EARTH SCIENCES AND MINERAL RESOURCES OF OKLAHOMA

INTRODUCTION

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Oklahoma is a region of complex and fascinating geology with a multitude of natural resources that originated from geologic processes acting over millions of years of Earth history (see Table 1). Several major sedimentary basins, set among mountain ranges and uplifts, lie beneath the State's surface (Fig. 1). Historically, classic studies of many areas in Oklahoma helped to develop fundamental scientific and engineering principles, including those involved in geology, petroleum exploration, and mineral production. The State has advanced-research programs in hydrology, soil science, and climatology, as well as a comprehensive network for monitoring earthquakes.

The topographic map of Oklahoma on page 2 shows mountains, plains, streams, and lakes, as well as spot elevations above sea level of different parts of the State.

Hundreds of millions of years ago, geologic forces within the Earth's crust caused parts of Oklahoma to subside forming major sedimentary basins, while adjacent areas were folded and thrust upward forming major mountain uplifts. Most outcrops in Oklahoma are sedimentary rocks, consisting mainly of shale, sandstone, and limestone; outcrops of igneous and metamorphic rocks, such as granite, rhyolite, gabbro, and gneiss, occur mostly in the Wichita and Arbuckle Mountains. The geologic history of Oklahoma is discussed on pages 3–5, and its present-day geologic map and cross sections are on pages 6 and 7.

Oklahoma's land surface has 27 geomorphic provinces. Each has a similar geologic character, with rocks that underwent a similar geologic history. Weathering and erosion have shaped rocks in these geomorphic provinces into landforms that are described on page 8.

Oklahoma is not known for its earthquake activity, as are California and other western states. However, about 50 earthquakes were detected in Oklahoma every year since 1977, when seismograph stations were installed to monitor low-intensity tremors. Commonly, only one or two earthquakes are strong enough to be felt locally by citizens; the others are detected by Oklahoma's network of 10 seismograph stations. The earthquake history of Oklahoma is told on page 9.

Oklahoma has abundant mineral resources that include petroleum (crude oil and natural gas), coal, and nonfuel minerals (such as limestone, crushed stone, sand and gravel, iodine, glass sand, gypsum, and shale). The value of petroleum, coal, and nonfuel minerals production reached $11.99 billion in 2004 (latest available data), making the mineral industry the State's largest source of revenue in recent years. Oklahoma's nonfuel resources and coal are discussed on page 10, and its petroleum resources are discussed on page 11.

Water resources in Oklahoma consist of surface water and ground water. Surface waters, shown on page 12, are streams and lakes supplied mainly by precipitation, and locally by springs and seeps. In most parts of Oklahoma, surface water and precipitation percolate down into the ground recharging major aquifers, and saturating other sediments and rock units. Page 13 describes the ground-water resources of Oklahoma. Outlines of stream systems or drainage basins, used for improving the management of Oklahoma surface-water resources, are shown on page 14.

Natural and man-made geologic hazards in Oklahoma are discussed on page 15. In Oklahoma, natural geological processes or conditions that can cause hazardous conditions or environmental problems include earthquakes, landslides, radon, expansive soils, floods, karst features, and salt dissolution/salt springs; some human activities that may create geological hazards include underground mining, strip mining, and disposal of industrial wastes.

The soils and vegetation of Oklahoma depend on local geology and climate; soils develop as parent material (that is, underlying rocks or sediments) is altered by climate, plants and animals, topographic relief, and time. Weathering of parent material helps develop soils shown on page 16. Soil characteristics and climate largely control the types of native vegetation that grow in various parts of Oklahoma (page 17).

Climate conditions in Oklahoma—including temperature and precipitation—and some other Oklahoma weather facts are shown on pages 18 and 19. Violent storms and tornadoes are common in Oklahoma, especially in the spring. Information about Oklahoma tornadoes is presented on page 19.

Finally, a glossary of selected terms and a list of references are given on pages 20 and 21, and a generalized stratigraphic column (Fig. 35) of outcropping rocks is represented on page 21.

Table 1. Geologic Time Scale Compared to a Calendar Year

GEOLOGIC ERA	GEOLOGIC PERIOD	BEGINNING (m.y.a.[1])	COMPARATIVE DATE*	DAY	HR	MIN
Cenozoic ("Recent Life")	Quaternary	1.6	December	31	20	53
	Tertiary	65	December	26	17	28
Mesozoic ("Middle Life")	Cretaceous	146	December	20	3	47
	Jurassic	208	December	15	3	6
	Triassic	245	December	12	3	4
Paleozoic ("Ancient Life")	Permian	286	December	8	11	28
	Pennsylvanian	320	December	5	19	14
	Mississippian	360	December	2	13	22
	Devonian	409	November	28	19	49
	Silurian	439	November	26	9	25
	Ordovician	504	November	20	15	12
	Cambrian	570	November	15	18	24
Precambrian		4,500	January	1	0	0

m.y.a.[1] = million years ago. Dates are approximate.
*Prepared by Neil H. Suneson.

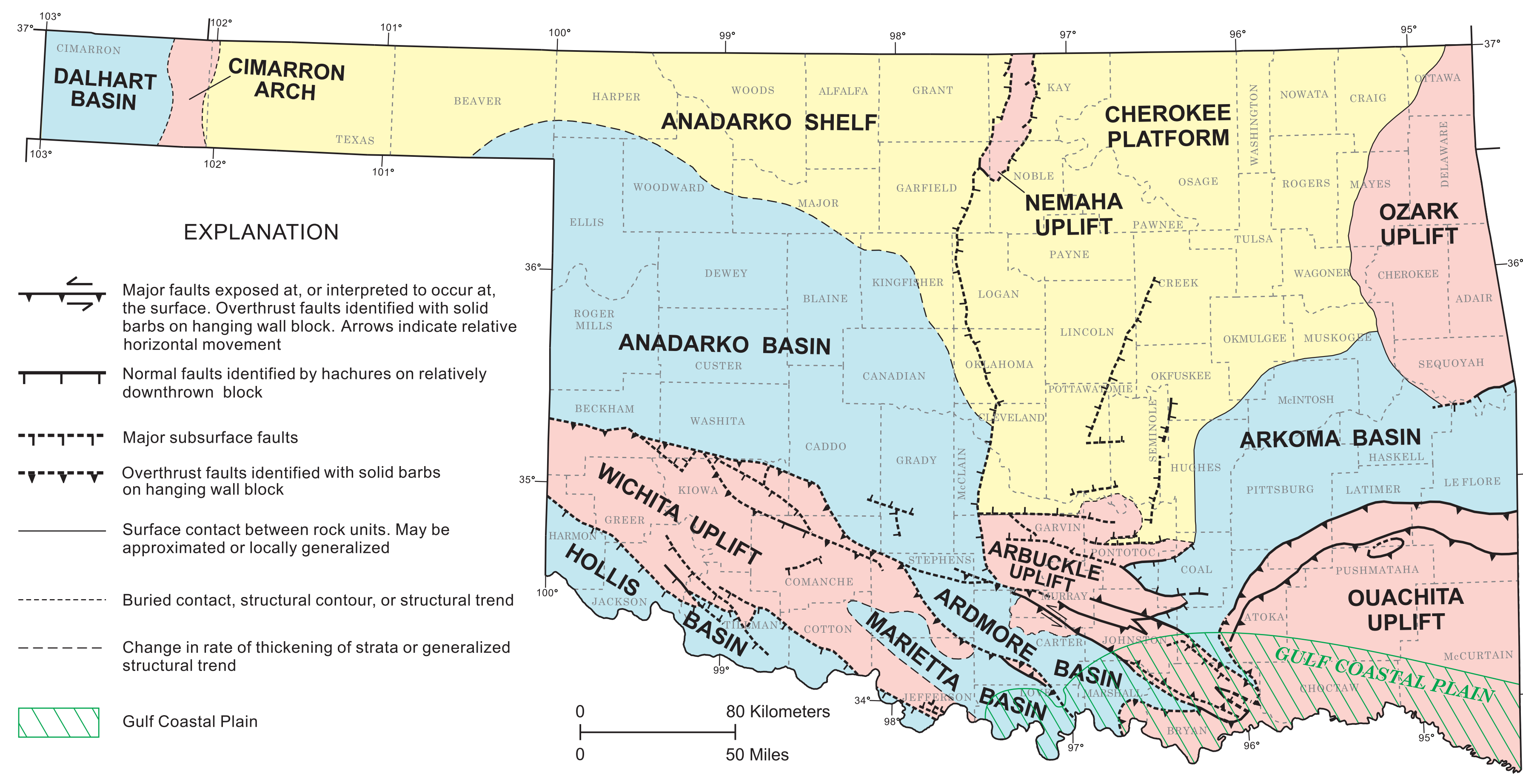
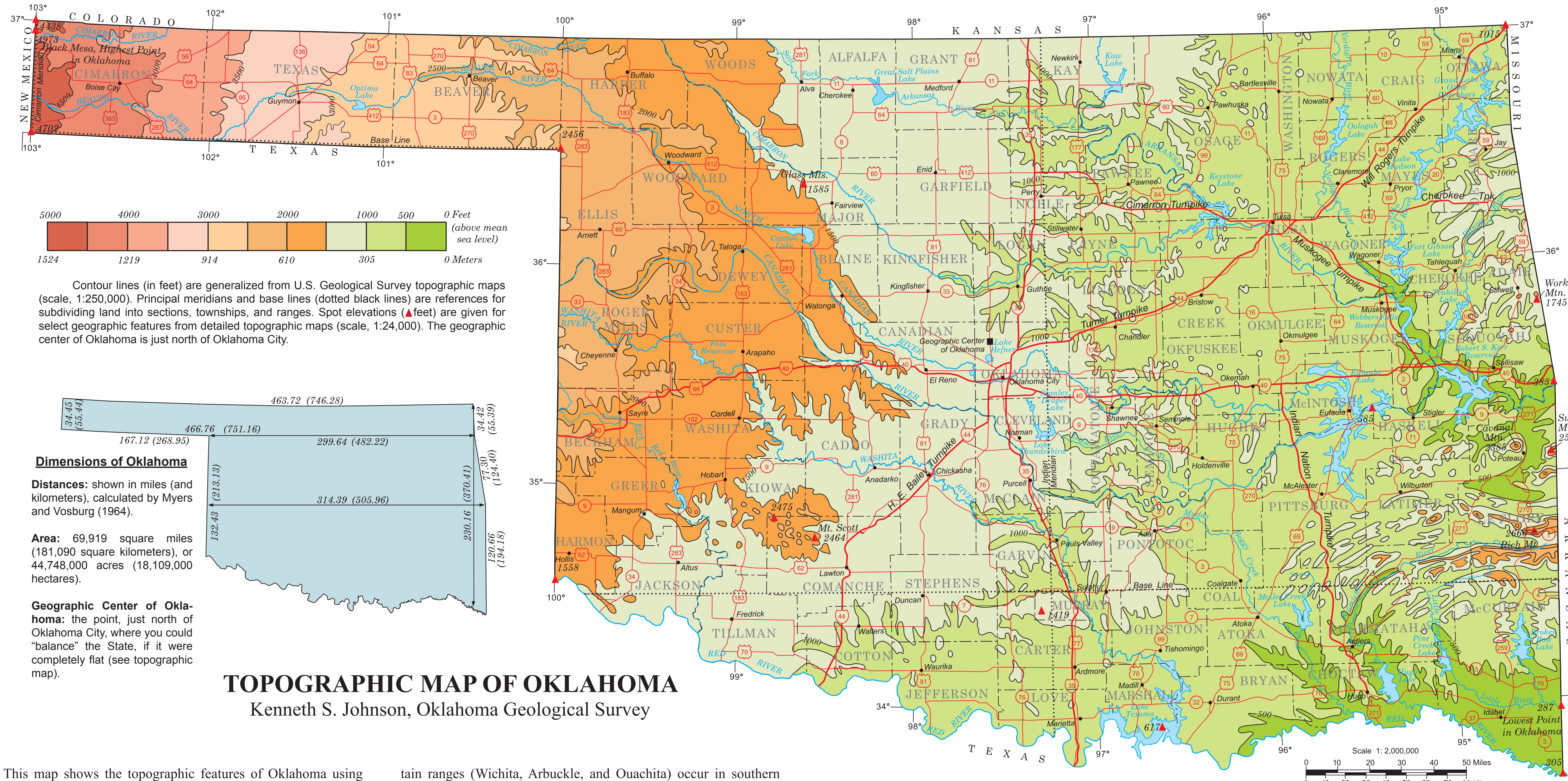


Figure 1. Major geologic provinces of Oklahoma (modified from Northcutt and Campbell, 1995) resulted from tectonic uplift and downwarping of the Earth's crust, mainly during the Pennsylvanian Period. Most province boundaries are structural features. Oklahoma is separated into six major uplifts (Ozark, Nemaha, Ouachita Mountain, Arbuckle, Wichita, and Cimarron) and six major basins (Arkoma, Anadarko, Ardmore, Marietta, Hollis, and Dalhart), and contains three areas of gently dipping strata (Anadarko Shelf, Cherokee Platform, and Gulf Coastal Plain).



Contour lines (in feet) are generalized from U.S. Geological Survey topographic maps (scale, 1:250,000). Principal meridians and base lines (dotted black lines) are references for subdividing land into sections, townships, and ranges. Spot elevations (▲feet) are given for select geographic features from detailed topographic maps (scale, 1:24,000). The geographic center of Oklahoma is just north of Oklahoma City.

Dimensions of Oklahoma

Distances: shown in miles (and kilometers), calculated by Myers and Vosburg (1964).

Area: 69,919 square miles (181,090 square kilometers), or 44,748,000 acres (18,109,000 hectares).

Geographic Center of Oklahoma: the point, just north of Oklahoma City, where you could "balance" the State, if it were completely flat (see topographic map).

TOPOGRAPHIC MAP OF OKLAHOMA

Kenneth S. Johnson, Oklahoma Geological Survey

This map shows the topographic features of Oklahoma using contour lines, or lines of equal elevation above sea level. The highest elevation (4,973 ft) in Oklahoma is on Black Mesa, in the northwest corner of the Panhandle; the lowest elevation (287 ft) is where Little River flows into Arkansas, near the southeast corner of the State. Therefore, the land surface slopes down to the east and southeast at an average of about 9 ft per mile; the slope ranges from about 15 ft per mile in the Panhandle to about 4 ft per mile in central and eastern Oklahoma. Spot elevations are shown at each map corner, at the highest points of several mountain ranges, and at other key places.

Mountains and streams help define the topography or landscape of Oklahoma. Mountains consist mainly of resistant rocks that were folded, faulted, and thrust upward over geologic time, whereas streams continuously erode less-resistant rocks, lowering the landscape to form hills, broad valleys, and plains. Three principal mountain ranges (Wichita, Arbuckle, and Ouachita) occur in southern Oklahoma, although mountainous and hilly areas exist in other parts of the State. The map on page 8 shows the geomorphic provinces of Oklahoma and describes many of the geographic features mentioned below.

Relief in the Wichita Mountains, mainly in Comanche and Kiowa Counties, ranges from about 400–1,100 ft. The highest elevation in the Wichitas is about 2,475 ft, but the best-known peak is Mt. Scott (2,464 ft). One can easily reach Mt. Scott's summit by car to observe spectacular views of the Wichitas and their surroundings.

The Arbuckle Mountains are an area of low to moderate hills in Murray, Johnston, and Pontotoc Counties. Relief ranges from 100–600 ft; the highest elevation (about 1,419 ft) is in the West Timbered Hills in western Murray County. Relief in the Arbuckles is low, but it is six times greater than any other topographic feature between Dallas, Texas, and Oklahoma City.

The Ouachita (pronounced "Wa-she-tah") Mountains in southeastern Oklahoma and western Arkansas is a curved belt of forested ridges and subparallel valleys. Resistant sandstone, chert, and novaculite form long ridges rising 500–1,500 ft above adjacent valleys that formed in easily eroded shales. The highest elevation is 2,666 ft on Rich Mountain. Major prominent ridges in the Ouachitas are the Winding Stair, Rich, Kiamichi, Blue, Jackfork, and Blackjack Mountains.

Other mountains scattered across the Arkansas River Valley in eastern Oklahoma include the Sans Bois Mountain range and Cavanal, Sugar Loaf, Poteau, Beaver, Hi Early, and Rattlesnake Mountains. These mountains typically are broad features rising 300–1,000 ft above wide, rolling plains. The highest summit is Sugar Loaf Mountain in northeastern Le Flore County with an elevation of 2,568 ft, rising about 2,000 ft above the surrounding plains. The largest mountainous area in the region is the Sans Bois Mountains, in northern Latimer and southern Haskell Counties.

The Ozark uplift in northeastern Oklahoma is a deeply dissected plateau consisting of nearly flat-lying limestones, cherts, and sandstones. The uplift includes parts of the Ozark Plateau, the Brushy Mountains, and the Boston Mountains. Relief typically is 50–400 ft, and the highest elevation (about 1,745 ft) is at Workman Mountain in southeastern Adair County.

The Glass Mountains is an area of "badlands" topography in north-central Major County. Calling them "mountains" is an exaggeration, because they are really prominent mesas, buttes, and escarpments in the Cimarron Gypsum Hills. Local relief ranges from 150–200 ft; the highest elevation is about 1,585 ft.

GEOLOGIC HISTORY OF OKLAHOMA

Compiled by Kenneth S. Johnson, Oklahoma Geological Survey

Due to forces within the Earth, parts of Oklahoma in the geologic past were alternately below or above sea level. Thick layers of sediments accumulated in shallow seas that covered large areas. The sediments were later buried and lithified (hardened to rock) into marine shales, limestones, and sandstones over geologic time. In areas near the ancient seas, sands and clays accumulated as alluvial and deltaic deposits that subsequently were lithified to sandstones and shales. When the areas were later elevated above the seas, rocks and sediments that had been deposited earlier were exposed and eroded. Uplift was accomplished by the gentle arching of broad areas, or by mountain building where rocks were intensely folded, faulted, and thrust upward.

The principal mountain belts, the Ouachita, Arbuckle, and Wichita Mountains, are in the southern third of Oklahoma (Fig. 2). These were the sites of folding, faulting, and uplifting during the Pennsylvanian Period. The mountain belts exposed a great variety of geologic structures and brought igneous rocks and thick sequences of Paleozoic sedimentary strata to the surface. The uplifts provide sites where one can observe and collect a great number of fossils, rocks, and minerals (see Table 1 and Figure 35).

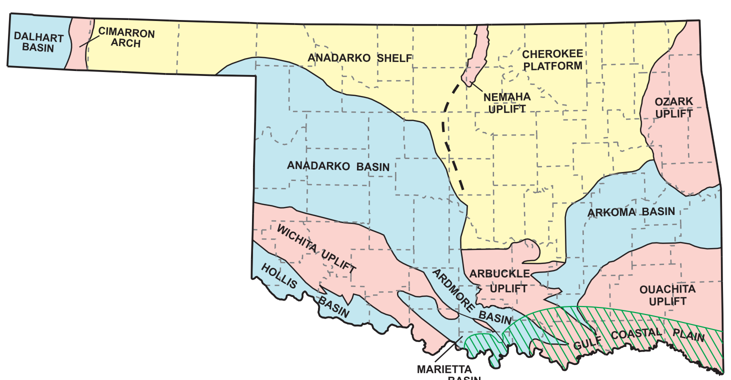


Figure 2. Major geologic provinces of Oklahoma (generalized from page 1, Fig. 1).

The principal sites of sedimentation were elongate basins that subsided more rapidly than adjacent areas, and received 10,000–40,000 ft of sediment. Major sedimentary basins were confined to the southern half of Oklahoma and include Anadarko, Arkoma, Ardmore, Marietta, Hollis, and Ouachita Basins; the Ouachita Basin is the site of today's Ouachita Mountains, and was active from Late Cambrian to Early Pennsylvanian. A smaller basin, the Dalhart Basin, is in the western Panhandle.

The following discussion is modified from Johnson (1971), Johnson and others (1989), and Johnson (1996). (Note that many geologic terms are defined in the Glossary of Selected Terms on pages 20 and 21. The stratigraphic column on page 21 illustrates principal Oklahoma rock formations and their ages).

Precambrian and Cambrian Igneous and Metamorphic Activity

Oklahoma's oldest rocks are Precambrian igneous and metamorphic rocks that formed about 1.4 billion years ago. Then in another episode of igneous activity, during the Early and Middle Cambrian, granites, rhyolites, gabbros, and basalts formed in southwestern and south-central Oklahoma. Heat and fluids of Cambrian magmas changed older sedimentary rocks into metamorphic rocks.

Precambrian and Cambrian igneous and metamorphic rocks underlie all of Oklahoma and are the floor or basement on which younger rocks rest. The top of the basement rocks typically is ~1,000 ft below the Earth's surface in the Ozark Uplift in northeastern Oklahoma, except where granite crops out at Spavinaw, in Mayes County. To the south and southwest, the depth to basement increases to 30,000–40,000 ft beneath deep sedimentary basins (Fig. 3). Adjacent to the basins, basement rocks were uplifted above sea level in two major fault blocks and are exposed in the Wichita and Arbuckle Mountains. Igneous rocks and hydrothermal-mineral veins crop out locally in these mountains.

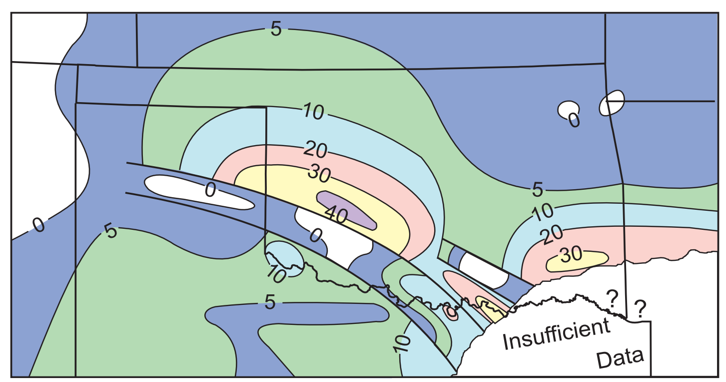


Figure 3. Generalized contours showing elevation (in thousands of feet below sea level) of the eroded top of Precambrian and Cambrian basement rocks in Oklahoma and parts of adjacent states.

Late Cambrian and Ordovician Periods

Following a brief period when newly formed Cambrian igneous rocks and ancient Precambrian rocks were partly eroded, shallow seas covered Oklahoma during the early Paleozoic Era. This began a long period of geologic time (515 million years) when parts of Oklahoma were alternately inundated by shallow seas and then raised above sea level. Many rocks that formed in the various sedimentary environments contain fossils and diverse mineral deposits.

The sea first invaded Oklahoma in the Late Cambrian and moved across the State from the east or southeast. The Reagan Sandstone, consisting of sand and gravel eroded from exposed and weathered basement, was deposited in southern and eastern parts of Oklahoma. Thick limestones and dolomites of the overlying Arbuckle Group (Late Cambrian and Early Ordovician) covered almost the entire State (Fig. 4). The Arbuckle Group marine sediments increase in thickness southward from 1,000–2,000 ft in northern shelf areas (Anadarko Shelf and Cherokee Platform) to about 7,000 ft in the Anadarko and Ardmore Basins, and in the Arbuckle Mountains. Thick deposits of black shale, sandstone, and some limestone are present in the Ouachita province in the southeast. Shallow-marine limestones, sandstones, and shales characterize Middle and Late Ordovician rocks throughout most of Oklahoma (Fig. 5). Some of the most widespread rock units include Simpson Group sandstones, Viola Group limestones, and the Sylvan Shale. These strata are up to 2,500 ft thick in the deep Anadarko and Ardmore Basins and in the Arbuckle Mountains. Thick layers of black shale, along with some chert and sandstone beds, occur in the Ouachita Mountains region to the southeast.

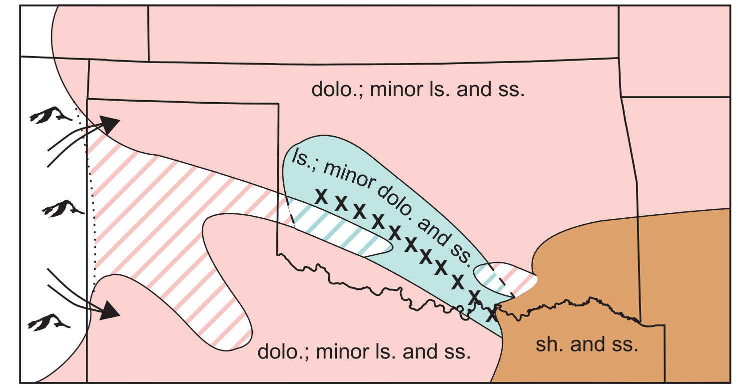
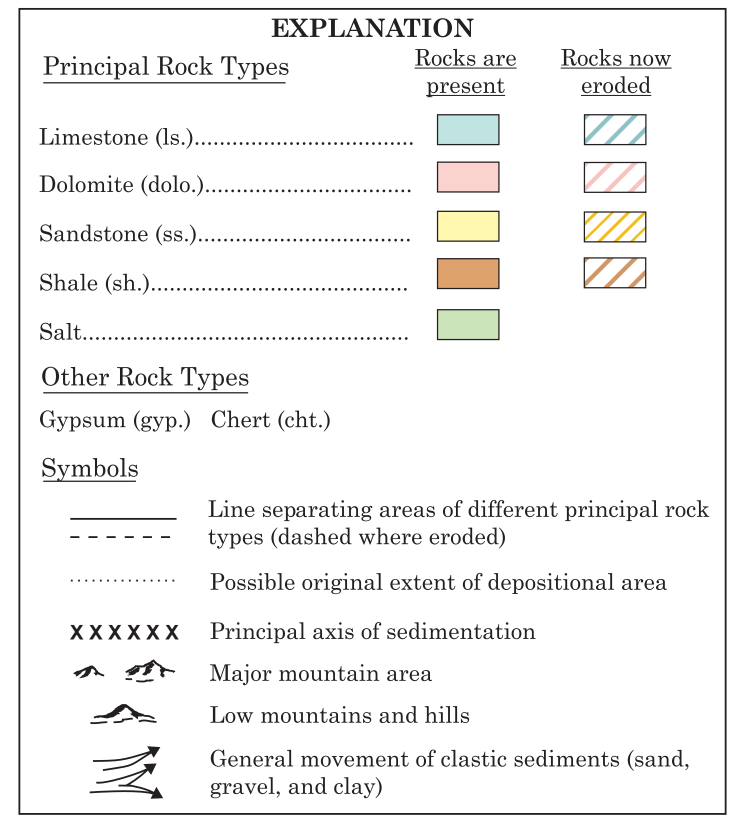


Figure 4. Principal rock types of Late Cambrian and Early Ordovician age in Oklahoma (explanation of map symbols, below, applies to Figures 4-18).



