EARTH SCIENCES AND MINERAL RESOURCES OF OKLAHOMA
EARTH SCIENCES AND MINERAL RESOURCES OF OKLAHOMA
Kenneth S. Johnson and Kenneth V. Luza, Editors
2008

OKLAHOMA GEOLOGICAL SURVEY
The University of Oklahoma
Charles J. Mankin, Director

Front Cover:
Photo County location
Alabaster Caverns..............................Woodward
Chimney Rock......................................Woodward
Gypsum sinkhole...............................Comanche
Copper mill at Creta............................Jackson
Lady Cave...........................................Washita

Back Cover:
Glass Mountains...............................Major
Sprinkler irrigation............................Caddo
Granite in Witchitas............................Comanche
Limestone in Arbuckles..........................Murray
Tombstone topography.........................Carter
Lake Altus...........................................Greer
Solar-salt pans....................................Woods
Turner Falls.........................................Murray
Glass sands.........................................Johnston
Hennessey Shale.................................Cleveland

Hennessey Shale...............................Cleveland
Solar-salt pans...................................
Lake Altus.........................................
Tombstone topography..........................
Granite in Witchitas.......................
Sprinkler irrigation............................
Glass Mountains...................................
Back Cover:
Lady Cave...........................................
Copper mill at Creta............................

Front Cover:
Photo County location
Alabaster Caverns..............................Woodward
Chimney Rock......................................Woodward
Gypsum sinkhole...............................Comanche
Copper mill at Creta............................Jackson
Lady Cave...........................................Washita

Back Cover:
Glass Mountains...............................Major
Sprinkler irrigation............................Caddo
Granite in Witchitas............................Comanche
Limestone in Arbuckles..........................Murray
Tombstone topography.........................Carter
Lake Altus...........................................Greer
Solar-salt pans....................................Woods
Turner Falls.........................................Murray
Glass sands.........................................Johnston
Hennessey Shale.................................Cleveland

TABLE OF CONTENTS
1 Introduction Kenneth S. Johnson, Oklahoma Geological Survey
2 Topographic Map of Oklahoma Kenneth S. Johnson, Oklahoma Geological Survey
3-5 Geologic History of Oklahoma Kenneth S. Johnson, Oklahoma Geological Survey
7 Geologic Cross Sections in Oklahoma Kenneth S. Johnson, Oklahoma Geological Survey
9 Earthquakes of Oklahoma Kenneth V. Luza, Oklahoma Geological Survey
10 Mineral Deposits and Resources of Oklahoma (Exclusive of Oil and Gas) Kenneth S. Johnson, Oklahoma Geological Survey
11 Oil and Gas Production and Facilities of Oklahoma Dan T. Boyd, Oklahoma Geological Survey
13 Principal Ground-Water Resources of Oklahoma Kenneth S. Johnson, Oklahoma Geological Survey
15 Geologic Hazards in Oklahoma Kenneth V. Luza and Kenneth S. Johnson, Oklahoma Geological Survey
16 Soil Map of Oklahoma Brian J. Carter and Mark S. Gregory, Department of Plant and Soil Sciences, Oklahoma State University
17 Vegetation of Oklahoma Bruce Hoagland, Oklahoma Biological Survey
18-19 Climate of Oklahoma Howard L. Johnson, Oklahoma Climatological Survey
20-21 References and Glossary of Selected Terms

This publication, printed by the University of Oklahoma Printing Services for the Oklahoma Geological Survey, is issued by the Oklahoma Geological Survey as authorized by Title 70, Oklahoma Statutes, 1981, Sections 231-238. 3,000 copies have been prepared for distribution at a cost of $17,121.06 to the taxpayers of the State of Oklahoma. Copies have been deposited with the Publications Clearinghouse of the Oklahoma Department of Libraries.
EARTH SCIENCES AND MINERAL RESOURCES OF OKLAHOMA

