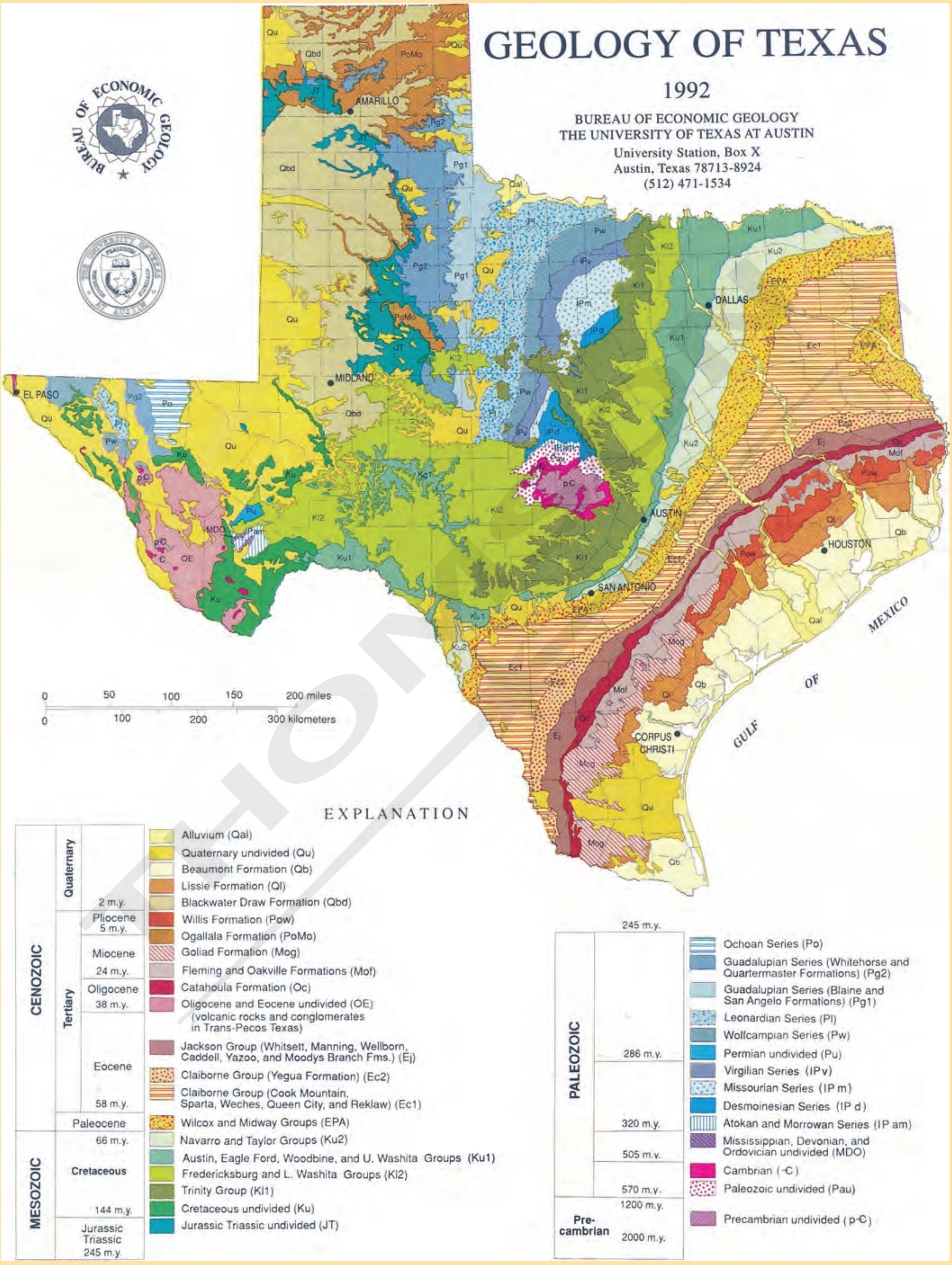
Texas

Rio Grande valley, west of Big Bend, with exposures of Tertiary volcanics.

The Geology of Texas

C. Reid Ferring

University of North Texas


GEOLOGY OF TEXAS
1992
BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN
University Station, Box X
Austin, Texas 78713-8924
(512) 471-1534
BUREAU OF ECONOMIC GEOLOGY
AMARILLO
MIDLAND
EL PASO
DALLAS
AUSTIN
SAN ANTONIO
HOUSTON
CORPUS CHRISTI
GULF OF MEXICO
0 50 100 150 200 miles
0 100 200 300 kilometers
EXPLANATION
CENOZOIC
Quaternary
2 m.y.
Tertiary
Pliocene
5 m.y.
Miocene
24 m.y.
Oligocene
38 m.y.
Eocene
58 m.y.
Paleocene
66 m.y.
MESOZOIC
Cretaceous
144 m.y.
Jurassic Triassic
245 m.y.
Alluvium (Qal)
Quaternary undivided (Qu)
Beaumont Formation (Qb)
Lissie Formation (Ql)
Blackwater Draw Formation (Qbd)
Willis Formation (Pow)
Ogallala Formation (PoMo)
Goliad Formation (Mog)
Fleming and Oakville Formations (Mof)
Catahoula Formation (Oc)
Oligocene and Eocene undivided (OE) (volcanic rocks and conglomerates in Trans-Pecos Texas)
Jackson Group (Whitsett, Manning, Wellborn, Caddell, Yazoo, and Moodys Branch Fms.) (Ej)
Claiborne Group (Yegua Formation) (Ec2)
Claiborne Group (Cook Mountain, Sparta, Weches, Queen City, and Reklaw) (Ec1)
Wilcox and Midway Groups (EPA)
Navarro and Taylor Groups (Ku2)
Austin, Eagle Ford, Woodbine, and U. Washita Groups (Ku1)
Fredericksburg and L. Washita Groups (Kl2)
Trinity Group (Kl1)
Cretaceous undivided (Ku)
Jurassic Triassic undivided (JT)
245 m.y.
PALEOZOIC
286 m.y.
320 m.y.
505 m.y.
570 m.y.
1200 m.y.
Pre-cambrian
2000 m.y.
Ochoan Series (Po)
Guadalupian Series (Whitehorse and Quartermaster Formations) (Pg2)
Guadalupian Series (Blaine and San Angelo Formations) (Pg1)
Leonardian Series (Pl)
Wolfcampian Series (Pw)
Permian undivided (Pu)
Virgilian Series (IPv)
Missourian Series (IP m)
Desmoinesian Series (IP d)
Atokan and Morrowan Series (IP am)
Mississippian, Devonian, and Ordovician undivided (MDO)
Cambrian (-C)
Paleozoic undivided (Pau)
Precambrian undivided (p-C)

ESSENTIAL QUESTIONS TO ASK

Texas.1 Introduction

- *Why is the geology of Texas important to students of physical geology and to all the inhabitants of the state today?*

Texas.2 Precambrian Texas

- *What tectonic events shaped the Proterozoic geologic record of Texas?*
- *When and how were the metamorphic and igneous rocks of the Llano region accreted to the ancient continent Laurentia?*

Texas.3 The Paleozoic Tectonic Cycle

- *What kinds of sediment were deposited during the Lower Paleozoic?*
- *What is the economic significance of these rocks today?*

Texas.4 The Ouachita Orogeny and Pangaea

- *What were the geologic results in Texas of the collision of Gondwana with Laurasia?*
- *How do the sedimentary rocks and structural styles of the Marathon area illustrate the collision?*

Texas.5 The Fort Worth Basin in the Late Paleozoic Era

- *What sedimentary environments characterized the Fort Worth Basin during and after the Ouachita orogeny?*
- *Why is this basin rich in oil and gas resources?*

Texas.6 Permian Red Beds and Evaporites

- *Why are red beds and evaporites characteristic of the Permian basins of central and west Texas?*
- *How does the geology of that region affect present-day land-use patterns?*

Texas.7 Breakup of Pangaea and Cretaceous Transgressions

- *What happened in Texas during and after the breakup of Pangaea?*
- *What were the results of the Cretaceous transgressions?*

Texas.8 Basin and Range Texas

- *What types of tectonic activity are indicated by the volcanic rocks in trans-Pecos Texas?*
- *How did the basin and range structural features form in that region?*

Texas.9 Llano Estacado

- *Which geologic processes led to the formation of the Llano Estacado?*
- *What is the Ogallala aquifer, and how is it recharged?*

Texas.10 Edwards Plateau and Balcones Fault Zone

- *When and how did the Edwards Plateau and Balcones Fault Zone form?*
- *How were these geologic features important to the initial settlement of Texas, and how are they important to Texans today?*

Texas.11 The Gulf Coastal Plain

- *How have transgressions and regressions shaped the geologic evolution of the Gulf Coastal Plain?*
- *What are the economic and environmental implications of using lignite to generate electricity?*
- *How did salt domes form, and why are economic resources concentrated around them?*

Texas.12 The Texas Gulf Coast

- *What are the principal features of the Texas Gulf Coast, and how did they form?*
- *How do hurricanes affect the coastal areas of Texas?*

Texas.1 Introduction

The decision to add this chapter on the geology of Texas to your textbook was based on the fact that you are taking this course in Texas and on the expectation that this discussion will increase the value you derive from learning about physical geology. There are practical reasons for illustrating physical geology concepts with examples from Texas. Perhaps most important is that these examples have been chosen to show the ways in which the geologic processes described in this textbook fit together in a story of how the Texas landscape developed over a vast period of time. These examples provide an excellent means of illustrating the **theory of plate tectonics**, translating it from a theoretical perspective into a regional one that is relevant and useful for a better understanding of the geologic history of the Texas region.

A substantial part of this chapter is devoted to illustrating why Texas is endowed with such vast energy resources, which define much of its economic structure and employ thousands of Texans. Although Texas is energy rich, it is water poor; therefore, we explore the distribution and character of the vital water resources in Texas. The factors of surface geology, climate, soils, and availability of groundwater are discussed in terms of the historical development of the state's agriculture and ranching industries, as well as patterns of settlement and urban growth.

Texas is part of the passive margin of the North American continent; thus, it is spared from geologic hazards such as large earthquakes and volcanic eruptions. But we will see that hurricanes and floods are frequent and often devastating events. Environmental protection in Texas entails considerable contributions from geologists, particularly with respect to minimizing the adverse environmental impacts realized through land-use activities such as lignite mining in the Gulf Coastal Plain. Along the way, you can pause to see examples of how the surface geology of our state adds to its diverse scenic beauty, which enriches our lives and contributes to the recreational and tourism industries. Indeed, one of the goals of this chapter is to nudge you to go see these places and enjoy their geologic stories firsthand.

The objective of your course in physical geology is to gain an understanding of the geologic processes that are characteristic of our planet and how the geology of our planet is important to our lives and livelihood. In terms of introducing geology to students, our curricula still follow the plan Charles Lyell first used in the 1830s. Lyell's *Principles of Geology* became the course you are taking now. It explores nature and the results of interactions among the geosphere, biosphere, and atmosphere.

A fundamental premise of Lyell's approach was that the geologic processes that operate today have not changed over time; therefore, we must study and understand the geologic present to interpret the geologic past. This approach is called **uniformitarianism**, and it is a cornerstone of the earth sciences. This chapter compares several modern environments with ancient settings in the rock record of Texas. These comparisons are supported by discussions in your text, including specific examples of how earth scientists formally apply this principle.

Lyell's companion volume, *Elements of Geology*, is taught today as historical geology, which examines the earth and life through time. Lyell eloquently labeled the sequences of ancient rocks and their included fossils as the "earth's autobiography." This chapter treats the geology of Texas chronologically, mainly because it enables us to take advantage of plate tectonics theory as we examine the autobiography of Texas.