Limestone and other Late Cambrian and Ordovician rocks exposed in the Arbuckle Mountains and on the flanks of the Wichita Mountains contain abundant fossils of early marine invertebrates such as trilobites, brachiopods, and bryozoans.

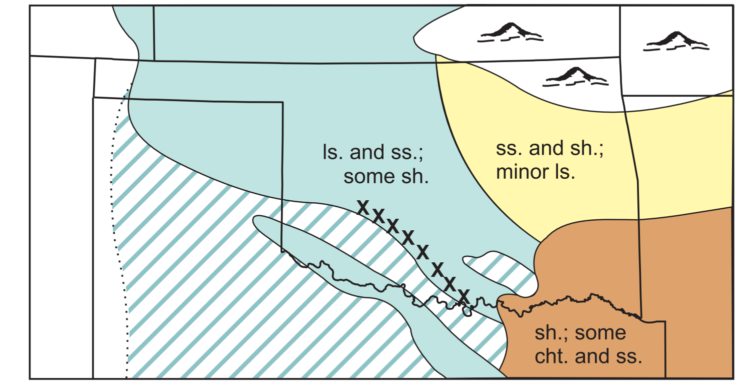


Figure 5. Principal rock types of Middle and Late Ordovician age in Oklahoma (see Fig. 4 for explanation of symbols).

Silurian and Devonian Periods

Silurian and Devonian sedimentary rocks in Oklahoma (except for deposits in the Ouachita Basin) are limestone and dolomite overlain by black shale (Fig. 6). The Hunton Group (latest Ordovician, Silurian, and Early Devonian) is commonly 100–500 ft thick (maximum, 1,000 ft) and was eroded from northern shelf areas. Invertebrate marine fossils, such as brachiopods, trilobites, and crinoids, are abundant in the Hunton in the Arbuckle Mountains and in equivalent strata in the Ozark Uplift.

After a period of widespread uplift and erosion, the Late Devonian to earliest Mississippian Woodford Shale was deposited in essentially the same areas as the Hunton, and northward into Kansas.

The pre-Woodford erosional surface is a conspicuous unconformity: 500–1,000 ft of strata were eroded over broad areas, and the Woodford or younger Mississippian units rest on Ordovician and Silurian rocks. The Woodford typically is 50–200 ft thick, but it is as thick as 600 ft in the Arbuckle Mountains. The Devonian–Mississippian boundary is placed at the top of the Woodford because only the uppermost few feet of Woodford is earliest Mississippian.

In the Ouachita Basin, sandstone and shale of the Blaylock and Missouri Mountain Formations are Silurian. The Arkansas Novaculite (chert) is Silurian, Devonian, and Early Mississippian. These three formations are 500–1,500 ft in total thickness.

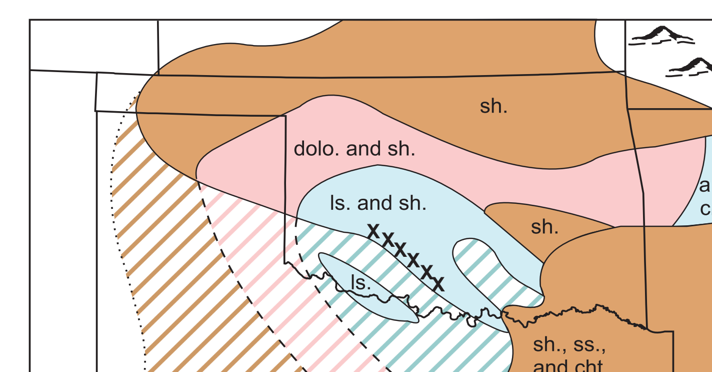


Figure 6. Principal rock types of Silurian and Devonian age in Oklahoma (see Fig. 4 for explanation of symbols).

GEOLOGIC HISTORY OF OKLAHOMA (continued)

Mississippian Period

Shallow seas covered most of Oklahoma during most of the first half of the Mississippian Period (Fig. 7). Limestone and chert are the dominant sedimentary rocks in most areas, and the Arkansas Novaculite occurs in the Ouachita Basin. Important units are Keokuk and Reeds Spring Formations in the Ozarks, Sycamore Limestone in southern Oklahoma, and "Mississippi lime" (a term for thick Mississippian limestones) in the subsurface across most of northern Oklahoma. Early Mississippian limestones, which are the youngest of the thick carbonate sequences in Oklahoma, provide evidence for early and middle Paleozoic crustal stability.

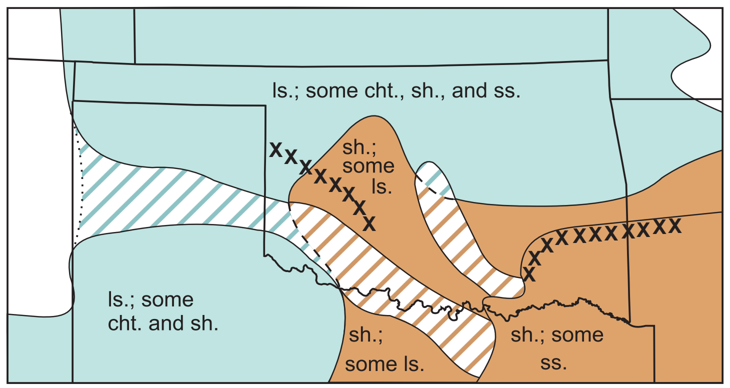


Figure 7. Principal rock types of Mississippian age in Oklahoma (see Fig. 4 for explanation of symbols).

Basins in southern Oklahoma in the last half of the Mississippian rapidly subsided, resulting in thick sedimentary deposits that consist predominantly of shale, with layers of limestone and sandstone (Fig. 7). Principal Mississippian formations in southern Oklahoma (excluding the Ouachitas) are the Caney Shale, Goddard Formation, and Springer Formation (which is partly Early Pennsylvanian): these and the underlying Sycamore Limestone are 1,500–6,000 ft thick in the Ardmore and eastern Anadarko Basins and nearby areas. The greatest thickness of Mississippian strata is 10,000 ft of interbedded sandstone and shale of the Stanley Group in the Ouachita Basin. Most Mississippian strata in central and north-central Oklahoma were eroded during the Early Pennsylvanian. In the western Anadarko Basin, Mississippian strata consist of cherty limestones and shales 3,000 ft thick, thinning to 200–400 ft east of the Nemaha Uplift.

Mississippian rocks host various fossils and minerals. Marine limestones and shales in the Arbuckle Mountains and Ozark Uplift contain abundant invertebrate marine fossils, such as crinoids, bryozoans, blastoids, and brachiopods. The Tri-State mining district in northeastern Oklahoma (Miami-Picher area) yielded beautiful crystals of galena, sphalerite, and calcite.

Pennsylvanian Period

The Pennsylvanian Period was a time of crustal unrest in Oklahoma: both orogeny and basin subsidence in the south; gentle raising and lowering of broad areas in the north. Uplifts in Colorado and New Mexico gave rise to the mountain chain referred to as the Ancestral Rockies. Sediments deposited earlier in the Wichita, Arbuckle, and Ouachita Uplifts were lithified, deformed, and uplifted to form major mountains, while nearby basins subsided rapidly and received sediments eroded from the highlands. Pennsylvanian rocks are dominantly marine shale, but beds of sandstone, limestone, conglomerate, and coal also occur. Pennsylvanian strata, commonly 2,000–5,000 ft thick in shelf areas in the north, are up to 16,000 ft in the Anadarko Basin, 15,000 ft in the Ardmore Basin, 13,000 ft in the Marietta Basin, and 18,000 ft in the Arkoma Basin.

Pennsylvanian rocks contain petroleum reservoirs that yield more oil and gas than any other rocks in Oklahoma, and they also have large coal reserves in eastern Oklahoma. The Pennsylvanian interests collectors for two reasons. (1) Pennsylvanian sediments contain abundant invertebrate and plant fossils in eastern and south-central Oklahoma. Invertebrates include various brachiopods, crinoids, bryozoans, gastropods,

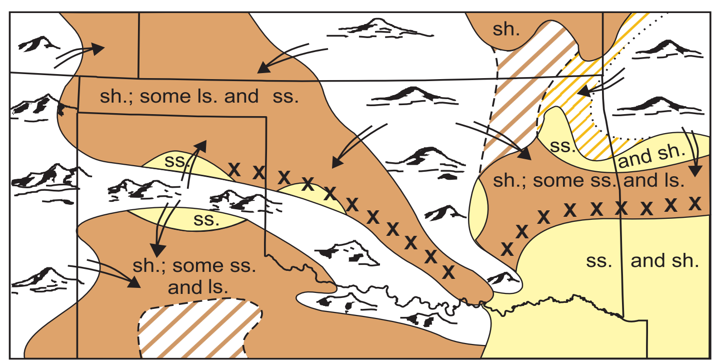


Figure 8. Principal rock types of Early Pennsylvanian (Morrowan and Atokan) age in Oklahoma (see Fig. 4 for explanation of symbols).

and bivalves. Plant remains include petrified wood, fossil leaves, and extensive coal strata. The primary vertebrate fossils are shark teeth. (2) Pennsylvanian mountain-building caused the uplift of deeply buried Precambrian through Mississippian rocks in the Wichita, Arbuckle, Ouachita, and Ozark Uplifts. The older, fossiliferous and mineral-bearing rocks now are exposed after the erosion of younger, overlying strata.

The Pennsylvanian Period, subdivided into five epochs of time, includes (from oldest to youngest): Morrowan (Early), Atokan, Desmoinesian (Middle), Missourian, and Virgilian (Late). Orogenies occurred in all five epochs, but each pulse of mountain building affected different areas by varying degrees.

Folding and uplift of pre-Morrowan rocks characterize a major Pennsylvanian orogeny, the Wichita orogeny (Morrowan and early Atokan), resulting in 10,000–15,000 ft of uplift in the Wichita Mountains and in the Criner Hills south of Ardmore (Fig. 8). Conglomerate and eroded granite fragments (locally called granite wash) commonly are present near major uplifts, and the coarse-grained rocks grade into sandstone and shale toward the basin centers.

A broad, north-trending arch rose above sea level across central Oklahoma during this time; along its axis, a narrow belt of fault-block mountains, the Nemaha Uplift, extended north from Oklahoma City into Kansas. A broad uplift also

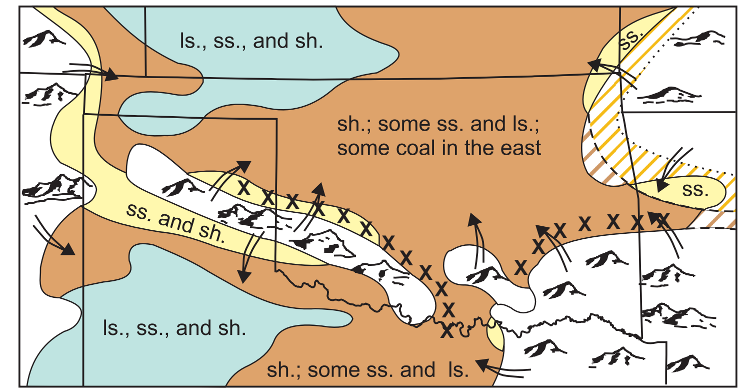


Figure 9. Principal rock types of Middle Pennsylvanian (Desmoinesian) age in Oklahoma (see Fig. 4 for explanation of symbols).

occurred at this time in the Ozark region of northeastern Oklahoma. The Morrowan and Atokan uplift resulted in erosion that removed all or part of the pre-Pennsylvanian rocks from the Wichita Mountains, Criner Hills, and central Oklahoma Arch. Less erosion occurred in other areas. The most profound Paleozoic unconformity in Oklahoma occurs at the base of Pennsylvanian rocks, and is recognized everywhere but in the deeper parts of major basins.

Principal pulses of deformation in the Ouachita Mountains

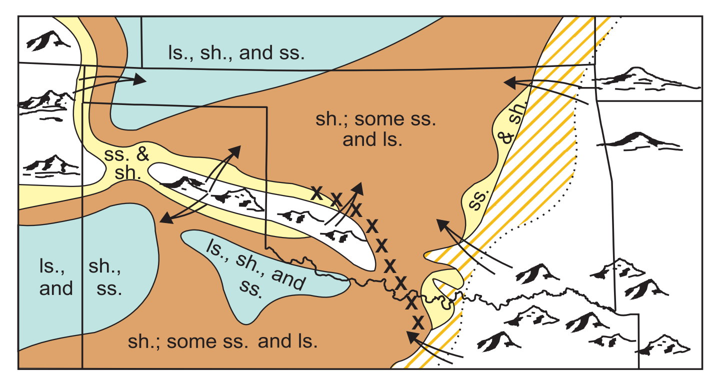


Figure 10. Principal rock types of Late Pennsylvanian (Missourian and Virgilian) age in Oklahoma (see Fig. 4 for explanation of symbols).

area probably started in the Mississippian, and the fold and thrust belt progressed northward. The pulses, known as the Ouachita orogeny, stopped by the end of the Desmoinesian (Fig. 9); the pulses included the northward thrusting of rocks (perhaps up to 50 mi of thrusting). Uplifting the Ouachita Mountains above sea level probably occurred during the Desmoinesian; the Ouachitas remained high into the Permian Period.

Downwarping of the Ouachita Basin shifted northward into the Arkoma Basin during Atokan and Desmoinesian times, and deformation ceased after folding and faulting of the Arkoma Basin. Of special importance in the Arkoma Basin and northeastern Oklahoma are Desmoinesian coal beds formed from plant matter that had accumulated in swamps. At widely scattered locations throughout eastern Oklahoma, Desmoinesian strata are well known for fossil trees, wood, and leaves.

The last major Pennsylvanian orogeny, the Arbuckle orogeny, was a strong compression and uplift during the Virgilian. The orogeny affected many mountain areas in southern Oklahoma and caused prominent folding in the Ardmore, Marietta, and Anadarko Basins (Fig. 10). Much of the folding, faulting, and uplift in the Arbuckle Mountains likely occurred in the late Virgilian. By the end of the Pennsylvanian, Oklahoma's mountain systems were essentially as they are today, although subsequent gentle uplift and associated erosion cut deeper into underlying rocks and greatly reduced the original height of the mountains.

Permian Period

Following Pennsylvanian mountain building, an Early Permian (Wolfcampian) shallow inland sea covered most of

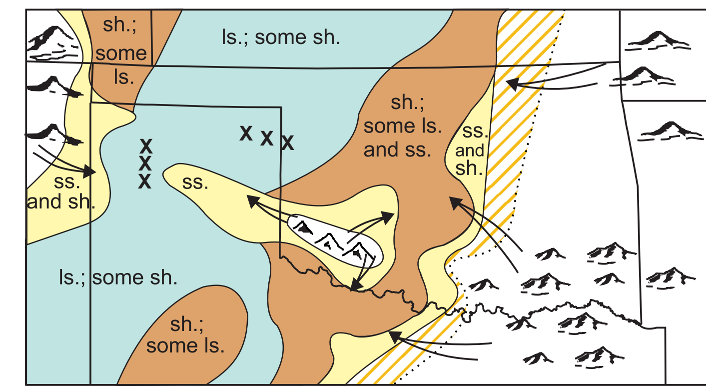


Figure 11. Principal rock types of Early Permian (Wolfcampian) age in Oklahoma (see Fig. 4 for explanation of symbols).

western Oklahoma and the Panhandle, extending north from west Texas to Nebraska and the Dakotas. Shallow-marine limestones and gray shales are found in the center of the ancient seaway (Fig. 11), grading laterally to the east and west

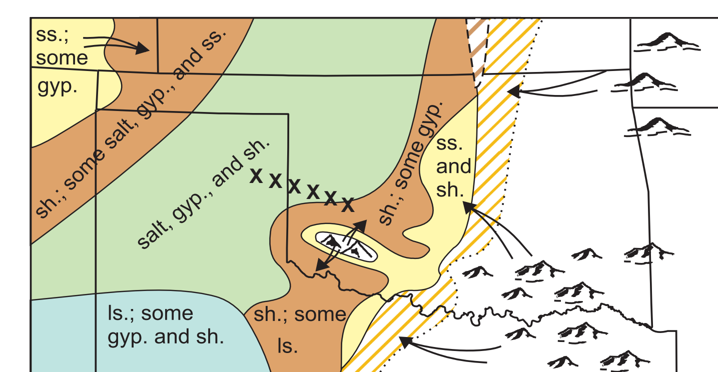


Figure 12. Principal rock types of Early Permian (Leonardian) age in Oklahoma (see Fig. 4 for explanation of symbols).

into limestones, red shales, and red sandstones (Permian red beds). During the later Leonardian (Early Permian; Fig. 12), evaporating sea water deposited thick beds of salt and gypsum (or anhydrite), such as the Wellington and Cimarron evaporites. Throughout the Early Permian, the Wichita, Arbuckle, Ouachita, and Ozark Mountains were still high, supplying eroded sand and mud to central and western Oklahoma. Alluvial, deltaic, and nearshore-marine red sandstone and shale characterize the Early Permian sea margin, interfingering with gray marine shale, anhydrite, limestone, dolomite, and salt that typically were deposited toward the center of the sea. Most Early Permian outcrops are red shales, although thin limestones and dolomites occur in north-central Oklahoma,

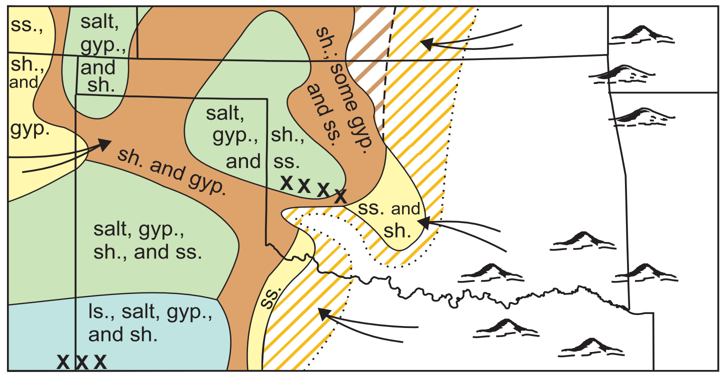


Figure 13. Principal rock types of Late Permian (Guadalupian) age in Oklahoma (see Fig. 4 for explanation of symbols).

and crossbedded sandstones are common in central and south-central areas. The red color, common in Permian rocks, results from iron oxides (chiefly hematite) that coat the grains in the sandstones and shales.

By the Late Permian, the Wichitas were mostly buried by sediment and the mountains to the east were largely eroded (Figs. 13-14). Red shale and sandstone typify Guadalupian rocks, although thick, white gypsum and thin dolomite beds of the Blaine and Cloud Chief Formations also occur. Thick salt units occur in the subsurface (Fig. 13). The Rush Springs Sandstone forms canyons in much of western Oklahoma. Latest Permian (Ochoan) rocks are mostly red-bed sandstones and shales, but they contain some gypsum and

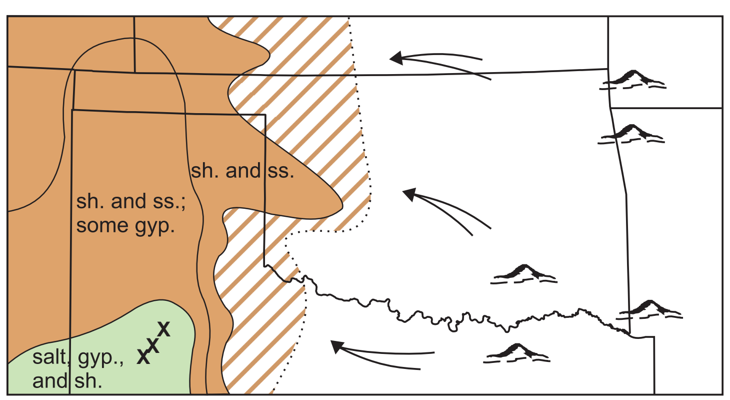


Figure 14. Principal rock types of Late Permian (Ochoan) age in Oklahoma (see Fig. 4 for explanation of symbols).

dolomite in the west (Fig. 14). The entire Permian sequence is commonly 1,000–5,000 ft thick, but can be 6,000–6,500 ft in deeper parts of the Anadarko Basin.

Permian sedimentary rocks in central and western Oklahoma contain various fossils and minerals. Fossils, though rare, include vertebrates (e.g., fish, amphibians, and reptiles), insects, and a few marine invertebrates. Minerals are more common and include gypsum (selenite and satin spar), halite (in subsurface and on salt plains), and rose rocks (barite rose, the official state rock of Oklahoma).

Triassic and Jurassic Periods

Triassic and Jurassic rocks are restricted to the Panhandle (Fig. 15); most of Oklahoma probably was above sea level at this time. Sandstones, shales, and conglomerates formed in central and western Oklahoma from sediments deposited mainly in rivers and lakes that drained hills and lowlands of Permian sedimentary strata. Hills in central Colorado and

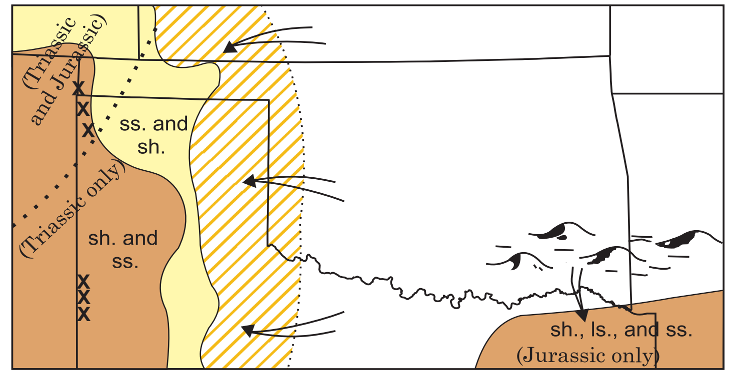


Figure 15. Principal rock types of Triassic and Jurassic age in Oklahoma (see Fig. 4 for explanation of symbols).

northern New Mexico also supplied some sediments. Triassic and Jurassic strata in the Panhandle are mostly red and gray, and are typically 200–700 ft thick.

Southeastern Oklahoma probably was an area of low mountains and hills and was the source of sediment eroded from the Ouachita Mountains. The Gulf of Mexico almost extended into Oklahoma during the Jurassic. Triassic and Jurassic fossils in Oklahoma include some invertebrates, petrified wood, and vertebrates such as dinosaurs, crocodiles, turtles, and fish. In the Panhandle, the Jurassic Morrison Formation is noteworthy because of its abundant dinosaur bones.

Cretaceous Period

Cretaceous seas covered all but northeastern and east-central Oklahoma (Fig. 16). The ancestral Gulf of Mexico extended across southeastern Oklahoma in the Early Cretaceous, and shallow seas extended north in the last great inundation of the western interior of the United States (including Oklahoma) during the Late Cretaceous. Shale, sandstone, and limestone are about 200 ft thick in the Panhandle and as thick as 2,000–3,000 ft in the Gulf Coastal Plain (Fig. 16). A major unconformity is exposed throughout the southeast, where

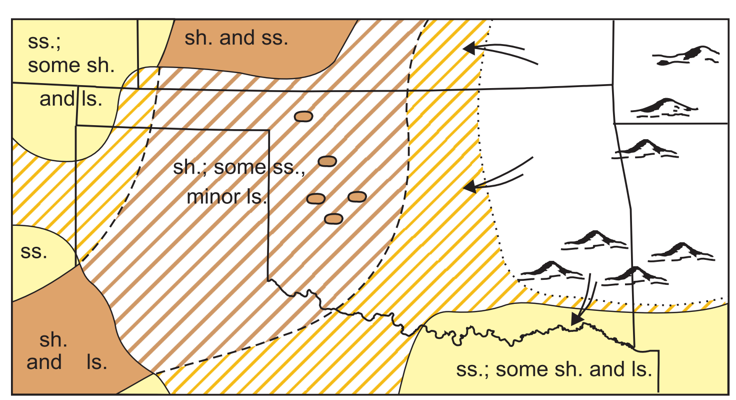


Figure 16. Principal rock types of Cretaceous age in Oklahoma (see Fig. 4 for explanation of symbols).

Cretaceous strata rest on rocks from the Precambrian through the Permian. Uplift of the Rocky Mountains in the Late Cretaceous and Early Tertiary caused a broad uplift of Oklahoma, imparting an eastward tilt that resulted in the final withdrawal of the sea.

Cretaceous marine rocks in southeastern and western Oklahoma contain shark teeth and various invertebrate fossils, such as oysters, echinoids, and giant ammonites. Nonmarine Cretaceous strata contain dinosaur bones.

Cretaceous strata have been eroded from almost all parts of western Oklahoma (Fig. 16), except where blocks of Cretaceous rock (several acres to several square miles wide) have dropped down several hundred feet into sinkholes formed by dissolution of underlying Permian salts.

Tertiary Period

The ancestral Gulf of Mexico extended almost to the southeast corner of Oklahoma in the Early Tertiary, and the shoreline gradually retreated southward through the remainder of the period. Oklahoma supplied some sediments deposited to the southeast, including gravels, sands, and clays (Fig. 17).

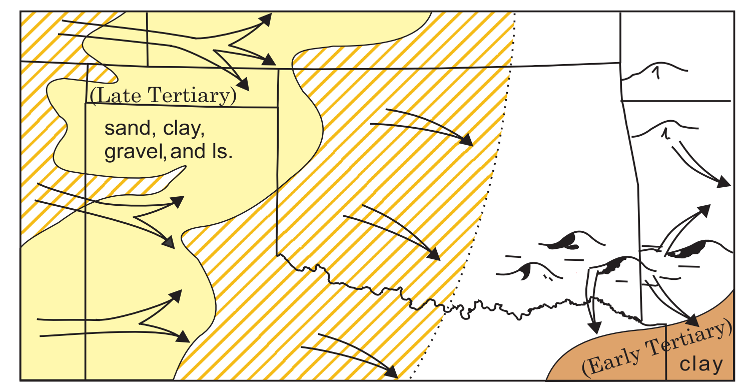


Figure 17. Principal rock types of Tertiary age in Oklahoma (see Fig. 4 for explanation of symbols).

In the Late Tertiary, a thick blanket of sand, silt, clay, and gravel eroded from the Rocky Mountains was deposited across the High Plains and farther east by a system of coalescing rivers and lakes. Some middle and upper parts of the Tertiary deposits consist of eolian sediment, and some fresh-water lakes had limestone deposits. Deposits in western Oklahoma, the Ogallala Formation, are 200–600 ft thick; they may have extended across central Oklahoma, thinning eastward. The nonmarine Ogallala contains fossil wood, snails, clams, and vertebrates such as horses, camels, rhinoceroses, and mastodons.

In the northwest corner of the Panhandle, a prominent layer of Tertiary basaltic lava that flowed from a volcano in southeastern Colorado caps Black Mesa.