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 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 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 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 primarily 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 geologic processes or conditions that 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 geologic 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

<table>
<thead>
<tr>
<th>GEOLOGIC ERA</th>
<th>GEOLOGIC PERIOD</th>
<th>BEGINNING (m.y.a.)</th>
<th>COMPARATIVE DATE*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td>Quaternary</td>
<td>1.6</td>
<td>December 31</td>
</tr>
<tr>
<td></td>
<td>Tertiary</td>
<td>0.6</td>
<td>December 26</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Cretaceous</td>
<td>146</td>
<td>December 20</td>
</tr>
<tr>
<td></td>
<td>Jurassic</td>
<td>208</td>
<td>December 15</td>
</tr>
<tr>
<td></td>
<td>Triassic</td>
<td>245</td>
<td>December 12</td>
</tr>
<tr>
<td>Paleozoic</td>
<td>Permian</td>
<td>286</td>
<td>December 8</td>
</tr>
<tr>
<td></td>
<td>Pennsylvanian</td>
<td>320</td>
<td>December 5</td>
</tr>
<tr>
<td></td>
<td>Mississippian</td>
<td>360</td>
<td>December 2</td>
</tr>
<tr>
<td></td>
<td>Devonian</td>
<td>409</td>
<td>November 28</td>
</tr>
<tr>
<td></td>
<td>Silurian</td>
<td>439</td>
<td>November 26</td>
</tr>
<tr>
<td></td>
<td>Ordovician</td>
<td>504</td>
<td>November 20</td>
</tr>
<tr>
<td></td>
<td>Cambrian</td>
<td>570</td>
<td>November 15</td>
</tr>
<tr>
<td>Precambrian</td>
<td>4,500</td>
<td>January 1</td>
<td></td>
</tr>
</tbody>
</table>

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 north-west 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 south 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-shé-tah”) Mountains in south-eastern Oklahoma and western Arkansas is a curved belt of forested ridges and subparallel valleys. Resistant sandstone, chert, and non-volcanic 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 eastern 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 and are 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.

A 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 Hunton 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 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 Arkansa Novaculite (chert) is Silurian, Devonian, and Early Mississippian. These three formations are 500–1,500 ft in total thickness.
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 Coosuk 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 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 and are shark teeth. (2) Pennsylvanian mountain-building caused important uplifts and erosion, with the deeper parts of major basins.

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.

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

Mississippian rocks are covered in Oklahoma by Pennsylvanian sandstones and shales. The Ouachita Basin, Ardmore, and eastern Anadarko Basins are the thickest parts of the deposits. Pennsylvanian sediments contain abundant invertebrate marine fossils and plant fossils. Pennsylvanian deposits 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. 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. Rocks in the Wichita, Arbuckle, Ouachita, and Ozark Uplifts are 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 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 Pennsylvanian Period.

Folding and uplift of pre-Morrowan rocks characterize a major Pennsylvanian orogeny, the Wichita orogeny (Mor-
Geologic History

ed sand and mud to central and western Oklahoma. Al-
luvial, deluvial, 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, dolomite in the west (Fig. 14). The entire Permian sequence is
characterized by red sand and shale, although thick 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-
mom (see Fig. 4 for explanation of symbols).

Figure 14. Principal rock types of Late Permian (Ochocoan) 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 ex-
tended into Oklahoma during the Jurassic. Triassic and Jurassic
silts in Oklahoma include some invertebrates, petrified wood, and vertebrates such as dinosaurs, crocodiles, turtles, and felines. 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 Cre-
taceous, and shallow seas extended north in the great inund-
ation of the western interior of the United States (including Oklahoma) during the Late Cretaceous. Sandstone, 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

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 thick in
deeper parts of the Anadarko Basin.

Permian sedimentary rocks in central and western Okla-
mom contain various fossils and minerals. Fossils, though rare, include vertebrates (e.g., fish, amphibians, and reptiles),
sects, and a few marine invertebrates. Minerals are more common and include gypsum (selenite and satinspar), 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).

