma sensor, gave drillers the tools to keep the lateral within coal beds >3 ft thick. Almost all (1,565) of the 1,600 horizontal CBM wells from 1998 through 2008 are in the basin. The success of horizontal CBM wells sparked an increase in drilling them over vertical wells. During 2005, 333 (94%) of the 353 CBM wells drilled in the basin were horizontal wells (**Figure 9**). Beginning in 2004, 27 horizontal and 8 directional CBM wells were drilled on the shelf (**Figure 10**).

Gas Fields

Coals are recognized as continuous accumulations. Schmoker (1999, p. 1) defined **continuous accumulations** as ***"petroleum accumulations that have large spatial dimensions and which lack well-defined downdip petroleum/water contacts."*** As such, CBM wells extend beyond conventional gas-field boundaries (e.g., Boyd, 2002). Rather than expanding the established gas-field boundaries to incorporate CBM wells, the Oklahoma Corporation Commission (OCC) began in 2001 to use county names in assigning CBM gas fields

Figure 7. Map showing Mulky-only coal-bed-methane (CBM) wells in Oklahoma (1994–2008).



(e.g., Le Flore County CBM Gas Area). However, conventional gas-field names are used in the field-name column in the CBM completions database when a CBM well occurs within an established gas-field boundary.

"Pennsylvanian" CBM

Beginning in 2005, the OCC passed spacing orders granting permission to report commingled CBM wells on the shelf as "Pennsylvanian" CBM wells (representing 248 of the 5,707 wells in **Figure 11**). This ruling may have decreased the amount of paperwork that companies need to file, but it does not provide the necessary details of what coal beds were perforated or how productive they are.

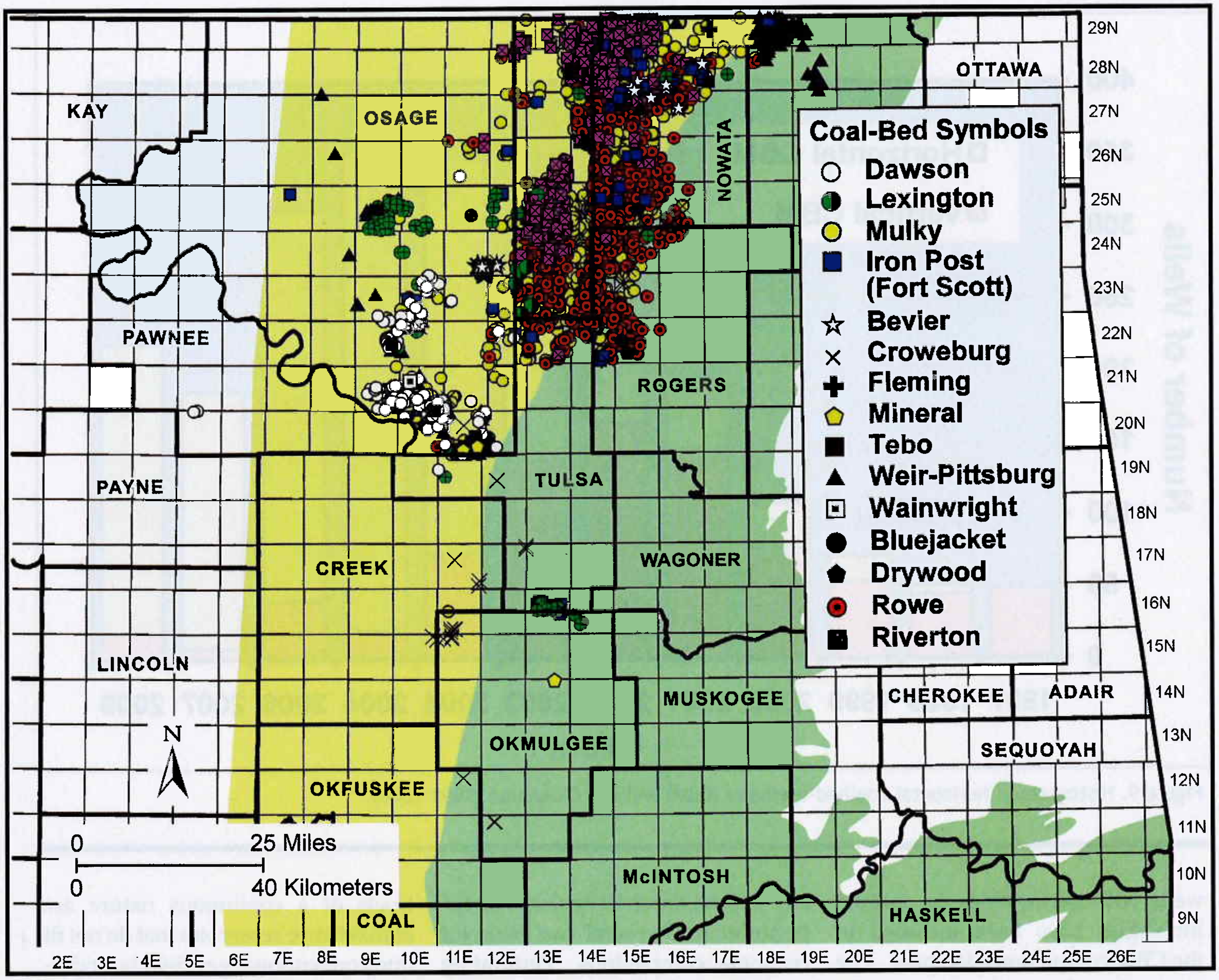


Figure 8. Map showing coalbed-methane (CBM) wells on northeast Oklahoma shelf (1994-2008). Only the shallowest coal bed is used to represent commingled CBM wells.

IMPLICATIONS AND CONCLUSIONS

From 1988 through 2008, 5,707 gas wells were completed to coal beds in the eastern Oklahoma coalfield. Several issues over these years have influenced the development and reporting of coalbed methane (CBM) wells in Oklahoma. The issues impacted what wells to include in a CBM completions database, and how they would be compared and evaluated.

Beginning in 1991 in the Arkoma basin ("basin") and beginning in 1994 on the northeast Oklahoma shelf ("shelf"), pre-existing petroleum wells were recompleted as CBM wells. These 738 CBM wells produced significant amounts of gas; however, they present a problem when summarizing gas production from them. When summarizing CBM production, either recompleted wells must be excluded so that gas produced from noncoal formations is not arbitrarily included, or gas produced from each recompleted well must be added separately, starting with the date of the recompletion as a CBM well. The former method was used in the past (Cardott, 2005) resulting in a conservative estimate of CBM-produced gas (cumulative production of 125 Bcf gas from 1,898 CBM wells on the shelf and 372 Bcf gas from 2,418 CBM wells in the basin from 1988 through 2008).

Beginning in 1992, some Oklahoma CBM wells have additional perforations in thin noncoal lithologies (sandstone, limestone, and shale). Because CBM is believed to contribute most of the produced gas, 330

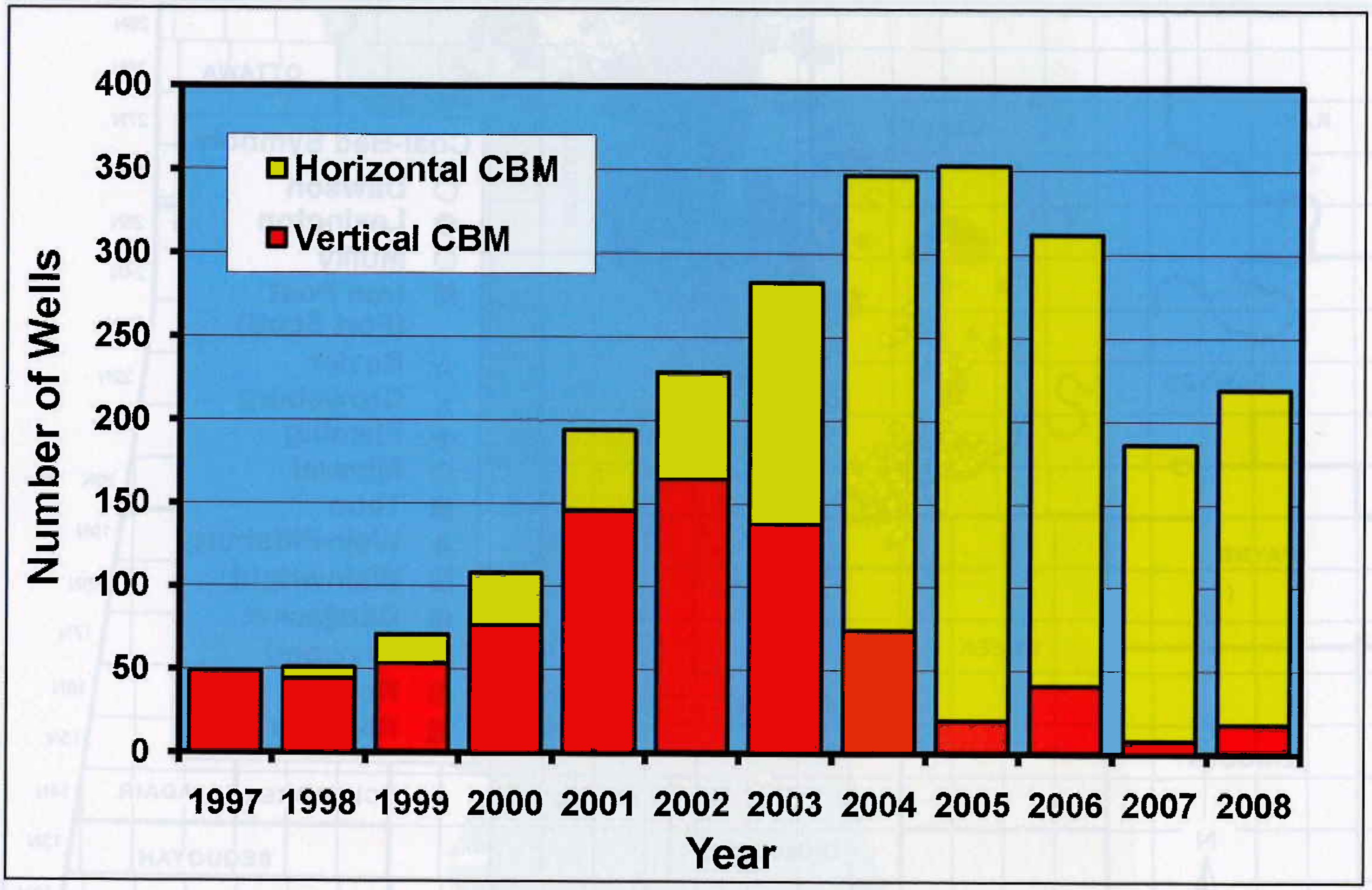


Figure 9. Histogram of horizontal coalbed-methane (CBM) wells in Oklahoma (1998-2008).

wells with perforations in noncoal lithologies have been included in the CBM completions database. The proportion of gas produced from the noncoal lithologies is unknown.

The Mulky coal on the shelf may be either an impure coal (e.g., high mineral matter content < 50% by weight) or it is absent. The 506 Mulky-only wells may be more accurately considered as producing gas from the Excello Shale and should be categorized as gas-shale wells. The Excello-Mulky of northeast Oklahoma and southeast Kansas was included in a recent United States shale-gas-plays map (EIA, 2009).

From 1995 through 2008, 824 CBM wells on the shelf commingled 2 to 9 coal beds each. The thin nature of the multiple coals encountered in any well on the shelf necessitates the perforating of several coal beds for economic completions. Perforating multiple coal beds, however, precludes knowing how much gas came from each coal bed. Only the shallowest coal bed is plotted, masking the contributions of the other coal beds.

Advances in horizontal drilling since 1999 has enabled drillers to stay within coal beds 3 to 10 ft thick, and expose the well to 14–5,771 ft of coal (average lateral length of 2,182 ft from 1,532 wells) than within the < 10 ft thickness of coal in a vertical well. Although 1,565 (98%) of the horizontal CBM wells are in the basin, 27 horizontal and 8 directional wells have been drilled on the shelf.

Coals of a continuous nature are blanket-type reservoirs that do not fit into conventional gas-field boundaries. Following a short period when established gas-field boundaries were extended, the Oklahoma Corporation Commission (OCC) began in 2001 to use county names in the assignment of CBM gas fields (e.g., Le Flore County CBM Gas Area).

Many (248) wells reported as "Pennsylvanian" CBM wells do not provide the necessary details for what coal beds were perforated or on how productive they are.

ACKNOWLEDGMENTS

I thank Dan Boyd and Stan Krukowski of the Oklahoma Geological Survey for critical reviews of this report.

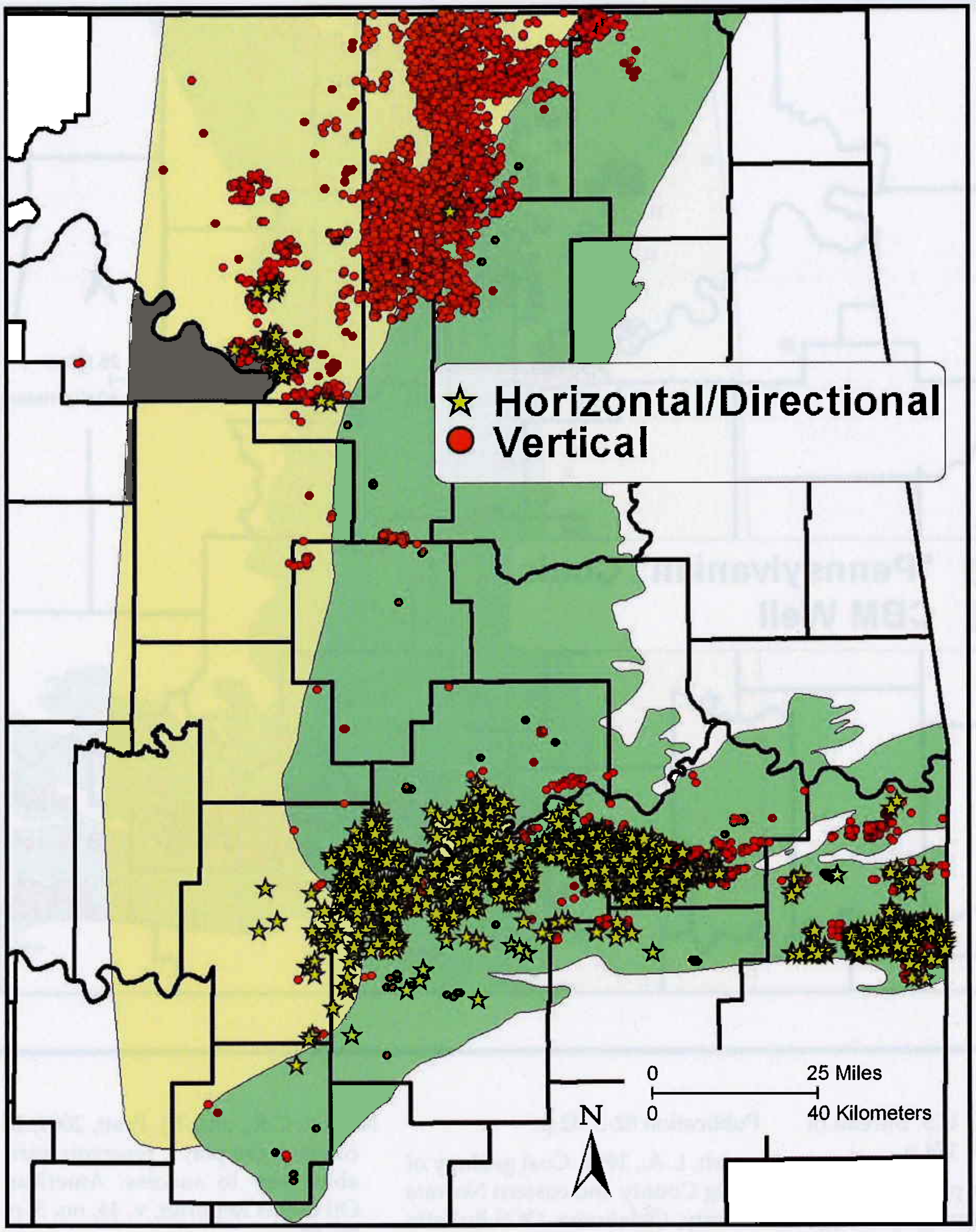


Figure 10. Map showing horizontal and directional coalbed-methane (CBM) wells in Oklahoma (1998-2008).