Quaternary Period

The Quaternary Period, the last 1.6 million years of Earth history, is divided into the Pleistocene Epoch (the "Great Ice Age") and the Holocene or Recent Epoch that we live in today. The boundary between the epochs is about 11,500 years ago, at the end of the last continental glaciation. During that time the glaciers extended south only as far as northeastern Kansas. Major rivers fed by meltwater from Rocky Mountain glaciers and the increased precipitation associated with glaciation sculpted Oklahoma's land (Fig. 18). Today's major drainage systems originated during the Pleistocene. The rivers' shifting positions are marked by alluvial deposits left as terraces, now tens to hundreds of feet above present-day flood plains.

The Quaternary is characterized as a time when rocks and loose sediment at the surface are being weathered to soil, and the soil particles then are carried away to streams and rivers. In this manner, hills and mountains are eroded, and sediments are transported to the sea, or are temporarily deposited in river beds and banks and in lake bottoms. Clay, silt, sand,

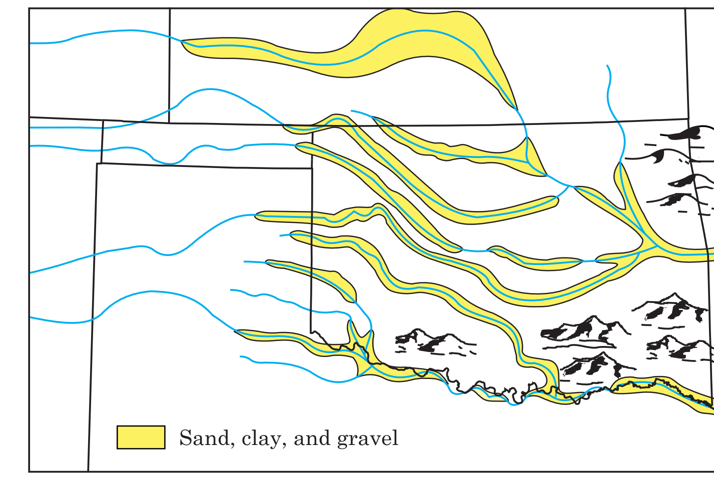
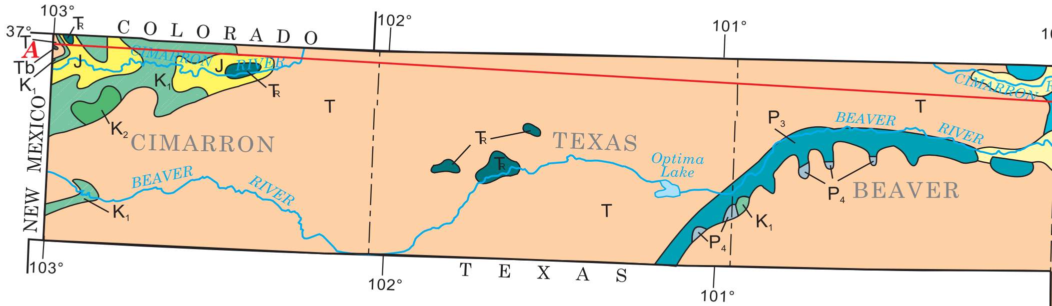
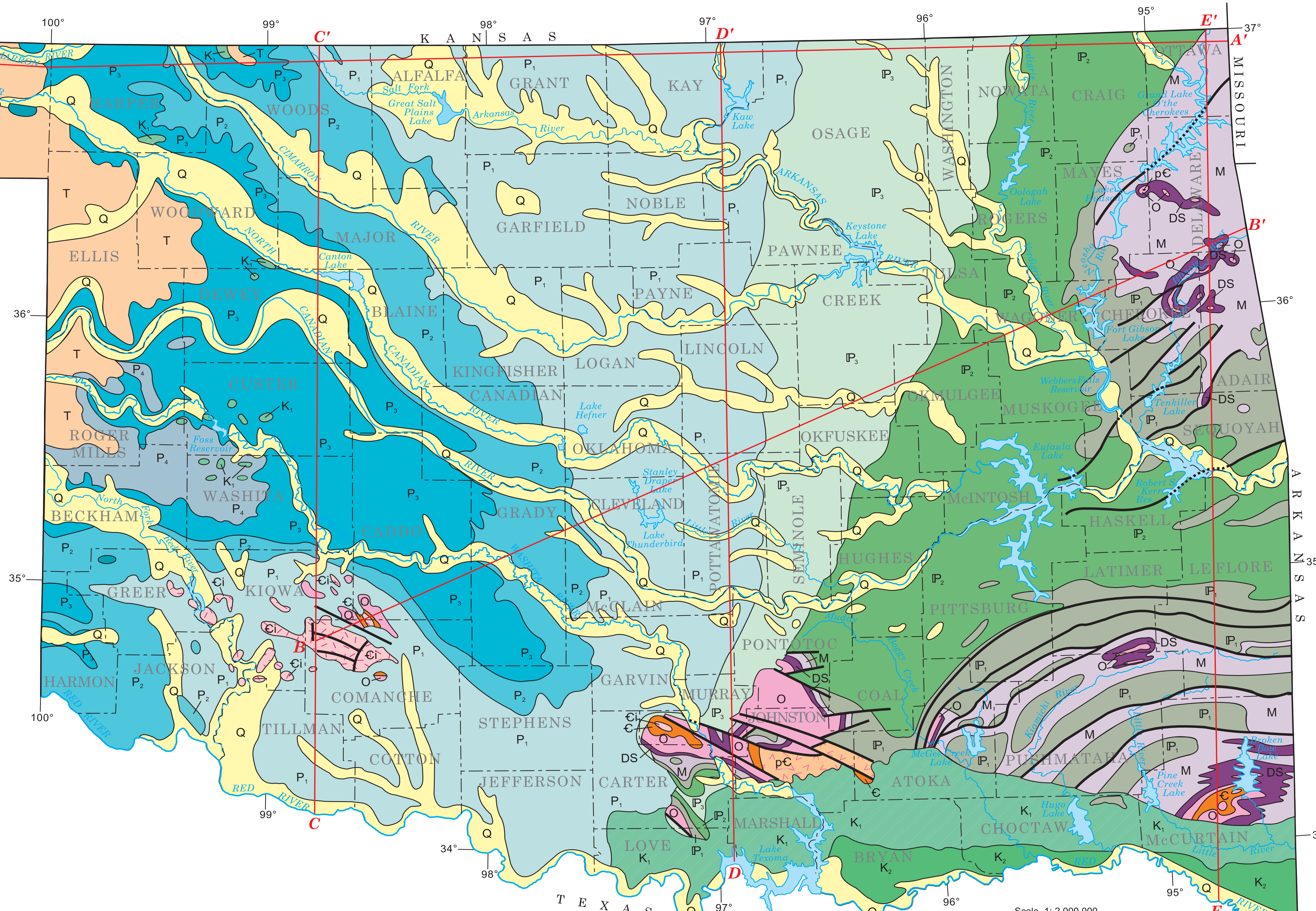


Figure 18. Major rivers of Oklahoma and principal deposits of Quaternary age (see Fig. 4 for explanation of symbols)

and gravel from Pleistocene and Holocene rivers and lakes are typically unconsolidated and 25–100 ft thick. Finding Pleistocene terraces more than 100–300 ft above modern flood plains attests to the great amount of erosion and down cutting performed by major rivers in the last 1.6 million years. Modern flood plains consist mainly of alluvium deposited during the Holocene.

Quaternary river-borne sediments decrease in grain size from west to east across Oklahoma; gravel, commonly mixed with river sands in the west, is abraded so much during transport that it is almost absent in the east. Eolian sediments characterize Quaternary deposits in parts of western Oklahoma: sand dunes, mainly on the north sides of major rivers, and some of the Ogallala (Tertiary) sands and silts, were reworked by Quaternary winds.

Quaternary sediments locally contain fossil wood, snail shells, and bones and teeth of land vertebrates (e.g., horses, camels, bison, mastodons, mammoths). Some fossils were eroded from the Ogallala and redeposited in the Quaternary. Horses, camels, mastodons, mammoths and other large animals lived in Oklahoma during the Pleistocene, but they died out at the end of the Pleistocene and the beginning of the Holocene.

GEOLOGIC MAP OF OKLAHOMA

Kenneth S. Johnson, Oklahoma Geological Survey

EXPLANATION

SEDIMENTS AND SEDIMENTARY ROCKS

- **Q** — **Quaternary—**Sand, silt, clay, and gravel in flood plain and terrace deposits of major rivers. Includes sand dunes in some terraces and local windblown sands on Tertiary rocks; generally 25–100 ft thick.
- **T** — **Tertiary—**River and windblown deposits of sand, clay, gravel, and caliche are deposited from ancient rivers draining the Rocky Mountains; generally 200–600 ft thick.
- **K_2, K_1** — **Cretaceous—**Nonmarine sand and clay, and marine limestone and clay are up to 3,000 ft thick in the southeast. Marine sandstone, limestone, and shale are about 200 ft thick in the Panhandle. Scattered collapsed blocks of marine limestone, sandstone, and shale are in the Anadarko basin. Cretaceous is divided into Lower (K_1) and Upper (K_2) units.
- **J** — **Jurassic—**Nonmarine, red and gray shale, sandstone, and conglomerate are in the Panhandle; generally 100–300 ft thick.
- **₮** — **Triassic—**Nonmarine, red and gray shale and sandstone in the Panhandle are commonly 200–500 ft thick.
- **P_4, P_3, P_2, P_1** — **Permian—**Shallow-marine, deltaic, and alluvial deposits of red sandstone and shale predominate. Outcrops of white gypsum are conspicuous, and thick salt deposits are widespread in the subsurface in the west; generally 1,000–6,500 ft thick. Permian is divided into Lower (P_1) and Upper (P_2, P_3, and P_4) units; lower part of P_1 is marine red sandstone and shale, with some thin beds of limestone.
- **$\mathbb{P}_3$, $\mathbb{P}_2$, $\mathbb{P}_1$** — **Pennsylvanian—**Mostly marine shale, with interbedded sandstone, limestone, and coal. Thickness is commonly 2,000–5,000 ft, but much greater in the Anadarko Basin (16,000 ft thick), Ardmore Basin (15,000 ft), Marietta Basin (13,000 ft), Ouachita Mountains (15,000 ft), and Arkoma Basin (18,000 ft). Thick conglomerates occur near the Wichita and Arbuckle Mountains. Units are divided into Lower ($\mathbb{P}_1$), Middle ($\mathbb{P}_2$), and Upper ($\mathbb{P}_3$) Pennsylvanian.
- **M** — **Mississippian—**Mostly cherty marine limestone, 200–3,000 ft thick in the north. Rocks are mostly marine shale and sandstone elsewhere; commonly 1,000–6,000 ft thick, but up to 10,000 ft thick in the Ouachita Mountains.
- **DS** — **Silurian–Devonian—**Marine limestone and dolomite, 100–1,000 ft thick, are overlain by black shale, 50–600 ft thick. In the Ouachita Mountains, the units, 500–1,500 ft thick, are chert, shale, and sandstone.
- **O** — **Ordovician—**Marine limestone and dolomite, with some sandstone and shale, thicken from 500–1,500 ft in the north to about 8,000 ft in the south. In the Ouachita Mountains, the units are shale, sandstone, and cherty limestone.
- **Є** — **Cambrian—**Rocks are marine limestone and dolomite, with a basal sandstone; generally 500–2,000 ft thick.

IGNEOUS AND METAMORPHIC ROCKS

- **Tb** — **Tertiary—**Basaltic lava flow, 50–85 ft thick, in the northwest corner of the Panhandle; caps Black Mesa.
- **Єi** — **Cambrian—**Outcrops of granite, rhyolite, and gabbro occur in the Wichita Mountains; rhyolite occurs in the Arbuckle Mountains. Igneous rocks formed from magma about 525 million years ago; nearly 20,000 ft thick.
- **pЄ** — **Precambrian—**Granite and gneiss (a metamorphosed igneous rock) crop out in the Arbuckle Mountains, and granite crops out in a small area in Mayes County. Formed about 1.4 billion years ago, these are the oldest rock outcrops in Oklahoma.

Symbols

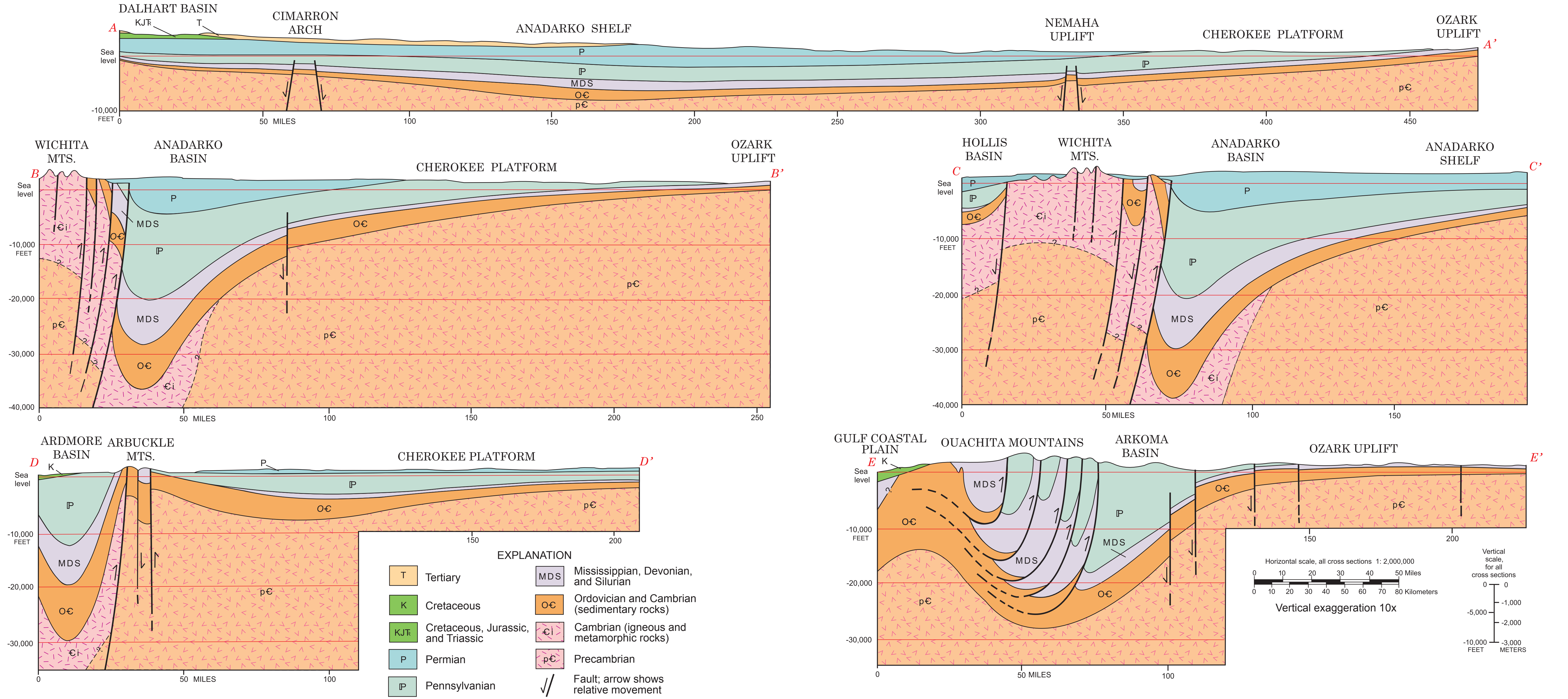
- Geologic contact
- Fault; dotted where concealed by Quaternary sediments
- *A–A′* Line of cross section (see p. 7)

The geologic map of Oklahoma shows rock units that crop out or are mantled by a thin soil veneer. Quaternary sediments laid down by streams and rivers locally overly Precambrian through Tertiary bedrock. The geologic map helps one understand the age and character of Oklahoma's rocks in assessing petroleum reservoirs, mineral deposits, construction sites, engineering properties, ground-water-aquifer characteristics, and to remedy environmental problems.

About 99% of all outcrops in Oklahoma are sedimentary rocks. Remaining outcrops are (1) igneous rocks, mainly in the Wichita and Arbuckle Mountains, (2) metamorphic rocks in the eastern Arbuckles, and (3) mildly metamorphosed rocks in the core of the Ouachita Mountains.

Rocks formed during every geologic period crop out in Oklahoma. About 46% of Oklahoma has Permian rocks exposed at the surface. Other extensive outcrops are Pennsylvanian (about 25%), Tertiary (11%), Cretaceous (7%), Mississippian (6%), Ordovician (1%), and Cambrian (1%); Precambrian, Silurian, Devonian, Triassic, and Jurassic rocks each are exposed in less than 1% of Oklahoma. These outcrops do not include the Quaternary river, terrace, and lake deposits overlying older rocks in Oklahoma.

Bedrock geology on this map is derived from Miser (1954). Quaternary alluvium and terrace deposits are derived from nine hydrologic atlases of Oklahoma prepared jointly by the Oklahoma Geological Survey and the U.S. Geological Survey (Marcher, 1969; Marcher and Bingham, 1971; Hart, 1974; Bingham and Moore, 1975; Carr and Bergman, 1976; Havens, 1977; Bingham and Bergman, 1980; Morton, 1981; Marcher and Bergman, 1983).



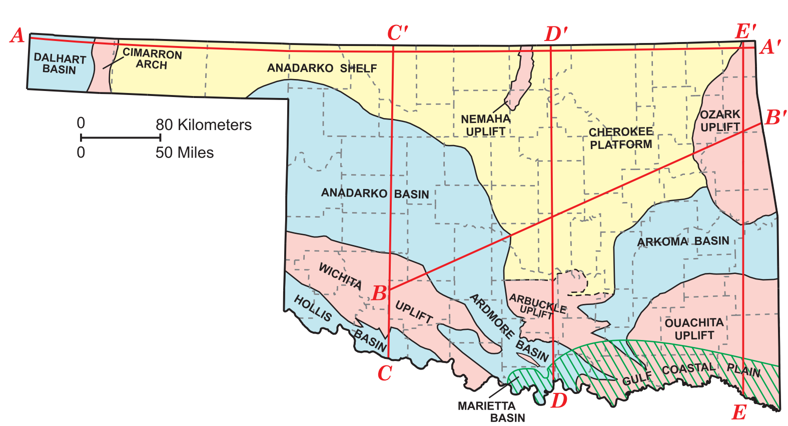


Figure 19. Geologic cross sections across the major geologic province map of Oklahoma (generalized from fig.1) : A-A', B-B', C-C', D-D' and E-E'.

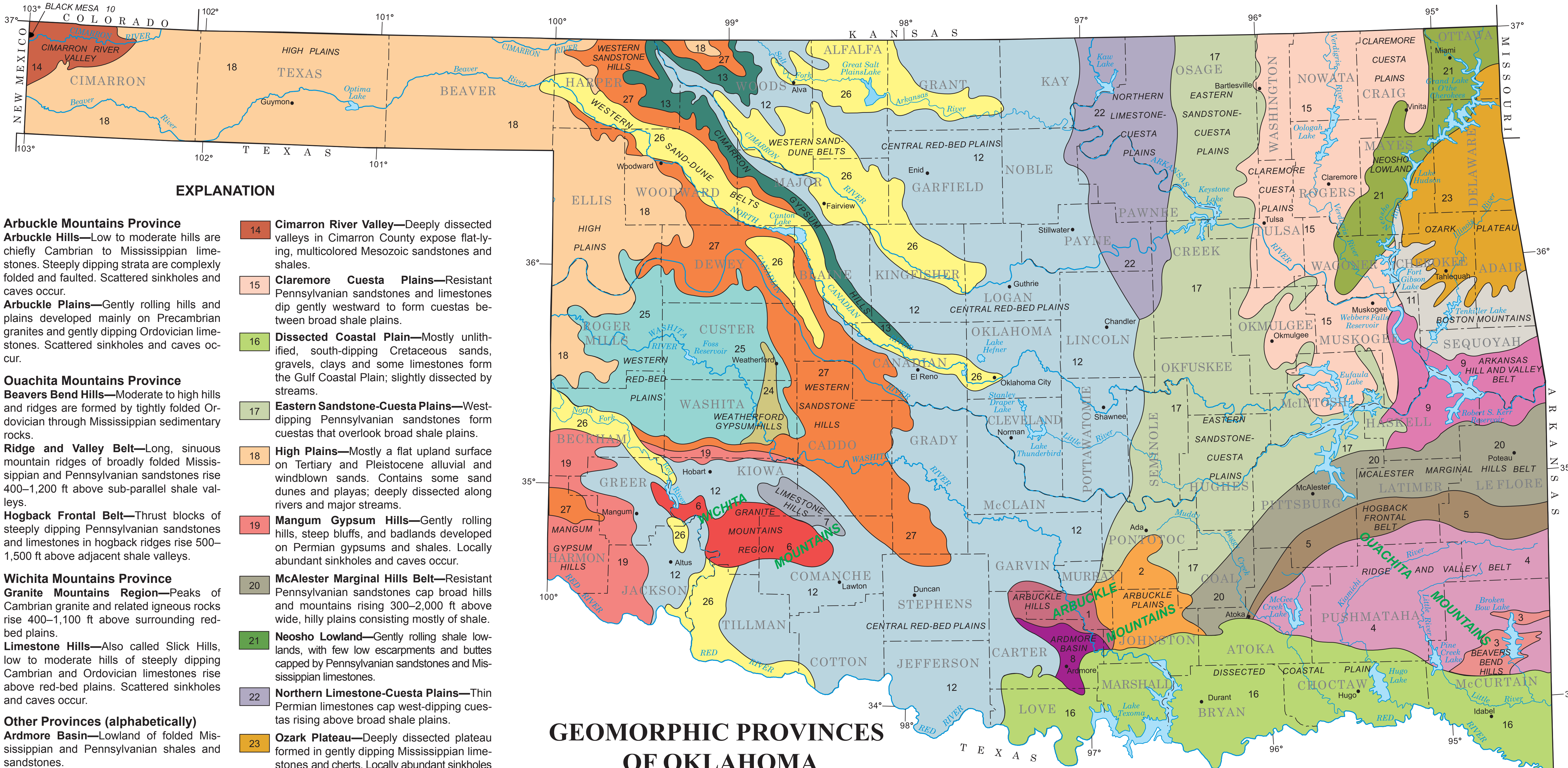
GEOLOGIC CROSS SECTIONS OF OKLAHOMA

Kenneth S. Johnson, Oklahoma Geological Survey

These cross sections show the subsurface configuration of rock units in Oklahoma, depicting the roots of mountain systems and the great depths of major sedimentary basins (Fig. 19). Data from the many petroleum wells drilled deep below the land surface (Oklahoma has more than 460,000 petroleum test holes) helped to create the cross sections.

By collecting and studying the drill cuttings, cores, and logs from petroleum tests, water wells, and mineral-exploration tests, and then integrating all these data with geologic mapping and geophysical studies, geologists can determine thickness, depth, and character of subsurface rock formations in most of Oklahoma. With these data, geologists then can do the following: (1) more precisely unravel the complex and exciting geologic history of Oklahoma; (2) more accurately assess location, quality, and quantity of Oklahoma's petroleum, mineral, and water resources; and (3) more effectively identify and attempt to remedy natural geohazards, such as earthquakes, flood-prone areas, sinkholes, landslides, and expanding soils, and man-induced conditions such as groundwater contamination, waste disposal, and mine-land subsidence.

Figure 19 (to the left) and the Geologic map of Oklahoma on page 6 show the lines of cross section. The horizontal scales of the cross sections are the same as for the Geologic Map on page 6: vertical exaggeration is 10x.



EXPLANATION

Arbuckle Mountains Province

1 **Arbuckle Hills—**Low to moderate hills are chiefly Cambrian to Mississippian limestones. Steeply dipping strata are complexly folded and faulted. Scattered sinkholes and caves occur.

2 **Arbuckle Plains—**Gently rolling hills and plains developed mainly on Precambrian granites and gently dipping Ordovician limestones. Scattered sinkholes and caves occur.

Ouachita Mountains Province

3 **Beavers Bend Hills—**Moderate to high hills and ridges are formed by tightly folded Ordovician through Mississippian sedimentary rocks.

4 **Ridge and Valley Belt—**Long, sinuous mountain ridges of broadly folded Mississippian and Pennsylvanian sandstones rise 400–1,200 ft above sub-parallel shale valleys.

5 **Hogback Frontal Belt—**Thrust blocks of steeply dipping Pennsylvanian sandstones and limestones in hogback ridges rise 500–1,500 ft above adjacent shale valleys.

Wichita Mountains Province

6 **Granite Mountains Region—**Peaks of Cambrian granite and related igneous rocks rise 400–1,100 ft above surrounding red-bed plains.

7 **Limestone Hills—**Also called Slick Hills, low to moderate hills of steeply dipping Cambrian and Ordovician limestones rise above red-bed plains. Scattered sinkholes and caves occur.

Other Provinces (alphabetically)

8 **Ardmore Basin—**Lowland of folded Mississippian and Pennsylvanian shales and sandstones.

9 **Arkansas Hill and Valley Belt—**Broad, gently rolling plains and valleys with scattered hills, 100–300 ft high, are capped by Pennsylvanian sandstones.

10 **Black Mesa—**Flat-topped erosional remnant of Tertiary basaltic lava flow that was extruded from a volcano in Colorado; the highest point in Oklahoma (elevation, 4,973 ft).

11 **Boston Mountains—**Deeply dissected plateau is capped by gently dipping Pennsylvanian sandstones.

12 **Central Red-Bed Plains—**Permian red shales and sandstones form gently rolling hills and broad, flat plains.

13 **Cimarron Gypsum Hills—**Escarpments and badlands developed on Permian gypsums and shales. Locally abundant sinkholes and caves occur.

14 **Cimarron River Valley—**Deeply dissected valleys in Cimarron County expose flat-lying, multicolored Mesozoic sandstones and shales.

15 **Claremore Cuesta Plains—**Resistant Pennsylvanian sandstones and limestones dip gently westward to form cuestas between broad shale plains.

16 **Dissected Coastal Plain—**Mostly unlithified, south-dipping Cretaceous sands, gravels, clays and some limestones form the Gulf Coastal Plain; slightly dissected by streams.

17 **Eastern Sandstone-Cuesta Plains—**Westdipping Pennsylvanian sandstones form cuestas that overlook broad shale plains.

18 **High Plains—**Mostly a flat upland surface on Tertiary and Pleistocene alluvial and windblown sands. Contains some sand dunes and playas; deeply dissected along rivers and major streams.

19 **Mangum Gypsum Hills—**Gently rolling hills, steep bluffs, and badlands developed on Permian gypsums and shales. Locally abundant sinkholes and caves occur.

