**INTRODUCTION**

Kenneth S. Johnson, Oklahoma Geological Survey

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 natural hazards.

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 geologic 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 seismic stations. Page 13 describes the ground-water resources of Oklahoma. Outcrops 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 geologic 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 general index is available at the end of the book.
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 northwestern 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 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-shetah”) Mountains in southeastern Oklahoma and western Arkansas is a curved belt of forested ridges and subparallel valleys. Resistant sandstone, chert, and non-vaculite 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).

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.

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 in the Arbuckle Mountains. Thick layers of black shale, along with some chert and sandstone beds, occur in the Ouachita Mountains region to the south.

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.

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 Hunt Group (latest Ordovician, Silurian, and Early Devonian) is common 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 Hunt 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 Hunt, 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 Arkansa Novaculite (chert) is Silurian, Devonian, and Early Mississippian. These three formations are 500–1,500 ft in total thickness.

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.

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

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

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

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 West, Arbusk, central Oklahoma, were uplifted, 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, 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, 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, Arbusk, Ouachita, and Ozark Uplifts. The older, fissiliferous and mineral-bearing rocks now are exposed after the erosion of younger, overlying strata.

Pennsylvanian rocks host various fossils and minerals. Marine limestones and shales in the Arbusk Mountains and the 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.

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 the southern Oklahoma (excluding the Ouachita Mountains) 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, 15,000 ft in the Ardmore Basin, 13,000 ft in the Marietta Basin, and 18,000 ft in the Arkoma Basin. Most Mississippian strata in 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 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 and the Ozark region of northeastern Oklahoma. (Fig. 9); the pulses included the northward thrusting of rocks referred to as the Ozark Uplift, stopped by the end of the Desmoinesian 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.

Permian Period

Following Pennsylvanian mountain building, an Early Permian (Wolfcampian) shallow inland sea covered most of western Oklahoma and the Panhandle, extending north from western Kansas to Nebraska and the Dakotas. Shallow-water limestones and gray shales are found in the center of the ancient seaway (Fig. 11), grading laterally to the east and west 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, Arbusk, Ouachita, and Ozark Mountains were still high, supplying 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 Virginian. 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 Virginian. 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.
eroded sand and mud to central and western Oklahoma. Al-
luvial, deluvial, and nearshore-marine red sandstone and shale characterizes the Early Permian sea margin, interdigitating 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, 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 Okla-
oma. Latest Permian (Ochoan) rocks are mostly red-bed sandstones and shales, but they contain some gypsum and 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 Okla-
oma 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 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 ex-
tended into Oklahoma during the Jurassic. Triassic and Juras-
sic 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 Creta-
ceous, and shallow seas extended north in the great inun-
dation 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 ma-
jor unconformity is exposed throughout the southeast, where Cretaceous strata rest on rocks from the Precambrian through the Permian. Uplift of the Rocky Mountains in the Late Cre-
taceous and Early Tertiary caused the broad Uplift of Oklahoma, imparing an eastward tilt that resulted in the final withdrawal of the sea.

Cretaceous marine rocks in southeastern and western Oklahoma contain shell teeth and various invertebrate fos-
sils, such as oysters, echinoids, and giant ammonites. Non-
marine Cretaceous strata contain dinosaur bones.

Cretaceous strata have been eroded from almost all parts of western Oklahoma (Fig. 16), except where blocks of Cret-
taceous 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 south-
west corner of Oklahoma in the Early Tertiary, and the shore-
line gradually retreated southward through the remainder of the period. Oklahoma supplied some sediments deposited to the southeast, including gravels, sands, and clays (Fig. 17).

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 co-
alescing 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 east-
ward. 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 to-
day. 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 Moun-
tain glaciers and the increased precipitation associated with glaciation sculpted Oklahoma’s land (Fig. 18). Today’s major drainage systems originated during the Pleistocene. The riv-
ers’ 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 riv-
ers. In this manner, hills and mountains are eroded, and sedi-
mments are transported to the sea, or are temporarily deposited in river beds and banks and in lake bottoms. Clay, silt, sand,
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 rock crops 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 overlaying older rocks in Oklahoma.

Bedrock geology on this map is derived from Mi-sier (1954). Quaternary alluvium and terrace deposits are derived from nine hydrologic atlas 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).

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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 ground-water 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.
A geographic 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 morphology 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 readily; 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 southeastern 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.