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, imparting 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-
east 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).

Quaternary Period

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
today. The boundary between the epochs is about 11,500 years
ago, at the end of the Pleistocene and the beginning of the Ho-
locene.

In the Late Tertiary, a thick blanket of sand, silt, clay, and
gavel 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
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 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
terries, now tens to hundreds of feet above present-day flood
plains.

The Quaternary is characterized as a time when rocks and
and gavel sediments 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-
ments 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 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 overlying older rocks in Oklahoma.

Bedrock geology on this map is derived from Miyer (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).
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.
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 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 sandstone, 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.
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, 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. Each earthquake has a common calibration. To determine the size of earthquakes, the Oklahoma Geological Survey uses three magnitude types: mbLg (similar to Richter magnitude), mHHz, and mDUR (Lawson and Luza, 1995).

Prior to statehood, the earliest documented earthquake in Oklahoma was 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; 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 1947, 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, 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.
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; 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, and gas production comes from Precambrian (more than 570 million years ago) and Cretaceous (65–146 million years ago).

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, and gas production comes from Precambrian (more than 570 million years ago) and 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 1886 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, of which 13% is considered recoverable.

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. 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.
Natural salt plains occur along some rivers where natural brines seep to the surface. In the Arkansas River drainage, seepage systems are most pronounced near Red River in McCurtain County, covering 272 acres (Oklahoma Water Resources Board, 1990). Oklahoma has 62 oxbow lakes covering at least 10 acres each; the largest, 272 acres, is near Red River in McCurtain County. These natural saline lakes are also known as brine lakes and are used for 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. There are more than 600 of these intermittent or ephemeral playa lakes, but only a few persist year-round (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 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).

### Table 4. Major lakes and reservoirs in Oklahoma

<table>
<thead>
<tr>
<th>Lake</th>
<th>Area</th>
<th>Drainage Area</th>
<th>Capacity</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Pool</td>
<td>Normal Pool</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(acres)</td>
<td>(square miles)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(acre-feet)</td>
<td>County/Countries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>noodle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eufaula</td>
<td>105,500</td>
<td>47,522</td>
<td>2,314,600</td>
<td>McIntosh; Pittsburg; Haskell</td>
</tr>
<tr>
<td>Texoma</td>
<td>88,000</td>
<td>36,719</td>
<td>2,643,300</td>
<td>Love; Marshall; Bryan; Johnston</td>
</tr>
<tr>
<td>Grand Lake Of The</td>
<td>46,500</td>
<td>10,208</td>
<td>1,872,500</td>
<td>Delaware; Okfuskee; Mayes</td>
</tr>
<tr>
<td>Cherokee</td>
<td>43,800</td>
<td>147,756</td>
<td>525,700</td>
<td>Haskell; Sequoyah; Le Flore</td>
</tr>
<tr>
<td>Wister</td>
<td>7,333</td>
<td>993</td>
<td>62,360</td>
<td>Le Flore</td>
</tr>
<tr>
<td>Canton</td>
<td>7,910</td>
<td>12,483</td>
<td>111,310</td>
<td>Blaine; Dewey</td>
</tr>
<tr>
<td>Foss</td>
<td>8,880</td>
<td>1,496</td>
<td>256,220</td>
<td>Custer</td>
</tr>
<tr>
<td>Waurika</td>
<td>10,100</td>
<td>562</td>
<td>203,100</td>
<td>Jefferson; Stephens; Cotton</td>
</tr>
<tr>
<td>Skiatook</td>
<td>10,190</td>
<td>354</td>
<td>322,700</td>
<td>Osage</td>
</tr>
<tr>
<td>Hudson</td>
<td>10,900</td>
<td>11,533</td>
<td>220,300</td>
<td>Mayes</td>
</tr>
<tr>
<td>Webbers Falls</td>
<td>11,600</td>
<td>754</td>
<td>918,070</td>
<td>Muskogee</td>
</tr>
<tr>
<td>Skiatook</td>
<td>13,610</td>
<td>754</td>
<td>322,700</td>
<td>Muskogee</td>
</tr>
<tr>
<td>Hugo</td>
<td>13,260</td>
<td>1,709</td>
<td>157,600</td>
<td>Cherokee</td>
</tr>
<tr>
<td>Terikiller</td>
<td>12,900</td>
<td>1,610</td>
<td>654,100</td>
<td>Cherokee; Sequoyah</td>
</tr>
<tr>
<td>Webberrys Falls</td>
<td>11,600</td>
<td>97,033</td>
<td>170,100</td>
<td>Muskogee</td>
</tr>
<tr>
<td>Hudson</td>
<td>10,000</td>
<td>533</td>
<td>220,300</td>
<td>Mayes</td>
</tr>
<tr>
<td>Skiatook</td>
<td>10,190</td>
<td>354</td>
<td>322,700</td>
<td>Osage</td>
</tr>
<tr>
<td>Waurika</td>
<td>10,100</td>
<td>562</td>
<td>203,100</td>
<td>Jefferson; Stephens; Cotton</td>
</tr>
<tr>
<td>Foss</td>
<td>8,880</td>
<td>1,496</td>
<td>256,220</td>
<td>Custer</td>
</tr>
<tr>
<td>Great Salt Plains</td>
<td>8,690</td>
<td>3,200</td>
<td>31,420</td>
<td>Atalissa</td>
</tr>
<tr>
<td>Canton</td>
<td>7,910</td>
<td>12,483</td>
<td>111,315</td>
<td>Blaine; Dewey</td>
</tr>
<tr>
<td>Wister</td>
<td>7,333</td>
<td>993</td>
<td>62,360</td>
<td>Le Flore</td>
</tr>
</tbody>
</table>

