The Teacher-Friendly Guide™
to the Earth Science of the South Central US

Edited by Mark D. Lucas, Robert M. Ross, & Andrielle N. Swaby
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Paleontological Research Institution
2015
Preface

Earth science is an inherently local subject. No two places share exactly the same sequence of events that led to the way they are today. In this sense, Earth science is a subject to be explored in one’s own neighborhood, examining the detailed sequence of rocks for the history that has gone on under our feet. What is not possible from only one location is making sense of why this particular sequence of events took place when and where it did, particularly relative to sequences in other places around it.

The distribution of rocks and landforms can be explained by processes that shape areas covering thousands of kilometers, such as the evolution of the Gulf Coast margin of the North American continent to the more stable, ancient continental interior. These processes link widely separated sequences in a common history.

Earth science educators at the Paleontological Research Institution, in working with teachers, have noted that no single source for educators exists that attempts to make sense of the disparate local features of the South Central United States in terms of a basic sequence of historical events and processes. Nationally distributed textbooks make few references specifically to the South Central region. While a number of reasonably good resources exist for individual states, these do not take enough geographic scope into account to show why, say, Missouri has abundant ancient limestones at the surface, while southern Louisiana and southeast Texas have young sand deposits, or why oil and gas are found in so many parts of Texas, but bituminous coal is more abundant in eastern Oklahoma. Further, these resources are not necessarily “teacher-friendly,” or written with an eye toward the kind of information and graphics that a secondary school teacher might need in their classroom. This Teacher-Friendly GuideTM is intended to fill this need for teachers.

Explaining why (for example, certain kinds of rocks and their mineral resources are found where they are) is the most effective way of providing students with a tool to remember and predict the nature of local Earth science. The South Central US (though, like states, an artificial political area) is of the right scale to discuss the evolution of significant portions of sedimentary basins, but also includes ancient igneous rocks. This means most Earth processes are illustrated by rocks present within a day’s drive, and that Earth phenomena can be illustrated with examples in areas students and teachers are likely to have been to or at least heard of. Since the rocks and landforms are relatively accessible, regional Earth science is an excellent subject for hands-on, inquiry-based teaching using, for example, real rocks and landforms. A transect across the South Central US in several places will reveal most major rock types that students should know and will come into contact with over the course of their lifetimes.

The chapters chosen are by no means an exhaustive list, but reflect especially the historical side of “solid Earth” geosciences. Each chapter starts with a brief review, then (in most chapters) describes the Earth science of five natural regions of the South Central. There is a resource list at the end of each chapter. There is a chapter on field work, not only on suggestions for how to do it, but how to integrate the field into your curriculum through “virtual fieldwork experiences.” There are chapters on Big Ideas in Earth system science—a few major conceptual ideas that run throughout the subject—and on using real-world regional Earth science in the context of the Next Generation Science Standards (NGSS).
This volume is part of a national series of seven *Teacher-Friendly Guides™* to regional Earth science, covering all 50 states. We also have two *Teacher-Friendly Guides™* to evolution, and other *Guides* in development.

We would hope for our students that, years from now, they will be able to make sense of the place they live and the places they visit, through a comprehension of a few Big Ideas and a basic grasp of the “big picture” story of geological history of their area. It is our hope that this book might help teachers, and their students, grasp such a coherent understanding of their regional and local Earth system science.

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February 2015
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How to Use this Guide

General philosophy of the Teacher-Friendly Guides™

This Guide is organized by regional geologic history because it helps make sense of local Earth science—Why does this place look the way it does? Why is this particular set of rocks, soil, landforms, water bodies, and local climate here? We recommend introducing geologic history into your curriculum early.

The idea of systems also runs through the Guide. Through systems we understand, for example, why geologic history controls where different types of rocks occur, helping us make sense of landforms and water bodies. Landforms and water bodies in turn influence local climate, and all of it influences life. Understanding a few essentials of geologic history and Earth systems allows us to make sense of the world around us.

Please incorporate ideas from the Guide into your existing curriculum. This Guide is a resource rather than a curriculum itself.

Understanding real-world Earth science is a lifelong learning experience. Don’t be intimidated by rocks that you don’t recognize, fossils with long names, or complicated weather patterns. Enjoy learning alongside your students and show that enjoyment.

A National Series of Guides

This Guide is one of seven covering the United States. There are also two Teacher-Friendly Guides™ to evolution, one focused upon bivalves and another focused on maize genetics. To learn more, visit www.teacherfriendlyguide.org, a website of the Paleontological Research Institution.

For the interactive website version of this Guide, visit www.teacherfriendlyguide.org. To download individual chapters for printing, visit the website for the South Central Guide and click “Downloads” on the chapter menu to the left.
Each Guide begins with five cross-cutting Big Ideas of Earth science. These have applications across the curriculum. Deep study of specific Earth science sites gives context and meaning to these most fundamental ideas, and in turn understanding these ideas facilitates a lifetime of making sense of Earth processes anywhere.

Each Guide ends with a chapter on fieldwork—even from the classroom. You and your students can begin to interpret the Earth science in your area, and bring back photos and data to re-visit your field sites—using “virtual fieldwork”—throughout the year. More information is available at www.virtualfieldwork.org.

Use the color geologic map as a reference tool while you read this Guide. The map is on the back cover of the printed Guides and available as a downloadable graphic on the website.

Cross-referencing

You do not have to read this Guide from front to back! Each chapter is written to stand alone. Main concepts are repeated in more than one chapter. In this way you can use read just what you need, in any order, as you approach particular units through the school year.

The chapters are cross-referenced, should you need to find more information about a particular concept or region. Bold-faced words are defined in a separate glossary, with selected words defined in chapter side bars.

For Further Information...

At the end of each chapter are lists of resources specific to that topic. There are lists of national and state-based resources, many of which cover multiple topics, at the end of the Guide.
Earth System Science: The Big Ideas

Like all scientific disciplines, the Earth sciences continually evolve over time. New discoveries fuel new ideas, providing an ever-increasing understanding of the planet. But of the overwhelming number of observations, theories, and principles that form the foundation of Earth system science, what is essential for every American to understand? All too often, curricula are too ambitious and, as a result, may fail to cover topics in any substantial depth. An alternative approach is to build one’s curriculum upon a foundation of focused, interconnected big ideas. A well-designed set of big ideas can provide an all-encompassing conceptual framework for any discipline, including Earth system science. Developed alongside scientists and Earth science teachers, this coherent set of big ideas illuminates what is fundamental to the Earth sciences:

1. The Earth is a system of systems.
2. The flow of energy drives the cycling of matter.
3. Life, including human life, influences and is influenced by the environment.
4. Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system.
5. To understand (deep) time and the scale of space, models and maps are necessary.

These ideas are designed to cover the breadth of any Earth science curriculum, but they must be dissected to build deep understanding. Each idea is essentially bottomless; that is, while a meaningful understanding of these ideas is readily attainable, the details contained within are endless. Each of the ideas can be understood, but the depth of understanding can vary greatly.

Introduction of these ideas also invites discussion of the nature of science. As curricula are designed and implemented, the traditional topics of Earth system science should be complemented with ideas on how we have come to know what we know about the natural world. Within our big ideas framework, we draw attention to the nature of science with two overarching questions:

1. How do we know what we know?
2. How does what we know inform our decision making?

These questions, when addressed in concert with the big ideas, provide a gateway into the nature and utility of the range of scientific ideas.
Big Idea 1: The Earth is a system of systems

The Earth is composed of many systems, which cycle and interact in both space and time. It is also part of a multitude of systems, nested in larger systems such as the solar system and the universe. Systems are composed of an untold number of interacting parts that follow simple rules; they can and do evolve.

For example:

Outlining the geologic history of any region demonstrates the concept of the Earth as a system of systems. **Plate tectonics** drives the formation of mountains. Subsequent **weathering** and **erosion** leads to the formation of **deltas** and the uplift of mountains. The Mississippi River has moved a tremendous mass of sediment, generated from erosion and **glacial outwash**, from the interior of North America into the Gulf of Mexico. This flow of sediment has contributed to the formation of the Coastal Plain region, and continues to alter the coastline of Louisiana today.

The planet’s systems are intimately connected: the forces of one system affect other systems nested within it. As **plates** collide, systems that drive plate tectonics are obviously linked to the formation of mountains, but they are ultimately linked to and influence much smaller systems. The intense heat and pressure resulting from collisions can lead to the **metamorphism** of existing strata, or it can melt existing rocks to later form **igneous rocks**.

See Chapter 4: Topography for more information about the Mississippi River and its alluvial plain.

Each of the remaining ideas operates across multiple systems within the larger Earth system.
**Big Idea 2: The flow of energy drives the cycling of matter**

The Earth is an open system. Energy flows and cycles through the system; matter cycles within it. This cycling is largely driven by the interaction of the differential distribution of solar radiation and internal heat: the constant flow of solar radiation powers much of Earth's ocean and atmospheric processes on the surface of the system, while the flow of heat from **radioactivity** within the Earth drives plate tectonics. For example:

One of the fundamental processes known to Earth system scientists is the rock cycle. The rock cycle illustrates the steps involved in the formation of one type of rock from another. It is a system that has operated since the Earth's origin, and it continues today. The energy that drives weathering and erosion, melting, or an increase in heat or pressure, drives the continuation of the rock cycle.

The landscape of the South Central that we see today has been shaped by the geologic forces of the past, and these forces are still active today. The movement of Earth's plates is driven by plate tectonics, illustrating how the flow of heat from radioactivity within the Earth drives plate tectonics. Evidence throughout the South Central's terrain tells a story that began billions of years ago with the formation of tectonic plates, and this story continues today as the Pacific and Juan De Fuca plates slide underneath and along the North American plates, generating **earthquakes** and volcanoes to the west along the Pacific coast. Tectonic activity is not limited to the Western US, however. Four of the largest North American earthquakes in recorded history were centered in the South Central US near New Madrid, Missouri in 1811 and 1812.

During the most recent **ice age**, glaciers advanced and retreated many times throughout the past two million years. One of the great questions in the Earth sciences revolves around the causes of these glacial cycles, with the general consensus pointing toward cyclic variations in the planet's tilt, movement about its axis, and its orbital shape around the sun. These variations lead to changes in the amount of solar radiation that reaches the Earth, which in turn affect global **climate**.

The rock cycle, plate tectonics, and the water cycle are all **convection**-driven. Without convection, Earth would be extraordinarily different.

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**atmosphere** • a layer of gases surrounding a planet.

**radioactivity** • the process by which an unstable atom loses energy by emitting radiation.

**earthquake** • a sudden release of energy in the Earth's crust that creates seismic waves.

**ice age** • a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.

**climate** • description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years.

**convection** • the rise of buoyant material and the sinking of denser material.

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See Chapter 6: Glaciers to learn more about the South Central during the ice age.
Big Idea 3: Life—including human life—influences and is influenced by the environment

Across its four-billion-year history, the course of life’s evolution has been intimately tied to the Earth’s physical environment. Global cooling led to the relatively recent spread of grasslands, which then triggered an evolutionary shift in many herbivorous mammals from browsing to grazing. Conversely, the evolution of life has altered the physical environment. Photosynthetic bacteria released free oxygen into the early oceans and atmosphere, making Earth habitable for later types of organisms. Humans, with their increasing population and expanding technology, have altered the landscape and the distribution of flora and fauna, and they are changing atmospheric chemistry in ways that affect the climate. Earth system processes also influence where and how humans live. For example:

With human populations increasing the world over, the emission of greenhouse gases has also increased dramatically. These gases alter the chemical composition of the atmosphere and directly influence the planet’s climate. It is generally agreed that the rapid and immense pouring of carbon dioxide into the atmosphere will lead to global warming, which will have incredible impacts throughout the world.

Around three million years ago, a land bridge formed between North and South America. For the first time in more than 150 million years, the two continents were linked, and the mammals inhabiting both lands migrated across the bridge. Horses, mastodons, cats, and dogs moved south, while opossums, porcupines, ground sloths, and armadillos moved north (to name a few). Today, half the mammal species in South America are descended from North American migrants.

The Great Plains region, which makes up much of the western portion of the South Central, supports extensive ranching and agriculture. The overwhelming majority of the region is either under cultivation, used for grazing livestock, or developed for residential and commercial use. When we ask, “Why does this place look the way it does?” the role of humans must be central to our answer.
Big Idea 4: **Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system**

The Earth processes operating today—everything from local erosion to plate tectonics—are the same as those operating since they first arose in Earth history, and these processes are obedient to the laws of chemistry and physics. While the processes that constantly change the planet are essentially fixed, their rates are not. Tipping points are reached that can result in rapid changes cascading through Earth systems. For example:

During the **Precambrian**, the evolution of photosynthetic organisms led to significant changes in the planet’s atmosphere. Prior to this event, there was little free oxygen in the atmosphere, but with photosynthesis producing oxygen as a waste product, the very existence of these organisms flooded the seas and atmosphere with free oxygen, changing the planet forever. But life’s evolution represents just one of the processes working upon Earth systems.

The New Madrid Seismic Zone has a long history of earthquake activity, with major quakes coming every few centuries, though it is has been generally calm for the last 200 years (which, from a geologic perspective, is a quite short amount of time). During the quakes of 1811 and 1812, the Mississippi River was rerouted, and, for a brief period, had at least one waterfall. The **seismic waves** from these events caused church bells to ring as far away as Boston, Massachusetts. Tectonic processes have been at work in the same way for billions of years, opening and closing oceans and building up and tearing down landscapes.

See Chapter 10: Earth Hazards for more information about earthquakes in the South Central.

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**Precambrian** • a geologic time period that spans from the formation of Earth (4.6 billion years ago) to the beginning of the Cambrian (541 million years ago).

**Seismic waves** • the shock waves or vibrations radiating in all directions from the center of an earthquake or other tectonic event.
Big Idea 5: To understand (deep) time and the scale of space, models and maps are necessary

The use of models is fundamental to all of the Earth sciences. Maps and models aid in the understanding of aspects of the Earth system that are too big or small for direct observation, or where observation is not possible. They also help make complex systems comprehensible through strategic simplification. When compared to the size and age of the universe, humanity is a speck in space and a blip in time; models assist in the comprehension of time and space at both sub-microscopic and immense scales. For example:

Much of scientists’ understanding of the inner workings of our planet is derived from mathematical modeling. It is not possible to directly measure the movement that occurs below Earth’s surface, but modeling of convection currents brings us closer to the true nature of these monumental geologic phenomena.

The observation of natural phenomena today, such as deposition along a riverbed, is critical for interpreting the geologic record. But for processes that operate on much larger, slower scales, modeling within the lab is required. The formation of horst and graben terrain, such as that found in the Basin and Range, is better understood by examining the effects of stress and strain in the laboratory.
In Conclusion

Taken individually, these big ideas and overarching questions represent important aspects of Earth system science, but together they are more significant. Keeping these ideas in mind—and considering how they arose through scientific methods and investigation—is invaluable as one proceeds throughout his or her curriculum, and it can provide a conceptual framework upon which to build an enduring understanding of the discipline.
Big Ideas

Resources

Books


Websites


Chapter 1: Geologic History of the South Central US: The Big Picture

Geologic history is the key to this guide and to understanding the story recorded in the rocks of the South Central. By knowing more about the geologic history of our area, you can better understand the type of rocks that are in your backyard and why they are there. We will look at the history of the South Central as it unfolds: as a series of major events that created and shaped the area over the past one billion years. These events will act as the framework for the topics to follow and will shed light on why our region looks the way it does!

The geologic time scale (Figure 1.1) is an important tool used to represent the history of the Earth—a standard timeline used to describe the age of rocks and fossils, and the events that formed them. It spans Earth’s entire history and is separated into four principle divisions.

The first of these, the Precambrian, extends from about 4.6 billion years ago to 541 million years ago. Little is known about this time period since very few fossils or unaltered rocks have survived. What few clues do exist indicate that life first appeared on the planet some 3.9 billion years ago in the form of single-celled organisms.

The second division, the Paleozoic, extends from 541 to 252 million years ago. Fossil evidence shows that during this time period, life evolved in the oceans and gradually colonized the land.

<table>
<thead>
<tr>
<th>Precambrian</th>
<th>Cambrian</th>
<th>Ordovician</th>
<th>Silurian</th>
<th>Devonian</th>
<th>Carboniferous</th>
<th>Permian</th>
<th>Triassic</th>
<th>Jurassic</th>
<th>Cretaceous</th>
<th>Neogene</th>
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</tr>
</tbody>
</table>
Geologic History

Geologic Time

How did geologists come up with the timeline for the history of the Earth? The geologic time scale was developed over the course of many years and through the combined work of geologists around the world. No rock record in any one place contains the complete sequence of rocks from Precambrian to present. Geology as a science grew as geologists studied individual sections of rock. Gradually, evolutionary successions of fossils were discovered that helped geologists determine the relative ages of groups of rocks. Rock units were then correlated with similarly aged rock units from around the world. The names you see for the different periods on the geologic time scale have diverse origins. Time periods were named after dominant rock types, geography, mountain ranges, and even ancient tribes like the Silurese of England and Wales, from which the “Silurian” period was derived.

The third division, the Mesozoic (from 252 to 66 million years ago), is also called the “age of reptiles” since dinosaurs and other reptiles dominated both marine and terrestrial ecosystems. It is also noteworthy that during this time the last of the Earth’s major supercontinents, Pangaea, began to assemble over 300 million years ago and lasted for almost 150 million years. All of the Earth’s continents were joined as one to form a giant supercontinent.

The last and current division, the Cenozoic, extends from the extinction of the dinosaurs, nearly 66 million years ago, to the present. With the demise of the dinosaurs, mammals became dominant and, subsequently, more diverse and highly developed. We humans don’t come into the picture until the last two million years. To get some perspective on this, if the entire geologic time scale were reduced to 24 hours, we wouldn’t come onto the stage until two seconds before midnight!

The Earth is dynamic, consisting of constantly moving plates that are made of a rigid continental and oceanic lithosphere overlying a churning, plastically flowing asthenosphere (Figure 1.2). These plates are slowly pulling apart, colliding, or sliding past one another with great force, creating strings of volcanic islands.
islands, new ocean floor, mountains, and earthquakes. The continents are likewise continuously shifting position relative to each other. This not only shapes the land, but also affects the distribution of rocks and minerals, natural resources, climate, and life.

Rocks and sediments are indicators of past geologic processes and the environments in which those processes took place. In general, igneous rocks, created through tectonic activity, reflect past volcanism. By looking at both their texture and chemistry we can determine the tectonic setting and whether or not the rocks formed at the surface or deep underground. Likewise, metamorphic rocks, created when sediment is subjected to intense heat and pressure, provide important clues to past mountain-building events, and geologists often use them to map the extent of now-vanished mountain ranges. Sedimentary rocks tell perhaps the most comprehensive story of the Earth’s history, as they record characteristics of far-away mountain ranges, river

See Chapter 2: Rocks to learn more about different rocks found in the South Central.
systems that transported the sediments, and the final environment in which the sediments accumulated and lithified. The size and shape of sediments in sedimentary rocks, as well as the presence of fossils and the architecture of sedimentary rock layers (sedimentary structures), can help us infer how the sediments were transported and where they were finally deposited. However, because rocks are often reformed into different rock types, ancient information is lost as the rocks cycle through the igneous, metamorphic, and sedimentary stages.

Fossils indicate both the type of life that once flourished in an area and the kind of climate in which that life existed. Paleontologists use groups of fossils found in the same place to construct pictures of entire ecosystems. These ecosystems of the past are matched to similar present-day ecosystems, whose climate conditions are then used to infer what sort of climate the fossilized organisms lived in. Unfortunately, few organisms are easily preserved as fossils, and many environments also do not lend themselves to preserving organisms as fossils. As a result, the clues that fossils give provide only glimpses of the ancient world, with many important details missing.
Landslides and geologic structures are also indicators of past geologic processes and the environments in which they occurred. For instance, the shape of a valley reflects the forces that carved it. Valleys with V-shaped profiles tend to be the products of stream erosion, whereas U-shaped valleys are more likely to have been carved by glaciers. Layers of intensely folded rock indicate a violent past of tectonic plate collisions and mountain building. Sedimentary structures, such as ripple marks or cross-bedding, can demonstrate the direction and energy level of the water that moved the sediment. Although landscapes tell us much about the geologic processes that created them, they inevitably change over time, and information from the distant past is overwhelmed by the forces of the more recent past.

Ultimately, geologists rely upon the preserved clues of ancient geologic processes to understand Earth’s history. Because younger environments retain more evidence than older environments do, the Earth’s recent history is better known than its ancient past. Although preserved geologic clues are indeed fragmented, geologists have become increasingly skilled at interpreting them and constructing ever more detailed pictures of the Earth’s past.

**Precambrian Beginnings:**
**Roots of the South Central**

The Earth is estimated to be approximately 4.6 billion years old. Rocks dating to 4 billion years old are found on almost every continent, but the oldest rocks known are 4.3-billion-year-old greenstone beds found along the eastern shore of Hudson Bay in northern Quebec. These are part of the Canadian shield, the ancient core of the North American continental landmass.

The Canadian shield has experienced very little tectonic activity (faulting and folding) for millions of years. Shields, or cratons, are the stable cores of all continents and are often covered by layers of younger sediments.

The oldest known materials in the world are 4.4-billion-year-old zircons from Western Australia.

See Chapter 3: Fossils for more information about the South Central’s prehistoric life.

See Chapter 4: Topography for more detail about the landscapes found in the South Central States.

See Chapter 3: Fossils for more information about the South Central’s prehistoric life.
Geologic History

Precambrian

Sedimentary Structures

Sedimentary rocks often reveal the type of environment in which they formed by the presence of structures within the rock. Sedimentary structures include ripple marks, cross-beds, mud cracks, and even raindrop impressions. Consider the type of environments in which you see these sedimentary structures today in the world around you.

Ripple marks suggest the presence of moving water (though wind can also create ripples and even dunes). Mud cracks indicate that the sediment was wet but exposed to the air so that it dried and cracked.

Cross-beds form as flowing water or wind pushes sediment downcurrent, creating thin beds that slope gently in the direction of the flow as migrating ripples. The downstream slope of the ripple may be preserved as a thin layer dipping in the direction of the current, across the natural flat-lying repose of the beds. Another migrating ripple will form an additional layer on top of the previous one.

colliding plates, tension from plates pulling apart, the addition of land to North America, weathering, and erosion have combined to slowly sculpt the form of the continent. More than a billion years ago, narrow strips of land collided with and compressed one another to form the Precambrian beginnings of the North American continent, also called Laurentia. From this proto-North America, sediment was eroded and transported by rivers and streams across the ancient continental margins and then into the adjacent oceans. The sediment deposited in the ocean waters on the eastern margin of Laurentia composes what is presently called the Grenville Belt.
The South Central States are divided up into five different geologic provinces or regions (Figure 1.3): the Central Lowland (1), Interior Highlands (2), Coastal Plain (3), Great Plains (4), and the Basin and Range (5). Among these regions, Precambrian-aged rock is exposed in only a few discrete places in Texas, Oklahoma, and Missouri, although it underlies larger swaths of the area. Much of the basement rock here is a remnant of volcanic islands and an associated submarine mountain range that formed about 1.4 billion years ago as magma welled up from the mantle and cooled into granite or erupted, forming rhyolite. These islands later collided with other microcontinents to form the bedrock of the proto-North American continent.

The oldest exposures in the South Central are found within the Saint Francois Mountains of the Interior Highlands. Granitic and rhyolitic igneous rocks represent the remains of a Proterozoic mountain range dating to nearly 1.5 billion years ago, and they form the core of the Highlands today. Further south, the Central Texas Uplift of the Great Plains province contains gneiss and granite that formed between 1.3 and 1 million years ago. The Franklin Mountains near El Paso, Texas, part of the Basin and Range province, also contain Precambrian-aged rock.

Figure 1.3: Geologic regions of the South Central.
During the next several tens of millions of years, parts of these mountains were buried in sediment that originated on Laurentia’s northeastern portion. The resulting sedimentary rock was subsequently metamorphosed, and it is now exposed at the Llano Uplift in a ring surrounding the previously mentioned older portion.

The remainder of the Precambrian period saw the formation of the supercontinent Rodinia about 1.1 billion years ago (Figure 1.4), along with its eventual breakup about 750 million years ago. The tectonic activity that generated the formation and breakup of Rodinia may have contributed to the metamorphism evident in the older rocks mentioned above. As Rodinia broke up, a rift began to form in what is now southwest Oklahoma. Magma rising near the surface cooled to form parts of the Wichita Mountains. The rifting eventually failed, but not before the crust had thinned sufficiently to create a series of inland basins in southwestern Oklahoma and western Texas.

By the close of the Precambrian, very little existed of the South Central as we know it today. Deposition of sediments within shallow seas during the Paleozoic and Mesozoic, followed by deposition from the eroding Rocky Mountains and Interior Highlands during the Cenozoic era, would later form the South Central familiar to geologists today.

**Seas and Mountains: Sediments of the Midcontinent**

During the Paleozoic, extensive deposition occurred in the South Central as shallow inland seas spread across the interior of the continent, covering North America’s Precambrian shield. Across the Interior Plains, which include significant sections of Kansas, Missouri, Oklahoma, and Texas, a sequence of sediments 1500 to 3000 meters (5000 to 10,000 feet) thick was deposited during the Paleozoic and much of the Mesozoic. In many areas of the Interior Plains, these sediments are found only at depth, with younger sediments from streams and other sources overlaying them at the surface.

Beginning in the Cambrian period, about 545 million years ago, the southern portion of the region was persistently submerged (Figure 1.5), and a further rise in sea level caused nearly the entire region to be inundated during the late
Geologic History

Figure 1.4: The supercontinent Rodinia, circa 1.1 billion years ago. Laurentia represents proto-North America. (See TFG website for full-color version.)

inland sea • a shallow sea covering the central area of a continent during periods of high sea level.

Figure 1.5: Earth during the early Cambrian, around 545 million years ago. (See TFG website for full-color version.)
Cambrian. During the Paleozoic, even the high areas of northwestern Texas and the Ozarks of Missouri were occasionally underwater. The basin that had formed in Oklahoma as Rodinia broke up (see Precambrian Beginnings), along with much of the southern portion of the South Central, contains rocks from this time, some of which preserve the region’s oldest fossils in what are now Oklahoma’s Wichita Mountains and Missouri’s Saint Francois Mountains. The Saint Francois Mountains are the core of the Ozarks, and represent the exposed portion of a Precambrian, igneous mountain chain. As the tallest point of the Ozarks, the Saint Francois Mountain range is thought to represent the only area of the central US to have never been submerged by the shallow seas of the Paleozoic and Mesozoic eras.

Ordovician-aged rocks in southern Missouri and northern Arkansas show sequences of sandstones, carbonates, and shales, which are indicative of fluctuating sea levels and shifting shorelines. Invertebrate fossils are not uncommon in these rocks. In Missouri, a layer of clay formed of volcanic ash hints at tectonic activity far off to the east. During the Ordovician, the South Central was rotated roughly 90° clockwise relative to its current position (Figure 1.6). New England, now located northeast of the South Central, was actually forming to the southeast at that time.

During the Silurian and Devonian periods, the South Central again saw the sea advance over the entire region, and then retreat to what is now its southeastern third. Very little bedrock is preserved from this time. During the Carboniferous, however, plate tectonics led to the initial stages of Pangaea’s assembly (Figure 1.7). As North America collided with Gondwana (a southern supercontinent), both the Appalachian Mountains and the South Central’s Interior Highlands were
formed. The Highlands can be divided into two distinct sections: the Ouachita Mountains to the south (west central Arkansas, southeastern Oklahoma, and, beneath the surface, significant parts of central Texas), and the Ozark Uplift to the north (southern Missouri, northern Arkansas, and northeastern Oklahoma). After their uplift, erosion shaped the Ozarks into a series of plateaus capped by more resistant layers that are cut extensively by stream and river valleys.

As the landmasses collided, ancient seafloor was compressed into a series of folds and faults, producing the Ouachita Mountains. Since the collision occurred in a north-south direction, these folds extend in an east-west direction. Once established, these mountains began to erode, filling the submarine basins that had formed in western Texas as Rodinia broke up. By the Permian, these basins were full of rich organic material. Today, they are collectively called the Permian Basin, an area famous for its petroleum production.

By the Permian, the assembly of Pangaea was essentially complete (Figure 1.8). Most of the South Central was above sea level at the dawn of the Mesozoic, partly due to regional uplift. Moreover, the arrangement of most of the land into a supercontinent resulted in a relatively low sea level. When the continental plates are amassed, they take up a comparatively smaller area on the surface of the Earth, and oceanic crust takes up a greater area. This means there are likely to be fewer rifts on Earth’s surface, and therefore fewer mid-oceanic ridges (underwater mountain ranges that can displace huge volumes of water). Because in this arrangement there is, on average, more distance for oceanic crust to cover before it subducts below a continent, it spends more of its time on the surface, allowing it to cool, condense, and sink. Therefore, overall, the seafloor is “lower,” and the sea level is subsequently lower near
Evidence for Pangaea

How do we know that Pangaea existed 250 million years ago? Fossil evidence and mountain belts provide some of the clues. For example, the Permian-age fossil plant *Glossopteris* had seeds too heavy to be blown across an ocean. Yet *Glossopteris* fossils are found in South America, Africa, Australia, India, and Antarctica! The mountain belts along the margins of North America, Africa, and Europe line up as well and have similar rock types, an indication that the continents at one time were joined as Pangaea. Despite the discovery of *Glossopteris* and other geologic evidence, the theory of continental drift was not accepted for decades, until the mechanisms of continental movement were discovered and reformulated under the modern theory of plate tectonics. The supercontinent Pangaea existed for approximately 100 million years, reaching its largest size during the Triassic period. During the Jurassic, the landmass began to fragment into the modern continents, which slowly moved toward their present-day positions over the following 150 million years.
the continental margins. As the Permian came to an end, the South Central transitioned to a terrestrial environment—in Texas, rocks from this time include **salt** and **gypsum** that were deposited as the sea retreated.

At the beginning of the Mesozoic, the South Central was a part of Pangaea, which broke up in several phases during this era. The Ouachita Mountains ran from the southwest to the northeast, where they were contiguous with the Appalachian Mountains, forming a huge range that extended from Mexico to Maine. By the end of the **Triassic**, the continental plates began to move apart once again, thinning the crust and causing it to **subside**. During the **Jurassic**, North and South America began to separate. Rifting in the Ouachitas opened up a growing basin between the Yucatan and South Central US that was eventually flooded by water from the Pacific Ocean—effectively creating the Gulf of Mexico. The Louann Salt formation, famous for its **impermeable salt domes**, was deposited in this basin over many millions of years. By the late Jurassic, the spreading rift had produced a substantial amount of oceanic crust, forming a deep and expanding floor to the Gulf and creating a connection with the newly developing Atlantic Ocean (*Figure 1.9*). The Gulf then began to function as a seaway, and the resulting circulation caused the deposition of salt to cease.

During the early **Cretaceous**, Pangaea entered its final stages of breakup. Far to the west, oceanic crust had been subducting under western North America for tens of millions of years, causing a series of volcanic island complexes to collide with and become accreted to that margin of the continent. The great weight of the resulting mountains, west and north of the South Central, caused the surrounding crust to sink, creating a foreland basin (*Figure 1.10*). By 115 million years ago, the Arctic Ocean had flooded the basin from the north, eventually reaching the northwestern tip of Kansas (*Figure 1.11*).
Geologic History

Seas & Mtns

hot spot • a volcanic region thought to be fed by underlying mantle that is anomalously hot compared with the mantle elsewhere.

Mississippi Embayment • a topographically low-lying basin in the south-central United States, stretching from Illinois to Louisiana.

Beginning 95 million years ago, North America passed over a hot spot in the mantle. The rising magma uplifted a portion of the Ouachita-Appalachian Mountains, creating an arch and causing the range to be preferentially weathered. After the South Central passed over the hot spot, the crust there had thinned significantly, and it began to cool and subside, eventually forming a basin. As the ocean flooded the area between the Interior Highlands and the Appalachians, what is now the Mississippi Embayment was created. The Embayment area today extends from the confluence of the Ohio and Mississippi Rivers in the north, to the Gulf of Mexico in the south. This is the origin of the relatively low, flat area that now separates the Appalachian and Ouachita mountain ranges.
Around 85 million years ago, the oceanic crust at North America’s western margin (the Farallon plate) began to subduct at an unusually shallow angle. It slid farther inland beneath the continent before finally sinking into the asthenosphere, downwarping the western part of the South Central. This created a basin that allowed the waters of the Gulf of Mexico to meet with those in the north, forming the Western Interior Seaway (Figure 1.12), which inundated a 1000-kilometer (620-mile) wide swath from Mexico to Alaska. During the very latest stages of the Cretaceous period, around 70 million years ago, the midcontinental sea was displaced by slow uplift of the continent.

The roots of the Mississippi Embayment can be traced as far back as the Precambrian. When the Precambrian supercontinent Rodinia broke apart, many smaller rifts in the crust formed adjacent to the major rift that was responsible for the separation of North America. One of the smaller rifts is located beneath the modern Mississippi Embayment. During parts of the Paleozoic era, a proto-Mississippi Embayment existed above the rift. During the Cretaceous, the ocean flooded the embayment; when the sea level fell, the Mississippi River was born.

The Farallon plate continued to collide with western North America, thrusting layers of rock up over each other and causing increasing volcanism to the west of the Western Interior Seaway. The Laramide Orogeny of the late Cretaceous and Paleogene periods—80 to 55 million years ago—changed the face of the United States. The rising ancestral Rocky Mountains provided sediment that filled the seaway, preserving an amazing variety of the organisms living in the basin. The uplift of the ongoing orogeny finally caused the water to split in the Dakotas and retreat south, to survive...
in parts of the Mississippi Embayment through the end of the Cretaceous. The now-exposed terrain—the flat floor of the former sea—provided the basis for the **topography** of the Interior Plains. Sediment from the mountains was transported to the coast by rivers and streams, building up successive layers that fanned out onto the continental shelf (Figure 1.13). The late Cretaceous was marked by high sea levels worldwide, in part due to the significant increase in plate tectonic activity that followed the break up of Pangaea (Figure 1.14). As Pangaea split apart, it changed the shape of the Earth’s ocean basins and created underwater ridges such as the Mid-Atlantic Ridge, where new oceanic crust continues to form today. The subsequent displacement of ocean water contributed to higher sea levels, and when sea levels rose, deposition of marine sediment also contributed to the Coastal Plain.
The coastal plains of south and west Texas formed as sediment washed off the still-growing Rockies. Farther east, watersheds originating in the Appalachians deposited sediment on the shores of the Gulf. The Rocky Mountains continued to rise and volcanic activity increased around 50 million years ago, which both produced large quantities of sediment (which was subsequently transported and deposited across the Interior Plains) and lava (which covered portions of westernmost Texas).

The Cenozoic:
Sea Level Changes Shape the Continent

The Cretaceous–Paleogene boundary marks one of the most significant physical and biological events in Earth’s history. The boundary, which is about 66 million years old, marks the contact between the Mesozoic and Cenozoic
Geologic History

Cenozoic

eras. It represents a time during which many marine and terrestrial animals and plants, from microscopic varieties to massive dinosaurs, suddenly became extinct. Many scientists accept that the Cretaceous extinctions resulted from the impact of a large meteorite that produced the Chicxulub impact crater along the northern coast of Mexico’s Yucatan Peninsula. The extinctions may also have been coupled with the regression of shallow seas and massive volcanism in India.

Because the North American plate was (and still is) drifting away from the Mid-Atlantic Ridge during the Cenozoic, mountain building along the plate’s eastern margin ceased. Instead, sediment eroding from existing mountains was gradually deposited along North America’s passive continental margin. Despite minimal tectonic activity in the Coastal Plain area throughout the last 140 million years, the face of the land continued to change significantly due to erosion, deposition, sea level fluctuations, and the ice age.

The Coastal Plain of the South Central US is the largest and generally youngest region. Its geology is also relatively straightforward: sediment eroded in the north and west since the Cretaceous has been transported and deposited on the shores of the Gulf of Mexico. In fact, the Coastal Plain’s outermost portion marks the approximate shoreline of the Gulf during the Cretaceous. Over the subsequent 70 million years, sediment from the west and north has filled in the Gulf, pushing the shore roughly 300 to 800 kilometers (190 to 500 miles).
east and south to its current position, with sediment deposits 15,000 to 18,000 meters (49,000 to 59,000 feet) thick. The depositional settings that formed the Coastal Plain are similar to those seen today, including river, floodplain, shoreline, delta, and shallow marine environments. The region is still an active environment of deposition, and deposits become increasingly younger toward the Gulf (Figure 1.15).

In Texas, the Coastal Plain extends west to the Balcones Fault and Escarpment, commonly regarded as the division between upland and lowland Texas. This relatively low-stress fault is thought to have formed 15 million years ago as a result of the Coastal Plain having “settled” relative to the bedrock of the upland (part of the Great Plains region), but it occasionally still generates small earthquakes. The entire state of Louisiana is found within the Coastal Plain, where Cenozoic deposits formed as the sea advanced and retreated on several occasions. The huge volume of sediment deposited by the Mississippi River helped to build the greatest breadth of the Coastal Plain, which stretches approximately 800 kilometers (500 miles) from southeastern Missouri to the Mississippi Delta.

Figure 1.15: Shoreline positions along the Coastal Plain during the past 70 million years. The shoreline reflects the regression that resulted from the last significant glacial advance of the modern ice age. (See TFG website for full-color version.)
By the Neogene, the Farallon plate lay shallowly under the North American plate for hundreds of kilometers eastward of the West Coast. Now situated more fully beneath what are now the South Central, Southwestern, and Rocky Mountain States, this extra layer of crust caused uplift and extension of the region, as the added thickness of buoyant rock (relative to the mantle) caused the entire area to rise isostatically. The Farallon plate was subjected to increasing temperatures as it subducted, causing it to expand; as heat dissipated to the overlying North American plate, that rock expanded as well. Finally, the high temperatures in the upper mantle caused the Farallon plate to melt, and the resulting magma was injected into the North American plate, destabilizing it. These processes caused the surface of the North American plate to pull apart and fault into the mountainous blocks of the huge Basin and Range province, a portion of which is found in West Texas.