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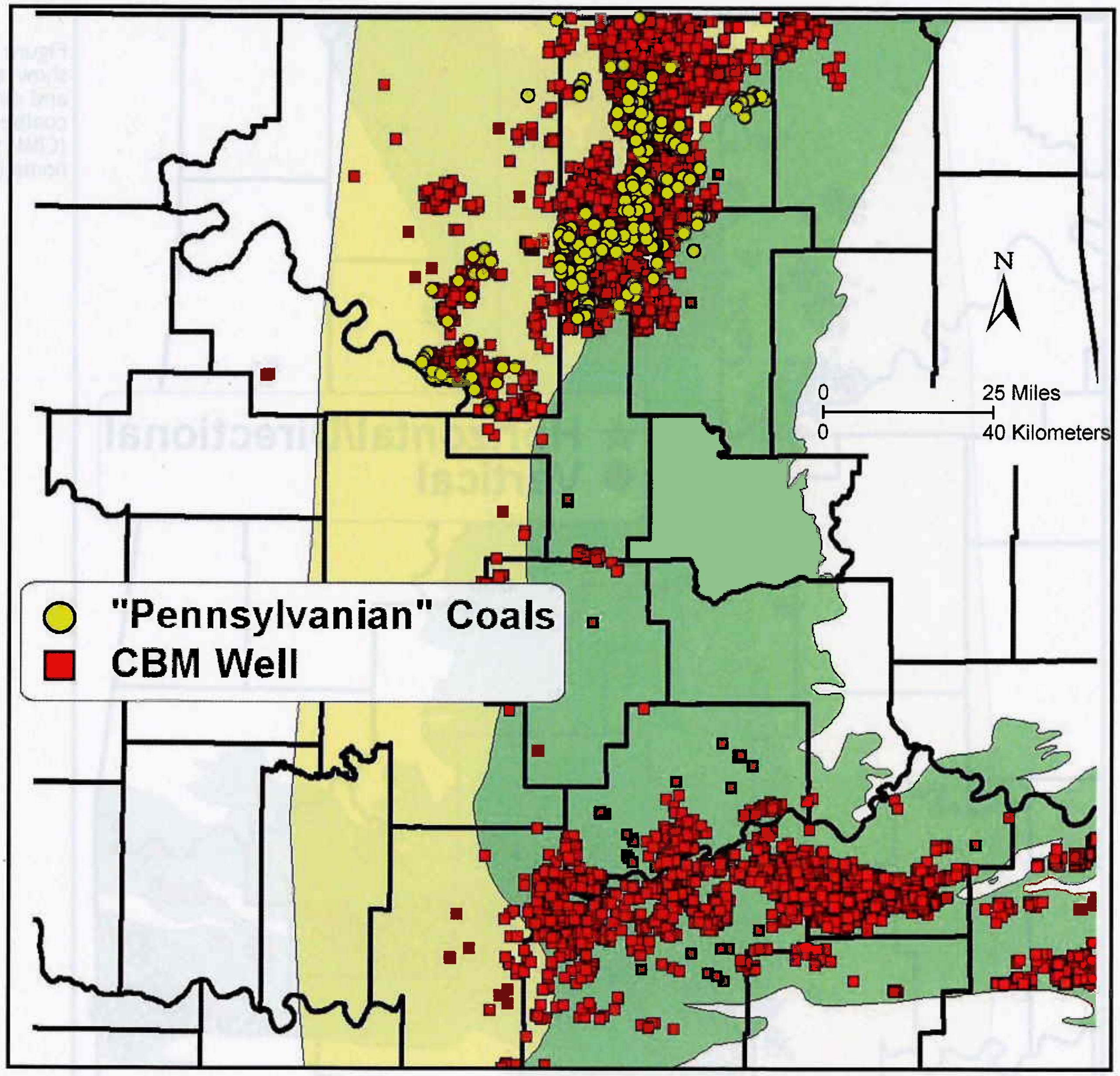
Figure 11. Map showing "Pennsylvanian" coalbed-methane (CBM) wells in Oklahoma (2005-2008).



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Industrial Uses of Mill Tailings in the Tri-State Lead-Zinc Mining District (Oklahoma, Kansas, and Missouri)*

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ABSTRACT

Zinc and lead ores (principally sphalerite and galena) were mined in the Tri-State Mining District (Oklahoma, Kansas, and Missouri) from 1848-1970. U.S. Bureau of Mines records indicate that a total of 181 million tons of crude ore were extracted from mines within Ottawa County, Oklahoma, during the mining period 1891-1970. About 96% of the crude ore, or 174 million tons, were spread across the landscape in various forms of mill tailings (coarse tailings piles, sand piles, and slime/flotation fines). Approximately 70% of the mill feed was discarded as coarse tailings (chat). The remainder went into concentrates, sands, and flotation ponds (slimes).

In the early years of the mining district, chat (particles less than ½-in. in diameter) was used to surface mine roads and later public roads. Washed and unwashed chat was used as ballast for the spur tracks that formed a network over the mining area. Railroad companies expanded chat use for ballast in rail yards, spur lines, and secondary branch lines outside the mining area. Washed chat was used as intermediate aggregate in concrete pavement. Hollow building blocks, sewer tile, and other forms of precast concrete used considerable quantities of washed chat. In much lesser amounts, tailings were used to make blasting sand, sawing sand, roofing granules, engine sand, and traction on icy streets. Eagle Picher installed a differential-density cone plant to produce minus 1 ½-in.-coarse tailings in 1939. This was sold to railroads for ballast on main line tracks. In the 1940s, large quantities of this material were shipped to war plants for ballast, concrete, and road construction at the plants. Concrete was used in structures and runways for military airfields. Today, washed and unwashed chat are used in various types of bituminous mixtures including hot and cold asphalt mixes; asphalt road bases; and asphalt slurry seals.

**Paper presented at 44th Forum of the Geology of Industrial Minerals May 11-16, 2008, Midwest City, Oklahoma.*

INTRODUCTION

Zinc and lead ores (principally sphalerite and galena) were mined in the Picher Mining Field (Picher Field) in northeastern Ottawa County, Oklahoma, and southeastern Cherokee County, Kansas, for more than 60 years. The Picher Field was part of the Tri-State Mining District in Missouri, Kansas, and Oklahoma (**Figure 1**). The eastern part of the Oklahoma portion of the Picher Field (the Peoria Camp) is situated on the west edge of the Ozark Plateau geologic province. The Ozark Plateau is a broad, low structural dome lying mainly in southern Missouri and northern Arkansas. However, the main part of the Picher Mining Field is within the Central Lowland physiographic province characterized by a nearly flat, treeless prairie underlain by Pennsylvanian shales.

Prior to 1918, southwest Missouri maintained leadership in domestic metal production. The output of its mines accounted for more than half the total domestic zinc production for several years before 1910. Peak production was reached in 1916 when Missouri produced 53% of the lead and 65% of the zinc mined in the Tri-State District (Brichta, 1959). In 1918, metal production shifted to the Miami-Picher District as mine operators abandoned the low-grade mines in southwest Missouri for the richer fields in Ottawa County, Oklahoma, and Cherokee County, Kansas. After 1919, 90% of the Tri-District output came from the Picher Field (Martin, 1946). By 1926, 227 mills were operating in Ottawa County.

U.S. Bureau of Mines records indicate that over 181 million tons of crude ore were extracted from mines within Ottawa County during the mining period 1891–1970; approximately 85% of the total production came from the Picher subdistrict (ASARCO Incorporated and others, 1995). About 1.7 million tons of lead concentrate and 8.9 million tons of zinc concentrate were produced from the crude ore in Ottawa County (ASARCO Incorporated and others, 1995). Combined lead and zinc concentrates comprised only 4% of the total crude ore. The remaining 96% of the crude ore, or about 174million tons, was spread across the landscape in various forms of mill tailings (chat piles, sand piles, and flotation fines). Approximately 70% of the mill feed was discarded in the form of coarse chat. The remainder went into concentrates, sands, and flotation ponds (Gray and Stroup, 1943).

The U.S. Environmental Protection Agency (EPA) added the Oklahoma portion of the Picher Mining Field to the National Priorities List (NPL) on September 8, 1983. The NPL is a list compiled by EPA pursuant to Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) section 105, 42 U.S.C. § 9605, of uncontrolled hazardous substance releases in the United States for long-term remedial evaluation and response. The area became known as the Tar Creek Superfund Site.

REGIONAL GEOLOGY

The geologic framework and origin of the lead and zinc deposits have been discussed by numerous authors. These publications include Siebenthal (1908), Weidman and others (1932), Reed and others (1955), Brockie and others (1968), and McKnight and Fischer (1970). The Picher Field straddles the Cherokee Platform–Ozark Plateau.

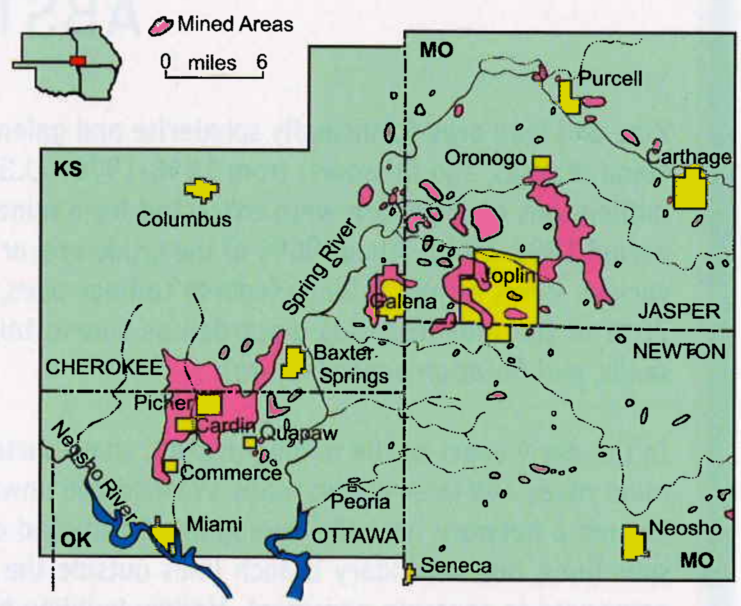

Figure 1. Tri-State Mining District (modified from Brichta, 1959).

The rock formations exposed at the surface in the mining field include Mississippian and Pennsylvanian units that are nearly flat, with a low, regional northwestward dip of about 20–25 ft/mile (**Figure 2**). Cambrian and Ordovician formations, primarily dolomite and chert with some sandstone and minor shale, are encountered only in deep drill holes and water wells in this area. Mississippian rock units, principally the Boone Formation, were the host for most ore deposits. The Boone Formation is composed of fossiliferous limestone and thick beds of nodu-

System	Series	Group, Formation, or lithology		BED
PENNSYLVANIAN	Desmoinesian	Krebs Group Mostly black and gray fissile shale with thin sandstone and limestone beds		
MISSISSIPPIAN	Chesterian	Fayetteville Shale Batesville Sandstone Hindsville Limestone		
	Meramecian	Quapaw Limestone		
		Boone Formation	Moccasin Bend Member	B C D ***E*** F ***G*** ***H***
			Baxter Springs Member	J ***K*** L
			Short Creek Oolite Member	***M***
	Osagean		Joplin Member	
			Grand Falls Chert Member	N ***O*** P Q
			Reeds Spring Member	R
	Kinderhokian and Upper Devonian		St. Joe Limestone	
MISSISSIPPIAN and DEVONIAN		Chattanooga Group		
ORDOVICIAN	Lower Ordovician	Mostly dolomite and limestone; some sandstone		
CAMBRIAN	Upper Cambrian	Mostly dolomite; some sandstone		
PRECAMBRIAN		Granite and volcanics		

Figure 2. Generalized correlation chart for the Picher Field (Mcknight and Fischer, 1970; Fowler and Lyder, 1932; Reed and others, 1955); important ore zones shown in red.

lar chert (**Figure 3**). The Boone Formation, which is 350–400 ft thick in the Picher area, is subdivided into seven members (in ascending order): St. Joe Limestone, Reeds Spring, Grand Falls Chert, Joplin, Short Creek Oolite, Baxter Springs, and Moccasin Bend (McKnight and Fisher, 1970). Fowler and Lyden (1932) and Fowler (1942) further subdivided these members into 16 beds in the Picher Field (**Figure 2**). Letters of the alphabet were used to distinguish individual beds, beginning with *B* near the top of the Moccasin Bend Member and ending with *R* in the Reeds Spring Member (**Figure 2**). In Oklahoma, the Boone Formation is not usually subdivided into members.