**GEOMORPHIC PROVINCES OF OKLAHOMA**

Neville M. Curtis, Jr., William E. Ham, and Kenneth S. Johnson, 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 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; most occurred in the El Reno vicinity, which also is the site of numerous earthquakes since 1908. Canadian County; most occurred in the El Reno vicinity, which also is the site of numerous earthquakes since 1908. Canadian County; most occurred in the El Reno vicinity, which also is the site of numerous earthquakes since 1908. Canadian County; most occurred in the El Reno vicinity, which also is the site of numerous earthquakes since 1908.

**Explaination**

The most common ways to express the size of earthquakes are by their intensity and magnitude. The intensity, reported on the Modified Mercalli (MM) Earthquake-Intensity Scale (modified from Wood and Neumann, 1931), is a subjective measure based on eyewitness accounts (Table 2). Intensity and magnitude. The intensity, reported on the Modified Mercalli (MM) Earthquake-Intensity Scale, is a subjective measure based on eyewitness accounts (Table 2). Intensity and magnitude.

<table>
<thead>
<tr>
<th>Date</th>
<th>Origin time (UTC)</th>
<th>Nearest town</th>
<th>Nearest town</th>
<th>Intensity MM</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962 Jan 21</td>
<td>00:03</td>
<td>El Reno</td>
<td>0°W</td>
<td>VII</td>
<td></td>
</tr>
<tr>
<td>1962 Jan 21</td>
<td>00:03</td>
<td>El Reno</td>
<td>0°W</td>
<td>VII</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2. Modified Mercalli (MM) Earthquake-Intensity Scale**

<table>
<thead>
<tr>
<th>Date</th>
<th>Origin time (UTC)</th>
<th>Nearest town</th>
<th>Nearest town</th>
<th>Intensity MM</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962 Jan 21</td>
<td>00:03</td>
<td>El Reno</td>
<td>0°W</td>
<td>VII</td>
<td></td>
</tr>
<tr>
<td>1962 Jan 21</td>
<td>00:03</td>
<td>El Reno</td>
<td>0°W</td>
<td>VII</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3. Oklahoma Earthquakes with Magnitudes 2.0 or Greater**

<table>
<thead>
<tr>
<th>Date</th>
<th>Origin time (UTC)</th>
<th>Nearest town</th>
<th>Nearest town</th>
<th>Magnitude mbLg</th>
<th>Magnitude mDUR</th>
<th>Magnitude m3Hz</th>
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</thead>
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<tr>
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<td>00:03</td>
<td>El Reno</td>
<td>0°W</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1962 Jan 21</td>
<td>00:03</td>
<td>El Reno</td>
<td>0°W</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Historical Earthquakes**

The New Madrid, Missouri, earthquakes of 1811 and 1812 probably are the earliest historical earthquakes tremors felt in present-day southeast Oklahoma. 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 McCurtain 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.
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. 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.
Oil and Gas

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; but once the seal is breached, the oil and gas can enter a hydrocarbon trap in which oil and gas accumulate. Most Oklahoma oil and gas fields are associated with reservoirs that produce chemicals derived from petroleum, and those 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 Refinery
  There were five major petroleum refineries operating in Oklahoma at the end of 2000, each with a daily capacity of 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 those 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 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.

**Exploration**

Oil and gas production comes from sedimentary basins of Pennsylvanian age (287–320 million years ago). Reservoirs across Oklahoma, and gas production comes from basin throughout the world. The basic process is the same, but the geology and hydrocarbon reservoirs differ.

**Formation**

Seepage (or migration) of oil and gas into the atmosphere is 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.
streams and tributaries, however, have decreased flooding frequency and plain. These broad, sand-filled channels reflect large changes in discharge active water courses occupying a small portion of the river bed or flood terraces, high above the flood plains of today’s streams that are years before finally carving out today’s major drainage basins. The posi drainage systems of today were established during the Pleistocene (the terms of geologic time. Stream positions shift as they cut deeper chan creeks funneling water to the main course.

All major streams in Oklahoma have broad, sand-filled channels with 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 channels 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.

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 channels 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.

Many major streams in Oklahoma have broad, sand-filled channels with active water courses occupying a small portion of the river bed or flood plains. 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 Seagoville Counties in the Ozark Plateau. They include parts of the Illinois River (1, see map), and Flint (2), Baros 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 northeastern Oklahoma are Salton 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 Booby 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 inflows 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. They are unique and multi-functional entities that serve a variety of ecological, economic, and recreational needs. The two largest are Lake Texoma (1) 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).
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 (1983), and John- nerson and Moore (1975), Carr and Bergman (1976), Havens (1977), Bingham and Bergman (1989), Morton (1983), Marcher and Bergman (1983), and John- nerson (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.