The Ice Age: Mountains of Ice

At the start of the Quaternary period, about 2.5 million years ago, continental ice sheets began to form in northernmost Canada. Throughout this period, the northern half of North America has been periodically covered by continental glaciers that originated in northern Canada (Figure 1.16). The Quaternary period is divided into two epochs: the Pleistocene and Holocene. During the Pleistocene, ice sheets advanced south and retreated north several dozen times. The Holocene epoch is the most recent (and current) period of retreat, called an interglacial interval. The most recent glacial advance in North America reached its maximum extent 25,000–18,000 years ago, while the beginning of the Holocene is considered to be 11,700 years ago, or about 9700 BCE.

The entire United States was affected by the cooling climate during the most recent ice age. A cooling climate contributes to the growth of continental glaciers: as more snow falls in the winter than melts in the summer, the snow packs into dense glacial ice. In this case, as snow and ice continued to accumulate on the glacier, the ice began to move under its own weight and pressure. The older ice on the bottom was pushed out horizontally by the weight of the overlying younger ice and snow. Glacial ice then radiated out from a central point, flowing laterally in every direction away from the origin (Figure 1.17). As a result, the continental glacier that originated in Canada migrated southwards toward the United States.

In the South Central, continental glaciers extended southward into northeastern Kansas and northern Missouri, as evidenced by quartzite erratics, till, glacial lake deposits, and loess. During this time, the ice advanced as far south as the Missouri River, and the meltwater from the glaciers likely cut through the landscape to form the river’s original valley. The predominant effects of the Pleistocene ice age on the Coastal Plain were the rise and fall of sea level,
subsequent erosion and deposition, and changes in weather, drainage patterns, and the distribution of plant and animal species. At the peak of the last glacial maximum, sea level dropped more than 100 meters (328 feet) below the current level (see Figure 1.15). Widely fluctuating sea levels drastically affected the erosion and deposition of sediment on the Coastal Plain, creating scarps and river terraces and steepening stream gradients, which resulted in more rapid streambed erosion.

Glaciers indirectly affected the majority of the South Central in a variety of ways. Meltwater from the north was filled with sediment that accelerated erosion, carving most of the region's modern river valleys into the landscape. As the flowing water approached the coast and slowed, it dumped its load of sediment, helping to build the Coastal Plain out into the Gulf of Mexico. Quaternary-aged
floodplains along the banks of the Mississippi and Missouri Rivers were also composed of a significant amount of glacial sediment. **Rock flour** from these floodplains was blown by the **wind**, covering much of Missouri and Mississippi in layers of **loess**. Deposits of this silt provide the foundation for the rich **soils** that exist in much of the central United States. Glacial meltwater and sediment also constructed the outermost 80 kilometers (50 miles) of the Coastal Plain, especially the Mississippi Delta. Nearly all of Louisiana’s surface is Neogene- or Quaternary-aged, unconsolidated or semi-consolidated sediment deposited by water.

The ice age continues today, but the Earth is in an interglacial stage, since the ice sheets have retreated for now. The current interglacial period has slowed both erosional and depositional processes in the South Central—this and a higher, more stable sea level allowed coastal features such as barrier islands and lagoons to form, resulting in the landscape we know today. The glacial-
Why was there an ice age?

What led to the formation of large continental glaciers in the Northern Hemisphere 2.5 million years ago? Movement of the Earth’s plates may have been a direct or indirect cause of the glaciation. As plates shifted, continents moved together and apart, changing the size and shape of the ocean basins, and altering ocean currents that transported heat from the equator to the poles. Sufficient precipitation in northern Asia and North America also enabled continental glaciers to grow and flow outward. The rise of the Himalayas exposed new rock that trapped carbon dioxide through chemical weathering; in turn, the decreased levels of carbon dioxide led to a global cooling. Finally, the presence of continental landmasses (Antarctica and to some extent Greenland) over or near the poles was also a major factor in the development of continental glaciers, as precipitation could now be deposited on these landmasses.

interglacial cycling of ice ages indicates that the world will return to a glacial stage in the future, but the impacts of human-induced climate change might radically shift the direction of these natural cycles.

See Chapter 9: Climate to learn more about how climate change affects the environment.
Resources

Books


Books and Articles on Geologic History of the South Central US


Maps

AAPG. 1966. *Mid-Continent Region Geological Highway Map*. AAPG, Tulsa, OK. (Covers Arkansas, Kansas, Missouri, and Oklahoma.)


Websites

*North America During the Last 150,000 Years*, compiled by J. Adams. 

*Color-coded Continents!*, US Geological Survey. (Reconstructions of color-coded continental motions from 620 million years ago through the present; maps from C. Scotese.)


*Paleogeography*, R. Blakey. (The older, but free, version of the site.)
https://www2.nau.edu/rcb7/RCB.html.

*Reconstructing the Ancient Earth*, Colorado Plateau Geosystems. (R. Blakey, updated site.)

*Tour of Geologic Time*, University of California Museum of Paleontology. (Online interactive geologic calendar exhibit.)

Activities

https://www.beloit.edu/sepm/Fossil_Explorations/Paleogeographic_Mapping.html.

Toilet Paper Analogy for Geologic Time, by J. Wenner, in: *Teaching Quantitative Skills in the Geosciences*, at Resources for Undergraduate Students and Faculty, SERC. (Demonstration of geological time using a 1000-sheet roll of toilet paper.)

*Understanding Geologic Time*, Texas Memorial Museum at the University of Texas at Austin. (Timeline activity for middle school students.)
Chapter 2: 
Rocks of the South Central US

There is an amazing diversity of rocks in the South Central that record more than a billion years of history—from 1.5-billion-year-old Precambrian rocks to deposits from the most recent ice age and sediments of the Coastal Plain. Colliding plates, rifting, inland seas, deposition, erosion, igneous and metamorphic activity, and recent glacial and modern coastal processes are all part of this story. The South Central's different rock types influence its topography and tell us where to look for certain fossils or natural resources. Each type of rock forms in a particular environment under particular conditions (Figure 2.1).

---

**Igneous Rocks of the South Central**
- rhyolite
- granite
- basalt
- gabbro
- lamproite
- tuff

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**Sediments of the South Central**
(not consolidated into rocks)
- gravel
- sand
- silt
- clay

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**Sedimentary Rocks of the South Central**
- chert
- gypsum
- dolomite
- siltstone
- chalk
- coquina

---

**Metamorphic Rocks of the South Central**
- schist
- gneiss
- phyllite
- quartzite
- novaculite

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**Figure 2.1: The rock cycle shows the relationships among the three basic types of rock.**

---

**Figure 2.1:**
- **ice age** • a period of global cooling of the Earth’s surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.
- **plates** • large, rigid pieces of the Earth’s crust and upper mantle, which move and interact with one another at their boundaries.
- **rift** • a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates.
- **inland sea** • a shallow sea covering the central area of a continent during periods of high sea level.
- **erosion** • the transport of weathered materials.
- **topography** • the landscape of an area, including the presence or absence of hills and the slopes between high and low areas.

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**CHAPTER AUTHORS**
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A rock is a naturally occurring solid substance composed of one or more minerals. Broadly speaking, there are three types of rock: sedimentary, igneous, and metamorphic. The rock cycle describes the many processes that produce rocks, while also illustrating the differences between the rock types. One type of rock may be transformed into either of the other types, often with the help of other parts of the Earth system, such as plate tectonics, the water cycle, and biological processes, to name a few.

Sedimentary rock is formed by the lithification of sediments (e.g., unconsolidated mineral and organic particles created through the weathering of other materials, such as rock and organic matter). Typically, sediments are created in an environment where erosion is a dominant force, and they are transported by wind, water, or ice to a depositional environment. For example, a rushing river can wear away the rock it is flowing over, and it also has enough energy to transport the resulting sediment to a lake. The water slows down, losing energy, and deposits the sediment on the bottom of the lake.

Sedimentary Rock Classification

Sedimentary rocks are classified by their sediment size or their mineral content, and each one reveals the story of the depositional environment where its sediments accumulated and were eventually lithified.

<table>
<thead>
<tr>
<th>Sediment size (decreasing size)</th>
<th>Sedimentary rock</th>
<th>Environment of deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravel</td>
<td>conglomerate</td>
<td>river beds, mountains</td>
</tr>
<tr>
<td>sand</td>
<td>sandstone</td>
<td>beaches, river sand bars, sand dunes</td>
</tr>
<tr>
<td>sand, silt, clay</td>
<td>graywacke</td>
<td>continental shelf</td>
</tr>
<tr>
<td>silt</td>
<td>siltstone</td>
<td>quiet water</td>
</tr>
<tr>
<td>clay</td>
<td>shale</td>
<td>very quiet water, lakes, swamps, shallow oceans</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mineral Content</th>
<th>Sedimentary Rock</th>
<th>Environment of Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>calcium carbonate skeletons of marine organisms</td>
<td>limestone</td>
<td>tropical reefs, beaches, warm shallow seas</td>
</tr>
<tr>
<td>precipitated calcium carbonate</td>
<td>travertine, tufa</td>
<td>hot springs, playas (dry lake beds), drying seas</td>
</tr>
<tr>
<td>gypsum</td>
<td>rock gypsum</td>
<td>playas, drying seas</td>
</tr>
<tr>
<td>halite</td>
<td>rock salt</td>
<td>playas, drying seas</td>
</tr>
</tbody>
</table>
Lithification of sediments occurs in several ways. As sediments build up and lower layers are buried more deeply, they may become permeated by water. Minerals dissolved in the water are precipitated, filling the spaces between particles and cementing them together. This cementation helps to form many common sedimentary rocks, such as **shale**, **sandstone**, and most **conglomerates**. The evaporation of water may also form sedimentary rocks by leaving behind **evaporites** (previously dissolved minerals) such as **salt**. Deposits of **calcium carbonate**, usually created through the accumulation of calcium carbonate skeletal material (such as clams and corals), form the sedimentary rocks **limestone** and **dolostone**.

**Igneous rocks** form from the cooling of **magma** (molten rock underground) or **lava** (molten rock at the Earth’s surface). When magma cools slowly underground, it has time to produce large crystals that are visible to the naked eye. Rocks that form in this manner, such as **granite**, are called **plutonic**. When magma comes to the surface (as lava), it cools quickly so that individual crystals are not visible, resulting in a **volcanic** rock such as **basalt**. In some circumstances, lava may cool so quickly that crystals do not form at all, creating a **glassy** rock such as **obsidian**. Smaller fragmental rocks that cool quickly at the surface form during explosive eruptions; these are called **pyroclastic** rocks, and they are composed of a variety of different volcanic ejecta.

**Igneous Rock Classification**

Igneous rocks are classified not only by their cooling rates and subsequent crystal sizes, but also in their chemical compositions. Rocks found in continental crust, such as granite, have high silica content and low iron and magnesium content. They are light in color and are called **felsic**. Rocks found in oceanic crust, like basalt, are low in silica and high in iron and magnesium. They are dark in color and are called **mafic**.

<table>
<thead>
<tr>
<th>Crystal size</th>
<th>Felsic</th>
<th>Intermediate</th>
<th>Mafic</th>
<th>Ultramafic</th>
</tr>
</thead>
<tbody>
<tr>
<td>large (plutonic)</td>
<td>granite</td>
<td>diorite</td>
<td>gabbro</td>
<td>peridotite</td>
</tr>
<tr>
<td>small (volcanic)</td>
<td>rhyolite</td>
<td>andesite</td>
<td>basalt</td>
<td>--</td>
</tr>
<tr>
<td>none (glassy)</td>
<td>obsidian, tuff, pumice</td>
<td>obsidian</td>
<td>obsidian</td>
<td>--</td>
</tr>
</tbody>
</table>

Every rock is capable of being melted, weathered, or changed by **heat** and pressure. Any rock that has been subjected to intense heat and pressure can **recrystallize** into a **metamorphic rock**. This process destroys features in the
rocks that would have revealed its previous history, transforming it into an entirely new form as the minerals within realign. The pressure to transform a rock may come from burial by sediment or from compression due to plate movements, while the heat may be from very deep burial or from contact with magma.

As you read through this chapter, keep in mind that once you understand the geologic events that have affected a given region, you should be able to predict the type of rocks found in that area. For example, when plates collide, compression and friction melt the crust. The rising magma forms igneous intrusions that crystallize below the surface, producing large-grained igneous rocks such as granite. The rising magma may break through the surface in the form of volcanoes, creating volcanic rocks such as basalt. Tectonic collision also leads to increased heat and pressure, creating metamorphic rocks. Basins adjacent to mountains fill with transported sediment, producing thick sequences of sedimentary rock.

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**Metamorphic Rock Classification**

Metamorphic rocks are classified differently depending on the protolith (parent rock) they are made from. The following chart shows common rocks and the metamorphic rocks that they can become.

<table>
<thead>
<tr>
<th>Parent rock</th>
<th>Metamorphic rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>shale</td>
<td>slate, phyllite, schist, gneiss (in order of increasing heat and pressure)</td>
</tr>
<tr>
<td>granite</td>
<td>gneiss</td>
</tr>
<tr>
<td>sandstone</td>
<td>quartzite</td>
</tr>
<tr>
<td>limestone</td>
<td>marble</td>
</tr>
<tr>
<td>peridotite</td>
<td>serpentinite</td>
</tr>
</tbody>
</table>

---

**Review**

- **compression** - flattening or squeezing as a result of forces acting on an object from all or most directions.
- **crust** - the uppermost, rigid outer layer of the Earth, composed of tectonic plates.
- **intrusive rock** - a plutonic igneous rock formed when magma from within the Earth’s crust escapes into spaces in the overlying strata.
What happens to a rock when it is metamorphosed?

When rocks are subjected to high enough temperatures or pressures, their characteristics begin to change. The weight of overlying rock can cause minerals to realign perpendicularly to the direction of pressure, layering them in a pattern called *foliation*, as exemplified in gneiss and schist. Recrystallization, as seen in marble and quartzite, results as rock is heated to high temperatures, and individual grains reform as interlocking crystals, making the resulting metamorphic rock much harder than its parent rock.

*Contact metamorphism* describes a metamorphic rock that has been altered by direct contact with magma. Changes that occur due to contact metamorphism are greatest at the point of contact. The farther away the rock is from the point of contact, the less pronounced the change.

*Regional or dynamic metamorphism* describes a metamorphic rock that has been altered due to deep burial and great pressure. This type of metamorphic rock tends to occur in long belts. Different types of metamorphic rock are created depending on the gradients of heat and pressure applied.
Why do we see different kinds of rocks at the surface?

As you walk across the surface of the Earth, you will observe an amazing variety of rock types. If all rocks were flat-lying layers and there was no erosion, then we would only see one type of rock exposed on the surface. Often, however, rocks have been worn away (eroded), and the underlying layers are now exposed at the surface. Layers of rock may also be tilted, folded, or faulted to reveal the underlying rocks at the surface.

When rocks are flat-lying layers and there is no erosion, folding, or faulting, the person walking across the surface sees only one rock type.

When rocks are worn away (often by streams), the person walking across the surface sees the underlying layers of rock exposed.

When rocks are folded or tilted, the person walking across the surface sees several layers of rock exposed.
Rocks of the Central Lowland
Region 1

The rocks of the Central Lowland, extending from northern Missouri southward into northern Texas, are primarily marine in nature. These sediments were mainly deposited during the late Paleozoic, as a shallow sea covered most of the area during the Carboniferous and Permian periods (Figure 2.2).

Missouri’s Central Lowland is composed almost entirely of Carboniferous-aged deposits, produced from the erosion of eastern mountains formed by the Appalachian Orogeny. Enormous quantities of sediment were transported westward and deposited within the shallow sea that covered the region. The dominant rocks in this area are Pennsylvanian in age, with a thin strip of Mississippian along their eastern margin. In northwestern Missouri, repeating patterns of marine limestones and shales interbedded with non-marine
sandstones indicate that the shallow sea advanced and retreated many times over this area of the state. The Carboniferous rocks of Missouri are famous for their fossil deposits as well as being important economic sources of lead and zinc. Beneath these deposits lie Precambrian igneous and metamorphic rocks, which form the core of the continent and the basement of the Interior Plains.

Northern Missouri showcases the effects of recent glacial advances in deposits of glacial drift and wind-blown loess. The Loess Hills, found along the Missouri River Valley, extend from Iowa into the northwestern corner of Missouri (Figure 2.3). The area also contains plentiful glacial erratics—these large boulders, transported from as far north as Canada, are most commonly composed of granite and quartzite.

In Kansas, exposed Paleozoic marine rocks decrease in age as one moves westward. The oldest rocks, from the Pennsylvanian, dominate the eastern margin of the state, and chiefly contain sandstones, shales, and limestones. The Cherokee Lowlands, an area of Pennsylvanian strata located in the state’s southeastern corner, are extremely rich in coal; this area is the largest center
Why are there different sedimentary rocks in different environments?

Most sedimentary rock deposited in underwater settings originated from material eroded on land and washed down streams or rivers before settling to the bottom of a body of water. Intuitively, the faster the water is moving, the larger the sediments it may carry. As the water slows down, the size of sediments it can carry decreases. Furthermore, the farther the grains of sediment are carried, the more rounded they become as they are tumbled against each other. In this way, rivers emptying into a sea are effectively able to sort sediment. Near the mouth of the river, the water is still relatively high-energy, dropping only the largest pieces; farther from the shore, the dropped particles get smaller. Therefore, conglomerates and sandstones are interpreted to have been deposited on or near the shore, siltstone farther from the shore, and shale in deep water quite far from shore where currents are slow enough that even very tiny particles may settle.

Increased distance from shore and water depth can also reduce the presence of oxygen in the water, causing organic material to decompose less completely. This causes darker, carbon-rich rocks (including some that contain exploitable fossil fuels) to form in these areas. Limestone is made primarily of calcium carbonate, the components of which are dissolved in the water. Living creatures, like coral and foraminifera, take those components out of the water to make calcium carbonate shells, which, after the creatures die, accumulate to become limestone. These shelled creatures tend to fare better in clear water, so limestone usually forms far from other sources of sediment. While this process happens over much of the seafloor, if more than 50% of the sediment being deposited is from another source, the rock that forms is, by definition, not limestone.
of coal mining in Kansas. To the west lie the Flint Hills, a band of Permian rocks containing prevalent chert and limestone. Many buildings in this area are constructed out of local limestone (Figure 2.4).

Although most surface rocks in Kansas’ Central Lowland are sedimentary, Woodson and Wilson counties are known for their exposures of lamproite, an intrusive igneous rock that pierced the Paleozoic shales during the

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**Coal** • a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation.

**Chert** • a sedimentary rock composed of microcrystalline quartz.

**Cretaceous** • a geologic time period spanning from 144 to 66 million years ago.

**Cambrian** • a geologic time period lasting from 541 to 485 million years ago.

**Rhyolite** • a felsic volcanic rock high in abundance of quartz and feldspar.

**Lamproite** • an ultramafic volcanic (extrusive) rock with high levels of potassium and magnesium that contains coarse crystals.

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Figure 2.4: The Chase County Courthouse in Cottonwood Falls, Kansas, constructed from Flint Hills limestone.
Cretaceous. The northeastern corner of the state, while underlain by the same Pennsylvanian and Permian sediments mentioned previously, is covered in glacial drift deposited during the ice age.

Shallow seas covered Oklahoma during most of the Paleozoic, leading to sedimentary deposits overlying nearly all of the Precambrian igneous and metamorphic bedrock in the Central Lowland. Only a single exposure of Precambrian rocks occurs in the state: the Arbuckle Mountains, which contain a 1.4-billion-year-old core of gneiss and granite capped by Cambrian rhyolite. About 750 million years ago, a rift began to form in what is now southwest Oklahoma. Magma rising to near the surface cooled to form a variety of granitic rocks, which are now the oldest parts of the Wichita Mountains, and the only Oklahoman Cambrian rocks other than those found in the Arbuckles.

A gneiss is a very highly metamorphosed rock with alternating bands of dark and light minerals. The dark bands are mafic and higher in magnesium and iron, while the lighter bands are felsic and higher in silicates. These bands may form because extreme temperature and pressure cause a chemical reaction that forces the different elements into separate layers. Banding may also occur when a set of varied protoliths are subjected to extreme shearing and sliding forces, causing them to stretch into stacked sheets.

During the Carboniferous, rivers flowing through Oklahoma deposited vast deltas, producing a swampy landscape that was periodically flooded by rising sea levels. The alternation of marine and non-marine environments led to the creation of cyclothems (Figure 2.5), alternating sequences of terrestrial and marine sedimentary layers dominated by thick limestones and dolomites. These Pennsylvanian formations cover almost 25% of Oklahoma’s surface.

The most intense period of mountain building in the region also occurred during the Pennsylvanian, with the uplift of the Ouachita, Wichita, and Arbuckle mountains. This orogenic episode downwarped the crust and created basins where thick layers of shale, sandstone, and limestone were deposited. In central Oklahoma, Permian rock predominates; it includes sand and mudstones made up of eroded sediment from the newly-formed Ouachitas, as well as thick layers of salt and gypsum deposited once the sea level began to regress.

In Texas, the Central Lowland is dominated by Permian rock, with a band of Pennsylvanian sediments and a small segment of Cretaceous shoreline sediment found to the east. After the Pennsylvanian rise of the Ouachitas to the north in Oklahoma, shallow seas were filled with sediment. As the inland seas retreated, the area became home to broad evaporite basins, where deposits of salt, gypsum, and red muds formed throughout the hot, arid environments of the late Permian (Figure 2.6). Today, these famous red beds are home to...
an extensive fauna of fossilized Permian amphibians, reptiles, and synapsids (ancient relatives of mammals).

See Chapter 3: Fossils for more information about Permian life in the South Central.

Figure 2.6: The Permian-age gypsum and red mudstones of the Quartermaster Formation are exposed in the red cliffs of Caprock Canyons State Park in Briscoe County, Texas.
Rocks of the Interior Highlands
Region 2

The mountainous regions of the Interior Highlands are dominated by uplifted sedimentary rock deposited within shallow seas, though the oldest rocks of the area are igneous in nature (Figure 2.7). The core of the Interior Highlands is made up of a Proterozoic mountain range that formed around 1.5 billion years ago. Today, these units—a suite of igneous rocks—crop out within the Saint Francois Mountains across an area of 13,000 square kilometers (5000 square miles). The oldest of these rocks are composed of rhyolite flows dating to 1.5 billion years ago. In some of these flows, slower cooling led to the formation of larger crystals—called phenocrysts—within the rhyolites. Hughes Mountain, a rhyolite edifice in the southeastern Saint Francois Mountains, is composed of intrusive rhyolites that fractured into columnar joints while cooling (Figure 2.8).

The Saint Francois Mountains also contain slightly younger intrusive granite that formed between 1.5 and 1.25 billion years ago. This granite is exposed in Elephant Rocks State Park (so named for a string of massive boulders that superficially resemble a chain of elephants), where spheroidal weathering has smoothly worn the ancient rocks away along preexisting fractures (Figure 2.9). The largest “elephant” in the park weighs 680 tons and is 8 meters (27 feet) tall, 7.6 meters (25 feet) long, and 5 meters (17 feet) wide.

In addition to rhyolite and granite, gabbro and basalt are common within the Saint Francois Mountains, with the latter being most commonly found in the form of dikes.
Figure 2.8: The Devil’s Honeycomb, an outcropping of columnar jointed rhyolite in Hughes Mountain State Natural Area.

**Columnar Jointing**

As a lava flow cools, it contracts, and the resulting force may cause the rock to crack. These cracks continue down to the bottom of the flow, resulting in five- or six-sided columns. Columnar joints are not restricted to basalt flows and can form in ashflow tuffs as well as shallow intrusions. The columns are generally vertical, but may also be slightly curved.
The Paleozoic rocks of the Interior Highlands consist of a suite of shale, sandstone, limestone, dolomite, and chert. During this time period, vast inland seas led to the deposition of sandstone near shore and shale and limestone in deeper waters, with coral reefs forming around the volcanic rocks of the Saint Francois Mountains. Within this seaway, sandstones, shales, carbonates, and chert accumulated. Deposits of shallow-water carbonates formed throughout the Paleozoic, with episodes of sea level regression and erosion occasionally disrupting their deposition.

After the collision of North America and Gondwana during the Pennsylvanian, the formation of the supercontinent Pangaea led to significant changes within the South Central States. The epicontinental seas that dominated the landscape for the previous 200 million years were squeezed out of the region, and marine deposits were severely affected by tectonic forces from

**Inland sea** may sound like a contradiction in terms, but there is a very simple, yet important, distinction that differentiates it from other seas: an inland sea is located on continental crust, while other seas are located on oceanic crust. An inland sea may or may not be connected to the ocean. For example, Hudson Bay is on the North American plate and connects to the Atlantic and Arctic oceans, while the Caspian Sea is on the European plate but does not drain into any ocean at all.
the surrounding, colliding continents. A rapid influx of clastic sedimentary rocks was followed by intense deformation. In Arkansas and Oklahoma, this folding and faulting resulted in the **Ouachita Orogeny**, which produced the Ouachita Mountains. The uplift exposed millions of years of buried marine strata, as well as Precambrian-aged granites and rhyolites. Today, the tilting limestone beds of the area create a distinct landscape known as “tombstone topography” (Figure 2.10).

The Ouachita Mountains are distinctive in that tectonic-induced volcanism, metamorphism, and intrusion played minimal roles in their formation, although low-grade metamorphism did lead to the formation of novaculite from existing chert (Figure 2.11). Novaculite is **dense** and therefore resistant to erosion; its layers stand out as ridges in the Ouachitas.

Unlike the Ouachita Mountains, the Ozark highlands in Missouri represent not folded bedrock but instead an uplifted plateau that formed during the Ouachita Orogeny. Erosion of these newly formed uplands led to the deposition of clastic sediment in basins to the north and south of the plateau. A colorful form of chert, called mozarkite, is also plentiful in the Ozarks and is the official state rock of Missouri.
Rocks of the Coastal Plain
Region 3

After the breakup of Pangaea during the Mesozoic, the North American plate drifted away from the Mid-Atlantic Ridge. Decreased tectonic activity along the continent’s eastern and southeastern edge led to the formation of a passive continental margin. The Coastal Plain extends along this margin, across the Gulf of Mexico and up through the Mississippi Embayment.

The sediment and rock of the Coastal Plain is geologically very young, ranging in age from the Cretaceous to the present (Figure 2.12). The region’s sediment and rock include gravel, sand, silt, clay, marl, limestone, and uncommon layers of concentrated shell material called coquina. Much of the Coastal Plain’s “rock” is actually unconsolidated sediment that has not had enough time to be lithified, cemented, or sufficiently compacted into hard rock. Coastal Plain sediment forms a wedge of gently dipping layers of sediment and sedimentary rock that thickens towards the Gulf of Mexico, overlying older bedrock (Figure 2.13). This sediment is 6100 meters (20,000 feet) thick in northern Louisiana, thickens to 12,000 meters (40,000 feet) at the coast, and reaches 18,000 meters (60,000 feet) offshore. Depending on the rates of cementation or compaction, it may take tens or even hundreds of millions of years before these layers of sediment are lithified.
Figure 2.12: Generalized geologic map of the Coastal Plain. (See TFG website for full-color version.)

Figure 2.13: Millions of years of sediment accumulation in the basins caused coastal areas to subside, creating a gentle slope toward the Gulf of Mexico.
The Coastal Plain surface and subsurface sediments of Arkansas, Missouri, and Louisiana are dominated by those deposited in alluvial or deltaic settings. This indicates that a major river system, such as the Mississippi, has existed since the initial formation of the Gulf of Mexico (which occurred during the breakup of Pangaea in the Mesozoic). A progression of fluvial, deltaic, and coastal deposits carrying sediments eroded from the Ouachitas has migrated into the Gulf over time, continually altering the coastline (Figure 2.14).

The state of Louisiana formed as a slow regression in sea level allowed the deposition of sediment to create a terrestrial environment at the edge of the Gulf. Approximately 25% of the state’s northern surface, consists of Paleogene- and Neogene-aged shales, sandstones, and gravels deposited within fluvial, deltaic, and shallow marine settings (Figure 2.15). The remaining 75% of the surface consists of Quaternary-aged silts, sands, and gravels deposited from channels, marshes, levees, and terraces.

Thousands of feet of salt are present under the fluvial deposits of the Mississippi. This thick layer of salt accumulated during the initial formation of the Gulf when flooding and evaporation occurred during the early stages of Pangaea’s breakup. Since the salt deposits are less dense than sandy and
muddy sediments, they moved plastically and vertically to form salt domes, some of which reach to and are exposed at the surface today. Louisiana’s few Cretaceous-aged outcrops, in Bienville Parish, consist of older marine deposits that were uplifted by the formation of these salt domes.

In Texas, the Coastal Plain is subdivided into several physiographic provinces (Figure 2.16). The Coastal Prairies along the Gulf of Mexico are dominated by Pleistocene deltaic sands, silts, and clays. Ever since our modern sea level was reached some 3000 years ago, thin coastal-barrier, lagoon, and delta sediments have been deposited along the Coastal Prairies. Further inland, along the Interior Coastal Plains, Cenozoic clay, shales, and uncemented sands are present, overlying Pliocene limestone. In the innermost part of the Coastal Plain (the Blackland Prairies), chalks and marls are present.

The Balcones Escarpment forms the western boundary of Texas’ Coastal Plain, and extends from approximately Dallas to San Antonio. It is the surface expression of the Balcones Fault—a fault system that is thought to have formed 300 million years ago during the Ouachita Orogeny. The escarpment features cliffs that expose walls of Cretaceous limestone (Figure 2.17), as well as subterranean caves. The rocks to the west of the Balcones Escarpment are more resistant to erosion than the soft sediments of the Coastal Plain are; as a result, erosion and weathering have served to accentuate the Escarpment’s height (Figure 2.18).

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**salt dome** • a largely subsurface geologic structure, consisting of a vertical cylinder of salt embedded in horizontal or inclined sedimentary strata.

**physiography** • a subfield of geography that studies the Earth’s physical processes and patterns.

**Pleistocene** • a subset of the Quaternary, lasting from 2.5 million to about 11,700 years ago.

**Cenozoic** • the geologic time period spanning from 66 million years ago to the present.

**Pliocene** • a geologic time interval extending from roughly 5 to 2.5 million years ago.

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**Figure 2.15**: The Kisatchie National Forest in north-central Louisiana contains some of the state’s oldest sediment, including Paleogene and Neogene silt, gravel, and shale.
Rocks of the Great Plains
Region 4

The Great Plains region is defined by the Rocky Mountains to the west and the Central Lowland to the east, with the Balcones Fault in Texas creating the divide between the Great Plains and the Coastal Plain in the southeast. The region’s geologic history is chiefly one of sedimentary deposition driven first by marine environments and, more recently, by terrestrial deposition from the erosion of the Rocky Mountains to the west (Figure 2.19).

The oldest rocks in the Great Plains can be found in the Llano Uplift of central Texas. This area contains an uplifted **batholith** of distinctive pink Precambrian granite (called the Town Mountain granite), and is famous for its large formations such as Enchanted Rock, the largest isolated outcrop of pink granite in the US (Figure 2.20). This granite formed 1.1 billion years ago during the Grenville Orogeny, when it intruded into the surrounding Precambrian Packsaddle **schist** and Valley Springs gneiss. The Llano Uplift also includes the only known

**chalk** • a soft, fine-grained, easily pulverized, white-to-grayish variety of limestone, composed of the shells of minute planktonic single-celled algae.

**batholith** • a large exposed structure of intrusive igneous rock that solidified at depth, and covers an area of over 100 square kilometers (40 square miles).

**schist** • a medium grade metamorphic rock with sheet-like crystals flattened in one plane.
Regions 3–4

quartz • the second most abundant mineral in the Earth’s continental crust (after feldspar), made up of silicon and oxygen ($\text{SiO}_2$).

exfoliation • a type of physical weathering in which overlying layers are weathered away, and the reduction of downward pressure allows the underlying rock to expand toward the surface.

Figure 2.17: Faulted Cretaceous limestone is exposed along the Balcones Escarpment at a roadcut on US 281 North.

deposits of ilanite (named for Llano County), a type of rhyolite containing large phenocrysts of feldspar and blue quartz (Figure 2.21).

The Town Mountain granite, exposed through the erosion of surrounding rock, is heavily exfoliated. Although granite is under tremendous pressure when it forms deep underground, it is at equilibrium with the surrounding rock because the pressure on it is equal in every direction. However, once it is exposed at the surface, the absence of significant downward pressure allows it to expand...
Figure 2.18: The Balcones Escarpment and its surrounding environments have been shaped by erosion.

Figure 2.19: Generalized geologic map of the Great Plains. (See TFG website for full-color version.)
Rocks

Figure 2.20: Enchanted Rock stretches across 260 hectares (640 acres) and rises approximately 130 meters (425 feet) above the surrounding landscape.

Figure 2.21: Precambrian ilanite from Texas.

upward. This expansion causes joints, or cracks, to form parallel to the surface, producing slabs that resemble the curved layers of an onion (Figures 2.22 and 2.23).
Throughout much of the Paleozoic era until the early stages of the Carboniferous, the Great Plains region was submerged in a shallow sea. Shales, limestones, dolostones, and sandstones dominate the Paleozoic strata of Oklahoma and Texas, although they are now buried by younger Neogene and Quaternary sediments. In Kansas, Paleozoic marine deposits are similarly buried by Neogene and Quaternary sediments.

In the Jurassic, the sea level regressed and the region became exposed. During this time, sandstones and shales were deposited in Texas by a large river system. In the Cretaceous, the Great Plains were covered again as a shallow
sea extended northward from the Gulf of Mexico across North America, and 1500- to 3000-meter-thick (5000- to 10,000-foot-thick) deposits of shale and limestone were formed. Cretaceous sediments are exposed within the Smoky Hills of Kansas—an area known for its sandstone, limestone, and chalk. The Dakota Sandstone is the oldest Cretaceous rock in the Great Plains, having formed around 95 million years ago. It is exposed at Mushroom Rock State Park in north-central Kansas, where hoodoos capped by sandstone concretions stand out from the landscape (Figure 2.24).

**Figure 2.24:** This hoodoo in Mushroom Rock State Park is made up of a concretion of erosion-resistant Dakota Sandstone atop a pillar of softer sedimentary rock. This “mushroom” is over 8 meters (25 feet) tall.
The Niobrara Chalk, laid down around 85 million years ago, formed from the carbonate shells of tiny marine microorganisms and is extremely rich in fossils. Found within the chalk is an extensive record of fossil vertebrates—from fish and birds to flying and swimming reptiles—that provides an incredible glimpse into the Western Interior Seaway of the Cretaceous period. The Niobrara Chalk is also known for its pillar- and spire-shaped outcrops (Figure 2.25).

With the rise of the Rocky Mountains to the west, erosion and Cenozoic-era volcanism produced sediment that was transported and deposited throughout the Great Plains. Gravel, sand, and mud dominate the region’s surface, with progressively younger sediment located farther from the mountain chain. This mass of eroded material eventually filled stream valleys and covered hills, creating a massive, gently sloping plain that was in place by five million years ago. The western third of Kansas and the panhandle of Oklahoma are capped by the Ogallala Formation, a unit of unconsolidated sands, gravels, and clays that eroded from the Rockies. The Ogallala Formation is extremely porous, and as a result it acts as an important aquifer for much of the Great Plains.

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**Rocks**

**Region 4**

**porosity** • the percentage of openings in a body of rock such as pores, joints, channels, and other cavities, in which gases or liquids may be trapped or migrate through.

**aquifer** • a water-bearing formation of gravel, permeable rock, or sand that is capable of providing water in usable quantities, to springs or wells.
The Basin and Range is a huge physiographic region that extends from southeastern Oregon to west central Mexico. Only a tiny portion of it is found within the South Central US, in far western Texas. Even so, the Basin and Range may be the South Central's most geologically complex region—in this tiny area of Texas, rocks can be found from nearly all periods of the Phanerozoic (Figure 2.26). This is largely because the region’s most recent geologic activity involved crustal extension that has exposed many deeper, older layers. During the Paleogene, magma upwelling from the mantle weakened the lithosphere, lowering its density. This stimulated uplift, stretching the bedrock in an east-west direction. The crust along the Basin and Range stretched, thinned, and faulted into some 400 separate mountain blocks. Movement along the faults led to a series of elongated peaks and down-dropped valleys, also called horst and graben landscapes. In a manner similar to books toppling when removing a bookend from a shelf, the blocks slid against each other as they filled the increased space (Figure 2.27).

The oldest rocks in the Basin and Range region, and in all of Texas, are part of the Franklin Mountains near El Paso (Figure 2.28). The coast of the ancient continent is represented by marble, the metamorphic product of limestone deposited 1.3 billion years ago. Multiple lava flows and magmatic intrusions...
Rocks 2

Region 5

**Figure 2.27:** Alternating basins and ranges were formed during the past 17 million years by gradual movement along faults. Arrows indicate the relative movement of rocks on either side of a fault.

**Figure 2.28:** The faulted rocks of Sneeds Cory, a popular rock-climbing route in the Franklin Mountains, are an excellent example of Precambrian layers that were tilted and fractured during the formation of the Basin and Range.

break up overlying quartzite that makes up the bulk of the area’s Precambrian rock.

Rocks 1.1 billion years of age are also found farther west near Van Horn, where Precambrian rock formed in somewhat deeper water. This rock has been more dramatically altered, with limestones and shales transformed into phyllite, schist, and quartzite. Just to the northwest, the Sierra Diablo Mountains contain billion-year-old, iron-rich red beds, along with a 950-million-year-old volcanic deposit.

Paleozoic rocks are well-represented in the Basin and Range. The Marathon Uplift near Marathon, Texas was created by the same forces that formed the Llano Uplift in the Great Plains, and it exposes a long sequence of sedimentary rocks. These begin in the Cambrian with a relatively thin package of shales, limestones, and sandstones that extend through to the Mississippian—only

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**phyllite** - a metamorphic rock that is intermediate in grade between slate and schist.

**iron** - a metallic chemical element (Fe).
950 meters (3100 feet) of rock were deposited over a period of 170 million years. However, sedimentation rates dramatically increased by the start of the Pennsylvanian, depositing more than 4200 meters (13,800 feet) of material by the beginning of the Permian, 60 million years later.