20 **McAlester Marginal Hills Belt—**Resistant Pennsylvanian sandstones cap broad hills and mountains rising 300–2,000 ft above wide, hilly plains consisting mostly of shale.

21 **Neosho Lowland—**Gently rolling shale lowlands, with few low escarpments and buttes capped by Pennsylvanian sandstones and Mississippian limestones.

22 **Northern Limestone-Cuesta Plains—**Thin Permian limestones cap west-dipping cuestas rising above broad shale plains.

23 **Ozark Plateau—**Deeply dissected plateau formed in gently dipping Mississippian limestones and cherts. Locally abundant sinkholes and caves occur.

24 **Weatherford Gypsum Hills—**Gently rolling hills occur in massive Permian gypsum beds, 100 ft thick. Locally abundant sinkholes and caves occur.

25 **Western Red-Bed Plains—**Gently rolling hills of nearly flat-lying Permian red sandstones and shales.

26 **Western Sand-Dune Belts—**Hummocky fields of grass-covered, stabilized sand dunes and some active dunes, occur mainly on north sides of major rivers. Sand is from Quaternary alluvium and terrace deposits.

27 **Western Sandstone Hills—**Slightly lithified, nearly flat-lying Permian red sandstones form gently rolling hills cut by steep-walled canyons.

GEOMORPHIC PROVINCES OF OKLAHOMA

Neville M. Curtis, Jr., William E. Ham, and
Kenneth S. Johnson, Oklahoma Geological Survey

A geomorphic province is part of the Earth's surface where a suite of rocks with similar geologic character and structure underwent a similar geologic history, and where the present-day character and landforms differ significantly from adjacent provinces. The term used here is the same as "physiographic province."

Most outcrops in Oklahoma consist of horizontal or gently dipping sandstones, sands, and shales of Pennsylvanian, Permian, Cretaceous, and Tertiary ages (see Geologic Map of Oklahoma on page 6). Some sandstones (mainly in eastern Oklahoma) are well indurated (cemented), but in most other parts of Oklahoma they are not so well indurated and erode easily; therefore, much of Oklahoma is gently rolling hills and broad, flat plains. Elsewhere, erosion-resistant layers of sandstone, limestone, or gypsum form protective caps on buttes, cuestas, escarpments, and high hills.

Among the more impressive geomorphic provinces are several mountain belts and uplifts in southern and northeastern Oklahoma. In the southern third of Oklahoma, well-indurated rocks were folded, faulted, and uplifted forming the Wichita, Arbuckle, and Ouachita Mountains. The mountains and high hills, the resistant rock units, and the complex geology of these three provinces contrast sharply with Oklahoma's typical rolling hills and broad plains. In hilly, wooded areas of the Ozark Plateau and Boston Mountains in northeastern Oklahoma, streams and rivers created sharp relief locally by cutting down into resistant limestones and sandstones.

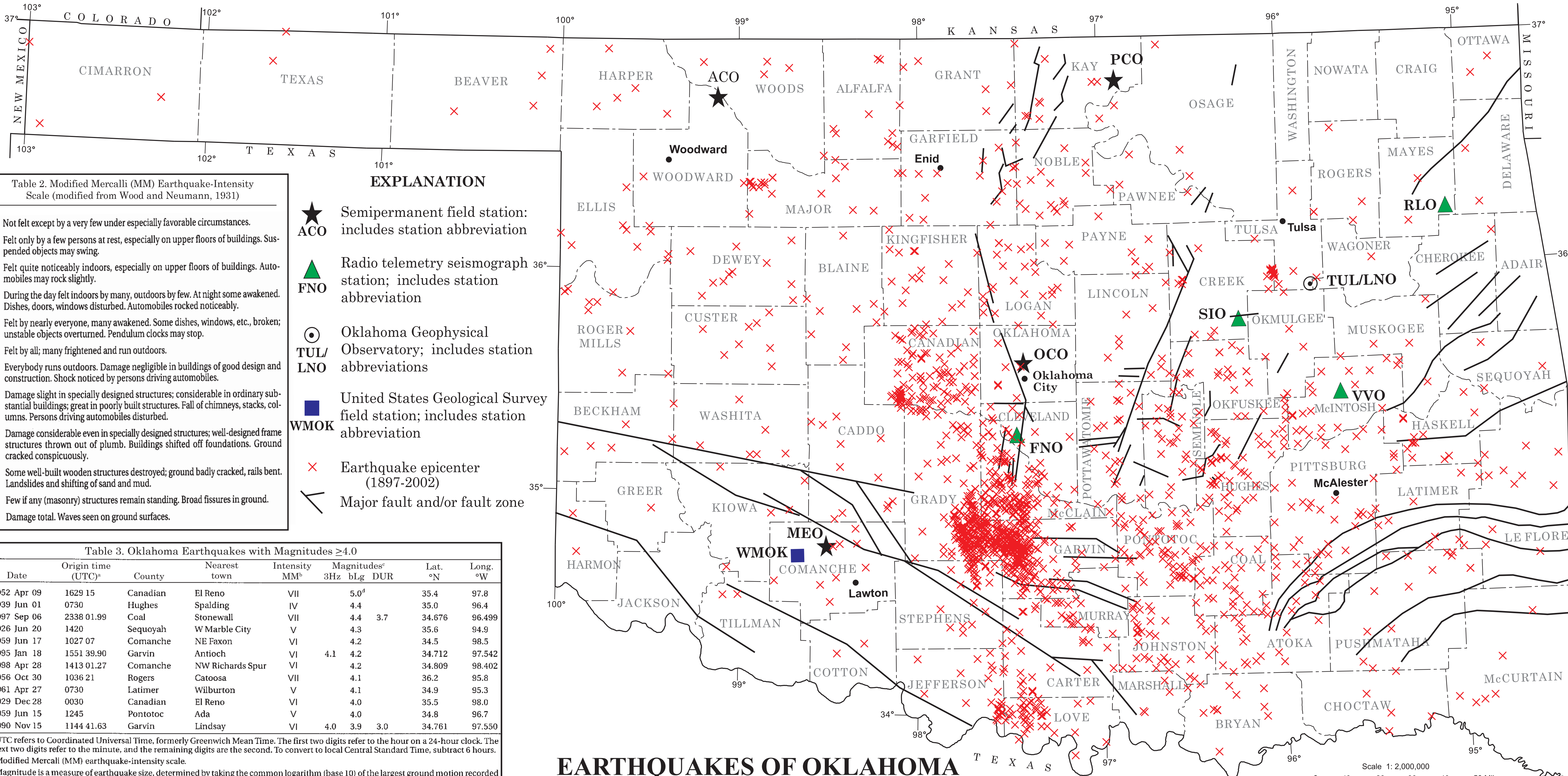


Table 2. Modified Mercalli (MM) Earthquake-Intensity Scale (modified from Wood and Neumann, 1931)	
I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Suspended objects may swing.
III	Felt quite noticeably 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.

Table 3. Oklahoma Earthquakes with Magnitudes ≥4.0

Date	Origin time (UTC)[a]	County	Nearest town	Intensity MM[b]	Magnitudes[c] 3Hz	bLg	DUR	Lat. °N	Long. °W
1952 Apr 09	1629 15	Canadian	El Reno	VII		5.0[d]		35.4	97.8
1939 Jun 01	0730	Hughes	Spalding	IV		4.4		35.0	96.4
1997 Sep 06	2338 01.99	Coal	Stonewall	VII		4.4	3.7	34.676	96.499
1926 Jun 20	1420	Sequoyah	W Marble City	V		4.3		35.6	94.9
1959 Jun 17	1027 07	Comanche	NE Faxon	VI		4.2		34.5	98.5
1995 Jan 18	1551 39.90	Garvin	Antioch	VI	4.1	4.2		34.712	97.542
1998 Apr 28	1413 01.27	Comanche	NW Richards Spur	VI		4.2		34.809	98.402
1956 Oct 30	1036 21	Rogers	Catoosa	VII		4.1		36.2	95.8
1961 Apr 27	0730	Latimer	Wilburton	V		4.1		34.9	95.3
1929 Dec 28	0030	Canadian	El Reno	VI		4.0		35.5	98.0
1959 Jun 15	1245	Pontotoc	Ada	V		4.0		34.8	96.7
1990 Nov 15	1144 41.63	Garvin	Lindsay	VI	4.0	3.9	3.0	34.761	97.550

[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 6 hours.
[b]Modified Mercali (MM) earthquake-intensity scale.
[c]Magnitude is a measure of earthquake size, determined by taking the common 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. Three magnitude types—mbLg (similar to Richter magnitude), m3Hz, and mDUR—are used by the OGS to determine the size of Oklahoma earthquakes (Lawson and Luza, 1995).
[d]The El Reno earthquake had a Gutenberg-Richter magnitude (mb) of 5.5.

EARTHQUAKES OF OKLAHOMA

Kenneth V. Luza, Oklahoma Geological Survey

In Oklahoma, ground motion due to earthquakes is recorded at 10 widely separated locations. The main recording and research facility, station TUL, is near Leonard, Oklahoma, in Tulsa County. About 50 minor earthquakes are located in Oklahoma each year, but only one or two typically are felt. Before 1962, only 59 Oklahoma earthquakes were known either from historical accounts or from seismograph stations in other states. The first seismographs were installed in 1961. From 1962 through 1976, 70 earthquakes were added to the earthquake data base. By 1977, 9 seismograph stations throughout Oklahoma were detecting and locating earthquakes. Over 1,550 earthquakes were located in Oklahoma from 1977 through 2002.

Earthquake Size

The most common ways to express the size of earthquakes are by their intensity and magnitude. The intensity, reported on the Modified Mercalli (MM) Scale, is a subjective measure based on eyewitness accounts (Table 2). Intensities are rated on a 12-level scale ranging from barely perceptible (I) to total destruction (XII). The scale is used to evaluate the size of historical earthquakes. Earthquake magnitude is related to the seismic energy released at the hypocenter, and based on the amplitude of earthquake waves recorded on instruments that have a common calibration. To determine the size of earthquakes, the Oklahoma Geological Survey uses three magnitude types: mbLg (similar to Richter magnitude), m3Hz, and mDUR (Lawson and Luza, 1995).

Historical Earthquakes

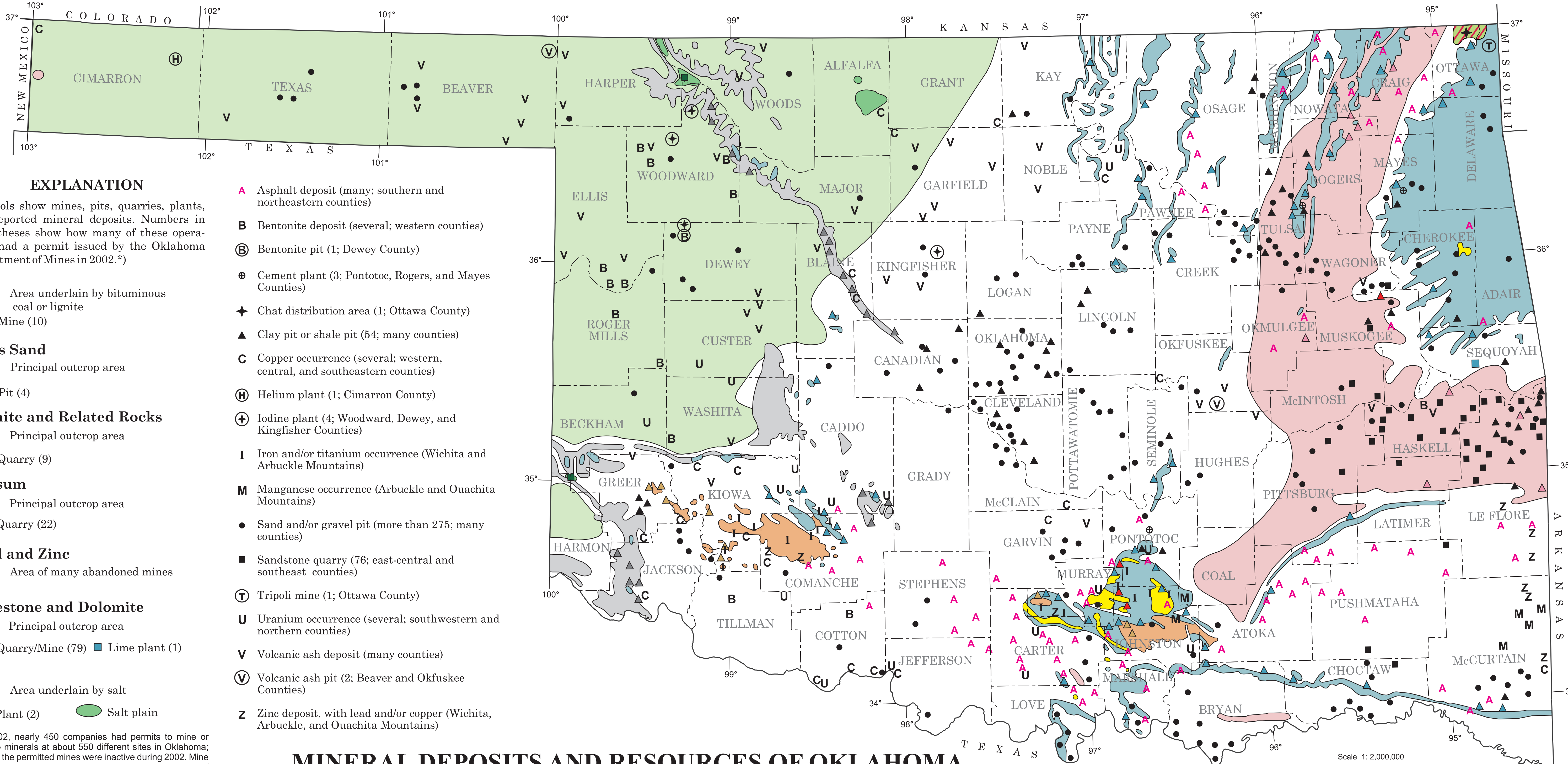
The New Madrid, Missouri, earthquakes of 1811 and 1812 probably are the earliest historical earthquake tremors felt in present-day southeast Oklahoma. Prior to statehood, the earliest documented earthquake epicenter in Oklahoma was on October 22, 1882. The earthquake, although it cannot be located precisely, produced MM VIII intensity effects near Fort Gibson, Indian Territory. The earliest documented locatable earthquake occurred near Jefferson in Grant County on December 2, 1897 (Stover and others, 1981).

On April 9, 1952, the largest known Oklahoma earthquake (with the possible exception of the 1882 Fort Gibson earthquake) occurred near El Reno in Canadian County (Table 3). The magnitude-5.5 earthquake caused a 50-ft-long crack in the State Capitol Office Building in Oklahoma City, and was also felt in Austin, Texas, and Des Moines, Iowa. The earthquake was felt in an area of 140,000 square miles, and produced MM VII–IX intensity effects near the epicenter.

Earthquake Distribution

Typical Oklahoma earthquake magnitudes range from 1.8 to 2.5, with shallow focal depths (less than 3 miles). Earthquakes have occurred in 72 Oklahoma counties; Washington, Nowata, Craig, Adair, and Jackson Counties have had no known earthquakes. Over 880 earthquake events have occurred in the Anadarko Basin since 1897. The majority are concentrated in a 25- by 37-mile area nearly parallel to a deep, subsurface fault zone in west McClain and Garvin Counties and southeast Grady County. Over 90% of the earthquakes in this zone have occurred since 1977. The apparent increase in seismic activity is due, in part, to improved earthquake detection. Only a few earthquakes have occurred in the shelf and deeper portions of the basin.

Before 1976, over half of Oklahoma earthquakes were located in Canadian County; most occurred in the El Reno vicinity, which also is the site of numerous earthquakes since 1908. Canadian County still experiences small-magnitude earthquakes each year. Another principal area of seismic activity is in Love, Carter, and Jefferson Counties. The first reported earthquake there occurred in 1974; several small earthquakes have been felt in the region since then. The Arkoma Basin in southeast Oklahoma is also seismically active. About 90% of all earthquakes there were located with seismometers. Typical magnitudes are less than 2.5.



EXPLANATION

(Symbols show mines, pits, quarries, plants, and reported mineral deposits. Numbers in parentheses show how many of these operations had a permit issued by the Oklahoma Department of Mines in 2002.*)

Coal
- Area underlain by bituminous coal or lignite
- Mine (10)

Glass Sand
- Principal outcrop area
- Pit (4)

Granite and Related Rocks
- Principal outcrop area
- Quarry (9)

Gypsum
- Principal outcrop area
- Quarry (22)

Lead and Zinc
- Area of many abandoned mines

Limestone and Dolomite
- Principal outcrop area
- Quarry/Mine (79) Lime plant (1)

Salt
- Area underlain by salt
- Plant (2) Salt plain

* In 2002, nearly 450 companies had permits to mine or produce minerals at about 550 different sites in Oklahoma; some of the permitted mines were inactive during 2002. Mine symbols on the map may represent more than one mine site, if two or more sites are close together. Annual reports and data on mining permits are available from the Oklahoma Department of Mines.

- A Asphalt deposit (many; southern and northeastern counties)
- B Bentonite deposit (several; western counties)
- (B) Bentonite pit (1; Dewey County)
- ⊕ Cement plant (3; Pontotoc, Rogers, and Mayes Counties)
- ✦ Chat distribution area (1; Ottawa County)
- ▲ Clay pit or shale pit (54; many counties)
- C Copper occurrence (several; western, central, and southeastern counties)
- (H) Helium plant (1; Cimarron County)
- (+) Iodine plant (4; Woodward, Dewey, and Kingfisher Counties)
- I Iron and/or titanium occurrence (Wichita and Arbuckle Mountains)
- M Manganese occurrence (Arbuckle and Ouachita Mountains)
- ● Sand and/or gravel pit (more than 275; many counties)
- ■ Sandstone quarry (76; east-central and southeast counties)
- (T) Tripoli mine (1; Ottawa County)
- U Uranium occurrence (several; southwestern and northern counties)
- V Volcanic ash deposit (many counties)
- (V) Volcanic ash pit (2; Beaver and Okfuskee Counties)
- Z Zinc deposit, with lead and/or copper (Wichita, Arbuckle, and Ouachita Mountains)

MINERAL DEPOSITS AND RESOURCES OF OKLAHOMA

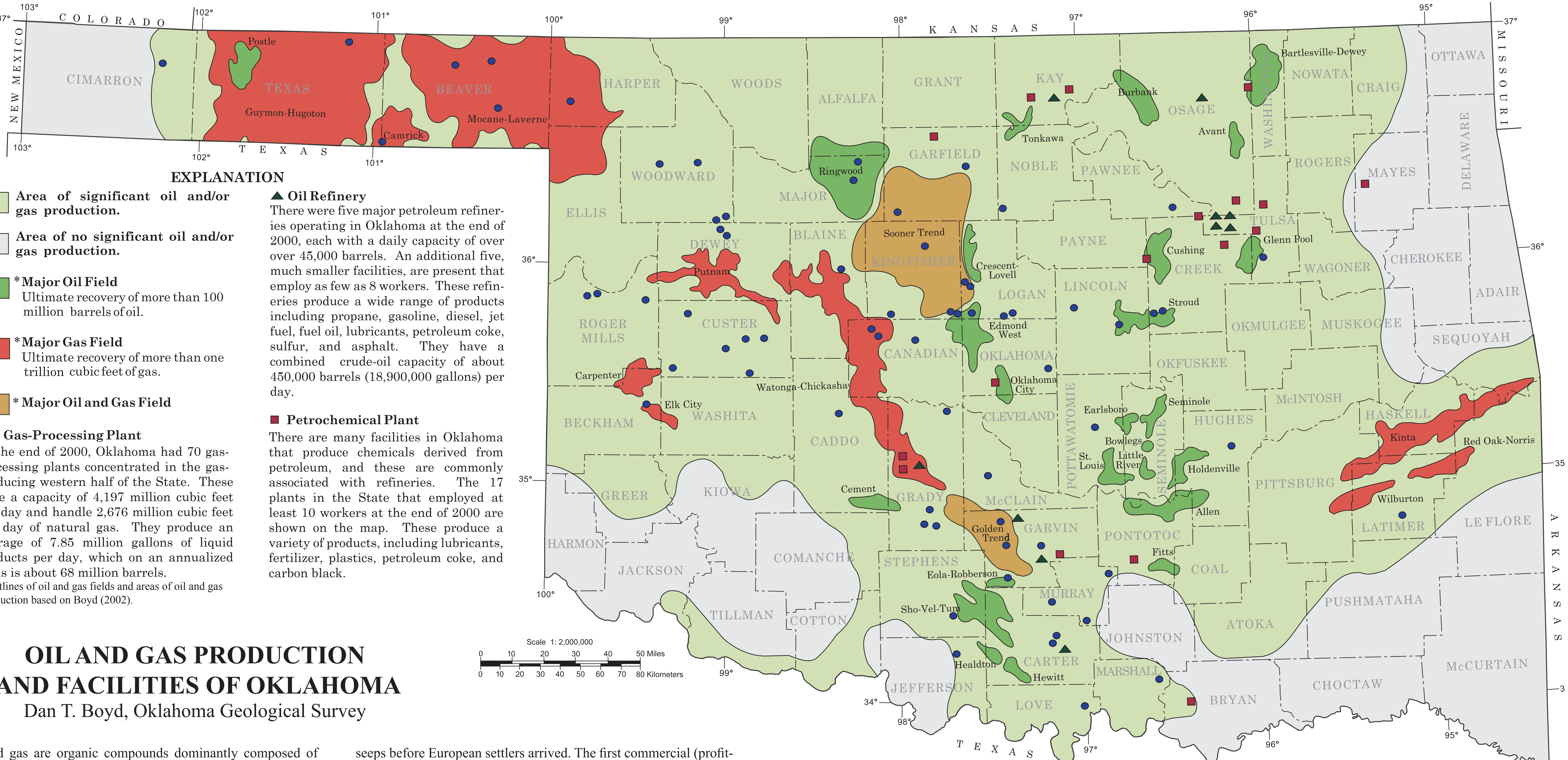
(Exclusive of Oil and Gas) Kenneth S. Johnson, Oklahoma Geological Survey

Oklahoma's mineral resources, produced in all 77 counties, include: nonfuel minerals such as limestone, gypsum, salt, clays, iodine, and sand and gravel; coal; and petroleum (crude oil and natural gas). In recent years, the mineral industry has been the State's greatest source of revenue. In 2004, the combined value of petroleum, coal, and nonfuel minerals produced in Oklahoma was about $12 billion; it reached a high of nearly $13 billion in 1982 and 1984. Total production of all minerals since statehood (1907) is valued at $231 billion.

Although Oklahoma petroleum production accounts for about 95% of Oklahoma's annual mineral output, nonfuel minerals and coal represent a significant part of the State's current economy and an important source of future wealth. The total estimated value of nonfuel-mineral and coal production in Oklahoma during 2004 was $558 million. Leading commodities produced during 2004 were crushed stone (valued at $195 million), portland cement (production data withheld), construction sand and gravel ($54 million), coal ($51 million), industrial sand and gravel ($32 million), gypsum ($21 million), and iodine ($16 million). Other commodities now produced in Oklahoma, or for which there are current mining permits, include clays and shale, salt, lime, granite, rhyolite, dolomite, sandstone, volcanic ash, and tripoli. Deposits and resources that are not mined now, or with no current mining permits, include asphalt, lead, zinc, copper, iron, manganese, titanium, and uranium. Oklahoma ranked first in U.S. production of gypsum and iodine (Oklahoma is the only producer of iodine in the U.S.); second in tripoli production; fourth in feldspar; seventh in common clays produced; and eighth in industrial sand and gravel.

Important reserves of certain high-purity minerals suitable as raw materials for manufacture of various chemicals include high-calcium limestone, high-purity dolomite, and glass sand in south-central and eastern parts of Oklahoma; gypsum and salt are widespread in western Oklahoma. Under proper economic conditions, the abundance and purity of these minerals would enable the manufacture of caustic soda, soda ash, chlorine, sulfur, sulfuric acid, lime, sodium silicate, and other chemicals. Oil, natural gas, and water, which are needed to manufacture these products, are plentiful in most of Oklahoma, and bituminous coal is abundant in eastern Oklahoma.

Historically, lead, zinc, and copper were very important to the economy of Oklahoma, although metals are no longer produced. The Miami-Picher area of Ottawa County was a center for lead-zinc production in the world-famous Tri-State Mining District of northeastern Oklahoma, southeastern Kansas, and southwestern Missouri. Ottawa County's underground mines produced approximately 1.3 million tons of lead and 5.2 million tons of zinc between 1891 and 1970, when the last mine was closed. Oklahoma led the nation in zinc production almost every year from 1918 through 1945. In the southwest corner of the State, near Altus (Jackson County), a surface copper mine produced approximately 1.88 million tons of ore between 1964 and 1975. A decline in copper prices and an increase in production costs caused the mine to close.



EXPLANATION

Area of significant oil and/or gas production.

Area of no significant oil and/or gas production.

***Major Oil Field**
Ultimate recovery of more than 100 million barrels of oil.

***Major Gas Field**
Ultimate recovery of more than one trillion cubic feet of gas.

*** Major Oil and Gas Field**

Gas-Processing Plant
At the end of 2000, Oklahoma had 70 gas-processing plants concentrated in the gas-producing western half of the State. These have a capacity of 4,197 million cubic feet per day and handle 2,676 million cubic feet per day of natural gas. They produce an average of 7.85 million gallons of liquid products per day, which on an annualized basis is about 68 million barrels.

*Outlines of oil and gas fields and areas of oil and gas production based on Boyd (2002).

Oil Refinery
There were five major petroleum refineries operating in Oklahoma at the end of 2000, each with a daily capacity of over over 45,000 barrels. An additional five, much smaller facilities, are present that employ as few as 8 workers. These refineries produce a wide range of products including propane, gasoline, diesel, jet fuel, fuel oil, lubricants, petroleum coke, sulfur, and asphalt. They have a combined crude-oil capacity of about 450,000 barrels (18,900,000 gallons) per day.

Petrochemical Plant
There are many facilities in Oklahoma that produce chemicals derived from petroleum, and these are commonly associated with refineries. The 17 plants in the State that employed at least 10 workers at the end of 2000 are shown on the map. These produce a variety of products, including lubricants, fertilizer, plastics, petroleum coke, and carbon black.