The Geologic Map of Texas

The front piece for this chapter is the geologic map of Texas. You should refer to this map frequently as you read the following sections, and especially when you consider the photographs of surface geologic scenes. The geology map and the **physiographic map** (Figure Texas.1) show much of the geologic history and modern environmental diversity of the state. Notice the strong correspondence between the features of these two maps. They demonstrate that the rocks and sediments of Texas are not just parts of a chronologic sequence, but in many areas are also associated with distinct landforms and environments. While examining the photographs in subsequent sections, you will see different patterns of erosion and markedly different vegetation communities, defined by the dramatic decrease in rainfall from east to west across this huge land area.

Geologic maps are marvelous tools for exploring the geologic history and character of the areas they portray. The ages of the rock units are indicated by their color so that our eyes can search for patterns in their spatial arrangements that make both physical and chronologic sense. For example, notice that the Paleozoic rocks in north central Texas (see shades of blue in the front piece illustration) are progressively younger from east to west. In contrast, the rocks of the coastal plain are progressively younger from west to east. The boundary between these two regions is best marked by the **Balcones Fault Zone** (see red in Figure Texas.1). Can you explain these patterns by identifying the processes that produced them?

Another interesting feature is the nature of the contact between Cretaceous rocks (see green in Figure Texas.1) and adjacent rocks in the central part of the state. In this region, they directly overlie older rocks of the Precambrian and Paleozoic eras, and the Triassic Period. What could account for this? How much time is "missing" between the Cretaceous and older rocks? You will find the answers to these questions, and hopefully some of your own questions, in the following discussions and accompanying figures.

Section Texas.1 Summary

- Learning about the geology of Texas provides local examples of the main themes of physical geology, especially the theory of plate tectonics.
- Texas has abundant geologic resources, including petroleum, coal, minerals, groundwater, and fertile soils.

► **Figure Texas.1** This map shows the principal physiographic regions of Texas. *Stars* indicate the locations of localities discussed in this chapter. Note the close correspondence between these physiographic regions and the surface geology of the state.

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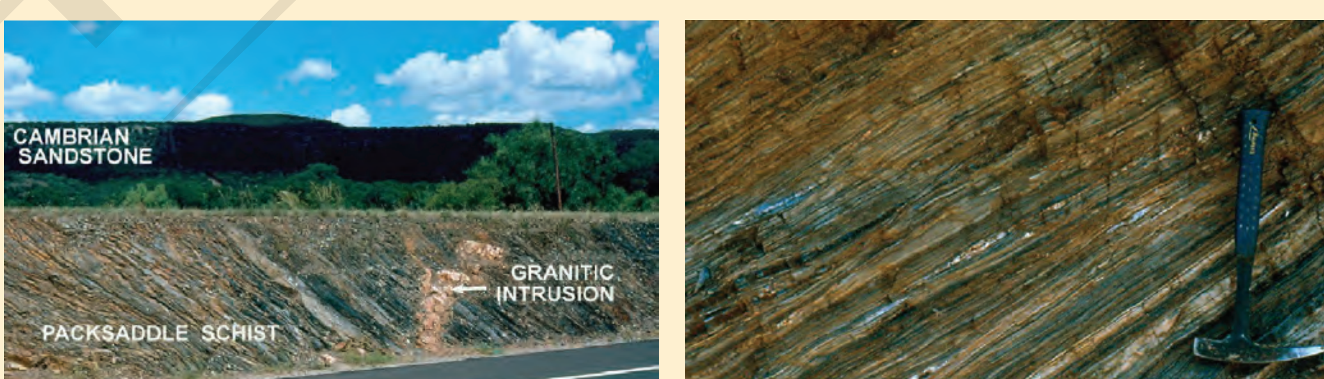
Texas.2 Precambrian Texas

The tectonic cycle that begins in the late Proterozoic is illustrated by rocks exposed in the Central Texas (Llano) Basin, the Van Horn area, and the Franklin Mountains near El Paso (see Figure Texas.1). The first two areas show evidence of an Andean-type **orogeny**, whereas the rocks in the Franklin Mountains indicate a passive continental margin. In the Llano Basin, sedimentary rocks were subjected to regional metamorphism, resulting in the formation of gneisses, schists, and a few zones with marble, a contact metamorphic rock. The igneous rocks associated with this mountain building phase are not known and presumably were removed during later rifting.

The Packsaddle Schist is an example of these rocks in the Llano area (Figure Texas.2). It was formed from sediments that derived from weathering and erosion of mafic igneous rocks, possibly associated with an island arc. Metamorphism of those sediments occurred about 1.3 billion years ago (1.3 Ga). About 1.1 Ga, the

► **Figure Texas.2**



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a The Packsaddle Schist, exposed here south of Llano, is one of several metamorphic rocks that formed about 1.3 billion years ago (1.3 Ga). A transgression that began in the middle Cambrian Period is registered by the sandstones in the background of this photo (see Figure Texas.7).

b The fabric of the Packsaddle Schist is not defined by sedimentary layers, but rather by schistosity, which developed through segregation of dark and light minerals that crystallized during metamorphism.

► **Figure Texas.3** Located just north of Fredericksburg, the prominent granite dome in this cluster is called Enchanted Rock. Granitic magmas intruded metamorphic rocks of the Llano area, including the Packsaddle Schist shown in Figure Texas.2a.

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metamorphic rocks at Llano were intruded by granitic magmas. All of these rocks are part of the **Grenville Province**, which was accreted to **Laurentia** in the late Proterozoic.

The intrusive rocks are expressed as small dikes and veins (see Figure Texas.2), up to quite large laccolithic bodies, such as Enchanted Rock (Figures Texas.3 and Texas.4). These are classic examples of exfoliation domes, illustrating physical weathering. A pegmatite exposed in a quarry near Llano nicely illustrates the sequence of mineral crystallization as predicted by Bowen's reaction series described in your textbook (Figure Texas.5). Note the faces of the large hexagonal crystal of **microcline**, surrounded by quartz. How can you tell which of these minerals formed last?

The state capital in Austin is made almost entirely from granite quarried near Marble Falls, and this stone can be seen in many of the late Victorian Period courthouses around the state. Gold is found in low quantities in the Llano area, but the semiprecious mineral topaz is quite common.

► **Figure Texas.4** Looking west from the summit of Enchanted Rock, one can see this classic example of an exfoliation sheet that has broken up into slabs, which are sliding down the dome. Limestone on the horizon formed during Cretaceous transgressions, and the flat surface is the Edwards Plateau. Faulting during the Tertiary Period contributed to the breakup and removal of the limestone that once covered the Precambrian granite.

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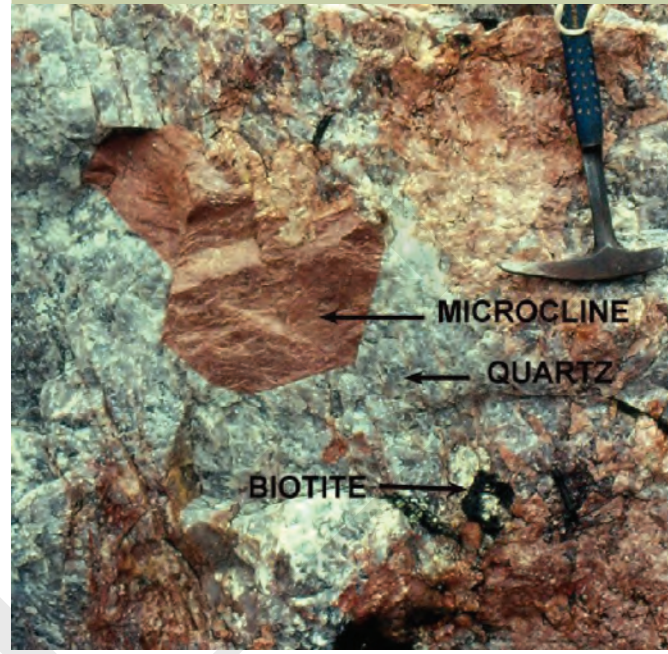
► **Figure Texas.5** This pegmatite near Llano, Texas, has three minerals that also dominate the Town Mountain granite: microcline (a potassium feldspar), biotite (a mica), and quartz. Notice that the quartz crystallized last, enveloping the mica and feldspar crystals, which formed at higher temperatures.



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Section Texas.2 Summary

- During the Proterozoic eon, metamorphic and igneous rocks were accreted to Laurentia as part of the Grenville Terrane.
- Rocks of Proterozoic age near Llano, Van Horn, and the Franklin Mountains demonstrate the nature of metamorphic and intrusive igneous processes.

Texas.3 The Paleozoic Tectonic Cycle

All of the Proterozoic rocks in Texas were subjected to weathering and erosion, which lasted until the Cambrian Period, when rifting in this part of Laurentia took place. Rocks associated with this rifting are exposed near Van Horn, and notably in Oklahoma's Arbuckle **aulacogen**, which was a failed arm of the Cambrian rift system.

A postrifting **transgression** began in the Cambrian Period and continued throughout almost all of the Ordovician Period, when a shallow sea covered all of Texas. Shallow seas that cover part of the craton are called epeiric seas; sometimes they are called subsiding seas, because by the process of

Figure Texas.6

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a These rocks, exposed in a road cut overlooking Lake LBJ in the Llano area, were deposited near the shoreline at the beginning of the Cambrian transgression. The Lion Mountain sandstone derives its green color from the iron-rich mineral glauconite, and it also has thin beds and pods of limestone with numerous fossils of trilobites and brachiopods.

b These symmetric wave ripples in the Welge Sandstone were formed along a Cambrian beach. The lower part of this bed shows extensive bioturbation through burrowing by organisms, whereas the upper part provides an excellent example of cross-bedded sedimentary structures.

subsidence, thick sequences of sedimentary rock can be preserved, even with little change in the sedimentary environment. The early stages of the Cambrian transgression in Texas are marked by beach and near-shore sandstones, including those dominated by quartz grains, which were derived from weathering of Precambrian granites. Cambrian deposits exposed near Kingston, Texas, include beds dominated by green, **glauconite** sands and contain abundant trilobite and brachiopod fossils (Figure Texas.6). As the transgression progressed, a shift from clastic to biogenic sedimentation completed, and thick limestones formed across virtually all of Texas (and surrounding parts of Laurentia) during the Ordovician. Most of these rocks are deeply buried, but surface exposures can be seen in the central basin, the Beach Mountains near Van Horn (Figure Texas.7), and the Franklin Mountains (Figures Texas.8 and Texas.9).

The ancient **sedimentary environments** of the Ordovician epeiric sea are comparable with the "carbonate factories" of the present-day Bahamas, where **calcareous algae** thrive in warm, clear ocean water. When these flourishing algae die, they break down into tremendous volumes of calcareous mud, which is then buried and lithified into limestone. The weight of these new rocks causes subsidence, and by this mechanism, tremendously thick accumulation of

Figure Texas.7 Located in the Beach Mountains near Van Horn, the limestone and dolomite of the El Paso Formation formed in the shallow epeiric sea that covered Texas during the Ordovician Period. These rocks overlie sandstones of latest Precambrian to Cambrian age.