The Permian rocks of the Basin and Range are primarily marine, formed in the foreland basins created by the Ouachita Orogeny to the east. The northeastern part of the Marathon Uplift, and the series of mountain ranges between El Paso and Pecos, include many Permian rocks—for example, the Guadalupe Mountains contain the massive limestone remains of a Permian barrier reef (Figure 2.29).

As the Permian came to a close, a retreating sea left salt deposits west of Pine Springs, and the region became terrestrial. During the Cretaceous, much of the Basin and Range was again flooded by the Western Interior Seaway. The remnants of limestones deposited at the seaway's bottom form the capstones of many of western Texas' characteristic mesas (Figure 2.30).

The Paleogene saw magma well up from the mantle from about 50 to 45 million years ago, intruding into the existent rock layers. By about 35 million years ago, upwelling intensified and the mantle began to uplift the crust, effectively tearing it and causing it to fracture and fault at the surface. This process formed the Basin and Range's current rugged landscape, created numerous igneous
intrusions, and it also fed the region’s volcanoes. Basalt flows and gabbro sills added to earlier andesite plutons to create thousands of feet of igneous rock (Figure 2.31).

While limited extensional forces continued to act on the Basin and Range up until 10 million years ago, the dominant activity in the region since the beginning of the Neogene has been erosion. The region’s valleys are being filled with sediment from the surrounding mountains and mesas, creating thick deposits in northwest-southeast trending bands (Figure 2.32).

A pluton is a large body of igneous rock that formed under the Earth’s surface through the slow crystallization of magma. The term comes from the name of Pluto, Roman god of the underworld.

andesite • a fine-grained extrusive volcanic rock, with a silica content intermediate between that of basalt and dacite.
Rocks

Region 5

bauxite • a whitish, grayish, brown, yellow, or reddish-brown rock composed of hydrous aluminum oxides and aluminum hydroxides.

soil • the collection of natural materials that collect on Earth’s surface, above the bedrock.

hydrothermal solution • hot, salty water moving through rocks.

Figure 2.31: Igneous landscapes of Big Bend National Park. Tuff Canyon is composed of welded pyroclastic flows that occurred during the Paleogene. Cerro Castellan, in the background, is made up of a dense lava flow underlain by tuff and basalt.

Figure 2.32: Basin fill in the Basin and Range.
State Rocks, Minerals, and Gems

Arkansas
State mineral: quartz
Arkansas produces some of the highest quality quartz crystals in the world. Most of the state’s quartz deposits are found in the Ouachita Mountains, where they crystallized into veins from hydrothermal solutions during the last phases of mountain building.

State rock: bauxite
This reddish brown rock is made up of chemically weathered Paleocene soils that were consolidated through weathering processes. Bauxite is a principle ore of aluminum and is economically important in Arkansas.

State gem: diamond
The diamonds of Arkansas originated in the mantle, where they crystallized approximately three billion years ago. Today, they are found in the remains of a 95-million-year-old eroded volcano whose exposed lava pipes were channels for magma that brought these diamonds from the mantle to the surface.

Kansas
Kansas has no state rocks or minerals.

Louisiana
State mineral: agate
Agate found in Louisiana today was originally formed in the limestones of the central US, where it precipitated from silica-rich liquids. After erosion released it from its original bedrock, the banded stone was carried into the state by ancient rivers.

The designated state “gem” is eastern oyster shell.

Missouri
State mineral: galena
Missouri is nicknamed “the Lead State” due to the prevalence of this shiny cubic mineral, the natural form of lead. Thanks to rich deposits of galena, Missouri is the largest producer of lead in the United States.

State rock: mozarite
This colorfull form of chert consists of silica and chalcedony, and is found in the Ordovician deposits of west-central Missouri. Its name is a portmanteau of Missouri (mo), Ozarks (zark), and the suffix –ite, meaning “rock.”
Oklahoma
State rock: **barite**
Also known as “desert rose,” these flower-like rock formations may be composed of large crystals of gypsum, **selenite**, or other evaporite minerals. Oklahoma’s barite crystallized 250 million years ago during the Permian.

Texas
State mineral: **silver**
Silver was first discovered in Texas in 1880, and has been mined intermittently since then.

State rock: petrified palmwood
Although technically a fossil, petrified palmwood became Texas’ state “rock” in 1969. Dying **trees** from the lush Cretaceous forests were occasionally covered by mud before decaying; their cellular structures were replaced by silicate minerals to form petrified wood.

State gem: Texas blue topaz
This silicate gemstone is only found in Mason County, near the Llano Uplift, where it occurs in Precambrian granite outcroppings. The largest gem-quality topaz ever found in Texas (and all of North America) weighs in at a whopping 1296 grams (2.8 pounds)!
Resources

Rock and Mineral Field Guides


Books


Websites

Atlas of Igneous and Metamorphic Rocks, Minerals and Textures, University of North Carolina Geology Department (Older but still useful resource.)

Rocks and Minerals of the South Central US


Gentile, R. J. 2015. Rocks and fossils of the central United States, with special emphasis on the greater Kansas City area. 2nd edition. University of Kansas, Department of Geology & Paleontological Institute, Special Publication 8, 221 pp.
Chapter 3: Fossils of the South Central US

Fossils (from the Latin word *fossilis*, meaning “dug up”) are the remains or traces of organisms that lived in the geologic past (older than the last 10,000 years), now preserved in the Earth’s crust. Most organisms never become fossils, but instead decompose after death, and any hard parts are broken into tiny fragments. In order to become fossilized, an organism must be buried quickly before it is destroyed by erosion or eaten by other organisms. This is why fossils are found almost exclusively in sediment and sedimentary rocks. Igneous rocks, which form from cooling magma or lava, and metamorphic rocks, which have been altered by heat and pressure, are unlikely to contain fossils (but may, under special circumstances).

Since rapid burial in sediment is important for the formation of fossils, most fossils form in marine environments, where sediments are more likely to accumulate. Fossils come in many types. Those that consist of an actual part of an organism, such as a bone, shell, or leaf, are known as body fossils; those that record the actions of organisms, such as footprints and burrows, are called trace fossils. Body fossils may be preserved in a number of ways. These include preservation of the original mineral skeleton of an organism, mineral replacement (chemical replacement of the material making up a shell by a more stable mineral), recrystallization (replacement by a different crystal form of the same chemical compound), permineralization (filling of empty spaces in a bone or shell by minerals), and molds and casts, which show impressions of the exterior or interior of a shell. Chemical fossils are chemicals produced by an organism that leave behind an identifiable trace in the geologic record, and it is chemical fossils provide some of the oldest evidence for life on Earth.

Paleontologists use fossils as a record of the history of life. Fossilized organisms are also extremely useful for understanding the ancient environment that existed when they were alive. The study of the relationships of fossil organisms to one another and their environment is called paleoecology.

Fossils are also the most important tool for dating the rocks in which they are preserved. Because species only exist for a certain amount of time before going extinct, their fossils only occur in rocks of a certain age. The relative age of such fossils is determined by their order in the stacks of layered rocks that make up the stratigraphic record (older rocks are on the bottom and younger rocks on the top—a principle called superposition). Such fossils are known as index fossils. The most useful index fossils are abundant, widely distributed, easy to recognize, and occur only during a narrow time span. This use of fossils to determine relative age in geology is called biostratigraphy.
Ancient Biodiversity

Since life began on Earth more than 3.7 billion years ago, it has continuously become more abundant and complex. It wasn’t until the beginning of the Cambrian period, around 541 million years ago, that complex life—living things with cells that are differentiated for different tasks—became predominant. The diversity of life has, in general, increased explosively through time since then. Measurements of the number of different kinds of organisms—for example, estimating the number of species alive at a given time—attempt to describe Earth’s biodiversity. With a few significant exceptions, the rate at which new species evolve is significantly greater than the rate of extinction.

Most species have a lifespan of several million years; rarely do species exist longer than 10 million years. The extinction of a species is a normal event in the history of life. There are, however, intervals of time during which extinction rates are unusually high, in some cases at a rate of 10 or 100 times the normal rate. These intervals are known as mass extinctions. There were five particularly devastating mass extinctions in geologic history, and these specific mass extinctions...
Discovering Ancient Environments

The kinds of animals and plants living in a particular place depend on the local environment. The fossil record preserves not only fossil organisms, but also evidence of what their environments were like. By studying the geological and biological information recorded in a rock that contains a fossil, scientists can determine some aspects of the paleoenvironment.

*Grain size and composition of the rock* can tell us what type of sediment surface the animal lived on, what the water flow was like, or whether it was transported in a current. Grain size also tells us about the clarity of the water. Fine-grained rocks such as *shales* are made of tiny particles of *silt* or *clay* that easily remain suspended in water. Thus, a fossil found in shale might have lived in muddy or very quiet water. *Filter-feeding* organisms, such as clams or corals, are not usually found in muddy water because the suspended sediment can clog their filters.

*Sedimentary structures*, such as asymmetrical ripples and *cross-beds*, can indicate that the organism lived in moving water. Mud cracks or symmetrical ripples are characteristic of shoreline or *intertidal* environments.

*Broken shells or concentrated layers of shells* may indicate transportation and accumulation by waves or currents.

*Color of the rock* may indicate the amount of oxygen in the water. If there is not enough oxygen in the water, organic material (carbon) in sediments will not decompose, and the rock formed will be dark gray or black in color.

extinction events have helped to shape life through time. Unfortunately, this is not just a phenomenon of the past—it is estimated that the extinction rate on Earth right now may be as much as 1000 times higher than normal, and that we are currently experiencing a mass extinction event.

Different fossils are found in different regions because of the presence of rocks deposited at different times and in a variety of environments. The availability of fossils from a given time period depends both on the deposition of sedimentary rocks and the preservation of these rocks through time.
Fossils of the South Central US
The rocks of the South Central United States preserve an excellent fossil record of the history of life (Figure 3.1). In the remainder of this chapter, we will highlight the major types of fossils present in most of the geologic periods represented by rocks in each state. The references at the end of the chapter should be consulted for details, especially for identifying particular fossils you might find.

Fossils of the Central Lowland and Interior Highlands
Regions 1–2
The geological core of the Interior Highland and Central Lowland regions is formed by a Proterozoic mountain range that formed around 1.5 billion years ago. Today, these igneous and metamorphic rocks crop out in the St. Francois Mountains across an area of around 13,000 square kilometers (5000 square miles) in southeastern Missouri. During the Paleozoic, this ancient mountain range formed an archipelago of islands and seamounts, surrounded by vast inland seas and ringed by coral reefs. Sandstone and limestone was deposited near the shore, while shale formed in deeper water.

The sediments accumulating in these shallow seas preserved an abundant record of the marine animals that lived there during the early Paleozoic. In southeastern Missouri, the Upper Cambrian Lamotte Sandstone formed in a near-shore environment, and contains brachiopods (Figure 3.2 and see box on p. 86) and mysterious trace fossils called Climactichnites (Figure 3.3), thought to have been made by large mollusks, perhaps similar to gastropods (snails). Other Cambrian rocks in Missouri contain trilobites (Figure 3.4 and see box on p. 87) and hyoliths (Figure 3.5).

Fossils from the Ordovician rocks of the Ozarks in southern Missouri and northern Arkansas include many mollusks, such as gastropods, bivalves, cephalopods (Figure 3.6), and monoplacophorans—animals with one capsule-shaped shell, which, in some forms, is somewhat coiled back on itself (Figure 3.7). Brachiopods (Figure 3.8), trilobites (Figure 3.9), corals (Figure 3.10), bryozoans, and echinoderms—including crinoids, cystoids, and sea stars—are also found here. In southeastern Missouri, Ordovician rocks have produced the remains of conodonts (see box on p. 92)—primitive vertebrates with small, eel-like bodies and complex arrangements of teeth. Conodonts are very important index fossils for rocks of this age.

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See Chapter 1: Geologic History for more about the formation of continents in the Proterozoic and Paleozoic.
The history of life in relation to global and regional geological events and the fossil record of the South Central US. (Time scale is not to scale.)

**Fossil Record of the South Central**

<table>
<thead>
<tr>
<th>ERA</th>
<th>Period</th>
<th>Geological Events</th>
</tr>
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<tbody>
<tr>
<td>Paleozoic</td>
<td>Cambrian</td>
<td>Formation of Lamotte Sandstone, containing many marine fossils (480Ma)</td>
</tr>
<tr>
<td></td>
<td>Ordovician</td>
<td>Earth’s surface is molten; frequent asteroid impacts (4.5Ga)</td>
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<tr>
<td></td>
<td>Silurian</td>
<td>Oldest rocks in South Central (St. Francois Mountains) form (1.5Ga)</td>
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<tr>
<td></td>
<td>Devonian</td>
<td>Marine life diversifies</td>
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<tr>
<td></td>
<td>Mississippian</td>
<td>Sea levels fall and fluctuate, forming coastal swamps and coal-bearing cyclothems (359-299Ma)</td>
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<tr>
<td></td>
<td>Pennsylvanian</td>
<td>Pangaea forms, global sea level falls (299Ma)</td>
</tr>
<tr>
<td></td>
<td>Permian</td>
<td>Terrestrial environments become commonly preserved—coal layers yield many tetrapods and plants (Central Lowland and Interior Highlands) (360–245Ma)</td>
</tr>
<tr>
<td></td>
<td>Triassic</td>
<td>South Central under shallow seas, reef building and dwelling organisms abundant (505–286Ma)</td>
</tr>
<tr>
<td></td>
<td>Jurassic</td>
<td>Tropical reefs form in Texas and New Mexico (255Ma)</td>
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<tr>
<td></td>
<td>Cretaceous</td>
<td>Pangaea begins to split apart (252–201Ma)</td>
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<tr>
<td></td>
<td>Tertiary</td>
<td>Global sea levels start to fall due to polar glaciation (55–30Ma)</td>
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<tr>
<td></td>
<td>Neogene</td>
<td>Global sea levels rise; widespread chalk deposition (145–66Ma)</td>
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<tr>
<td></td>
<td>Quaternary</td>
<td>Rifting forms restricted seaways between North and South America (present Gulf of Mexico); large salt deposits form (201–145Ma)</td>
</tr>
<tr>
<td></td>
<td>Submerged Zones of the South Central</td>
<td>Limestone - a sedimentary rock composed of calcium carbonate (CaCO₃).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bivalve - a marine or freshwater animal characterized by right and left calcareous shells (valves) joined by a hinge.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gastropod - a marine, freshwater or terrestrial gastropod, a muscular foot for gliding and internal asymmetry caused by torsion.</td>
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<tr>
<td></td>
<td></td>
<td>Hyolith - animals with cone-shaped shells and uncertain affinities that existed throughout the Paleozoic.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bryozoan - a marine deposit, calcareous animal consisting of a simple, coiled skeleton with internal asymmetry caused by torsion.</td>
</tr>
</tbody>
</table>
Brachiopods

Brachiopods are filter-feeding animals that have two shells and are superficially similar to bivalves (such as clams). Instead of being mirror images between shells (symmetrical like your hands), brachiopod shells are mirror images across each shell (symmetrical like your face). Internally, brachiopods are substantially different from bivalves, with a lophophore (filter-feeding organ made of thousands of tiny tentacles), and a small and simple gut and other organs. Bivalves, in contrast, have a fleshier body and collect their food with large gills.

The difference between the shells of a typical brachiopod (left) and a typical bivalve mollusk (right). Most brachiopods have a plane of symmetry across the valves (shells), whereas most bivalves have a plane of symmetry between the valves.
Trilobites are iconic Paleozoic fossils, but were more common in the Cambrian and Ordovician than in later periods. They were arthropods, and had well-defined head, tail, and thoracic (leg-bearing) segments. Most had large compound eyes, often with lenses that are visible to the naked eye. In life, they had antennae like many other arthropods, but since these were not mineralized, they only fossilize under exceptional circumstances. Many could roll up for protection, and several species also had large spines.
Figure 3.5: Hyolithid. About 1–2 centimeters (less than 1 inch) long.

Figure 3.6: Cephalopods. A) Straight (orthocone) nautiloid shell and restoration. These animals reached lengths of more than 4 meters (12 feet), making them among the largest invertebrate animals that ever lived. Specimens up to 25 centimeters (1 foot) long are frequently found. B) Restoration of an ellesmeroid nautiloid from the Ordovician of Missouri. About 10–15 centimeters (4–6 inches) long.
Cephalopods

Cephalopods, such as squid, octopods, nautiloids, ammonoids, and belemnites, are mollusks with tentacles and beak-shaped mouths for catching prey. Some cephalopods such as belemnites and living cuttlefish have internal shells, while others have straight or coiled shells, such as those of ammonoids or nautiloids. Still other cephalopods, such as the octopus have no shell. The mass extinction at the end of the Cretaceous, famous for eliminating the dinosaurs, also eliminated belemnites and ammonoids, which had been extremely diverse during the Mesozoic. Ammonoids are useful index fossils, especially in Mesozoic rocks.

Figure 3.7: Monoplacophorans in limestone (highlighted), Lower Ordovician, Barry County, Missouri. Pocketknife at bottom of photo is about 8.5 centimeters (3.5 inches) long. Inset shows top and sides views of an individual shell in detail.
3

Fossils

Regions 1–2

**sessile** • unable to move, as in an organism that is permanently attached to its substrate.

**rugose coral** • an extinct group of corals that were prevalent from the Ordovician through the Permian.

**tabulate coral** • an extinct form of colonial coral that often formed honeycomb-shaped colonies of hexagonal cells.

**scleractinian coral** • a colonial or solitary marine invertebrate animal characterized by an encrusting calcareous skeleton enclosing polyps that capture prey with small tentacles equipped with stinging cells (nematocysts).

Figure 3.8: Ordovician brachiopods from Missouri. A) Strophomena. 1–2 centimeters (0.5–1 inch) wide. B) Resserella. About 1 centimeter (0.5 inches) wide. C) Pionodema. About 1 centimeter (0.5 inches) wide.

Figure 3.9: Ordovician trilobites. A) Isotelus iowensis, Missouri. B) Homotelus bromidensis, Oklahoma.

Figure 3.10: Ordovician rugose corals from Missouri. A) Favistella (colonial). About 8 centimeters (3.2 inches) wide. B) Streptelastra subregulare (solitary, “horn” coral). About 3 centimeters (1 inch) tall.
Corals are sessile relatives of jellyfish and sea anemones. They possess stinging tentacles, which they use to feed on small planktonic prey. Each group of coral possesses distinctly shaped “cups” that hold individual animals, or polyps. Colonial corals live in colonies of hundreds or even thousands of individuals that are attached to one another. Solitary coral lives independently, as a single isolated polyp.

**Rugose corals** were both colonial and solitary (solitary forms are often called “horn corals”). **Tabulate corals** were exclusively colonial and produced a variety of shapes, including domed and chainlike forms. These corals receive their name from the table-like horizontal partitions within their chambers. Both rugose and tabulate corals went extinct at the end of the Permian. Modern corals—*scleractinians*—appeared in the Triassic, and include both solitary and colonial species. Many scleractinian corals have photosynthetic symbiotic algae in their tissues, called zooxanthellae. This algae provides nutrition to the coral polyps, helping them to grow more rapidly.

The oldest rocks in the Central Lowland are **Devonian** deposits in southwestern Missouri and northeastern Oklahoma, where marine invertebrates, such as corals, trilobites, crinoids, and cephalopods, shared the waters with fishes including shark-like *acanthodians* (*Figure 3.11*).

After the mass extinction in the late Devonian (see *Figure 3.1*), trilobites never regained their previous abundance and diversity, and post-Devonian trilobites are relatively rare. In the **Mississippian** of Missouri, however, and in the **Pennsylvanian** of Texas, small trilobites are locally common (*Figure 3.12*).
Conodonts are tiny tooth-shaped fossils (0.2–5 millimeters long) found in marine rocks of Cambrian through Triassic age. They have long been among the most important index fossils in these rocks, allowing the rocks to be dated through biostratigraphy. For many years, paleontologists did not know what kind of animal they belonged to, but in 1983 a very well-preserved fossil was found in Scotland that showed conodonts to belong to small fish-like animals just a few centimeters long that were distant relatives of bony fish.

Isolated conodont elements (Silurian).

Restoration of what the conodont animal may have looked like alive. Length 2–4 centimeters (1–2 inches).

Figure 3.11: Silurian acanthodian fish (life restoration and spine). These fish reached lengths of up to 30 centimeters (1 foot).
Mississippian and Pennsylvanian rocks in Missouri, western Arkansas, and eastern Oklahoma contain ammonoids (Figure 3.13) and graptolites, both pelagic groups that were once common and diverse but are now extinct. Mississippian limestone beds in Missouri and Arkansas preserve the inhabitants of an ancient reef system, including corals, bryozoans (Figure 3.14), brachiopods, and fishes. Abundant echinoderms are also present, including blastoids (Figure 3.15), crinoids (such as Missouri’s state fossil, Delocrinus missouriensis [Figures 3.16 and 3.17]), and large echinoids (sea urchins) (Figure 3.18). The Mississippian is sometimes called “the age of crinoids” because they were so abundant in the shallow seas of this period.

**ammonoid** • a group of extinct cephalopods belonging to the Phylum Mollusca, and possessing a spiraling, tightly-coiled shell characterized by ridges, or septa.

**graptolite** • an extinct colonial invertebrate animal characterized by individuals housed within a tubular or cup-like structure.

**pelagic** • free-swimming; of or in a zone of open water that is neither close to the bottom nor near the shore.

**system** • a set of connected things or parts forming a complex whole.

**blastoid** • an extinct form of stemmed echinoderm, similar to crinoids, possessing a nut-shaped body covered with interlocking plates.
Graptolites (meaning “rock writing”) are an extinct group of colonial, free-floating organisms. They lived from the Cambrian to the Carboniferous, and were relatives of modern hemichordates such as acorn worms. Graptolites are frequently preserved as thin black sawblade-like streaks across black shale; tiny cups along these structures held individual animals. Graptolites are often useful as index fossils.

A) Specimen with many fragments of colonies of Climacograptus. Slab is 7.5 centimeters (3 inches) on each side. B) Restoration of what graptolite colonies may have looked like when they were alive, floating in the water.

Figure 3.14: The bryozoan Archimedes sp., Carboniferous. A) Archimedes colonies consisted of a screw-shaped axis, with a spiral fan connected to the “threads” of the screw. The tiny bryozoan animals lived in chambers on the fan. In some localities, thousands of these “fossil screws” cover the ground. They are less than 2.5 centimeters (1 inch) long. B) Archimedes life restoration.
Figure 3.15: Blastoid. Pentremites sp., Carboniferous. About 1–2 centimeters (0.75 inches) long.

Figure 3.16: Crinoids, Upper Mississippian, Arkansas. A) Phanocrinus. Crown and part of stem. Specimen about 5 centimeters (2 inches) tall. B) Linocrinus. Crown and part of stem. Specimen about 6 centimeters (2.4 inches) tall.
Figure 3.17: Crinoid, Delocrinus missouriensis. A) Restoration of the entire animal, attached to the sea floor. About 30 centimeters (1 foot) tall. B) Specimen of the crown (calyx) with arms. About 5 centimeters (2 inches) tall. C) Bottom view of the cup portion of the calyx. About 2 centimeters (0.8 inches) in diameter.
Crinoids are echinoderms, related to sea urchins and sea stars. These invertebrate animals feed by using their arms to filter food out of the water. Most were attached to the sediment by a stalk that ended in a root-like structure called the holdfast—however, some forms were free floating. Crinoid fossils are most commonly found as “columnals,” pieces of the stalk that hold the head (calyx) above the surface. The calyx and the holdfast are only occasionally preserved.
In the Pennsylvanian, the sea began to drain away from the Interior Highlands and Central Lowland. Pennsylvanian rocks in northern and western Missouri and eastern Kansas and Oklahoma indicate cyclical fluctuations between shallow marine and terrestrial environments, preserved in repeating layers of shale, limestone, and sandstone interspersed with thick seams of coal. These coal beds, representing terrestrial near-shore swamps, were formed from great thicknesses of decomposing plants, including giant horsetails, tree ferns, scale trees (lycopsids or “club mosses”), and the conifer-like Cordaites (Figure 3.19). Conversely, the marine deposits here contain abundant bivalves, bryozoans, echinoids, crinoids, gastropods, corals, trilobites, and brachiopods (Figure 3.20).
Several fossil lagerstätten deposits are known from the Pennsylvanian and Permian of Kansas. These deposits, which formed along the shoreline of a shallow sea, contain abundant and beautifully preserved terrestrial tetrapods and insects as well as many marine invertebrates and fish. The Garnett locality in Andersen County preserves an incredible record of life during the Pennsylvanian in a series of stream channel infills. *Petrolacosaurus* (Figure 3.21), one of the earliest known diapsid reptiles, can be found at this site.

The Elmo Limestone in Dickinson County is famous for its fossil insects and xiphosurids (the group of arthropods that includes horseshoe crabs) (Figures 3.22 and 3.23). Other examples of deposits containing similar faunas include the Robinson locality in Brown County and the Hamilton locality in Greenwood County.

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** Regions 1–2

- **conifer** • a woody plant bearing cones that contain its seeds.

- **lagerstätte** • fossil deposit containing animals or plants that are preserved unusually well, sometimes even including the soft organic tissues.

- **Permian** • the geologic time period lasting from 299 to 252 million years ago.

- **tetrapod** • the first four-limbed animals (early land vertebrates) and all of their descendants.

- **diapsid** • a vertebrate animal possessing two holes behind the orbit (eye hole) in each side of its skull.

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*Figure 3.20: Pennsylvanian brachiopods from Missouri. A) Dictyoclostus sp., about 5 centimeters (2 inches) wide. B) Derbyia sp., about 3 centimeters (1.5 inches) wide. C) Echinoconchus sp., about 5 centimeters (2 inches) wide.*

*Figure 3.21: Restoration of Petrolacosaurus, about 40 centimeters (16 inches) long.*

*Figure 3.19 (AT LEFT): Restorations of coal swamp plants. A) Lepidodendron, a lycopod (club moss); reached 30 meters (100 feet) tall. B) Medullosa, a tree fern; reached 10 meters (35 feet) tall. C) Calamites, a sphenopsid (horsetail); reached 20 meters (65 feet) tall. D) Cordaites, a conifer-like seed plant; reached 10 meters (35 feet) tall.*
The skulls of reptiles are distinct from our own in several important respects. One of the most striking differences is that the typical reptile skull looks like a “box within a box.” Unlike the arrangement in our own skulls, the braincase of most reptiles is not built of the bones that make up the outermost layer of the skull. Instead, there is a second set of interior bones (these are largely absent in mammals like us), that surround the braincase; the space between these two layers is filled mostly with muscles. Different groups of reptiles have modified this continuous outer wall of bone by evolving openings, or “apses,” in the skull. The resulting structures are the basis for terms that describe the types of reptilian skulls and the reptile groups that possess them. *Anapsid* skulls (such as those of turtles) have no openings. *Synapsid* skulls (such as those of mammal ancestors) have one opening. *Diapsids* (such as lizards, crocodilians, and dinosaurs) have two openings.
Figure 3.22. Paleolimulus. Late Pennsylvanian-Early Permian of Kansas. About 1 centimeter (0.4 inches) long.

Figure 3.23: Meganeuropsis is an extinct genus of griffinfly, Order Meganisoptera, and includes the largest known insect that ever lived, with an estimated wingspan of up to 70 centimeters (28 inches), and a body length from head-to-tail of almost 43 centimeters (17 inches). This wing, from Noble County, Oklahoma, in the collection of Harvard’s Museum of Comparative Zoology, is about 33 centimeters (13 inches) long.
The beginning of the Permian saw continued sea level fluctuations, and shallow marine deposits from this time in eastern central Kansas contain faunas similar to those of the Pennsylvanian. As the period continued, however, the climate became much drier, and shallow seas were restricted to central Kansas. To the west of these beds, Permian rocks contain the remains of lungfish, sharks, and other fishes. In Oklahoma and Texas, the shallow sea retreated to the west, and thick layers of gypsum and salt were deposited, indicating that evaporation rates were high. Rare fossils of insects, amphibians, and reptiles, as well as vertebrate footprints, have been collected from the youngest Paleozoic rocks in Oklahoma. The Dolese Quarry near Lawton (Comanche County), for example, has produced a great diversity of tetrapods in soft white claystone, including the common small anapsid reptile Captorhinus aguti (Figure 3.24). Permian “red bed” deposits in western and north central Texas (such as the

![Figure 3.24: Captorhinus. Reconstructed skeleton and life restoration, about 30 centimeters (12 inches) long.](image)

![Figure 3.25: Eryops. Reconstructed skeleton and life restoration, 1.5-2.0 meters (5-6.5 feet) long.](image)
Quartermaster Formation) are famous for their abundance of early Permian reptiles including synapsids—a group that includes the ancestors of modern mammals. Here, well-known tetrapods like the sail-backed Dimetrodon and Edaphosaurus, the giant amphibian Eyrops, and the enigmatic Diadectes dominate the fauna (Figures 3.25–3.27).

See Chapter 2: Rocks for more information about Permian red beds in Texas.

Figure 3.26: Dimetrodon grandis, one of the larger species of Dimetrodon. Skull and life restoration, about 3 meters (9 feet) long.
Above the Permian layers are fossil-bearing Triassic strata, forming a ribbon from the western part of the Texas panhandle southeast to near Abilene. The temporal boundary between the Permian and Triassic marks the greatest mass extinction known (see Figure 3.1). While its effect on marine ecosystems was particularly devastating, life on land was dramatically affected as well. Many kinds of tetrapods disappeared, which may have cleared the path for a new group of tetrapods—dinosaurs (which first appeared in the middle Triassic) —to dominate the land.

The Triassic rocks of Texas crop out along the border between the Great Plains and Central Lowland regions. A variety of early dinosaurs are found in here, along with crocodile-like (at least in appearance) phytosaurs, and synapsids (Figure 3.28).
**Cretaceous** rocks exposed in southern Oklahoma and north central Texas contain a variety of marine mollusks, including bivalves, gastropods, and ammonites. **Cenozoic** rocks are largely absent from this area, but **Pleistocene gravels** in southwestern Oklahoma (Tillman County) have produced the

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**Mastodons and Mammoths**

These two kinds of ancient elephants (or, more technically, proboscideans) are frequently confused. Both were common during the Pleistocene, but they had different ecological preferences and are usually found separately. Mammoths are close cousins of modern African and Asian elephants; mastodons are more distant relatives, from a separate line of proboscideans that branched off from the modern elephant line in the Miocene. Mastodons have a shorter, stockier build and longer body; mammoths are taller and thinner, with a rather high “domed” skull. In skeletal details, the quickest way to tell the difference is with the teeth: mastodons have teeth with conical ridges, a bit like the bottom of an egg carton; mammoths, in contrast, have teeth with numerous parallel rows of ridges. The teeth are indicative of the two species’ ecological differences. Mastodons preferred to bite off twigs of brush and trees, while mammoths preferred tough siliceous grasses. Thus, mastodon teeth are more suitable for cutting, while mammoth teeth are more suitable for grinding.

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A mammoth tooth, suitable for grinding grass and softer vegetation. About 25 centimeters (1 foot) long.

A mastodon tooth, suitable for chewing twigs and tree leaves. About 20 cm (8–9 inches) long.

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**Cretaceous** • a geologic time period spanning from 144 to 66 million years ago.

**Cenozoic** • the geologic time period spanning from 66 million years ago to the present.

**Pleistocene** • a subset of the Quaternary, lasting from 2.5 million to about 11,700 years ago.

**Gravel** • unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).
Fossils

Regions 1–3

bones of glyptodonts (see Figure 3.42). Glacial-age deposits in Dallas County, Texas also contain the bones and teeth of mammoths and mastodons. Late Pleistocene mammals are abundant at several localities in Kansas, including along the banks of the Kansas River from Topeka to Kansas City, and several finds have been made in greater Kansas City itself for more than the past century. Another famous site is the Kimmswick Bone Bed in Jefferson County in eastern Missouri (at Mastodon State Historic Site), which not only contains abundant fossil mastodon and other bones, but also stone tools made by some of the earliest human residents of this part of North America.

See Chapter 6: Glaciers to learn more about the history of glaciers in the South Central.

Fossils of the Coastal Plain
Region 3

The sediments that accumulated to form the Coastal Plain of Texas and Louisiana were deposited by numerous rivers that drained the land to the north and northwest. This process began in the late Cretaceous, and the Mississippi River continues to drain the central US today, contributing to the coastline of the Gulf of Mexico. The oldest sediments on the Coastal Plain (from the late Cretaceous) appear in an irregular northeast-southwest-oriented band farthest from the modern coastline (Figure 3.29). Roughly parallel bands of sediments of decreasing age outcrop toward the coast, with the youngest sediments accumulating right at the shore today.

The late Cretaceous sediments of the Coastal Plain are frequently rich in fossils, including shark teeth (Figures 3.30 and 3.31) and ammonites (both the usual coiled forms, and unusual irregular or uncoiled forms, known as heteromorphs) (Figure 3.32). Oysters and other bivalves including Inoceramus (Figure 3.33) are also present, as well as are rare mosasaur and plesiosaur remains. These fossiliferous Cretaceous sediments are found from the base of the Edwards Plateau near the Mexican border to Dallas and into the sliver of Coastal Plain on the eastern half of the Oklahoma-Texas border. The latter area yields rare dinosaur skeletons, most spectacularly (in Atoka County, Oklahoma) the gigantic sauropod Sauroposeidon (Figure 3.34).

See Chapter 4: Topography to find out more about the Edwards Plateau.

The line of late Cretaceous layers continues along the landward edge of the Coastal Plain into Arkansas, bordering the Interior Highlands. This boundary forms a line from the southwest to northeast corners of the state. Cretaceous layers, however, only crop out in the corners of Arkansas, as they are buried by younger sediment in the state’s center. These strata contain large clams and bivalves, ammonites, gastropods, echinoids, shark teeth, and the occasional

See Chapter 4: Topography to find out more about the Edwards Plateau.

mammoth • an extinct terrestrial mammal belonging to the Order Proboscidea, from the same line that gave rise to African and Asian elephants.

mastodon • an extinct terrestrial mammal belonging to the Order Proboscidea, characterized by an elephant-like shape and size, and massive molar teeth with conical projections.

mosasaur • an extinct, carnivorous, marine reptile characterized by a streamlined body for swimming, a powerful fluked tail, and reduced, paddle-like limbs.

plesiosaur • a member of a group of extinct long-necked Mesozoic marine reptiles.
marine reptile. A few pockets of Cretaceous-aged rock are also found in Louisiana, where salt domes have pushed up through the overlying Cenozoic sediment, occasionally carrying Cretaceous shark teeth to the surface.

The great majority of sediment exposed in the Coastal Plain is Cenozoic in age. Paleogene-aged strata are, for the most part, sandwiched between the western rim of Cretaceous deposits, and the youngest layers of Neogene and Quaternary sediment, which are found nearest the Gulf and along the Mississippi River Valley (see Figure 3.29). Paleogene marine deposits in Texas, southern portions of Arkansas, and northern parts of Louisiana are abundantly fossiliferous, yielding shark teeth, corals, clams and snails (Figure 3.35), and the bones of early whales like Basilosaurus (Figure 3.36).

See Chapter 2: Rocks to learn more about the sediments of the Coastal Plain.
Ammonoids are a major group of cephalopods that lived from the Devonian to the end of the Cretaceous. Both nautiloids (the group that today contains the chambered nautilus) and ammonoids have chambered shells subdivided by walls, or septa (plural of septum). These shells are frequently, but not always, coiled. The term “ammonoid” refers to the larger group of these extinct cephalopods, distinguished by complex folded septa. Within ammonoids, “ammonites” is a smaller sub-group, distinguished by the extremely complex form of their septa. Ammonites were restricted to the Jurassic and Cretaceous periods. The form of the septa in nautiloids and ammonoids is not visible in a complete shell; it is most often seen in the trace of the intersection between the septum and the external shell. This trace is called a suture. Sutures are usually visible in fossils when sediment has filled the chambers of a shell, and the external shell has been broken or eroded away.

Ammonite shell break-away cross section; surface plane of a septum and sediment-filled chamber.
Figure 3.30: Cretaceous shark teeth from Kansas. A) B) and C) Scapanorhynchus, up to 1 centimeter (0.5 inches) long. D) Leptostyrax, about 1.4 centimeters (0.6 inches) long. E) and F) Carcharias amonensis, about 0.7 centimeters (0.3 inches) long. G) Cretodus, about 4.5 centimeters (1.8 inches) long.

Figure 3.31: Cretaceous shark teeth from Texas. A) Serratalamna, about 1.5 centimeters (0.6 inches) long. B) Protolamna, about 1.5 centimeters (0.6 inches) long. C) Pseudocorax, about 1 centimeter (0.4 inches) long. D) Palaeogaleous, about 3–4 millimeters (0.1–0.2 inches) long.

Figure 3.32: Baculites, a straight-shelled heteromorph ammonite from the Cretaceous. A) Complex folded septa in shell. B) Life restoration. Usually around 3–4 centimeters (2 inches) in diameter and up to 60 centimeters (2 feet) long.
Fossils

Region 3

Figure 3.33: Cretaceous bivalves of Texas. A) “Ram’s horn” oyster, Exogyra costata, about 10 centimeters (4 inches) long. B) Inoceramus, about 15 centimeters (6 inches) wide.

Bivalves

Clams and their relatives, such as mussels, scallops, and oysters, are mollusks possessing a pair of typically symmetrical shells. Most are filter feeders, collecting food with their gills. Paleozoic bivalves typically lived on the surface of the sediment (“epifaunally”), but in the Mesozoic they evolved the ability to burrow more deeply into the sediment and live “infaunally.” This innovation led to the rapid evolution of a large number of groups present in the modern oceans.

Gastropods

Commonly known as snails, gastropods are among the most diverse group of organisms in the ocean today. Modern gastropod mollusks encompass terrestrial, freshwater, and marine species, and include varieties with and without shells (e.g., slugs). Only insects have more named species. The soft parts of gastropods are similar to those of bivalves in some respects, but snails have a head and are usually much more active than clams.
Figure 3.34: Silhouette of a restoration of Sauroposeidon. White bones in the neck represent known pieces of the skeleton based on fossils. The rest of the body form has been inferred by comparison with other brachiosaur dinosaurs.