PRINCIPAL GROUND-WATER RESOURCES OF OKLAHOMA

Kenneth S. Johnson, Oklahoma Geological Survey
Table 5. Total estimated available water for each stream system or subsystem in the Red River and Arkansas River drainage basins within Oklahoma.

<table>
<thead>
<tr>
<th>Stream System</th>
<th>Red River and Tributaries*</th>
<th>Drainage Area (sq mi)</th>
<th>Total Estimated Available Water (billion cu ft)</th>
<th>Arkansas River and Tributaries*</th>
<th>Drainage Area (sq mi)</th>
<th>Total Estimated Available Water (billion cu ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1 Main stem of Red River</td>
<td>410</td>
<td>1,345</td>
<td>2,912,988</td>
<td>3-1 Potomac River</td>
<td>1,149</td>
<td>1,028,272</td>
</tr>
<tr>
<td>1-2 Little River</td>
<td>2,204</td>
<td>866</td>
<td>3,310,370</td>
<td>3-2 Middle North Canadian River</td>
<td>758</td>
<td>55,529</td>
</tr>
<tr>
<td>1-3 Kiarnochi River</td>
<td>1,821</td>
<td>3,080</td>
<td>114,247</td>
<td>3-3 Upper North Canadian River</td>
<td>650</td>
<td>3,660</td>
</tr>
<tr>
<td>1-4 Mudzy Biggy Creek</td>
<td>2,551</td>
<td>3,660</td>
<td>8,398</td>
<td>3-4 Upper Canadian River</td>
<td>2,161</td>
<td>1,485,317</td>
</tr>
<tr>
<td>1-5 Main stem of Red River</td>
<td>1,11</td>
<td>2,021</td>
<td>1,866</td>
<td>3-5 Lower Canadian River</td>
<td>2,021</td>
<td>6,056</td>
</tr>
<tr>
<td>1-6 Blue River</td>
<td>678</td>
<td>2,642</td>
<td>2,048,652</td>
<td>3-6 Middle North Canadian River</td>
<td>1,136</td>
<td>192,887</td>
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<tr>
<td>1-7 Main stem of Red River</td>
<td>332</td>
<td>947</td>
<td>947,012</td>
<td>3-7 Upper Kansas River</td>
<td>2,537</td>
<td>692,965</td>
</tr>
<tr>
<td>1-8-1 Lower Washita River</td>
<td>2,364</td>
<td>804</td>
<td>804,012</td>
<td>3-8 Lower Cimarron River</td>
<td>2,021</td>
<td>103,666</td>
</tr>
<tr>
<td>1-8-2 Middle Washita River</td>
<td>1,660</td>
<td>396</td>
<td>396,065</td>
<td>3-9 Middle Cimarron River</td>
<td>1,179</td>
<td>292,814</td>
</tr>
<tr>
<td>1-8-3 Upper Washita River</td>
<td>2,264</td>
<td>1,136</td>
<td>1,136</td>
<td>3-10 Upper Kansas River</td>
<td>1,136</td>
<td>3,660</td>
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<tr>
<td>1-9 Washita River headwaters</td>
<td>1,037</td>
<td>1,795</td>
<td>1,795</td>
<td>3-11 Lower Cimarron River</td>
<td>1,795</td>
<td>195,058</td>
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<tr>
<td>1-10 Main stem of Red River (Waltz)</td>
<td>650</td>
<td>980</td>
<td>980,065</td>
<td>3-12 Lower Caney Creek</td>
<td>697</td>
<td>27,298</td>
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<tr>
<td>1-11 Prewitts (or Oklahoma)</td>
<td>337</td>
<td>3,677</td>
<td>3,677</td>
<td>3-13 Salt Fork Arkansas River</td>
<td>516</td>
<td>3,081</td>
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<tr>
<td>1-12 Elk Creek</td>
<td>1,101</td>
<td>2,161</td>
<td>2,161</td>
<td>3-14 Washita River</td>
<td>2,143</td>
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<tr>
<td>1-13-1 East Cache Creek</td>
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<td>947</td>
<td>947,012</td>
<td>3-15 Little River</td>
<td>2,143</td>
<td>2,469,260</td>
</tr>
<tr>
<td>1-13-2 Deep Red Creek and West Cache</td>
<td>1,101</td>
<td>3,677</td>
<td>3,677,070</td>
<td>3-16 Little River</td>
<td>1,136</td>
<td>994,284</td>
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<td>1-14 Main stem of Red River (Cache Creek)</td>
<td>380</td>
<td>44,587</td>
<td>44,587,000</td>
<td>3-17 Grimes Creek</td>
<td>1,177</td>
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<tr>
<td>1-15-1 Lower North Fork of Red River</td>
<td>1,396</td>
<td>1,795</td>
<td>1,795,000</td>
<td>3-18 Upper North Fork of Red River</td>
<td>1,136</td>
<td>944,284</td>
</tr>
<tr>
<td>1-15-2 Upper North Fork of Red River</td>
<td>860</td>
<td>947</td>
<td>947,012</td>
<td>3-20 North Dakota River</td>
<td>1,136</td>
<td>1,345,000</td>
</tr>
<tr>
<td>1-16 Salt Fork of Red River</td>
<td>714</td>
<td>1,177</td>
<td>1,177</td>
<td>3-21 Kansas River</td>
<td>1,136</td>
<td>1,205,310</td>
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<tr>
<td>1-17 Main stem of Red River (Salt Fork of Red River)</td>
<td>492</td>
<td>1,177</td>
<td>1,177,000</td>
<td>3-22 Lower Washita River</td>
<td>1,177</td>
<td>1,177,000</td>
</tr>
<tr>
<td>1-18 Elk Fork of Red River</td>
<td>567</td>
<td>353</td>
<td>353,012</td>
<td>3-23 Lower Washita River</td>
<td>353</td>
<td>353,012</td>
</tr>
<tr>
<td>1-19 Grand (Naoshio) River</td>
<td>53</td>
<td>53</td>
<td>53,065</td>
<td>3-24 Poteau River</td>
<td>53</td>
<td>53,065</td>
</tr>
<tr>
<td>1-20 Poteau River</td>
<td>650</td>
<td>214</td>
<td>214,065</td>
<td>3-25 Judd Creek</td>
<td>214</td>
<td>214,065</td>
</tr>
</tbody>
</table>