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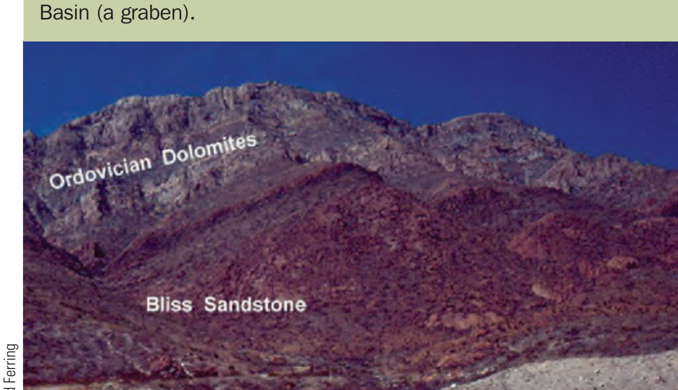
Figure Texas.8 The Bliss Sandstone (Cambrian) and the overlying Ordovician dolomites are exposed in the Franklin Mountains near El Paso. These sedimentary rocks formed during the early Paleozoic transgression and contain fossils of corals, mollusks, and trilobites. This east-facing slope formed along a Miocene Epoch normal fault that separates this uplifted block (a horst) from the broad Hueco Basin (a graben).



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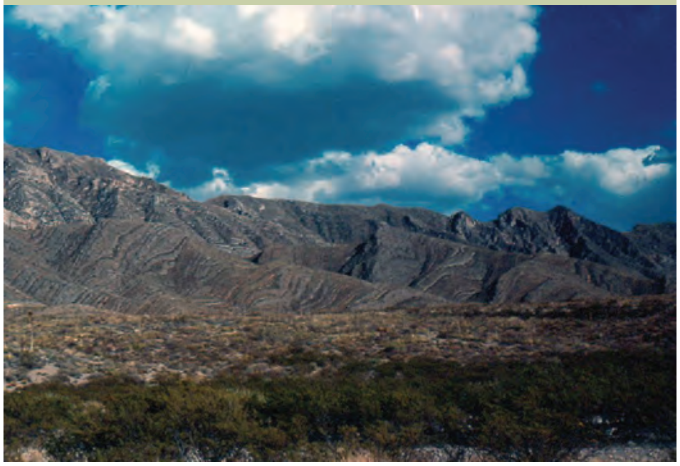
▶ **Figure Texas.9** This is the west-facing slope of the Franklin Mountains. The rocks at the summit are Devonian-Mississippian in age, and those below belong to the Pennsylvanian Magdalena Formation. All of these rocks formed in shallow, clear marine environments. Because the major source of these carbonates was calcareous algae, these are good examples of biogenic rocks.



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limestone occurs with no change in water depth. It is estimated that the depth of Texas's Ordovician sea was always on the order of less than 10 meters.

After deposition, many of the Ordovician limestones were changed diagenetically into dolomite. In this process, the limestone was altered to dolomite by substitution of about half of the calcium ions in calcite with the smaller magnesium ion. This process increases the porosity of the rocks by about 15%, which makes them ideal **reservoir rocks** for hydrocarbons. Thus, the Ordovician rocks have abundant algae-derived organic matter as a source for hydrocarbons and have abundant, highly porous reservoirs. These rocks are among the most important sources of oil and gas in this region. Of special importance are natural gas reservoirs in west Texas that are up to 6,000 meters deep. Royalties on much of those reserves are owned by the State of Texas and by law are used to subsidize (your) higher education!

Section Texas.3 Summary

- During the Lower Paleozoic, a transgression resulted in creation of an epeiric sea that covered all of Texas.
- Thick sequences of Ordovician dolomites contain large reserves of oil and natural gas.

Texas.4 The Ouachita Orogeny and Pangaea

The Ouachita orogeny in Texas brought a dramatic end to the Paleozoic tectonic cycle. Over a very long period, perhaps as long as 50 million years, the ocean between Texas (the southern end of Laurentia) and South America (the northern end of **Gondwana**) was closed, and finally, those continents collided and became part of the supercontinent Pangaea. When the collision actually took place, rocks that formed during the collision, as well as older Paleozoic rocks, were pushed up onto the continent as part of the Ouachita Mountains. The ancient Ouachita Mountains extended from Marathon to northeast Texas and into Oklahoma. At the same time, Africa and Europe also were colliding with Laurentia, resulting in the Appalachian orogeny in the eastern United States.

Between Marathon and Oklahoma, the traces of these mountains are deeply buried, and they can be reached only by drilling. But the former axis of the Ouachita Mountains follows almost exactly the path of the Balcones Fault Zone (see Figure Texas.1). The Ouachita orogeny had both immediate and long-lasting effects, and as explained in the following discussions, the geologic history of the Texas interior west of the Ouachita Mountains is very different from the history of the Gulf of Mexico Basin, which was formed after the rifting of South America away from Texas.

The effects of the Ouachita orogeny in Texas are, in part, structural, as considerable faulting took place. But the main effects, and the most important ones for people today, were in the patterns of sedimentation that accompanied and followed this collision, for those late Paleozoic sediments contain important geologic resources that are vital to the economy of Texas.

Rocks of the Mississippian and Pennsylvanian periods in Texas reveal that the second tectonic cycle was beginning. In dramatic exposures in the hills near Marathon, there are rhythmically arranged thin beds of sandstone and siltstone called **flysch** (Figure Texas.10). These flysch deposits have a total thickness of more than 3 kilometers (km) near

▶ **Figure Texas.10** Two major events in the geologic history of Texas are recorded in these rocks. The flysch sediments of the Pennsylvanian Haymond Formation were deposited as turbidites, then folded and faulted during the Ouachita orogeny. After an enormous interval of erosion, the ocean transgressed over Texas during the Cretaceous Period. Rock creep caused the distinctive bending of the rocks near the surface.

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▶ **Figure Texas.11** These hogbacks near Marathon were formed in rocks that were intensely folded and faulted during the Ouachita orogeny, when South America collided with North America. At the end of that collision, Texas became part of the supercontinent Pangaea.

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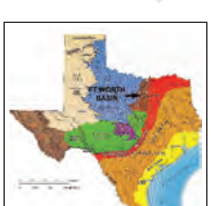
Marathon. They were deposited by **turbidite** flows, which were supplied by great volumes of sediment being shed off of mountains that were being created as South America approached Laurentia from the south. The flysch deposits at Marathon were overlain by coarse-textured sediments called **molasse.** These sandstones and conglomerates indicate a shift from marine to terrestrial environments at the completion of the continental collision. Discussions in your textbook covering plate tectonics have excellent illustrations of this kind of convergent plate boundary.

The structural features of the Marathon area include numerous anticlines and synclines interrupted by high-angle reverse faults, all of which are underlain by a long **thrust fault,** indicating that these rocks were pushed up onto the continent. These have been eroded into distinctive landforms evident today, such as the **hogbacks** formed by the Silurian Caballos Novaculite (Figure Texas.11). The entire package of Paleozoic rocks near Marathon was pushed up onto the continent along a long, low-angle thrust fault.

Section Texas.4 Summary

- During the late Paleozoic, South America collided with Texas, creating the Ouachita Mountains and adding these continents to the supercontinent Pangaea.
- Rocks exposed in the Marathon area reveal the nature and patterns of sedimentation and structural deformation that accompanied the collision.



Texas.5 The Fort Worth Basin in the Late Paleozoic Era

In north central Texas, sediments were shed from the west front of the Ouachita Mountains into the Fort Worth Basin during and after the Ouachita orogeny, providing another example of tectonic controls on the character and rate of sedimentation. Although small deposits of coal have been mined in these deposits, the Fort Worth Basin is much more important as a major producer of oil and gas.

▶ **Figure Texas.12** In the past few years, drilling for natural gas in the Mississippian Barnett Shale west of Dallas-Fort Worth has been intense. These wells are 5 km west of Denton. The one in the foreground has been completed.

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At the base of this basin, overlying early Paleozoic rocks, is the Mississippian Period Barnett Shale, which is buried about 2,000 meters below the surface. This organic-rich shale has abundant natural gas reserves, which are now being developed extensively with technologies including horizontal drilling and slick water **fracking** (Figure Texas.12). Horizontal drilling greatly increases the area of gas extraction, and injection of water (without the sand usually used in fracking) into the shale enhances permeability, increasing the flow of gas to the well.

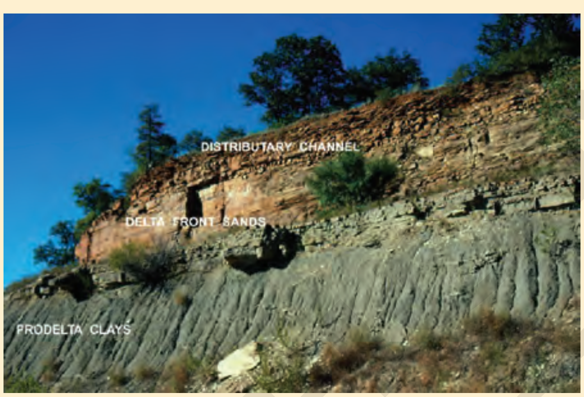
The overlying Pennsylvanian Period deposits in the Fort Worth Basin were delivered from both the Ouachita and Arbuckle mountains, which underwent episodic uplift and erosion during the very long Ouachita orogeny (Figure Texas.13a). This resulted in the **progradation** of numerous deltas on to the shelf, with sandy deposits near the delta, and muds settling on the shelf and in the interdelta bays. Delta progradation resulted in a vertical sequence of **sedimentary facies** of organic-rich prodelta muds, overlain by increasingly coarser delta front and channel deposits (see Figure Texas.13b). Quite rapid subsidence and lateral shifting of delta positions through time resulted in emplacement of an impermeable shale or limestone "cap" over these deltaic deposits, making the channel sands ideal petroleum reservoirs.

Carbonate banks and larger platforms developed away from the deltas, where clearer water supported algae, which were the base of the food chain (see Figure Texas.13c). Reefs were colonized by filter-feeding animals that also required clear water; these include corals, crinoids, bryozoans, and brachiopods, as well as numerous bottom-dwelling and burrowing organisms, such as urchins and mollusks, including numerous gastropods that "grazed" on surface coatings of algae and organic debris. Many of these buried reefs are targets for oil exploration as well.

Thick Pennsylvanian limestone northwest of Fort Worth has been actively quarried because the regional supplies of stream gravel were largely exhausted. Rock crushers break the hard limestone into aggregate, which is used to make concrete. The Dallas-Fort Worth region is one of the fastest-growing areas of the country, creating huge

Figure Texas.13

(a) During and after the Ouachita orogeny, rivers flowed west into the Fort Worth Basin in north central Texas. Deltas prograded into the shallow shelf, which also supported carbonate banks and platforms where the water was clearer.



(b) These rocks near Mineral Wells, Texas, were formed from sediments deposited by a Pennsylvanian delta that prograded westward (right to left) into the Fort Worth Basin (a). Similar rocks, buried thousands of feet deep, are important reservoirs of oil and gas.

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(c) This Pennsylvanian coral reef is a good example of the "muddy" reefs of the late Paleozoic Era. The calcareous mud matrix was contributed by algae, which formed the base of the food chain in these reefs and supported colonies of filter-feeding organisms. such as the solitary corals shown here.

demands for concrete by the residential, public, and commercial sectors.

Section Texas.5 Summary

- The Fort Worth Basin has thick Mississippian and Pennsylvanian deposits that formed in response to the Ouachita orogeny.
- There are substantial deposits of oil and natural gas in the Fort Worth Basin.