Figure 3.35: Cenozoic marine mollusks from the Gulf Coastal Plain of Texas, Louisiana, and Arkansas. A) Venericardia natchitoches, Late Paleocene, Natchitoches Parish, Louisiana. About 4 centimeters (1.5 inches) wide. B) Crassatellites trapaquara, Early Eocene, Bastrop County, Texas. About 5.5 centimeters (2.2 inches) wide. C) Cubitostrea sellaeformis, Early Eocene, Bastrop County, Texas. About 13 centimeters (5 inches) wide. D) Athleta wheelockensis, Middle Eocene, Crockett County, Texas. About 3 centimeters (1.5 inches) wide. E) Turritella nasuta, Early Middle Eocene, Houston County, Texas. About 4 centimeters (1.6 inches) long. F) Turritella arenicola, Late Eocene, Jefferson County, Arkansas. About 3.8 centimeters (1.5 inches) long.
Basilosaurus was first described by Richard Harlan in 1843, who believed the few bones he found belonged to a marine reptile (hence the name “saurus”). Basilosaurus was a member of an early group of whales known as archaeocetes, which included the ancestors of the two major groups of modern whales—the toothed whales (odontocetes), such as porpoises and sperm whales, and the baleen whales (mysticetes), such as humpback and blue whales. Archaeocetes inhabited the equatorial oceans during the Paleocene and Eocene. The vertebra pictured in Figure 3.36B was found in Arkansas in 1945, and represents the northernmost archaeocete fossil ever found.
Abundant tiny fossils called foraminifera (Figure 3.37) are found throughout the Coastal Plain’s Cretaceous and Cenozoic sediments. Foraminifera, or “forams,” as they are frequently called, are single-celled organisms (protists) with shells made of calcium carbonate. They live in the ocean in huge numbers, both at the bottom and floating in the water column, and are extremely important as index fossils and paleoenvironmental indicators in Cretaceous and Cenozoic sediments.

Terrestrial deposits in eastern Texas, dating from the early Miocene (e.g., Fleming Formation, exposed near Toledo Bend Reservoir), include abundant bones and teeth of amphibians, reptiles, and rodents (Figure 3.38). Larger mammals are also present, including carnivores, tapirs, pigs, and bizarre extinct forms such as the large herbivore Moropus (Figure 3.39). The Coastal Plain’s Miocene sediments also contain petrified wood, including palm (Palmoxylon), the Texas state rock and Louisiana state fossil (Figure 3.40).

By the Quaternary period, the glaciation of North America was underway. Many Neogene mammals had gone extinct by this time, yet mastodons, horses, and camels remained common. Fossils from this time are found on the Coastal Plain of Texas and Louisiana, and in the Mississippi River Valley in Louisiana, Arkansas, and the southeasternmost corner of Missouri. The youngest deposits of the Coastal Plain—for example, in the counties around Corpus Christi, Texas—contain the fossils of camels, saber-toothed cats, mammoths, glyptodonts, and dire wolves.
Figure 3.40. Sliced and polished piece of the fossil trunk of the palm *Palmoxylon*, Oligocene, from the Catahoula Formation, Louisiana. 18 centimeters (7 inches) wide.

Figure 3.39: Cenozoic land mammals from the Texas Coastal Plain A) Early horse, *Archaeohippus*. Reconstructed skeleton and life restoration, about 1 meter (3 feet) tall at the shoulder. B) Large clawed herbivore, *Moropus*. Reconstructed skeleton and life restoration, about 2.5 meters (8 feet) tall at the shoulder.
(Figures 3.41–3.43). Because they were the dominant life on land, and because their relatively large, heavy bones preserve more easily, it is easy to focus on Quaternary mammals; however, major groups of flora and fauna shared the landscape with these beasts, and their remains are occasionally found as well. For example, shells of freshwater bivalves are common, as well as those of land and freshwater gastropods, and petrified wood and pollen are also found.

Figure 3.41: Camelops hesternus. A) Jaw fragment, about 20 centimeters (8 inches) long. B) Restoration, about 2.2 meters (7 feet) tall at the shoulder.
Figure 3.42: Glyptodont. A) Skeleton, with and without the external armor. B) Detail of the bony scutes that form the solid outer armor. Glyptodonts reached lengths of up to 3 meters (10 feet).
The Waco Mammoth Site, in McLennan County, central Texas, contains the fossil bones of 24 Columbian mammoths (*Mammuthus columbi*) and other Pleistocene mammals. The site, discovered in 1978, is the largest known concentration of a single herd of mammoths dying from the same event, which is believed to have been a flash flood.

The Great Plains of Texas, Oklahoma, and Kansas are dominated by mid to late Mesozoic- and Cenozoic-aged rocks. Little of the bedrock in the region is older than 145 million years.

**Mesozoic**
Significant fossil-bearing rocks dating to the Triassic can be found in the valleys of north central Texas, but they are better exposed in the Central Lowland region and are therefore discussed in the preceding section. Similarly, the Jurassic is not well-represented in this region, but the western panhandle of Oklahoma includes a small but important exposure of terrestrial shales and sandstones, which contain turtles, crocodiles, freshwater fish, and Oklahoma’s state fossil, the large allosaur *Saurophaganax* (Figure 3.44).

The Cretaceous rocks of Kansas contain abundant remains of late Mesozoic marine life, including some of the best fossils in the world from this time period. Fossils of marine invertebrates indicate that a warm, shallow sea covered the western part of the state, while terrestrial plant fossils and coal seams in central Kansas represent near-shore swamps. These swamps mark the shore of the great Western Interior Seaway, which divided North America into two landmasses as it extended from the Gulf of Mexico to the Arctic Ocean (Figure 3.45). The flat floor of this inland sea provided the basis for the modern topography of the Interior Plains.
The Western Interior Seaway was home to numerous open-water animals, which are represented by the abundant and beautifully preserved fossils found in the Niobrara Chalk of Kansas. These animals included mosasaurs (Figure 3.46), plesiosaurs (Figure 3.47), giant turtles, sharks, and other fishes, including the enormous *Xiphactinus* (Figure 3.48). The diverse invertebrate fauna includes ammonoids, crinoids, echinoids, bivalves (especially inoceramids and *rudists*), and gastropods (Figures 3.49–3.51). Vertebrates in the Cretaceous deposits of Kansas also include *pterosaurs* and birds (Figures 3.52 and 3.53). Interestingly, coprolites—fossilized feces (Figure 3.54)—are also fairly common.

**Figure 3.45: The Western Interior Seaway.**

### Region 4

**rudists** • an extinct group of box- or tube-shaped bivalves that arose during the Jurassic.

**pterosaurs** • extinct flying reptiles with wingspans of up to 15 meters.
Figure 3.46: A) Mosasaur tooth, about 5 centimeters (2 inches) long. B) Restoration of the Cretaceous mosasaur Tylosaurus. About 15 meters (50 feet) long.

Figure 3.47: Restoration of Elasmosaurus, a large plesiosaur from the Niobrara Chalk of Kansas. About 14 meters (46 feet) long.
Figure 3.48: Skeleton of the giant Cretaceous fish Xiphactinus, Kansas. About 5 meters (16 feet) long.

Figure 3.49: Cretaceous ammonites from Texas. A) Eopachydiscus (about 40 centimeters [16 inches] in diameter). B) Perrinites (about 15 centimeters [6 inches] in diameter). C) Didymoceras (about 15 centimeters [6 inches] wide).
Figure 3.50: The Whitestone Member of the Walnut Formation is a limestone of mid-Cretaceous age exposed in Travis and Williamson counties in south central Texas. Known as “Cordova Limestone,” it is a popular facing stone for buildings such as the Houston City Hall. It contains abundant molds and casts of marine bivalves (Trigonia) and gastropods (Turritella) (inset).

Figure 3.51: Hemiaster sp., an irregular echinoid (sea urchin) from the Cretaceous of Texas. About 6 centimeters (1.4 inches) long.
Figure 3.52: A) Skeleton of the pterosaur Pteranodon from the Cretaceous of Kansas, which had a wingspan of up to 6 meters (20 feet). B) Life restoration.

Figure 3.53: Cretaceous toothed birds of Kansas. A) and B) The large flightless Hesperornis. About 6 feet (1.8 meters) long. Reconstructed skeleton and life restoration. C) and D) The smaller flying Ichthyornis, with a wingspan around 50 centimeters (20 inches). Reconstructed skeleton and life restoration.
Most Cretaceous fossils in western Kansas are found in chalk, a carbonate rock made up primarily of the fossils of microscopic marine algae, called coccolithophores (Figure 3.55). Today, such sediments accumulate mainly in the deep sea, but during the Cretaceous, when sea levels were much higher than today, chalk accumulated in shallow (100–300 meter [328–984 foot]) inland seas in both North America and Europe. The Cretaceous period is named for the abundance of chalk that accumulated during this time; the Latin word for chalk is creta.

In the Western Interior Seaway, chalk formed in marine environments with relatively little wave or current energy, and on seafloors where dissolved oxygen concentrations were low. This led to conditions that were not particularly favorable for bottom-living organisms, but that were exceptionally good for preserving whatever died there. The Smoky Hill Chalk Member of the Niobrara Chalk Formation is famous for its spectacularly preserved marine vertebrates, including mosasaurs, plesiosaurs, fish, pterosaurs, and birds. The few benthic organisms that were able to tolerate the low oxygen levels include the stalkless crinoid Uintacrinus (Figure 3.56) as well as rudist and inoceramid bivalves (Figures 3.57 and 3.58).

In Texas, extensive Cretaceous outcrops are preserved in the Edwards Plateau. There, limestone units produce a host of marine invertebrate fossils. Gastropods, bivalves (including reef-forming rudists), echinoderms, corals, and petrified wood (in layers formed on or near land) may also be found. Rare fossil fish, dinosaur, pterosaur, and various marine reptile bones have been found along the Great Plains side of the Balcones Escarpment. The most famous fossil remains in this area, however, are dinosaur trackways found in more than a dozen locations.
Figure 3.55: Microscopic view of chalk, showing that it is composed almost completely of the shells of protists called coccolithophores. Scale bar = 4 nanometers (4 x 10^-9 meters; about 0.0000001575 inches).

Figure 3.56: Large slab with many individuals of the stemless crinoid Uintacrinus, from the Niobrara Formation of Kansas. Uintacrinus was previously thought to have been a floating form, but more recent research suggests that it lived on the soft chalk bottom of the Western Interior Seaway. Field of view about 0.3 meters (1 foot).
Figure 3.57: Giant inoceramid bivalve, Platyceramus platinus, from the Cretaceous Niobrara Chalk of Kansas. About 1.2 meters (4 feet) in diameter.

Figure 3.58: Rudists were unusual cone- or cylinder-shaped bivalves that clustered together in reef-like structures and went extinct at the end of the Mesozoic era. They ranged in size from a few centimeters to more than 50 centimeters (1.5 feet) tall.
on and north of the Edwards Plateau (Figure 3.59 and 3.60). The variety of footprints is attributed to theropods, ornithiscians, and sauropods, though the precise species are impossible to know. Some of the theropod footprints may have been made by *Acrocanthosaurus* (Figure 3.61), one of the largest known carnivorous dinosaurs. Skeletal remains of *Acrocanthosaurus* have been found in early Cretaceous rocks in Oklahoma and Texas, and also Wyoming.

### Cenozoic

In the late Cretaceous, the Western Interior Seaway retreated and the Rocky Mountains rose to the west; streams carried gravel, sand, and silt that eroded from these newly formed mountains. The sediments filled wide, shallow valleys to create a broad, gently dipping plain that contains a variety of terrestrial and freshwater fossils, including gastropods, clams, algae, and the occasional plant. By the middle Eocene, the environment became wetter and cooler. Mammals
Figure 3.60: Dinosaur tracks from the bed of the Paluxy River at Dinosaur Valley State Park, near Glen Rose, Somervell County, Texas. The round footprints were made by a brachiosaur sauropod, perhaps Paluxysaurus or Sauroposeidon; the three-toed prints were made by a theropod, such as Acrocanthosaurus. The tracks were made in the early Cretaceous period, about 113 million years ago, and represent the first sauropod trackway ever discovered.

Figure 3.61: Acrocanthosaurus. Reconstructed skeleton and life restoration, about 11.5 meters (38 feet) long.
Giant Sauropods of Many Names

In the 1970s and 1980s, paleontologists labeled sauropod fossils from the lower Cretaceous of Texas as the genus *Pleurocoelus* (which had originally been described from Maryland). In 1997, Texas formally designated *Pleurocoelus* as the official state dinosaur. In 2004, however, study of a huge trove of sauropod bones from the Jones Ranch locality in Hood County, Texas, showed that the fossils previously called *Pleurocoelus* represented a new kind of dinosaur, which was named *Paluxysaurus jonesi*. In 2009, a resolution was passed by the Texas Legislature to amend the name of the state dinosaur to *Paluxysaurus*. More recent research, however, has suggested that some or all of these fossils may belong to the genus *Sauroposeidon* (see Figure 3.34). *Sauroposeidon* is known from incomplete skeletal remains found in Oklahoma, Texas, and Wyoming, and it is not clear exactly which group of sauropods it belongs to. This uncertainty affects estimates of its size. Extrapolations based on *Brachiosaurus* indicate that the head of *Sauroposeidon* could reach 18 meters (59 feet) in height with its neck extended, which would make it the tallest known dinosaur. With an estimated length of up to 34 meters (112 feet) and a mass of perhaps 65 tons, it would also be among the longest and heaviest. *Sauroposeidon* may, however, be more closely related to another group of sauropods, the titanosaurians, in which case these measurements are likely overestimates.

*Reconstructed skeleton of Paluxysaurus, early Cretaceous of Texas.*
were the dominant animals on land, including a mix of extinct, extirpated, and extant animals that would look out of place in North America today. The Miocene-Pliocene Ogallala Group of Kansas and Oklahoma has produced abundant remains of rodents, horses, and land tortoises, among others (Figure 3.62). (Interestingly, it was Charles Darwin who first realized that horses had originally evolved in the Americas, spread throughout the world, became extinct in the New World, and were finally reintroduced by the Spanish.) Pleistocene deposits of central Texas have yielded the bones of sloths and glyptodonts, among other forms.

**Fossils of the Basin and Range Region 5**

The portion of the Basin and Range region in far western Texas includes most of “Big Bend Country,” which is a name frequently used for westernmost Texas. The oldest rocks here date to the Permian, when three “fingers” of a shallow sea created tropical marine basins in western Texas and New Mexico. A fossilized reef formed on the Permian shoreline of the Delaware Basin, built largely by algae, sponges, brachiopods, and bryozoans (Figure 3.63). Like modern reefs, this reef complex was built from the shells of organisms, most of

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**Figure 3.62: Fossil mammals from the Miocene Ogallala Group of Kansas and Oklahoma. A) Horse, *Cormohipparion*, about 1 meter (3 feet) long. B) Rhinoceros, *Teleoceras* sp., about 4 meters (12 feet) long.**
which were made of calcium carbonate ($\text{CaCO}_3$), the same composition as limestone. This structure also provided a haven for a great variety of other animals: corals, crinoids, cephalopods, fusilinids (unusually large forams; Figure 3.64), and gastropods thrived there.

**Figure 3.63: Permian reefs of Texas.** A) Map showing the paleogeographic relationship of the reefs to the topographic lows and highs of the shallow sea that covered the area at the time. The reef occupied the rim of the Delaware Basin. B) Delicate fossil brachiopods and bryozoans, preserved as silica, from the Glass Mountains of Texas.
After the reef was buried by sediment, much of its calcium carbonate was replaced by other minerals dissolved in groundwater. The most important of these minerals was silica (SiO$_2$), which has the same composition as glass. The resulting “glass” fossils can be freed from their surrounding limestone by treating the rock with acid, which dissolves the rock, leaving the often-delicate fossils behind (see Figure 3.63B).

Big Bend National Park, on the Rio Grande River, has been the site of numerous discoveries of late Cretaceous dinosaur fossils. Over 90 dinosaur species, nearly 100 plant species, and more than two dozen fish, frogs, salamanders, turtles, crocodiles, lizards, and even early mammals have been discovered in the Cretaceous rocks there. The fossil record in Big Bend continues uninterrupted into the Cenozoic.

Following the Permian, there is a roughly 150-million-year gap in Big Bend Country’s fossil record. The next oldest fossils in the region are from the late Cretaceous and record a very different scene. Around 100 million years ago, the area was covered by the Western Interior Seaway. Fossilized mollusks, corals, fish, shark teeth, and giant marine reptiles, including mosasaurs, are found in the oldest layers. The somewhat younger Aguja Formation represents a swampy coal forest and contains a diversity of fossil plants, ammonites, turtles, 60 species of dinosaurs, and Deinosuchus—a giant crocodilian up to 10.6 meters (35 feet) long (Figure 3.65). The overlying Javelina Formation is thought to record the boundary between the end of the Cretaceous and the Paleogene. Like the Aguja, this formation preserves the remains of a coastal “coal forest,” and it preserves a variety of famous reptiles including Tyrannosaurus rex, Alamosaurus (perhaps the largest dinosaur known from North America; Figure 3.66), and the giant pterosaur Quetzalcoatlus (Figure 3.67).
Figure 3.65: Reconstructed skull of Deinosuchus.

Figure 3.66: Alamosaurus, reconstructed skeleton and life restoration.
Some layers of early Paleogene terrestrial sediments (e.g., the Tornillo Formation) found in Big Bend Country preserve a snapshot of life on land around between 65 and 50 million years ago, including fish, reptiles, and mammals (Figure 3.68).

Figure 3.68 (AT RIGHT): Early Paleogene fossil mammals found in Big Bend National Park. A) Phenacodus, about 60 centimeters (24 inches) high at the shoulder. B) Coryphodon, about 1 meter (3.3 feet) high at the shoulder. C) Protorohippus (previously known as Hyracotherium), about 35 centimeters (14 inches) high at the shoulder.

Figure 3.67: Life-sized model restoration of Quetzalcoatalus, the largest known flying animal. This pterosaur from the late Cretaceous of Texas had a wing span of 10–11 meters (33–36 feet). This model hung for 30 years in the National Museum of Natural History in Washington, DC. In 2015, it was transferred permanently to the Museum of the Earth in Ithaca, New York.
State Fossils

Arkansas
Arkansas has no state fossil.

Missouri
*Delocrinus missouriensis* (Crinoid; Pennsylvanian) (*Figure 3.17*).

Kansas
Kansas has no state fossil.

Louisiana
*Palloxylon* (Palm; **Oligocene**) (*Figure 3.40*).

Oklahoma
*Saurophaganax maximus* (Theropod; Jurassic) (*Figure 3.44*).

Texas
*Paluxysaurus jonesi* (Sauropod; Cretaceous) (*Sauropod box, p. 129*).

**Oligocene** • a geologic time interval spanning from about 34 to 23 million years ago.
Resources

General Books on the Fossil Record and Evolution


Guides to Collecting and Identifying Fossils


Books and Articles on Fossils of Specific Areas


Fossils

Resources


Websites on Fossils of Specific States

Kansas

Louisiana
The Virtual Petrified Wood Museum, Mike Viney. (Includes images from across the country, including Louisiana, e.g., http://petrifiedwoodmuseum.org/OligoceneLouisiana.htm.)

Missouri

Oklahoma

Texas
Chapter 4: Topography of the South Central US

Does your region have rolling hills? Mountainous areas? Flat land where you never have to bike up a hill? The answers to these questions can help you understand the basic topography of your region. The term **topography** is used to describe the changes in elevation over a particular area and is, generally speaking, the result of two processes: deposition and **erosion**. These processes can occur over an enormous range of timescales. For example, a flash flood can erode away tons of rock in a matter of hours, yet which rock is broken down and which remains can depend on how it was formed hundreds of millions of years ago. In the South Central, topography is intimately tied to **weathering** as well as to the type and structure of the underlying bedrock, but it is also a story of **plate tectonics** and its associated folding, **faulting**, and **uplift**.

Weathering includes both the mechanical and chemical processes that break down a rock. **Wind**, water, and ice are the media by which physical weathering and erosion occur. Streams are constantly eroding their way down through bedrock to sea level, creating valleys in the process. Given sufficient time, streams can cut deeply and develop wide flat **floodplains** on valley floors. Streams, oceans, and ice also deposit the material they erode, creating new topographical features elsewhere.

The pounding action of ocean waves on a coastline contributes to the erosion of coastal rocks and sediments, while the emptying of a river can lead to the building of a **delta**. The deposition of fine **silt** that has been ground from rock by **glaciers** can lead to the formation of wind-blown deposits called **loess**, as seen in Missouri and Kansas. And though its effect is less pronounced in the South Central than in other areas, ice can change the landscape due to frequent episodes of freezing and thawing. On a small scale, as water trapped in **fractures** within the rock freezes and thaws, the fractures continue to widen (Figure 4.1). This alone can induce significant breakdown of large rock bodies.

**Figure 4.1**: Physical weathering from a freeze-thaw cycle.
Working in conjunction with mechanical weathering, chemical weathering also helps to break down rocks. Some minerals contained in igneous and metamorphic rocks that are formed at high temperatures and pressures (far below the surface of the Earth) become unstable when they are exposed at the surface where the temperature and pressure are considerably lower, especially when placed in contact with water. Unstable minerals transition into more stable minerals, resulting in the breakup of rock. Weak acids, such as the carbonic acid found in rainwater, promote the disintegration of certain types of rocks. Limestone and marble may be chemically broken down as carbonic acid reacts with the carbonate mineral composition of these rocks, forming cavities and caverns. Other sedimentary rocks held together by carbonate cement are also particularly susceptible to chemical weathering.

The specific rock type at the surface has an important influence on the topography of a region. Certain rocks are able to resist weathering and erosion more easily than are others; resistant rocks that overlie weaker layers act as caps and form ridges. The Western Interior Seaway of the Cretaceous collected and preserved sediments that became sedimentary rocks, such as the chalk deposits of Kansas’ Great Plains region. Sedimentary rocks weather and erode differently than do crystalline (and generally harder) igneous and metamorphic rocks, such as those found in Texas’ Llano Uplift. Silica-rich igneous rocks have a crystalline nature and mineral composition that resists weathering far better than do the cemented grains of a sedimentary rock. The metamorphic equivalents of sedimentary and igneous rocks are often even more resistant due to recrystallization. There are exceptions, however, such as schist, which is much weaker than its pre-metamorphic limestone or sandstone state. Landscapes of unconsolidated sediments, like beaches, deltas, and alluvial fans, are the least resistant to erosion. The unconsolidated sediments of the Coastal Plain region along the Gulf of Mexico are not yet even considered rocks. The limited degree of cementation, compaction, and interlocking crystals found in these sediments makes it difficult for them to stand up to the effects of wind, chemical weathering, and water.

The underlying structure of rock layers also plays an important role in surface topography. Sedimentary rocks are originally deposited in flat-lying layers that rest on top of one another. The movement of tectonic plates creates stress and tension within the crust, especially at plate boundaries. Intrusions and salt domes beneath the surface may also cause deformation of the crust. All these different sources of geological stress can deform the flat sediment layers through folding, faulting, or overturning. These terms are collectively used to describe rock structure, and they can also be used to determine which forces have affected rocks in the past. The folding of horizontal rock beds followed by erosion and uplift brings layers of rock to the surface. Faulting likewise exposes layers at the surface to erosion, due to the movement and tilting of blocks of crust along the fault plane. Since tilted rocks expose underlying layers, resistant layers stick out and remain as ridges, while surrounding layers of less resistant rock erode away.
An area’s glacial history is also important to topography, and the glacial ice sheet of the most recent ice age covered the northernmost part of the South Central, leaving its mark on the landscape. The Loess Hills of northwestern Missouri formed from the blowing and deposition of fine-grained, glacier-pulverized rock fragments, and the Missouri River’s original valley was cut by the erosive action of melting glacial ice. As the ice age came to an end, sediment-laden meltwater flowed southward, sculpting river valleys and depositing sediment to form the Coastal Plain.

Just as we are able to make sense of the type of rocks in an area by knowing the geologic history of the South Central, we are able to make sense of its topography (Figure 4.2) based on rocks and structures resulting from past geologic events.

Topography is a central element of the broader concepts of geomorphology or physiography, which also include consideration of the shape (not just the height) of land forms, as well as the bedrock, soil, water, vegetation, and climate of an area, and how they interacted in the past to form the landscape we see today. A physiographic province is an area in which these features are similar,
The regions of the South Central US that we use in this book are examples of major physiographic provinces.

Topography of the Central Lowland Region 1

The Central Lowland is part of the Interior Plains of the United States, bounded by the Great Plains to the west. This region was affected by glaciation, with its northernmost areas smoothed during the glacial advances of the most recent ice age.

During the Quaternary, a 152-meter (500-foot) thick ice sheet from the extensive Kansan glacial stage (a sub-stage of the Pre-Illinoian glaciation) covered Kansas’ northeastern corner as well as Missouri’s northern third. Glacial scouring flattened the landscape, leaving behind smooth, rolling hills. The ice sheet also left behind layers of till, clay, gravel, and wind-blown silt (called loess), which contributed to the area’s rich soil. These glacial deposits are underlain by shales and limestones that formed in a shallow sea during the late Paleozoic. While most evidence of the glaciers’ advance has already been erased by erosion, glacial erratics—large boulders of red quartzite carried from as far north as South Dakota—are prevalent throughout the Central Lowland’s glaciated area. In Wabunsee County, Kansas, whole ridges are composed entirely of such boulders. These ridges may have originally been valleys that filled up with the erratics, which in turn were more resistant to erosion than the surrounding rock—meaning that erosion eventually broke down the valley walls, leaving behind a ridge of the boulders that had once filled the valley. This phenomenon is called topographic inversion.

In Kansas, south of the glacial deposits, the Osage Cuestas area (Figure 4.3) is characterized by a series of east-facing escarpments formed by gently dipping Paleozoic limestones and shales. The combination of resistant limestone and more easily eroded shale led to the formation of the cliffs we see today (Figure 4.4), whose steep faces range from 15 to 60 meters (50 to 200 feet) in height.
Escarpments form when faulting or erosion acts to create a cliff or steep slope that separates two level or gently sloping topographical surfaces. Typically, cliffs created by faulting are called “scarps,” while “escarpments” are those formed by the differential erosion of resistant layers that alternate with softer strata.
Directly west of the Osage Cuestas lie the Flint Hills (see Figure 4.3), which are also composed of erosion-resistant limestone alternating with softer shales. Unlike the gently sloping strata of the Cuestas, the rocks of the Flint Hills lie in flat layers—here, differential erosion has led to a stairstep landscape (Figure 4.5). The Flint Hills also differ from the Cuestas in that their limestone layers contain hard nodules of chert (also called flint), which further enhances the limestone’s resistance to erosion. Karst features such as sinkholes, caves, and springs are common in the Flint Hills (see box on p. 150).

The Central Lowland of Oklahoma and Texas, also known in part as the Osage Plains (Oklahoma) and the North-Central Plain (Texas), is an area of rolling terrain and prairies. These landscapes began to form during the Paleozoic, when an inland sea covered the region. Tectonic activity has played a minimal role in altering the region, so the area’s largely flat topography was preserved after the sea receded. The Arbuckle Mountains in south central Oklahoma are one exception—an anticline structure (Figure 4.6), this low mountain chain formed as the land buckled and folded during the Ouachita Orogeny, which occurred to the southeast during the Carboniferous. The Arbuckles reach heights of 90–150 meters (300–500 feet) above the surrounding terrain. Water has worked its way through fractures in the underlying limestone to create a series of more than 1000 caves and conduits that serve as a major freshwater aquifer.

Texas’ North-Central Plain is bounded to the west by the Caprock Escarpment, a cliff of erosion-resistant calcium carbonate that rises as high as 300 meters (1000 feet) above the plains.
Topography of the Interior Highlands
Region 2

The Interior Highlands is a mountainous region that spans Oklahoma, Arkansas, and Missouri. It is the only major highland region between the Appalachian and Rocky mountains. Its three major topographic divisions are the Ouachita Mountains, Arkansas Valley, and Ozark Uplift (Figure 4.7).

Figure 4.6: An anticline, an upward fold in layered rocks.

Figure 4.7: The Interior Highlands and its three major topographic divisions.
Ouachita Mountains
The Ouachita Mountains of southeastern Oklahoma and west central Arkansas formed during the Carboniferous, when the ocean between Gondwana and North America began to close. Initially, this collision created the Appalachian Mountains; later, Gondwana’s collision with the North American continent during the Pennsylvanian (Figure 4.8) generated the folding and faulting event that led to the formation of the Ouachita Mountains. This collision, which occurred in a north-south direction, created folds that extend in a roughly east-west direction, compared to the more north-south orientation of the Appalachian and Rocky Mountains (Figure 4.9).

Figure 4.8: Earth during the late Carboniferous, around 300 million years ago.

Figure 4.9: Geographic orientations of North America’s major mountain ranges.
East-west mountain ranges are quite unusual in North America, and the fact that most mountain ranges here are north-south has interesting cultural implications. As settlement and migration occurred over the continent, the mountains formed barriers, forcing regional isolation and lifestyle changes. This is different from the spread of humans through Asia and Europe, where most mountains run east-west, resulting in migration along latitudinal lines that allowed for similar climate and growing seasons throughout the path of settlement.

Today, the rounded topography of the Ouachitas speaks to their age. These mountains are distinctive in that volcanism, metamorphism, and intrusions are notably absent throughout most of the range. The lack of weathering-resistant rocks has also helped to shape these mountains. Much like the similarly aged Appalachians, the Ouachitas’ once-great peaks have been blunted by 300 million years of weathering and erosion.

Arkansas Valley
The Arkansas Valley is situated between the Ouachita Mountains and Ozark Uplift. During the Ouachita Orogeny, as the mountains were folded upward, the rock of the Arkansas Valley was warped downward. This is a structural trough, meaning it was created through deformation of the crust as opposed to being carved by a river or other process of erosion. The Arkansas Valley is up to 65 kilometers (40 miles) in width, and its area includes features common to the Ouachitas and the Ozarks. The Arkansas Valley Hills subdivision, to the northeast of the Arkansas River, contains dissected plateaus similar to but much lower in height than those of the Ozarks. To the south of the Arkansas River, the valley is filled with folded strata and ridges that mark a transition to the Ouachita mountain system.

Arkansas Valley also has its own set of characteristic physical features: isolated flat-topped mesas (Figure 4.10). One of these, Mount Magazine, is the highest point of the Interior Highlands, reaching 839 meters (2753 feet). Some 670

Figure 4.10: The flat-topped mesas of the Arkansas Valley, seen from atop Petit Jean Mountain.
meters (2200 feet) separate its summit from the valleys that surround it. Both the flat floor of the valley and the steep sides of the mesas are a result of erosion by the Arkansas River.

Ozark Uplift
The Ouachita Orogeny led to the formation of both the Ouachita Mountains and the Ozark Uplift to the north. The two areas, however, formed in very different ways, which significantly affected the region’s topography. The Ouachitas are the result of folding, and their rock units are twisted and tilted; in contrast the Ozark Uplift is the result of uplift during the orogeny, and the strata there are therefore fairly horizontal. Since their initial uplift in the late Paleozoic, stream and river valleys have extensively dissected the Ozarks, carving into the once-flat plateau. The radial areas between these streams are often so broad as to make travelers think they are traversing a flat terrain. The Boston Mountains represent the highest section of the Ozark Uplift, with the highest named peak—Turner Ward Knob—standing at 751 meters (2463 feet) in elevation, but nearby, unnamed peaks reach beyond 760 meters (2500 feet).

The Saint Francois Mountains in southeast Missouri (Figure 4.11) are the core of the Ozarks, representing an exposed portion of an igneous mountain chain from the Precambrian. They contain the tallest point of the Ozark area and the highest point within Missouri, achieving altitudes of nearly 610 meters (2000 feet) above sea level. The Saint Francois Mountains are thought to represent the only part of the American Midwest that was not submerged by the shallow seas of the Paleozoic and Mesozoic.

In Missouri, the action of groundwater contributed to the formation of more than
6000 caves and caverns within the state’s Paleozoic limestones. Missouri is famous for its caves, and many of them are popular tourist attractions. Meramec Caverns, Missouri’s most visited cave, is a limestone cavern system extending 7.4 kilometers (4.6 miles) beneath the Ozarks (Figure 4.12). Other famous locations include the Mark Twain Cave, which is the oldest public cave in the state; it played a pivotal role in Twain’s *The Adventures of Tom Sawyer*. These types of caverns—as well as sinkholes—are common in areas with limestone bedrock, which is easily dissolved by the acids in groundwater and rain. Such dissolution over long periods of time eventually leads to the formation of karst topography. This landscape of fractured rock can include features like towers, terraces, and complex drainage systems, which appear both above and beneath the surface of the bedrock.

**Figure 4.12: Limestone structures within Meramec Caverns.**

**Topography of the Coastal Plain Region 3**

In terms of its geology, the Coastal Plain is the least complicated region of the United States. Following the breakup of Pangaea, as the North American plate began drifting away from the Mid-Atlantic Ridge, mountain building along the eastern margin of North America ceased. A long period of erosion continued from the Cretaceous through the Quaternary, as sediment that eroded from the...
Karst topography refers to a region where the landscape’s features are largely the result of chemical weathering by water, resulting in caves, sinkholes, disappearing and reappearing streams, cliffs, and steep-sided hills called towers. These structures form when water picks up carbon dioxide from the atmosphere and ground to form carbonic acid. Even this fairly weak and dilute acid dissolves carbonate rocks (such as limestone) relatively easily, resulting in dramatic features while other rock is comparatively unaffected. Karst is found in every state except Hawaii, and as an aquifer it is the source of a significant amount of our drinking water. While common, karst is not always easily identifiable since it is often not expressed at the surface or its topography has been affected by other factors. Karst topography is a relatively mature type of landscape, taking many tens of thousands of years to develop, and it can indicate that a region has been free of other forms of erosion, or deposition, for an extended period. Karst topography in the South Central is present wherever water has eroded the limestone bedrock, including parts of the Flint Hills, Arbuckle Mountains, southern Missouri, and the Edwards Plateau.
mountains was gradually deposited along North America’s passive continental margin to build the Atlantic and Gulf Coastal plains. Sediment was transported from the mountains by rivers and streams to the coast, building up successive layers of sediment that fanned out onto the continental shelf (Figure 4.13).

When sea level rose, deposition of marine sediment also contributed to the Coastal Plain. The late Cretaceous was marked by very high sea levels worldwide, in part due to the significant increase in plate tectonic activity that followed increased volcanism at the mid-ocean ridges after the breakup of Pangaea. As ocean basins change in shape, sea level goes up and down. Mid-

\[ \text{passive margin} \cdot \text{a tectonically quiet continental edge where crustal collision or rifting is not occurring.} \]
ocean ridges are one of the major topographic features displacing water, and they increase sea level as they grow in height or length. The **Mississippi Embayment** also formed during the Cretaceous (Figure 4.14) when the ocean flooded the area between the Interior Highlands and the Appalachians. When sea level later fell due to glaciation, erosion removed some material from the Coastal Plain.

Throughout the **Cenozoic** era, the Coastal Plain extended 400 kilometers (250 miles) into the Gulf of Mexico, with sediment deposits 15,000 to 18,000 meters (50,000 to 60,000 feet) thick. The depositional settings of the South Central’s Coastal Plain are similar to those seen today, including river, floodplain, shoreline, delta, and shallow marine environments. The Mississippi River Delta is an extremely important coastal area in North America, and it is the United States’ largest drainage basin, creating a very active depositional environment. The deposits become increasingly younger toward the gulf, due to a depositional process called **progradation**. During this process, the river forms a deposit at its margin, and then overflows it and deposits material on the far side in a continual outward movement (Figure 4.15).
Figure 4.14: The Mississippi Embayment (with shoreline changes over the past 140 million years). (See TFG website for full-color version.)

Figure 4.15: Evolution of the Mississippi River Delta over the past 6000 years.
The entire state of Louisiana is found within the Coastal Plain, with Cenozoic deposits forming as the sea advanced and retreated on several occasions. The topography of Louisiana is limited, with the highest point—Driskill Mountain—at 163 meters (535 feet) above sea level, and the lowest point—New Orleans—at an average elevation of 2 meters (6.5 feet).

In Texas, the Coastal Plain extends west to the Balcones Fault and Escarpment, commonly regarded as the division between upland and lowland Texas. Similarly to the Osage Cuestas, the Inner Coastal Plain of Texas also contains a series of cuesta escarpments.

The Coastal Plain also includes many salt dome formations, which are prevalent in both Texas and Louisiana. These salt domes began as evaporite deposits that formed during the Jurassic. After later sedimentation covered the salt beds, the salt, which is lower in density and more flexible than the overlying layers, began to drift upward. This movement creates dome-shaped structures that warp the surface sediment, creating both positive and negative topography (Figure 4.16). The Five Islands in Louisiana are an excellent example of positive dome-shaped topography. They are formed from five salt domes, each around three kilometers (two miles) in diameter, which were uplifted to form tall dome-shaped hills in Louisiana’s Gulf Coast marshlands.

The shape and structure of salt domes make them excellent traps for pockets of oil and gas, and such pockets are especially prevalent in the Texas Gulf Coast. As a result, salt domes are critically important in the

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**evaporite** • a sedimentary rock created by the precipitation of minerals directly from seawater, including gypsum, carbonate, and halite.

**Jurassic** • the geologic time period lasting from 201 to 145 million years ago.

**salt** • a mineral composed primarily of sodium chloride (NaCl).

**density** • a physical property of minerals, describing the mineral’s mass per volume.

**oil** • See petroleum: a naturally occurring, flammable liquid found in geologic formations beneath the Earth’s surface and consisting primarily of hydrocarbons.

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*Figure 4.16: The formation of a salt dome.*
process of prospecting for fossil fuels in the Gulf. Emptied salt domes have also been used as storage caverns for liquid gas and chemical waste.

**Topography of the Great Plains Region 4**

The Great Plains region is a product of two earlier geologic events: the presence of the Western Interior Seaway during the Cretaceous, and the onset of the Laramide Orogeny during the late Cretaceous and early Paleogene. The Western Interior Seaway retreated thanks in part to uplift that occurred during the formation of the Rocky Mountains; the flat floor of this former sea, left exposed after it receded, provided the basis for the topography of the Interior Plains. These marine rocks are only found at depth beneath today's Great Plains, buried by an overlying sequence of rocks deposited by streams, wind, and glaciers during the Cenozoic era. The Rocky Mountains continued to rise, and volcanic activity increased around 50 million years ago, providing large quantities of sediment that were transported and deposited across the Interior Plains.