The ore deposits in the Picher Mining Field occurred

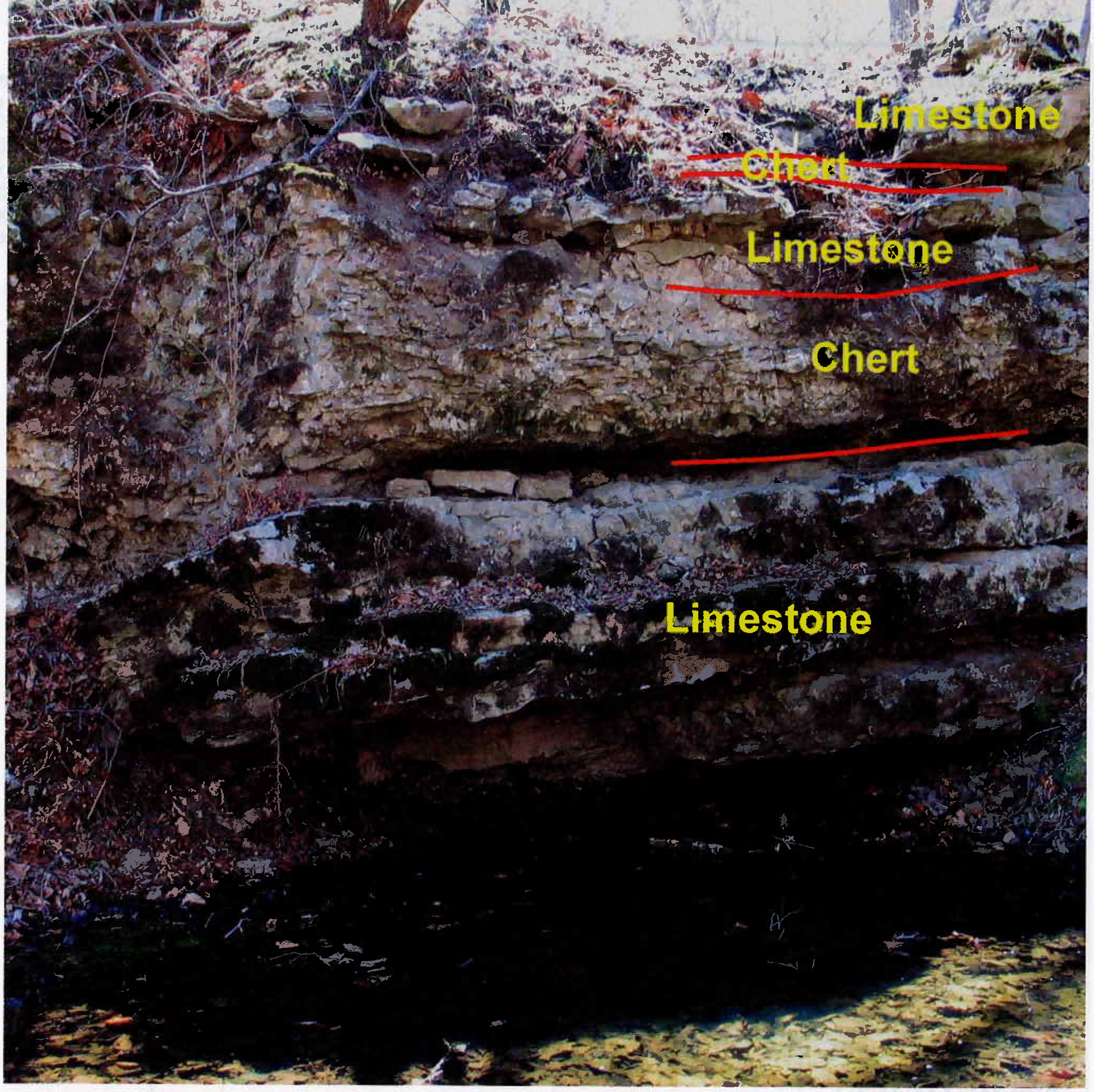

Figure 3. Exposure of the upper part of the Boone Formation on the east side of the Picher Field.

mainly in the upper half of the Boone Formation. A majority of the mine workings are within the *M* bed. Other important ore zones were within the *K*, *G*, *H*, *E*, and Chesterian beds. Sheet ground, or low-grade blanket deposits, occurred within the Grand Falls Chert Member (generally corresponds to the O bed).

Nearly all the ore bodies in the Picher Mining Field occurred as tabular masses (whose horizontal dimensions exceed their thickness). Some ore bodies were blanket-like bodies, dominantly irregular or lobate in plan, but tended to be slightly elongated and curved. These bodies graded laterally into others, called runs, which were flat, narrow, elongate, and usually curvilinear. Many of the runs tended to form closed but irregular-shaped rings around barren cores. Some runs were vertical and vary from 10-15 ft wide and over 100 ft high. Vertical runs had steep inclined walls and generally followed near vertical fracture zones in the rocks. Some smaller ore bodies, called "pockets," had a somewhat circular shape. They usually were separated from the main ore body by slightly mineralized and/or barren rock. Many ore pockets occurred in highly brecciated rock described locally as "boulder ground." Boulder ground was composed of 1–5 ft-angular, silicified and/or dolomitized blocks of fracture rock cemented by ore and gangue minerals (Weidman and others, 1932; McKnight and Fischer, 1970).

MINE AND MILL MINE DEVELOPMENT

Mine Development

The first documented discovery of lead in the Tri-State District was near Joplin, Missouri in 1848. With the exception of the Galena area of Cherokee County, Kansas, which was discovered and mined in the 1870s, mining in the Tri-State District prior to the turn of the century was almost exclusively limited to the Missouri portion of the Tri-State District. Because of the limited scope of mining, the Tri-State District was generally referred to as the Southwest District of Missouri or Joplin region until the early 1900s. Southwestern Missouri maintained leadership in domestic metal production through 1917.

The first discovery and earliest mining in Indian Territory (Ottawa County, Oklahoma) was reported in the vicinity of Peoria in 1891 (Weidman and others, 1932). Although there were some subsequent discoveries and mine operations near Quapaw and Commerce in the early 1900s, the real expansion of mining in the Oklahoma portion of the Tri-State District occurred at the current site of Picher after a major ore discovery around 1914 by the Picher Lead Company. Following this discovery, there was a major expansion of mining in what became known as the Picher Mining Field of Oklahoma and Kansas. The Oklahoma portion of the field was well defined by the end of 1917 with hundreds of mining companies developing mines. In the latter part of 1917, Kansas began producing crude ore from the Picher Field. The year 1918 marked an abrupt decrease in production in southwestern Missouri, as operators abandoned the low-grade mines in that part of the Tri-State District and moved their mills to the richer fields in Ottawa County, Oklahoma.

All lands in the Oklahoma portion of the Tri-State District during the period of mining were within the original Quapaw Indian Reservation boundary. In 1895, the reservation was subdivided into 236 200-acre allotments and 231 40-acre allotments for tribal members (Stroup and Stroud, 1967).

The terms of the early mining leases required exploration work upon the leased land to begin almost immediately and to continue in good faith, without interruption, until ore in paying quantities was discovered. After discovering ore, the leases required that the ore body be developed and put into production at once. Lease agreements frequently specified the type of developments and facilities for each mining unit. A Congressional act of 1921 stipulated royalty rates and lease agreements for Indian allottees. The act required that all ore was to be milled on each lease regardless of the size of the lease. The regulation required more concentrating mills be built than were actually necessary to process the mined ore. The net result was an excessive number of mill tailings (chat) piles created by the mills. Stroup and Stroud (1967) reported that approximately 5,000 acres were overlain by mine and mill tailings.

The peak mining period occurred in the 1920s. By the 1930s, most of the higher grade ores were removed. The 1940s were characterized by increased mechanization: slushers were introduced in the late 1930s and track-mounted shovels in the early 1940s; rubber-tired diesel trucks of 10-ton capacity were perfected for underground haulage in 1946. Over 50 miles of underground roads, which utilized chat, were built for the rubber-tired vehicles. These technological developments contributed greatly to the recovery of lower-grade ores.

In 1950, Eagle-Picher developed a 35-ft-high Jumbo that consisted of a telescoping tower and work platform mounted on caterpillar tracks. The platform could support a work crew and up to 3 air driven drills.. By 1952, a Jumbo capable of reaching 70 ft was in operation. Jumbos were used to recover ore left in high working faces, roofs, and pillars. Because of depressed metal markets, many operations were cut back or suspended in 1957. By midyear 1958, all major mining operations were closed. Mining was resumed in 1960 at a reduced rate, and the last record of significant production occurred in 1970.

Mill Development

The basic milling practice used in the Tri-State District was gravity and/or mechanical concentration. Gravity concentration, as developed in the district, utilized jigs and tables to remove chert and other gangue minerals from zinc and lead sulfides. Gravity concentration practices used in Ottawa County were developed in the Missouri portion of the district, with the jigs, tables, and other milling equipment manufactured primarily in Joplin, Missouri. The

Figure 4. Large boulder pile near mill foundation.

gravity mills were commonly known as Joplin-type mills. They typically had the capacity to process 25-30 tons of ore per hour and normally operated for 10 hours per day. In the middle 1910s, the U.S. Bureau of Mines research determined that flotation was adaptable to the ores in the Tri-State District (Wright, 1918). Various reagents and frothing agents were used to recover additional lead and zinc lost in the fine tailings (slimes). In 1917, Eagle-Picher Lead and Zinc Company's (Eagle-Picher) East Netta Mill was redesigned for a flotation circuit.

The 1920s marked the maturity of the field. A flotation process was adopted by a few mills during World War I, and by the middle 1920s the process was in wide use. The use of the flotation process as an adjunct to jigging and tabling in the last half of the 1920s ensured the recovery of 80%-85% of the zinc sulfide in the crude ore, compared to 58%-70% recovery estimated for the older milling. In the latter half of the 1920s, zinc recovered from reworked fine and coarse tailings became an important factor in zinc production (Keiser, 1927).

The Great Depression brought very low metal prices that led to a significant reduction in crude ore production. Inefficient mills closed and numerous mine and mill workers became unemployed. The 1930s witnessed the growth of central milling in the field. The first mill built to treat ore from several tracts was the Bird Dog Mill of Commerce Mining & Royalty Co., completed in 1930. The plant was designed to process 2,750 tpd on a 14-hr basis. Sampling and milling of ores from several different leases proved economically feasible. In 1932, Eagle Picher completed a central mill near the southwest corner of the field. The initial capacity, rated at 3,600 tons, was shortly increase to 5,500 tpd, with an ultimate capacity of 18,000 tpd.

Tailings Mills

Approximately 96% of crude ore milled ended up as tailings in the Picher Mining Field. Approximately 174 million tons of tailings were generated during the milling process including 139 million tons of coarse tailings (chat), 21million tons of sand tailings, and 14 million tons of flotation tailings (ASARCO Incorporated and others, 1995). These figures did not include tailings from crude ore that was shipped to Oklahoma custom mills; and tailings generated outside the state that were re-treated at Oklahoma tailings mills.

In the middle to late 1920s, some mills were converted to plants that only re-milled tailings. Improvements in the flotation process and the elimination of the primary crusher made it possible to retreat

Figure 5. Boulders used to stabilize slime-pond embankments.

tailings at a lower cost than milling crude ore. In 1928-1929, 5.5 million tons of tailings were retreated in Oklahoma. Additional mills were converted to tailings mills and some new tailings mills were even built. Most tailings mills had a capacity of less than 100 tons per hour. In 1934, there were 18 tailings mills in operation in the Picher Mining Field that milled 12,000 tpd of tailings (Burris and others, 1934). By the end of 1933, an additional 6.5 million tons were retreated in Oklahoma. This represented about 23% of total zinc concentrate produced in the district. Peak production from tailings came in 1936 when 28% of the zinc concentrates for the Tri-State District were derived from tailings (McKnight and Fischer, 1970).

By 1940, most of the tailings were retreated for the first time and some a second time. During World War II, the remaining tailings were reprocessed again, and some even for a third time (McKnight and Fischer, 1970). The number of tailings mills increased during the early and middle 1940s. By January 1948, most available tailings were re-treated at least twice and only five tailings mills were in operation. The number of tailings mills continued to decline in the 1950s.

The mining and milling operations during the mining period created several hundred chat piles. Only about a dozen of the larger chat piles remain today. The larger aggregate in two of these chat piles is used in asphalt mixtures for highways. The finer chat particles in the <40 mesh (U.S. Standard sieve mesh number) size are left on-site after washing and screening. Some tailings piles attained heights of nearly 200 ft. The former Eagle-Picher central mill tailings pile north of the town of Commerce was among the tallest and near the end of the mining period contained approximately 12 million tons of tailings. From 1970 to 1982, it was removed except for its base material.

INDUSTRIAL USES

Three mine and mill waste materials produced during the mining and milling of lead-zinc ores in the Picher Field: boulders (mine waste); coarse tailings (chat; includes sand tailings); and flotation tailings (slimes). In the early years of the mining district, coarse tailings were used to surface roads around the mines; and later public roads. Chat was used as ballast for the spur tracks forming a network over the mining area. Railroad companies outside the mining field found chat was ideal for ballast and extended its use to rail yards and secondary tracks. The use of chat in concrete mill piers was soon extended to other uses of concrete. As time progressed, still other uses were developed, but most required careful processing.

About 5.5 million tons of chat was shipped from the Oklahoma portion of the mining field in 1928-1929. The 1930s marked the beginning of larger tailings shipments out of the mining field. Beginning in the late 1960s and early 1970s the transition of chat sales from railroad ballast to use in asphalt mixtures occurred. Today, a small, but well established market for chat in transportation applications exists. Approximately 95% of this chat is used in various bituminous mixtures for roads, parking lots, and driveways. There is no current evidence that chat is used in portland cement concrete. Netzeband (1937) provides an excellent summary of products from mill tailings. Listed below are some uses of chat that Netzeband identified in the early and middle 1930s.

Boulders—Ore was hoisted to the surface and dumped upon a grate (grizzly) with 6- to 8-in. openings; the undersized dropped into a hopper. The oversize was "sledged through" by men who also culled the barren or lean boulders. The barren boulders were dumped onto piles near the derrick (**Figure 4**). They were shipped from the district as a source of rip-rap and were mostly "one-man" sizes (10-12 in. maximum dimensions, weighing 75-100 lb). They were used extensively for protecting railroad and slime pond embankments (**Figure 5**), prevention of stream-channel erosion, and a small proportion went to make rubble concrete used in mill piers (**Figure 6**). Recently, boulders were used to fill open and caved mine shafts.

Crushed Rock—A majority of chat piles contained particles less than ½-in. in diameter. In 1939, Eagle-Picher installed a differential-density cone plant at their central mill to produce minus 1 ½-in. size coarse tailings (**Figure 7**). The gradation of this product was all minus 1 ½-in. to plus 30 mesh, and graded between these two sizes in almost straight-line proportions (Gray and Stroup, 1942). The new method of concentration made more desirable ballast (Type B) and the demand for this product increased sharply. In the early 1940s, Eagle-Picher shipped this material to war plants for ballast, highway construction in the plants, and concrete used in structures and runways for military airfields. In 1942, production of chat at Eagle-Picher's central mill averaged between 8,000 and 10,000 tons daily. The demand, at

Figure 6. Boulders used to occupy space in mill piers.

Figure 7. Coarse tailings, minus 1.5 in., produced at Eagle-Picher's central mill.

that time, exceeded output. In July, 1967, Eagle-Picher sold over 74,500 tons of chat to various railroad companies (Westfield and Blessing, 1967). In the early 1980s, its stockpile was removed and presumably sold for railroad ballast. In 1975, the AZCON Corporation, formerly American Zinc, terminated its ballast shipping business in Picher, Oklahoma. AZCON was second to Eagle-Picher in chat sales.

Pile-(Bank) Run Chat—This is unprocessed tailings produced by the mills. Pile-run chat weighs approximately 93 lbs per cubic ft or about 1.25 tons per cubic yd (Netzeband, 1937). Pile-run chat was used on farm and residential driveways, barnyards, public roads, and as Type A (unwashed) railroad ballast. Today, some of it is used in various types of bituminous mixtures for roads, driveways, and parking lots if certain highway department specifications are met.

Washed Chat—This type of chat was washed to remove the minus-100-mesh material. The washing removed many impurities such as metallic minerals and shale, leaving a clean product. Washed chat had a number of uses, but between 80% and 85% was used for Type A (washed) railroad ballast (Netzeband, 1937). It could tamped easily by hand in laying or realigning track; drains well; and was not subject to volume changes during freeze-thaw cycles. Washed chat was used extensively as intermediate aggregate in concrete. Its hardness and toughness increased the wear quality of concrete pavement. The angularity of chat fragments increased concrete stability and flexural strength. Hollow building blocks, sewer tile, and other forms of precast concrete used considerable quantities of washed chat. Today, almost all washed chat is used as an aggregate in various types of bituminous mixtures including hot mix and cold asphalt road surfaces, asphalt road base, and asphalt slurry seals.