Texas.6
Permian Red Beds and Evaporites

In the early and middle Permian Period, thick limestone deposits accumulated in central and west Texas, in the sea that was bounded on the east and south by the Ouachita Mountains. In west Texas, deposition during the Permian Period was concentrated in basins that were created by faulting perpendicular to the trend of the Ouachita collision. The greatest amount of deposition centered on the Midland Basin, where thousands of meters of Permian limestone overlay the Lower Paleozoic rocks. By the late Permian Period, however, cyclical sea level changes, driven by the expansion and retreat of glaciers in Gondwana, resulted in periodic isolation of separate closed basins. In the Delaware Basin, the one closest to the open sea, the Capitan Reef flourished around the rim of the basin when sea levels were high (Figure Texas.14). When sea level fell, thick beds of evaporitic calcite and gypsum filled

Figure Texas.14 El Capitan Peak, a prominent feature of the Guadalupe Mountains in west Texas, is part of the Permian reef that encircled the Delaware Basin. Just across the New Mexico state line, Carlsbad Caverns formed in this limestone.

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▶ **Figure Texas.15** These red beds and gypsum layers exposed in Palo Duro State Park are part of the Caprock Escarpment, which is the eastern edge of the Llano Estacado (see Figure Texas.26). The red beds were formed during the arid conditions in the Permian Period. The highest light beds are part of the Triassic Dockum Group.

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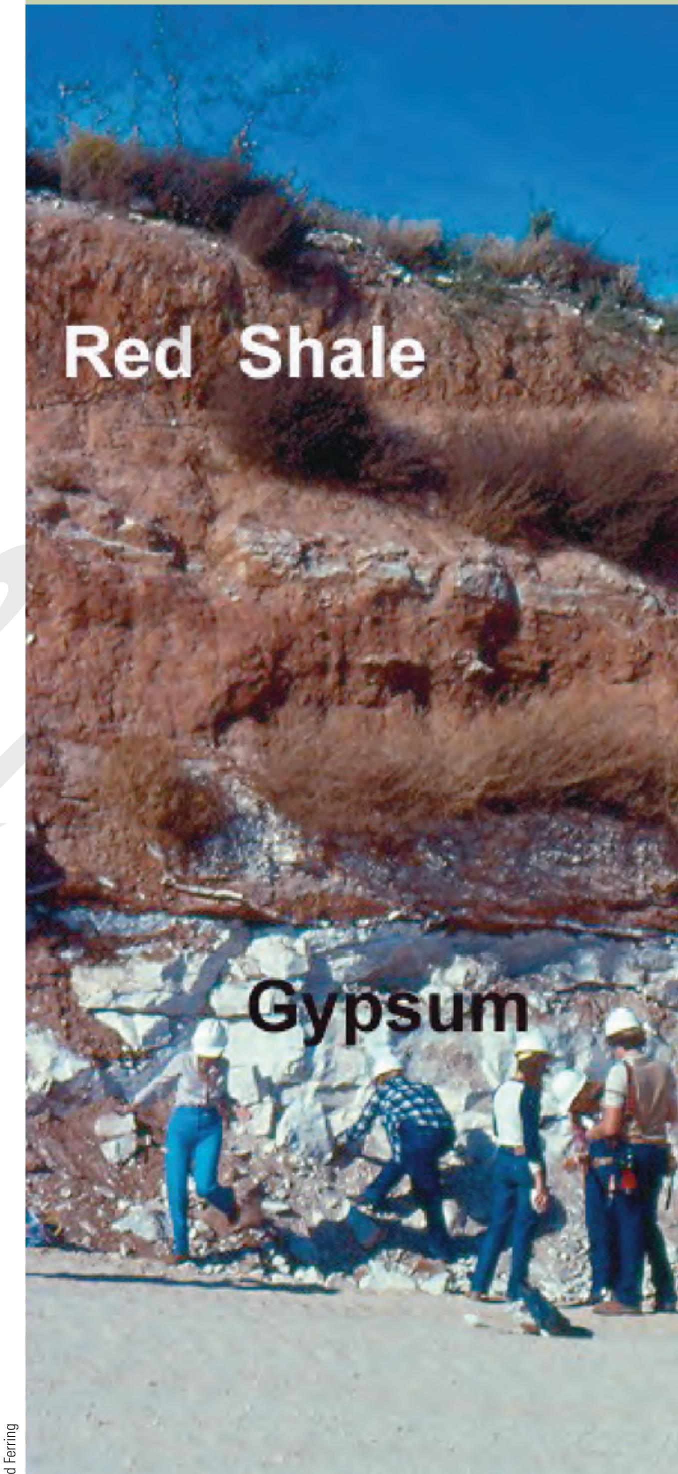
▶ **Figure Texas.16** Gypsum is mined in this quarry near Sweetwater, in the Red Bed Plains. Formed in evaporitic "ponds" during the arid Permian Period, this gypsum is used to manufacture Sheetrock wallboard and Portland cement.



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the closed basin. The Capitan Reef rocks are now part of the Guadalupe Mountains. Notably, the famous Carlsbad Caverns formed in these limestones, just across the border in New Mexico.

In the late Permian Period, Texas was near the equator and tropical climates contributed to deep weathering of sediments exposed around the interior basins during times of low sea level. Lasting evidence of this weathering is preserved as "red beds," which derive their color from oxidized forms of iron and aluminum. Excellent examples of these are exposed in the walls of Palo Duro Canyon, just below the Caprock Escarpment of the Llano Estacado (Figure Texas.15). This section of sediments includes multicolored beds of sandstone and shale, locally called Spanish skirts. The reddest beds are those that were most intensely weathered.

Water trapped in these interior basins evaporated, resulting in the precipitation of gypsum and halite. Shallowly buried deposits of gypsum are mined in open pits near Sweetwater (Figure Texas.16). The gypsum is used for manufacturing Portland cement and also wallboard, which is made by creating a muddy slurry from the gypsum, which is then extruded between sheets of paper, where it forms a hard layer of interlocking gypsum crystals (hence the name Sheetrock).

In the North Central Plains (see Figure Texas.1), also referred to as the Red Bed Plains, Permian salts are dissolved easily by percolating water. As a result, much of the groundwater and surface water in this region is too salty for drinking or irrigation. Even the water in Lake Texoma, which is on the Red River downstream from the Red Bed Plains, is too salty for municipal use.

At Palo Duro Canyon, the light-colored Triassic sandstone at the top of the section conformably overlays the Permian beds. This section thus preserves the Permo-Triassic contact, which signals the end of the Paleozoic and the beginning of the Mesozoic. Erosion dominated the rest of the Triassic Period and continued into the Jurassic, when rifting created the Gulf of Mexico Basin. Therefore, no further deposition occurred over most of Texas west of the Gulf Basin until the postrifting transgression of the early Cretaceous Period. The next section addresses this subject.

Section Texas.6 Summary

- During the Permian Period, thick deposits of limestone, red beds, and evaporites accumulated in deep basins in central and west Texas.
- Dissolution of Permian salts in north central Texas greatly reduces freshwater supplies.

Texas.7
The Breakup of Pangaea and Cretaceous Transgressions

During the Jurassic Period, the continents of North and South America rifted apart, as part of the breakup of Pangaea. In Texas, no evidence of the rifting is preserved at the surface, but parts of Jurassic rift basins have been reached by drilling on the Gulf Coastal Plain. Most notably, the early Jurassic Gulf Basin was closed, and thick deposits of halite, called the Louann Salt, formed there by evaporation. We revisit the Louann Salt in Section Texas.11.

After erosion of the continent for much of the Triassic and Jurassic periods, and after the Gulf was connected to the Caribbean-Atlantic, there were two Cretaceous transgressive cycles, which at their highest stands not only covered all of Texas but also continued northward to the Arctic. Everywhere in Texas, except deeply buried under the Gulf Coastal Plain, Cretaceous rocks overlie much older, eroded rocks. We have seen examples of this near Enchanted Rock (see Figure Texas.4) and at Marathon (see Figure Texas.10). Since the end of the Cretaceous, the Texas part of the Gulf of Mexico Basin has been filling in quite rapidly with sediments. This phase of Texas geologic history is called the Gulfian Cycle. As the Gulf Coastal Plain was constructed, Tertiary tectonics caused dramatic changes in the landscapes of central and west Texas.

Lower Cretaceous rocks over most of the Edwards Plateau are limestone and **marl,** as can be seen in a section of the Glen Rose Formation near Kerrville (Figure Texas.17a). As mentioned earlier, these thick sequences of quite similar sediments developed because they formed in environments where carbonate sediments were rapidly generated and where subsidence maintained those environments, mainly by keeping water depths relatively constant. Mangrove swamps and shallow lagoons, far from any rivers in Yucatan, are good modern analogs for many of the Lower Cretaceous sedimentary environments in Texas (see Figure Texas.17b). Some of the erosional surfaces in these sections are the result of hurricanes, which were apparently common in Texas during the Cretaceous Period, because global climates then were significantly warmer than today. This is illustrated by the fact that during the Cretaceous Period, coral reefs formed as far north as 70° North latitude, well above the Arctic Circle. Today, reefs cannot form much above 35°, because the oceans are too cold for corals. Globally warm conditions during the Cretaceous Period also supported phenomenal populations of rapidly evolving **phytoplankton,** which was the base of the food chain for the Cretaceous oceans. In fact, the term *Cretaceous* refers to the common **chalk** deposits of that period, which are made of the calcareous skeletons of those phytoplankton.

Lower Cretaceous rocks in north central Texas and in the trans-Pecos region (especially Big Bend) include terrestrial deposits because they were closer to coastlines. These are the rocks that contain Texas' dinosaur fossils and track ways such as near Glen Rose and Grapevine, Texas. Cretaceous marine sediments, exposed on the western edge of the Gulf Coastal Plain, preserve many fossils of large marine reptiles, including plesiosaurs and mosasaurs.

Cretaceous limestone is quarried extensively, especially along the eastern edge of the Edwards Plateau, closest to rapidly growing cities (Figure Texas.18). The hard, white varieties of limestone and chalk, usually called Austin stone, were widely used for public buildings and big homes in

Figure Texas.17

(a) These limestone and marl beds, exposed near Kerrville, belong to the Cretaceous Glen Rose Formation. These rocks form part of the Edwards Plateau, which is the recharge zone for the Edwards Aquifer.

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(b) This mangrove swamp in western Yucatan, Mexico, is a modern analog for the sedimentary environments in which the Glen Rose limestone was formed. Like the ancient environments, these swamps and shallow lagoons are inhabited by clams, oysters, urchins, and crustaceans.

▶ **Figure Texas.18** This quarry in Cretaceous rocks near Austin is one of many that are used to produce crushed stone aggregate, lime for cement, and dimension stone for construction and landscaping.

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the nineteenth century. This stone is still popular among architects, giving even modern-looking structures a connection to Texas' geologic and historic past.

The K/T Boundary and the Age of Mammals in Texas

It is well known that at the end of the Cretaceous Period, there was a profound mass extinction, which ended the Age of Reptiles (the Mesozoic Era) and ushered in the Age of Mammals (the Cenozoic Era). This is often called the K/T boundary, based on the geologic map symbols for Cretaceous and Tertiary, respectively. On the geologic map of Texas, the K/T boundary can be seen on the western edge of the Gulf Coastal Plain as a line separating the last Cretaceous rocks (Ku2, green) with the first Tertiary rocks (PWA, stippled orange).

During the Cenozoic Era, mammals diversified rapidly on all the continents and in the oceans as well. Texas has an excellent fossil record of mammalian evolution, but it is contained mainly in sediments in the western part of the state. There the Tertiary landscape evolved in quite dramatic ways, in response to a sequence of compressional and then extensional **intraplate tectonics**. These tectonic changes appear to be related to an eastward extension of the zone of subduction of the Pacific Plate under the western edge of North America, which resulted in compressional uplift and volcanism. A further lowering of the subduction angle may have contributed to the subsequent extensional regimen, when **basin and range** features developed not only in trans-Pecos Texas but also over most of the western United States. The regional manifestations of this phase of intraplate tectonism are discussed in the following sections.