*Data from the Oklahoma Water Resources Board (1990).*

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 rock.

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), Barons 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 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 (Sutton) (8) Salt Plains on Elm Fork in north Harmon County; and Jackson County Salt Plain (9). Downstream in both drainage basins, fresh-water inflows dilute 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.
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 and Bergman (1971), Hart (1974), Bingham and Moore (1975), Carr and Bergman (1976), Havens (1977), Bingham and Bergman (1980), Morton (1983), Marcher and Bergman (1983), and John-

* 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

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 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.

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 Okla-

### EXPLANATION

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>AQUIFER</th>
<th>PRINCIPAL LITHOLOGY</th>
<th>COMMON YIELD (gallons per minute)</th>
<th>GENERAL MINERAL CONTENT OF WATER</th>
</tr>
</thead>
<tbody>
<tr>
<td>QU</td>
<td>Quaternary alluvium and terrace deposits (Q)</td>
<td>Sand, silt, and gravel</td>
<td>10–50 (up to 2,000)</td>
<td>Low to high (alluvium) low (terrace)</td>
</tr>
<tr>
<td>OG</td>
<td>Ogallala Formation (T)</td>
<td>Sand, silt, and gravel</td>
<td>25–1,500</td>
<td>Low</td>
</tr>
<tr>
<td>AR</td>
<td>Arbuckle Sandstone (Tremont Group) (K)</td>
<td>Sandstone and sand</td>
<td>10–50</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>ELK</td>
<td>Elk City Sandstone (P)</td>
<td>Sandstone</td>
<td>25–300</td>
<td>Low</td>
</tr>
<tr>
<td>FSH</td>
<td>Rush Springs Sandstone and Marlow Formation (P)</td>
<td>Sandstone</td>
<td>25–300</td>
<td>Low to moderate; moderate to high in north</td>
</tr>
<tr>
<td>BRF</td>
<td>Blaine Formation and Dog Creek Shale (P)</td>
<td>Gypsum and dolomite</td>
<td>300–2,500</td>
<td>Moderate to high</td>
</tr>
<tr>
<td>CH</td>
<td>Cedar Hills Sandstone (P)</td>
<td>Sandstone</td>
<td>150–300</td>
<td>Low to high</td>
</tr>
<tr>
<td>GAR</td>
<td>Garber Sandstone and Wellington Formation (P)</td>
<td>Sandstone</td>
<td>25–400</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>OSC</td>
<td>Oscar Group, area a (P)</td>
<td>Sandstone</td>
<td>25–50</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>OSC2</td>
<td>Oscar Group, area a (P)</td>
<td>Sandstone</td>
<td>50–180</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>VFA</td>
<td>Vancleave Formation and Ada Group (P)</td>
<td>Sandstone</td>
<td>25–150</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>NS</td>
<td>Niose Sandstone (K)</td>
<td>Sandstone</td>
<td>10–50</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>KDL</td>
<td>Kendrick and Reeds Spring Formations (“Boone”) (M)</td>
<td>Limestone and chert or cherty limestone</td>
<td>5–50</td>
<td>Low</td>
</tr>
<tr>