Screened Chat—This contained a lower percentage of fines than washed chat. It was used in place of washed chat where fewer fines were required. They were much cleaner and more closely sized than washed chat. Many lumber dealers and supply houses stocked screened chat as an intermediate aggregate for concrete. Paving sand was made from screened and washed chat. It was clean, hard, and angular, and used as a substitute for river sand in concrete.

Other Uses of Chat Products—Tailings were used to make blow sand, blasting sand, sawing sand, rock dust, roofing granules, engine sand, and for traction on icy streets. Blow sand was used extensively as a dash on stucco work and applied with an air gun. It was a clean, angular product that did not discolor in weathering through oxidation. Its source was carefully selected to avoid metallic minerals, especially marcasite. Blasting sand was a uniformly, closely sized product used to clean boiler flues and sheets, castings, and to remove paint. Its uniform hardness and grain angularity made it a superior product allowing the product to compete over a larger market area. Sawing sand was used in dimension stone quarries around Bedford, Indiana, and Carthage, Missouri. Rock dust was usually obtained from the slime ponds. Most of this material was minus 65 mesh, with a large percentage around 200 mesh. It was used for absorbing and holding oils, and as a filler to close voids and improve density. Its high absorptive qualities made it ideal for blotting oils at gasoline stations.

In 1969 American Zinc Co. began to construct a chert-grit screening plant in Picher, Oklahoma, to compete with other companies in Webb City, Missouri, and Galena, Kansas. New markets had opened for sized chert grits (minus 10 to 80mesh) in the chemical, paint, anti-corrosive, filtering, sand-blasting, and metalizing industries. The grits were left over from screening and washing chat for asphalt paving aggregate. American Zinc projected that these materials could sell for as much as $19.00 per ton.

CHAT PROPERTIES AND MARKETS

Chat Properties

Most chat, washed and unwashed, is used as aggregate in hot and cold asphalt mixes. There is no known use of chat in portland cement concrete (PCC). Chat makes superior asphalt because of its particle-size distribution, durability, angularity, and low moisture absorption. Cubicle shape is another desirable property of a good aggregate. The coarse aggregate in raw chat (particles retained on a 4.75 mm, No. 4 sieve) has less than 5% flat or elongated particles. Raw chat is harder than some aggregates such as limestone, making it more desirable in road surfaces because it does not wear down as fast as other materials. Chat also exceeds the Oklahoma Department of Transportation (ODOT) durability indices making it attractive for use in asphalt.

Raw chat, which is composed mostly of crushed chert, has numerous fracture faces. According to one asphalt company, the angular qualities of chat allow it to interlock in the asphalt mix forming a desired skeletal framework. Raw chat also has numerous inter-granular voids in the loose aggregate form. Asphalt with too many voids within the skeletal framework loses strength and requires excessive oil to fill the voids. If the asphalt contains too many chat fines, the angular qualities of chat are altered and additional oil is required to coat the fines. Therefore a balance between angularity, chat fines, and other aggregates are necessary for blending to make desirable asphalt aggregate.

Oklahoma, Kansas, and Missouri Departments of Transportation have adopted aggregate standards for hot mix asphalt and PCC developed by the American Association of State Highway and Transportation Officials (AASHTO). The clay- and silt-sized particles often adhere to larger particles that can adversely affect the quality of hot mix asphalt and PCC. AASHTO standards specify limits for the amount of aggregate, on a percent basis, in hot mix asphalt and PCC according to aggregate size and gradation. The aggregate sizes included in the AASHTO standards range from .075 mm to 9.5 mm which is within the range of particles found in raw chat.

AASHTO limits particle size distribution finer than 50 mesh to 7% to 60% for aggregate in asphalt. Oklahoma has over 200 mix designs for hot mix asphalt (Wasiuddin and others, 2005) and Kansas has eight (John Crofoot, Heckert Construction, 2008, personal communication). In concrete, the particle size distribution less than minus 50 mesh is limited by Oklahoma and Missouri to between 5% and 30%; for Kansas the range is from 7% to 30%. Chat is not approved by the ODOT for use in PCC due to the potential alkali-silica reaction and freeze-thaw durability issues.

To meet particle size specifications, raw chat is mixed with other aggregates by dry sizing or by washing (wet sizing) the chat. All chat is blended with other aggregates in various asphalt mixes. In northeast Oklahoma and southeast Kansas, aggregates come from nearby limestone quarries. The amount of chat used varies from 20% to 50%. Wasi-

Table 1: Particle size distribution (percent passing) for three chat piles

Sieve Size/Number	Sieve Size (mm)	Kenoyer	Atlas	Ottawa
1/2 inch	12.7	100.0	100.0	100.0
3/8 inch	9.53	99.9-100.0	99.9	99.9
4	4.75	80.3-86.1	80.4	82.0
10	2.00	43.1-65.4	52.7	50.1
40	0.420	15.8-17.3	22.6	18.7
80	0.177	7.7-8.6	14.3	10.3
200	0.074	3.1-3.9	7.4	5.6

(Datin and Cates, 2002)

Figure 8. Storage bins for limestone chips (1), mine chat (2), limestone screenings (3), and 1 1/8-in. limestone rock (4).

uddin and others (2005) found that 80% of raw chat, when combined with non-chat aggregates, meets ODOT standards and specifications for hot mix asphalt pavement applications.

Each chat pile has a slightly different particle size distribution; and there is some variation within individual piles. In 1999-2000, Datin and Cates (2002) analyzed three chat piles (**Table 1**): Ottawa, Atlas, and Kenoyer. The greatest variation in particle size occurred in the fraction passing 40 mesh. Chat in the Ottawa and Atlas piles was washed, screened, and sold as aggregate in various asphalt mixes. By 2007, all the marketable chat was removed from both piles. Chat in the Kenoyer pile is used directly by a local asphalt company in three types of asphalt mixes.

Chat Markets

The authors estimate that over 100 million tons of chat were shipped out of the Picher Field in the past 85 years. Based on chat sales records, over 85% chat was sold as railroad ballast and the remainder for other commercial use. Chat was shipped on hundreds of thousands of railcars for railroad ballast between 1920 and 1982. During the first two and a half years of operation at the central mill, Eagle-Picher shipped 35,000 railcars of chat. American zinc shipped over 40,683 railcars from 1937 to 1946. During World War II, Eagle-Picher shipped 100 railcars of chat per day. Chat sold for $.30 per ton in the 1950s and increased to $.80 per ton in the 1970s.

Over the past 50 years numerous attempts were made to estimate the amount of mill tailings remaining in the Picher Field. Records of the Tri-State Zinc and Lead Ore Producers Association at the Baxter Springs, Kansas Heritage Center and Museum list 64 tailings piles in the Picher Field containing over 500,000 tons in 1947. This does not include smaller chat piles, fine tailings in flotation ponds, and/or the bases of the remaining chat piles in the field. Accurate estimates are difficult to obtain due to the irregular shapes of most chat piles, the varying depths of the flotation ponds, and the increase in vegetative cover over some tailings. The most recent estimate made by AATA International, Inc (2005) for the EPA is 39 million tons of tailings in chat piles. In 2009, there are 12 chat piles that contain more than 500,000 tons. Some estimates made in recent years have focused on the amount of marketable chat remaining in the Picher Field. Estimates of the total tonnage of marketable tailings vary from 25.5 million tons to 50.5 million tons.

The use of chat in asphalt, concrete, and other projects is driven by several economic factors. Most chat sold in the Picher Field (80%) is transported to Kansas for use in state and commercial projects. Ninety percent of the chat is used in state funded asphalt road projects. The remainder is used in commercial projects such as paving parking lots in shopping centers and streets in housing developments. There is practically no chat sold for use in concrete mixes.

The primary economic driving force that affects the use of asphalt is state revenue. The amount of federal and state funding provided by state legislatures determines the number of miles of roads paved each year. The second factor is the price of asphalt cement (oil). Asphalt cement cost $175 per ton in 2004 and $400-$1,100 per ton in 2008. The price depends on the type of oil required in the asphalt mixture.

Recent increases in diesel fuel have impacted the distance chat can be economically transported from the Picher Field. A few years ago, chat could compete with local sources of aggregate within a 600-mile radius of Picher. Current fuel prices have reduced the market area to about 300 miles (Larry Bingham, Bingham Sand and Gravel Co., personal communication, 2008). The price charged per ton of chat, about $4, has not changed in the past couple years. If diesel fuel prices continue to increase, a price adjustment inevitably will have to be made. Currently, over a million tons of chat are processed and sold from the Picher Field annually.

A TYPICAL ASPHALT PLANT

Teeter's asphalt plant is one of two asphalt plants located in the Oklahoma portion of the Picher Field. Teeter Asphalt and Materials Company began in 1983 as a partnership between Steven Teeter and

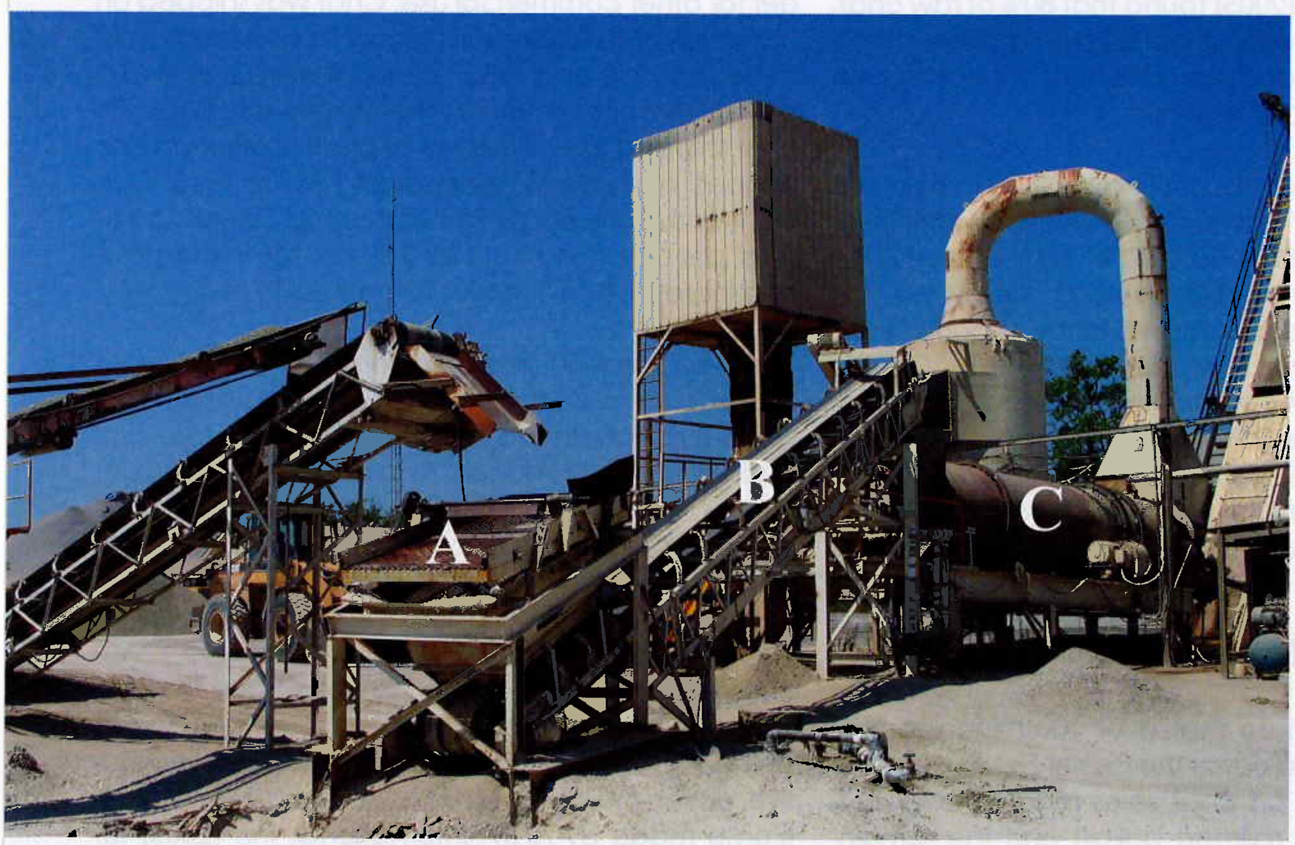

Figure 9. Primary or scalper screen (A), belt scales (B), and drum mixer (C).

Figure 10. Asphalt storage silos at 70-ton capacity (A) and 35-ton capacity (A'); and flue gas scrubber unit (B).

his father, Roy Teeter. Larry Teeter, Steven's brother, began Teeter's paving in 1984 and his business is located in Quapaw, Oklahoma. The asphalt plant employs about 5 full-time works.

The plant utilizes chat directly from the pile for various asphalt mixes. Chat is used directly from the mine site when the minus 80-mesh fraction is less than 3% to 5%; however, most chat piles contain over 5% minus-80-mesh particles. Chat from these piles is washed and screened to remove silt and very fine sand-size particles. When chat is passed over a No. 4 screen during the washing process, a 3/16-in. and/or larger chip and manufactured sand are produced.

Chat is mixed with limestone rock and/or chips, and limestone screenings (fine limestone particles produced from crushing limestone into rock and chips) to produce asphalt at this location. Three types of asphalt mixes, Type A, Type B insoluble, and Type C insoluble, are made at this plant. Mix Type A is usually used as base coarse asphalt. One-and-one eighth-inch limestone rock, ¾-in.limestone chips, and limestone screenings are blended with mine chat to make base coarse asphalt. A 2- to 4-in. layer of this type asphalt is laid over a 6-in. thick sub base layer of crushed limestone rock. Type A asphalt utilizes the largest size aggregate and least amount of asphalt cement, about 5%.

Mix Types B and C insoluble contain about 50% chat. The amount of asphalt needed to pave a typical county road with a one-inch-thick layer is 103-104 lbs per square yard. A one mile long, 22-ft-wide road paved with a 3-in.-thick layer of asphalt would require about 2,000 tons of asphalt. About 1,000 tons or 740 cubic yd of chat are needed to pave this hypothetical county road.

ENVIRONMENTAL ISSUES

In 1980, the Governor of Oklahoma formed the Tar Creek Task Force, comprised of 24 local, state, and federal agencies, to investigate the effects of acid mine drainage on the area's surface and groundwater supplies. The Task Force investigated the problem in 1980 and 1981 with the assistance of Hittman and Associates, Inc. Based upon information discovered by the Task Force, the EPA proposed, in July 1981, to add the The Picher Field to the NPL. The area was listed on the NPL on September 8, 1983; and became known as the Tar Creek Superfund Site.

Operable Unit 1 (OU1) response actions at the Site were managed as a State-lead project and the EPA provided a majority of the funds. The lead State technical agency for the Site was the Oklahoma Water Resources Board, and the lead State administrative agency was the Oklahoma State Department of Health. On July 1, 1993, State responsibility for all aspects of the project was consolidated when the project was transferred to the newly created Oklahoma Department of Environmental Quality (ODEQ). ODEQ remains the lead agency for activities at the Site.

The EPA issued its first Record of Decision (ROD) for the Site on June 6, 1984. The 1984 ROD called for 1) the prevention of the downward migration of mine water into the Roubidoux Aquifer and 2) a dike and diversion program to eliminate major inflow points. Initially, 66 well sites in Kansas and Oklahoma were identified for closure. Forty-three wells were plugged and sites restored (IT Corporation, 1985). During remediation, an additional 17 well sites were located. Fourteen wells were cleared and plugged (Engineering Enterprises, Inc., 1986). The dike and diversion and well-plugging programs were completed in December 22, 1986.