Section Texas.7 Summary

- In the Jurassic Period, South America rifted away from Texas, forming the Gulf of Mexico Basin.
- In the Cretaceous Period, marine transgressions covered Texas, leaving thick limestone deposits.

Texas.8 Basin and Range Texas

In the Tertiary Period, the compressional phase of intraplate tectonism mentioned earlier transformed Texas west of the Pecos River (the trans-Pecos) into a dynamic landscape studded with scores of volcanoes. The peak of this volcanic activity was in the Oligocene Epoch, when all of the older rocks in this region were intruded by magmas, leaving some small **plutons**, but many more volcanic features, including a number of **calderas**.

Most of the trans-Pecos volcanoes preserved today are eroded remnants, much smaller than when they were active. Resistant **volcanic necks** contribute to the beautiful desert landscape, especially in Big Bend National Park (Figure Texas.19). Most of the volcanoes in this region were fed by felsic magmas, producing common rhyolite and rhyolite porphyry (Figure Texas.20). But there are also many mafic rocks, especially basalt, indicating a pattern called **bimodal volcanism**; that is, the chemical composition of the magmas that fed different volcanoes ranges from felsic to mafic. Bimodal volcanism is characteristic of intraplate tectonism, where deep magmatic sources had mafic, mantle-like compositions, whereas nearby volcanoes were fed by shallower, continental sources with felsic composition. Formation of the Tertiary Rio Grande Rift in nearby New Mexico was accompanied by bimodal volcanism, as can be seen in the juxtaposition of andesitic and basaltic rocks near Santa Fe.

The high silica content of the felsic magmas caused extremely violent eruptions that produced huge volumes of pyroclastic ash. Winds carried those ashes to the east, where they became buried within the Ogallala Formation under the present-day High Plains (see Section Texas.9). Ash beds are also preserved in a number of the Tertiary formations of

▶ **Figure Texas.19** The Chisos Mountains, in the heart of Big Bend National Park, are a series of necks that have been exposed by erosion of the softer lavas and ashes that formed these once tall volcanoes.

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► **Figure Texas.20** Willow Mountain, near Terlingua, Texas, is the neck of a rhyolitic volcano. Note the well-expressed columnar jointing of these rocks and the talus slopes formed by erosion.

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► **Figure Texas.21** Big Bend National Park is within the Chihuahuan Desert. This desert pavement, studded with cacti and the spindly Ocatillo, was formed by wind erosion (deflation) of the surface sediments, leaving behind an "armored" surface of pebbles and cobbles.

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the Gulf Coastal Plain. Ash weathers quickly into fertile soils, and the extensive grasslands of that period nourished the rapidly evolving communities of grazing animals, including horses, which populated the ancestral Great Plains environments.

Today, much of trans-Pecos Texas is within the Chihuahuan Desert, which is just one of the low-latitude deserts of the Northern Hemisphere. Visitors to Big Bend are treated to a scenic landscape that has formed in the desert climate. The student of physical geology will quickly recognize the results of weathering and erosion typical of deserts, including extensive sheets of sediment eroded from the volcanic peaks. Those surfaces are capped by desert pavements, composed of pebbles and cobble "armor" that have been left behind after long periods of wind erosion called **deflation** (Figure Texas.21).

After the major period of volcanic activity in the trans-Pecos, extensional tectonics resulted in formation of the Texas portion of the vast basin and range province of the western United States. The result was a series of northerly trending uplifted blocks, called ranges or horsts. Many older rocks are exposed in these uplifts, including the Precambrian through

► **Figure Texas.22** These salt flats, on the floor of a graben-type valley, are separated from the Guadalupe Mountains in the background by a series of normal faults. The salt crusts are deflated and blown to the edges of the flat, forming dunes in the distance.

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Paleozoic sequences of the Franklin and Beach Mountains (see Figures Texas.7 and Texas.8) and the Permian rocks of the Guadalupe Mountains (see Figure Texas.14).

The basins between these uplifted blocks are graben-type valleys formed between pairs of normal faults. The Hueco Basin (also called by the Spanish name *Bolson*), lies between the Franklin and Hueco uplifts near El Paso. The Salt Basin formed below El Capitan Peak west of the Guadalupe Mountains (Figure Texas.22). Up to several kilometers of sediment fill these basins. The deposits include stream deposits, windblown sand and silt, and also evaporites, such as the gypsum and halite seen on the surface of the Salt Basin.

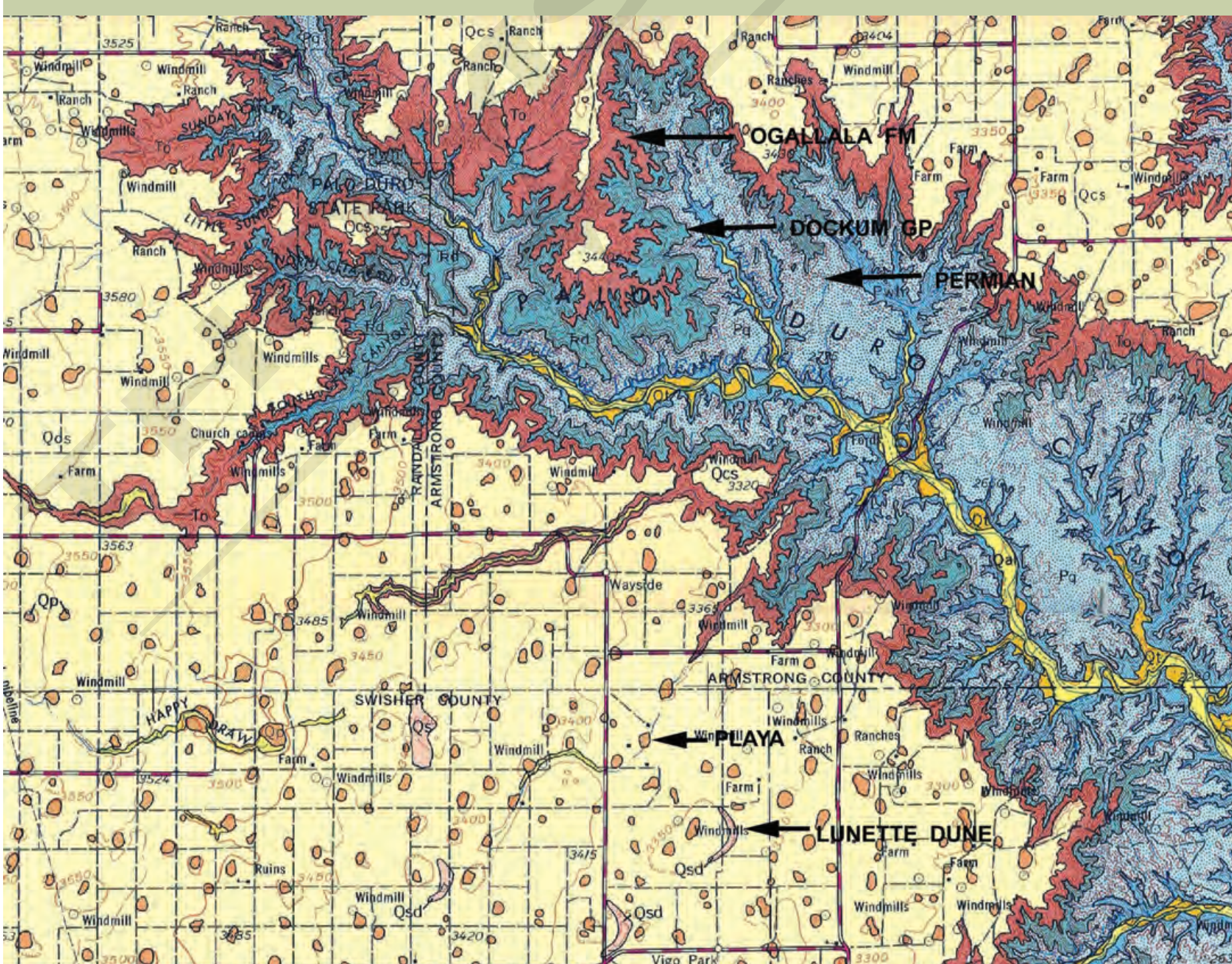
One of the Tertiary faults flanking a basin near the Rio Grande River was reactivated in 1931, producing the Valentine earthquake. This earthquake, the strongest recorded in Texas, registered 6.0 on the Richter scale. Buildings were damaged near the epicenter, and the earthquake was felt over much of Texas. Since then, Texas has experienced a number of smaller earthquakes, rarely above Richter 4.0.

Section Texas.8 Summary

- Intraplate tectonics resulted in volcanism and creation of basin and range features in the trans-Pecos region of Texas.

Texas.9
The Llano Estacado

In the Tertiary Period, uplift of the southern Rocky Mountains increased rates of erosion. As a result, a ramp of sediment called the High Plains was deposited on the eastern front of the Rockies, from Texas to Canada. The part of the High Plains in Texas is called the Llano Estacado. The Ogallala Formation includes most of the sediments that formed this feature. The lower part of the Ogallala is composed of fluvial sand and gravel. The upper part is composed of **eolian** sand and silt, as well as thick zones of



▶ Figure Texas.23 This map shows the eastern edge of the Llano Estacado (Southern High Plains), with the Caprock Escarpment surrounding Palo Duro Canyon. The extremely flat surface of the High Plains is dotted by more than 20,000 playa lakes. Lunette dunes are usually on the east sides of playa depressions because of prevailing westerly winds.

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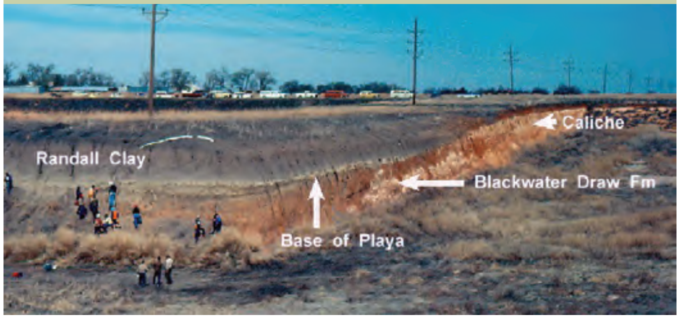
▶ **Figure Texas.24** This playa lake has been exposed in a borrow pit on the north side of Lubbock. The Randall Clay has filled the basin over the last 10,000 years. Mammoth bones and 11,000 year-old Clovis Paleoindian spear points are found in some of these playa lake deposits.



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caliche (locally called the Caprock). Caliche is hardened calcium carbonate formed by soil processes characteristic of arid and semiarid landscapes. The lower part of the Ogallala Formation is the Ogallala aquifer, which provides almost all of the water needs for this region, where irrigation is necessary for crop farming.

The extremely flat surface of the Llano Estacado formed as the Pecos River cut northward, intercepting the Rocky Mountain drainages and isolating the Llano Estacado. In geomorphic terms, the streams that formerly crossed the Llano Estacado were beheaded by the Pecos River. After that, only wind could bring sediments to the Llano Estacado, and a flat blanket of silt and sand accumulated (Figure Texas.23). On the western edge of the Llano Estacado, there are number of periodically active sand dune fields, and at its southern end is Monahans State Park, which contains a large dune complex that began accumulating in the late Pleistocene.