*Tributaries not shown on the map of stream systems are shown on page 12 (Rivers, Streams, and Lakes of Oklahoma). Water withdrawals extend into many 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.

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

Table 5 summarizes the total estimated available water for each system or subsystem. The Red River basin contains about 10,150,000 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 9,050,000 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.

The Oklahoma Water Resources Board (OWRB) divides Oklahoma 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 subsystems (Fabian and Kennedy, 1998).
Flood-Prone Areas—
Areas of Karst and Salt Dissolution—
Landslides—
Earthquakes—
Expansive Soils—
Geological Survey (Water Resources Division), the U.S. Army Corps of Engineers, and county courthouses, city-engineer offices, or city-planning departments. 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, governmental, 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 water power plants, and to provide information necessary to establish insurance rates. Earthquakes frequently occur in three principal areas in Oklahoma (Fig. 21), including: Cana-.

**Expansive Soils**—Clay-rich soils, 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 geological units in Oklahoma having high shrink-swell potential are Cretaceous shales underlying bedrock. The landslide threat is higher where natural slopes exceed a 2:1 gradient.

**Landslides**—Landslides and slump areas are a common highway-construction problem in parts of Oklahoma. Hill slopes in southwestern Oklahoma and parts of Kansas and Missouri (Fig. 25). Underground mines extracting gypsum, 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 earth’s 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 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 mining districts 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 dolostone, limestone, and clay-rich sandstone, sandstone, 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.
Western Oklahoma—The Canadian Plains and Valley MLRA contains brown, loamy soils developed on sandstone cobbles, shale, and associated foot slopes (clays) under mid and short grasses. Soils of the Cross Timbers are dark, loamy with clay subsoils developed on loamy sands under oak-hickory forests. Coastal Prairie soils are light-colored, sandy, and loamy with clayey subsoils developed on sandstone and shale under oak-hickory forests.

Central Oklahoma—Soils in the Central Rolling Red Prairies are dark and loamy with clayey subsoils developed on loamy sands, sandy loams, and alluvial deposits under tall grasses. Soils of the Cross Timbers are dark, loamy with clayey subsoils developed on loamy sands under oak-hickory forests.

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 forest and tall grasses. Soils in the Ouachita Mountains are light-colored, sandy, and loamy with clayey subsoils developed on sandstone and shale under oak-hickory forests. Arkansas River and Valley soils are light-colored, sandy, and loamy with clayey subsoils developed on steep slopes and ridges and are very deep and loamy on gentle slopes and shales in valleys.

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.
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 in 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. Grasslands 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.