In 1989, the EPA promulgated rule (54 FR 36592) that exempted extraction/beneficiation wastes from regulation under Resource Conservation and Recovery Act (RCRA) Subtitle C hazardous waste regulations (see 40 CFR 261.4 (b) (7)). Therefore, chat became an exempted waste and was not subject to regulation under RCRA Subtitle C. This exemption does not, however, affect CERCLA jurisdiction over chat, nor does it affect the jurisdiction of RCRA, Section 7003, as long as the chat is a solid waste.

Blood-lead data collected by the Indian Health Service (IHS) between February 1992 and May 1993 indicated that 34% of children tested in the Picher area had blood-lead levels greater than or equal to 10 µg/dL, the national standard (Ackerman 1994). The actual source(s) of the lead exposure for the children with elevated blood-lead levels was unidentified, but several possible sources were noted, including living in proximity to mill tailings (chat) piles.

From August 1994 to July 1995, the EPA sampled soils in high access areas (e.g., day care centers, school yards, and playgrounds) and residential properties in the Tar Creek Superfund Site. The EPA concluded the source of lead contamination was mill tailings. On August 15, 1995, the EPA issued an Action Memorandum calling for the excavation and on-site disposal of lead-contaminated soil in residential areas of Picher, Cardin, Quapaw, Commerce, and North Miami. Removal of contaminated soil in residential areas originally began in June 1996 as an emergency removal action. The removal of chat from lawns, yards, driveways, and recreation areas in the Picher area became Operable Unit 2 (OU2) when the EPA's record of decision was issued on August 27, 1997. This program was completed in 2007.

The Washington D. C. Office of the Bureau of Indian Affairs (BIA) placed a moratorium on the removal or sale of mill tailings and pond tailings on Indian owned lands on October 6, 1997. At that time, mill tailings were routinely used on county and private roads, in driveways, and as fill in residential yards, and in other commercial projects. Chat sales continued from privately owned tailings piles. In February 2005, the BIA signed an agreement with the EPA Region 6 to resume the sale of chat on Tribal lands and lands administered by the BIA. The draft sales agreement prepared by the BIA required buyers of chat on tribal lands to use it in a fashion which is deemed acceptable by the EPA. The agreement is similar to the certification used on non-tribal lands.

Studies by Dames and Moore (1993), Drake (1999), Guthrie (1999), University of Oklahoma/Surbec-Art Environmental (2000), Datin and Cates (2002), and others found the concentrations of lead, cadmium, and zinc in chat increase with decreasing particle size. The chat that passed minus 40 sieve contained up to 80% of the lead in 20% of the total chat volume (Datin and Cates, 2002). On May 10, 2000, the ODEQ issued "Mine Tailings Usage Guidelines for Residential Properties." The guidelines delineated inappropriate uses of mill tailings including use as fill material, base, and surface material in residential areas.

In August 2005 President George W. Bush signed the Safe, Accountable, Flexible, and Efficient Transportation Equity Act of 2005 (HR 3 or "the Act") or better known as the Transportation Bill). The Act amended Subtitle F of the Solid Waste Disposal Act (42 U. S. C.

6961 et seq) by adding Section 6006 which required the EPA to develop rules governing the use of chat in transportation construction projects funded, in whole or in part, with Federal funds. Section 6006 was further amended to require the EPA to develop guidelines for the safe use of chat in non-transportation cement and concrete projects.

On July 18, 2007, EPA issued the final chat usage regulations and guidelines. EPA determined the following uses of chat in transportation construction projects, funded in whole or in part with Federal funds, are not likely to present a threat to human health and the environment:

(1) Chat used as an aggregate in hot mix, warm mix, and cold mix asphalt road surfaces, asphalt road base, asphalt slurry seals/microsurfacing, and epoxy bridge anti-skid surfacing.

(2) Chat used as an aggregate in portland cement concrete, granular road base, stabilized road base, chip seals, and flowable fill if:

(a) the product is tested using the Synthetic Precipitation Leaching Procedure (SPLP, EPA SW 846 Test Method 1312) and the resulting metals in the leachate do not exceed the National Primary Drinking Water Standards Maximum Contaminant Level for lead of 0.015 mg/l and cadmium of 0.005 mg/l and the leachate also does not exceed the National Recommended Water Quality Criteria chronic standard for zinc of 120 µg/l: or

(b) EPA or a State environmental agency has determined based on a site-specific risk assessment and after notice and opportunity for public comment, the leachate will not exceed the National Primary Drinking Water Standard Maximum Contaminant Level.

Unacceptable uses of chat include use as unencapsulated surface material; fill material in yards; playgrounds; parks; and ball fields; school or daycare centers; playground sand; vegetable gardening in locations with contaminated chat; sanding of icy roads; sandblasting; development of land for residential use over chat pile bases; use of remilled asphalt roads that used chat on residential properties as fill material; use as an agricultural amendment; and use of chat piles for recreation (EPA, 2007; 2007a).

In February 2008, the EPA Region 6 issued the Record of Decision for Operable Unit 4 (OU4) "Chat Piles, Other Mine and Mill Waste, and Smelter Waste in the Tar Creek Superfund Site, Ottawa County, Oklahoma." The selected remedy for OU4, Alternate 5, was voluntary relocation of residents in the Picher/Cardin area, phased consolidation of chat, chat sales regulations, and on-site disposal. EPA extended the time frame for chat sales to 30 years.

SUMMARY

Zinc and lead ores (principally sphalerite and galena) were mined in the Picher Field in northeastern Ottawa County, Oklahoma, and southeastern Cherokee County, Kansas, for more than 60 years. The U.S. Bureau of Mines records indicate that 181 million tons of crude ore were extracted from mines within Ottawa County, Oklahoma, during the mining period 1891-1970. About 96% of the crude ore, or 174 million tons, were spread across the landscape in various forms of mill tailings (coarse tailings piles, sand piles, and slime/flotation fines). From the late 1920s to the middle 1950s mill tailings were retreated to recover additional lead and zinc remaining from the gravity concentration milling process.

The U.S. Bureau of Mines records do not include crude ore and tailings from outside the state that were milled in Oklahoma, and/or tailings that were shipped into Oklahoma for sale as railroad ballast. The total amount of tailings generated from all sources probably exceeded 200 million tons (Stewart, 1984).

Boulders (mine waste), coarse tailings (chat), and flotation tailings (slimes) were produced in abundant quantities. Boulders were used as rip-rap and to stabilize railroad and slime pond embankments. Mill tailings that remained from the former Picher Mining Field provided an abundant source of material for beneficial industrial uses. In the early years of the mining district, coarse tailings were used to surface roads around the mines, and later public roads; and as ballast for the spur tracks that formed a network over the mining area. Railroads found chat was ideal for ballast and extended its use to mainline tracks. The use of chat in concrete mill piers was soon extended to other forms of concrete. Other historical uses of mill tailings included basting sand, sawing sand, roofing granules, and engine sand. Over 100 million tons of chat was shipped out of the Picher Field in the past 85 years. Estimates of the total tonnage of marketable tailings that remain vary from 25.5-50.5 million tons.

Today most chat, washed and unwashed, is used as aggregate in hot and cold asphalt mixes. There are no known use of chat in portland cement concrete (PCC). Oklahoma, Kansas, and Missouri Departments of Transportation have adopted aggregate standards for hot mix asphalt and PCC. Most chat sold in the Picher Field (80%) is transported to Kansas for use in state and commercial projects. Ninety percent of the chat is used in state funded asphalt road projects. The rest of the chat (10%) is used in commercial projects such as paving parking lots in shopping centers and in streets in housing

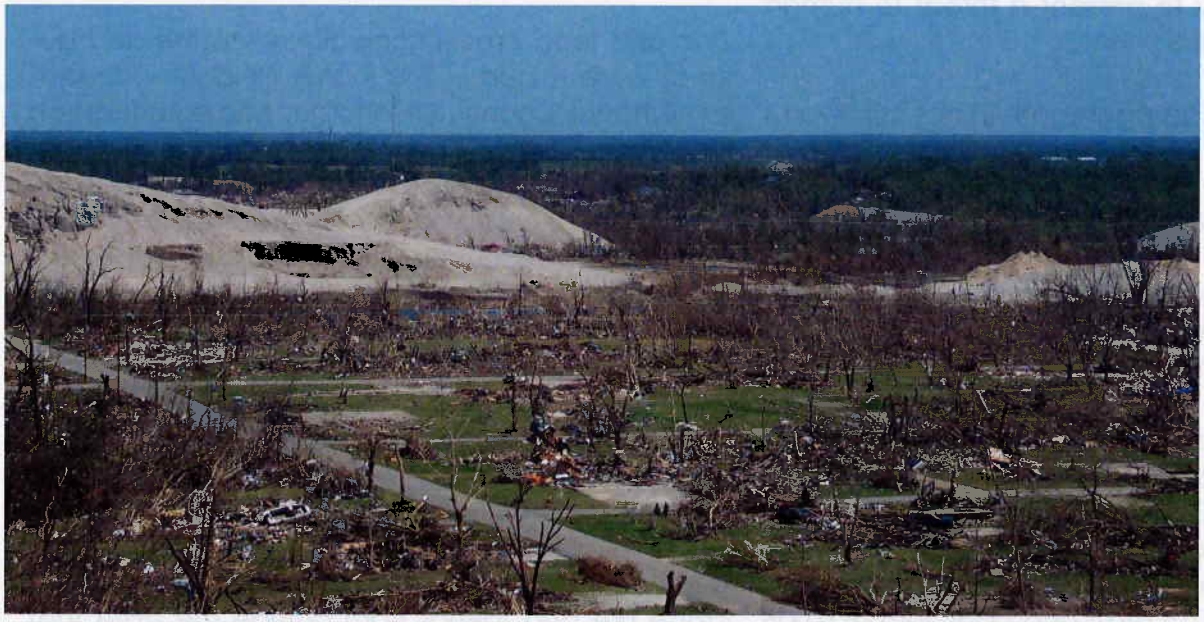

Figure 11. Kenoyer edition after the May 10, 2008 tornado.

Figure 12. Picher (foreground) and Mineral Heights edition near top of photograph after May 10 tornado.

developments. There is practically no chat sold for use in concrete mixes. Recent increases in diesel fuel have reduced the distance that chat can be economically transported to 300 miles or less. Currently, over a million tons of chat are processed and sold from the Picher Field annually.

A 1993 study of blood-lead levels by the Indian Health Service found that 34% of Native American children in the Picher area had blood-lead levels above the national standard. The EPA began a program (OU 2) to remove chat from lawns, yards, driveways, and recreation areas in the Picher area in 1996. In 2007, The EPA issued updated chat usage regulations and guidelines for acceptable uses of chat. The uses include aggregate in hot mix, warm mix, and cold mix asphalt road surfaces, asphalt road base, asphalt slurry seals, and epoxy bridge anti-skid surfacing. Other products must be tested using the Synthetic Precipitation Leaching Procedure. The leachate cannot exceed the National Primary Drinking Water Standards Maximum Contaminant Levels for lead, cadmium, and zinc.

EPILOG

A tornado destroyed over 40% of the town of Picher, Oklahoma, on Saturday afternoon, May 10, 2008, a day before the beginning of the 44th annual Forum on the Geology of Industrial Minerals. The National Weather Service Forecast Office in Tulsa, Oklahoma, rated the tornado an EF4 on the enhanced Fujita Scale. Winds associated with the tornado were estimated at 165-175 mph (U.S. National Weather Service, 2008). Seven fatalities in Picher were associated with the storm. Disaster officials estimated 114 homes were destroyed and 30 homes were heavily damaged (Gillham, 2008). The Kenoyer edition, the southwest part of town, southeast Picher, and the Mineral Heights edition were severely damaged (**Figures 11-12**).

ACKNOWLEDGMENTS

We like to express sincere appreciation to Stephen Teeter who provided information about his family's asphalt business. Special thanks to Mick Williams and Larry Bingham, Bingham Sand and Gravel, for their information about how chat is processed and marketed for asphalt aggregate. We would like to thank Heckert Construction, an asphalt paving contractor in Pittsburg, Kansas, especially John Crofoot, for data and specifications about various asphalt mixes used in Kansas.

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Figure 1. Garber Sandstone, spillway to dam at Lake Thunderbird. The vegetation-covered "smiley faces" (arrows) near the top of the outcrop probably mark the bases of stacked channel fills. The slight permeability contrast between the channel-fill sandstone and the underlying sandstone causes water to seep out of the rock at the base of the channel, promoting vegetation growth. *Photo by Neil Suneson, OGS Geologist.*

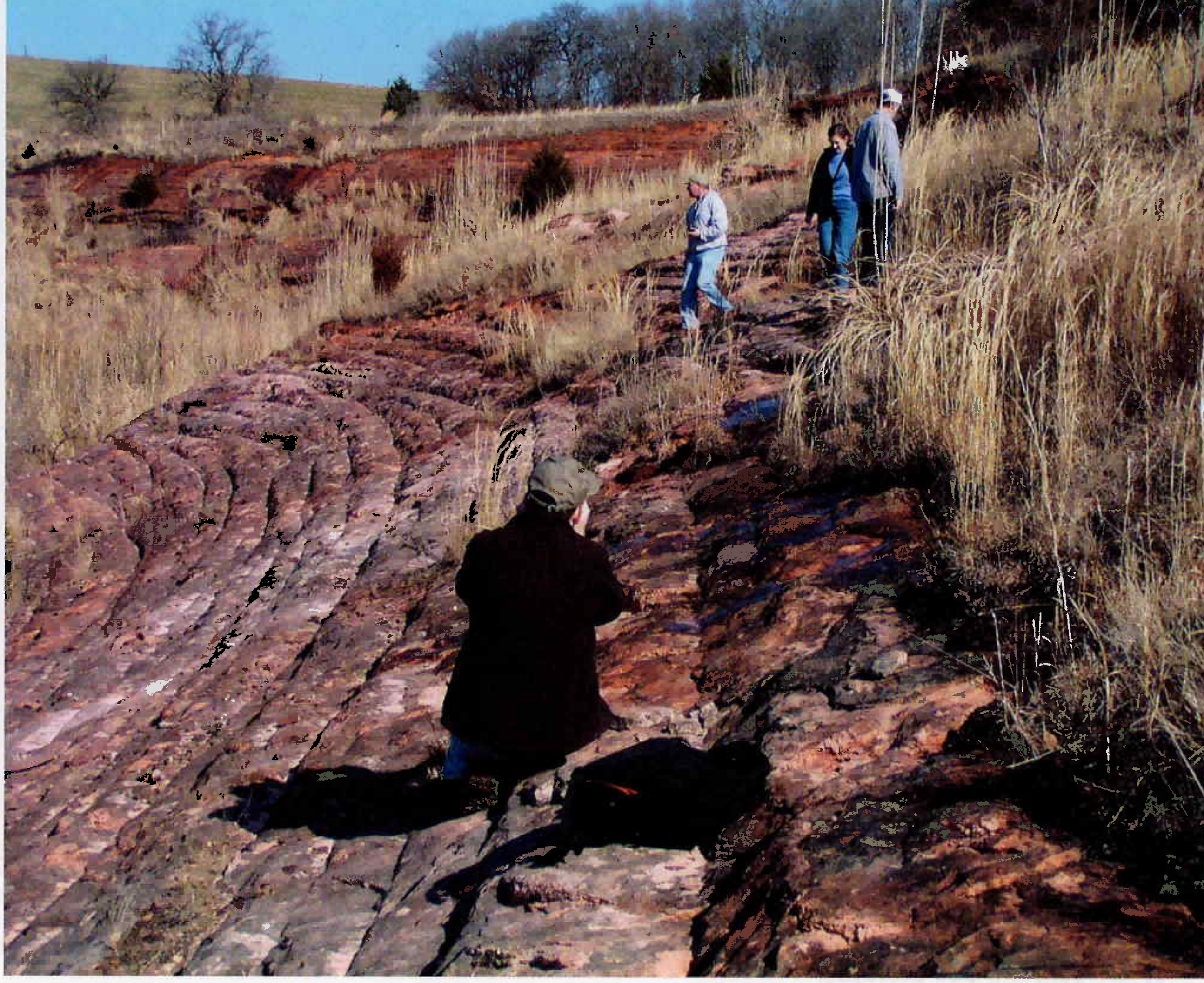
GARBER – WELLINGTON FIELD TRIP REPORT

Neil H. Suneson
Oklahoma Geological Survey

INTRODUCTION

The Oklahoma Water Resources Board (OWRB), in cooperation with the U.S. Geological Survey (USGS) and several other state and federal agencies, is conducting an investigation of the Garber – Wellington Aquifer (also known as the Central Oklahoma Aquifer) to address growing concerns about the future of water availability in central Oklahoma. The USGS will characterize the geohydrologic framework of the aquifer and will develop a groundwater-flow model, which will be used to predict the impacts of long-term groundwater withdrawals on the aquifer and to simulate water-management strategies. Presently, water users are allowed to withdraw 2 acre-feet/year under temporary permits (Mashburn, 2010). The study is funded with State monies through the Oklahoma Comprehensive Water Plan and federal funds through the U.S. Bureau of Reclamation and USGS.