Extending southward from western Kansas into Texas, the Great Plains represent one of the largest regions of the South Central, second only to the Coastal Plain. Across this expanse, the region's topography is rather diverse, and can be divided into five distinct areas: the Central Texas Uplift, High Plains, Pecos Valley, Edwards Plateau, and the Plains Border (Figure 4.17).

**Central Texas Uplift**

Figure 4.17: The Great Plains and its five major topographic divisions. (See TFG website for full-color version.)
Uplift of this mountainous portion of the Great Plains began as the continental interior was raised during the Western Interior Seaway’s retreat at the close of the Cretaceous period, some 65 million years ago. The uplift is a dome of Precambrian rock—a body of granite surrounded by a ring of metamorphic gneiss and schist that formed between 1.3 and 1 billion years ago.

Since its formation, weathering and erosion from streams have led to the landforms visible in the uplift today. Enchanted Rock is perhaps the area’s most spectacular feature. This granitic dome extends 130 meters (425 feet) above the surrounding terrain, and it is visible for miles from the surrounding basin.

High Plains
The High Plains represents the largest area of the South Central’s Great Plains, and it is composed of sediments that originated in the Rocky Mountains to the west. Water and wind flowing from the high mountains carried loose sediment—gravel, sand, silt, and mud—eastward. This mass of eroded material eventually filled stream valleys and covered hills, creating a massive, gently sloping plain that was in place by five million years ago—meaning these sediments are quite young on the scale of geologic time. Because the sediment was carried in an eastward direction, the coarsest sediments are found farther to the west, while finer strata are observed in the east. Today, the area stands as a little-modified, five-million-year-old depositional surface. The Ogallala Formation, a unit of unconsolidated sands, gravels, and clays, caps the High Plains and is a major aquifer for much of the region (Figure 4.18). As one of the world’s largest aquifers, it supplies drinking water to over two million people.

In Texas, the High Plains forms a broad mesa, bounded by steep escarpments that separate it from the lowlands to the east and west. Rivers that run over the edges of these escarpments have eroded the landscape, leading to the formation of dramatic gorges such as the Palo Duro Canyon (Figure 4.19). The second largest canyon in the United States, its walls expose strata from the Permian red beds of the Quartermaster Formation up to the Cenozoic caprock of the Ogallala Formation.

The canyon is roughly 110 kilometers (70 miles) long, has an average width of 10 kilometers (6 miles), and an average depth of 250 meters (820 feet).
Figure 4.18: Extent of the Ogallala aquifer and its saturated thickness as measured in 1997. (See TFG website for full-color version.)

Pecos River Valley
Exposed across just a small area within the South Central, the Pecos River Valley is a broad valley formed by erosion, driven by the Pecos River. The
development of the north-south Pecos diverted the original east-west streams that deposited the Ogallala Formation; therefore, the Great Plains no longer receives sediment from the western highlands to replenish the **topsoil**.
The Pecos Valley follows the river from elevations of more than 4000 meters (13,000 feet) in the Sangre de Cristo Mountains of New Mexico, southward through grassland and desert to the Edwards Plateau before finally emptying into the Rio Grande through a vast gorge. To the east, the Ogallala Formation of the High Plains forms a rim rock at the top of the Mescalero Escarpment; to the West lies Texas’ Basin and Range region.

**Edwards Plateau**

As the Pecos River continues south of the Pecos Valley, it enters the Edwards Plateau. This area consists primarily of limestone that was deposited in the inland sea during the Cretaceous. Because it weathers easily in the presence of water, the plateau’s limestone forms a very diverse landscape today. The Pecos River cuts 120 to 150 meters (400 to 500 feet) below the level of the plateau’s surface, while the Devils, West Nueces, and Nueces rivers cut similarly through the plateau to the east. The plateau’s southeastern edge is formed by the Balcones Escarpment.

In the northeast, karst topography is prominent; sinkholes dot the plateau’s surface, often connecting to caverns that formed below due to the action of groundwater. One example is Devil’s Sinkhole (*Figure 4.20*), an enormous vertical shaft (15 meters [50 feet] wide at the surface) that drops 45 meters (140 feet) into a huge, 95-meter-wide (320-foot-wide) limestone cavern.

*See Chapter 10: Earth Hazards to learn how karst can lead to the formation of sinkholes and other dangers.*

*Figure 4.20: Devil’s Sinkhole, in Edwards County, Texas.*
Topography

Regions 4–5

Plains Border
Like the Edwards Plateau, the Plains Border is an area shaped by water. Here, a large number of east-west river valleys cut through and shape the landscape. In the north-central section of Kansas, known as the Smoky Hills, rivers have cut several hundred meters (yards) through the High Plains strata to expose Cretaceous-aged marine deposits of sandstone, limestone, and chalk. As a result of the dissolution of salt and gypsum beneath the surface, sinks and collapses are also found within this area.

Topography of the Basin and Range Region 5
The Basin and Range possesses perhaps the most unique topography of the South Central, if not of the entire United States. It covers a large area of the US and is extensive in the Rocky Mountain, Southwestern, and Western states, while only just reaching the South Central in westernmost Texas. Basin and Range topography is characterized by alternating valleys and mountainous areas, oriented in a north-south, linear direction.

The formation of this topography is directly related to tectonic forces that led to crustal extension—the pulling of the crust in opposite directions. After the Laramide Orogeny ended in the Paleogene, tectonic processes stretched and broke the crust, and the upward movement of magma weakened the lithosphere from underneath. Around 20 million years ago, the crust along the Basin and Range stretched, thinned, and faulted into some 400 mountain blocks. The pressure of the mantle below uplifted some blocks, creating elongated peaks and leaving the lower blocks below to form down-dropped valleys. The boundaries between the mountains and valleys are very sharp, both because of the straight faults between them and because many of those faults are still active.

These peaks and valleys are also called horst and graben landscapes (Figure 4.21). Such landscapes frequently appear in areas where crustal extension

Figure 4.21: A horst and graben landscape occurs when the crust stretches, creating blocks of lithosphere that are uplifted at angled fault lines.
occurs, and the Basin and Range is often cited as a classic example thereof. In the Basin and Range, the crust has been stretched by up to 100% of its original width. As a result of this extension, the average crustal thickness of the Basin and Range region is 30–35 kilometers (19–22 miles), compared to a worldwide average of around 40 kilometers (25 miles).

Broadly, the topography of west Texas follows the pattern of the greater Basin and Range, with numerous small ranges trending southeast from El Paso and Guadalupe National Park, parallel to the Rio Grande. The graben areas between the mountainous horsts are relatively flat and arid. Alluvial fans spread outward from the feet of the mountains where streams have deposited sediment on a gentle slope, creating a brief transition zone between the distinct topographies. Within the graben (regionally referred to as “bolsons”), mesas are often found in which a tough limestone caprock has protected lower layers from erosion. The shape of these mesas can provide clues about the amount of local precipitation: greater rainfall increases chemical weathering, resulting in more rounded hills. Generally, as one travels westward the margins of these mesas become sharper, since average rainfall decreases and mechanical weathering becomes increasingly dominant. In the South Central, the Basin and Range merges into the Rio Grande Rift, a continental rift that stretches from Chihuahua, Mexico to central Colorado. As it is difficult to identify where the two areas join together, it is possible that many of the south-central Basin and Range formations are more properly part of the Rio Grande Rift.

There are a few exceptions to the Basin and Range pattern in west Texas. The Davis Mountains and the smaller ranges between Marfa and Presidio were formed during the early Neogene, when welling magma actually reached the surface, and they are therefore composed mostly of volcanics. This distinct, though related, origin is the reason that these ranges deviate from the typical northwest-southeast orientation of the horst and graben ridges located in this area. The Davis Mountains (Figure 4.22) are part of the Trans-Pecos Volcanic

Figure 4.22: The northern Davis Mountains.
Topography

Region 5

caldera • a collapsed, cauldron-like volcanic crater formed by the collapse of land following a volcanic eruption.
tuff • a pyroclastic rock made of consolidated volcanic ash.

Big Bend National Park, near the southern edge of western Texas, has perhaps the most complex topography in the area. It was shaped by a variety of major geologic events: the upwelling of magma and formation of volcanic ranges during the middle Cenozoic, the \textit{compressional forces} of the Laramide Orogeny, and the genesis of horst and graben landscapes. Since the conclusion of these events, erosion continues to slowly shape the landscape (Figure 4.23).

Field, which consists of at least 12 \textit{calderas} and associated ash flow \textit{tuffs}, and also contains seven named peaks greater than 2400 meters (8000 feet) tall. These giant volcanoes erupted between 40 and 20 million years ago, making them part of a wave of supervolcano eruptions that occurred throughout the southwest during the \textit{Oligocene}. These eruptions also led to the formation of the Superstition Mountains in Arizona, the Mogollon Mountains in New Mexico, and the San Juan Mountains in Colorado.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{El Solitario in Big Bend Ranch State Park, the eroded remains of an uplifted granitic igneous intrusion.}
\end{figure}
**Highest and Lowest Elevations (by State)**

**Arkansas**
The highest point in Arkansas is Signal Hill, which is 839 meters (2753 feet) high. It is one of two peaks on Mount Magazine, a flat-topped plateau located in the Ozark National Forest. Arkansas’ lowest point, at 17 meters (55 feet) above sea level, is the portion of the Ouachita River that enters Louisiana.

**Kansas**
Kansas, while notoriously flat, slopes downward to the east. Mount Sunflower, half a mile from the state’s western border, is nearly indistinguishable from the surrounding flatland at 1231 meters (4309 feet) above sea level. The “summit” of this tongue-in-cheek topographic high point includes a sunflower sculpture made from railroad spikes and a plaque that reads “nothing happened here in 1897.” The Verdigris River at Kansas’ border with Oklahoma is the state’s lowest point, at 207 meters (679 feet) above sea level.
Topography

Elevations

**Louisiana**
At an elevation of 163 meters (535 feet), Driskill Mountain might more properly be called a hill. This landform, located in north central Louisiana, was shaped by the erosion of unconsolidated Paleogene sediments. The state’s lowest point lies within the city of New Orleans, at 2 meters (6.5 feet) below sea level—a series of levees protect the city from being submerged.

**Missouri**
Taum Sauk Mountain is Missouri’s highest point. Although it stands just 540 meters (1772 feet) above sea level, this mountain is part of the ancient St. Francois Mountains and is several times older than the Appalachians. Taum Sauk and the surrounding mountains are among the only landforms in the US to have never been submerged in prehistoric seas. Missouri’s lowest point, at 70 meters (230 feet), is located where the Saint Francis River borders Arkansas.

**Oklahoma**
Oklahoma’s highest point is Black Mesa, at 1516 meters (4975 feet) in elevation. It is located in the westernmost part of the Oklahoma panhandle, less than a mile east of the New Mexico border. Over 18 tons of dinosaur bones have been recovered from the Black Mesa. The lowest point in Oklahoma lies at 88 meters (289 feet) above sea level and is located on the Little River at the Arkansas border.

**Texas**
Guadalupe Peak, an ancient limestone reef that rises abruptly from the Chihuahuan Desert, is the highest point in Texas at 2667 meters (8751 feet) above sea level. It is located within Guadalupe Mountains National Park, just 16 kilometers (10 miles) south of the New Mexico border. The lowest area in Texas is the shore of the Gulf of Mexico, which lies at sea level.
Resources

Books


Websites

*Color Landform Atlas of the US.* (Low resolution shaded relief maps of each state.)

*OpenLandform Catalog*, Education Resources, OpenTopography. (High resolution topographic images that may be useful in teaching.)

*Teaching Geomorphology in the 21st Century*, On the Cutting Edge, Strong Undergraduate Geoscience Teaching, SERC. (A set of resources for college level, some of which may be adaptable to secondary education.)

*Teaching with Google Earth*, On the Cutting Edge, Starting Point: Teaching Entry Level Geoscience, SERC.

Websites on Specific Areas

http://www.encyclopediaofarkansas.net/encyclopedia/entry-detail.aspx?entryID=441#.


*Geomorphology of the Flint Hills, East-Central Kansas*, J. S. Aber, Emporia State University.


http://www.kgs.ku.edu/Extension/Physio.html.
Chapter 5:
Mineral Resources of the South Central US

What is a mineral?
A mineral is a naturally occurring solid with a definite chemical composition and crystalline structure. Minerals provide the foundation of our everyday world. Not only do they make up the rocks we see around us in the South Central, they are also used in nearly every aspect of our lives. The minerals found in the rocks of the South Central are used in industry, construction, machinery, technology, food, makeup, jewelry, and even the paper on which these words are printed.

Elements: The Building Blocks of Minerals

Elements are the building blocks of minerals. The mineral quartz, for example, is made of the elements silicon and oxygen, and, in turn, is also a major component of many rocks. Most minerals present in nature are not composed of a single element, though there are exceptions such as gold. Elements such as copper (Cu), lead (Pb), zinc (Zn), and even silver (Ag), gold (Au), and diamond (C) are not rare, but they are usually widely dispersed in rocks and occur at very low average concentrations. Eight elements make up (by weight) 99% of the Earth’s crust, with oxygen being the most abundant (46.4%). The remaining elements in the Earth’s crust occur in very small amounts, some in concentrations of only a fraction of one percent (Figure 5.1). Since silicon (Si) and oxygen (O) are the most abundant elements in the crust by mass, it makes sense for silicates (e.g., feldspar, quartz, and garnet) to be some of the most common minerals in the Earth’s crust and to therefore be found throughout the South Central.

Minerals provide the building blocks for rocks. For example, granite, an igneous rock, is typically made up of crystals of the minerals feldspar, quartz, mica, and amphibole. In contrast, sandstone may be made of cemented grains of feldspar, quartz, and mica. The minerals and the bonds between the crystals define a rock’s color and resistance to weathering.
Several thousand minerals have been discovered and classified according to their chemical composition. Most of them are silicates (representing approximately a thousand different minerals, of which quartz and feldspar are two of the most common and familiar), which are made of silicon and oxygen combined with other elements (with the exception of quartz, SiO$_2$). Carbonate rocks are made of carbon and oxygen combined with a metallic element; calcium carbonate (CaCO$_3$) is the most common example, and most of it today originates as skeletal material precipitated by organisms. Other mineral categories include native elements (such as gold), oxides and sulfur-bearing minerals, and salts.

Metallic minerals are vital to the machinery and technology of modern civilization. However, many metals occur in the crust in amounts that can only be measured in parts per million (ppm) or parts per billion (ppb). A mineral is called an ore when one or more of its elements can be profitably removed, and it is almost always necessary to process ore minerals in order to isolate the useful element. For example, chalcopyrite (CuFeS$_2$), which contains copper, iron, and sulfur, is referred to as a copper ore when the copper can be profitably extracted from the iron and sulfur. Ores are not uniformly distributed in the crust of the Earth, but instead occur in localized areas where they are concentrated in amounts sufficient for being economically extracted by mining.

Non-metallic minerals do not have the flash of a metal, though they may have the brilliance of a diamond or the silky appearance of gypsum (CaSO$_4$·2H$_2$O). Generally much lighter in color than metals, non-metallic minerals can transmit light, at least along their edges or through small fragments.

**Mineral Identification**
Although defined by their chemical composition and crystal structure, minerals are identified based on their physical properties. A variety of properties must usually be determined when identifying a mineral, with each such property eliminating possible alternatives.
Hardness is a very useful property for identification, as a given mineral can only exhibit a narrow range of hardnesses, and since it is easily testable, this property can be used to quickly and simply minimize the number of possibilities. Hardness is important because it helps us understand why some rocks are more or less resistant to weathering and erosion. Quartz, with a rating of 7 on the Mohs scale, is a relatively hard mineral, but calcite (CaCO$_3$), rating 3 on the Mohs scale, is significantly softer. Therefore, it should be no surprise that quartz sandstone is much more resistant to erosion and weathering than limestone, which is primarily made of the mineral calcite. Quartz is a very common mineral in the Earth’s crust, and it is quite resistant due to its hardness and relative insolubility. Thus, quartz grains are the dominant mineral type in nearly all types of sand.

Color is helpful in identifying some minerals such as sulfur, but it is uninformative or even misleading in others such as garnet. Luster describes how light is reflected from a mineral's surface and it can range from adamantine, seen in diamonds, to dull or earthy (effectively no luster), such as in kaolinite. Crystal form, if visible, can also be diagnostic. For example, fluorite and calcite may appear superficially similar, but fluorite forms cubic crystals while calcite forms trigonal-rhombohedral crystals. Relatedly, crystals may have planes of weakness that cause them to break in characteristic ways, called cleavage. Or they may not, but instead display fracture when broken. Mica and graphite have very strong cleavage, allowing them to easily be broken into thin sheets, while quartz and glass (the latter not being a mineral) have no cleavage.
instead displaying a distinctive curved fracture form known as conchoidal. The density of a mineral may also aid in identifying it (e.g., metals tend to be very dense). Finding the exact density is straightforward, but it does require measuring the volume of the sample. Placing an unknown mineral in water (or other liquid) to find its volume by displacement can be a risky undertaking since several minerals react violently with water, and many more break down with exposure. A mineral’s streak is obtained by dragging it across a porcelain plate, effectively powdering it. The color of the powder eliminates conflating variables of external weathering, crystal habit, impurities, etc. Some minerals are magnetic (affected by magnetic fields), while a few are natural magnets (capable of producing a magnetic field).

Most minerals can be identified by process of elimination after examining a few of these properties and consulting a mineral identification guide. Mineral testing kits often include several common objects used to test hardness: a porcelain streak plate, a magnet, and a magnifying glass. Some minerals have rare properties, which may be more difficult to test. For example, there are minerals that exhibit luminescence of all types, giving off light due to a particular stimulus. Some minerals are radioactive, usually due to the inclusion of significant amounts of uranium, thorium, or potassium in their structure. Carbonate minerals will effervesce when exposed to hydrochloric acid. Double refraction describes the result of light passing through a material that splits it into two polarized sets of rays, doubling images viewed through that material. For example, a single line on a sheet of paper will appear as two parallel lines when viewed through a clear calcite crystal.

There are many more interesting and distinguishing properties that minerals may possess, and there are many more elaborate and precise means for identifying them. The branch of geology that studies the chemical and physical properties and formation of minerals is called mineralogy.

What Are Minerals Used For?
Mineral resources fall into many different categories, including industrial minerals, construction materials, gemstones, and metallic and non-metallic ores. Some minerals and rocks are abundant and are used in the construction industry or in the manufacturing of many of the products we commonly find in stores. Construction materials include dimension stone (e.g., sandstone, limestone, and granite), which is used for the exterior or interior of structures.

Minerals used in manufacturing include kaolinite for ceramics, gypsum for wallboard, fluorite for the fluoride in toothpaste, and halite for common table and rock salt. We also seek out specific rock types and sediment to use in the construction of buildings, highways, and bridges. Many of the statues in museums are commonly made of marble, jade, or soapstone. Granite, travertine, and other decorative stones are increasingly used to beautify our home interiors and to make art, in addition to being used in public buildings.
Some minerals are considered to be precious or semi-precious and are used in jewelry, including diamond and some crystalline forms of quartz.

Metallic minerals have many applications and are used to manufacture many of the items we see and use every day. For example, iron comes from hematite and magnetite, and from it we make steel. Lead, from the mineral galena, is used in the manufacture of batteries and in the solder found in electronic devices. Titanium, from the mineral ilmenite, is used in airplanes, spacecraft, and even white nail polish. Aluminum comes from bauxite and is known for being both lightweight and strong—many of the parts that make up today’s automobiles are made of this metal. Copper comes from a variety of copper-bearing minerals, including chalcopyrite, and is used to make electrical wire, tubing, and pipe.
Mineral Formation

Economically recoverable mineral deposits are formed by geologic processes that can selectively concentrate desirable elements in a relatively small area. These processes may be physical or chemical, and they fall into four categories:

Magmatic processes separate minor elements of magma from the major elements and concentrate them in a small volume of rock. This may involve the early crystallization of ore minerals from the magma while most other components remain molten, or late crystallization after most other components have crystallized. Magmatic processes responsible for the formation of mineral deposits are usually associated with igneous intrusions (formed during mountain building events, rifting, and volcanic activity), which can range in composition from granite (felsic) to gabbro (mafic). Metamorphism may also cause recrystallization of minerals and concentration of rare elements. Under conditions of extreme high-temperature metamorphism, minerals with the lowest melting temperatures in the crust may melt to form small quantities of pegmatite magmas.

Hydrothermal processes involve hydrothermal solutions that dissolve minor elements dispersed through large volumes of rock, transport them to a new location, and precipitate them in a small area at a much higher concentration. Hydrothermal solutions are commonly salty, acidic, and range in temperature from over 600°C (~1100°F) to less than 60°C (140°F). Some of these fluids may travel very long distances through permeable sedimentary rock. Eventually, the hydrothermal fluids precipitate their highly dissolved load of elements, creating concentrated deposits.

Sedimentary processes gather elements dispersed through large volumes of water and precipitate them in a sedimentary environment, such as in sedimentary layers on the ocean floor or on lakebeds. Sedimentary mineral deposits form by direct precipitation from the water.

Weathering and erosion break down large volumes of rock by physical and chemical means and gather previously dispersed elements or minerals into highly concentrated deposits. Residual weathering deposits are mineral deposits formed through the concentration of a weather-resistant mineral, as a result of surrounding minerals being eroded and dissolved. In contrast, mineral deposits formed by the concentration of minerals in moving waters are called placer deposits.

A mineral is not necessarily restricted to one method of concentration or environment of formation. For example, economically important deposits of gypsum may form as a precipitate from evaporating water. However, gypsum formation may also be associated with volcanic regions where limestone and sulfur gases from the volcano have interacted, or from other areas as a product of the chemical weathering of pyrite.
What are hydrothermal solutions?

Hydrothermal solutions move away from their source of heating through cracks, faults, and solution channels into the adjacent cooler rocks. While the water moves quickly through fractures and openings in the rock (where it experiences changes in pressure or composition and dilution with groundwater), it can cool rapidly. This rapid cooling over short distances allows concentrations of minerals to be deposited. When a hydrothermal solution cools sufficiently, the dissolved salts form a precipitate, leaving behind minerals in a vein or strata-bound deposit.
Minerals in the South Central
Throughout the South Central, the deposition of sediment has left behind an abundance of deposits useful for construction materials. River systems and glaciers deposited sand and gravel, while ancient seas that spread across the area also left behind thick deposits of halite and gypsum. The advance of inland seas and the subsequent deposition of marine detritus also made possible the widespread existence of energy resources (fossil fuels) throughout the area, most notably oil, natural gas, and coal. Some of the natural gas produced in the South Central also contains helium in sufficient concentrations to be profitably extracted—it originates from the decay of radioactive elements in the source rocks of accumulated natural gas.

Periods of igneous activity commonly produce metals. However, some sources of metals in sedimentary rocks resulted not from igneous activity, but rather from chemical reactions that took place within rocks either as they formed or at some time after their formation—the hydrothermal precipitation of minerals is one such example. Igneous activity also contributes to the occurrence of non-metallic minerals and gemstones. For example, diamonds form near the Earth’s mantle, but are often carried toward the surface by explosive volcanic eruptions.

Mineral Resources of the Central Lowland
Region 1

Mineral resources in the Central Lowland have accumulated primarily due to the deposition of sediment (Figure 5.2). The region’s surface rocks are sedimentary strata from the Pennsylvanian and Permian, covered by glacial, river, and wind-blown deposits from the Quaternary and Holocene. Sources of non-organic sediment (sand and finer-grained materials) are derived from erosion, while organic carbonate sediment accumulated in shallow seas to form limestone. Ancient forests produced layers of organic debris that eventually formed coal. All of these depositional patterns have also been influenced by cyclical fluctuations in sea level, producing cyclothsms: repeated sequences of terrestrial shale, sandstone, and coal layered with marine shale and limestone (Figure 5.3). Episodes of Quaternary glaciation and erosion in northeast Kansas and northern Missouri left behind discontinuous patches of glacial deposits consisting of till interspersed with sand and gravel outwash. As a result of all these processes, sand, gravel, stone, limestone, and clay occur abundantly throughout the Central Lowland, and all are quarried for use in construction. Industrial sand is mined at several locations in Oklahoma and Texas, primarily for use in glassmaking.
Mining is a profit-focused undertaking. The profitability of mining minerals or rocks depends on a number of factors, including the concentrations of recoverable elements or material contained in the deposit; the anticipated amount of the deposit that can be mined; its accessibility using current mining methods and technologies; its marketability; and lastly the cost of returning the site to its original state once the extraction phase of mining has ended (reclamation). All these factors determine the choice of mining method. Types of mining include underground (tunnel or shaft), surface (open pit or quarry), hydraulic operations (placer), solution using hot water, and seawater evaporation ponds. Once a mineral resource has been removed from the ground, the next step is to process it in order to recover its useful elements or to transform it so that it can be used in manufacturing or other industrial processes.

Modern mining is accomplished in three phases: exploration, extraction, and reclamation. Exploration is performed to determine the extent of the mineral resource and usually involves extensive use of drilling and geophysical techniques to determine the shape, size, and quality of the resource. Extraction involves removing the mineral resource from the ground. Reclamation is done when mining ceases and is designed to restore the land to a condition where it can be used for other purposes. This last phase usually involves removing sources of contamination, which can be considerable depending on the scope of the mining activity. A good example of the need for an extensive and expensive cleanup of past activity is in the Tri-State mining district in southeast Kansas, northeast Oklahoma, and southwest Missouri, where lead and zinc deposits were actively mined for many decades in the late 19th and early 20th centuries.
5 Mineral Resources

Region 1

Pangaea • supercontinent, meaning “all Earth,” which formed over 250 million years ago and lasted for almost 100 million years.

Carboniferous • a geologic time period that extends from 359 to 299 million years ago.

Climate • a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).

Figure 5.2: Principal mineral resources of the Central Lowland.

Figure 5.3: An example of a cyclothem.
During and after the formation of Pangaea, the humid and tropical Carboniferous environment transitioned to the hot and arid climate of the Permian. These arid conditions led to the formation of hypersaline, shallow seas with restricted circulation, and layers of evaporite minerals were deposited as these seas evaporated. Today, Permian evaporite beds in Kansas, Oklahoma, and Texas are mined for halite and gypsum.

Halite is mined in two ways. When deposited in thick beds, salt can be excavated by mechanically carving and blasting it out. This method, called “room and pillar” mining, usually requires that pillars of salt be left at regular intervals to prevent the mine from collapsing (Figure 5.4). Another method, called solution mining, involves drilling a well into a layer of salt. In some cases, the salt exists as part of a brine that can then be pumped to the surface and the water then removed, leaving the salt behind. In others, fresh water is pumped down to dissolve the salt, and the solution is brought back to the surface where the salt is removed (Figure 5.5).

Selenite, a variety of gypsum, is commonly found where Permian rocks appear at the surface, most notably in the Salt Plains of Oklahoma. In many locations, crystals of selenite are impregnated with sand and clay and are often referred to as “sand crystals.” In Salt Plains National Wildlife Refuge, groundwater seeping through salt- and gypsum-saturated sand becomes concentrated with these minerals, spurring the formation of selenite crystals with a distinctive hourglass-shaped sand inclusion (Figure 5.6). The Salt Plains are the only place in the world where this phenomenon occurs. Barite roses can also be found at the surface in central Oklahoma (Figure 5.7). Due to their attractive form, sand crystals and barite roses are often sought after as collectibles.
Figure 5.5: An example of solution mining that involves the pumping of fresh water through a borehole drilled into a subterranean salt deposit.

Figure 5.6: A selenite crystal from Salt Plains National Wildlife Refuge, Oklahoma with distinctive hourglass-shaped sand inclusion. Individual crystals up to 18 centimeters (7 inches) long have been found at this locality.
Igneous activity has also contributed to the formation of minerals found in the Central Lowland. During the late Cretaceous, eastern Kansas experienced episodes of volcanism. Some magma solidified in the necks of erupting volcanoes, eventually becoming kimberlite. These deposits, exposed by erosion at several locations in northeastern Kansas, yield small garnets. In southeastern Kansas, igneous intrusions led to the formation of lamproite sills and pipes. The lamproite contains shiny flakes of mica (Figure 5.8), which, when first observed in the 1870s, led to reports of silver and the formation of a mining town called Silver City. Although the lamproite does not actually contain silver, it is still mined today for its mica (used in polymers, coatings, and construction). In addition, the lamproite itself is ground and used as a mineral supplement in cattle feed.

Ancient sedimentation patterns and tectonic activity have favored the placement of widespread fossil fuel resources in the Central Lowland. Processing plants in Texas and Kansas recover commercial quantities of helium gas, an important byproduct of natural gas extraction. Non-commercial deposits of asphalt, formed by the breakdown of petroleum in the underlying rock, are also common in eastern Oklahoma.

The Central Lowland does not contain economically viable metal deposits. However, copper-bearing minerals can be found in the Permian rocks of southern Kansas, parts of Oklahoma, and north-central Texas.
Mineral Resources of the Interior Highlands
Region 2

The Interior Highlands region consists of two areas of uplifted rock—the Ozark Uplift and the Ouachita Mountains—which have existed since the formation of Pangaea. Thick sequences of Paleozoic limestone and dolomite, with lesser thicknesses of sandstone and shale, underlie the area occupied by the Ozarks, except in the St. Francois Mountains (where erosion has stripped away the sedimentary cover and exposed Precambrian granite). Nodules of chert are present and often abundant in most of the limestone and dolomite. The weathering and erosion of these rocks has produced the chert gravels that mantle much of the Ozark Uplift.

See Chapter 4: Topography to learn more about the Ozark Uplift and Ouachita Mountains.
The Interior Highlands is a source of several industrial minerals, primarily from sedimentary rocks. Episodes of marine transgression have left behind considerable resources for construction materials, including clay, limestone, sandstone, and granite (Figure 5.9). Deposits of tripoli (porous, weathered limestone mixed with silica) and novaculite (a form of chert) are mined in Missouri, Arkansas, and Oklahoma for use as abrasives. Tripoli is also used as filler in plastics, rubber, paint, and even toothpaste! Novaculite has been mined since prehistoric times; Native Americans used it to make arrow and spear points (Figure 5.10), and it has been quarried for use as whetstones since the 1800s.

Metals have also generated a historically important mining industry in the Interior Highlands. Lead, zinc, copper, and silver are all found in significant quantities.

See Chapter 2: Rocks to learn more about novaculite.

Figure 5.9: Principal mineral resources of the Interior Highlands.

Figure 5.10: A novaculite arrowhead found in the Ozark Mountains.
quantities, and are thought to have precipitated from hydrothermal solutions during the Carboniferous and Permian. Lead mining first began in southeastern Missouri around 1720, and it has continued into the present. There are three mining districts in the Missouri portion of the Ozark Uplift: the Southeast Lead District, the Tri-State, and the Central (Figure 5.11). The Southeast Lead District includes the Old Lead Belt on the eastern side of the St. Francois Mountains and the New Lead Belt on the western side. Smaller, localized deposits of lead ores are located in northern Arkansas and southeastern Oklahoma. The Southeast Lead District contains the highest known concentration of galena, a lead-bearing ore, in the world (Figure 5.12). More than 17 million tons of lead have been produced in Missouri since mining began there, valued at more than 5 billion dollars. The Southeast Lead District produces about 70% of the US lead supply, most of which is used in the manufacture of batteries and ammunition.

Of Missouri’s three mining districts, perhaps the most famous is the Tri-State, which includes southwest Missouri around Joplin, and adjacent areas in southeast Kansas and northeast Oklahoma (Figure 5.13). The discovery of
ore in Joplin occurred in 1838, and mining reached full swing by the beginning of the Civil War. Both sides fought over the mines, each trying to secure a source of lead for the war effort. This conflict resulted in the suspension of most mining operations until after the war’s end. Lead mining resumed after the war, and zinc production began in the early 1870s. In the western part of the Tri-State District, the ore bodies are deeper, and mining was conducted underground, but in the east the ore bodies are shallower and were mined using pits. Production of metals from the district fluctuated with the economic fortunes of the country and the need for wartime supplies. Production began dropping after World War II, and the last mine closed in 1970. During the district’s life, 4000 mines produced 23 million tons of zinc concentrates and 4 million tons of lead concentrates, accounting for 50% of the zinc and 10% of the lead used in the US. Today, some of the Tri-State’s mines have become Superfund sites due to the quantities of toxic waste left behind after the closure of the mines. The Tar Creek Superfund site, located near the towns of Picher and Cardin in Oklahoma, was originally a major lead-zinc mining area. After its closure, the mine left behind about 75 million tons of chat, or lead-contaminated dust.
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(Figure 5.14). Waste materials, acids, and heavy metals have seeped into the groundwater, contaminating local aquifers and other freshwater sources. The severe environmental and health impacts of Tar Creek’s mining waste have lead the EPA to declare Picher, Oklahoma as one of the most toxic places in the US.

In addition to lead and zinc, mines in the Interior Highlands have also produced significant quantities of silver and copper. Other metallic elements are also present, including cadmium, nickel, and cobalt. Pyrite, calcite, dolomite, and quartz specimens from the region are highly prized by collectors.

Mining for iron ore began in Missouri in the mid-19th century, and has been intermittent since 2000. The ores precipitated from hydrothermal solutions, filling sinkholes and fractures in limestone, dolomite, and the Precambrian rocks of the St. Francois Mountains. The Interior Highlands’ iron mines produce hematite and magnetite, unique among the iron ores for its magnetic properties.
Mineral Resources of the Coastal Plain Region 3

The Coastal Plain is underlain by thousands of feet of sedimentary rock and sediments that were deposited in both marine and terrestrial environments. Strata underlying this region consist of limestones, shales, and sandstones that were deposited in river valleys as well as in shallow seas, deltas, bays, and beaches. Cycles of deposition, erosion, and stability are tied to changes in sea level, which in turn have been influenced by Quaternary glacial and interglacial periods. Throughout the Cenozoic, the Mississippi River has continually deposited sediment in its alluvial plain, contributing to its evolving delta system. Offshore, Louisiana and Texas continue to experience the deposition of sediment from rivers emptying into the Gulf of Mexico.

Mineral resources in the Coastal Plain have accumulated primarily as a result of sedimentary processes (Figure 5.15). Sand and gravel, limestone for cement, crushed stone, and clay are mined throughout the region. Halite, gypsum, and industrial sand are produced in Texas and Louisiana, and bromine is extracted from brine wells located in Arkansas and Texas. Sulfur is produced from sources associated with salt domes in the Texas coastal plain, and as a byproduct from the processing of oil and gas. Zeolites—porous alumino-silicate minerals with cation-exchange properties that can transform hard water into soft water—are mined in south-central Texas.

Figure 5.14: Residential area in Ottawa County, Oklahoma near the Tar Creek site. Note the proximity of several large lead-contaminated chat piles.

See Chapter 4: Topography for more about the Mississippi River Delta.
Although the Coastal Plain is primarily made up of sedimentary strata, small areas of Cretaceous igneous intrusions are located in southwestern Arkansas. Deposits of diamonds and other gemstones do not appear here in commercially viable quantities, but individuals may prospect for and freely remove diamonds and other gemstones they find from the Crater of Diamonds State Park in Pike County, Arkansas. These minerals are found in an ancient volcanic pipe or conduit—the volcano was so explosive that it brought minerals like diamonds,

Coastal Plain clays include fire clay, ball clay, kaolin, and bentonite. Fire clay is used in the production of refractory brick, and ball clay is used to produce ceramic products. Kaolin is used in ceramics, as well as a stabilizing agent or filler in many products. Bentonite is used in drilling muds and can be used as a sealant in instances where it is important to provide a barrier for water flow through rock or sediment.
Mineral Resources

For centuries, humans have recognized the importance of gemstones, precious metals, and other mineral resources in our world. These resources are not only aesthetically pleasing but also have practical applications in various industries, from jewelry to electronics. The Coastal Plain region holds a wealth of mineral resources, both metallic and nonmetallic, that are essential to modern society.

**Olivine and Garnet**

Olivine, an iron-magnesium silicate mineral, is a common constituent of magnesium-rich, silica-poor igneous rocks. It typically forms at great depths within the Earth’s crust. Garnet, another iron-magnesium silicate mineral, is less abundant but still widely distributed. Both olivine and garnet can be found in the Coastal Plain region, often in the form of weathered fragments from ancient volcanic activity.

**Volcanic Activity and Mineral Deposits**

When the ancient vent exploded, it left behind a crater filled with volcanic material. Today, minerals can be collected from within the weathered crater. Over 75,000 white, brown, and yellow diamonds have been found in the park, including “Uncle Sam,” the largest diamond ever found in the United States, and the Strawn-Wagner Diamond, the world’s only “perfect” diamond (Figure 5.16). Other gems and minerals found in the park include amethyst, banded agate, jasper, peridot, garnet, quartz, calcite, barite, and hematite.

**Metallic Resources**

Metals are not currently mined for commercial purposes in the Coastal Plain. While some deposits of metal-bearing minerals do occur in Texas and Arkansas, most of these deposits are either too small or low grade to be profitably mined.

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**Figure 5.16: The Strawn-Wagner Diamond, found at Crater of Diamonds state Park in 1990, was cut to 1.09 carats and graded “perfect” by the American Gem Society and Gemological Institute of America. It is the only diamond in the world to receive such a grading. Crater of Diamonds State Park purchased the diamond for $34,700, and it is currently on exhibit there.”