<td>ARK</td>
<td>Arkansas Novaculite and Bigks Chert (M, D, S, O)</td>
<td>Fractured chert and novaculite</td>
<td>10–50</td>
<td>Low</td>
</tr>
<tr>
<td>RGF</td>
<td>Redioux,ies,es, and Emience Formations (O, C)</td>
<td>Cherty dolomite and sandstone</td>
<td>50–250</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>SIM</td>
<td>Simpson and Arbuckle Groups (O, C)</td>
<td>Limestone, dolomite, and sandstone</td>
<td>25–600</td>
<td>Low</td>
</tr>
<tr>
<td>ART</td>
<td>Articolle and Timbertop Hills Group (O, C)</td>
<td>Limestone, dolomite, and some sandstone</td>
<td>25–600</td>
<td>Low to moderate</td>
</tr>
</tbody>
</table>

*Symbols in parentheses indicate geologic age, as shown on the Geologic Map of Oklahoma on page 6.
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>Red River System</th>
<th>Arkansas River System</th>
<th>Total Estimated Available Water (acre-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Area (sq mi)</td>
<td>Drainage Area (sq mi)</td>
<td>Total Estimated Available Water (acre-ft)</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>1-1 Main stem of Red River (Arkansas River to Arkansas state line)</td>
<td>410</td>
<td>24,928</td>
</tr>
<tr>
<td>1-2 Little River</td>
<td>2,204</td>
<td>2,814,256</td>
</tr>
<tr>
<td>1-3 Kiemlich Creek</td>
<td>1,821</td>
<td>2,049,652</td>
</tr>
<tr>
<td>1-4 Muddy Boggy Creek</td>
<td>2,561</td>
<td>1,977,143</td>
</tr>
<tr>
<td>1-5 Main stem of Red River (Blue River to Kiemlich River)</td>
<td>111</td>
<td>89,800</td>
</tr>
<tr>
<td>1-6 Blue River</td>
<td>678</td>
<td>349,130</td>
</tr>
<tr>
<td>1-7 Main stem of Red River (Lake Texoma Dam to Blue River)</td>
<td>332</td>
<td>194,773</td>
</tr>
<tr>
<td>1-8-1 Lower Washita River</td>
<td>1,160</td>
<td>220,242</td>
</tr>
<tr>
<td>1-8-2 Upper Washita River</td>
<td>2,286</td>
<td>329,386</td>
</tr>
<tr>
<td>1-8-3 Washita River headwaters</td>
<td>1,037</td>
<td>34,427</td>
</tr>
<tr>
<td>1-9 Main stem of Red River (Salt Fork of Red River)</td>
<td>650</td>
<td>209,000</td>
</tr>
<tr>
<td>1-10 Bayou to Lake Texoma Dam</td>
<td>337</td>
<td>71,783</td>
</tr>
<tr>
<td>1-11 Mud Creek</td>
<td>938</td>
<td>1,260,770</td>
</tr>
<tr>
<td>1-12 Beaver Creek</td>
<td>882</td>
<td>227,144</td>
</tr>
<tr>
<td>1-13-1 East Cache Creek</td>
<td>931</td>
<td>246,003</td>
</tr>
<tr>
<td>1-13-2 Deep Red Creek and West Cache Creek</td>
<td>1,101</td>
<td>231,457</td>
</tr>
<tr>
<td>1-14 Main stem of Red River (Cache Creek to North Fork of Red River)</td>
<td>380</td>
<td>44,587</td>
</tr>
<tr>
<td>1-15-1 Lower North Fork of Red River</td>
<td>1,136</td>
<td>156,566</td>
</tr>
<tr>
<td>1-15-2 Upper North Fork of Red River</td>
<td>860</td>
<td>90,858</td>
</tr>
<tr>
<td>1-16 Salt Fork of Red River</td>
<td>714</td>
<td>192,887</td>
</tr>
<tr>
<td>1-17 Main stem of Red River (Salt Fork of Red River to Texas state line)</td>
<td>492</td>
<td>19,680</td>
</tr>
<tr>
<td>1-18 Elms Fork of Red River</td>
<td>567</td>
<td>69,332</td>
</tr>
</tbody>
</table>