Today, more than 20,000 **playa lakes** are present on the Llano Estacado (Figure Texas.24), and many older lake deposits are buried. These **ephemeral** lake basins formed by a combination of deflation, as indicated by dunes around their margins, and dissolution of underlying carbonates (a karstic process). In the late Pleistocene, extinct mammals such as mammoth, horses, camels, saber-toothed cats, and large, fast bears populated this region. Playa lakes were frequented by these animals, and 11,000-year-old Clovis spear points have been found in association with mammoth bones at the Miami Site, a late Pleistocene playa north of Amarillo. These playas collect seasonal rainfall, some of which percolates down, recharging the Ogallala aquifer. But many parts of the Ogallala Aquifer have experienced progressive lowering of the water table, making water resources management critical for sustaining this region's farming and cattle industries.

Section Texas.9 Summary

- In the late Tertiary Period, the Texas High Plains was constructed by deposition of fluvial and eolian sediments.
- The Ogallala aquifer is lowered by periodic droughts, reducing supplies of water for irrigation.

Texas.10
The Edwards Plateau and Balcones Fault Zone

During the Miocene Epoch, while the basin and range features were formed by extensional tectonics in the trans-Pecos, the central part of the state was subjected to **epeirogenic uplift**, creating the Edwards Plateau (see Figure Texas.1). This uplift was accommodated by up to 500 meters of displacement along the Balcones Fault Zone, which is a series of normal faults, with downward movement towards the coastal plain. The Balcones Escarpment defines the eastern margin of the Edwards Plateau, extending from west of San Antonio to near Dallas, where it bends into east Texas.

During epeirogenic uplift, larger rivers will erode deeply into resistant bedrock, forming what are called **entrenched valleys.** Perhaps the most famous example of this process is the Grand Canyon, which formed as a result of epeirogenic uplift of the Colorado Plateau. The same kinds of forces caused the Brazos River to form a long series of entrenched meanders across the Paleozoic and Cretaceous rocks of northern Texas (Figure Texas.25).

From near Austin to San Antonio, streams also adjusted to the uplift by eroding deep valleys just upstream from the Balcones Fault Zone. In a local twist in perspective, that area of deep valleys is called the Hill Country, which is one of the most scenic parts of the state, popular with tourists, campers, and hunters (Figure Texas.26).

As Texas was colonized, first by Spaniards and then by Euro-Americans, major settlements were established and persisted in a repeated pattern, where larger rivers crossed the Balcones Escarpment. The nineteenth-century settlements of San Antonio, Austin, Waco, and Dallas-Fort Worth were ideally situated for growth, because they were located at the convergence of waterways, springs, and fords, where

▶ **Figure Texas.25** While Tertiary volcanoes were erupting in west Texas, the central part of the state was experiencing broad regional uplift. This caused larger rivers, such as the Brazos River, to become entrenched deeply into bedrock. Here, a large sandy point bar of the Brazos River stands opposite the cut bank in an entrenched meander.

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▶ **Figure Texas.26** Popular with tourists, the scenic "Hill Country" of central Texas is actually an area of deeply eroded valleys. These rivers cut down into Cretaceous bedrock, as the Edwards Plateau was uplifted along the Balcones Fault Zone.

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wagons could cross the rivers that flowed over bedrock. This string of cities also grew along the boundary between the agriculturally rich coastal plain and the ranch country to the west. Thus, they were ideally situated to become centers of trade, transportation, culture, and government.

The western margins of the Edwards Plateau merge with the arid Basin and Range Province and the semiarid High Plains. Rain falling on the central part of the plateau percolates down into the basal Cretaceous rocks, forming the Edwards Aquifer, one of the most important sources of water in the state. Groundwater from the Edwards Aquifer is released to the surface along the Balcones Fault Zone in a series of springs that supply water to cities, including San Antonio and Austin. As recent decades have shown, the level of the Edwards Aquifer drops quite rapidly during droughts, and conservation of groundwater resources is a major concern for all of the communities of that region.

The geology of the Edwards Plateau has influenced land-use patterns in other ways. Relatively low rainfall and hard limestone combine to form thin, poor soils, which are characteristic of the Edwards Plateau. Historically, that area is noted for sheep and goat herding, which have enhanced soil erosion through overgrazing. Thin soils also promote extremely high rates of surface runoff during storms, especially hurricanes that frequently penetrate this part of Texas after crossing the coast. Over the years, many lives have been lost, especially at low water crossings, where people attempted to escape approaching flash floods. As a result, arrays of flood detectors have been installed that warn unsuspecting people in downstream areas of an advancing flood.

Section Texas.10 Summary

- In the Miocene Epoch, the epeirogenic uplift created the Edwards Plateau and the Balcones Fault Zone.
- The Edwards aquifer is the major supply of water for cities in central Texas.

Texas.11 The Gulf Coastal Plain

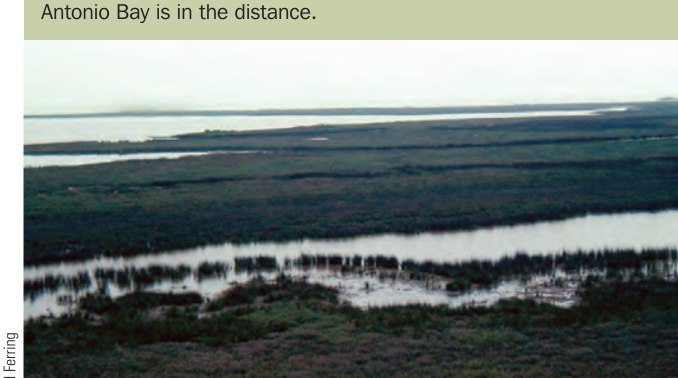
The Cenozoic Gulf Coastal Plain Province covers about one fourth of Texas (see Figure Texas.1). The geology of this region is especially important because it supports agriculture and forestry industries, holds significant groundwater resources, and contains enormous energy reserves of petroleum and **lignite**.

Examination of the geologic map of Texas demonstrates that the coastal plain began forming at the end of the Cretaceous Period. Since then, the coastline has shifted far into the Gulf of Mexico Basin. In east Texas, the Cenozoic coastal plain is about 425 km (265 miles) wide. Between Dallas and Galveston, the Trinity River valley has a gradient of just 0.4 meters/km (1.8 ft/mile)! This extremely gentle relief extends far out into the Gulf, following Texas's broad continental shelf. The Cenozoic package of sediments underlying the coastal plain and the shelf is extremely thick. Just offshore from Corpus Christi, those deposits are approximately 12 km (40,000 ft) thick.

Construction of the Cenozoic coastal plain was clearly dominated by progradation of sediments into the Gulf Basin. Stated in terms of relative sea level, this was a long period of marine regression. But within this overall pattern, there were also transgressions, when sediment supply decreased and the position of the shoreline either remained stationary or shifted inland. Those conditions were similar to the present Texas coast, which has a system of salt marshes, bays, and muddy lagoons separated from the continental shelf environments by sandy barrier islands (Figure Texas.27). Shelf deposits composed of organic-rich clay form the most fertile soils of the coastal plain. These black, clayey soils follow the coastal prairie zone from Corpus Christi to the Louisiana border, supporting cotton and dry rice agriculture (see Figure Texas.1).

In contrast to periods of marine transgression, large deltaic systems prograded into the Gulf during recessional

▶ **Figure Texas.27** Many of the Tertiary deposits of the Gulf Coastal Plain formed in environments such as these near the Aransas National Wildlife Refuge. A salt marsh is in the foreground, and San Antonio Bay is in the distance.



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► **Figure Texas.28** This exposure of Tertiary Wilcox sediments in east Texas illustrates short-term changes in sedimentary environments caused by processes such as shifting positions of river channels and flood plains.

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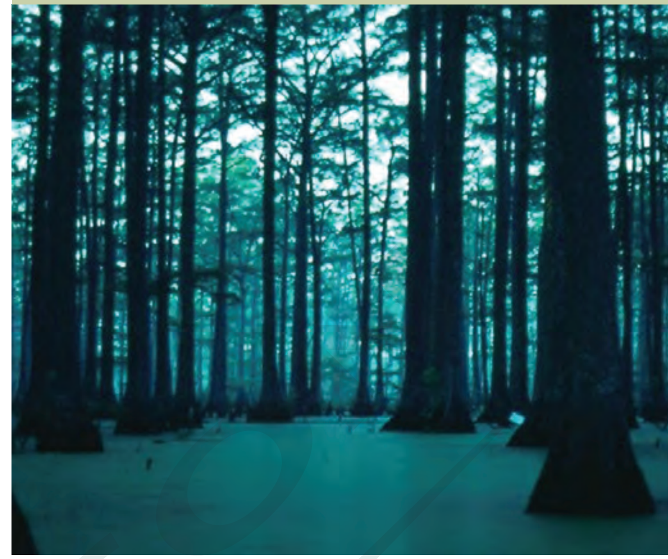
stages. This is well illustrated by the diverse sequences of sedimentary rocks of the Wilcox Group that were deposited during the Paleocene and Eocene epochs. The sedimentary facies of the Wilcox Group rocks reflect the complex mosaic of sedimentary environments of the coastal plain and adjacent shelf (Figure Texas.28). Especially common in fluvial environments were tropical hardwood swamps, in which thick accumulations of plant debris were buried and transformed into lignite. A contemporary cypress swamp near the Red River is an excellent analog for the sedimentary environments in which the organic matter for lignite accumulated (Figure Texas.29). Similar environments can be seen today at Caddo Lake, located near Marshall. Remarkably, Caddo Lake is the only natural lake in Texas.

Texas is the greatest consumer of coal in the United States, and most of that coal is lignite, which is mined in Texas and

► **Figure Texas.29** This cypress swamp near the Red River is a good analog for the hardwood swamp environments in which lignite formed on the Tertiary coastal plain of Texas.



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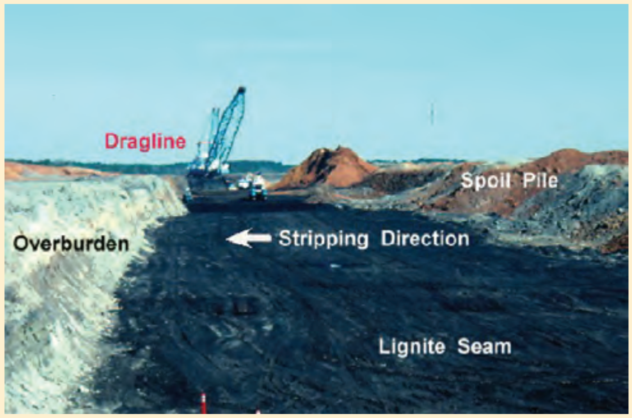
used to generate electricity. Shallow lignite seams, covered by sediments or soft rocks, are mined using the dragline sidecasting method (Figure Texas.30a). This method involves removal of the overburden with enormous draglines, exposing a long strip of lignite. The lignite is removed, then hauled to the nearby generating plant for immediate use (see Figure Texas.30b). Overburden from the next strip is used to backfill the section just mined, and the process continues until the leased area has been completed. The mine area is reclaimed by resurfacing with soil that had been stacked separately during overburden removal, followed by planting of vegetation according to the needs of the landowners who leased their property to the mining companies.