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**Key Mineral Definitions**

- **Olivine**: An iron-magnesium silicate mineral that is a common constituent of magnesium-rich, silica-poor igneous rocks.
- **Agate**: A crystalline silicate rock with a colorful banded pattern. It is a variety of chalcedony.
- **Jasper**: A speckled or patterned silicate stone that appears in a wide range of colors.
Mineral Resources of the Great Plains

The near-surface geology and mineral resources of the Great Plains region result from a complex suite of factors (Figure 5.17). Marine and terrestrial Cretaceous deposits indicate that several periods of sea level rise and fall were associated with the expansion and contraction of the Western Interior Seaway, which extended from what is now western Illinois to central Utah. Deposition ended with the final retreat of the sea and the uplift of the Rocky Mountains. Uplift in Colorado and New Mexico was renewed in the Miocene and Pliocene, gently tilting the underlying strata eastward. This tilting is more pronounced in the Texas panhandle than it is in western Kansas. Mountain streams transported and deposited large volumes of eroded sediment onto the plains, resulting in a thick blanket of sand, gravel, silt, and clay on top of eroded Mesozoic and Permian strata throughout the region. The sands and gravels here are rich in quartz and feldspar from the weathering and erosion of igneous and metamorphic rocks in the Rocky Mountains to the west. Sand, gravel, limestone, and other construction materials are mined throughout the Great Plains, and building stone is quarried from rocks near the Llano Uplift in central Texas.
Cyclical changes in climate during the Quaternary and Holocene initiated episodes of stream erosion, uncovering underlying Permian rocks containing layers of halite and gypsum. In and near river valleys, the movement of groundwater dissolved these soluble minerals, further accelerating the pace of erosion. Sediments were carried and deposited by the wind during drought periods and by streams during wet periods, leading to the development of soil horizons rich in deposits of caliche (Figure 5.18). Caliche forms when water infiltrates the soil, dissolves soluble material, and evaporates, leaving behind precipitated minerals in the pore space between soil grains. A zone of cemented material forms within the soil if this happens repeatedly. Layers of caliche accumulate to tens of feet in some locations, and multiple layers are commonly found throughout the Great Plains. Caliche is commonly collected for use as an additive in cement.

Beginning in the Miocene, episodes of volcanism in the Western and Southwestern US produced widespread ashfalls that covered much of the Great Plains. Deposits of silicate volcanic ash, as well as sands and gravels derived from the erosion of basaltic lavas, are present in the sediments at many locations in the Great Plains, such as the Pearlette Ash Bed in Kansas (Figure 5.19). This volcanic ash was mined between the 1930s and 1950s for use in concrete, abrasives, and as a cleaning material.

Figure 5.18: A shelf of caliche in central Texas.
Widespread fossil fuel resources in the Great Plains have led to the recovery of several associated elements that are often found alongside gas and oil. Oklahoma is the nation’s sole producer of iodine, extracted from deeply buried gas brines that occur in the Woodward Trench in northwest Oklahoma. Helium and sulfur are recovered from the Hugoton Gas Field in southwestern Kansas and the panhandles of Oklahoma and Texas. This area contains the largest reserve of helium in the United States; helium collected here is piped to the National Helium Reserve in Amarillo, Texas, for safekeeping and storage (Figure 5.20).

Potash is mined commercially from Permian deposits in west Texas. Potash is a name used for a variety of salts containing potassium, with mined potash being primarily potassium chloride. The majority of potash is used as fertilizer, but an increasing amount is being used in a variety of other ways: water softening, snow melting, a variety of industrial processes, as a medicine, and to produce potassium carbonate.
The Basin and Range province of west Texas is underlain by sedimentary, igneous, and metamorphic rocks ranging in age from Precambrian to Neogene. These are exposed in north-south oriented, fault-bounded mountain ranges, with considerable amounts of eroded sediment filling the valleys in between ranges (Figure 5.21). Taken together, these peaks and valleys (also called horst and graben landscapes) produce basin and range topography, formed as a result of stretching and thinning of the lithosphere during the Paleogene, when crustal extension and faulting led to the formation of almost 400 separate mountain blocks.

The mineral resources that are mined commercially in the Basin and Range are limited to talc and bentonite, industrial minerals used in manufacturing (Figure 5.22). Crushed stone, sand, and gravel are quarried as construction materials, and sulfur is extracted from oil at a plant in El Paso County.

Deposits of barite and fluorite have been found in this region, but they are of no commercial value and are not currently mined. Sources of metals (including uranium, tungsten, zinc, tin, iron, manganese, lead, silver, molybdenum, and mercury) have also been discovered in El Paso County, but these are typically too small to be of commercial value.
Mineral Resources

Region 5

Figure 5.21: An example of basin fill in the Basin and Range.

Figure 5.22: Principal mineral resources of the Basin and Range.
Resources

Books


State-based Resources


Chapter 6: Glaciers in the South Central US

Most people may not picture the South Central as an area that once contained glaciers, but the northern parts—northern Kansas and Missouri—were reached by the most extreme glacial advances of the late Pleistocene (Figure 6.1), and weathering and deposition indirectly associated with glaciation have occurred in other parts of this area. During the Quaternary period, which began just 2.6 million years ago and extends to the present, ice at times extended southward from the Hudson Bay area and over the northern United States. These ice sheets scraped away and ground up whatever rock was at the surface. When the ice finally retreated, it deposited the rock and dirt it had been carrying, influencing the landscape long after the ice was gone. Because glaciers affected the South Central in ways that do not directly correspond with bedrock in its different regions (which is not to say that bedrock is irrelevant), this chapter is instead organized according to the geographic areas associated with glacial processes.

Figure 6.1: Southernmost extent of glaciation over North America, at a time when glaciers covered parts of northern Kansas and Missouri.
What is a glacier?

A glacier is a large mass of ice (usually covered by snow) that is heavy enough to flow like a very thick fluid. Glaciers form in areas where more snow accumulates than is lost each year; a cold climate and sufficient moisture in the air for the precipitation of snow are both necessary factors that permit at least some snow to last year round. As new snow accumulates, it buries and compresses old snow, transforming it from a fluffy mass of snowflakes into ice crystals with the appearance of wet sugar, known as firn. As this firn is buried deeper, it coalesces into a mass of hard, dense ice that is riddled with air bubbles. Much of this transformation takes place in the high part of a glacier where annual snow accumulation outpaces snow loss—a place called the accumulation zone. At a depth greater than about 50 meters (165 feet), the pressure is high enough for plastic flow to occur. Ice flow is driven by gravity, and it causes movement downhill and out from the center (Figure 6.2). Once the ice becomes thick enough, it flows outward to the ablation zone, where ice is lost due to melting and calving. The boundary between these two zones, the equilibrium line, is found where annual ice accumulation equals annual ice loss. Because the altitude of this line is dependent on local temperature and precipitation, glaciologists frequently use it to assess the impact of climate change on glaciers.

Most broadly, there are two types of glaciers: smaller alpine glaciers and larger continental glaciers. Found in mountainous regions, alpine glaciers have a shape and motion that is largely controlled by topography, and they naturally flow from higher to lower altitudes. Alpine glaciers may fill part of a single valley, or they may cap an entire mountain range.
Continental glaciers are much larger, and they are less controlled by the landscape, tending to flow outward from their center of accumulation. It is not surprising that today’s continental glaciers, also called ice sheets, are found in the high latitude polar regions of Greenland and Antarctica where temperatures are low most of the year. Keep in mind that there must be landmasses at high latitudes for continental glaciers to occur, as by definition they cannot form over open water. While persistent sea ice can and does form, the fact that it floats prevents it from flowing as a glacier does. The glaciers that stretched over northern North America as recently as 20,000 years ago were primarily continental ice sheets.

While only the two broadest categories of glaciers are discussed here, glaciers exist in a variety of forms. Even these broadest of distinctions are not quite so clear-cut (e.g., continental glaciers often have tongues that feed into valleys, which may become alpine glaciers).

In summary, glaciers grow when it is cool enough for an ice sheet to accumulate snow more quickly than it melts. As they grow, ice sheets become so massive that they flow outwards, covering an increasing area until melting at the margins catches up to the pace of accumulation. Glaciers that reached the South Central states of Kansas and Missouri flowed from centers of accumulation far to the north (in what is now Canada), and glacial growth southward through the Midwest was more a result of this lateral flow than of direct precipitation from falling snow. By 18,000 years ago, the ice was in retreat due to a slight warming of the climate—it was not actually flowing backwards, but melting faster than it was accumulating and advancing.

**Glacial Landscapes**

The interaction of glaciers with the landscape is a complex process. Glaciers alter landscapes by erosion, transporting, and depositing rock and sediment. Scouring abrades bedrock and removes sediment, while melting causes the ice to deposit sediment. Glacial features like moraines, drumlins, and kettle occasionally break the pattern of gently rolling hills found in most of the Midwest north of Kansas and Missouri (Figure 6.3). Even in areas where glaciers did not reach, glacial runoff changed the landscape—meltwater loaded with abrasive sediment carved the landscape, making it more rugged.

Continental glaciers also affect the landscape by depressing the Earth’s crust with their enormous mass, just as a person standing on a trampoline will cause the center to bulge downwards. The effect is quite substantial, with surfaces being lowered by hundreds of meters. Of course, this means that when the glacier retreats and the mass is removed, the crust will rise to its former height.
Glaciers

Review

*isostasy* • an equilibrium between the weight of the crust and the buoyancy of the mantle.

*reef* • a feature lying beneath the surface of the water, which is a buildup of sediment or other material built by organisms, and which has positive relief from the sea floor.

*plucking* • process in which a glacier “plucks” sediments and larger chunks of rock from the bedrock.

*frost wedging* • weathering that occurs when water freezes and expands in cracks.

*sand* • rock material in the form of loose, rounded, or angular grains, and formed as a result of the weathering and decomposition of rocks.

*clay* • the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet.

in a process known as *isostasy* (Figure 6.4). Dramatic results include marine reefs lifted high above sea level and marine sediments composing coastal bluffs.

**Erosion**

Thousands of years of scraping by ice can have dramatic, and sometimes dramatically varied, effects on a landscape. Glaciers erode the land they flow over via abrasion and plucking. Harder bedrock will be scratched and polished by sediment stuck in the ice, while frost wedging, when water freezes and expands in cracks, can eventually break chunks of rock away. Softer bedrock is much more easily carved and crushed. Abrasion, or scouring, occurs when rock fragments in the ice erode bedrock as the glacier moves over it. Plucking involves glaciers literally pulling rock from underlying bedrock. The flowing ice cracks and breaks rock as it passes over, pieces of which become incorporated in the sheet or bulldozed forward, in front of the glacier’s margin. The less resistant rock over which glaciers move is often eroded and ground-up into very fine sand and clay (called rock flour). Once eroded, this material is carried away by the ice and deposited wherever it melts out.
More resistant igneous and metamorphic rock is often polished and scratched by the grinding action of sediments trapped in the glacial ice. Streams of meltwater from the glacier, frequently gushing and full of sediment, cause significant amounts of scour as well. The abrasive sediments in the flowing water create potholes in the bedrock and plunge pools at the base of waterfalls. At the edge of the sheet, where the ice at last succumbs to melting, the rock is finally deposited. Piles of this rock form some of the distinctive landforms found in Kansas and Missouri today.

The nature of the glacier causing the erosion is also crucial. Because continental glaciers spread from a central accumulation zone, they cannot go around peaks in their path, so they instead slowly crush and scrape them away. For the most part, this results in flatter landscapes. Conversely, alpine glaciers tend to follow the existing topography, flowing downhill. This frequently causes them to scour existing low points, making them lower still. While this gouging increases the overall relief of an area, anything directly in the path of the ice is flattened. For example, a glacier might deepen a valley while surrounding peaks remain high, yet the valley itself, initially cut by a narrow stream into a sharp V-shape, is smoothed into a distinctive U-shape by the wider glacier.

Deposition
As glaciers scrape over the earth, sediment is incorporated into or shoved ahead of the advancing ice. The unsorted mixture of boulders, gravel, sand, silt, and clay that is picked up and later deposited by glaciers is called till. It is important to note that whether a glacier is advancing, in equilibrium, or retreating, its ice is still flowing forward, like a conveyor belt that is constantly depositing till at its margin. In places where a glacier stopped its advance and then melted back, a ridge of till that had been pushed in front of it is left behind, marking the farthest extent of the glacier’s margin, or terminus. A ridge of till formed this way is called a moraine, and it may range in length from hundreds to thousands of meters (see Figure 6.3). A drumlin is a teardrop-shaped hill of till that was trapped beneath a glacier and streamlined in the direction of the flow of the ice moving over it (Figure 6.5). The elongation of a drumlin provides an excellent clue to the direction of flow during an ice sheet’s most recent advance.
Meltwater flowing off a glacier also leaves behind deposits. Unlike till deposits, meltwater deposits are well sorted: large rocks can only be moved by high-energy water, while finer sand and mud are washed downstream until enough energy is lost so that even they are dropped. In other words, the faster the water is moving, the coarser the sediment deposited (Figure 6.6). As a glacier melts, streams of sediment-laden meltwater often create networks of braided streams in front of the glacier. Streams of meltwater flowing under a glacier can deposit sand and gravel, and when an ice sheet retreats, these snaking ridges of stream deposits, known as eskers, are left behind (Figure 6.7).

Other glacial features include kettles, kames, and erratics. Kettles are depressions left behind by the melting glacier. Blocks of ice may be broken off from the glacier and buried or surrounded by meltwater sediments (Figure 6.8). When the ice eventually melts, the overlying sediments have no support, so they frequently collapse and form a depression that often fills with water to become a lake. Kames are formed in nearly the opposite way: layers of sediment fill in depressions in the ice, leaving mound-like deposits of sorted sediment after the glacier retreats (Figure 6.9). Often, kettles and kames occur near one another.
Erratics are rocks that the ice sheet picked up and transported farther south, sometimes hundreds of kilometers (miles) from their origin. They are often distinctive because they are a different type of rock than the bedrock found in the area to which they have been transported. For example, boulders and pebbles of igneous and metamorphic rocks are often found in areas where the bedrock is sedimentary. It is sometimes possible to locate the origin of an erratic if its composition and textures are highly distinctive. The pink-colored Sioux quartzite erratics found across much of northwestern Kansas are one such example; they originated in the area where Minnesota, South Dakota, and Iowa intersect.

Periglacial Environments

Though little of the South Central was covered by ice sheets, much of the area felt their effects. The portion covered by the ice sheet was scoured and covered with glacial deposits, while the

Figure 6.7: Eskers are composed of sand and gravel deposited by streams that flowed under the ice, partially filling the sub-ice channel. When the ice melts, the sinuous deposit remains.

Figure 6.8: Kettle lakes form where large, isolated blocks of ice become separated from the retreating ice sheet. The weight of the ice leaves a shallow depression in the landscape that persists as a small lake.
area south of the ice sheet developed its own distinctive landscape and features due to its proximity to the ice margin. This unglaciated but still affected area is called a periglacial zone.

There are a variety of features associated with a periglacial zone that also provide clues to the extent of the most recent ice sheet. In the tundra-like environment of a periglacial zone, aeolian, or windblown deposits, are common. Sand dunes and wind-transported sediments are found in former periglacial areas of the South Central.

The permafrost associated with the periglacial area, in which the ground is frozen much of the year, can cause mass movement of sediment. When the surface layer of the permafrost ground thaws, it is full of moisture. This water-heavy layer of soil may move rapidly down a hill in a process called solifluction.

Physical weathering of the bedrock is magnified in the periglacial environment because of the freeze-thaw cycles associated with permafrost. When water enters the cracks and fissures in the ground and subsequently freezes, the ice wedges the cracks farther and farther apart (Figure 6.10). Freeze-thaw is important in any climate that cycles above and below the freezing point of water. Because ice takes up more space than water, the pre-existing cracks and fractures are widened when the water freezes. Along ridges, rocks are eventually broken off as ice wedges continue to expand in joints and fractures. The boulders and blocks of bedrock roll downhill and are deposited along the slope or as fields of talus. Frost action also brings cobbles and pebbles to the surface to form

The average annual air temperature in a periglacial area is between -12° and 3°C (10° and 37°F). Though the surface of the ground may melt in the summer, it refreezes in the winter.
nets, circles, polygons, and garlands of rocks. These unusual patterns of sorted rock are known as **patterned ground**. Solifluction and ice wedging are found exclusively where the ground remains perennially frozen yet is not insulated by an ice sheet. Such conditions only occur in areas adjacent to ice sheets. While conditions like these existed in parts of the South Central and must have led to the formation of patterned ground, any evidence has subsequently been covered with glacial sediment or eroded away.

**Physical weathering is the break-up of rock due to physical processes (such as erosion by wind, water, and ice) rather than chemical processes.**

![Figure 6.10: Physical weathering from a freeze-thaw cycle.](image)

### Glaciers and Climate

Glaciers are sometimes called the “canary in the coal mine” when it comes to climate change. This is because alpine glaciers are highly sensitive to changes in climate. For instance, a glacier grows (advances) when it accumulates more ice than it loses from melting or calving. Advances tend to happen when cold, wet years dominate the local climate. On the other hand, a glacier will shrink (retreat) during warm, dry periods as it loses more ice than it gains each year.

As discussed in the chapter on climate, for much of Earth’s history there have not been persistent ice sheets in high latitudes. Any time that the world is cool enough to allow them to form is called an “ice age.” Based on this definition, we are living in an ice age right now! The current ice age began about 34 million years ago when ice sheets were first forming on Antarctica, followed by on Greenland at least 18 million years ago, and finally on North America, which defined the beginning of the Quaternary period (about 2.6 million years ago). When most people use the phrase “the ice age,” however, they are referring to the **last glacial maximum** during which much of North America and Europe covered in ice thousands of meters (feet) thick and many kinds of large, wooly mammals roamed the unfrozen portions of those continents.

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The Quaternary period is divided into two epochs. The earlier Pleistocene encompasses the time from 2.6 million to 11,700 years ago, including all of the Quaternary up until the most recent episode of glacial retreat—the beginning of the Holocene. During the Pleistocene, there were several dozen intervals of glaciation separated by warmer interglacial intervals characterized by glacial retreat. In North America, these cycles are known as the pre-Illinoian (1.8 million–302,000 years ago), Illinoian (191,000–131,000 years ago), Sangamonian (131,000–85,000 years ago), and Wisconsinan (85,000–11,000 years ago). The Illinoian and Wisconsinan were cooler periods that saw glaciers advance, while the Sangamonian was a warm interglacial period.

The pre-Illinoian glaciation included many glacial and interglacial periods that were once subdivided into the Nebraskan, Aftonian, Kansan, and Yarmouthian ages. New data and numerical age dates suggest that the deposits are considerably more complicated; they are now lumped together into a single period. Most of the glacial features to the north in the Midwest were created during the Pleistocene, while glaciers that extended far enough to reach Kansas and Missouri only occurred during glaciations in the pre-Illinoian period.

**Ice on a Schedule**

The enormous continental glaciers that define an ice age are so large that their extent is most directly affected by global trends, while mountain glaciers are much more susceptible to local and short-term changes in climate. Continental ice sheets advance and retreat in cycles that last tens of thousands of years and are controlled to a large extent by astronomic cycles.

Scientists continue to debate the particular causes of the onset of glaciation in North America over two million years ago. Movement of the Earth's tectonic plates may have been a direct or indirect cause of the glaciation. As plates shifted, continents moved together and apart, changing the size and shape of...
Glaciers

Seeking Detailed Records of Glacial-Interglacial Cycles

While glaciers have advanced over central North America and retreated again dozens of times during the Quaternary, each advance scruped away and reworks much of what was previously left behind, making it difficult to reconstruct the precise course of events.

Therefore, to investigate the details of any associated climate change we must seek environments that record climate change and are preserved in the geologic record. Since the 1970s, the (international) Deep Sea Drilling Project has provided a treasure trove of data on coincident changes in the ocean, preserved in sediments at the ocean bottom (Figure 6.11). In the 1980s, coring of ice sheets in Greenland and Antarctica provided similar high-resolution data on atmospheric composition and temperature back nearly one million years.

Astronomic Cycles and Ice Sheets

The cyclical movements of ice sheets seem primarily to be caused by specific astronomic cycles called Milankovitch cycles, which change the amount of light the Earth receives, particularly when comparing the summer to the winter. The cycles, predicted through principles of physics a century ago, are related to the degree of tilt of the Earth, the Earth’s distance to the sun, and the point in the Earth’s revolution around the sun during which the Northern Hemisphere experiences summer. When the cycles interact such that there is milder seasonality (cooler summers and warmer winters) at high latitudes in the Northern Hemisphere, less snow melts in summer, which allows glaciers to grow. The cyclicity of glacial-interglacial advances was about 40,000 years from before the start of the Quaternary until about a million years ago. For reasons that aren’t clear, however, the cycles changed to about 100,000 years. If not for human-induced climate change, we might expect glaciers to approach Kansas and Missouri again in about 80,000 years!

the ocean basins. This, in turn, altered oceanic currents. Mountain building, which occurred when continents collided, erected obstacles to prevailing winds and changed moisture conditions. The freshly exposed rock from the rising of the Himalayas also combined with atmospheric carbon dioxide through chemical weathering; this consequent decrease in levels of atmospheric carbon dioxide was at least partially responsible for global cooling. Finally, the presence of continental landmasses over one pole and near the other was also a major factor enabling the development of continental glaciers.

plates • large, rigid pieces of the Earth’s crust and upper mantle, which move and interact with one another at their boundaries.

atmosphere • a layer of gases surrounding a planet.
The data from these programs have revealed that the Earth experienced dozens of warming and cooling cycles over the course of the Quaternary period. Traces of the earlier and less extensive Pleistocene glacial advances that must have occurred have been completely erased on land, so these advances were unknown before records from deep-sea cores and ice cores revealed them. These glaciations may have had indirect impacts on the South Central, particularly on sea level variations along the Gulf Coastal Plain, but they did not likely reach Missouri and Kansas.

The direct influence of continental glaciers upon the surface of the South Central US is limited because even during the most extreme intervals of Pleistocene glaciation, the Laurentide Ice Sheet barely reached as far south as northern Missouri and Kansas (see Figure 6.1). Glacial deposits that exist in Missouri and Kansas can be difficult to date to a specific glacial advance and are simply labeled as pre-Illinoian. There were perhaps five pre-Illinoian glaciations in Missouri, representing glaciations as recently as a few hundred thousand years ago, and two in Kansas, the most recent being about 600,000 years ago.
Glacial drift, including large numbers of rocks from outcrops that occur farther north, is the primary evidence that remains of these glaciers (Figure 6.13). Larger glacial landforms that probably existed have since eroded away. Among the most distinctive glacial erratics found in the South Central are quartzite boulders, known as the Sioux quartzite, dragged by glaciers from the area.
of Sioux Falls, South Dakota (Figure 6.14). Perhaps because quartzite is so resistant to erosion, boulder fields of this rock can be especially prominent.

By 18,000 years ago, the ice sheet was in retreat due to a slight warming of the climate. Though the ice sheet alternately moved forward and melted backward, overall it was on the retreat. Even during glacial advance, the glacier was always melting at its fringes. During times of glacial retreat, the ice sheet was not actually flowing backwards—the glacier continued to flow forward, but it was melting faster than it was advancing.

The Loess Hills
The Loess Hills of extreme western Iowa, extending into northwesternmost Missouri, are named after a glacial deposit formed of windblown rock flour: *loess*. This type of glacial feature is found in significant quantities in only a few places on Earth. These hills form narrow, 320-kilometer (200-mile) long, north-south bands immediately east of the Missouri and Mississippi River *floodplains*, and thinner deposits across Kansas and central Missouri (Figure 6.15). They were formed during several glacial/interglacial cycles when glaciers ground down the bedrock. Later, as the ice retreated, meltwater deposited the fine sediments in expansive mudflats. When the mudflats dried, strong westerly winds blew the sand into great dunes, and the finest material (silt and clay) was carried even farther in massive dust clouds. The dunes were eventually stabilized by
vegetation and matured into hills, but their loose material is still easily eroded and carved. Slumping, mudslides, and undercutting caused by wind and water have produced steep slopes and a landscape of narrow ridges (Figure 6.16).

See Chapter 2: Rocks for a cross-sectional diagram of the Loess Hills.

Figure 6.15: Thickness of loess deposits in the South Central US (See TFG website for full-color version.)
Much of the soil throughout the eastern South Central is composed, in part, of sediment blown from huge mudflats on the banks of the ancient Missouri River, which was a major channel for floods of glacial meltwater. In and around the South Central US, loess deposits occur along the bluffs of the Missouri and Mississippi rivers, and may form hills several hundred meters high. Often, exposed loess will form steep faces of fine silt. The loess can become the base of rich soils and is part of the basis for the “corn belt,” an intensively agricultural area spanning much of the Midwest and extending into the Dakotas, Nebraska, Kansas, and Missouri.

The Coastline and Glaciers

It may seem surprising that the very southernmost part of the South Central US, along the coastline, would be among the areas of the South Central most influenced by glaciers. The reason is not related to the action of the flowing glaciers themselves, but rather the amount of water stored in glaciers globally: during glacial advances, so much water (ultimately evaporated from the surface of the ocean) is trapped in glaciers that sea level can drop by over 100 meters (330 feet). Thus, as recently as 20,000 years ago, what are now bays and river
mousta along the coast of Texas and Louisiana were dry land many kilometers from the shore, as was much of the continental shelf that rims the coastline (Figure 6.17).

During each interglacial period, as sea level rose, the nature of the coastline was influenced by the erosion that had taken place in the previous glacial period, particularly in river valleys. For example, the Mississippi River cut more deeply into the land and transported more sediment during intervals of lower sea level, and, conversely, slightly higher floodplains from previous interglacial periods can be observed along the edge of the existing Holocene floodplain. The Missouri and Mississippi were conduits for some of the melting of the continental ice sheets; this meltwater contained glacially eroded sediments that contributed greatly to the Mississippi’s broad floodplains and **delta**.

As sea level rose to near current levels, it took time for sediments to accumulate just offshore and for the system of barrier islands, lagoons, bays, and estuaries that we know today to develop. The evolution of the coastline and associated changes over the past ten thousand years influenced the history of ecosystems and human settlement of the area.
## Resources

### Books


### Glaciers in the South Central US


### Activities

Beyond Penguins and Polar Bears, College of Education and Human Ecology, The Ohio State University. (Lesson plans for grades K-5, including topics such as glacial ice, ice movement, and glacial erosion.) http://beyondpenguins.ehe.osu.edu/issue/icebergs-and-glaciers/hands-on-lessons-and-activities-about-glaciers.

Glacier Power, Earth Observing and System Data and Information System (EOSDIS), NASA. (Middle school glacier education resources.) https://earthdata.nasa.gov/featured-stories/featured-research/glacier-power.

Impact of Change in Glacier Ice, Alaska Seas and Rivers Curriculum, Alaska Sea Grant. (Grade 8 lesson plan on glacier retreat.) https://seagrant.uaf.edu/marine-ed/curriculum/grade-8/investigation-2.html.

Learning about Glaciers, Glacier Research Group, Portland State University Geology Department. (High school and college level educational resources.) http://glaciers.us/Learning-About-Glaciers.


National Snow and Ice Data Center (NSIDC) Educational Resources. (High school- and college-level educational resources.) http://nsidc.org/cryosphere/education-resources/.
Chapter 7: Energy in the South Central US

Everything we do depends upon energy—without it there would be no civilization, no sunlight, no food and no life. Energy moves people and goods, produces electricity, heats our homes and businesses, and is used in manufacturing and other industrial processes. But what is energy? **Energy** is the **power** derived from the utilization of physical or chemical resources. In this chapter, we are especially interested in the energy used to provide light and **heat**, or to power machines.

For most of human history, the way we captured and used energy changed little. With very few exceptions*, materials were moved by human or animal power, and heat was produced largely through the burning of wood. Nearly all the energy to power human society was, in other words, **biomass**. But the transition from brute force and wood burning to the various industrial sources of energy—and the accompanying adoption of energy-intensive lifestyles—has occurred remarkably quickly, in the course of just the last several generations. This has caused changes in virtually every aspect of human life, from economics to war to architecture. Much of the rural US was without access to electricity until the 1930s, and cars have been around only slightly longer. Our energy system (how we get energy and what we use it for) has changed and is changing remarkably quickly, though some aspects of the energy system are also remarkably resistant to change.

The use of **wind** to generate electricity, for example, grew very quickly in the late 2000s and early 2010s. In 2002, wind produced less than 11 million megawatt hours (MWh) of electricity in the US. In 2011, it produced more than 120 million MWh—more than 1000% growth in ten years! That aspect of change stands in contrast to our long-lasting reliance on **fossil fuels**, such as **coal**, oil, and **natural gas**. Our reliance on fossil fuels is driven by a number of factors: the low power, the rate at which energy is transferred, usually measured in watts or, less frequently, horsepower.

**heat** the transfer of energy from one body to another as a result of a difference in temperature or a change in phase.

**biomass** organic material from one or more organisms.

**wind** the movement of air from areas of high pressure to areas of low pressure.

**fossil fuels** fuel for human use that is made from the remains of ancient biomass.

**coal** a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation.

*Exceptions include the use of sails on boats by a very small percentage of the world’s population to move people and goods, and the Chinese use of natural gas to boil brine in the production of salt beginning roughly 2000 years ago.

Electricity is a good example of an **energy carrier**: a source of energy that has been subject to human-induced energy transfers or transformations.

**Wind power**, on the other hand, is a **primary energy source**: a source of energy found in nature that has not been subject to any human manipulation.

CHAPTER AUTHOR
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Energy production and use not only changes across time, but also with geography, as we will see by looking at energy production and use across the different regions of the US.

What do different units of energy mean?
Heat is energy, and heat is at the root of all the ways that we move materials or generate light, so measurements of heat can be thought of as the most basic way to measure energy. The British Thermal Unit (abbreviated Btu or BTU) is the most commonly used unit for heat energy and is approximately the amount of heat required to raise one pound of water by one degree Fahrenheit. A Btu is also roughly 1055 joules, or the amount of energy released by burning a single wooden match. A joule is the energy expended (or work done) to apply a force of one newton over a distance of one meter. Since a typical apple weighs about one newton, lifting an apple one meter requires about a joule of energy. That means that one Btu—the energy contained in a wooden match—is equivalent to the total amount of energy required to lift an apple 1000 meters, or one kilometer.

This comparison of the energy of heat to the energy of motion (kinetic energy) might be a little confusing, but energy is transformed from one type to another all the time in our energy system. This is perhaps most obvious with electricity, where electrical energy is transformed into light, heat, or motion at the flip of a switch. Those processes can also be reversed—light, heat, and motion can all be transformed into electricity. The machines that make those transitions in either direction are always imperfect, so energy always degrades into heat when it is transformed from one form to another.

Another measure of energy, the kilowatt-hour (kWh), represents the amount of energy required to light ten 100-watt light bulbs for one hour. Figure 7.1 compares different ways to make and use one kWh.

How do we look at energy in the Earth system?
The concepts used to understand energy in the Earth system are fundamental to all disciplines of science; energy is an interdisciplinary topic. One cannot study physics or understand biomes, photosynthesis, fire, evolution, seismology, chemical reactions, or genetics without considering energy. In the US, every successive generation has enjoyed the luxury of more advanced technology (e.g., the ability to travel more frequently, more quickly, and over greater distances), and we require more and more energy to maintain these new lifestyles and to power new technologies.

Figure 7.2 shows the sources and uses of energy in the US, by sector. The Energy Information Administration (EIA) categorizes energy as coming from one
Figure 7.1: Examples of uses and sources of 1 kilowatt-hour.

One 100-watt incandescent bulb (1800 lumens) for 10 hours
One 28-watt compact fluorescent bulb (1800 lumens) for 38 hours

Producing 1 kilowatt-hour requires:
One lb. of coal or 7.5 cubic ft. of natural gas or 8.5 oz. of gasoline

Consumption based on traditional thermal power plant production, which loses about 50% of energy as waste heat, plus electrical transmission losses of about 7%.

Figure 7.2. US energy production sources and use sectors for 2011. Petroleum provides more energy than any other source, and most of it is used for transportation. More energy is used to generate electricity than for any other use, and electricity is generated by all five energy sources. Nuclear is unique among sources in that all of the energy it generates goes to a single sector: electric generation.
Review

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petroleum • a naturally occurring, flammable liquid found in geologic formations beneath the Earth’s surface.

renewable energy • energy obtained from sources that are virtually inexhaustible (defined in terms of comparison to the lifetime of the Sun) and replenish naturally over small time scales relative to human life spans.

nuclear • a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus.

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Energy

of five sources (petroleum, natural gas, coal, renewable energy, and nuclear electric power) and being used in one of four energy sectors (transportation, industrial, residential & commercial, and electric power). All of the energy that powers our society comes from one of these five sources and is used in one of these four sectors.

The more we come to understand the Earth system, the more we realize that there is a finite amount of consumable energy, and that harvesting certain resources for use in energy consumption may have wide ranging and permanent effects on the planet’s life. Understanding energy within the Earth system is the first step to making informed decisions about energy transitions.

**Becoming “Energy Literate”**

Energy is neither lost nor gained within the universe, but rather is constantly flowing through the Earth system. In order to fully understand energy in our daily lives—and make informed decisions—we need to understand energy in the context of that system. Becoming energy literate gives us the tools to apply this understanding to solving problems and answering questions. The Seven Principles of Energy, as detailed in *Energy Literacy: Energy Principles and Fundamental Concepts for Energy Education* are as follows:

<table>
<thead>
<tr>
<th>Principle</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Energy is a physical quantity that follows precise natural laws</td>
</tr>
<tr>
<td>2</td>
<td>Physical processes on Earth are the result of energy flow through the Earth system.</td>
</tr>
<tr>
<td>3</td>
<td>Biological processes depend on energy flow through the Earth system.</td>
</tr>
<tr>
<td>4</td>
<td>Various sources of energy can be used to power human activities, and often this energy must be transferred from source to destination.</td>
</tr>
<tr>
<td>5</td>
<td>Energy decisions are influenced by economic, political, environmental, and social factors.</td>
</tr>
<tr>
<td>6</td>
<td>The amount of energy used by human society depends on many factors.</td>
</tr>
<tr>
<td>7</td>
<td>The quality of life of individuals and societies is affected by energy choices.</td>
</tr>
</tbody>
</table>

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*Energy Literacy: Energy Principles and Fundamental Concepts for Energy Education* is a publication of the US Department of Energy. It can be accessed for free online; see Resources for more information.
Each principle is defined by a set of fundamental concepts that can help clarify ties to curriculum. Keeping these energy principles in mind when we teach others about energy can help us contextualize and make relevant our own energy consumption and its effect on the Earth system.

**Energy in the South Central Regions**

The South Central contains widespread energy resources (fossil fuels), most notably oil and natural gas (Figure 7.3) and coal (Figure 7.4). Many of these resources were generated in the **Paleozoic** by the advance of **inland seas** and subsequent deposition of marine detritus. As a result, nearly all of the energy produced and consumed in the South Central is derived from fossil fuel resources. Of the South Central states, Missouri alone produces more energy from “clean” sources (including biomass, nuclear, and renewables) than it does from fossil fuels; however, its energy consumption is dominated by coal, with more than 80% of the state’s power generated from that source.

*Figure 7.3: Areas of oil and gas production in the South Central states of the US.*
Ancient sedimentation patterns and tectonic activity have favored the placement of widespread fossil fuel resources in this region. Organic-rich sediments were deposited in Paleozoic inland seas that spread across much of the region. Parts of the Central Lowland also favor the production of wind energy.

Conventional Oil and Gas
The Central Lowland is home to several basins with thick sections of late Paleozoic fossil fuel-bearing deposits, including the Forest City and Cherokee Basins in Kansas, the Arkoma and Anadarko Basins in Oklahoma, and the Fort Worth Basin in northern Texas (Figure 7.5). It is possible to make sense of why we find petroleum and natural gas in these areas by understanding the history of marine environments. Mud with relatively high organic matter content tends to accumulate in shallow continental seas and in coastal marine environments, especially beyond the mouths of large rivers. The South Central has long been home to both of these environments—when organic matter
Fossil fuels—oil, natural gas, and coal—are made of the preserved organic remains of ancient organisms. Coal and lignite result from the burial, compaction, and heating of preserved plant matter, whereas petroleum and natural gas originate deep underground through a slow process involving the low-grade heating of sedimentary source rocks that contain an abundance of organic matter. In either case, organic matter only preserves when the rate of accumulation is higher than the rate of decay. This happens most often when the oxygen supply is sufficiently low that oxygen-loving bacteria cannot thrive, greatly slowing breakdown of organic matter. In this way, the organic matter can be incorporated into the buried sediment. The organics are compacted and heated with the rest of the rock, eventually transforming into fossil fuels.

The history of surface environments, evolution of life, and geologic processes beneath the surface have all influenced where fossil fuel deposits formed and accumulated. The largest oil and gas reserves were at one time nutrient-rich seas with abundant surface phytoplankton and organic-rich bottom sediments; the largest coal beds were swampy environments where fallen forest trees and leaves were buried in stagnant muds.

originally accumulated on sedimentary deposits in these basins, they were situated along the southern part of the continent, covered by a shallow sea.

Conventionally, finding oil and gas has not been as simple as finding organic-rich rock layers. Oil and gas can flow both within and between rock layers, wherever the number and size of paths between pores, fractures, and other spaces (permeability) is large enough. Because oil and gas are under pressure, they will move gradually upward to areas of lower pressure and will rise all the way to seeps at the surface unless they are blocked by a caprock—that is, one or more layers with permeability so low that they effectively block the flow of liquids and gases. If the fossil fuel happens to rise beneath a caprock in the shape of a concave surface (such as an anticline, certain faults, or a salt dome), the fossil fuels may accumulate in what geologists call a “reservoir.” Reservoirs are

Fossil Fuels

- anticline • a layer of rock folded (bent) along an axis, concave side down (i.e., in an upside down “u” or “v” shape).
- fault • a fracture in the Earth’s crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side.
- salt dome • a largely subsurface geologic structure, consisting of a vertical cylinder of salt embedded in horizontal or inclined sedimentary strata.
Reservoir rocks in the Central Lowland include both sandstones and carbonate rocks. In this area, many reservoir rocks can be accessed through one well due to the large thicknesses of sedimentary rocks in the many depositional basins. A number of the reservoirs are Pennsylvanian in age, often covering thousands of meters of sandstone and shale.

typically found in porous sedimentary layers and thin natural fractures. Most oil and gas has been extracted using the “conventional” technique of seeking such reservoirs and drilling into them, allowing the gas or oil to come to the surface through a vertical well.

sandstone • sedimentary rock formed by cementing together grains of sand.

carbonate rocks • rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms.

Pennsylvanian • a subperiod of the Carboniferous, spanning from 323 to 299 million years ago.

shale • a dark, fine-grained, laminated sedimentary rock formed by the compression of successive layers of silt- and clay-rich sediment.