Figure 2. Close-up of "smiley face." The base of the channels is marked by vegetation, and when we visited the outcrop in March water was coming out of the outcrop. Due to the high porosity and permeability of the Garber Sandstone, the water quickly seeped back into the outcrop. Chris Neel (brown shirt), John Harrington (in back, walking down outcrop), Noel Osborn (dark jacket), Rick Wicker (gray sweatshirt, blue hat). *Photo by Neil Suneson, OGS Geologist.*



A technical team representing the USGS, OWRB, Tinker Air Force Base (TAFB), the Association of Central Oklahoma Governments (ACOG), and the Oklahoma Geological Survey (OGS) has met several times over the last year and individuals from these organizations are studying various aspects of the aquifer. One of the final goals is to produce a report on the geohydrology of the Garber-Wellington Aquifer, including a groundwater flow model. This report will form the basis for OWRB permit recommendations.

On March 5, 2010, 11 geologists and hydrogeologists from the five organizations met to examine the Garber Sandstone and Wellington Formation (Leonardian, Upper Permian) east of Norman. (Attendees: USGS - Marvin Abbott, Shana Mashburn, Stan Paxton, Jerrod Smith; OWRB - Chris Neel, Noel Osborn, Bob Sandbo, Rick Wicker; ACOG - John Harrington; TAFB - Scott Bowen; OGS - Neil Suneson). One of the goals of the field trip was to examine the differences between sandstones in the Garber and sandstones in the Wellington. Another was to determine whether there is a regional unit that separates the Garber and Wellington that can be used for surface and subsurface mapping. Finally, the group wanted to examine surface exposures of the aquifer.

I led the field trip, but the information that I shared with the group came largely from discussions I've had over the years with OGS geologist Tom Stanley. Tom and OGS GIS Specialist Russell Standridge are responsible for the most current geologic map of the Oklahoma City metro area titled ***"Geologic map compilation of the Oklahoma City metro area, central Oklahoma"*** (Stanley and Standridge, 2008). Stanley has mapped the Garber - Wellington contact from where it is relatively well-defined in and north of the Lake Arcadia area to the Lake Thunderbird area, and it is his mapping that I relied upon.

FIELD-TRIP STOPS

Stop 1. Lower part of Hennessey Shale. SW¼NW¼ sec. 13,

T. 8 N., R. 2 W. (On private property – visit with permission only). Approximately 50 ft stratigraphically above T/Garber. In addition to exposing an excellent and typical part of the lower Hennessey Shale, some small Permian vertebrates have been collected here (Olson, 1967). Well-preserved unidirectional current features (ripple surfaces, ripple bedding, and small scour troughs) are located near the top of the exposure.

Stop 2. Garber Sandstone. Spillway, Lake Thunderbird dam (Figures 1, 2). Approximately 90 ft stratigraphically above the B/Garber. Excellent exposure of thick section of mostly channel-fill sandstones.

Stop 3. Top of Wellington Formation. Approx. midpoint of section line road (Robinson St.) between SE¼ sec. 24 and NE¼ sec. 25, T. 9 N., R. 1 E., immediately west of Cleveland-Pottawatomie County line. Sandstone and calcareous-nodule-bearing siltstone/mudstone in Wellington Fm.

Stop 4. Probable Iconium Member, Wellington Formation (Figure 3). Along Hwy 9, Pink, Oklahoma; south side of Hwy 9. Very NW corner sec. 17, T. 9 N., R. 2 E. Approximately 65 ft stratigraphically below T/Wellington. Interbedded muddy siltstones and very fine grained sandstones; probably typical of overall fine-grained upper part of Wellington.

Stop 5. Probable Fallis Member, Wellington Formation. Approximately 0.25 mi south of intersection of Hwys 9 and 102, east side of Hwy 102. NW¼ sec. 13, T. 9

Figure 3. Fieldtrip participants examining Iconium Member, Wellington Formation, near Pink. From left to right: Shana Mashburn, Chris Neel, Scott Bowen, Stan Paxton, Bob Sandbo (with sunglasses), Noel Osborn (mostly blocked), John Harrington (T-shirt), Marvin Abbott. *Photo by Neil Suneson, OGS Geologist.*

N., R. 2 E. Low-angle cross-bedded sandstone.

Stop 6. Probable Fallis Member, Wellington Formation (Figure 4). Approximately 0.7 mi west of Hwys 9 and 102 intersection, north side of Hwy 9 adjacent to Brown Cemetery. SW ¼ sec. 11, T. 9 N., R. 2 E. Approximately 140 ft stratigraphically below T/Wellington. Cross-stratified and planar-bedded sandstone.

Stop 7. Garber - Wellington contact. On E-W section line road approximately 1 mi NW of Pink, approximately 0.75 mi east of Pecan Creek. Just west of midpoint between secs. 6 and 7, T. 9 N., R. 2 E. Outcrop of Garber Sandstone on top of hill; Wellington poorly exposed below ridge-capping sandstone. Prominent Garber scarp visible to west. Projecting due west to the Garber - Hennessey contact (near Stop 1), thickness of Garber would be 480 ft (if dip is 30 ft/mi*; 640 ft (40 ft/mi), or 800 ft (50 ft/mi). *Best guess per Stanley and Standridge (2008).

Stop 8. Garber Sandstone. On same E-W section line road as Stop 7. NW corner sec. 9, T. 9 N., R. 1 E. Approximately 160 ft stratigraphically above B/Garber.

DISCUSSION

We saw lots of red sandstone. At the end of the day, we agreed that there was little visible difference in hand samples between the sandstones in the Garber and Wellington. A worthwhile project would be to document this field observation with careful collection and petrographic examination of samples at known stratigraphic positions within the two formations; perhaps there is some difference in the accessory mineralogy of the two units.

An interesting observation is that most of the sandstones appear in hand sample to be very well sort-

Figure 4. Fallis Member, Wellington Formation, at Brown Cemetery stop. The lensoid outcrop pattern is characteristic of channel sandstones. From left to right: Bob Sandbo, Jerrod Smith, Chris Neel, Shana Mashburn, Rick Wicker, Noel Osborn. *Photo by Neil Suneson, OGS Geologist.*

ed. This is somewhat unusual for sediments deposited in a fluvial environment. This observation should be documented. Is it possible that many of the sandstones were sourced in an area (to the east and now eroded) dominated by aeolian sediments?

We also agreed that the Garber-Wellington contact mapped by Tom Stanley (Stanley and Standridge, 2008) is probably accurate. He appears to have correctly identified the siltstone-rich upper part of the Wellington Formation (mapped as the Iconium Member to the north) and the immediately overlying thick sandstones as the lower part of the Garber. This relation appears to carry into the subsurface.

We discussed the three geologic maps of this area that are in common use. The most recent (Stanley and Standridge, 2008) appears to agree with the oldest (Miser, 1954), and these are very different from the map most commonly used in Garber - Wellington Aquifer studies (Bingham and Moore, 1975). The first two maps show the top of the Wellington near Pink and the base near the intersection of Hwys 9 and 102. The latter shows the Garber extending east to the highway intersection and the Wellington extending to near Tecumseh.

Finally, there was some discussion about the use of the term "Oscar Group" for the sequence of strata underlying the Wellington. Stanley, in his mapping, does not use the term and has pointed out to me that it is not accepted by the U.S. Geological Survey. It first appeared in the literature in Bingham and Moore (1975) and was used by Fay (1997); however, its current use does not conform to the North American Code of Stratigraphic Nomenclature and it should be abandoned.

In summary, sandstones in the Garber Sandstone and Wellington Formation look very similar in outcrop. Detailed petrographic studies will be required to verify whether there are any differences; this could have paleogeographic implications. In addition, the petrography of both units *along strike* should be conducted. The Garber and Wellington can be divided only where the generally fine-grained Iconium Member can be recognized.

Acknowledgments

Noel Osborn and Stan Paxton read (and corrected) an early version of this report and made many useful changes.

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Oklahoma Earthquakes, 2007

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INTRODUCTION

More than 930,000 earthquakes occur throughout the world each year (Tarbuck and Lutgens, 1990). Approximately 95% of these earthquakes have a magnitude of <2.5 and usually are not felt by humans (**Table 1**). Only 20 earthquakes, on average, exceed a magnitude of 7.0 each year. An earthquake that exceeds a magnitude of 7.0 is considered to be a major earthquake and serious damage could result. (See the Catalog section, below, for a discussion of earthquake magnitude.)

Earthquakes tend to occur in belts or zones. For example, narrow belts of earthquake epicenters coincide with oceanic ridges where plates separate, such as in the mid-Atlantic and eastern Pacific Oceans. Earthquakes also occur where plates collide and/or slide past each other. Although most earthquakes originate at plate boundaries, a small percentage occurs within plates. The New Madrid (Missouri) earthquakes of 1811–12 are examples of large and destructive intraplate earthquakes in the United States.

The New Madrid earthquakes of 1811–12 were probably the earliest historical earthquake tremors felt in what is now southeastern Oklahoma (then part of Arkansas Territory). Before Oklahoma became a state, the earliest documented earthquake occurred on October 22, 1882, probably near Fort Gibson, Indian Territory, although it cannot be located precisely (Ross, 1882; Indian Pioneer Papers, date unknown). The Cherokee Advocate newspaper reported that at Fort Gibson "the trembling and vibrating were so severe as to cause doors and window shutters to open and shut, hogs in pens to fall and squeal, poultry to run and hide, the tops of weeds to dip, [and] cattle to lowe" (Ross, 1882, p. 1). These observations indicate Modified Mercalli (MM)-VIII intensity effects. (See the following section on Distribution of Oklahoma Earthquakes for information about the MM earthquake-intensity scale.) The next documented earthquake in Oklahoma occurred near Jefferson, Grant County, on December 2, 1897 (Stover and others, 1981). The next known Oklahoma earthquake happened near Cushing, Payne County, in December 1900. This event was followed in April 1901 by two additional earthquakes in the same area (Wells, 1975) at plate boundaries, a small percentage occurs within plates. The New Madrid (Missouri) earthquakes of 1811–12 are examples of large and destructive intraplate earthquakes in the United States.

The largest known Oklahoma earthquake (with the possible exception of the 1882 earthquake) occurred near El Reno, Canadian County, on April 9, 1952. This magnitude-5.5 (mb, Gutenberg-Richter) earthquake caused a 50-ft-long crack in the State Capitol Office Building in Oklahoma City. It was felt throughout Oklahoma and in parts of seven other states. The total

TABLE 1. — ESTIMATED NUMBER OF WORLDWIDE EARTHQUAKES PER YEAR BY MAGNITUDE (Modified from Tarbuck and Lutgens, 1990)

MAGNITUDE	ESTIMATED NUMBER PER YEAR	EARTHQUAKE EFFECTS
<2.5	>900,000	Generally not felt, but recorded
2.5-5.4	30,000	*Minor to moderate earthquakes* Often felt, but only minor damage detected
5.5-6.0	500	*Moderate earthquakes* Slight damage to structures
6.1-6.9	100	*Moderate to major earthquakes* Can be destructive in populous regions
7.0-7.9	20	*Major earthquakes* Inflict serious damage if in populous regions
≥8.0	1-2	*Great earthquakes* Produce total destruction to nearby communities

felt area was about 362,000 km^2 (Docekal, 1970; Kalb, 1964; von Hake, 1976); Des Moines, Iowa, and Austin, Texas, were at the northern and southern limits. From 1897 through 2007, 1,879 earthquakes were located in Oklahoma.

INSTRUMENTATION

A statewide network of seven seismograph stations was used to locate 20 earthquakes in Oklahoma for 2007 (**Figure 1**). The network consists of a central station (TUL/LNO), four radio-telemetry seismograph stations (FNO, RLO, SIO, VVO), and two field stations (MEO and PCO). The U.S. Geological Survey (USGS) established a seismograph station, WMOK, 19 km southwest of the Oklahoma Geological Survey's (OGS) station at Meers (MEO). WMOK does not record continuously. When triggered by moderately strong ground motion, WMOK transmits a short segment of data to the National Earthquake Information Service in Golden, Colorado. WMOK is used mostly for distant earthquakes, although it sometimes records some of the larger Oklahoma earthquakes. Because WMOK is so near MEO, its arrival times do not improve the accuracy of location of Oklahoma earthquakes.

Central Station

The OGS Observatory station, TUL/LNO, is about 3.2 km south of Leonard, Oklahoma, in southeastern Tulsa County. At this site, digital and analog (paper) records from all stations are analyzed to detect, identify, and locate Oklahoma earthquakes. Seismometers at the central station are installed on a pier in a 4-m-deep underground walk-in vault, and in an 864-m-deep borehole. The vault is designated by the abbreviation TUL, and the borehole has the international station abbreviation, LNO. In the vault, three Baby Benioff seismometers and a 3-component Guralp CMG3-TD seismometer record vertical, north-south, and east-west ground motion. Each Baby Benioff seismometer produces signals recorded on a drum recorder that uses a heat stylus and heat sensitive paper. (The original drum recorders used light beams to record on photopaper. The drum recorders were converted to ink recording, and later to more reliable recording on heat sensitive paper.)