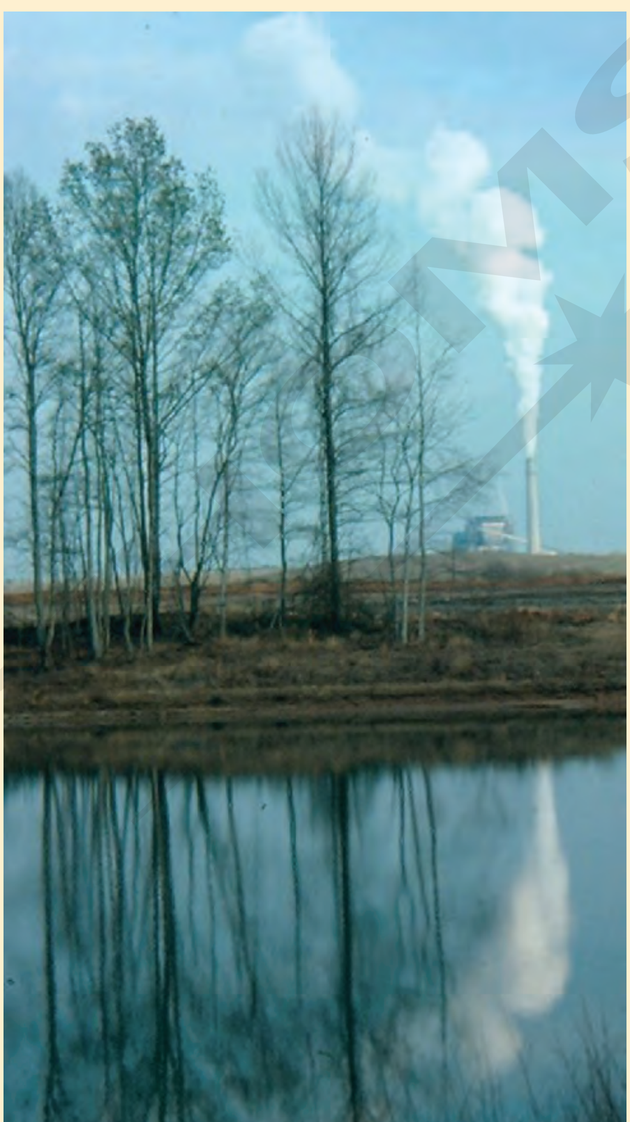
Both the mining and burning of lignite pose risks to the environment. In addition to surface reclamation, shallow groundwater must be protected from contamination during and after mining. Lignite has higher sulfur content than bituminous coal or anthracite, thus increasing the risk for acid rain that can contaminate nearby bodies of water. This problem has been reduced, but not eliminated, by use of "scrubbers" that use dissolved lime to help neutralize smokestack emissions (see Figure Texas.30b). Burning lignite entails significant emissions of CO_2, which contribute to the greenhouse effect and global warming; needless to say, this issue is one of increasing international concern and a focus for lively debates at home.

It is certain that lignite mining will become even more common in the future. At current rates of consumption, the shallow lignite reserves are estimated to last about 400 years. Deeper lignite reserves are even larger, but exploitation of those deposits by any method can threaten the extremely important aquifers of the Wilcox Group. No doubt, lignite mining and the associated efforts to preserve the quality of Texas' environment will be familiar issues to the next generation of Texans.

Figure Texas.30



a The South Hallsville Mine near Tyler provides lignite for the nearby electrical generating plant. These lignite beds are exposed and removed by colossal-sized machinery such as the dragline at the far end of the strip that is about to be mined.



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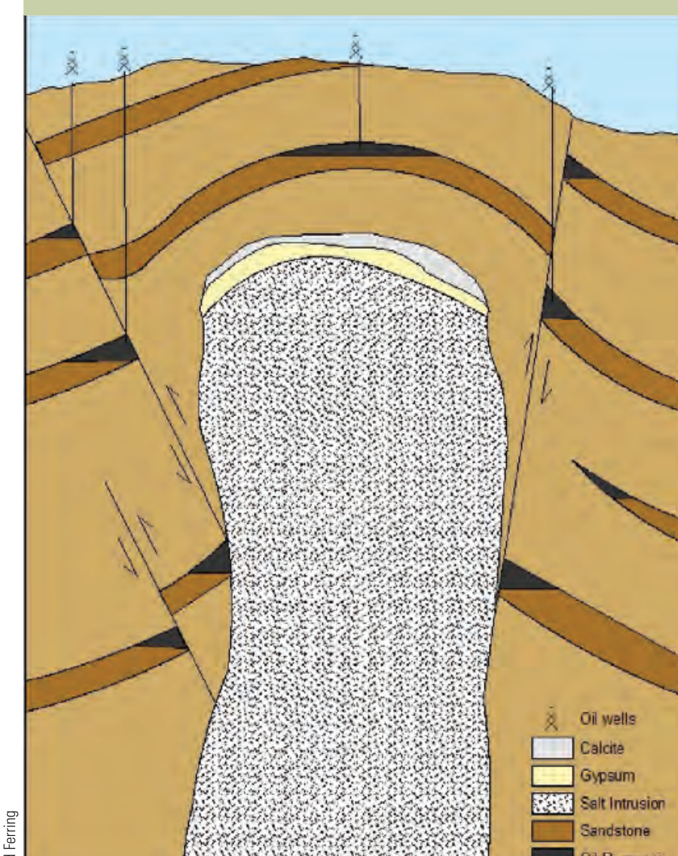
b Protection of the environment is a major challenge for the lignite industry, yet significant strides have been made to maintain air and water quality near mines and generating plants.

The Gulf Coastal Plain has enormous petroleum reserves. Although these reserves are widely distributed, active oil fields are concentrated around two principal geologic features. The first is a series of fault zones that roughly follow contours around the Gulf Basin. These differ from the tectonically induced faults discussed earlier in this chapter. They are called growth faults, and they formed along trends where high rates of sedimentation induced rapid subsidence. The lower parts of growth faults commonly bend toward the Gulf Basin, and in some cases, huge blocks of sedimentary rocks slide along nearly horizontal fault planes. All of this faulting results in formation of numerous traps for the hydrocarbons, not only on the coastal plain, but also out on the continental shelf where numerous offshore drilling platforms have been constructed.

The other geologic features that concentrate petroleum reserves are salt domes. These domes are common throughout east Texas, forming the western part of their more general distribution about the lower Mississippi valley. As mentioned in Section Texas.7, thick deposits of halite accumulated in the early Gulf Basin that was opened by rifting during the Jurassic Period. Burial under thousands of meters of younger sedimentary rocks mobilized the salt, forcing it upward as discrete plumes. The rising salt intrusions warped and faulted the surrounding rocks, creating ideal traps for oil and gas (Figure Texas.31).

Figure Texas.31 As thick Cretaceous-Tertiary sediments accumulated rapidly in the Gulf of Mexico basin, the deeply buried Jurassic Louann Salt was compressed, forcing numerous plumes of salt up through the overlying rocks, creating salt domes and giant oil fields.



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Salt domes have been targets for oil exploration ever since the Spindletop discovery well was brought in near Beaumont in 1901. In 9 days, this first Texas "gusher" blew an estimated 1 million barrels of oil into the air, forever changing Texas and the oil industry. In addition to oil and natural gas, salt domes concentrate significant sulfur deposits, which are dissolved and brought to the surface. Because the salt has almost no permeability and cannot be dissolved by oil, huge caverns created within large salt bodies are used to store large portions of our nation's strategic oil reserves. Last, it should be mentioned that these salt bodies are mined for their salt, mainly for industrial purposes and for deicing roads.

Section Texas.11 Summary

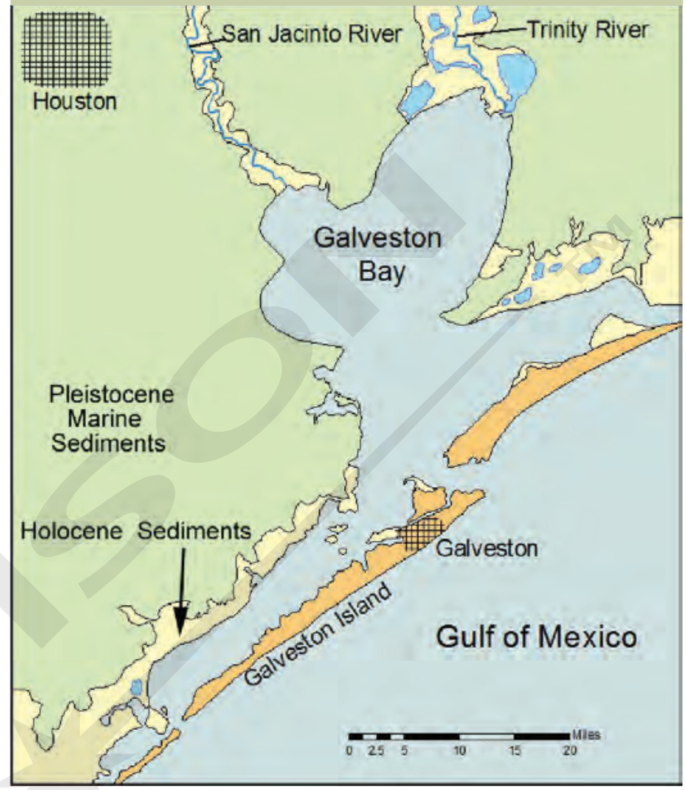
- The Gulf Coastal Plain was constructed during prolonged Tertiary regression of the Gulf of Mexico.
- This region contains vital resources including petroleum, lignite, and groundwater.

Texas.12
The Texas Gulf Coast

The last topic of this chapter is the present coast of Texas, which is an excellent example of a submergent coast. Its most obvious feature is the nearly continuous barrier island complex, which is separated from the mainland by salt marshes and shallow lagoons (see Figure Texas.27). These are excellent habitats for sport fishing and also serve as feeding areas for migratory ducks and geese in winter. The Intracoastal Canal, which extends from Brownsville to Florida behind the barrier islands, is a vital corridor for barge traffic. Galveston and Corpus Christi bays are among the busiest seaports in the United States, serving the agricultural, petroleum, and manufacturing sectors of Texas' economy. All of the canals and ship channels in Texas must be maintained by dredging because of infilling sediment that is delivered by rivers and as washover during storms. At Port Aransas, long jetties extend out into the Gulf, along the ship channel leading to Corpus Christi. The jetties, made of huge blocks of Precambrian granite quarried near Marble Falls, were constructed in the 1930s to keep longshore drift from filling in the channel.

Rivers with high sediment loads, especially the Rio Grande and Brazos rivers, have deltas, but the dominant forces of waves and longshore currents prevent the deltas from prograding beyond the barrier island chain (see Figure Texas.1). The bays of smaller rivers, including the Nueces, Colorado, and Trinity rivers, are good examples of **drowned estuaries**, created as sea levels rose during the last deglaciation (Figure Texas.32). These bays are separated from the Gulf of Mexico by barrier islands. The barriers have "passes" that are created and maintained by washover during hurricanes and by the seaward return of storm surge waters after the hurricanes move inland.

▶ **Figure Texas.32** Barrier islands fringe almost the entire Texas coast, which is dominated by waves, currents, and storms. Galveston Bay is a drowned estuary, as are all the major bays farther south. In 1900, before construction of a protective seawall, more than 6,000 inhabitants of Galveston died during a hurricane. And still today, these low coastal areas are threatened by potentially devastating storms, such as hurricanes Katrina and Rita in 2005.



Reid Ferring

All too often, hurricanes make their landfall along the Texas coast, and over the past century, the loss of lives and property has been devastating. The tragedies caused by hurricanes Katrina and Rita persist today for thousands of displaced persons, and the damage done to offshore drilling rigs and submarine pipeline networks is still being repaired. Texas is especially vulnerable to hurricanes because of the extensive low-lying areas that can be flooded easily by storm surges. Barrier islands retard the return flow of storm surge waters, lengthening the period of flooding and hampering recovery and rescue efforts. Larger storms are able to overtop the seawalls constructed in Galveston and Corpus Christi, and the populations in these areas are clearly at risk any time that a storm approaches.