Figure 7.5: Sedimentary basins containing significant fossil fuel accumulations, and the area of these basins covered by shale formations in which horizontal drilling and hydraulic fracturing are used.
Oil and Gas

Oil and gas form from organic matter in the pores of sediments subjected to heat and pressure. The organic matter is primarily composed of photosynthetic plankton that die and sink to the bottom of large water bodies in vast numbers. Shale in particular is often organic rich, because organic matter settles and accumulates in the same places that mud (clay and silt particles) settles out of the water. In most environments, organic matter is recycled by bacteria before it can be buried, but the quiet waters where mud accumulates are often relatively stagnant and low in oxygen. In these places, the bacterial decay rate is low relative to the rate of organic matter sinking and to the rate that the organic matter becomes buried in muddy sediments. Under such conditions, organic matter may accumulate enough to make up several percent or more of the deposited sediment.

Because oil and gas are under pressure, they will move gradually upward to areas of lower pressure through tiny connections between pore spaces and natural fractures in the rocks. Reservoir rocks typically have a considerable amount of pore space, and to be viable there must be a way of trapping the oil and gas, such as through a geologic structure or a change in rock type that will prevent the resource from escaping. Often, natural gas and oil are trapped below the surface under impermeable layers that do not have sufficient spaces for liquids and gases to travel through. Folds or “arches” in impermeable layers, or faults in rock layers, are common ways of trapping oil and gas below the surface.

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**clay** - the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet.

**silt** - fine granular sediment most commonly composed of quartz and feldspar crystals.

**fault** - a fracture in the Earth’s crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side.
Shale Gas

Some impermeable, or “tight,” layers contain oil and gas that has never escaped. Since the early 2000s, horizontal drilling has been combined with a method to fracture rocks beneath the surface, releasing gas and oil trapped in source rocks that have very low permeability. This method uses high volumes of water introduced at high pressure through horizontal wells along the source rock layer, to create thousands of tiny fractures (Figure 7.6). Most horizontal wells are drilled where the shale is about 100–150 meters (330–490 feet) thick. The fractures are held open by small grains of sand carried by gel in the water, increasing its viscosity. A number of chemicals are added to the water to increase the recovery of fossil fuels, including a chemical to reduce friction as the mixture is introduced (thus the term “slickwater”). “Slickwater, high-volume hydraulic fracturing”—often shortened to “hydraulic fracturing” or simply “fracking”—has greatly increased the accessibility of available fossil fuel resources and the production rate of oil and gas. It has also been controversial, in part because of associated environmental impacts.

The Fort Worth Basin is best known today for the Barnett Shale, an organic-rich shale that made international news when horizontal drilling and hydraulic fracturing were first used together to extract natural gas directly from layers in which the gas formed and was still trapped. Like other such shale gas layers, the Barnett Shale was originally mud that accumulated on a poorly oxygenated ocean bottom, in this case during the Mississippian period. The Barnett Shale extends to the southwest into the Permian Basin, part of the Great Plains region.

Another “tight shale” in the news is the Woodford Shale, which is mostly late Devonian and partly early Mississippian in age. The most productive geological units are found in the Arkoma Basin of southeast Oklahoma, but they do extend west into the Anadarko Basin.

Coal

The Central Lowland is also known for its coal deposits (see Figure 7.4). Coastal deltaic swamps and Paleozoic forests provided plant matter that, upon submergence and burial, eventually produced deposits of coal. These deposits are found in Pennsylvanian-age rocks which are stratigraphically above (and thus younger than) the Barnett Shale.

See Chapter 10: Earth Hazards to learn about the recent increase in Oklahoma’s earthquakes, linked to destabilization related to hydraulic fracturing.

See Chapter 3: Fossils for more on the swamps and forests of the Carboniferous period.

Unless rock layers are overturned, older rocks are found at the bottom and younger rocks are found at the top of a sedimentary sequence. This is known as the Law of Superposition.
Bituminous coal in the Central Lowland was mined heavily, especially in the early 1900s, and mostly from relatively thin Pennsylvanian-age beds ("seams") near the surface. Bituminous coal deposits of a similar age are mined to the north in the Midcontinent Basin, sometimes known as the "Western Interior Coal Region," which covers parts of eastern Oklahoma and Kansas and western Missouri (as well as the tip of eastern Nebraska and southern Iowa). These thin coal seams are deposited in cycles of marine and terrestrial sediments known as cyclothems (Figure 7.7). Such thin, shallow coal seams were excavated using electrically-powered mining shovels to scoop enormous quantities of fragmented rock and overburden. West Mineral, a town in southeasternmost Kansas, is home to Big Brutus (Figure 7.8), a 49-meter-tall (160-foot-tall) giant stripping shovel designed to dig coal from depths of 6 to 21 meters (20 to 69 feet). Although it is not the largest such shovel ever built, it was the second largest of its kind in operation during the 1960s and 70s.
As leaves and wood are buried more and more deeply, pressure on them builds from overlying sediments, squeezing and compressing them into coal. The coal becomes gradually more enriched in carbon as water and other components are squeezed out: peat becomes lignite, bituminous, and eventually anthracite coal, which contains up to 95% carbon. Anthracite has the fewest pollutants of the four types of coal, because it has the highest amount of pure carbon. By the time a peat bed has been turned into a layer of anthracite, the layer is one-tenth its original thickness.

The Carboniferous period takes its name from the carbon in coal. A remarkable amount of today’s coal formed from the plants of the Carboniferous, which included thick forests of trees with woody vascular tissues.
Energy

Figure 7.7: An example of a cyclothem: alternating sequences of marine and non-marine sedimentary rocks, characterized by their light and dark colors.

Figure 7.8: Big Brutus, a 49-meter-tall (160-foot-tall) giant stripping shovel used in the 1960s and 70s to mine coal in southeastern Kansas. Today, it has been preserved as a national landmark, and is the largest electric shovel still in existence. Inset shows people standing next to rear treads, for scale.
The southernmost coal-bearing units in the Central Lowland are found in the Arkoma Basin, covering parts of Arkansas and Oklahoma. These are known especially for “coalbed methane”—natural gas extracted from subsurface coal deposits several hundred meters below the surface. An additional byproduct of natural gas extraction is the recovery of large quantities of helium gas at processing plants in Texas and Kansas.

Energy Production
In addition to the infrastructure associated with the extraction of fossil fuel resources, oil refineries, coal, and natural gas plants dot the Central Lowland from Missouri through Texas. Wind in the southwest part of the region, along the boundary with the Great Plains, also plays a role in local energy production (see Figure 7.19).

The only major nuclear power plant in the region is the Callaway Nuclear Generating Station in Auxvasse Township in Missouri (Figure 7.9). This plant, which began operating in 1984, produces about 1300 MW—9% of the state’s energy consumption. In 2012, the plant entered a proposal to build a second tower, which would more than double its capacity.
Energy in the Interior Highlands
Region 2

Precipitation and the relatively high topographic area associated with the Ozark Uplift provide the region with great potential for hydroelectric power (Figure 7.10), which uses the gravitational force of falling or rushing water to rotate turbines that convert the water’s force into energy. More than 30 small- to medium-sized hydroelectric plants (from less than 2 to almost 400 megawatts) are distributed along the Arkansas, White, and Buffalo rivers in Arkansas, eastern Oklahoma, and southern Missouri (Figure 7.11). Almost all of these power plants are located within the Ozark Plateau. One exception is Arkansas Electric Coop’s 35 MW capacity Dam 2, which sits near the confluence of the Arkansas and Mississippi rivers. There are also three pumped storage facilities within the region, where water is pumped uphill into reservoirs in times of excess production, essentially acting as batteries. These are larger in capacity than most of the power plants, ranging from 186 MW to 440 MW.

Even though the Interior Highlands produces the most hydroelectricity of all regions in the South Central, the power generated by these plants pales in comparison to that produced by the region’s fossil fuel-powered facilities.
example, Arkansas’ largest power plant is the Union Power Partners natural gas plant, which has a 2020 MW capacity. Overall, coal is the major source of power for the Interior Highlands, providing the region with over ten times more electricity than hydropower.

A minor amount of fossil fuel resources exist within the Arkansas Valley. Natural gas and oil are extracted from sandstones that were deposited in early Pennsylvanian river systems and deltas. An accumulation of plant remains from ancient swamps and forests has also yielded coal resources within the basin. The southern part of the region supports several refineries.

**Energy in the Coastal Plain**

**Region 3**

Oil and natural gas resources are abundant in the Coastal Plain and are produced from reservoir rocks on- and offshore in Texas and Louisiana, as well as from Pennsylvanian sandstone in southwestern Arkansas and southeastern Oklahoma. Other fossil fuel resources include lignite and bituminous coal from Texas and Louisiana. The Coastal Plain also supports a variety of alternative energy sources, including wind, hydro, biomass, and nuclear power generation.
Conventional Oil and Gas
As **Pangaea** broke apart during the **Jurassic**, the Gulf of Mexico opened and began to take shape. In its early stages, the Gulf experienced periods of restricted marine circulation, during which **salt** was deposited through evaporation in flat layers now known as the **Louann Salt Formation**. These salt deposits, which now underlie much of the Coastal Plain, contribute to the character and size of oil fields under eastern Texas and Louisiana (Figure 7.12).

Since the late Jurassic, the Gulf of Mexico has been accumulating thick sediment deposits, which have been supplemented since that time by sediments **eroded** from the Mississippi River watershed in central North America. The Coastal Plain along Texas and Louisiana was submerged under high sea levels for much of the late **Cretaceous** and **Paleogene**, and it is now the site of thick layers of **limestone**, shale, and sandstone. Many late Cretaceous and early Paleogene shales became source rocks for oil, significant quantities of which have migrated stratigraphically into the sandstone and porous limestone, ultimately pooling.
in reservoirs trapped under a variety of impermeable sedimentary deposits such as gypsum, anhydrite, limestone, and dolomite. Southeastern Texas and southern Louisiana are together known as the East Texas Oil Field, which is the second largest oil field in the US outside of Alaska. Oil accumulated throughout the Coastal Plain in large part because of the region’s underlying Jurassic salt layers. Salt structures occur in abundance along the Gulf of Mexico (see Figure 7.12), which explains the geographic distribution of oil and gas reservoirs—impermeable rocks pushed up by salt domes became caprock where oil could be trapped.

Gushers, an icon of oil exploration during the late 19th and early 20th centuries, occurred when highly pressurized reservoirs were breached by simple drilling techniques. Oil or gas would travel up the borehole at a tremendous speed, pushing the drill bit out and spewing out into the air. One of the most famous oil gushers, Lucas Gusher at Spindletop oil field in Beaumont, Texas (Figure 7.13), is credited with starting the Texas Oil Boom in 1901 that stimulated the growth of the oil industry (Figure 7.14). At its peak, Lucas Gusher ejected 100,000 barrels of oil per day before it slowed enough to be capped off. Although iconic, gushers were extremely dangerous and wasteful; as well as spewing thousands of barrels of oil onto the landscape, they were responsible for the destruction of life and equipment. The advent of specialized blowout prevention valves in the 1920s enabled workers to prevent gushers and to regain control of blown wells. Today, this equipment is standard in both on- and offshore oil mining.

**Salt Domes**

Rock salt (the mineral halite) is solid and impermeable, but when it is under very high pressure it can flow like a thick liquid. When a layer of salt is buried under thousands of feet of overlying sediment, it will start to deform. Because it is less dense than the rocks above it, it flows upward toward areas of lower pressure, forming geological structures named for their shapes (e.g., domes, canopies, tables, and lenses). Salt domes are extremely common geologic features along the Gulf Coast, and their origin lies in the Jurassic, when salt was deposited through evaporation in flat layers now known as the Louann Salt Formation. Today, this salt layer is covered by over 6000 meters (20,000 feet) of sedimentary rock, through which the salt has moved upward with time, forming hundreds of salt domes.
As salt structures grow, they in turn influence the topography of the surrounding landscape, creating zones of uplift, surrounding areas of subsidence, fractures, and faults. When salt flows upward, it deforms the surrounding strata, creating gaps in which oil and gas may pool and be trapped. Oil and gas also accumulate under and along the salt structures. Salt domes have led to some of the most prolific oil reservoirs in the Gulf Coast, both on- and offshore. In addition, due to their inherent impermeability, the salt domes themselves are often solution-mined (by pumping water underground to dissolve the salt) to create caverns that have been used to store petroleum, gas, and even chemical waste.
Offshore Oil and Gas

Today, oil and gas production associated with Coastal Plain sediments has moved mostly offshore, into the Gulf of Mexico. Much of this oil and gas formed and was trapped in similar ways to that onshore, with salt structures leading to offshore traps (see Figure 7.12). Substantial amounts of sediment were eroded from the midcontinent into the Gulf of Mexico by way of river drainage systems, including the ancestral Red, Mississippi, and Sabine rivers. Offshore reservoirs
How does oil drilling work?

Once an oil trap or reservoir rock has been detected on land, oil crews excavate a pit around the area where the well will be drilled. Once the initial hole is prepared, an apparatus called a drilling rig is set up. The rig is a complex piece of machinery designed to drill through rock to a predetermined depth. A typical drilling rig usually contains generators to power the system, motors and hoists to lift the rotary drill, and circulation systems to remove rock from the borehole and lubricate the drill bit with mud. It also contains high-pressure blowout prevention equipment to prevent pressurized oil or gas from rising uncontrollably to the surface after being tapped. The support structure used to hold the drilling apparatus is called a derrick. In the early days of oil exploration, drilling rigs were semi-permanent structures and derricks were left onsite after the wells were completed. Today, however, most rigs are mobile and can be moved from well to well. Once the well has been drilled to a depth just above the oil reservoir, a cement casing is poured into the well to structurally reinforce it. Once the casing is set and sealed, oil is then allowed to flow into the well, the rig is removed, and production equipment can be put in place to extract the oil.

Offshore drilling follows much the same process as onshore drilling, but utilizes a mobile offshore drilling unit (MODU) to dig the well. There are several different types of MODUs, including submersible units that sit on the sea floor, drilling ships, and specialized rigs that operate from atop floating barges.

now exist where sandy sediments accumulated, not just on the continental shelf, but also in deeper submarine fans along the continental slope and even abyssal plain. Many of the offshore reservoirs are found in thick Paleocene to Miocene deposits, with Cretaceous and Eocene-age source rocks. Drilling in the deepest parts of the Gulf is extremely challenging due in part to weather, harsh environments, and water pressure at depth. This became publicly apparent during the Deepwater Horizon oil spill event in 2010, when a seafloor gusher discharged 4.9 million barrels of oil over a period of 87 days before it was capped (Figure 7.15).

Paleocene • a geologic time interval spanning from about 66 to 56 million years ago.

Miocene • a geological time unit extending from 23 to 5 million years ago.

Eocene • a geologic time period extending from 56 to 33 million years ago.

weather • the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity.
Shale Gas
Like the Barnett Shale in the Central Lowland, the late Jurassic Haynesville Shale is a source rock that became a major target for hydraulic fracturing in the mid-2000s. The unit lies greater than 3000 meters (9800 feet) under the surface in large parts of southwestern Arkansas, northwest Louisiana, and east Texas, and is about 70–100 meters (230–330 feet) thick. The formation varies geographically, and includes shale, sandstone, and limestone, but it is the shale that retains large amounts of natural gas trapped in its pores.

The Haynesville Shale, stratigraphically above and slightly younger than the Louann Salt Formation, was deposited during the Jurassic as the Gulf of Mexico continued to expand. At this time, the continental shelf was an oxygen-poor environment with restricted circulation, and black organic-rich shales are commonly laid down in these low-oxygen environments.

The late Cretaceous Eagle Ford Shale in south Texas is another extremely productive onshore area for the extraction of both gas and oil through hydraulic fracturing. The Eagle Ford Shale was deposited along the edge of the continental shelf in quiet, slightly oxygen-poor conditions. Drilling began in 2008, and within a few years the area was one of the largest oil and gas producers in the US. The Eagle Ford is about 20–100 meters (70–230 feet) thick, and it is drilled across a wide spectrum of depths, from about 1300 to over 4000 meters (4300–13,100+ feet) deep, accounting for the variety of hydrocarbons extracted.
Coal
Texas produces more lignite than any other state due to the presence of extensive Eocene-age deposits along the Gulf Coastal Plain, formed from flowering plants living in marshy environments, brackish lagoons, and between streams near the Eocene coastline. These deposits also extend across northern Louisiana and eastern Arkansas, east into Mississippi and Alabama, and north into the Mississippi Embayment (see Figure 7.4). The coal deposits are relatively young and have not been deeply buried, thus the coal has not been subjected to the sort of pressures and temperatures that yield higher-grade coal.

Fossil Fuel Refining and Distribution
In the southern part of the coastal plain, refineries are king; Texas and Louisiana are the two largest producers and refiners of crude oil in the nation, and Louisiana has one of the largest shipping ports for oil in the US. Natural gas also drives the Coastal Plain; harvest of natural gas and the infrastructure to move this energy resource throughout the region are extensive, and this allows for natural gas to be one of the most consumed energies in this region. Louisiana has six deep-draft ports—including the LOOP (the Louisiana Offshore Oil Port)—that transfer large quantities of oil and other commercial goods for shipping around the country, and the world.

Salt domes in the Coastal Plain are also used to store large quantities of oil and gas. Storage caverns are created by injecting the salt with water to dissolve a cavity within the salt structure—a process called solution mining (Figure 7.16). The United States Strategic Petroleum Reserve is one such storage operation, currently holding 619 million barrels of oil in caverns across four salt domes in Texas and Louisiana. Other salt dome storage facilities include Clovelly Dome, which is used to store crude petroleum before it is shipped to refineries, and the Regas Terminal, which stores 127 million cubic meters (4.5 billion cubic feet) of natural gas in a cavern larger than the Eiffel Tower.

Alternative Energy
Although the vast majority of energy in the Coastal Plain is derived from fossil fuels, there is also a variety of alternative and renewable energy production in the region. The Guadalupe River supports a handful of small hydropower plants, and a few wind farms are scattered along the southern Gulf Coast, in areas of favorable wind conditions (see Figure 7.19). The largest of these, Gulf Wind, is a 283 MW project located in Kenedy County, Texas. The Coastal Plain is also rich in biomass resources—organic materials burned to generate energy—with many areas generating up to 200,000 tons of biomass material every year from forestry, urban waste, and agriculture. A cluster of biomass power plants can be found near the city of Houston, producing 29 MW of power, enough to provide around 10% of Houston’s annual electricity demand.

The Coastal Plain also supports a few nuclear power plants. The South Texas Nuclear Project Electric Generating Station is a 2560 MW nuclear power station, located along the Colorado River about 140 kilometers (90 miles) from Houston. There are two nuclear facilities in Louisiana: the Waterford and River Bend reactors, both located along the Mississippi River.
Figure 7.16: Solution mining is used to create a storage cavern inside a salt dome.
Energy in the Great Plains
Region 4

The Great Plains region contains extensive oil and gas resources, specifically from the Hugoton-Panoma gas fields across the northern end of the region and the Permian Basin in Texas. Wind energy is also a major component of power generation in the Great Plains, and some of the largest wind farms in the world are located here.

Oil and Gas
At its southern end in Texas, the Great Plains region contains the Permian Basin, which extends beneath an area approximately 400 kilometers (250 miles) wide and 480 kilometers (300 miles) long (see Figure 7.5). During the Permian, western Texas was covered by an inland sea that featured an ecologically diverse reef system of sponges, algae, bryozoans, and brachiopods. The basin’s reservoir rocks are formed from an extensive, porous framework of preserved limestone and dolostone reefs, formed in a shallow marine setting when the basin was isolated from the accumulation of weathered sediments. Organic-rich shales laid down below, around, and within these reef complexes are the source rocks for the petroleum in the basin. Reservoirs in the Permian Basin have been tapped for oil since the early 20th century (Figure 7.17). Conventional drilling in the Permian Basin had been declining for several decades before hydraulic fracturing was introduced in the late 2000s, restoring the Permian Basin as one of the top US oil producing basins.

Figure 7.17: An oil pumpjack near Electra, Texas. Pumpjacks are part of piston pumps used to lift liquid out of oil wells lacking enough internal pressure to push oil to the surface unaided.
The Hugoton-Panoma gas field, with reservoir rocks including Pennsylvanian and Permian sandstone, limestone, and dolomite, covers 22,000 square kilometers (8500 square miles) across southwestern Kansas, the panhandle of Oklahoma, and northwest Texas (Figure 7.18). Discovered in 1918, it is an extensive natural gas field from which fuel was extracted in large quantities through conventional drilling from the 1930s onward. It was one of the most productive gas fields in the world at its peak in the 1960s and 1970s, producing 19.4 million cubic meters (684.9 million cubic feet) of gas in 1968. The total amount of gas produced is estimated to be 693.8 million cubic meters (24.5 trillion cubic feet) with reserves estimated at 792.9 million cubic meters (28 trillion cubic feet). Unconventional drilling in shale gas units, however, has overtaken the prominence of the Hugoton field. By 2011, production had dropped to 3.7 million cubic meters (129.4 million cubic feet). Hugoton also happens to have long been
one of the world’s primary sources of helium, which has recently become the primary drilling target there.

See Chapter 5: Mineral Resources to learn more about the extraction of helium.

**Wind Farms**

In Texas, oil and gas may be king, but in the low, flat land of the Great Plains, wind energy is fast becoming a major component of energy production. The South Central currently has the highest wind energy capacity in the US, primarily due to wind farms in western and central Texas (but also in parts of the panhandle of Oklahoma, and southwest Kansas). There are more than 50 major wind energy power plants in this area, with proposals for even more plants to come online. The area’s largest wind farms, some among the world’s largest, are located just south of where the Great Plains region borders the Central Lowland (e.g., in the counties of Nolan, Tyler, Sterling, and Coke) ([Figures 7.19 and 7.20](#)). In these areas, wind speed is relatively high and the population is relatively sparse, making broad-scale wind farms more practical than in some other parts of the country. Because of challenges in transmitting large amounts of electrical energy, however, most of this energy is used locally.

*Figure 7.19: Wind speeds in the South Central US. Locations of the largest wind farms are marked in green. Smaller wind farms, not indicated, are much more broadly distributed. (See TFG website for full-color version.)*
Figure 7.20: The Roscoe Wind Farm in Roscoe, Texas, has 634 wind turbines and a total capacity of 781.5 MW, making it the sixth largest wind farm in the world and the third largest in the US.

Energy in the Basin and Range
Region 5

Bordered by the Rio Grande and the Davis and Glass mountain regions, this region is sparsely populated, and it has very little resource development. Some natural gas is extracted from older Paleozoic rocks near the Pecos River, and two small wind farms produce energy in the Sacramento and Hueco Mountains.

Energy Facts by State

Because of many local laws and guidelines, energy production and use is highly dictated by each state government. Below is a state-by-state assessment of energy production and use in the South Central US (from http://www.eia.gov/state/).
Arkansas

- Marketed natural gas production in Arkansas more than doubled from 2008 to 2012; in 2012 it accounted for 4.1% of US marketed production.

- Arkansas, the top rice-producing state as of 2013, typically experiences an increase in natural gas consumption in the industrial sector (including agriculture) in the fall when natural gas is used to dry rice after harvest.

- Coal-fired electric power plants in Arkansas supplied 53% of the state’s electricity in 2013 and relied on coal deliveries via railcar from Wyoming.

- Independent power producers provided over 21% of net electricity generation in Arkansas in 2013.

- Biomass supplied all of Arkansas’ non-hydroelectric renewable energy resources for electricity generation in 2013.
Kansas

- The Hugoton Gas Area, which contains one of the top-producing natural gas fields in the US, is found in southwestern Kansas, as well as in parts of the Texas and Oklahoma panhandles.

- The Mid-Continent Center, located in south central Kansas, is a key natural gas supply hub that takes production from several states in the region and pipes it east toward major consumption markets.

- In 2013, Kansas ranked tenth in crude oil production among the 50 states, excluding federal offshore areas.

- Electric utilities in Kansas provided 82% of the state’s net electricity generation in 2013; 61% of net electricity generation came from coal-fired electric power plants.

- In 2013, 19% of net electricity generation in Kansas came from wind energy.

**Kansas Energy Consumption Estimates, 2012**

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Energy Consumed in Trillion BTUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>267.9</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>140.4</td>
</tr>
<tr>
<td>Motor Gasoline excl. Ethanol</td>
<td>108.2</td>
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<tr>
<td>Distillate Fuel Oil</td>
<td>63.1</td>
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<tr>
<td>Jet Fuel</td>
<td>56.5</td>
</tr>
<tr>
<td>LPG</td>
<td>50.5</td>
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<tr>
<td>Residual Fuel</td>
<td>37.1</td>
</tr>
<tr>
<td>Other Petroleum</td>
<td>37.1</td>
</tr>
<tr>
<td>Nuclear Electric Power</td>
<td>86.8</td>
</tr>
<tr>
<td>Hydroelectric Power</td>
<td>56.5</td>
</tr>
<tr>
<td>Biomass</td>
<td>50.5</td>
</tr>
<tr>
<td>Other Renewables</td>
<td>50.5</td>
</tr>
<tr>
<td>Net Interstate Flow of Electricity</td>
<td>13.9</td>
</tr>
</tbody>
</table>

**Kansas Energy Production Estimates, 2012**

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Energy Produced in Trillion BTUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>336.4</td>
</tr>
<tr>
<td>Natural Gas - Marketed</td>
<td>253.4</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>86.8</td>
</tr>
<tr>
<td>Nuclear Electric Power</td>
<td>58.3</td>
</tr>
<tr>
<td>Biofuels</td>
<td>56.1</td>
</tr>
<tr>
<td>Other Renewable Energy</td>
<td></td>
</tr>
</tbody>
</table>
Louisiana

- The Henry Hub in Erath, Louisiana is the interconnect for nine interstate and four intrastate pipelines that provide access to major markets throughout the country. Henry Hub is used as the pricing point for natural gas futures trading on the New York Mercantile Exchange.

- The Louisiana Offshore Oil Port (LOOP) is the only port in the United States capable of offloading deep-draft tankers.

- The US Strategic Petroleum Reserve’s two Louisiana facilities consist of 29 salt caverns capable of holding almost 300 million barrels of crude oil.

- In 2012, Louisiana ranked third among all states in total energy consumption per capita, primarily because of heavy use in the industrial sector, which includes many refineries and petrochemical plants.

- With 19 operating refineries, Louisiana was second only to Texas as of January 2014 in both total and operating refinery capacity.

---

**Louisiana Energy Consumption Estimates, 2012**

- Coal: 238.8 Trillion BTUs
- Natural Gas: 1575.5 Trillion BTUs
- Motor Gasoline excl. Ethanol: 247.8 Trillion BTUs
- Distillate Fuel Oil: 206.7 Trillion BTUs
- Jet Fuel: 245.5 Trillion BTUs
- LPG: 164.1 Trillion BTUs
- Residual Fuel: 164.1 Trillion BTUs
- Other Petroleum: 89.9 Trillion BTUs
- Nuclear Electric Power: 15.6 Trillion BTUs
- Hydroelectric Power: 117.1 Trillion BTUs
- Biomass: 81.9 Trillion BTUs
- Other Renewables: 2.5 Trillion BTUs

**Net Interstate Flow of Electricity:** 387.1 Trillion BTUs

---

**Louisiana Energy Production Estimates, 2012**

- Coal: 53 Trillion BTUs
- Natural Gas - Marketed: 3058.7 Trillion BTUs
- Crude Oil: 409.9 Trillion BTUs
- Nuclear Electric Power: 164.1 Trillion BTUs
- Biofuels: 107.6 Trillion BTUs
- Other Renewable Energy: 107.6 Trillion BTUs
Missouri
- Missouri was the first state west of the Mississippi River to produce coal in commercial quantities.
- The Rockies Express (REX) is a 107-centimeter, 2702-kilometer (42-inch, 1679-mile) natural gas pipeline stretching from Colorado to Ohio. The REX West portion of the system passes near Kansas City before terminating in northeast Missouri.
- Nine out of ten Missouri households use a central air conditioning system.
- In 2013, coal supplied 83% of Missouri’s net electricity generation.
- Missouri has one nuclear power plant, Callaway Nuclear Generating Station, which contributed 9% of the state’s net electricity generation in 2013.
- Renewable energy resources accounted for nearly 3% of Missouri’s net electricity generation in 2013; most of that generation came from conventional hydroelectric power and wind.

Missouri Energy Consumption Estimates, 2012

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Energy Consumed in Trillion BTUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>258.9</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>346.6</td>
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<tr>
<td>Motor Gasoline excl. Ethanol</td>
<td>171.4</td>
</tr>
<tr>
<td>Distillate Fuel Oil</td>
<td>19.5</td>
</tr>
<tr>
<td>Jet Fuel</td>
<td>27.2</td>
</tr>
<tr>
<td>LPG</td>
<td>45.8</td>
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<tr>
<td>Residual Fuel</td>
<td>6.8</td>
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<tr>
<td>Other Petroleum</td>
<td>65.3</td>
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<tr>
<td>Nuclear Electric Power</td>
<td>112.3</td>
</tr>
<tr>
<td>Hydroelectric Power</td>
<td>12.6</td>
</tr>
<tr>
<td>Biomass</td>
<td>1.8</td>
</tr>
<tr>
<td>Other Renewables</td>
<td>12.6</td>
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<tr>
<td>Net Interstate Flow of Electricity</td>
<td>1.8</td>
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</tbody>
</table>

Missouri Energy Production Estimates, 2012

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Energy Produced in Trillion BTUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>9.2</td>
</tr>
<tr>
<td>Natural Gas - Marketed</td>
<td></td>
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<tr>
<td>Crude Oil</td>
<td>1</td>
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<tr>
<td>Nuclear Electric Power</td>
<td>112.3</td>
</tr>
<tr>
<td>Biofuels</td>
<td>33.9</td>
</tr>
<tr>
<td>Other Renewable Energy</td>
<td>49.5</td>
</tr>
</tbody>
</table>
Oklahoma

- Cushing, Oklahoma is where prices are settled for the New York Mercantile Exchange’s benchmark West Texas Intermediate (WTI) crude oil futures. WTI is a grade of crude oil produced in Texas and southern Oklahoma.

- Excluding Federal offshore areas, Oklahoma ranked fifth in crude oil production in the nation in 2013.

- Oklahoma is one of the top natural gas-producing states in the nation, accounting for 7.1% of US gross production and 8.4% of marketed production in 2013.

- Oklahoma had five operating petroleum refineries with a combined daily capacity of over 500,000 barrels per day (3% of the total US operating distillation capacity) as of January 2014.

- In 2013, Oklahoma ranked fourth in net electricity generation from wind, which provided almost 15% of the state’s net generation.

### Oklahoma Energy Consumption Estimates, 2012

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Trillion BTUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>135.1</td>
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<tr>
<td>Natural Gas</td>
<td>712.8</td>
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<tr>
<td>Motor Gasoline excl. Ethanol</td>
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<td>Distillate Fuel Oil</td>
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<td>Jet Fuel</td>
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<td>LPG</td>
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<td>Residual Fuel</td>
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<td>Other Petroleum</td>
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<tr>
<td>Nuclear Electric Power</td>
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<td>Biomass</td>
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<td>Other Renewables</td>
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<tr>
<td>Net Interstate Flow of Electricity</td>
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### Oklahoma Energy Production Estimates, 2012

<table>
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<tr>
<td>Coal</td>
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<tr>
<td>Crude Oil</td>
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<tr>
<td>Nuclear Electric Power</td>
<td>116.3</td>
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<tr>
<td>Biofuels</td>
<td></td>
</tr>
<tr>
<td>Other Renewable Energy</td>
<td></td>
</tr>
</tbody>
</table>
Texas

- Texas was the leading crude oil-producing state in the nation in 2013, and it exceeded production levels even from the federal offshore areas.

- Texas accounted for 29% of US marketed natural gas production in 2013, making it the leading natural gas producer among the states.

- As of January 2014, Texas’s 27 petroleum refineries had a capacity of over 5.1 million barrels of crude oil per day, accounting for 29% of total US refining capacity.

- Texas leads the nation in wind-powered generation capacity with over 12,000 megawatts. In 2013, Texas generated almost 36 million megawatt hours of electricity from wind energy.

- West Texas Intermediate (WTI), a grade of crude oil produced in Texas and southern Oklahoma, is traded in the domestic spot market at Cushing, Oklahoma, where it serves as a benchmark for oil pricing.

- The average annual electricity cost per Texas household is $1801, among the highest in the nation; the cost is similar to other warm weather states like Florida, according to EIA’s Residential Energy Consumption Survey.
Energy and Climate Change  
The Future of Energy in the US

Americans have come to rely on a diverse and abundant energy system, one that provides a continuous supply of energy with few interruptions. However, climate change is projected to play a big part in altering our supply, production, and demand for energy. Increases in temperatures will see an increase in energy for cooling, while projected increases in the occurrence of hurricanes, floods, tornados, and other extreme weather events will continue to have a significant effect on the infrastructure of power grids and energy delivery systems. Drought and water shortages are already affecting energy production and supply. For example, in the Northeast, mild winter temperatures prior to the winter of 2013–2014 had decreased energy demands for heat, but they did not fully offset increased demands for cooling, and the regionally harsher winter of 2013–2014 saw increased demands for heating fuels. These types of disruptions affect us both locally and nationally, are diverse in nature, and will require equally diverse solutions.

Energy is a commodity, and supply and demand around the world will also affect the US energy system. As the global population grows, and industrialization of the world continues, demand for energy will increase even further as resources are depleted. These factors can significantly affect US energy costs through competition for imported and exported energy products. Mediation of our energy production could have a huge positive impact on climate change. Unfortunately, there is no energy production system or source currently available that is truly sustainable. All forms of energy have negative impacts on the environment, as do many of the ways in which we use them.

Until we have a sustainable means of producing and delivering energy, we need to consider which means of energy production and transport make the least impact; we are faced with a sort of “energy triage.” The answer to this problem will be multifaceted, depending in large part on which energy resources and delivery methods are available in each part of the US. The sources of energy that provide the least impact for the best price for people living in the South Central are probably not the same as those for people living in other areas, such as the Southwest or Northeast.

Adaptation—changing our habits of energy use and delivery—can also make it easier for our existing energy infrastructure to adjust to the needs brought on by climate change. Investing in adaptation can pay off in the short term by reducing risks and vulnerabilities, thus minimizing future risks. Increasing sustainable energy practices (including harvesting and production) and
improving infrastructure and delivery methods can go a long way toward not only decreasing the effects of climate change, but also our energy security.

Some of these changes are grounded in the development of new technologies for energy production and energy efficiency; others may be related to changes in behavior. These changes in technology and behavior may go hand in hand; roughly 2% of electricity production now goes to data centers, for example—a use that did not exist in 1985. Additionally, the Internet is rapidly changing other ways we use energy, allowing us to telecommute and changing the way we shop.

In closing, some key points to keep in mind regarding the future of energy are:

1. Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of extreme weather events are expected to increase.

2. Higher summer temperatures are likely to increase electricity use, causing higher summer peak loads, while warmer winters are likely to decrease energy demands for heating. Net energy use is projected to increase as rising demands for cooling outpace declining heating energy demands.

3. Both episodic and long-lasting changes in water availability will constrain different forms of energy production.

4. In the longer term, sea level rise will affect the coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.

5. As we invest in new energy technologies, future energy systems will differ from the present in uncertain ways. Depending on the way in which our energy system changes, climate change will introduce both new risks and new opportunities.
Resources

Books: General Resources on Energy


Richards, J. 2009. Wind Energy. Macmillan Library, South Yarra, Victoria, Canada, 32 pp. (For primary school age.)


Websites: General Resources on Energy


Energy Resources in the South Central US

For detailed production and capacity data for power plants, see the interactive map at http://www.eia.gov/state.


Energy

Resources


Chapter 8:
Soils of the South Central US

It’s sometimes easy to take the soil beneath our feet for granted. Yet soil has always been with us—it is the foundation of our houses and roads, and from the soil comes our food, fiber, and paper. Soil is the interface between living earth and solid rock, between biology and geology. The engineer, the scientist, and the gardener may all look at the soil beneath them in different ways, but perhaps no one has a more integral relationship with soil than a farmer. The economic success of producing crops is intimately tied to the quality of the soil upon which those crops grow, and the most successful farmers are well versed in the science of their soil. Soils store and purify water, and they exchange gasses with the atmosphere. They support agriculture and natural ecosystems and provide a grassy surface for our parks and fodder for our gardens. Everyone, everywhere, every day, depends upon the soil.

What is Soil?
Generally, soil refers to the top layer of earth—the loose surface of earth as distinguished from rock—where vegetation grows. The word is derived (through Old French) from the Latin solum, which means “floor” or “ground.” Soil is one of the most important resources we have—the most basic resource upon which all terrestrial life depends. The South Central has a wide variety of soils, and each type of soil has a story to tell of its origin.

Soils form from the top down, and typically reach a depth of about one meter (3.3 feet) at their more developed stages, although some can reach much deeper. Soils are composed of a mixture of two key ingredients. The first is plant litter, such as dead grasses, leaves, and fallen debris. Worms, bacteria, and fungi do the job of breaking these down into the nutritious organic matter that helps soil to nourish future plant growth. The second important component of soil is the sediment derived from the weathering of rock that is then transported by wind, water, or gravity. Both of these components influence the texture (Figure 8.1) and consistency of the soil, as well as the minerals available for consumption by plants.

All soils might seem alike, but there can be vast differences in soil properties even within small areas! A single acre may contain several different soil types, each with its own assets and drawbacks. Some types of soil are clayey or prone to flooding, while others are stable enough to be used as a foundation for buildings. The most identifiable physical properties of soils are texture, structure, and color, which provide the basis for distinguishing soil horizons. Texture refers to the percentage of sand, silt, and clay that makes up the soil. Soil textures have specific names, as indicated in Figure 8.1.
Generally, the best agricultural soils are those with about equal amounts of clay, silt, and sand. A soil of that type is called a **loam**. Soils that are mostly sand do not hold water very well and dry quickly, while soils with too much clay may never dry out.

Soil structure refers to the way the soil forms clumps, known as **peds**. Peds are identified by the shape of the soil clods, which take the form of balls, blocks, columns, and plates. These structures are easiest to see in recently plowed fields, where the soil is often granular and loose or lumpy.