OIL AND GAS PRODUCTION AND FACILITIES OF OKLAHOMA

Dan T. Boyd, Oklahoma Geological Survey

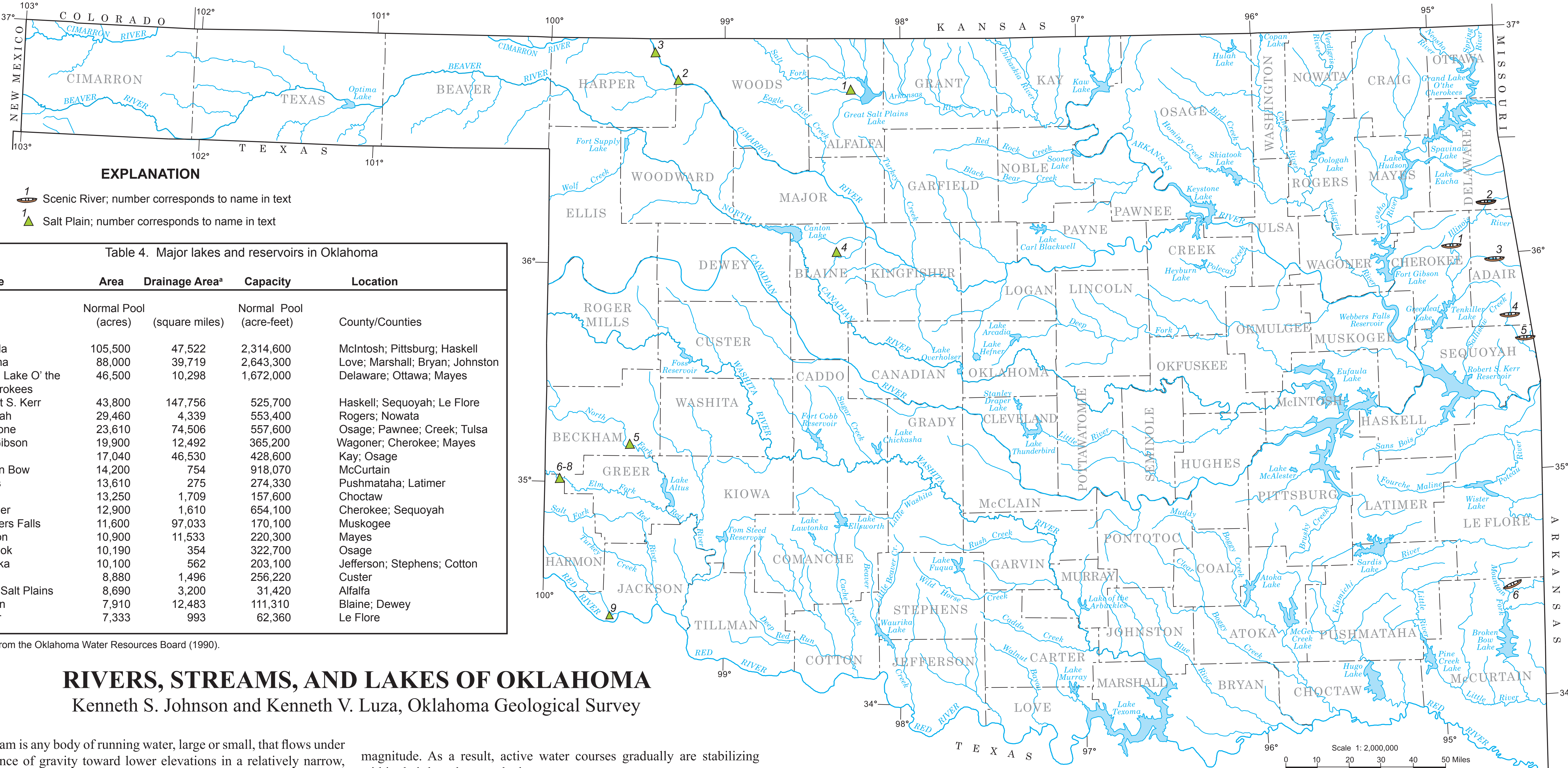
Oil and gas are organic compounds dominantly composed of hydrogen and carbon, hence the name "hydrocarbons." They form from microscopic organisms, deposited with sediments that later become sedimentary rocks after deep burial in a geologic basin. Temperature and pressure increase with depth of burial, and over geologic time the organic remains convert to oil and gas through thermal alteration. The oil and gas migrate from fine-grained source rocks into coarser, more permeable rocks. Because oil and gas are buoyant, they migrate upward until impermeable rocks block the path of movement. Such a barrier (seal) blocks further migration; the geometry of the seal is a factor that determines the size of the hydrocarbon trap in which oil and gas accumulate. Most Oklahoma oil and gas production comes from sedimentary basins of Pennsylvanian age (287–320 million years ago). Reservoirs across Oklahoma, however, range from Precambrian (more than 570 million years ago) to Cretaceous (65–146 million years ago).

Native Americans in Oklahoma discovered and used oil from seeps before European settlers arrived. The first commercial (profitable) oil well was drilled in 1896 near Bartlesville, in present-day Washington County. Oil production increased rapidly after 1900, providing the impetus for statehood in 1907. Annual production peaked at 278 million barrels in 1927 with many intermediate highs and lows since then. Statewide production declined continuously since 1984, near the end of the last major drilling boom. Cumulative oil production in Oklahoma is about 14.7 billion barrels, with a 2005 production rate of 167,000 barrels per day. In 2005 the average production rate per oil well in Oklahoma was just more than 2 barrels per day, highlighting the maturity of the industry. Consumption of petroleum products in Oklahoma is about 50% greater than its production of crude oil.

Oklahoma's 2005 annual crude-oil production of about 61 million barrels represents slightly more than 3% of the national output and makes the State the fifth largest crude-oil producer in the country. This production rate represents one-quarter of the 1927 peak. At an average price of $50 per barrel, annual production has a value of more than $3.0 billion. At the end of 2005, the U.S. Department of Energy placed Oklahoma's proved oil reserves at 588 million barrels.

Natural gas, almost always associated with oil, was considered a nuisance or drilling hazard in the early days. Exploration did not target natural gas widely in Oklahoma until the second half of the twentieth century. Cumulative gas production through 2005 is 95.6 trillion cubic feet; annual production peaked in 1990 at about 6.2 billion cubic feet per day. In 2005, production averaged about 4.4 billion cubic feet per day. Oklahoma's natural-gas industry is relatively young. Drilling in Oklahoma, especially for exploration, is dominated now by wells with gas objectives. Gas production is likely to remain strong well into the 21st century. In 2005, annual natural-gas production was about 1.6 trillion cubic feet, about 8% of U.S. production, making Oklahoma the third largest U.S. gas producer. The 2005 production rate is about two-thirds the peak reached in 1990. At a market price of about $5 per thousand cubic feet, the 2005 volume has a value of nearly $8 billion. At the end of 2005, the U.S. Department of Energy reported proved gas reserves in Oklahoma at 17.1 trillion cubic feet. Statewide gas production is about three times consumption.

Data cited here are from records compiled and maintained by the Oklahoma Corporation Commission, the Oklahoma Department of Commerce, and the Energy Information Administration of the U.S. Department of Energy.



EXPLANATION

1 Scenic River; number corresponds to name in text

1 Salt Plain; number corresponds to name in text

Table 4. Major lakes and reservoirs in Oklahoma

Lake	Area	Drainage Area[a]	Capacity	Location
	Normal Pool (acres)	(square miles)	Normal Pool (acre-feet)	County/Counties
Eufaula	105,500	47,522	2,314,600	McIntosh; Pittsburg; Haskell
Texoma	88,000	39,719	2,643,300	Love; Marshall; Bryan; Johnston
Grand Lake O' the Cherokees	46,500	10,298	1,672,000	Delaware; Ottawa; Mayes
Robert S. Kerr	43,800	147,756	525,700	Haskell; Sequoyah; Le Flore
Oologah	29,460	4,339	553,400	Rogers; Nowata
Keystone	23,610	74,506	557,600	Osage; Pawnee; Creek; Tulsa
Fort Gibson	19,900	12,492	365,200	Wagoner; Cherokee; Mayes
Kaw	17,040	46,530	428,600	Kay; Osage
Broken Bow	14,200	754	918,070	McCurtain
Sardis	13,610	275	274,330	Pushmataha; Latimer
Hugo	13,250	1,709	157,600	Choctaw
Tenkiller	12,900	1,610	654,100	Cherokee; Sequoyah
Webbers Falls	11,600	97,033	170,100	Muskogee
Hudson	10,900	11,533	220,300	Mayes
Skiatook	10,190	354	322,700	Osage
Waurika	10,100	562	203,100	Jefferson; Stephens; Cotton
Foss	8,880	1,496	256,220	Custer
Great Salt Plains	8,690	3,200	31,420	Alfalfa
Canton	7,910	12,483	111,310	Blaine; Dewey
Wister	7,333	993	62,360	Le Flore

[a]Data from the Oklahoma Water Resources Board (1990).

RIVERS, STREAMS, AND LAKES OF OKLAHOMA

Kenneth S. Johnson and Kenneth V. Luza, Oklahoma Geological Survey

A stream is any body of running water, large or small, that flows under the influence of gravity toward lower elevations in a relatively narrow, clearly defined channel. Each major drainage system in Oklahoma consists of a principal river, with many smaller tributary rivers, streams, and creeks funneling water to the main course.

The condition and flow rates of Oklahoma streams are temporary in terms of geologic time. Stream positions shift as they cut deeper channels into their banks, while their tributaries erode nearby uplands. Major drainage systems of today were established during the Pleistocene (the last 1.6 million years). Streams flowed across Oklahoma for millions of years before finally carving out today's major drainage basins. The positions of earlier streams are marked now by alluvial deposits remaining as stream terraces, high above the flood plains of today's streams that are eroding deeper into underlying rocks.

All major streams in Oklahoma have broad, sand-filled channels with active water courses occupying a small portion of the river bed or flood plain. These broad, sand-filled channels reflect large changes in discharge (floods) that occur from time to time. Many man-made dams on major streams and tributaries, however, have decreased flooding frequency and magnitude. As a result, active water courses gradually are stabilizing within their broad stream beds.

All Oklahoma streams are within two major drainage basins: the Red River basin, and the Arkansas River basin (see page 14). The two rivers and their many tributaries flow into Oklahoma from neighboring states, while all surface water from Oklahoma flows into Arkansas, via the Red, Arkansas, and Little Rivers, and Lee Creek. Major rivers and tributaries flow mainly east and southeast across Oklahoma.

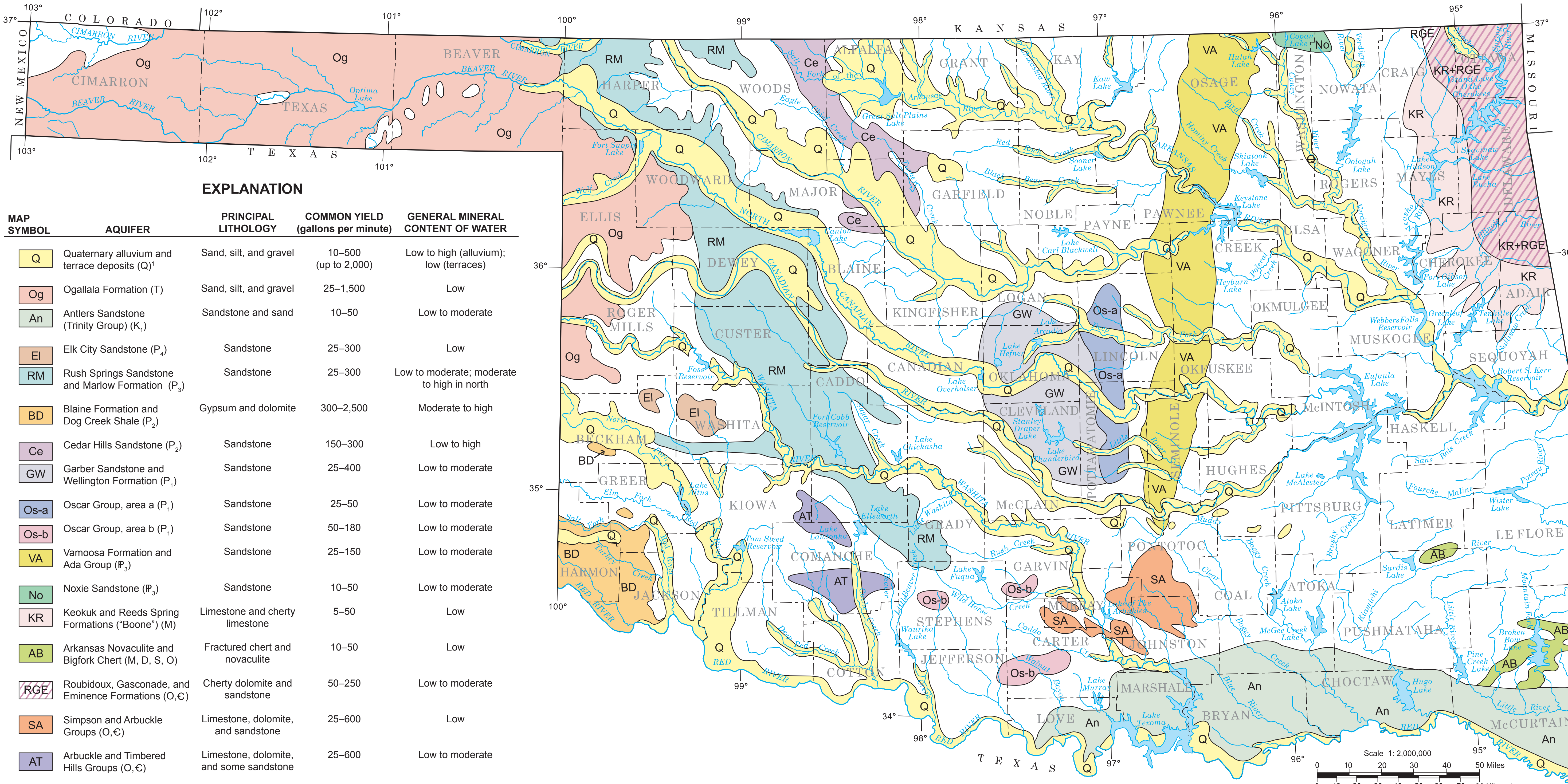
Six scenic rivers flow in eastern Oklahoma and several natural salt plains and saline rivers are present in the west. Five scenic rivers in the Arkansas River drainage are in Adair, Cherokee, Delaware, and Sequoyah Counties in the Ozark Plateau. They include parts of the Illinois River (1, see map), and Flint (2), Baron Fork (3), Little Lee (4), and Lee (5) Creeks. The upper part of Mountain Fork (6), which flows into Broken Bow Lake in the Ouachita Mountains in McCurtain County, is in the Red River drainage.

Natural salt plains occur along some rivers where natural brines seep to the surface. In the Arkansas River drainage, Great Salt Plains (1) on Salt Fork is the largest salt flat covering about 25 square miles. Others in northwestern Oklahoma are Big Salt Plain (2) and Little Salt Plain (3) on the Cimarron River, and Ferguson Salt Plain (4) in Blaine County. Salt plains in the Red River drainage are Boggy Creek Salt Plain (5) on North Fork Red River; Kiser (6), Robinson (7), and Chaney (Salton) (8) Salt Plains on Elm Fork in north Harmon County; and Jackson County Salt Plain (9). Downstream in both drainage basins, fresh-water inflow dilutes saline river waters, making the water usable for municipalities, livestock, and industrial purposes before reaching Keystone Lake or Lake Texoma.

There are many lakes and reservoirs in Oklahoma; most are man-made, created by damming streams for flood control, water supply, recreation, fish, wildlife, and hydroelectric power. Lakes on the Arkansas and Verdigris Rivers aid in navigation along the McClellan-Kerr Navigation System. Major lakes are formed behind dams built by the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and the Grand River Dam Authority. Various state and federal agencies, cities, and other entities own and operate large lakes. Farmers and landowners have built many smaller lakes and ponds. Table 4 lists the 20 Oklahoma lakes with the largest surface areas.

A series of oxbow and playa lakes are the only natural lakes in Oklahoma (Oklahoma Water Resources Board, 1990). Typically crescent-shaped, oxbow lakes occupy abandoned channels of meandering streams and occur mainly in flood plains of the Red, Arkansas, Washita, North Canadian, and Verdigris Rivers in central and eastern Oklahoma. Oklahoma has 62 oxbow lakes covering at least 10 acres each; the largest, near Red River in McCurtain County, covers 272 acres (Oklahoma Water Resources Board, 1990).

Playa lakes form in shallow, saucer-like depressions scattered across the semiarid High Plains in northwestern Oklahoma and the Panhandle. Playa lakes have no outflow, holding water during and after rainy seasons before evaporating, or losing water by infiltrating into the ground. Oklahoma has about 600 of these intermittent or ephemeral playa lakes, but only a few persist year-round (Oklahoma Water Resources Board, 1990).



EXPLANATION

MAP SYMBOL	AQUIFER	PRINCIPAL LITHOLOGY	COMMON YIELD (gallons per minute)	GENERAL MINERAL CONTENT OF WATER
Q	Quaternary alluvium and terrace deposits (Q)[1]	Sand, silt, and gravel	10–500 (up to 2,000)	Low to high (alluvium); low (terraces)
Og	Ogallala Formation (T)	Sand, silt, and gravel	25–1,500	Low
An	Antlers Sandstone (Trinity Group) (K_1)	Sandstone and sand	10–50	Low to moderate
El	Elk City Sandstone (P_4)	Sandstone	25–300	Low
RM	Rush Springs Sandstone and Marlow Formation (P_3)	Sandstone	25–300	Low to moderate; moderate to high in north
BD	Blaine Formation and Dog Creek Shale (P_2)	Gypsum and dolomite	300–2,500	Moderate to high
Ce	Cedar Hills Sandstone (P_2)	Sandstone	150–300	Low to high
GW	Garber Sandstone and Wellington Formation (P_1)	Sandstone	25–400	Low to moderate
Os-a	Oscar Group, area a (P_1)	Sandstone	25–50	Low to moderate
Os-b	Oscar Group, area b (P_1)	Sandstone	50–180	Low to moderate
VA	Vamoosa Formation and Ada Group (₽$_3$)	Sandstone	25–150	Low to moderate
No	Noxie Sandstone (₽$_3$)	Sandstone	10–50	Low to moderate
KR	Keokuk and Reeds Spring Formations ("Boone") (M)	Limestone and cherty limestone	5–50	Low
AB	Arkansas Novaculite and Bigfork Chert (M, D, S, O)	Fractured chert and novaculite	10–50	Low
RGE	Roubidoux, Gasconade, and Eminence Formations (O,Є)	Cherty dolomite and sandstone	50–250	Low to moderate
SA	Simpson and Arbuckle Groups (O,Є)	Limestone, dolomite, and sandstone	25–600	Low
AT	Arbuckle and Timbered Hills Groups (O,Є)	Limestone, dolomite, and some sandstone	25–600	Low to moderate

[1]Symbols in parentheses indicate geologic age, as shown on the Geologic Map of Oklahoma on page 6.

PRINCIPAL GROUND-WATER RESOURCES OF OKLAHOMA

Kenneth S. Johnson, Oklahoma Geological Survey

An "aquifer" consists of rocks and sediments saturated with good- to fair-quality water, and that is sufficiently permeable to yield water from wells at rates greater than 25 gal/min (gallons per minute). This map shows the distribution of the principal aquifers in Oklahoma and was modified from Marcher (1969), Marcher and Bingham (1971), Hart (1974), Bingham and Moore (1975), Carr and Bergman (1976), Havens (1977), Bingham and Bergman (1980), Morton (1981), Marcher and Bergman (1983), and Johnson (1983).

Bedrock aquifers in Oklahoma consist of sandstone, sand, limestone, dolomite, gypsum, or fractured novaculite and chert. Aquifer thicknesses range from 100 ft to several thousand feet. Depth to fresh water ranges from a few feet to more than 1,000 ft; most wells are 100–400 ft deep. Wells in these aquifers yield 25–300 gal/min, although some wells yield as much as 600–2,500 gal/min. Water in most bedrock aquifers has low to moderate mineral content, about 300–1,500 milligrams per liter dissolved solids.

Ground water is also present in Quaternary alluvium and terrace deposits that consist mainly of unconsolidated sand, silt, clay, and gravel. "Alluvium" refers to sediments in present-day stream channels or flood plains, whereas "terrace deposits" refer to older alluvium that remains (usually at an elevation above the present-day flood plain) after a stream shifts its position or cuts a deeper channel. Alluvium and terrace deposits are among the most recent geologic deposits; therefore, they overlie bedrock aquifers where the two are mapped together. The thickness of Quaternary deposits ranges from 10 to 50 ft (locally up to 100 ft). Wells in alluvium and terrace deposits yield 10–500 gal/min of water (locally several thousand gal/min); most of this ground water has less than 1,000 milligrams per liter dissolved solids.

Fresh water stored in Oklahoma aquifers results from the downward movement of meteoric (precipitation) and surface waters that enter each aquifer at its recharge area. Fresh water may displace saline water that originally may have occupied parts of the aquifer. The system is dynamic; water percolating downward to the water table recharges the aquifer continuously. The vertical or horizontal rate of ground-water flow in the aquifers probably ranges from 5 to 100 ft per year; under certain geologic and hydrologic conditions, such as in cavernous or highly fractured rocks, flow can range up to more than 1,000 ft per year.

Large areas of Oklahoma, shown uncolored on the map, are underlain mostly by shale or other low-permeability rocks that typically yield only enough water for household use (about 1–5 gal/min). Highly mineralized (saline) water, unfit for most uses, is present beneath fresh-water zones in these rocks, and beneath fresh-water aquifers. The depth to the top of this saline water ranges from less than 100 ft in some places, up to 3,000 ft in the Arbuckle Mountains.

The Oklahoma Water Resources Board (1990) estimated that Oklahoma's principal aquifers contain 320 million acre-feet of fresh water, perhaps half of which is recoverable for beneficial use. Wells and springs tapping these aquifers currently supply more than 60% of the water used in Oklahoma, chiefly in the west where surface-water is less abundant.

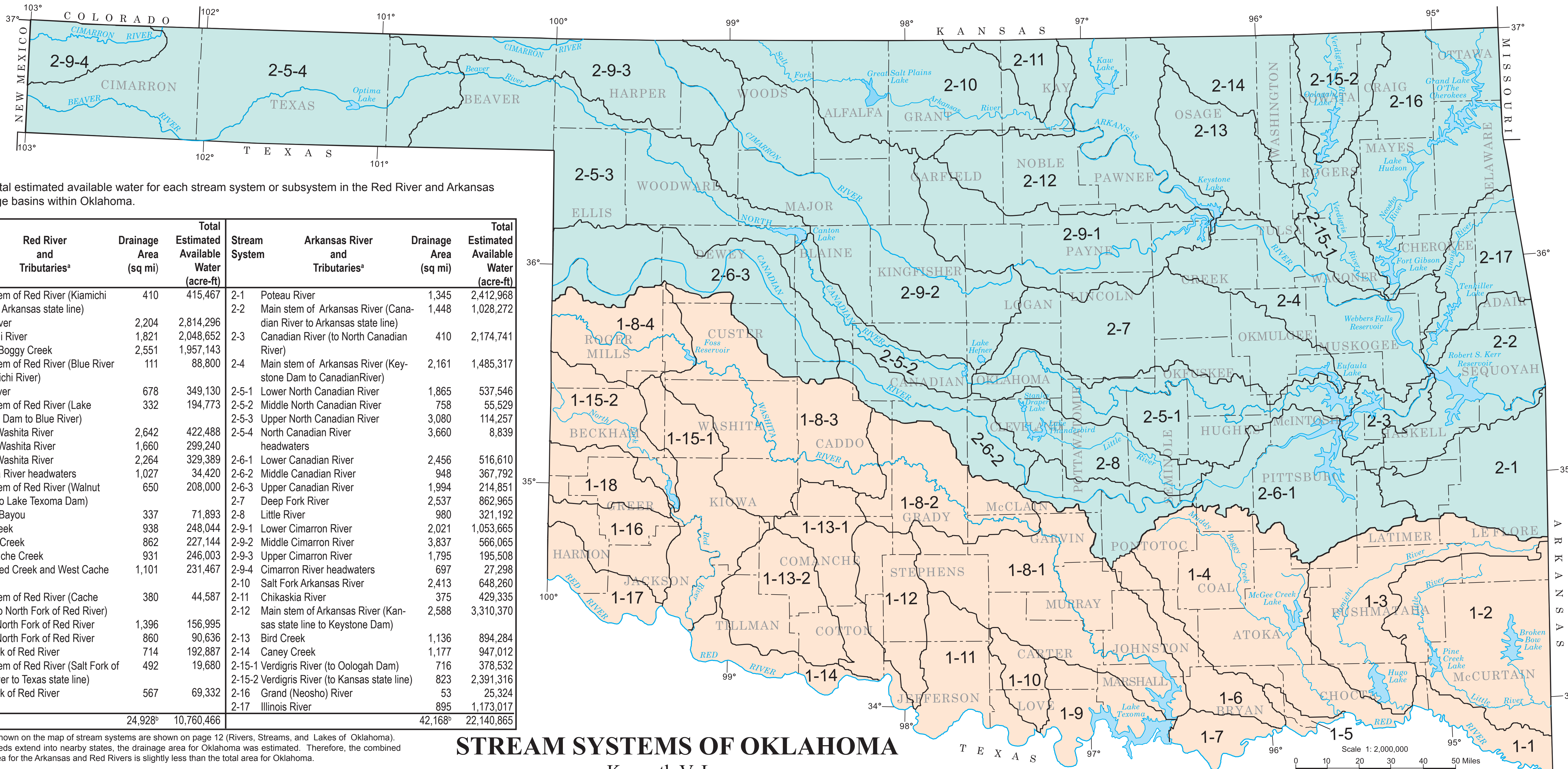


Table 5. Total estimated available water for each stream system or subsystem in the Red River and Arkansas River drainage basins within Oklahoma.