The vegetation types discussed in this publication are shaded or highlighted on the accompanying map. The map is included to provide a visual representation of the vegetation types described in the text.
Temperature

<table>
<thead>
<tr>
<th>Season</th>
<th>Averaged Temperature</th>
<th>Normal (1971-2000)</th>
<th>Warmest Year</th>
<th>Coldest Year</th>
<th>Record Low Temperature</th>
<th>Record High Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>°F</td>
<td>29.2°</td>
<td>32.0°</td>
<td>-12.2°</td>
<td>-10.0°</td>
<td>30.1°</td>
</tr>
<tr>
<td>Spring</td>
<td>°F</td>
<td>50.5°</td>
<td>53.2°</td>
<td>37.4°</td>
<td>54.1°</td>
<td>58.2°</td>
</tr>
<tr>
<td>Summer</td>
<td>°F</td>
<td>81.0°</td>
<td>87.7°</td>
<td>71.8°</td>
<td>71.4°</td>
<td>93.0°</td>
</tr>
<tr>
<td>Autumn</td>
<td>°F</td>
<td>61.2°</td>
<td>63.9°</td>
<td>41.8°</td>
<td>43.3°</td>
<td>70.2°</td>
</tr>
</tbody>
</table>

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. Transition periods of spring and autumn separate the two extremes.

Winter weather is controlled by the polar jet stream, a continuous band of cold air showers that travel southward across North America. In the spring, the jet stream breaks up into individual storms that can be tracked for several days or longer, providing Oklahoma with some of the year's most pleasant weather.

CLIMATE OF OKLAHOMA

Howard L. Johnson, Oklahoma Climatological Survey

Table 6. Oklahoma Weather Facts

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Statewide/Averaged Annual Precipitation (inches)</th>
<th>Normal (1971-2000)</th>
<th>18.94 in.</th>
<th>36.44 in.</th>
<th>38.22 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Precipitation</td>
<td>36.44 in.</td>
<td>18.94 in.</td>
<td>10.05 in.</td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>Precipitation</td>
<td>38.22 in.</td>
<td>10.05 in.</td>
<td>36.44 in.</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>Precipitation</td>
<td>45.28 in.</td>
<td>36.44 in.</td>
<td>38.22 in.</td>
<td></td>
</tr>
<tr>
<td>Autumn</td>
<td>Precipitation</td>
<td>36.44 in.</td>
<td>38.22 in.</td>
<td>36.44 in.</td>
<td></td>
</tr>
</tbody>
</table>

Winter precipitation is associated with cold fronts that move southward from Canada and the north central United States. Spring precipitation is associated with thunderstorm systems along the lee trough. Summer precipitation is associated with tropical storms and hurricanes. Autumn precipitation is associated with remnants of hurricanes that strike the Texas coast or the Gulf of Mexico. Most 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.
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 and vegetables. Home gardeners are sensitive to these dates. The average frost-free period ranges from 24 weeks in the western Panhandle to 33

Tornadoes

Tornadoes are violent columns of rotating air associated with very strong thunderstorms. Disastrous tornado 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 be 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.

Table 7. Fujita F-scale of Tornado Intensity

<table>
<thead>
<tr>
<th>F-scale</th>
<th>Severe Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>Weak Tornado</td>
</tr>
<tr>
<td>F1</td>
<td>Moderate Tornado</td>
</tr>
<tr>
<td>F2</td>
<td>Significant Tornado</td>
</tr>
<tr>
<td>F3</td>
<td>Sever Tornado</td>
</tr>
<tr>
<td>F4</td>
<td>Devastating Tornado</td>
</tr>
<tr>
<td>F5</td>
<td>Incredible Tornado</td>
</tr>
</tbody>
</table>

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.


REFERENCES


2. The reports of the Clinton and Woodward quadrangles in the Woodward series are part of the Woodward series published by the Oklahoma Geological Survey (OGS) (2017). These reports contain a variety of data, including geologic maps, stratigraphic sections, and hydrologic data. The data are used to understand the geology and hydrology of the area.

3. The Clinton quadrangle is located in the northeastern part of Oklahoma, and the Woodward quadrangle is located in the north-central part of the state. Both quadrangles are part of the Ozarkian Province, which is characterized by a series of uplifted, folded, and faulted basins.

4. The Clinton quadrangle is underlain by the Clinton Group, which is composed of sedimentary rocks deposited during the Pennsylvanian Period. The group is overlain by the Ozark Uplift, which is composed of crystalline basement rocks.

5. The Woodward quadrangle is underlain by the Woodward Group, which is composed of sedimentary rocks deposited during the Mississippian and Pennsylvanian Periods. The group is overlain by the Northwest Plains, which are composed of sedimentary rocks deposited during the Cretaceous Period.

6. The Clinton and Woodward quadrangles are part of the larger Oklahoma Geological Survey (OGS) quadrangle series, which consists of over 100 smaller quadrangles that cover the entire state of Oklahoma.