The Guralp CMG3-TD ultra-broadband seismometer senses everything from the solid earth tides with their mHz frequencies to the high frequencies of Oklahoma earthquakes, which may approach 100 Hz. The CMG3-TD seismometer has a Global Positioning System (GPS) time receiver and digitizers in the case. The three digitizers each produce 200 samples per second. The CMG3-TD in the vault is a temporary replacement for the similar borehole seismometer, which currently is being rebuilt under warranty at the Guralp factory in the United Kingdom. When the borehole seismometer is operating again, it will provide the 200-sample-per-second signals from the central station that are used to detect and locate earthquakes in Oklahoma.

A Guralp eight-channel rack digitizer records the remote stations (RLO, VVO, and SIO) at 200 samples per second. Data are digitized and recorded by Guralp SCREAM software running on a PC. These samples are assembled into time-tagged data-compressed packets and transmitted at 38,400 bits per second to the Guralp SCREAM data acquisition software. Guralp SCREAM software, which runs on a PC, uncompresses the packets, organizes them into one-hour files on a disk, and will display one or more windows containing one or several moving traces. The windows may contain as little as one second or as much as 24 hours of ground motion. All digital data are archived on writable CD-

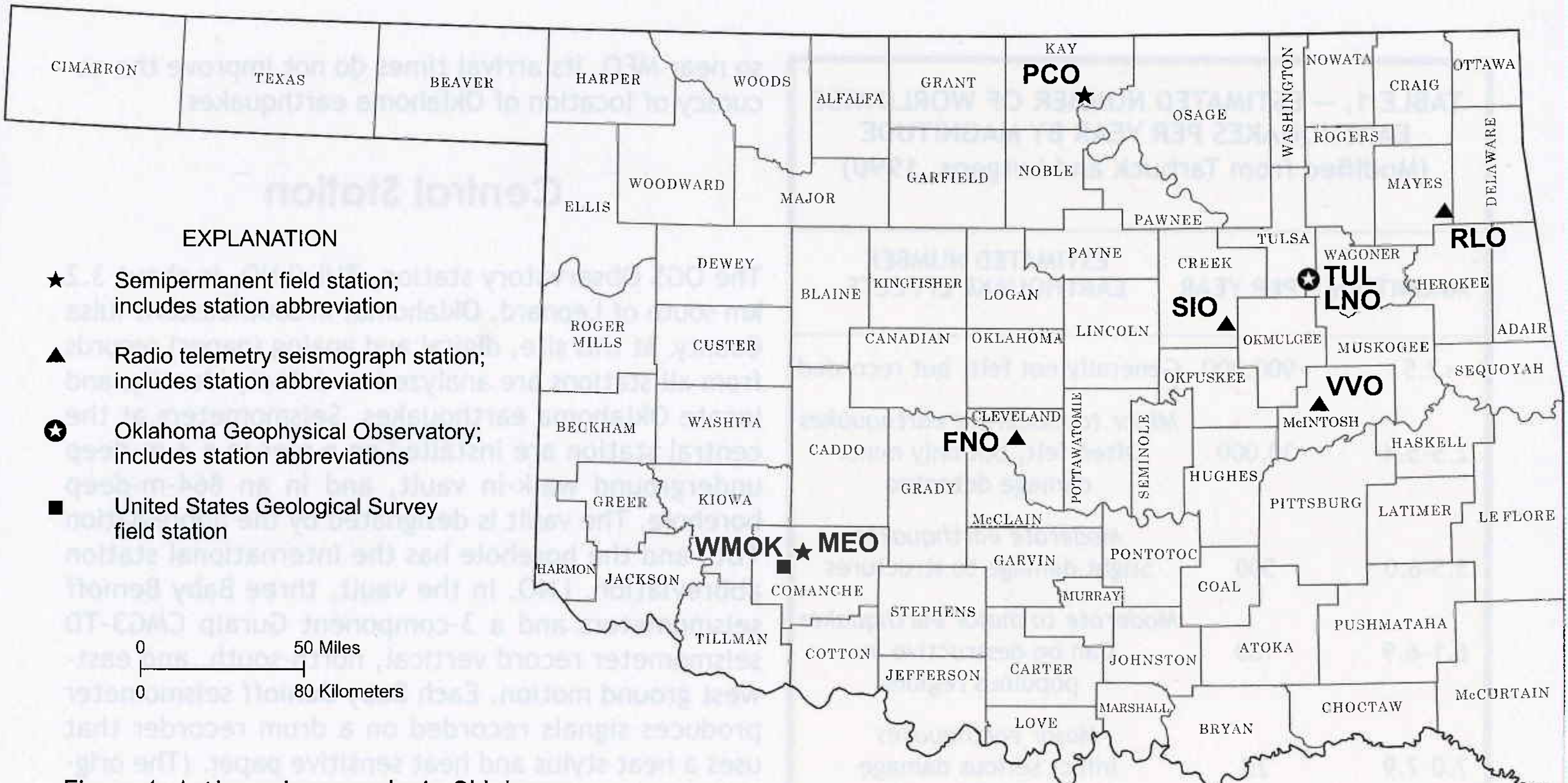

Figure 1. Active seismographs in Oklahoma.

ROMs. About two new CDs are added each week.

SCREAM sends slower packets (20 samples per second, and four samples per second) to another PC running SCREAM, and to the University of Indiana via the internet. From Indiana, the packets are sent continually or in once-per-day batches to a number of secondary schools in the United States. The slower packets lack the high frequencies characteristic of Oklahoma earthquakes, but are very useful for studying teleseisms (distant earthquakes), which occur daily in the Earth's seismic belts. For distant earthquakes above magnitude 6, packages of the 20-sample-per-second, vertical, north-south, and east-west signals containing about one hour of recording are made at the Observatory. These are sent by internet file transfer protocol to the PEPP (Princeton Earth Physics Project) data base, which is used primarily by American secondary schools.

Radio Telemetry Stations

Three radio-telemetry stations, (1) at Rose Lookout (RLO) in Mayes County, (2) at the Bald Hill Ranch near Vivian (VVO) in McIntosh County, and (3) at the Jackson Ranch near Slick (SIO) in Creek County, have Geotech S-13 seismometers in shallow tank vaults. The seismic signals are amplified and used to frequency modulate an audio tone that is transmitted to Leonard with 500-mW FM transmitters at various frequencies in the 216-220-MHz band.

Antennas on a 40-m-high tower near the OGS Observatory receive signals from the three radio-telemetry sites. These electrical signals are carried 350 m overland to the outside of the Observatory building. In a box on the outside wall, the electrical signals are converted to optical signals. The optical signals are sent through ~6 m of plastic fiber into the building, where they are converted back to electrical signals. This optical link is used to prevent wires from carrying lightning-induced surges into the building and damaging digitizers and computers.

The radio-telemetry signals are frequency-modulated audio tones. Discriminators convert the tones back into a voltage similar to the voltage produced at the field seismometer. These voltages are recorded on a 48-hour-paper-seismogram drum recorder, one recorder per station. The paper records are used mainly to backup the computer system.

The radio-telemetry signals are transmitted to three channels (one channel per station) on the Guralp rack digitizer. Each digitizer channel produces 200 samples per second. The digitizer includes a GPS satellite receiver. The signals are assembled in memory into timed packets. The packets are transmitted to a PC running Guralp SCREAM data acquisition software.

A fourth radio-telemetry station, FNO, was installed in Norman in central Oklahoma on April 28, 1992. The seismometer, Geotech S-13, is on a concrete pad, about 7 km northeast of Sarkeys Energy Center (the building that houses the OGS main office). A discriminator converts the audio-signal frequency fluctuations to a voltage output. The voltage output is amplified and recorded by a Sprengnether MEQ-800 seismograph recorder (located in an OGS display case) at a trace speed of 60 mm/min.

Field Stations

Seismograms are recorded at two volunteer-operated seismographs (MEO and PCO). Each station consists of a Geotech S-13 short-period vertical-motion-sensing seismometer in a shallow tank vault, or in an abandoned mine shaft (station MEO). The seismometer signal runs through 60-600 m of cable in surface PVC conduit to the volunteer's house or other building. The volunteer has a Sprengnether MEQ-800B timing system amplifier-filter-drum recorder, which records 24 hrs. of seismic trace at 1 mm/min in a spiral path around the paper on the drum. A time-signal radio receiver tuned to the National Institute of Standards and Technology and high-frequency radio station WWV is used to set the time. The volunteers mail the seismograms to the Observatory weekly (or more often, if requested). When an earthquake is felt in Oklahoma, the volunteer operators FAX seismogram copies to the Observatory so that the earthquake can be located rapidly.

Oklahoma earthquake catalogs, earthquake maps, some seismograms, and related information are on the Internet at
http://www.okgeosurvey1.gov

DATA PROCESSING AND ANALYSIS

Data are processed on two networked Sun UNIX workstations—a SPARC20 and a SPARC 2+. All network digital and analog short-period (frequencies > 1 Hz) and broadband seismograms are scanned for earthquakes in and near Oklahoma. The arrival times of P and S phases are recorded on a single-page form in a loose-leaf notebook. The arrivals then are entered into the SPARC20 or the SPARC 2+ using a user-friendly flexible program written in the Nawk language. The program uses the entries to write an input file with a unique file name.

From the input files, the hypocenters are located by Johannes Schweitzer's (1997) program HYPOSAT 3.2c. A Nawk program manages the input to HYPOSAT and puts the output in a single file and writes a line in an overall catalog file.

HYPOSAT must have a velocity model of the crust and top of the mantle to calculate travel times of P and S to each station from each successive hypocenter tried in the program. The nine-layer-plus-upper-mantle Chelsea model for Oklahoma, derived by Mitchell and Landisman (1971), is used exclusively for locating Oklahoma earthquakes. This model and three other Oklahoma models are outlined on the Observatory Web site at http://www.okgeosurvey1.gov/level2/ geology/ok.crustal.models.html.

Each hypocenter is usually run in a preliminary form using the first four or so P and/or S arrivals from about four stations. Later, after all seismograms have been read, a final location is determined. The solutions are added manually to a catalog on the Observatory Web site at http://www.okgeosurvey1.gov/level2/okeqcat/okeqcat.2002.html.

DISTRIBUTION OF OKLAHOMA EARTHQUAKES, 2007

All Oklahoma earthquakes recorded on seismograms from three or more stations are located. In 2007, 28 Oklahoma earthquakes were located (**Figure 2; Table 2**). Thirteen earthquakes were reported felt (**Tables 3, 4**). The felt and observed effects of earthquakes generally are given values according to the Modified Mercalli (MM) Intensity scale, which assigns a Roman numeral to each of 12 levels described by effects on humans, man-made constructions, or natural features (**Table 5**).

On January 8, a magnitude 2.5 (MDUR) earthquake (event no. 1852) occurred in Coal County about 8 km south of Tupelo (**Tables 2, 3**) at 3:46 pm local time.

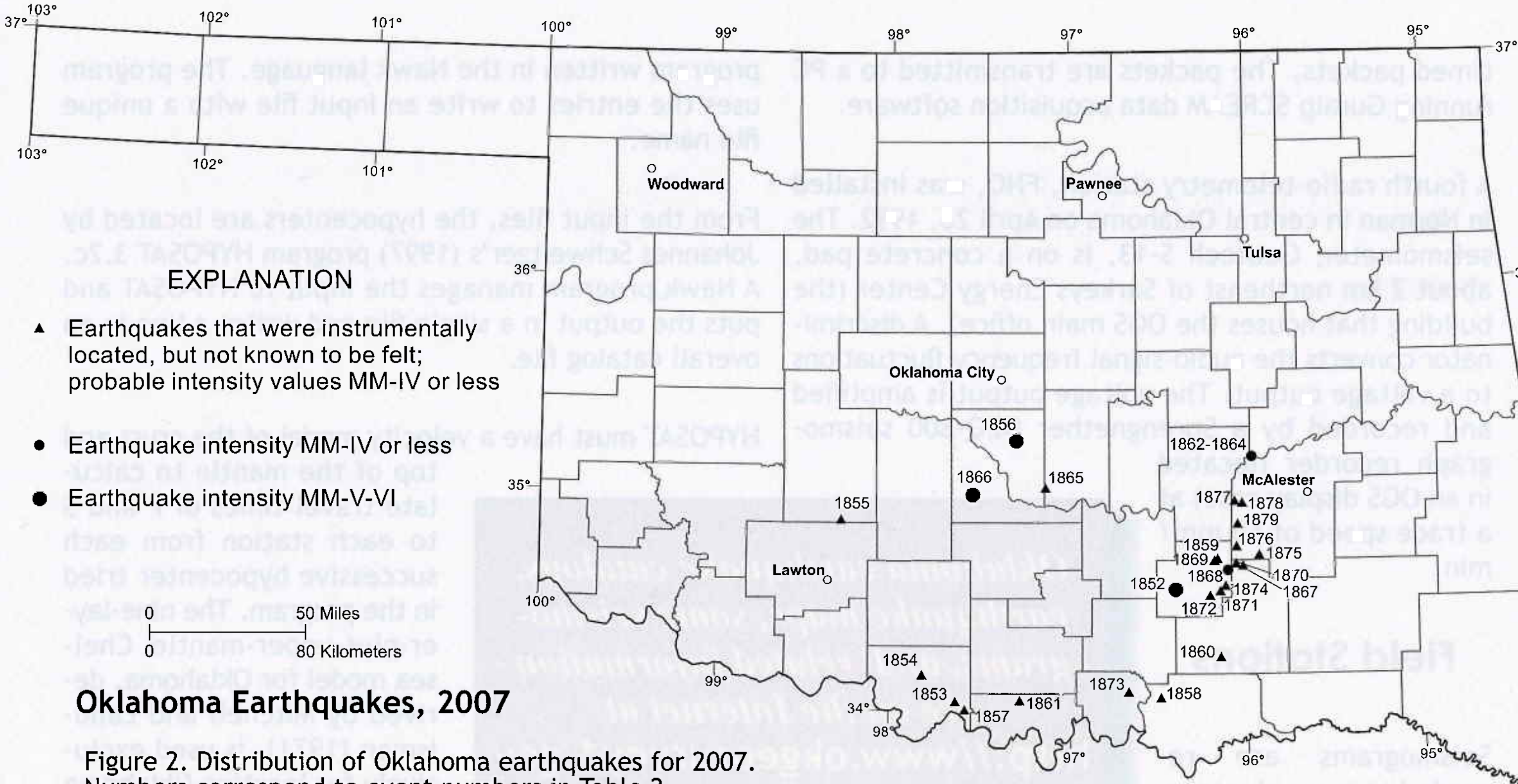

Figure 2. Distribution of Oklahoma earthquakes for 2007. Numbers correspond to event numbers in Table 2.