Section Texas.12 Summary

- Texas has a submergent coast, with bays, marshes, and lagoons behind an extensive barrier island system.
- Frequent hurricanes threaten the coastal environments and the populations who live along the coast.

Review Workbook

SUMMARY

Texas.1 Introduction

■ *Why is the geology of Texas important to students of physical geology and to all the inhabitants of the state today?*
Learning about the geology of their state helps Texas students better understand the principles of physical geology and makes them more aware of how the state's geologic past is related to the ways in which its residents interact with its landscape and exploit its resources today.

Texas.2 Precambrian Texas

■ *What tectonic events shaped the Proterozoic geologic record of Texas?*
The genesis of Proterozoic rocks in Texas is indicated by process sequences such as erosion, sedimentation, regional metamorphism, and postorogenic igneous intrusion.

■ *When and how were the metamorphic and igneous rocks of the Llano region accreted to the ancient continent Laurentia?*
The metamorphic suite of Proterozoic rocks in Texas was accreted to Laurentia and became part of the much larger accretionary Grenville Terrane because of the highly compressional tectonic regimen about 1.3 billion years ago (Ga). The intrusive suite was accreted about 0.2 billion years later.

Texas.3 The Paleozoic Tectonic Cycle

■ *What kinds of sediment were deposited during the Lower Paleozoic?*
Sandstone overlain by thicker deposits of limestone, much dolomitized, were deposited in the Cambrian and Ordovician periods.

■ *What is the economic significance of these rocks today?*
These rocks hold tremendous petroleum reserves.

Texas.4 The Ouachita Orogeny and Pangaea

■ *What were the geologic results in Texas of the collision of Gondwana with Laurasia?*
The collision caused prolonged orogeny and proportionate structural and sedimentary responses.

■ *How do the sedimentary rocks and structural styles of the Marathon area illustrate the collision?*
The rocks at Marathon show a sequence from rapid preorogenic marine sedimentation to intense thrust faulting and lastly to terrestrial sedimentation.

Texas.5 The Fort Worth Basin in the Late Paleozoic Era

■ *What sedimentary environments characterized the Fort Worth Basin during and after the Ouachita orogeny?*
The Fort Worth Basin was flanked on the east by the Ouachita Mountains, from which active deltas prograded onto a shelf that had carbonate banks and platforms.

■ *Why is this basin rich in oil and gas resources?*
Those environments produced abundant hydrocarbons, as well as ideal reservoirs and traps.

Texas.6 Permian Red Beds and Evaporites

■ *Why are red beds and evaporites characteristic of the Permian basins of central and west Texas?*
Periodic isolation of evaporitic basins surrounded by weathered and eroded landforms were the depositional environments for those rocks.

■ *How does the geology of that region affect present-day land-use patterns?*
Today, those salts make their way into the surface and groundwater systems, dramatically reducing water quality and water use potentials.

Texas.7 Breakup of Pangaea and Cretaceous Transgressions

■ *What happened in Texas during and after the breakup of Pangaea?*
Rifting in the Jurassic Period created the Gulf of Mexico Basin, which became an open ocean just before Cretaceous transgressions.

■ *What were the results of the Cretaceous transgressions?*
The transgressions left thick packages of sedimentary rocks over most of the state and deeply buried below the Gulf Coastal Plain.

Texas.8 Basin and Range Texas

■ *What types of tectonic activity are indicated by the volcanic rocks in trans-Pecos Texas?*
Extensive bimodal volcanism is indicated by mainly Oligocene Epoch lava, and ash resulting from a compressional phase of intraplate tectonics.

■ *How did the basin and range structural features form in that region?*
The basin and range features primarily formed during the Miocene Epoch when tensional conditions promoted normal faulting.

Texas.9 The Llano Estacado

■ *Which geologic processes led to the formation of the Llano Estacado?*
The Llano Estacado was constructed by accumulating fluvial sediments from the Rocky Mountains, followed by finer sediments that were deposited by wind.

■ *What is the Ogallala aquifer, and how is it recharged?*
The fluvial deposits in the lower part of the Ogallala Formation are the Ogallala aquifer. Abundant playa lake basins promote some recharge of the aquifer, which still falls during droughts.

Texas.10 The Edwards Plateau and Balcones Fault Zone

■ *When and how did the Edwards Plateau and Balcones Fault Zone form?*
The Edwards Plateau formed in the Miocene Epoch by epeirogenic uplift, which was accommodated along the Balcones Fault Zone, separating the plateau from the Gulf Coastal Plain.

■ *How were these geologic features important to the initial settlement of Texas, and how are they important to Texans today?*
Locations where springs fed by the Edwards aquifer were near rivers crossing the fault zone were chosen by early settlers of cities from San Antonio to Dallas. The Edwards aquifer is a major source of water today.

Texas.11 The Gulf Coastal Plain

■ *How have transgressions and regressions shaped the geologic evolution of the Gulf Coastal Plain?*
Those different sedimentary cycles promoted varied accumulations of organic matter that were sources for rich accumulations of petroleum and lignite.

■ *What are the economic and environmental implications of using lignite to generate electricity?*
Lignite can be used to fire generating plants almost indefinitely, and at a reasonable cost; but both the mining and burning of lignite are, without any remediation, harmful to the environment. This threat is the source of considerable efforts to minimize those problems.

■ *How did salt domes form, and why are economic resources concentrated around them?*
Salt domes formed when halite was compressed under thick sediments in the Gulf Basin, forcing it to rise through the overlying deposits. As the salt column rose, it created numerous traps by faulting.

Texas.12 The Texas Gulf Coast

■ *What are the principal features of the Texas Gulf Coast, and how did they form?*
The Gulf Coast of Texas is marked by its low-gradient and high-wave energy. It exhibits bays, salt marshes, and lagoons behind an extensive series of barrier islands.

■ *How do hurricanes affect the coastal areas of Texas?*
Hurricanes attack the fragile landforms along the coast, delivering large volumes of both sediment and saltwater, together with massive erosion potential. Their threats to the lives and homes of people who live in low coastal areas are realized too often, as shown by the devastation of hurricanes Katrina and Rita.

ESSENTIAL TERMS TO KNOW

Aulacogen The failed arm of a triple-junction rift, left behind on the edge of the continent after the new ocean opens.

Balcones Fault Zone The zone of normal faults that defines the eastern edge of the Edwards Plateau and the Coastal Plain of Texas.

Basin and range Low mountain forms that consist of upraised blocks bounded by normal faults and separated by graben-type valleys.

Bimodal volcanism Volcanism in a region usually subjected to extensional tectonics, characterized by magmatic compositions ranging from felsic to mafic.

Calcareous algae Algae that produce large amounts of carbonate mud composed of minute calcite crystals that help support the algal organism during life.

Caldera A large volcano with a central crater that formed when collapse was induced by evacuation of the magma chamber below.

Caliche A hard, thick zone of calcium carbonate that formed by soil activity, usually in regions with arid to semiarid climates.

Chalk A rock composed of the calcareous skeletons (tests) of marine phytoplankton.

Deflation Removal of fine-grained sediments by wind.

Drowned estuary The mouth of a river valley that has been inundated by ocean waters during the sea level increase accompanying deglaciation.

Entrenched valley A valley that has been incised into bedrock in response to regional uplift.

Eolian Adjective applied to sedimentary processes and deposits associated with wind.

Epeirogenic uplift More or less uniform uplift of large areas in the absence of compressional mountain building.

Ephemeral Adjective applied to streams or bodies of standing water that carry or contain water only after rains or rainy seasons.

Flysch Thick accumulations of thinly bedded sandstones, shales, and marls that were rapidly deposited in basins in advance of a continental convergence.

Fracking Fracturing of rocks that surround a gas or oil well, induced by injecting water and sand into the rocks under high pressure to increase the porosity of the reservoir and the flow of hydrocarbons to the well.

Glauconite A green silicate mineral that commonly occurs as granular clasts in marine sandstones.

Gondwana The continent that formerly included Africa, South America, Antarctica, India, Australia, and Madagascar.

Grenville Province Huge masses of rocks that were added to the eastern and Texan edges of Laurentia in the middle Proterozoic Era.

Hogback A sharp, steep ridge created by erosion of steeply dipping rocks.

Intraplate tectonics Tectonic activity that occurs usually within continents, well away from plate margins.

Laurentia Name given to the North American continent as it appeared until its collision with Baltica in the Silurian Period.

Lignite A low-grade coal formed of plant remains that were concentrated, buried, and altered more than peat but less than higher grades of coal.

Marl A calcareous shale.

Microcline A low-temperature potassium feldspar, commonly found as pink to red crystals in granites and especially in pegmatites.

Molasse Terrigenous sediments deposited as a continental collision neared completion.

Orogeny A mountain building event.

Physiographic map A map divided into provinces that reflect a similar geologic history of deposition and erosion; it usually has distinctive soils, vegetation, and climate.

Phytoplankton Floating plants, many of which produce minute skeletons made of silca or carbonate material.

Playa lake A shallow, usually circular, and usually ephemeral lake.

Pluton A body of intrusive igneous rock.

Progradation The seaward growth of a landform by active sedimentation, such as a delta.

Reservoir rocks Porous rocks that can contain liquids, including water and petroleum, as well as natural gas.

Sedimentary environment A depositional setting with distinctive physical, chemical, and organic agents that impart distinctive properties to the sedimentary deposits that form there.

Sedimentary facies A horizontally and vertically distinct body of sediments that is different from adjacent sediments on the basis of physical, chemical, or organic properties.

Theory of plate tectonics A theory that integrates the scientific understanding of the causes, processes, and geologic results of the movement of lithospheric plates relative to each other.

Thrust fault A low-angle reverse fault.

Transgression A rise in sea level relative to the adjacent land.

Turbidite A gravity-induced flow of sediment down a submarine slope.

Uniformitarianism The premise that geologic processes happening today have operated in similar ways in the past.

Volcanic neck A standing mass of material that solidified in a volcanic pipe that usually has been exposed by erosion.

MORE ON TEXAS GEOLOGY

Following is a list of some ways that you can explore the geology of Texas:

The single best source for information about the geology of Texas is the Bureau of Economic Geology, affiliated with the University of Texas at Austin. The bureau sells maps, guidebooks, resources for amateur geologists, and many scientific publications that cover virtually all aspects of the subject. Look for them online at http://www.beg.utexas.edu.

The best way to enjoy and learn about the geology of Texas is to see it. A good way to do that is to visit state and national parks. Many of the photographs in this chapter depict scenes in parks.

Contact or visit the Texas Cooperative Extension Office of your county, located in the County Seat. They can provide you with information and literature about the soils, vegetation, and land-use practices in your county.

If you are taking this course in a geology department, you have the opportunity to take additional courses in geology. Look at your university course catalog, or better yet, visit the department to get information on their geology curriculum. If there is not a geology department on your campus, talk to your instructor about local options, or visit the websites of local universities to learn about the geology courses they offer. Almost all geology courses offered at colleges and universities in Texas are uniformly coded, and credits transfer virtually automatically.

If you are really interested in geology, you should consider becoming a student member of The Geologic Society of America. For a low membership fee (and some other optional costs), you can attend regional and national meetings, all of which encourage student papers and offer outstanding field trip opportunities. More information is available online at: http://www.geosociety.org.

Many museums around the state have geologic exhibits. Check your local listings.

When you travel in Texas, be sure to take a copy of the *Roadside Geology of Texas*, written by Darwin Spearing and published by Mountain Press Publishing Company, Missoula, Montana. You will also want a copy of the state highway geology map, which is available from the Bureau of Economic Geology.