*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.

**Note:** Tributaries not shown on the map of stream systems are shown on page 12 (Rivers, Streams, and Lakes of Oklahoma). 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.
Geologic Hazards in Oklahoma

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

Introduction

Oklahoma is a region of geologic hazards. Natural hazards include flooding, landslides, earthquakes, and radon, while anthropogenic hazards include underground mining, strip mining, and chemical and biological contamination. This publication will provide an overview of the geologic hazards in Oklahoma.

Flooding

Flooding is a common hazard in Oklahoma. The state is located in a region of high precipitation, and many areas are prone to flood. Floods can occur due to heavy rainfall, snowmelt, and the release of water from reservoirs. The state has a history of floods, with the 1951 flood being the worst in the state's history.

Landslides

Landslides are a common problem in Oklahoma, particularly in the eastern part of the state. They are caused by a variety of factors, including heavy rainfall, earthquakes, and the movement of soil and rock downslope.

Earthquakes

Earthquakes are a concern in Oklahoma, particularly in the eastern part of the state. The state is located in a seismic zone, and earthquakes can cause damage to buildings and infrastructure.

Radon

Radon is a naturally occurring radioactive gas that can build up in homes and other buildings. It is a concern in Oklahoma, particularly in areas with high radon levels. Radon can cause lung cancer, and the U.S. Environmental Protection Agency has set guidelines for radon levels in homes.

Underground Mines

Underground mining is a significant industry in Oklahoma, and it can pose hazards to the environment and public health. The state has a history of mining for coal and other minerals, and the mining industry has been associated with water contamination, air pollution, and other environmental problems.

Conclusion

Oklahoma is a region with a variety of geologic hazards. The state has a history of flooding, landslides, earthquakes, and radon, as well as underground mining. The state and federal governments have taken steps to address these hazards, but there is still much work to be done.
Western Oklahoma—The Canadian Plains and Valley MLRA contains brown, loamy soils developed on sandstone and siltstone, with moderately clayey subsoils. These soils are under tall grasses. Coastal Plain soils are light colored, acid, and sandy on sandy soils developed on well-drained, gently sloping areas.

Central Oklahoma—Soils in the Central Rolling Red Prairies are dark and loamy, with clayey subsoils developed on loess and siltstone. These soils are under mixed prairies or savannah. Arkansas Ridge and Valley soils are deep, dark-colored, with clayey subsoils developed on deep, loamy soils under mixed prairies or savannah. Coastal Plain soils are light colored, acid, and sandy on sandy soils developed on well-drained, gently sloping areas.