TABLE 2. — Oklahoma Earthquake Catalog for 2007

Event no.	Date and origin time (UTC)[a]					County	Intensity MM[b]	m3Hz	Magnitudes mbLg	MDUR	Latitude deg (N)	Longitude deg (W)	Depth (km)	
1852	Jan	8	21	46	2.91	Coal	VI			2.5	34.536	-96.429	5.00R[c]	C[d]
1853	Jan	9	8	25	2.71	Jefferson				2.2	34.033	-97.643	5.00R	C
1854	Jan	9	10	32	40.68	Jefferson				2.1	34.133	-97.836	5.00R	C
1855	Jan	15	11	16	34.20	Caddo				2.5	34.864	-98.328	5.00R	C
1856	Feb	12	18	32	34.35	Cleveland	VI			3.0	35.215	-97.271	5.00R	C
1857	Feb	18	18	29	35.90	Jefferson				2.0	33.999	-97.607	5.00R	C
1858	Feb	23	20	3	19.13	Bryan				2.2	34.037	-96.493	5.00R	C
1859	Mar	13	11	11	28.27	Coal				2.0	34.679	-96.155	5.00R	C
1860	Mar	14	15	54	23.59	Atoka				2.3	34.245	-96.147	5.00R	C
1861	Mar	30	20	20	25.39	Love				2.4	34.043	-97.288	5.00R	C
1862	May	27	21	3	22.11	Pittsburg	IV			3.2	35.149	-95.976	5.00R	C
1863	May	27	21	10	6.67	Pittsburg				2.4	35.149	-95.976	5.00R	C
1864	May	27	22	45	46.34	Pittsburg				2.1	35.149	-95.976	5.00R	C
1865	Jul	11	5	37	4.01	Pottawatomie				2.4	34.997	-97.134	5.00R	C
1866	Sep	1	19	18	27.85	McClain	V			2.3	34.962	-97.576	5.00R	C
1867	Sep	2	7	59	48.81	Atoka				2.2	34.666	-96.076	5.00R	C
1868	Sep	2	10	56	51.45	Coal	F			1.8	34.627	-96.117	5.00R	C
1869	Sep	2	17	35	28.04	Coal				2.1	34.668	-96.169	5.00R	C
1870	Sep	3	0	4	5.30	Atoka				1.8	34.648	-96.044	5.00R	C
1871	Sep	8	15	27	10.60	Coal				1.8	34.534	-96.156	5.00R	C
1872	Sep	8	16	35	6.07	Coal				2.2	34.524	-96.219	5.00R	C
1873	Sep	24	13	47	42.29	Marshall				1.9	34.053	-96.673	5.00R	C
1874	Oct	25	4	1	15.26	Coal				2.2	34.552	-96.130	5.00R	C
1875	Oct	26	21	18	19.37	Pittsburg				2.3	34.699	-95.947	5.00R	C
1876	Nov	13	16	58	54.29	Pittsburg				2.3	34.735	-96.061	5.00R	C
1877	Nov	22	18	3	8.20	Pittsburg				1.8	34.949	-96.074	5.00R	C
1878	Nov	22	18	37	19.58	Pittsburg				2.3	34.941	-96.027	5.00R	C
1879	Dec	16	15	2	29.65	Pittsburg				2.6	34.852	-96.048	5.00R	C

[a]UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time. The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the second. To convert to local Central Standard Time, subtract six hours.

[b]Modified Mercalli (MM) earthquake-intensity scale (see Table 4).

[c]5.00R indicates that the depth was restrained to 5.00 km from the beginning of the calculation.

[d]C refers to the Chelsea velocity model (Mitchell and Landisman, 1971).

TABLE 3. – Earthquake Reported Felt in Oklahoma, 2007

Event no.	Date and origin time (UTC)[a]	Nearest City	County	Intensity MM[b]
1852	Jan 8 21 46 2.91	8 km S of Tupelo	Coal	VI
1856	Feb 12 18 32 34.35	14 km ENE of Norman	Cleveland	VI
1862	May 27 21 3 22.11	12 km W of Indianola	Pittsburg	IV
1866	Sep 1 19 18 27.85	near Criner	McClain	V
1868	Sep 2 10 56 51.45	13 km E of Centrahoma	Coal	F

The earthquake was felt in Milburn (3 reports), Coleman (6 reports), Atoka (5 reports), Wapanuka (3 reports), Ada (3 reports), Durant (3 reports). The OGS received a felt report from individuals living in the communities of Stringtown, Tuska, Caddo, Clarita, Bromide, and Tupelo (**Figure 3**). The earthquake was felt over 6,000 km2 and produce MM-VI effects in Coleman. A homeowner in Ada reported "the water in the pool was rippling". In Stringtown, an individual stated "house shook throughout".

From February 11-19, 10 earthquakes (5 of which were reported felt) occurred in south Oklahoma City (**Table 4**). Only one earthquake, event no. 1856, was located about 14 km east-northeast of Norman. This magnitude 3.0 (MDUR) earthquake produced 298 felt reports. A majority of the felt reports came from Oklahoma City, Del City, Midwest City, and Tinker Air Force Base (**Figure 4**). This earthquake was felt over 2,900 km2 and produced MM-VI effects at one location in Oklahoma City. Some people described hearing what sounded like a clap of thunder and/or feeling the

January 8, 2007, Coal County Earthquake (Event 1852) Modified Mercalli Intensity Values

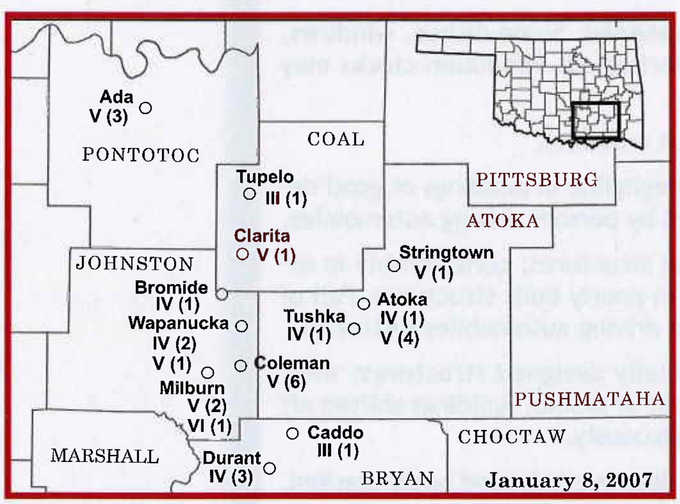

Figure 3. Modified Mecalli (MM) intensity values (Roman numerals) for the January 8 earthquake (event no. 1852) in Coal County (Tables 2, 3). Numbers in parentheses indicate the number of felt reports.

February 12, 2007, Cleveland County Earthquake (Event 1856) Modified Mercalli Intensity Values

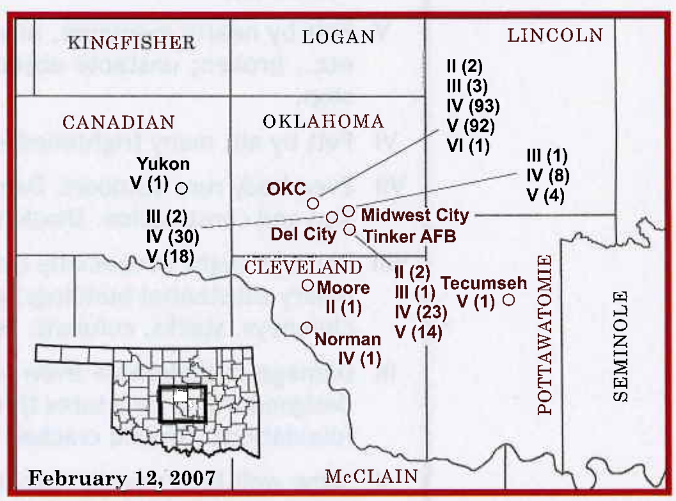

Figure 4. Modified Mecalli (MM) intensity values (Roman numerals) for the Februay 12 earthquake (event no. 1856) in Cleveland County (Tables 2, 3). Numbers in parentheses indicate the number of felt reports.

TABLE 4: South Oklahoma City Earthquakes, February 2007

Date	Event No.	Time	Magnitude	MM-Intensity
11 February		3:23 AM CST	1.5	
11 February		7:31 AM CST	1.9	II
11 February		8:07 AM CST	1.7	
11 February		8:09 AM CST	1.8	
12 February	1856	12:32 PM CST	3.0	VI
12 February		6:16 PM CST	2.7	
12 February		6:35 PM CST	1.7	
14 February		8:10 PM CST	1.7	V
19 February		12:12 AM CST	2.0	III
19 February		12:29 AM CST	1.3	I

Table 5: Modified Mercalli (MM) Earthquake-Intensity Scale (Abridged) (Modified from Wood and Neumann, 1931)

I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings. Automobiles may rock slightly.
IV	During the day, felt indoors by many, outdoors by few. At night some awakened. Dishes, doors, windows disturbed. Automobiles rocked noticeably.
V	Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction. Shock noticed by persons driving automobiles.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings; great in poorly built structures. Fall of chimneys, stacks, columns. Persons driving automobiles disturbed.
IX	Damage considerable even in specially designed structures; well-designed frame structures thrown out of plumb. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed; ground badly cracked, rails bent. Landslides and shifting of sand and mud.
XI	Few if any (masonry) structures remain standing. Broad fissures in ground.
XII	Damage total. Waves seen on ground surfaces.

ground wobble for a few seconds.

A magnitude 3.2 (MDUR) earthquake (event no. 1862) occurred 12 km west of Indianola in Pittsburg County on May 27 (**Tables 2, 4**). This earthquake was reported felt in Stroud. The individual stated "the house shook once and it sounded like distant explosion or sonic boom".

On September 1, a magnitude 2.3 (MDUR) earthquake (event no. 1866) occurred near Criner in McClain County (**Tables 2, 3**). Three felt reports, one each from Lindsay, Payne, and Oklahoma City, were submitted to OGS. The Lindsay report stated "sounded like a sonic boom or explosion". A magnitude 1.8 (MDUR) earthquake (event no. 1862) occurred 13 km east of Centrahoma in Coal County on September 2. This earthquake was reported felt in Pauls Valley.

In 2007 earthquake-magnitude values ranged from a low of 1.8 (MDUR) in several counties to a high of 3.2 (MDUR) in Pittsburg County (event no. 1862). Eight earthquakes were located in Pittsburg and 7 earthquakes were located in Coal Counties. Counties that experienced multiple earthquakes include Jefferson and Atoka.

CATALOG

For both preliminary and final locations, the catalog of Oklahoma earthquakes is in HTML (world wide web) format; one HTML page contains all earthquakes that occurred in one year (a single page lists earthquakes for multiple years prior to 1977). For absolute uniformity, the catalog is stored only in HTML format. One copy is on a ONENet server. (ONENet is the network of the Oklahoma Regents for Higher Education.) The server copy, at the world wide web address http://www.okgeosurvey1.gov, is used both for public distribution and for in-house reference. A second (backup) copy is on a Sun SPARC20 workstation at the Observatory in Leonard, Oklahoma.

Each event in the catalog is sequentially numbered and arranged according to date and origin time. The numbering system is compatible with the system used by Lawson and Luza (1980-1990, 1993-1994, 1995a, 1995b, 1996-2005, 2009), Lawson and others (1991, 1992), and for the *Earthquake Map of Oklahoma* (Lawson and Luza, 1995b). The sequential event number is not found on the world wide web catalog.

The dates and times for cataloged earthquakes are given in UTC. UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time. The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the seconds. To convert to local Central Standard Time, subtract six hours.

Earthquake magnitude is a measurement of energy and is based on data from seismograph records. The magnitude of a local earthquake is determined by taking the logarithm (base 10) of the largest ground motion recorded during the arrival of a seismic-wave type and applying a standard correction for distance to the epicenter. An increase of one unit in the magnitude value corresponds to a tenfold increase in the amplitude of the earthquake waves. There are several different scales used to report magnitude. Table 2 has three magnitude scales, which are mbLg (Nuttli), m3Hz (Nuttli), and MDUR (Lawson). Each magnitude scale was established to accommodate specific criteria, such as the distance from the epicenter, as well as the availability of certain seismic data.

For earthquake epicenters located 11-222 km from a seismograph station, Otto Nuttli developed the m3Hz magnitude scale (Zollweg, 1974). This magnitude is derived from the following expression:

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

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Lg waves, near 3 Hz in frequency, measured in nanometers; T is the period of the Lg waves measured in seconds; and $\triangle$ is the great-circle distance from epicenter to station measured in kilometers.

In 1979, St. Louis University (Stauder and others, 1979, p. 28) modified the formulas for m3Hz. The OGS Observatory has used this modification since January 1, 1982. The modified formulas have the advantage of extending the distance range for measurement of m3Hz out to 400 km, but they also have the disadvantage of increasing m3Hz by about 0.12 units compared to the previous formula. Their formulas were given in terms of log(A) but were restricted to wave periods of 0.2-0.5 sec. In order to use log(A/T), we assumed a period of 0.35 sec in converting the formulas for our use. The resulting equations are:

(epicenter 10-100 km from a seismograph)

$$m3Hz = \log(A/T) - 1.46 + 0.88 \log(\triangle)$$

(epicenter 100-200 km from a seismograph)

$$m3Hz = \log(A/T) - 1.82 + 1.06 \log(\triangle)$$

(epicenter 200-400 km from a seismograph)

$$m3Hz = \log(A/T) - 2.35 + 1.29 \log(\triangle).$$

Otto Nuttli's (1973) earthquake magnitude, mbLg, for seismograph stations located 55.6-445 km from the epicenter, is derived from the following equation:

$$mbLg = \log(A/T) - 1.09 + 0.90 \log(\triangle).$$

Where seismograph stations are located between 445 and 3,360 km from the epicenter, mbLg is defined as:

$$mbLg = \log(A/T) - 3.10 + 1.66 \log(\triangle),$$

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Lg waves, near 1 Hz in frequency, measured in nanometers; T is the period of Lg waves measured in seconds; and D is the great-circle distance from epicenter to station measured in kilometers.

The MDUR magnitude scale was developed by Lawson (1978) for earthquakes in Oklahoma and adjacent areas. It is defined as:

$$MDUR = 1.86 \log(DUR) - 1.49,$$

where DUR is the duration or difference, in seconds, between the Pg-wave arrival time and the time the final coda amplitude decreases to twice the background-noise amplitude. Before 1981, if the Pn wave was the first arrival, the interval between the earthquake-origin time and the decrease of the coda to twice the background-noise amplitude was measured instead. Since January 1, 1982, the interval from the beginning of any P wave (such as Pg, P*, and/or Pn) to the decrease of the coda to twice the background-noise amplitude has been used.

Earthquake detection and location accuracy have been greatly improved since the installation of the statewide network of seismograph stations. The frequency of earthquake events and the possible correlation of earthquakes to specific tectonic elements in Oklahoma are being studied. It is hoped that this information will provide a more comprehensive data base that can be used to develop numerical estimates of earthquake risk that give the approximate frequency of earthquakes of any given size for various regions of Oklahoma. Numerical risk estimates could be used for better design of large-scale structures, such as dams, high-rise buildings, and power plants, as well as to provide the information necessary to evaluate insurance rates.

ACKNOWLEDGMENTS

Volunteer seismograph-station operators and landowners at various locations in Oklahoma make possible the operation of a statewide seismic network.

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Created by the Oklahoma Territorial Legislature in 1890, the University of Oklahoma is a doctoral degree-granting research university serving the educational, cultural, economic and health-care needs of the state, region and nation. The Norman campus serves as home to all of the university's academic programs except health-related fields. The OU Health Sciences Center, which is located in Oklahoma City, is one of only four comprehensive academic health centers in the nation with seven professional colleges. Both the Norman and Health Sciences Center colleges offer programs at the Schusterman Center, the site of OU-Tulsa. OU enrolls more than 30,000 students, has more than 2,400 full-time faculty members, and has 20 colleges offering 163 majors at the baccalaureate level, 166 majors at the master's level, 81 majors at the doctoral level, 27 majors at the doctoral professional level, and 26 graduate certificates. The university's annual operating budget is $1.5 billion. The University of Oklahoma is an equal opportunity institution.