Stream System	Red River and Tributaries[a]	Drainage Area (sq mi)	Total Estimated Available Water (acre-ft)
1-1	Main stem of Red River (Kiamichi River to Arkansas state line)	410	415,467
1-2	Little River	2,204	2,814,296
1-3	Kiamichi River	1,821	2,048,652
1-4	Muddy Boggy Creek	2,551	1,957,143
1-5	Main stem of Red River (Blue River to Kiamichi River)	111	88,800
1-6	Blue River	678	349,130
1-7	Main stem of Red River (Lake Texoma Dam to Blue River)	332	194,773
1-8-1	Lower Washita River	2,642	422,488
1-8-2	Middle Washita River	1,660	299,240
1-8-3	Upper Washita River	2,264	329,389
1-8-4	Washita River headwaters	1,027	34,420
1-9	Main stem of Red River (Walnut Bayou to Lake Texoma Dam)	650	208,000
1-10	Walnut Bayou	337	71,893
1-11	Mud Creek	938	248,044
1-12	Beaver Creek	862	227,144
1-13-1	East Cache Creek	931	246,003
1-13-2	Deep Red Creek and West Cache Creek	1,101	231,467
1-14	Main stem of Red River (Cache Creek to North Fork of Red River)	380	44,587
1-15-1	Lower North Fork of Red River	1,396	156,995
1-15-2	Upper North Fork of Red River	860	90,636
1-16	Salt Fork of Red River	714	192,887
1-17	Main stem of Red River (Salt Fork of Red River to Texas state line)	492	19,680
1-18	Elm Fork of Red River	567	69,332
		24,928[b]	10,760,466

Stream System	Arkansas River and Tributaries[a]	Drainage Area (sq mi)	Total Estimated Available Water (acre-ft)
2-1	Poteau River	1,345	2,412,968
2-2	Main stem of Arkansas River (Canadian River to Arkansas state line)	1,448	1,028,272
2-3	Canadian River (to North Canadian River)	410	2,174,741
2-4	Main stem of Arkansas River (Keystone Dam to CanadianRiver)	2,161	1,485,317
2-5-1	Lower North Canadian River	1,865	537,546
2-5-2	Middle North Canadian River	758	55,529
2-5-3	Upper North Canadian River	3,080	114,257
2-5-4	North Canadian River headwaters	3,660	8,839
2-6-1	Lower Canadian River	2,456	516,610
2-6-2	Middle Canadian River	948	367,792
2-6-3	Upper Canadian River	1,994	214,851
2-7	Deep Fork River	2,537	862,965
2-8	Little River	980	321,192
2-9-1	Lower Cimarron River	2,021	1,053,665
2-9-2	Middle Cimarron River	3,837	566,065
2-9-3	Upper Cimarron River	1,795	195,508
2-9-4	Cimarron River headwaters	697	27,298
2-10	Salt Fork Arkansas River	2,413	648,260
2-11	Chikaskia River	375	429,335
2-12	Main stem of Arkansas River (Kansas state line to Keystone Dam)	2,588	3,310,370
2-13	Bird Creek	1,136	894,284
2-14	Caney Creek	1,177	947,012
2-15-1	Verdigris River (to Oologah Dam)	716	378,532
2-15-2	Verdigris River (to Kansas state line)	823	2,391,316
2-16	Grand (Neosho) River	53	25,324
2-17	Illinois River	895	1,173,017
		42,168[b]	22,140,865

[a]Tributaries not shown on the map of stream systems are shown on page 12 (Rivers, Streams, and Lakes of Oklahoma).
[b] Where watersheds extend into nearby states, the drainage area for Oklahoma was estimated. Therefore, the combined total drainage area for the Arkansas and Red Rivers is slightly less than the total area for Oklahoma.

STREAM SYSTEMS OF OKLAHOMA

Kenneth V. Luza,
Oklahoma Geological Survey

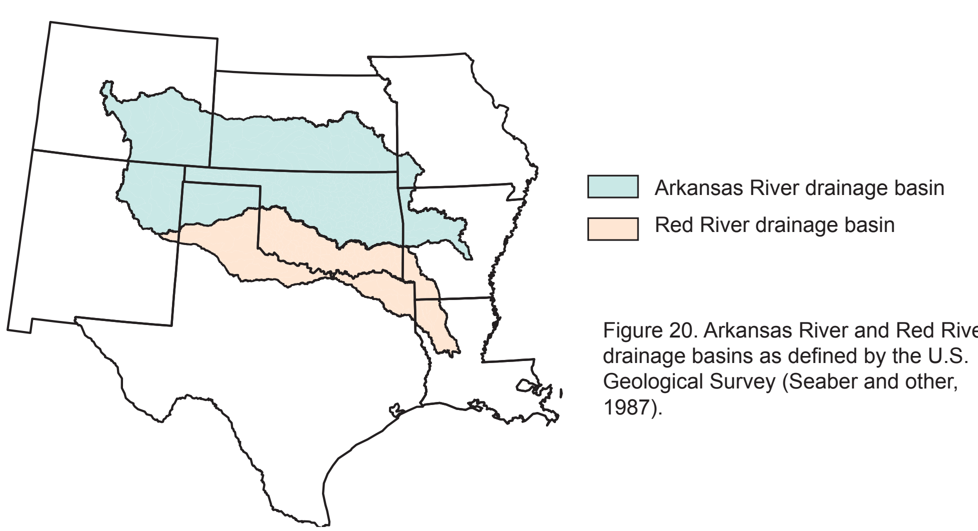


Figure 20. Arkansas River and Red River drainage basins as defined by the U.S. Geological Survey (Seaber and other, 1987).

Oklahoma is within the Red River and Arkansas River basins (Fig. 20); about one-third is within the Red River drainage basin. Two small tributaries in eastern New Mexico join to form the Red River. The Red River flows east through the Texas Panhandle, along the Oklahoma-Texas border, and through Arkansas and Louisiana to its confluence with the Atchafalaya River near the Mississippi River. The Arkansas River originates near Leadville, Colorado, flows east to Great Bend, Kansas, then southeast entering Oklahoma in Kay County, and then flows into Arkansas near Fort Smith before eventually entering the Mississippi River in southeastern Arkansas. The Oklahoma Water Resources Board (OWRB) divides Oklahoma into stream systems and subsystems to manage surface water resources better (Table 5). OWRB matches stream-system boundaries and drainage areas to the hydrologic boundaries developed by the U.S. Geological Survey (U.S. Geological Survey, 1976; Seaber and others, 1987; and Rea and Becker, 1997). The Red River drainage basin in Oklahoma is subdivided into 18 stream systems; three (1-8, 1-13, and 1-15) are divided further into stream subsystems (Varghese, 1998). The Arkansas River basin in Oklahoma is subdivided into 17 stream systems; four (2-5, 2-6, 2-9, and 2-15) are divided further into stream subsystems (Fabian and Kennedy, 1998).

Table 5 summarizes the total estimated available water for each stream system or subsystem. The Red River basin contains about 10,750,000 acre-feet of available water; the Arkansas River basin contains about 22,150,000 acre-feet of available water. The totals must be adjusted by subtracting the sediment pool storage (the portion of a lake or reservoir reserved for sediment accumulation during the lifetime of the impoundment) and the volume of water necessary to accommodate dependable yields in other reservoirs and lakes. Since 1997, the adjusted total estimated available water was 9,450,000 acre-feet for the Red River basin, and 21,350,000 acre-feet for the Arkansas River basin (Fabian and Kennedy, 1998; Varghese, 1998). The adjusted total estimated available water is used to allocate water for municipal, industrial, and agricultural uses.

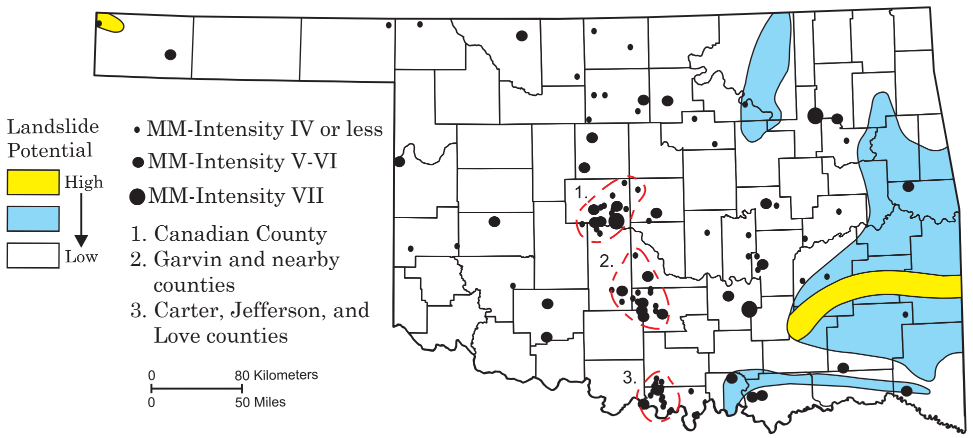


Figure 21. Map of Oklahoma shows felt-earthquake locations (Oklahoma Geological Survey data), seismic areas (numbers and dashed red lines; also see page 9), and landslide potential (modified from Radbruch-Hall and others, 1982).

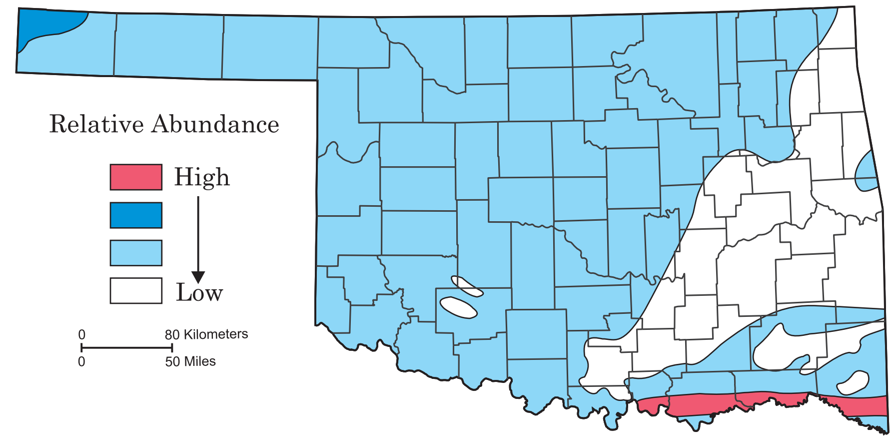


Figure 22. Map shows relative abundance of expansive soils in Oklahoma (modified from Schuster, 1981).

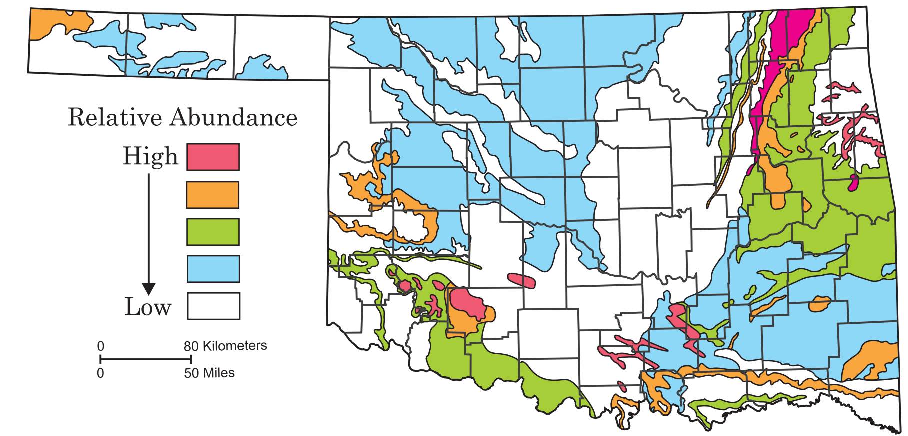


Figure 23. Map shows relative abundance of uranium minerals in Oklahoma capable of generating indoor-radon concentrations in excess of the U.S. Environmental Protection Agency standard (more than 4 picocuries per liter of air) (modified from Flood and others, 1990).

GEOLOGIC HAZARDS IN OKLAHOMA

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Natural Geologic Hazards

Natural geologic hazards are events or processes that have caused, or may cause, hazardous conditions. Some examples in Oklahoma are earthquakes, landslides, expansive soils, radon, floods, and karst/salt dissolution.

Earthquakes—Geologists' ability to detect and accurately locate earthquakes in Oklahoma was greatly improved after a statewide network of seismograph stations was installed (see page 9). The frequency of earthquakes and their possible correlation to specific fault zones are being studied. This information hopefully will provide a data base to use in developing numerical estimates of earthquake risk, including earthquake magnitude, for various parts of Oklahoma. Numerical-risk estimates could lead to better-designed, large-scale structures such as dams, high-rise buildings, and power plants, and to provide information necessary to establish insurance rates.

Earthquakes frequently occur in three principal areas in Oklahoma (Fig. 21), including: Canadian County (1); Garvin and nearby counties (2); and Love, Jefferson, and Carter Counties (3). The southeast part of Oklahoma is another area of low-level earthquake activity.

Landslides—Landslides and slumps are a common highway-construction problem in parts of Oklahoma. Most landslides occur in the eastern one-third of Oklahoma (Hayes, 1971), due to wetter climate (39–59 inches of precipitation per year) and steep slopes associated with mountainous terrain (Fig. 21). In eastern Oklahoma, thick shales weather quickly and produce large quantities of clay-rich colluvium. The colluvium occurs on slopes as a veneer about three feet thick, masking underlying bedrock. The landslide threat is higher where natural slopes exceed a 2:1gradient.

Expansive Soils—Clay-rich shales, or soils from the weathering of shales, may contain smectite clay minerals, such as montmorillonite, that swell up to 1.5 to 2.0 times their original dry volume after adding water. Over 75% of Oklahoma bedrock units are possible sources for expansive soils (Fig. 22). Soil saturation from rainfall, lawn watering, or sewer leakage may cause major damage by soils expanding under sidewalks, highways, utility lines, and foundations. If construction takes place on wet expanded soils, then shrinkage may occur after drying, resulting in severe cracking in structures.

Principal geologic units in Oklahoma having high shrink-swell potential are Cretaceous shales that crop out in southern Oklahoma. Other shales that locally have moderately high shrink-swell potential are several Pennsylvanian units in the east and several Permian units in central Oklahoma.

Radon—Radon is a naturally occurring radioactive gas formed by the radioactive decay of uranium. The generation of indoor-radon concentrations in excess of the U.S. Environmental Protection Agency standard (more than 4 picocuries per liter of air) does not require ore-grade uranium (more than 500 parts per million). Rocks and residual soils with much lower amounts of uranium under favorable conditions can generate above-normal radon levels (Fig. 23).

Uranium is associated with various rock types and geologic environments in Oklahoma. Seven types of uranium occurrences are based on the mode of uranium enrichment and the size, distribution, and geologic continuity of that occurrence: (1) granitic rocks and associated late-stage intrusions (dikes and sills); (2) arkosic sediments (weathered granite detritus); (3) dark, organic-rich shales; (4) phosphatic black shales; (5) lignite and bituminous coal; (6) local point sources; and (7) stratiform deposits (confined to certain Permian stratigraphic units in western and southwestern Oklahoma).

Flood-Prone Areas—Flood plains are areas adjacent to rivers and streams that occasionally flood but are normally dry, sometimes for many years. When storms produce more runoff than a stream can carry in its channel, waters rise and flood adjacent lowlands. Floods can occur at any time in Oklahoma, but major floods are frequent in spring and fall (Tortorelli and others, 1991). Flood-prone areas are identified and mapped by the U.S. Geological Survey (Water Resources Division), the U.S. Army Corps of Engineers, and private contractors for the National Flood Insurance Program administered by the Federal Emergency Management Agency (FEMA). The FEMA program intends to delineate areas that have about 1 chance in 100 on average of being inundated in any particular year (a 100-year-flood frequency). The program uses available information on past floods and, in some places, detailed field surveys and inspections to determine flood frequency. Many early maps of flood-prone areas are being revised, especially where urban development has occurred.

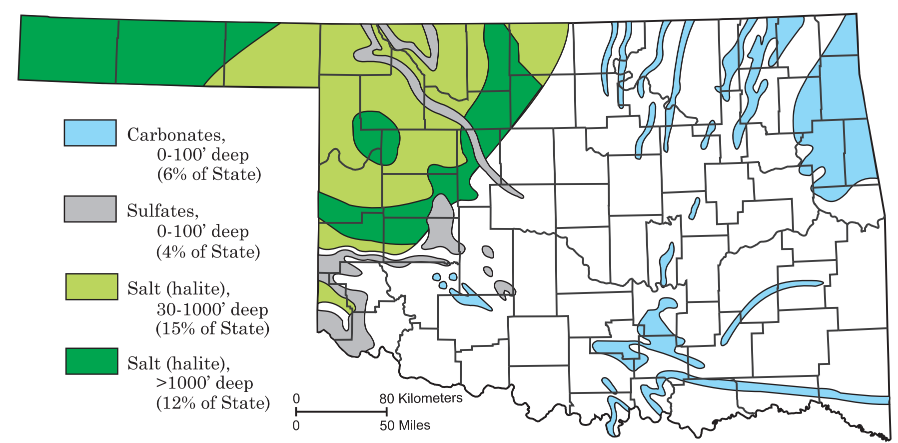


Figure 24. Map shows general distribution of karst terrains in Oklahoma (modified from Johnson and Quinlan, 1995).

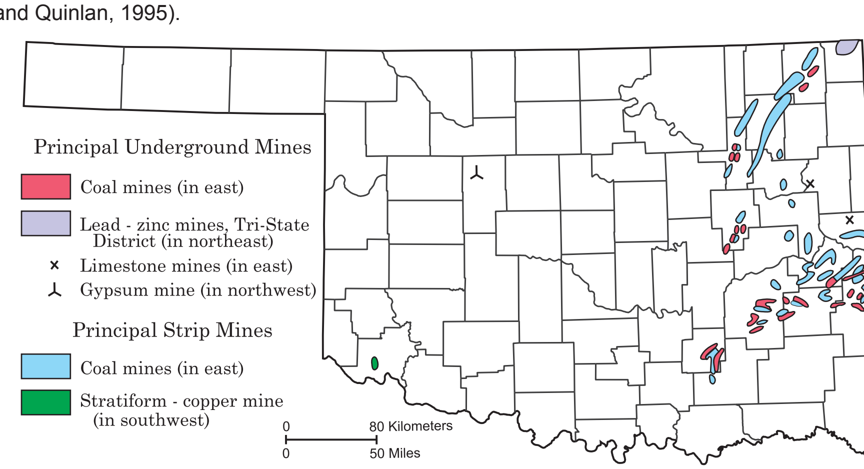


Figure 25. Map shows general locations of principal underground mines and strip mines in Oklahoma (from Johnson, 1974; Friedman, 1979); only coal and copper strip mines are shown.

As of June 2002, FEMA identified over 350 Oklahoma communities and/or counties for participation in the national flood-insurance program. A map-panel index is available for every participating community. One may examine flood-insurance-rate maps at county-clerk offices, city halls, county courthouses, city-engineer offices, or city-planning departments.

Areas of Karst and Salt Dissolution—Where water-soluble rocks (e.g., limestone, dolomite, gypsum, anhydrite, salt) are at or near the surface, karst and dissolution features are prone to develop by the dissolving action of circulating ground water. Resulting sinkholes and caverns are potential hazards if the land surface subsides or collapses into the underground voids. The Ozark Mountains in northeastern Oklahoma, the Arbuckle Mountains in south-central Oklahoma, and the Limestone Hills in southwestern Oklahoma (Fig. 24) are the principal areas where karst features develop in limestone and dolomite. Gypsum and shallow salt deposits can cause karst and dissolution problems in many areas in western Oklahoma.

Limestone, dolomite, gypsum, and anhydrite beds that crop out, or are within 20 ft of the surface, represent the greatest potential for karst development and its associated environmental and engineering problems. Where soluble rocks are 20–100 ft deep there exists less (yet real) potential for karst development and associated problems.

Man-Made Geologic Hazards

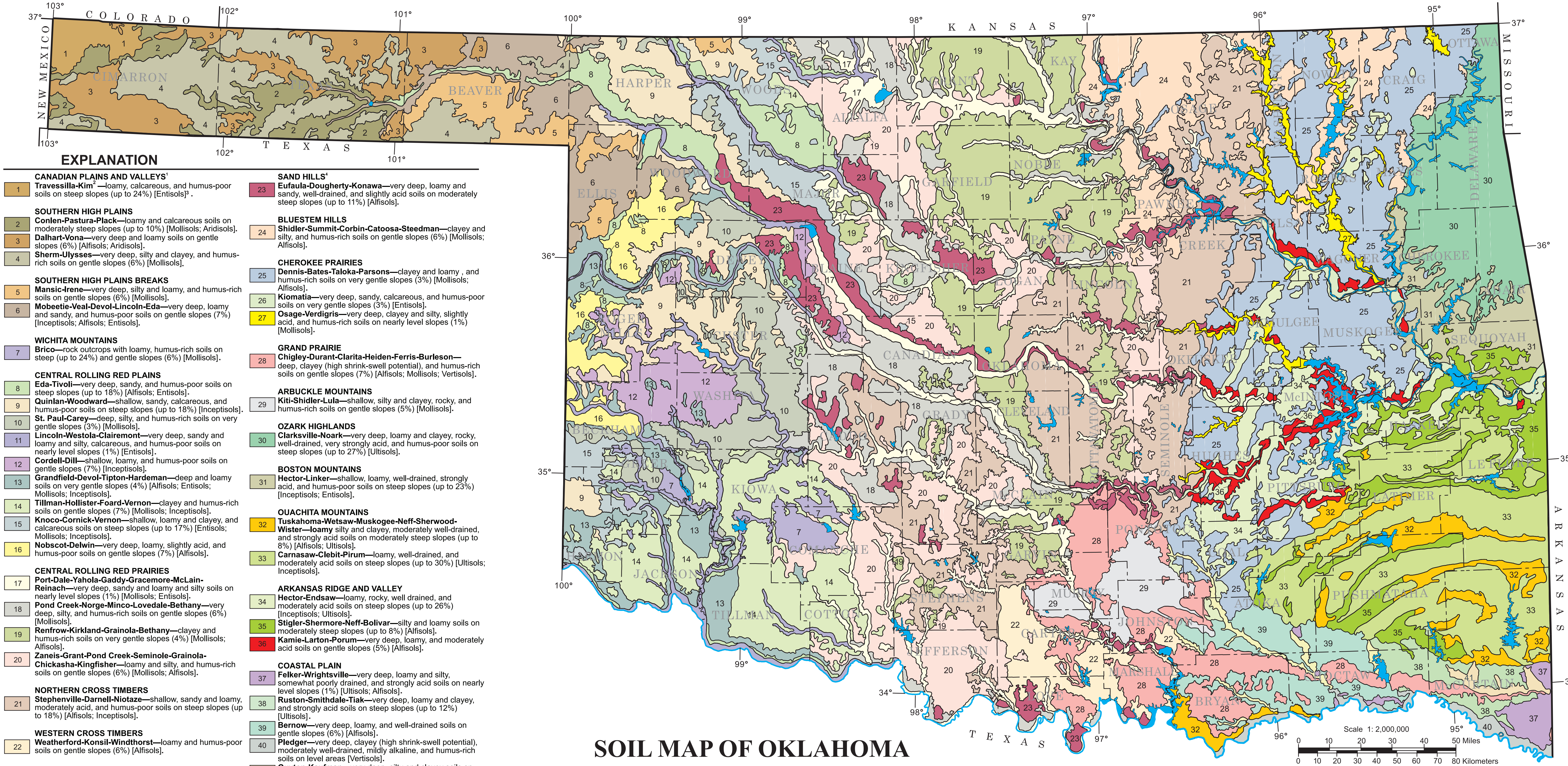
Some human activities that may create present or future geologic hazards in Oklahoma include underground mining, strip mining, and disposal of industrial wastes.

Underground Mines—Since the early 1800s, Oklahomans have intermittently conducted underground mining. Major underground mining occurred from 1872 through the 1940s in eastern Oklahoma coal fields, and from 1904 through 1970 in the Tri-State lead-zinc district in northeastern Oklahoma and parts of Kansas and Missouri (Fig. 25). Underground mines extracting gypsum, limestone, base metals, and asphalt in other districts also created potential hazards such as: (1) roof-rock collapse, causing surface subsidence or collapse; (2) acidic or toxic mine waters; and (3) mine flooding.

Strip Mines and Open-Pit Mines— Oklahomans have operated strip mines and open-pit mines since pioneer days in the early 1800s (Fig. 25). Large-scale quarrying and open-pit mining for stone, sand and gravel, asphalt, and other nonfuel resources began in the late 1800s. Significant strip-mining in eastern Oklahoma coal fields began about 1915 with the development of large earth-moving equipment. Land disturbed by surface mining is a potential problem because: (1) spoil piles and fill material may not be fully compacted, leading to subsiding or settling; (2) ponds and ground water in the area may be acidic or toxic; and (3) highwalls and quarry benches may be unstable.

Industrial-Waste Disposal in Geologic Formations—Solid- and liquid-industrial-waste disposal in Oklahoma includes surface burial in soils or rock units, and subsurface injection for liquid-industrial waste (Johnson and others, 1980). The primary concern in selecting a suitable waste-disposal site is the assurance that waste will remain isolated from ground water aquifers and the biosphere for as long as the waste is hazardous to humans and the environment.

Rock units in Oklahoma favored for surface disposal are impermeable sedimentary rocks, such as shale and clay; porous and permeable sedimentary rocks, such as sandstone, limestone, and dolomite, are most desirable for subsurface waste disposal (Johnson and others, 1980). The porous and permeable rock units should be surrounded by impermeable strata to assure waste containment.



EXPLANATION

CANADIAN PLAINS AND VALLEYS[1]

1 — **Travessilla-Kim**[2] **—**loamy, calcareous, and humus-poor soils on steep slopes (up to 24%) [Entisols][3] .

SOUTHERN HIGH PLAINS

2 — **Conlen-Pastura-Plack—**loamy and calcareous soils on moderately steep slopes (up to 10%) [Mollisols; Aridisols].

3 — **Dalhart-Vona—**very deep and loamy soils on gentle slopes (6%) [Alfisols; Aridisols].

4 — **Sherm-Ulysses—**very deep, silty and clayey, and humus-rich soils on gentle slopes (6%) [Mollisols].

SOUTHERN HIGH PLAINS BREAKS

5 — **Mansic-Irene—**very deep, silty and loamy, and humus-rich soils on gentle slopes (6%) [Mollisols].

6 — **Mobeetie-Veal-Devol-Lincoln-Eda—**very deep, loamy and sandy, and humus-poor soils on gentle slopes (7%) [Inceptisols; Alfisols; Entisols].

WICHITA MOUNTAINS

7 — **Brico—**rock outcrops with loamy, humus-rich soils on steep (up to 24%) and gentle slopes (6%) [Mollisols].

CENTRAL ROLLING RED PLAINS

8 — **Eda-Tivoli—**very deep, sandy, and humus-poor soils on steep slopes (up to 18%) [Alfisols; Entisols].

9 — **Quinlan-Woodward—**shallow, sandy, calcareous, and humus-poor soils on steep slopes (up to 18%) [Inceptisols].

10 — **St. Paul-Carey—**deep, silty, and humus-rich soils on very gentle slopes (3%) [Mollisols].

11 — **Lincoln-Westola-Clairemont—**very deep, sandy and loamy and silty, calcareous, and humus-poor soils on nearly level slopes (1%) [Entisols].

12 — **Cordell-Dill—**shallow, loamy, and humus-poor soils on gentle slopes (7%) [Inceptisols].

13 — **Grandfield-Devol-Tipton-Hardeman—**deep and loamy soils on very gentle slopes (4%) [Alfisols; Entisols; Mollisols; Inceptisols].

14 — **Tillman-Hollister-Foard-Vernon—**clayey and humus-rich soils on gentle slopes (7%) [Mollisols; Inceptisols].