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 sandstone and siltstone. Arkansas Ridge and Valley soils are light colored, acid, and sandy on sandy soils developed on well-drained, gently sloping areas.

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.

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 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 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 direct contact with one another. 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 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 direct contact with one another. 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.
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 temperatures.)

Mean annual temperatures increase from north to south (Fig. 26A). Mean seasonal temperatures are also given (Fig. 26B). Mean seasonal precipitation is shown (Fig. 27A-B).

Moisture arrives from the Gulf of Mexico, borne on southerly winds across Oklahoma. The size, location, and strength of circulating air masses determine if southerly winds deliver either warm, moist air from the Gulf of Mexico, or hot, dry air from the desert Southwest. 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.

Precipitation

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 55.7 inches at Smithville (McCurtain County) in the Ouachita Mountains to 16.86 inches at Regnier (Curtain County) in the panhandle. 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.

CLIMATE OF OKLAHOMA

Howard L. Johnson, Oklahoma Climatological Survey

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 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.

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 55.7 inches at Smithville (McCurtain County) in the Ouachita Mountains to 16.86 inches at Regnier (Curtain County) in the Panhandle. 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.

The wettest period is springtime, the season with the heaviest thunderstorm activity (Fig. 27A). Spring rain associated with thunderstorms 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.

Table 6. Oklahoma Weather Facts

<table>
<thead>
<tr>
<th>Season</th>
<th>Average Annual Precipitation (in inches)</th>
<th>Maximum Rainfall (in inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>10.77</td>
<td>33.49</td>
</tr>
<tr>
<td>Spring</td>
<td>21.37</td>
<td>50.00</td>
</tr>
<tr>
<td>Summer</td>
<td>15.82</td>
<td>24.90</td>
</tr>
<tr>
<td>Autumn</td>
<td>9.37</td>
<td>13.88</td>
</tr>
</tbody>
</table>

*For the period of 1992-2000 unless otherwise noted.
*Compiled by the Oklahoma Climatological Survey from U.S. National Weather Service data.
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).

Crowing 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.

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 Tulsai County in the northeast.

April through June is the most active period (Fig. 33), but tornadoes can occur 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.
ACKNOWLEDGMENTS

The manuscript and maps were reviewed by John Simms, Northeastern State University, Tahlequah, Oklahoma, along with Neil H. Suneson and several other Oklahoma Geological Survey staff members. They made many significant recommendations that have been incorporated in the publication, and we are grateful for their assistance.

 Numerous individuals assisted in various phases of the project. Special thanks to Ian Butler, Oklahoma Biological Survey, who provided a digital file of Ducks and Fletcher’s Game Type Map at a scale of 1:500,000 that we used to prepare the vegetation map (page 17). Robert S. Fabian of the Oklahoma Water Resources Board provided a digital file of Duck and Fletcher’s Game Type Map at a scale of 1:50,000.

Prepared by Neil H. Suneson

Figure 35. The generalized stratigraphic column shows selected rock units of Oklahoma. Ages of geologic-time periods are approximate. Rock units separated by commas show the youngest first; rock units with hyphens are definite or interchangeable. Shaded areas represent unconformities. Row or column height does not indicate thickness of rock units. The reader may refer to Figure 1 that illustrates the major geologic provinces of Oklahoma. Sources used to compile the stratigraphic column are Huffman (1956), Zeller (1968), Sutherland and Manger (1979), Bingham and Bergman (1980), Hills and Kottlowski (1983), Lucas and others (1987), and Markin (1987), and Arbenz (1989).
Glass Mountains
Sprinkler irrigation
Granite in Witchitas
Solar-salt pans
Lake Altus
Limestone in Arbuckles
Tombstone topography
Glass sands
Turner Falls
Hennessey Shale