15 — **Knoco-Cornick-Vernon—**shallow, loamy and clayey, and calcareous soils on steep slopes (up to 17%) [Entisols; Mollisols; Inceptisols].

16 — **Nobscot-Delwin—**very deep, loamy, slightly acid, and humus-poor soils on gentle slopes (7%) [Alfisols].

CENTRAL ROLLING RED PRAIRIES

17 — **Port-Dale-Yahola-Gaddy-Gracemore-McLain-Reinach—**very deep, sandy and loamy and silty soils on nearly level slopes (1%) [Mollisols; Entisols].

18 — **Pond Creek-Norge-Minco-Lovedale-Bethany—**very deep, silty, and humus-rich soils on gentle slopes (6%) [Mollisols].

19 — **Renfrow-Kirkland-Grainola-Bethany—**clayey and humus-rich soils on very gentle slopes (4%) [Mollisols; Alfisols].

20 — **Zaneis-Grant-Pond Creek-Seminole-Grainola-Chickasha-Kingfisher—**loamy and silty, and humus-rich soils on gentle slopes (6%) [Mollisols; Alfisols].

NORTHERN CROSS TIMBERS

21 — **Stephenville-Darnell-Niotaze—**shallow, sandy and loamy, moderately acid, and humus-poor soils on steep slopes (up to 18%) [Alfisols; Inceptisols].

WESTERN CROSS TIMBERS

22 — **Weatherford-Konsil-Windthorst—**loamy and humus-poor soils on gentle slopes (6%) [Alfisols].

SAND HILLS[4]

23 — **Eufaula-Dougherty-Konawa—**very deep, loamy and sandy, well-drained, and slightly acid soils on moderately steep slopes (up to 11%) [Alfisols].

BLUESTEM HILLS

24 — **Shidler-Summit-Corbin-Catoosa-Steedman—**clayey and silty, and humus-rich soils on gentle slopes (6%) [Mollisols; Alfisols].

CHEROKEE PRAIRIES

25 — **Dennis-Bates-Taloka-Parsons—**clayey and loamy , and humus-rich soils on very gentle slopes (3%) [Mollisols; Alfisols].

26 — **Kiomatia—**very deep, sandy, calcareous, and humus-poor soils on very gentle slopes (3%) [Entisols].

27 — **Osage-Verdigris—**very deep, clayey and silty, slightly acid, and humus-rich soils on nearly level slopes (1%) [Mollisols].

GRAND PRAIRIE

28 — **Chigley-Durant-Clarita-Heiden-Ferris-Burleson—**deep, clayey (high shrink-swell potential), and humus-rich soils on gentle slopes (7%) [Alfisols; Mollisols; Vertisols].

ARBUCKLE MOUNTAINS

29 — **Kiti-Shidler-Lula—**shallow, silty and clayey, rocky, and humus-rich soils on gentle slopes (5%) [Mollisols].

OZARK HIGHLANDS

30 — **Clarksville-Noark—**very deep, loamy and clayey, rocky, well-drained, very strongly acid, and humus-poor soils on steep slopes (up to 27%) [Ultisols].

BOSTON MOUNTAINS

31 — **Hector-Linker—**shallow, loamy, well-drained, strongly acid, and humus-poor soils on steep slopes (up to 23%) [Inceptisols; Entisols].

OUACHITA MOUNTAINS

32 — **Tuskahoma-Wetsaw-Muskogee-Neff-Sherwood-Wister—loamy** silty and clayey, moderately well-drained, and strongly acid soils on moderately steep slopes (up to 8%) [Alfisols; Ultisols].

33 — **Carnasaw-Clebit-Pirum—**loamy, well-drained, and moderately acid soils on steep slopes (up to 30%) [Ultisols; Inceptisols].

ARKANSAS RIDGE AND VALLEY

34 — **Hector-Endsaw—**loamy, rocky, well drained, and moderately acid soils on steep slopes (up to 26%) [Inceptisols; Ultisols].

35 — **Stigler-Shermore-Neff-Bolivar—**silty and loamy soils on moderately steep slopes (up to 8%) [Alfisols].

36 — **Kamie-Larton-Porum—**very deep, loamy, and moderately acid soils on gentle slopes (5%) [Alfisols].

COASTAL PLAIN

37 — **Felker-Wrightsville—**very deep, loamy and silty, somewhat poorly drained, and strongly acid soils on nearly level slopes (1%) [Ultisols; Alfisols].

38 — **Ruston-Smithdale-Tiak—**very deep, loamy and clayey, and strongly acid soils on steep slopes (up to 12%) [Ultisols].

39 — **Bernow—**very deep, loamy, and well-drained soils on gentle slopes (6%) [Alfisols].

40 — **Pledger—**very deep, clayey (high shrink-swell potential), moderately well-drained, mildly alkaline, and humus-rich soils on level areas [Vertisols].

41 — **Guyton-Kaufman—**very deep, silty and clayey soils on nearly level slopes (1%) [Alfisols; Vertisols].

[1]Major Land Resource Area: area of similar land use based on soils, climate, and water resources.
[2]Soil Association: two or more prevalent soil series in a Major Land Resource Area (MLRA).
[3][Soil Order]: grouping of one or more soil series by a major property. (Each order is defined in the Glossary.)
[4]Sand Hills: eolian deposits occur across the boundaries of several Major Land Resource Areas (MLRA).

SOIL MAP OF OKLAHOMA

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Soil-survey staff of the Natural Resources Conservation Service (NRCS), U.S. Department of Agriculture, have identified and mapped over 20,000 different kinds of soil in the United States. Most soils are given a name that typically comes from the place where the soil was first mapped. Named soils are referred to as a soil series.

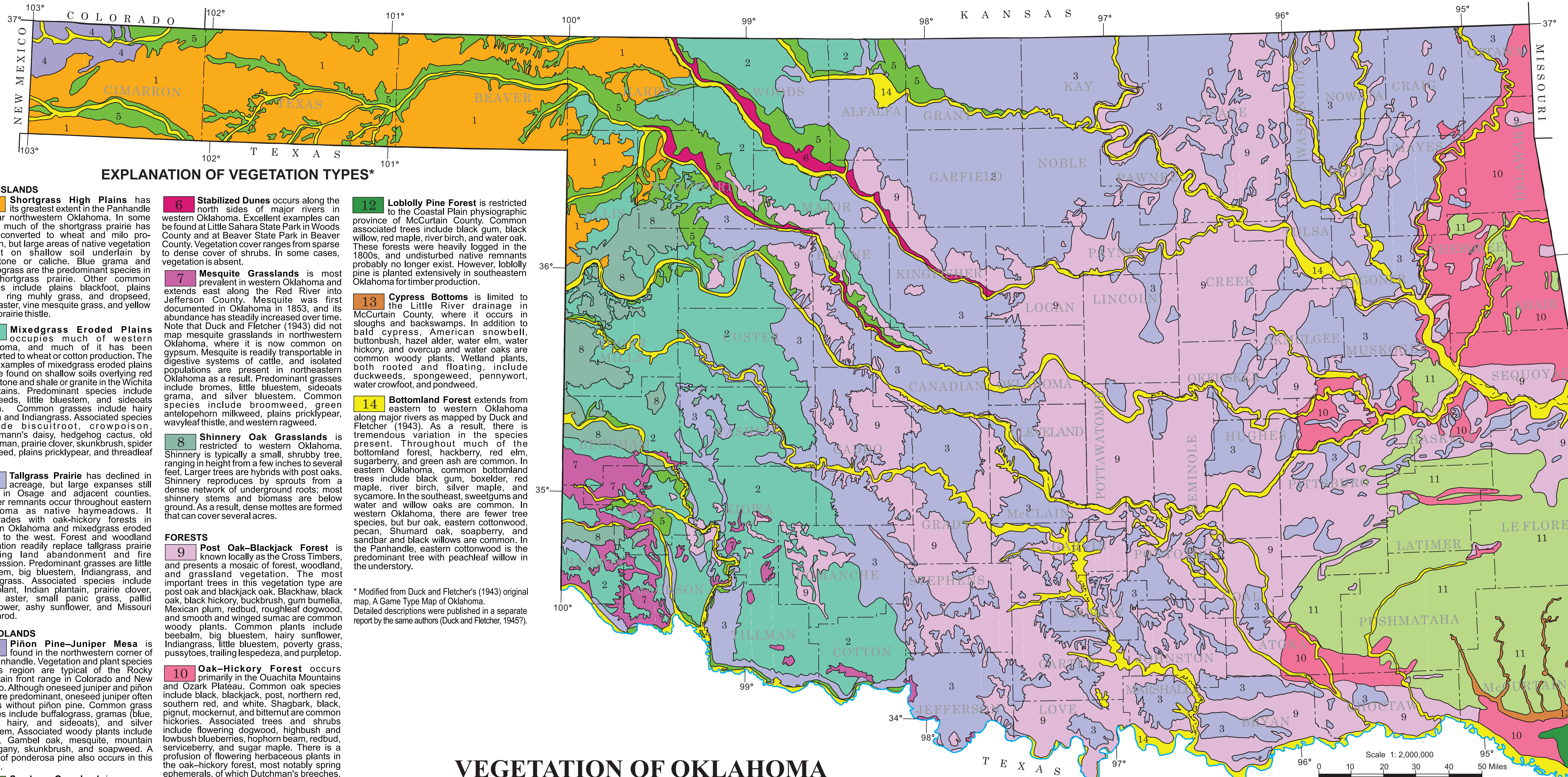
Geology, topography, climate, plants and animals, and time are major factors in soil formation. Color, texture, size and shape of soil aggregates, kind and amount of rock fragments, distribution of plant roots, pH, and other features are used to characterize soils. After a soil is described and its properties are determined, soil scientists assign the soil to one of 12 taxonomic orders and/or one of many suborders. Seven of 12 orders (shown in brackets in the explanation) are represented on this map. The taxonomic classification used in the United States is based mainly on the kind and character of soil properties and the arrangement of horizons within the soil profile (NRCS, 1999). Carter and Gregory (1996) and Gray and Galloway (1959) group Oklahoma's major soil associations by Major Land Resource Areas (MLRA) and/or geographic regions.

Western Oklahoma—The Canadian Plains and Valleys MLRA contains brown, loamy soils developed on sandstone escarpments, basalt, and associated foot slopes (breaks) under mid and short grasses. Soils in the High Plains and Breaks consist of dark-colored loams and clay loams with moderately clayey subsoil on limey unconsolidated loams, silts, and caliche developed under mid and short grasses. In the Central Rolling Red Plains, dark to various shades of red soils with clay to loam subsoils are developed on Permian shales, mudstones, and siltstones under mid and short grasses. This MLRA contains brown to light-brown loams and sands with clay-loam to sand under mid grasses, scrub oaks, cedars, and shrubs.

Central Oklahoma—Soils in the Central Rolling Red Prairies are dark and loamy with clayey to loamy subsoils developed on Permian shales, mudstones, sandstones and/or alluvial deposits under tall grasses. Soils of the Cross Timbers are light colored, sandy with reddish subsoils on various sandy materials developed under mostly post oak, blackjack oak, and some hickory forests with prairie openings (savannah). The Bluestem Hills–Cherokee Prairies contain deep, dark-colored soils mostly with clay subsoils developed on shales, sandstones, and limestones under tall grasses. Soils in the Grand Prairie–Arbuckle Mountains MLRAs are dark and loamy to clayey with subsoils developed in shales and limestones under tall grasses near the Arbuckle Mountains and southeastern Oklahoma. Thin and stony soils develop on Precambrian granites in the Arbuckle Mountains beneath mid grasses, scrub oaks, cedars, and shrubs.

Eastern Oklahoma—The Ozark Highlands–Boston Mountains have brown to light-brown, silty soils with reddish clay subsoils on cherty limestones (Ozarks) and sandstones and shales (Boston Mountains). These soils develop under oak-hickory-pine forests and tall grasses. Soils in the Ouachita Mountains are light colored, acid, sandy, and loamy with clayey subsoils developed on sandstones and shales under oak-hickory-pine forests. Arkansas Ridge and Valley soils are loamy, rocky, and well drained where developed on steep slopes and ridges or are very deep and loamy on gentle slopes and shales in valleys. Coastal Plain soils are light colored, acid, and sandy with clay-loam to clay subsoils developed mostly on sandstones under pine-oak (east) and oak-hickory (west) forests.

Detailed information for each major soil type is published by the NRCS in its soil surveys of nearly all 77 Oklahoma counties. The surveys can be examined at local NRCS offices, typically located in county seats.



VEGETATION OF OKLAHOMA

Bruce W. Hoagland, Oklahoma Biological Survey

EXPLANATION OF VEGETATION TYPES*

GRASSLANDS

1 Shortgrass High Plains has its greatest extent in the Panhandle and far northwestern Oklahoma. In some areas, much of the shortgrass prairie has been converted to wheat and milo production, but large areas of native vegetation persist on shallow soil underlain by sandstone or caliche. Blue grama and buffalograss are the predominant species in the shortgrass prairie. Other common species include plains blackfoot, plains zinnia, ring muhly grass, and dropseed, tansy aster, vine mesquite grass, and yellow spine prairie thistle.

2 Mixedgrass Eroded Plains occupies much of western Oklahoma, and much of it has been converted to wheat or cotton production. The best examples of mixedgrass eroded plains can be found on shallow soils overlying red sandstone and shale or granite in the Wichita Mountains. Predominant species include dropseeds, little bluestem, and sideoats grama. Common grasses include hairy grama and Indiangrass. Associated species include biscuitroot, crowpoison, Engelmann's daisy, hedgehog cactus, old plainsman, prairie clover, skunkbrush, spider milkweed, plains pricklypear, and threadleaf daisy.

3 Tallgrass Prairie has declined in acreage, but large expanses still occur in Osage and adjacent counties. Smaller remnants occur throughout eastern Oklahoma as native haymeadows. It intergrades with oak-hickory forests in eastern Oklahoma and mixedgrass eroded plains to the west. Forest and woodland vegetation readily replace tallgrass prairie following land abandonment and fire suppression. Predominant grasses are little bluestem, big bluestem, Indiangrass, and switchgrass. Associated species include lead plant, Indian plantain, prairie clover, heath aster, small panic grass, pallid coneflower, ashy sunflower, and Missouri goldenrod.

WOODLANDS

4 Piñon Pine–Juniper Mesa is found in the northwestern corner of the Panhandle. Vegetation and plant species in this region are typical of the Rocky Mountain front range in Colorado and New Mexico. Although oneseed juniper and piñon pine are predominant, oneseed juniper often occurs without piñon pine. Common grass species include buffalograss, gramas (blue, black, hairy, and sideoats), and silver bluestem. Associated woody plants include cholla, Gambel oak, mesquite, mountain mahogany, skunkbrush, and soapweed. A stand of ponderosa pine also occurs in this region.

5 Sandsage Grasslands is common on deep sand deposits and dunes in western Oklahoma. Sandsage is a low-growing shrub with narrow, gray-green leaves, which is often cleared to increase the productivity of pasture grasses for cattle grazing. Predominant grasses include sand reed, little bluestem, sand bluestem, and sand dropseed. Mapleleaf grape, netleaf hackberry, sand plum, silky prairie clover, skunkbrush, soapweed, and spectacle pod are also common. Most species occurring in sandsage grasslands also can be found in stabilized dunes and shinnery-oak grasslands. These three vegetation types so thoroughly intergrade that they are indistinguishable in parts of western Oklahoma.

6 Stabilized Dunes occurs along the north sides of major rivers in western Oklahoma. Excellent examples can be found at Little Sahara State Park in Woods County and at Beaver State Park in Beaver County. Vegetation cover ranges from sparse to dense cover of shrubs. In some cases, vegetation is absent.

7 Mesquite Grasslands is most prevalent in western Oklahoma and extends east along the Red River into Jefferson County. Mesquite was first documented in Oklahoma in 1853, and its abundance has steadily increased over time. Note that Duck and Fletcher (1943) did not map mesquite grasslands in northwestern Oklahoma, where it is now common on gypsum. Mesquite is readily transportable in digestive systems of cattle, and isolated populations are present in northeastern Oklahoma as a result. Predominant grasses include bromes, little bluestem, sideoats grama, and silver bluestem. Common species include broomweed, green antelopehorn milkweed, plains pricklypear, wavyleaf thistle, and western ragweed.

8 Shinnery Oak Grasslands is restricted to western Oklahoma. Shinnery is typically a small, shrubby tree, ranging in height from a few inches to several feet. Larger trees are hybrids with post oaks. Shinnery reproduces by sprouts from a dense network of underground roots; most shinnery stems and biomass are below ground. As a result, dense mottes are formed that can cover several acres.

FORESTS

9 Post Oak–Blackjack Forest is known locally as the Cross Timbers, and presents a mosaic of forest, woodland, and grassland vegetation. The most important trees in this vegetation type are post oak and blackjack oak. Blackhaw, black oak, black hickory, buckbrush, gum bumelia, Mexican plum, redbud, roughleaf dogwood, and smooth and winged sumac are common woody plants. Common plants include beebalm, big bluestem, hairy sunflower, Indiangrass, little bluestem, poverty grass, pussytoes, trailing lespedeza, and purpletop.

10 Oak–Hickory Forest occurs primarily in the Ouachita Mountains and Ozark Plateau. Common oak species include black, blackjack, post, northern red, southern red, and white. Shagbark, black, pignut, mockernut, and bitternut are common hickories. Associated trees and shrubs include flowering dogwood, highbush and lowbush blueberries, hophorn beam, redbud, serviceberry, and sugar maple. There is a profusion of flowering herbaceous plants in the oak–hickory forest, most notably spring ephemerals, of which Dutchman's breeches, Solomon's seal, troutlillies, Virginia waterleaf, wake robin, and wild ginger are but a few.

11 Oak–Pine Forest is limited to the Ouachita Mountains and Ozark Plateau. The presence of shortleaf pine distinguishes oak–pine forest from oak–hickory forest. Otherwise, associated species are similar to those of the oak–hickory forest. Shortleaf pine forests vary from closed canopy, pine–mixed oak stands to open canopy woodlands of predominantly shortleaf pine. The degree of canopy closure is controlled by fire.

12 Loblolly Pine Forest is restricted to the Coastal Plain physiographic province of McCurtain County. Common associated trees include black gum, black willow, red maple, river birch, and water oak. These forests were heavily logged in the 1800s, and undisturbed native remnants probably no longer exist. However, loblolly pine is planted extensively in southeastern Oklahoma for timber production.

13 Cypress Bottoms is limited to the Little River drainage in McCurtain County, where it occurs in sloughs and backswamps. In addition to bald cypress, American snowbell, buttonbush, hazel alder, water elm, water hickory, and overcup and water oaks are common woody plants. Wetland plants, both rooted and floating, include duckweeds, spongeweed, pennywort, water crowfoot, and pondweed.

14 Bottomland Forest extends from eastern to western Oklahoma along major rivers as mapped by Duck and Fletcher (1943). As a result, there is tremendous variation in the species present. Throughout much of the bottomland forest, hackberry, red elm, sugarberry, and green ash are common. In eastern Oklahoma, common bottomland trees include black gum, boxelder, red maple, river birch, silver maple, and sycamore. In the southeast, sweetgums and water and willow oaks are common. In western Oklahoma, there are fewer tree species, but bur oak, eastern cottonwood, pecan, Shumard oak, soapberry, and sandbar and black willows are common. In the Panhandle, eastern cottonwood is the predominant tree with peachleaf willow in the understory.

* Modified from Duck and Fletcher's (1943) original map, A Game Type Map of Oklahoma. Detailed descriptions were published in a separate report by the same authors (Duck and Fletcher, 1945?).

The best reference for the study of Oklahoma vegetation is *A Game Type Map of Oklahoma* (Duck and Fletcher, 1943) published by the State of Oklahoma Game and Fish Commission (now the Oklahoma Department of Wildlife Conservation). Duck and Fletcher and a team of researchers used aerial photography, soils maps, and extensive field surveys to map the distribution of major vegetation types. Their map is considered a potential vegetation map; it shows the distribution of vegetation in the absence of human intervention. The map is still widely used to study Oklahoma vegetation, ecology, and geography and is a testament to their thorough and conscientious work.

Duck and Fletcher's map clearly reveals the influence of climate, particularly the precipitation gradient, on the distribution of vegetation in Oklahoma. As rainfall decreases from 55 inches in the southeast to 13 inches in the northwest, forests give way to grasslands. However, the boundary between grassland and forest vegetation is dynamic; prolonged droughts can change the boundary between the two vegetation types. Length of growing season is another climatic variable that affects cultivated crops and natural vegetation. Counties in the Red River valley have a longer growing season than those along the Kansas border. Some plants, such as buffalo currant, therefore, bloom a week earlier in Love County than in Grant County.

Geology and soils also play integral roles in determining the distribution of vegetation. For example, sugar maple trees can be found in the deeply eroded Permian sandstone canyons of Canadian and Caddo Counties, about 150 miles west of the Ozark Plateau and Ouachita Mountains where they are common. Limestone produces soils with high clay content that tend to be somewhat alkaline. Black dalea, Engelmann's pricklypear, shortlobe oak, and Ashe juniper are species that occur in regions where limestone and dolomite predominate, such as the Arbuckle Mountains and Slick Hills. Gypsum deposits in western Oklahoma support salt-tolerant plants, such as redberry juniper, gypsum phacelia, and woolly paperflower.

Distribution of vegetation is also influenced by such disturbances as fire and grazing by large animals. In the absence of fire, grasslands are often replaced by forests and shrublands. Woodlands, which are characterized by scattered trees that are not in direct contact with one another, transform into closed-canopy forests in the absence of fire. Eastern red cedar is one species that is very sensitive to fire and has proliferated in the absence of fire.

The vegetation types mapped by Duck and Fletcher (1943) can be segregated into three categories: grasslands, woodlands, and forests. Grasslands are areas where various grass species predominate on the landscape. Trees and shrubs may be present at particular sites, but they are not abundant and often are restricted to bottomlands or other favorable habitats. Woodlands are areas where trees and shrubs are more abundant, but their crowns are not in contact with one another. Because of the open nature of woodlands, grass species predominate in the understory. Forests are areas where trees predominate and their crowns interlock, resulting in significant shade that favors the growth of shrubs and herbaceous species adapted to such conditions.

Table 6. Oklahoma Weather Facts[ab]

Temperature		
Statewide-Averaged Temperature		
Normal (1971-2000)		60.2 °F
Warmest Year	1954	63.7 °F
Coolest Year	1892	58.2 °F
Record Low Daily Temperature (2 occurrences)		
Vinita, Craig County (February 13, 1905)		-27 °F
Watts, Adair County (January 18, 1930)		
Record Daily High Temperature (6 Occurrences)		
Alva, Woods County (July 18, 1936)		120 °F
Altus, Jackson County (July 19 and August 12, 1936)		
Poteau, LeFlore County (August 10, 1936)		
Tishomingo, Johnston County (July 26, 1943)		
Tipton, Tillman County (June 27, 1994)		
Precipitation		
Statewide-Averaged Annual Precipitation		
Normal (1971-2000)		36.44 in.
Wettest Year	1957	48.21 in.
Driest Year	1910	18.95 in.
Greatest Reported Annual Total at Individual Station		
Kiamichi Fire Tower, Le Flore County	1957	84.47 in.
Smallest Reported Annual Total at Individual Station		
Regnier, Cimarron County	1956	6.53 in.
Greatest Reported Daily Precipitation at Individual Station		
Enid, Garfield County (October 11, 1973)		15.68 in.
Snowfall		
Greatest Reported Seasonal Snowfall Total for Individual Station		
Beaver, Beaver County (October 1911-March 1912)		87.3 in.
Greatest Reported Monthly Snowfall at Individual Station		
Buffalo, Harper County (February, 1971)		36.5 in.
Greatest Reported Daily Snowfall at Individual Station		
Buffalo, Harper County (February 21, 1971)		23.0 in.
Maximum Reported Snow Depth		
Buffalo, Harper County (February 22, 1971)		36.0 in.
Earliest Measurable Snowfall of Season		
Kenton, Cimarron County (September 17, 1971)		3.0 in.
Latest Measurable Snowfall of Season		
Billings, Noble County (May 6, 1954)		0.2 in.
Tornadoes		
Average Annual Number of Tornadoes (1950-2000)		54.1
Most Tornadoes in One Year	1999	146
Fewest Tornadoes in One Year	1988	17
Deadliest Tornado (Woodward, April 9, 1947)		107 deaths

[a]For the period of 1892-2000 unless otherwise noted.
[b]Compiled by the Oklahoma Climatological Survey from U.S. National Weather Service data.

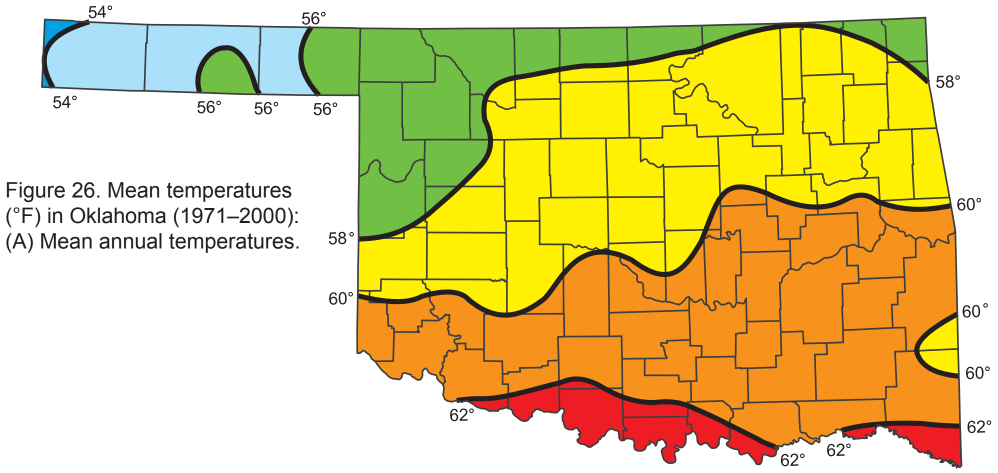


Figure 26. Mean temperatures (°F) in Oklahoma (1971–2000): (A) Mean annual temperatures.

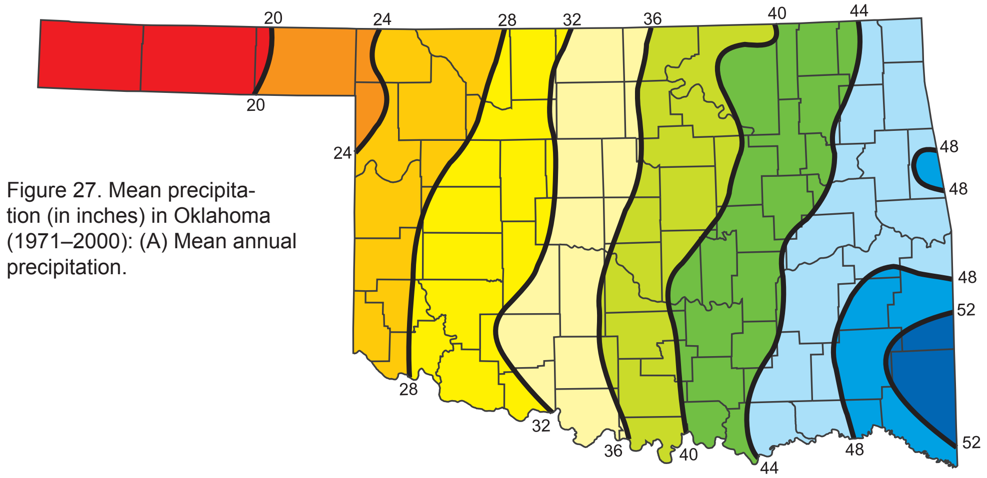
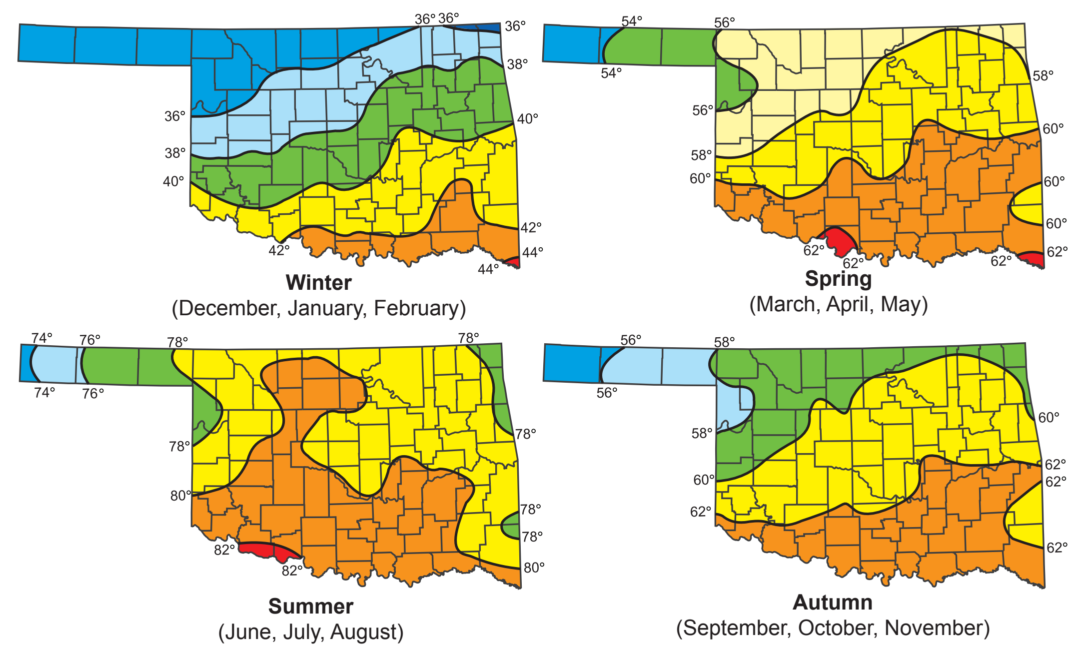
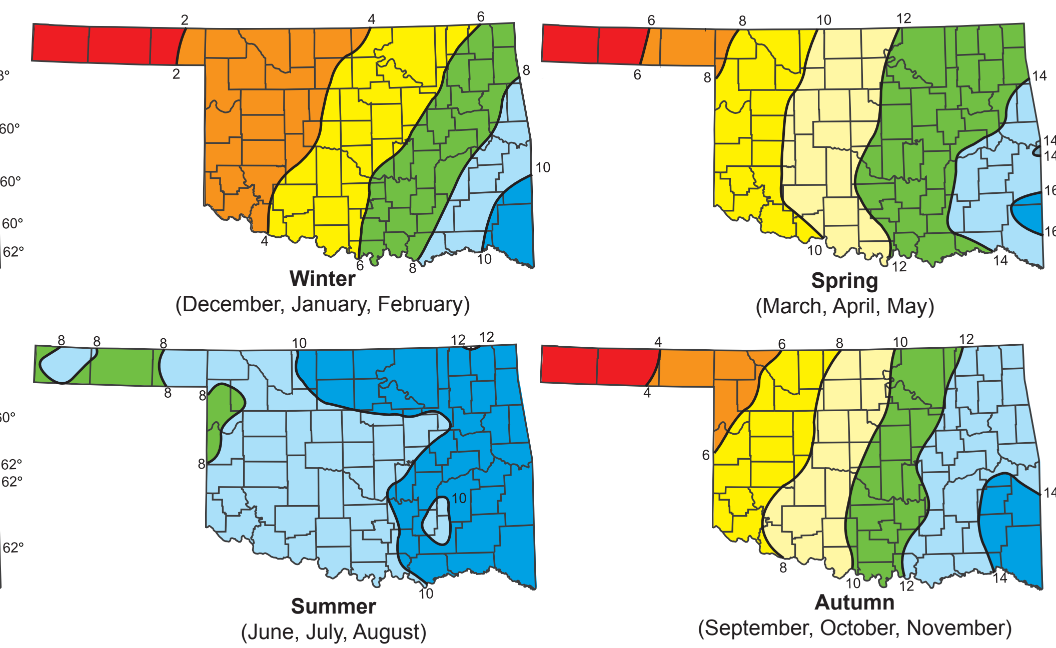


Figure 27. Mean precipitation (in inches) in Oklahoma (1971–2000): (A) Mean annual precipitation.



(B) Mean seasonal temperatures.



(B) Mean seasonal precipitation.

CLIMATE OF OKLAHOMA

Howard L. Johnson, Oklahoma Climatological Survey

Temperature

Oklahoma is far enough north to experience weather systems that can bring rapid changes in temperature; but also far enough south so that episodes of Arctic air during the cold months are short-lived. Oklahoma is in the continental interior, which leads to hot summers. But its climate is modified sufficiently by warm, moist air from the Gulf of Mexico to produce relatively mild winters. (Table 6 gives statewide-averaged annual temperature.)

Mean annual temperatures increase from north to south (Fig. 26A). Oklahoma weather is dictated by four seasons, which are common to temperate latitudes (Fig. 26B). Oklahoma experiences distinctive cold (winter) and hot (summer) seasons. Transitional periods of spring and autumn separate the two extremes.

Winter weather is controlled by the polar jet stream, a continuous band of strong winds found 5 to 8 miles above the Earth. Outbreaks of cold surface air from the Arctic normally are associated with southerly migrations of the jet stream. Periods of mild winter weather occur when the jet stream stays well to the north. The jet stream plays an important role in developing new storm systems along fronts that mark the transition between cold and warm air masses.

Winter ends as cold fronts decrease in frequency, and encounter progressively warmer and more humid air masses in the spring. Approaching springtime cold fronts are frequently preceded by intense thunderstorms accompanied by a rapid drop in temperature.

In summer the jet stream normally flows far north of Oklahoma, and high pressure (an extension of the Bermuda High) builds over the southeastern United States. The air around the Bermuda High circulates clockwise with its center over the Atlantic Ocean, resulting in persistent southerly winds across Oklahoma. The size, location, and strength of circulating air determine if southerly winds deliver either warm, moist air from the Gulf of Mexico, or hot, dry air from the desert Southwest.

Autumn is usually gentle, with successive air masses becoming progressively cooler until winter is established. Cool spells in autumn are often separated by mild, dry periods known as Indian Summer that can last for several days or longer, providing Oklahoma with some of the year's most pleasant weather.

Precipitation

Proximity to the Rocky Mountains and Gulf of Mexico affects Oklahoma weather and climate. The Rocky Mountains form a barrier to prevailing westerly winds in the upper atmosphere, inducing a semi-permanent trough of low-pressure air at lower elevations to the east. This "lee trough" normally is located in eastern Colorado and western Kansas, extending south into the Oklahoma and Texas Panhandles. This trough intensifies the southerly surface winds that prevail across Oklahoma most of the year. Across Texas and Oklahoma, interaction between warm, moist air from the Gulf and outbreaks of cold air from the Arctic frequently forms new weather systems along the lee trough.

The weather systems grow in size and strength spawning violent thunderstorms over the southern plains, especially in the spring, providing much of Oklahoma's rainfall. Occasionally, the storms produce high winds, hail, and tornadoes.

Moisture arrives from the Gulf of Mexico, borne on southerly winds prevalent most of the year. The distance from the Gulf often is measured by the dryness of the air. The east and southeast are relatively moist, but western regions with higher elevations are dry, with warm days and cool nights.

Oklahoma's geographic diversity and size commonly create situations where one area experiences drought while another has surplus water. Annual and seasonal variations in precipitation are quite large. Mean annual precipitation across Oklahoma ranges from 55.71 inches at Smithville (McCurtain County) in the Ouachita Mountains to 16.86 inches at Regnier (Cimarron County) in the Panhandle (Fig. 27A). Much rainfall is associated with thunderstorms lasting a few hours, although extended periods of rain do occur. Water from snow represents a very small portion of annual precipitation (Fig. 27 A-B).

The wettest period is springtime, the season with the heaviest thunderstorm activity (Fig. 27B). Spring rain associated with thunderstorm systems often accompanies severe weather or tornadoes; locally rains may be heavy. The highest statewide precipitation is in May, followed by June and September. In September and October, Oklahoma experiences sporadic heavy rains associated with remnants of hurricanes that strike the Texas coast or the west coast of Mexico. Many one-day record rainfalls occur in autumn.

Locally heavy rainfall occurs anytime in association with a "thunderstorm train," which happens when successive thunderstorms traverse the same path. Such rainfalls can measure more than 12 inches.

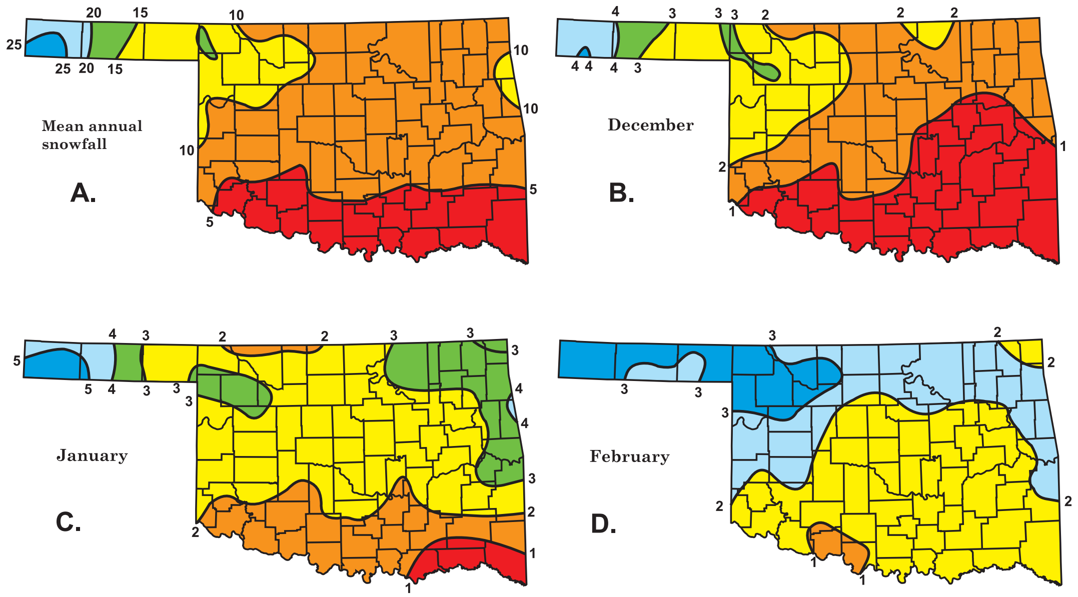


Figure 28. Mean snowfall (in inches) recorded in Oklahoma (1971–2000): (A) Mean annual snowfall; (B) Mean monthly snowfall for December; (C) Mean monthly snowfall for January; (D) Mean monthly snowfall for February.

Winter Storms/Snowfall

Occasionally bitterly cold, Oklahoma's winter weather is not as consistent as the summer heat. Winter storms move through the State fairly quickly, leaving time for temperatures to moderate before the next storm arrives.

Figure 28A shows mean annual snowfalls. December and March snowfall patterns and amounts (Fig. 28B) are similar. January and February (Figs. 28C–D) are the snowiest months, in the mean. The greatest snowfall is in the Panhandle; the least is in the southeast (Fig. 28).

Growing Season

The dates between the last freeze (temperature less than 32°F) in spring and the first freeze in fall (Figs. 29–30) define the growing season for fruits and vegetables. Home gardeners are sensitive to these dates. The average frost-free period ranges from 24 weeks in the western Panhandle to 33 weeks along the Red River in south-central Oklahoma. The two-month difference in the growing season affects the variation in cultivated and natural vegetation across Oklahoma. The average date of the last freeze is in the south in late March. The last frost in the western Panhandle is about a month later. Average dates for the first freezes range from mid-October in the western Panhandle to early November in the south.

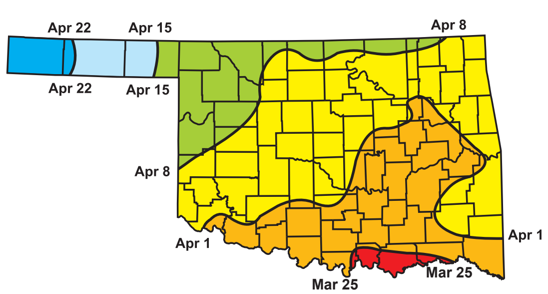


Figure 29. Mean annual date of the last freeze is in the spring in Oklahoma (1971–2000).

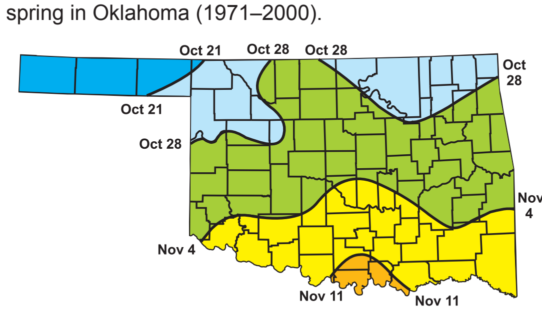


Figure 30. Mean annual date of the first freeze is in autumn in Oklahoma (1971–2000).

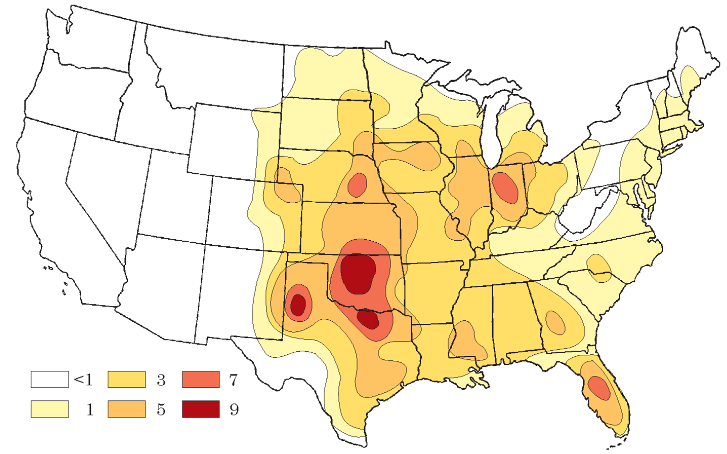


Figure 31. Average number of tornadoes in the United States recorded per year per 10,000 square miles (map courtesy National Oceanic and Atmospheric Administration).

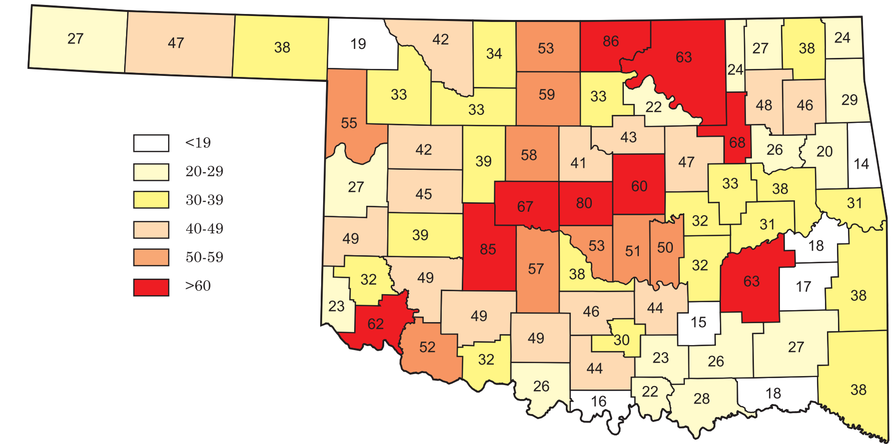


Figure 32. Number of tornadoes reported in each county in Oklahoma, 1950–2000 (data provided by Doug Speheger, National Weather Service, Norman, Oklahoma, 2001).

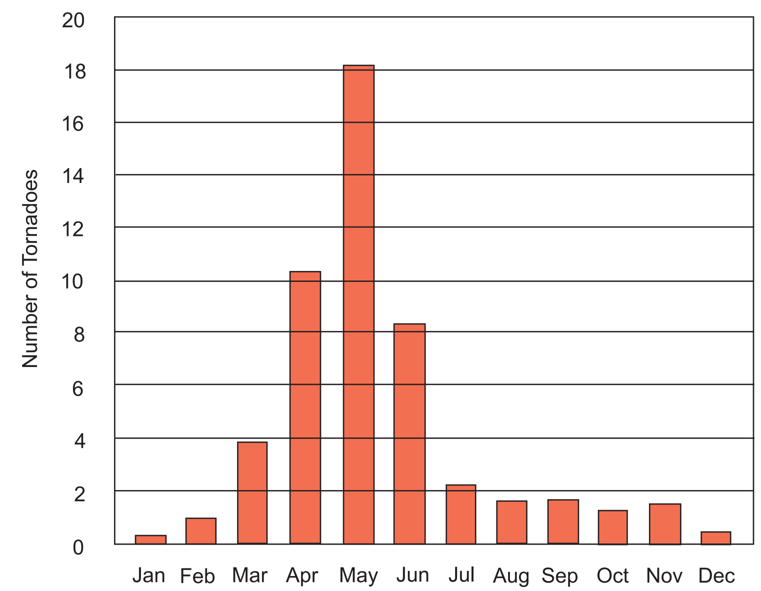


Figure 33. Average number of tornadoes reported in Oklahoma by month, 1950–1991 (modified from Johnson and Duchon, 1994, fig. 4-14).

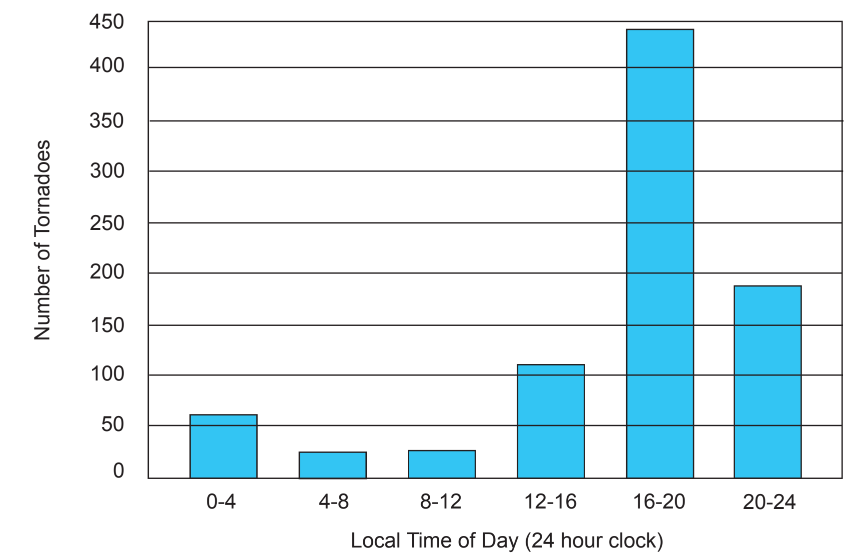


Figure 34. Number of F2 or greater tornadoes reported in Oklahoma by time of day, 1950–1991 (modified from Johnson and Duchon, 1994, fig. 4-15).

Tornadoes

Tornadoes are violent columns of rotating air associated with very strong thunderstorms. Disastrous tornadic events—such as the tri-state (Texas/Oklahoma/Kansas) tornado outbreak of April 9, 1947 that killed 181 people (107 in Woodward); the Snyder tornado of May 10, 1905 that killed 97 people; and the May 3, 1999 tornadoes that affected Oklahoma and Kansas killing 49 people—have led to an enduring association between Oklahoma weather and tornadoes.

The highest frequency of tornadoes occurs in an area extending from Iowa to north-central Texas (Fig. 31) in a region (especially Oklahoma, Kansas, and north Texas) known as Tornado Alley. Most tornadoes, moving from southwest to northeast (but movement in any direction is possible) are small, leaving only a short path of destruction. Figure 32 shows tornado reports in each county from 1950 to 2000. Oklahoma, Kay, and Caddo Counties produced the most reports; Adair and Coal Counties have the fewest reports. An axis of maximum activity extends from Jackson County in the extreme southwest to Tulsa County in the northeast.

April through June is the most active period (Fig. 33), but tornadoes can occur in any month. May is the most active month, when 36% of Oklahoma's tornadoes occur; 22% occur in April; and 16% occur in June. Tornadoes can occur any hour of the day, but they are most frequent in late afternoon and evening (Fig. 34).

The F-scale (Table 7), designated for its creator, Professor Tetsuya Fujita, is used to classify tornadoes. The F-scale is based on tornado strength as determined from an analysis of the damage path. Damage from F0 and F1 events is not major, but F2 and F3 events cause extensive damage. Categories F4 and F5 denote violent tornadoes that leave wide paths of total destruction.

One of the most significant tornado outbreaks happened on May 3, 1999 in Oklahoma and Kansas, when more than 70 tornadoes occurred. The tornado causing the greatest damage (the greatest effect was on residential areas) was an F5 tornado that struck south Oklahoma City and nearby communities. That tornado produced a 38-mile-long path of destruction from near Chickasha to Midwest City. It destroyed over 2,750 homes and apartments and 8,000 other homes were damaged. There were 41 fatalities and about 800 injuries (FEMA, 1999). Advance warnings by the National Weather Service and continuous live coverage by Oklahoma City radio and television stations saved many lives.

Table 7. Fujita F-scale of Tornado Intensity

F-Scale a Severity	Estimated Wind	Speed
F0	Weak Tornado	40–72 mph
F1	Moderate Tornado	73–112 mph
F2	Significant Tornado	113–157 mph
F3	Severe Tornado	158–206 mph
F4	Devastating Tornado	207–260 mph
F5	Incredible Tornado	261–318 mph

[a]The F-scale, designated for its inventor (Tetsuya Fujita), classifies tornadoes according to an analysis of the path of destruction. For example, F0 and F1 tornadoes do not cause major damage, while F4 and F5 tornadoes commonly leave wide paths of total destruction.

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GLOSSARY OF SELECTED TERMS (MOSTLY FROM JACKSON, 1997)

Acre-foot—The volume of liquid and/or solid required to cover 1 acre to a depth of 1 foot.

Alluvium—Flat-surfaced deposits of sand, silt, clay, and gravel in stream beds and on flood plains of present-day rivers and streams.

Alfisols—Soil order identified by increasing clay content with increasing soil depth. Subsoil contains significant amounts of calcium (Ca+2), magnesium (Mg+2), and potassium (K+1) in soil-water solution. Surface is acidic (pH less than 7).

Anhydrite—A mineral or sedimentary rock composed of calcium sulfate, $CaSO_4$; it alters readily to gypsum.

Aridisols—Soil order identified by lack of plant-available water for many months. Soils support only desert plants. Soils can also be very shallow or salty.

Aquifer—A permeable rock or deposit that is water bearing.

Asphalt—A solid or semisolid oil residue remaining in rocks after escape of the gaseous and more liquid components.

Barrel—42 U.S. gallons.

Basalt—A dark-colored fine-grained igneous rock (magma) formed from lava that flowed onto the surface of the earth. Oklahoma basalts are dark gray or black.

Basin—A large area that sank faster than surrounding areas during much of geologic time and in which a great thickness of sediments was deposited.

Bentonite—An absorbent clay formed by decomposition of volcanic ash.

Calcite—A mineral, calcium carbonate, $CaCO_3$; the principal component of limestone and a common cement of sandstones.

Caliche—A porous sedimentary rock consisting of sand or gravel cemented by calcium carbonate.

Chat—The crushed chert, limestone, and dolomite that is left as a by-product of mining and milling lead-zinc ores.

Chert—A dense sedimentary rock or mineral consisting of microscopic particles of silica (quartz). Occurs in layers and as isolated masses. Flint and novaculite are varieties of chert.

Climatology—The science that deals with climates and their phenomena.

Coal—A combustible black sedimentary rock consisting mostly of partly decomposed and carbonized plant matter.

Colluvium—Loose and incoherent mass of soil material and/or rock fragments usually deposited at the base of a slope.

Conglomerate—A sedimentary rock consisting largely of rounded gravel or pebbles cemented together in a finer matrix.

Crude oil—Unrefined hydrocarbons that exist as a liquid in a subsurface reservoir.

Cubic foot (gas)—Amount of gas that will occupy a cubic foot at atmospheric pressure (14.73 pounds per square inch at sea level) and 60° Fahrenheit.

Cuesta—A ridge with a long, gentle slope capped by a hard layer of rock and terminated by a steep slope.

Cumulonimbus—Exceptionally dense and vertically developed cloud type, occurring both as isolated clouds and as a line or wall of clouds; generally accompanied by heavy rain, lightning, and thunder.

Dimension stone—Any stone suitable for cutting and shaping into blocks and slabs for building or ornamental purposes.

Dolomite—A sedimentary rock consisting mostly of the mineral dolomite, $CaMg(CO_3)_2$, formed from dolomite muds and fossil fragments or, more commonly, by alteration of limestone.

Earthquake—A sudden motion or trembling in the earth caused by the abrupt release of slowly accumulated strain.

Earthquake intensity—A measure of the effects of an earthquake at a particular place. Intensity depends not only on the earthquake magnitude, but also on the distance from the origin of the earthquake and on local geology.

Earthquake magnitude—A measure of the strength of an earthquake determined by seismographic observations; determined by taking the common 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. Three magnitude scales, mbLg, m3Hz, MDUR, are used to report magnitude for Oklahoma earthquakes. 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 (see Lawson and Luza, 1995, for detailed explanation).

Entisols—Soil order identified by the properties of the parent material (rock