Soil color is its most obvious physical property. The color is influenced by mineral content, the amount of organic material, and the amount of water it routinely holds. The colors are identified by a standard soil color chart called the Munsell chart.

Five main variables affect the characteristics of soil worldwide. In the South Central, all soils are the products of subtle differences among these five factors:

1. **Parent material** is the original geologic material from which the soil formed. This can be bedrock, preexisting soils, or other materials such as **till** or **loess**.
2. *Climate* strongly determines the temperature regime, amount of moisture, and type of *biota* that interact with the *parent material*. This affects the extent of chemical and physical weathering on the soil-forming material.

3. *Topography*, or landscape, of the area is related to the relative position of the soil on the landscape. This includes the presence or absence of hills and the slopes between high and low areas. *Topography* influences natural drainage. Gravity moves water down slopes to depressions or streams and pulls free water downward through the soil. Soils on hills tend to be dry, and soils in depressions and valleys are often wet or saturated. Areas with steep slopes that are susceptible to frequent *erosion* typically have very young soils, as they do not have long to develop before the ingredients are rearranged and the clock is reset. Flatter, more arid areas may have more time to develop, but they have significantly less plant life and will produce a very different soil than will a wetter environment.

4. *Biota* or living organisms that live on or in the material affect soil development through their influence on the amount and distribution of organic matter in the soil. For example, plants contribute significantly to the formation of *humus*, and animals alter a soil’s characteristics by leaving behind decayed remains and wastes. Decomposers like bacteria and fungi help to free up the nutrients locked away in these remains and wastes, and these freed nutrients are then recycled and used by new life forms within the same soil. In fact, more than 90% of the nutrients used by a forest in a given year are derived from the decomposition of old organic matter fallen to the forest floor. Animal burrows also create spaces in the soil horizons that allow for deeper penetration of air and water, which, in turn, aid plant development. For its part, organic matter impacts the water-holding capacity of the soil, the soil’s fertility, and root penetration.

5. *Time* is required for soils to develop while the four elements mentioned above interact. Older soils have deeper and thicker subsoils than do younger soils, but only if other soil forming factors remain constant. In west-central Kansas, for example, it takes approximately 500 years to generate a new 2.5 centimeters (1 inch) of *topsoil* beneath the prairie grass—but it only takes a few years for erosion and weathering to destroy the same amount of unprotected topsoil.

Several types of *chemical reactions* are important for soil development; of these, acid-base reactions are some of the most important and complex. When carbon dioxide (CO$_2$) dissolves in water it forms weak carbonic acid. CO$_2$ found in soil water can come from the atmosphere, where it dissolves in rainwater. Even more CO$_2$ usually comes from the soil itself, where it is produced by respiring organisms. The amount of CO$_2$ in soil gases can easily reach levels ten times higher than the amount found in the atmosphere (over 4000 ppm in soil vs. 400 ppm in the atmosphere), making soil water potentially more acidic than rainwater. As this acidic water slowly reacts with fresh minerals, it
buffers the soil’s pH and keeps it in a range (6-8) preferred by many organisms. Acid-driven weathering breaks down the soil’s primary igneous minerals, typically transforming them to silica-rich clays. As the soil’s primary minerals are depleted, it loses the ability to buffer acidity, and the pH of highly weathered soil can drop to around 4. These weathered soils tend to be rich in aluminum, iron, and titanium.

In highly weathered settings, soil loses most of its nutrients, and the store of nutrients that remains is mostly found in organic matter. In weathered soils, only the top 25 cm (10 inches) or so may be very biologically active, and rooting depths are very shallow. If this thin layer is lost to erosion, the underlying mineral soil may be infertile and incapable of rapid recovery.

Soil Orders
Just as rocks are classified into different types based on how they formed (igneous, metamorphic, or sedimentary), their mineral composition, and other characteristics, soils also have their own classification scheme. Soil develops in horizons, or layers, whose formation is dependent on the available ingredients, environmental conditions, and the time to mature. More mature soils will develop a variety of horizons unique to their environmental conditions, creating a soil profile. Some horizons are completely absent in certain profiles while others are common to most. Each horizon corresponds to a stage in the weathering of rock and decay of plant matter, and each is found at a specific position beneath the surface (Figure 8.2).

![Figure 8.2: A typical soil profile shows the transition from the parent material (horizon C) to the highly developed or changed horizons (O through B). Not every soil profile will have all the horizons present.](image-url)
Soils can also be categorized by their location (northern vs. southern soils), the type of vegetation growing on them (forest soils vs. desert soils), their topographic position (hilltop soils vs. valley soils), or other distinguishing features. The system used to classify soils based on their properties is called **soil taxonomy** (*Figure 8.3*), and it was developed by the United States Department of Agriculture (USDA) with the help of soil scientists throughout the country. It provides a convenient, uniform, and detailed classification of soils throughout the country (*Figure 8.4*), allowing for an easier understanding of how and why different regions have developed unique soils.

In soil taxonomy, all soils are arranged into one of 12 major units, or **soil orders**. These 12 orders are defined by diagnostic horizons, composition, soil structures, and other characteristics. Soil orders depend mainly on **climate** and the organisms within the soil. These orders are further broken down into 64 suborders based on properties that influence soil development and plant growth, with the most important property being how wet the soil is throughout the year. The suborders are, in turn, separated into great groups (300+) and subgroups (2400+). Similar soils within a subgroup are grouped into even more selective families (7500+), and similar soils within families are grouped together into the most exclusive category of all: a series. There are more than 19,000 soil series described in the United States, with more being defined every year.

*Figure 8.3: Soil taxonomy.*

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**sedimentary rock**
- rock formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter.

**climate**
- a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).
Figure 8.4: Dominant soil orders of the United States. (See TFG website for a full-color version.)
## The 12 soil orders

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Controlling Factors</th>
<th>Percentage of global ice-free land surface</th>
<th>Percentage of US ice-free land surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfisols</td>
<td>Highly fertile and productive agricultural soils in which clays often accumulate below the surface. Found in humid and subhumid climates.</td>
<td>climate and organisms</td>
<td>~10%</td>
<td>~14%</td>
</tr>
<tr>
<td>Andisols</td>
<td>Often formed in volcanic materials, these highly productive soils possess very high water- and nutrient-holding capabilities. Commonly found in cool areas with moderate to high levels of precipitation.</td>
<td>parent material</td>
<td>~1%</td>
<td>~2%</td>
</tr>
<tr>
<td>Aridisols</td>
<td>Soils formed in very dry (arid) climates. The lack of moisture restricts weathering and leaching, resulting in both the accumulation of salts and limited subsurface development. Commonly found in deserts.</td>
<td>climate</td>
<td>~12%</td>
<td>~8%</td>
</tr>
</tbody>
</table>
### The 12 soil orders (continued)

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Description</th>
<th>Dominant Controlling Factors</th>
<th>Percentage of Land Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entisols</td>
<td>Soils of relatively recent origin with little or no horizon development. Commonly found in areas where erosion or deposition rates outpace rates of soil development, such as floodplains, mountains, and badland areas.</td>
<td>time and topography</td>
<td>~16%</td>
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<tr>
<td>Gelisols</td>
<td>Weakly weathered soils formed in areas that contain permafrost within the soil profile.</td>
<td>climate</td>
<td>~9%</td>
</tr>
<tr>
<td>Histosols</td>
<td>Organic-rich soils found along lake coastal areas where poor drainage creates conditions of slow decomposition and peat (or muck) accumulates.</td>
<td>topography</td>
<td>~1%</td>
</tr>
<tr>
<td>Inceptisols</td>
<td>Soils that exhibit only moderate weathering and development. Often found on steep (relatively young) topography and overlying erosion-resistant bedrock.</td>
<td>time and climate</td>
<td>~17%</td>
</tr>
</tbody>
</table>
## The 12 soil orders (continued)

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Description</th>
<th>Factors Influencing</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mollisols</strong></td>
<td>Agricultural soils made highly productive due to a very fertile, organic-rich surface layer.</td>
<td>climate and organisms</td>
<td>~7% ~22%</td>
</tr>
<tr>
<td><strong>Oxisols</strong></td>
<td>Very old, extremely leached and weathered soils with a subsurface accumulation of iron and aluminum oxides. Commonly found in humid, tropical environments.</td>
<td>climate and time</td>
<td>~8% ~.02%</td>
</tr>
<tr>
<td><strong>Spodosols</strong></td>
<td>Acidic soils in which aluminum and iron oxides accumulate below the surface. They typically form under pine vegetation and sandy parent material.</td>
<td>parent material, climate, and organisms</td>
<td>~4% ~4%</td>
</tr>
<tr>
<td><strong>Ultisols</strong></td>
<td>Soils with subsurface clay accumulations that possess low native fertility and are often red hued (due to the presence of iron oxides). Found in humid tropical and subtropical climates.</td>
<td>climate, time, and organisms</td>
<td>~8% ~9%</td>
</tr>
</tbody>
</table>
Vertisols are clayey soils with high shrink/swell capacity. During dry periods, these soils shrink and develop wide cracks; during wet periods, they swell with moisture.

| Vertisols | Clayey soils with high shrink/swell capacity. During dry periods, these soils shrink and develop wide cracks; during wet periods, they swell with moisture. | parent material | ~2% | ~2% |

**Dominant Soils of the South Central**

Eight soil orders are found in the South Central, with the greatest diversity found within the Coastal Plain.

**Alfisols** are partially leached soils with a high degree of fertility that form primarily in forested regions. These soils tend to develop in cooler, more forested environments, and they commonly form a band separating more arid areas from humid areas. They are found throughout the South Central region, particularly in the Coastal Plain and Central Lowland (Figure 8.5).

**Aridisols** are very dry soils that form in arid environments, such as the Basin and Range region (Figure 8.6). Water content is very low or even nonexistent for most of the year, leading to limited leaching. The lack of leaching means that there is abundant calcium carbonate in the soils, which makes them quite alkaline. This soil type is unsuitable for plants that are not adapted to store water or to survive extreme drought.

**Entisols** are soils of recent origin with poorly developed horizons, typically formed near floodplains. They are not common in the South Central, but they are found in all five of its regions (Figure 8.7).

**Histosols** are carbon-rich soils, where half or more of the upper 80 centimeters (32 inches) is organic. They contain high concentrations of organic matter, due to their development in wetland environments with poor drainage and a slow rate of decomposition. They are saturated year round, and are often called bogs, moors, peats, or mucks. In the South Central, they are found along the coast of Louisiana in the Coastal Plain (Figure 8.8).

**Inceptisols** are soils with poorly developed horizons that are associated with steep slopes and resistant parent material. They are located in cool to very warm, humid, and subhumid regions. They often overlie erosion-resistant bedrock and are scattered around most regions of the South Central (Figure 8.9).
Figure 8.5: Alfisols of the South Central.

Figure 8.6: Aridisols of the South Central.
Figure 8.7: Entisols of the South Central.

Figure 8.8: Histosols of the South Central.
Figure 8.9: Inceptisols of the South Central.

Figure 8.10: Mollisols of the South Central.
Figure 8.11: Ultisols of the South Central.

- oxidation • a chemical reaction involving the loss of at least one electron when two substances interact.
- delta • a typically wedge-shaped deposit formed as sediment is eroded from mountains and transported by streams across lower elevations.
- alluvial • a thick layer of river-deposited sediment.
- outwash plain • large sandy flats created by sediment-laden water deposited when a glacier melts.
- glacier • a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.

Figure 8.12: Vertisols of the South Central.
Mollisols are the dominant soils of grasslands. The thick, black A horizon makes these soils extremely productive and valuable to agriculture. They are one of the most abundant soil types in the South Central (Figure 8.10).

Ultisols are soils with clay accumulations below the surface (often red, due to iron oxides) and low native fertility. They form in humid areas and, like Alfisols, have a clay-enriched subsoil. Ultisols often support forest vegetation, so they are most common in the forested areas of the South Central (Figure 8.11).

Vertisols are very dark soils, rich in swelling clays. Their distinguishing feature is that they form deeply cracked surfaces during dry periods, but they swell again in the wet season, which seals all the cracks. As a result, they are very difficult soils to build roads or other structures on. Vertisols are found primarily in the Coastal Plain region (Figure 8.12).

Geology of the South Central: Parent Material
The South Central is home to a variety of parent materials—the minerals and organic matter from which its soils are derived (Figure 8.13). The floodplain and delta of the Mississippi River provide alluvial sediments: silt- and clay-rich parent materials that produce agriculturally rich soils. In fact, the Mississippi River floodplain and delta together represent the largest contiguous set of alluvial deposits in the US (Figure 8.14). Many of these deposits result from glacial outwash.

Although the South Central was not subjected to the degree of glaciation experienced by more northern regions of the US, the pre-Illinoian glacial advance did reach the northern part of Missouri and the northwest portion of Kansas. This glaciation lead to the accumulation of loess deposits (Figure 8.15), carried by wind and deposited by river systems, that are responsible for the development of some of the extremely productive agricultural soils found there today.

Weathered sedimentary rock is perhaps the most ubiquitous parent material in the South Central. Sandstone, siltstone, limestone, and shale are among the most common bedrocks across the South Central States; over time, erosional processes have contributed to the formation of soils from all of these sedimentary substrates.
Mollisols are the dominant soil type in the Central Lowland region, formed where organic matter accumulates beneath prairie grasses and in poorly drained forests (Figure 8.16). In many cases, these soils are underlain by thick deposits of glacial loess, which has contributed to their rich nutrient content (see Figure 8.15). Mollisols are highly productive dark soils, and most of the native grassland that produces them has been converted to agricultural land. Tallgrass prairie once covered more than 69 million hectares (170 million acres) of North America. 

hectare • a metric unit of area defined as 10,000 square meters.
America, but today nearly 96% of it has been converted to agricultural land (Figure 8.17). The Mollisols of the Central Lowland have a distinct zonation in type, reflecting the region’s climatic gradation from wetter in the east to drier in the west. The dominant Mollisols in Missouri, eastern Kansas, and east-central Oklahoma are wetter and occur close to the \textit{water table}, while those in west-central Oklahoma and north-central Texas form under semi-arid climates. These drier Mollisols, belonging to the suborder Ustolls, can become even more dusty and dry during drought conditions, limiting crop yields and leading to damaging dust storms such as those that occurred during the Dust Bowl of the 1930s.

Alfisols are also very common in the Central Lowland, particularly in northeastern Missouri. They generally form in forested areas as a result of weathering processes that leach minerals from the surface layer into the subsoil, where nutrients are retained. Alfisols in the Central Lowland exhibit the same type of wet-dry zonation as the Mollisols.
Entisols, young soils lacking in horizons, are found where erosion and deposition occur faster than the rate of soil formation. In the Central Lowland, they typically appear in floodplains where alluvial sediments are deposited. They are present along the Missouri River and are scattered along river courses throughout Oklahoma and northern Texas.

Inceptisols and Vertisols can be found scattered throughout the southern part of the Central Lowland region (Oklahoma and Texas).
Soils

Figure 8.16: An example of a Mollisol soil. These soils have a rich, dark surface horizon and are high in organic matter content.

Figure 8.17: Tallgrass Prairie National Preserve near Strong City, Kansas. This type of grassland is a typical environment for the formation of Mollisols. Today, most of it has been converted for use in agriculture.
Soils of the Interior Highlands
Region 2

The most common soils in the Interior Highlands are Ultisols, especially in forested, higher-elevation areas. Ultisols are rich in clay, and red in color due to their high iron and aluminum content (Figure 8.18). They are low in fertility, with most nutrients concentrated in the uppermost horizon. Ultisols tend to be acidic and are therefore poorly suited to agriculture, although they can be improved using fertilizer and lime.

Moisture-rich Alfisols of the suborder Udalfs are more common in the lower-elevation portions of this region, especially Missouri. They are fertile and can support a reasonable amount of plant growth.

Other soil types that appear in the Interior Highlands are uncommon. Vertisols occur only in parts of the lower valley of the Arkansas River, and Entisols appear along only a few streams in southern Missouri. Likewise, Inceptisols are rare, occurring only in the lower-elevation parts of Missouri. In stark contrast to the Central Lowland, Mollisols are also extremely rare in this region, and are only found in isolated valleys in Missouri.

Figure 8.18: Vivid red Ultisols are exposed at the surface near a roadside in western Arkansas. (See TFG website for full-color version.)

Soils of the Coastal Plain
Region 3

The only Histosols in the South Central occur in coastal Louisiana, especially in the Mississippi Delta. These organic soils form from the slow decomposition of organic detritus in wetland environments (Figure 8.19). Swampy, waterlogged soils are often drained to accommodate human settlement, which causes
them to condense and subside. In addition, a series of floodwater-diverting levees block the coast of Louisiana from receiving new alluvial sediments that would counteract subsidence. These factors and others have contributed to the loss of Louisiana’s wetlands, in turn reducing the protection such wetlands provide against hurricanes.

Ultisols are common in the forested part of the Coastal Plain region, spanning northwestern Louisiana and eastern Texas. These clay-rich soils are interspersed with Alfisols, which are common in southeastern Missouri, eastern Arkansas, central Louisiana, and southeastern Texas. The Alfisols in Texas show a climate gradation from warm, moist soils in the coastal areas to drier soils in the inland parts of the Coastal Plain.

Most Entisols in the South Central are found along the Mississippi River, but they are also scattered along the Red River in central Louisiana and in Texas near the coastline. These soils, generated by the deposition of floodplain alluvium (Figure 8.20), are often highly productive for agricultural use.

Most of the South Central’s Vertisols are found in the Coastal Plain. During dry periods, these clayey soils shrink and form wide cracks at the surface (Figure 8.21); these cracks seal shut again when moisture enters the soil. Because Vertisols shrink and swell so readily, it is extremely difficult—and even dangerous—to build structures or roads on top of them. The action of shrinking...
Region 3

**Cretaceous** • a geologic time period spanning from 144 to 66 million years ago.

**basalt** • an extrusive igneous rock, and the most common rock type on the surface of the Earth.

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Figure 8.20: Entisols at the mouth of Long King Creek, Polk County, Texas.

Figure 8.21: Cracks in a dried-out Vertisol clay found in Arkansas.
and swelling within the soil also prevents the formation of distinct horizons. Drier-condition Vertisols are very common in a belt that follows clay-rich Cretaceous rocks corresponding to the Balcones Escarpment; they develop from parent materials rich in magnesium and calcium, such as limestone and basalt. Wetter-condition Vertisols are found along the lower Mississippi River, the Red River in Louisiana, and some of the larger rivers in southeastern Texas, such as the Brazos River.

Aridisols do occur in the Coastal Plain region, but not near the coast. They are limited to the hot interior of southern Texas, in areas that are generally higher in elevation.

Mollisols are relatively uncommon and are found mostly in southeastern Texas, away from the coast. These soils form under drier conditions, like the Mollisols in the Texas portion of the Central Lowland.

Inceptisols are scattered along streams in eastern Louisiana and eastern Texas, and along the edge of northeastern Arkansas in a belt of slightly higher-elevation terrain.

### Soils of the Great Plains Region 4

The most common soils in the Great Plains area are Mollisols, which are widespread throughout the region. These loamy soils are well-drained and permeable, containing ample organic matter and a high nutrient content (see Figure 8.16). Most Great Plains Mollisols have been cultivated for use as farmland. In a portion of West Texas, they occur above igneous parent material, but they otherwise occur atop a variety of geologic substrates. In the Mollisols of Texas, carbonate minerals and salts leaching from upper layers of the soil often accumulate to such a degree that they form a cemented soil horizon called caliche.

Alfisols in the Great Plains are mostly limited to drier and slightly higher-elevation plateaus of northern Texas, such as the Llano Estacado, where they are interspersed with Mollisols. Aridisols occur in the lower-elevation portions of this area, especially around the border with southeastern New Mexico. Entisols are very limited in extent, occurring mostly along the Canadian and Pecos rivers. Inceptisols are likewise limited and are found only in the northernmost parts of Texas in the Great Plains region. Vertisols are limited to a small area in western Texas.

See Chapter 2: Rocks for more about the Balcones Escarpment.

See Chapter 5: Mineral Resources to learn more about the formation and uses of caliche.
Soils of the Basin and Range
Region 5

The Basin and Range region is very rugged, but its soils do not follow any particular pattern coinciding with elevation and slope. Instead, the soils tend to correspond particularly well to the region’s underlying geology. Unsurprisingly, Aridisols—dry, coarse soils formed from the weathering of limestones and carbonate parent material deposited in ancient seas—are the most common soil type in the Basin and Range (Figure 8.22). Due to a lack of precipitation that would leach out soluble minerals, Aridisols contain high concentrations of gypsum, carbonates, and salt, which sometimes solidifies into caliche.

See Chapter 2: Rocks for more on the formation of different rock types in the Basin and Range.

Figure 8.22: An example of an Arisol soil. These coarse-grained soils are found in desert or arid environments.

Mollisols are common in the Basin and Range, but are almost entirely limited to an area in the central part of the region that contains an igneous geologic substrate. Entisols are the most common soils outside the area occupied by Mollisols, and occur mostly on Permian and late Cretaceous rocks.

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gypsum • a soft sulfate mineral that is widely mined for its use as fertilizer and as a constituent of plaster.

Permian • the geologic time period lasting from 299 to 252 million years ago.
State Soils

Just as many states have official state flowers, birds, and fossils, they also have official soils. State soils are most often determined by a vote of soil scientists in the state, and, absent any political wrangling, usually represent the most productive soils and those that most closely resemble everyone’s favorite soil: loam. As mentioned earlier, loam soils are almost equal parts sand, silt, and clay.

Arkansas
The state soil of Arkansas is a group of Vertisols, known as Stuttgart soils, that covers some 81,000 hectares (200,000 acres). These soils are found in the Lower Mississippi Valley, and they are ideal for rice production.

Kansas
The dominance of Mollisols in the Great Plains extends into Kansas, so it is not surprising that the state soil of Kansas—the Harney series—is made up of Mollisols. Covering 1.6 million hectares (4 million acres), Harney soils make Kansas one of the largest producers of wheat, grain sorghum, and silage.

Louisiana
The state soil of Louisiana is the Ruston series. A type of Ultisol, Ruston soils are found in woodland environments, and they cover roughly 300,000 hectares (740,000 acres) of the state.

Missouri
In Missouri, along the Missouri and Mississippi rivers, Menfro soils, a type of Alfisol, cover about 315,000 hectares (780,000 acres). These well-drained, loamy soils are used to grow a variety of crops ranging from corn to grapes to tobacco.

Oklahoma
In Oklahoma, the state soil is called the Port series—Mollisols that cover 400,000 hectares (1 million acres) of land. These soils are agriculturally productive, and most areas of the Port series are used as cropland, supporting alfalfa, wheat, grain sorghum, and cotton.

Texas
Houston Black, a Vertisol, is the state soil of Texas. It covers 600,000 hectares (1.5 million acres) in a north-south trending belt in the far western portion of the Coastal Plain, where crops of cotton and corn are grown.
8 Soils

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Climate is a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years. These factors interact with and are influenced by other parts of the Earth system, including geology, geography, insolation, currents, and living things.

Because it is founded on statistics, climate can be a difficult concept to grasp, yet concrete examples can be illuminating. Terms like “desert,” “rain forest,” and “tundra” describe climates, and we have gained a general understanding of their meaning. Climate can also encompass the cyclical variations a region experiences; a region with a small temperature variation between winter and summer—San Francisco, for example—has a different climate from one that has a large variation, such as Buffalo. Scientists have settled on 30 years as the shortest amount of time over which climate can be defined, but it can of course also define time periods millions of years in length.

You cannot go outside and observe climate. Weather, on the other hand, can be observed instantly—it is 57 degrees and raining right now. Weather varies with the time of day, the season, multi-year cycles, etc., while climate encompasses those variations. Our choice of clothing in the morning is based on the weather, while the wardrobe in our closet is a reflection of climate. Residents of the South Central have a diverse wardrobe. While the entire area experiences seasonal change, the greatest variation occurs in the north, so those living in the interior states have a greater need for warm winter clothes than do those who live along the coast.

Past Climates
Climate, like other parts of the Earth system, is not static but changes over time, on both human and geologic time scales. Latitude, for example, has a very direct effect on climate, so as the continents shift over geologic time, the climates on them also shift. Furthermore, the conditions on Earth as a whole have varied through time, altering what kinds of climates are possible. The land that is now the South Central US has been arid, warm-temperate, and tropical at different times during the past 500 million years!

Ancient climates are reconstructed through many methods. Written records and tree rings go back hundreds of years, glacial ice cores hundreds of thousands of years, and fossils and rocks that indicate different climates go back hundreds of millions of years. These clues, coupled with modeling and a knowledge of physics and chemistry, help climatologists put together an increasingly detailed history of the Earth’s climate, and of that of the South Central. Unfortunately, we do not have as clear an understanding of climate for the earliest part of Earth history as we do for the later parts, because the oldest rocks are much more...
difficult to find. However, we can still say something about the climate of the ancient Earth, in large part due to our knowledge of atmospheric chemistry.

Ancient Atmosphere
Not long after the Earth first formed, more than 4.5 billion years ago, its atmosphere was composed mostly of hydrogen and helium. Volcanic activity and collisions with meteorites and comets added water vapor, carbon dioxide (CO₂), and nitrogen to the atmosphere. As the Earth cooled enough for liquid water to form, the vapor formed clouds from which the rain poured forth in such a deluge as the planet will never experience again. These torrential rains were constant for millions of years, absorbing salt and other minerals from the soil as the rainwater coursed to the lowest areas, forming Earth’s oceans and seas.

At this time, the sun produced significantly less energy than it does today, so one might expect that once the oceans formed, they would continue to cool and eventually freeze. Yet temperatures stabilized, perhaps because there was a greater concentration of potent greenhouse gases in the atmosphere and less land surface to reflect light, so temperatures remained high enough for liquid water to exist. Indirectly, the ocean was responsible for the final ingredient of the modern atmosphere because it was home to the first life on Earth. Photosynthetic bacteria appeared perhaps as early as 3.5 billion years ago, but the abundant iron and organic matter quickly absorbed the oxygen they produced. After hundreds of millions of years, these sinks were filled, and free oxygen could finally build up in the atmosphere. With this addition, the modern atmosphere was complete, though the relative amounts of the gases composing it would, and still continue to, shift. The composition of the atmosphere and the huge volume of water on Earth are two of the most important factors affecting climate.

While the atmosphere was forming about 3.7 billion years ago, the surface of the Earth was cooling to form a solid crust of rock (although there are indications that this process may have started as early as 4.4 billion years ago). Regardless of precisely when this took place, it represented the beginning of tectonic processes that have continued ever since. Molten rock from the mantle constantly wells up from deep fissures and solidifies into relatively dense rock, while more buoyant rock floats higher on the magma and is pushed around on
the slow conveyor belts of mantle-formed rock (Figure 9.1). Denser rock forms oceanic plates that are lower and covered in water, and lighter rock forms continental plates, though part or all of a continental plate may be submerged under a shallow sea. The motion of these plates, the rearranging of the continents, and the amount and types of minerals exposed to the atmosphere play a huge role in the climate. Not only do the continents and oceans move through different climate zones, but the continents also affect climate based on their size, and the weathering of rock on the continents plays a large role in the composition of the atmosphere. For example, rock that is enriched in organic matter will release abundant amounts of carbon dioxide as it weathers, while rock rich in feldspar and mica will take up carbon dioxide.

Nearly one billion years ago, the Earth began fluctuating between warm and cool periods lasting roughly 150 million years each. During the cool periods, there is usually persistent ice at the poles, while during the warm periods there is little or no glaciation anywhere on Earth. Today, we are still in a cool period—although the world has been cooler than it is at present, it has been much hotter for much of its history (Figure 9.2). Through the shifting global climate and the movement of the continents, what is now the South Central has at times been submerged beneath a shallow sea, a verdant plain filled with swamps and rivers, and even buried under ice.

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**density** • a physical property of minerals, describing the mineral’s mass per volume.

**magma** • molten rock located below the surface of the Earth.

**plates** • large, rigid pieces of the Earth’s crust and upper mantle, which move and interact with one another at their boundaries.

**weathering** • the breakdown of rocks by physical or chemical means.

**feldspar** • an extremely common, rock-forming mineral found in igneous, metamorphic and sedimentary rocks.

**mica** • a large group of sheetlike silicate minerals.
Snowball Earth

There is evidence suggesting that the entire surface of the planet has been covered in ice several times, a hypothesis called Snowball Earth (Figure 9.3). Glacial deposits discovered near Lake Huron and elsewhere show that starting about 2.4 billion years ago the entire surface of the Earth may have been covered in ice for as long as 300 million years, an event known in North America as the Huronian glaciation. At that time the continental plates made up less than half as much of the Earth’s surface as they do today and were unified as the continent Arctica. It may have been early life’s production of oxygen that reacted with and lowered the amount of the greenhouse gas methane in the atmosphere, which tipped the Earth towards a series of cooling feedbacks, causing ice to spread from pole to pole.

An ice-covered planet would remain in that state because almost all of the sun’s energy would be reflected back into space, but this did not happen on Earth because of plate tectonics—the Snowball Earth cycle was eventually disrupted by volcanic activity. While the Earth was covered in ice, volcanoes continued to erupt, dumping carbon dioxide and methane into the atmosphere. While these gases are usually removed from the atmosphere by organisms and the weathering of rocks, this was not possible through miles of ice! After millions of years, the concentrations of methane and CO$_2$ increased to the point that greenhouse warming began to melt the ice sheets. Once the melting started, more of the sun’s energy was absorbed by the surface, and the warming
feedbacks began. Because the oceans had been covered, nutrients derived from volcanic gases and chemical changes in the rocks accumulated in the waters. Once they were re-exposed to light, a population explosion of cyanobacteria produced more and more oxygen, which was capable of combining with freshly thawed carbon sources to make more carbon dioxide, further enhancing the warming.

For the next 1.5 billion years, the South Central, free of ice, drifted around the surface of the Earth. A new supercontinent—Rodinia—formed, and the part that is now North America was stable, forming what is known as a craton, or continental interior relatively free of the folding and faulting that characterizes continental margins that are subjected to mountain building and other plate tectonic processes. About 850 million years ago, during the Cryogenian, the Earth entered a 200-million-year ice age, during which there were two more Snowball Earth cycles. Although the part of Rodinia that would eventually become North America was located near the equator, the fact that North
Past

America was at such a low latitude, yet had glaciers, is strong evidence that the Earth really did freeze over completely. However, no direct evidence for any of the Snowball Earth cycles comes from rocks in the South Central.

Life and Climate

With the start of the Paleozoic era, climates across the world were warm, and North America was located in the low and warmer latitudes of the Southern Hemisphere. As the Cambrian progressed, North America moved northward; by about 480 million years ago, what would become the South Central US was located just below the equator (Figure 9.4). In Texas, the presence of Cambrian sandstone indicates that sediments were carried to the sea from the land to the northwest. East of the sandstone, a rich and diverse marine fauna, including trilobites, brachiopods, bivalves, sponges, and other invertebrates, is contained within dolomite and limestone units. Although sedimentary rocks of Cambrian age are only exposed in Texas, most of the South Central was probably home to warm, shallow seas that persisted into the Ordovician.

See Chapter 3: Fossils for more information about life in the Paleozoic.

Figure 9.4: The location of the continents during the A) early and B) late Cambrian. Note the position of North America relative to the equator.

At the end of the Ordovician, from 460 to 430 million years ago, the Earth fell into another ice age, but Silurian and Devonian fossils in Oklahoma (including trilobites and brachiopods) indicate that the South Central still contained warm, shallow seas through the early Devonian. After an episode of uplift and erosion, however, the environment changed dramatically. The seas became deeper, and plankton productivity grew so high that it depleted all the oxygen from the seafloor and sediments. The lack of oxygen allowed organic matter to accumulate instead of decaying, leading to the deposition of black, carbon-rich
shale. Drill cores show us that this rock occurs throughout the subsurface in the western two-thirds of Oklahoma and northern Texas; it is one of the richest sources of petroleum in those states.

From 430 to 300 million years ago, North America moved north across the equator, and the cycle of warming and cooling was repeated yet again. Glaciation in the southern hemisphere occurred during the late Devonian, while the supercontinent Gondwana was located over the South Pole. At the same time, while the South Central States were still submerged, the oceans between Gondwana and North America began to close (Figure 9.5). By the early Carboniferous, ice capped the South Pole and began to expand northward. Although the Earth's temperature fell during this time and the growing glaciers far to the south caused sea levels to drop, the northern part of the South Central returned to a warm, shallow sea with limestone and abundant marine life, including brachiopods, corals, and echinoderms, while the southern part accumulated thick deposits of sandstone and shale. By the late Carboniferous, North America had collided with Gondwana, advancing the formation of Pangaea—a supercontinent composed of nearly all the landmass on Earth. The Ouachita Mountains, remnants of what was once a chain of mountains that may have been as high and broad as the Tibetan Plateau, bear witness to this event. Sedimentary rocks indicate that most of the South Central was now covered by rivers and plains; Oklahoma, Kansas, and Arkansas had flourishing coastal swamps filled with vegetation that has since been transformed into rich coal beds by heat and pressure. Many Carboniferous rocks in the South Central, especially in Kansas, are cyclic, showing repeated episodes of sea level fall and rise as the ice cap in the Southern Hemisphere advanced and retreated.

During the Permian, as sea levels dropped, shallow marine waters gave way to lowland coastal areas, and most of the South Central also became terrestrial. The Permian Basin in western Texas remained marine, however, and an enormous barrier reef formed around its rim. Part of this reef can be seen at El Capitan in Guadalupe Mountains National Park (Figure 9.6). During the Permian, the climate was drier than that of the Carboniferous, and extensive salt and gypsum deposits indicate that evaporation rates were high. A shift in plant type—from water-loving ferns and horsetails to plants better adapted for drier conditions—is further evidence of arid conditions during this time. By the end of the Permian, the southern ice sheets had disappeared, and desert conditions existed in the core of the supercontinent (as indicated, for example, by what look like sand dunes preserved in sedimentary rocks).

Around 220 million years ago, the South Central moved north from the equator. The Earth remained warm and ice-free at the poles through much of the Mesozoic era, until worldwide temperatures began to dip again around 150 million years ago. After reaching its greatest size during the Triassic period, Pangaea began to break apart into continents that would drift toward their modern-day positions. The South Central’s climate gradually shifted, becoming wetter. Triassic rocks are known only from far western Oklahoma and Texas,
where they contain a rich terrestrial and lake fauna of fishes, amphibians, and reptiles.

Jurassic outcrops in western Oklahoma are terrestrial and contain petrified wood, dinosaurs, and other reptiles indicative of lake environments, revealing that the environment there did not change much from the Triassic (except to become a bit wetter). Farther south, however, the breakup of Pangaea caused the Gulf of Mexico to rift open, flooding it with seawater. Because the climate was still relatively warm and dry, evaporation rates were high, and extremely thick deposits of salt accumulated there. These salt deposits have played a
key role in trapping petroleum along the Gulf Coast. At the same time, the portion of the South Central that bordered the coastline began to subside, and thick deposits of coastal and marine sediments began to accumulate, a process that continues to this day.

The Earth warmed near the beginning of the Cretaceous, and sea level rose. Throughout the Cretaceous, sea level was an average of 100 meters (330 feet) higher than it is today, largely as a result of water displacement by continental rifting and rapid sea-floor spreading. Shallow seaways spread over many of the continents, and by the start of the late Cretaceous, North America was divided in two by an inland sea known as the Western Interior Seaway (Figure 9.7). This sea flooded most of the South Central, covering older rocks and creating a wide belt of Cretaceous- and younger-aged rock that extends many hundreds of miles up the Mississippi River and covers all of Louisiana, about half of Texas, and parts of Arkansas, Oklahoma, and Missouri.

At the close of the Cretaceous, 65 million years ago, global climates (though still much warmer than those of today) were cooler than at the era’s start. At the very end of the Cretaceous, the Gulf Coast experienced an enormous disruption when an asteroid or comet collided with Earth in what is now the northern Yucatán Peninsula in Mexico, just a few hundred miles away. The impact vaporized both water and rock, and formed tiny glassy spheres, called glassy rock. A cloud of fine dust from this impact spread around the globe, causing a temporary climate cooling and darkness for three to five years after the impact.
After that event, the climate may have cooled briefly (as suggested, for example, by an abundance of ferns), but it soon rebounded to a warmer state, and continued to warm into the Eocene.

By the early Cenozoic, the continents had approached their modern configuration, and India began to collide with Asia to form the Himalayas. The formation of the Himalayas had a significant impact on global climate, as the newly exposed rock began to serve as a sink to take up atmospheric CO₂. With the reduction of this greenhouse gas, global temperatures cooled. Antarctica moved south, and by 30 million years ago, temperatures were low enough that glaciers began to grow on its mountains. The South Central continued to accumulate sediment brought in by myriad rivers, including the antecedents to the Mississippi River. Sea level dropped, and the continued withdrawal of the sea is reflected in almost-parallel belts of progressively younger rocks that extend toward the Gulf Coast.
Eventually, a sheet of sea-ice formed over the Arctic, and ice sheets spread over northern Asia, Europe, and North America, signaling the start of the most recent ice age. Since just 800,000 years ago, a type of equilibrium has been reached between warming and cooling, with the ice caps growing and retreating primarily due to the influence of astronomical forces. The ice reached northern Missouri and northeastern Kansas during its maximum extent, while the rest of the South Central merely experienced a cooler climate than it does at present. The area was also somewhat wetter than it is today, with wetlands and forests covering much of what would later become grassland. Rocks of this age contain fossils of terrestrial vertebrates such as horses, camels, bison, mastodons, and mammoths. Much of the Mississippi River’s great delta and alluvial fan was deposited when the glacial ice melted, creating rivers that eroded older rocks as well as carrying sediments previously scoured by the glaciers.

Present Climate of the South Central

The location of the South Central and its direct relationship to the Gulf of Mexico strongly influence the area’s weather. Since it encompasses locations along the coast as well as areas farther inland, the South Central experiences nearly every variety of extreme weather. Heat and cold waves, droughts, floods, blizzards, tornados, and hurricanes are all considerations for the residents of the South Central.

See Chapter 10: Earth Hazards for more information on extreme weather in the South Central.

Silicate and carbonate rocks both weather chemically in reactions that involve CO₂ and water, typically creating clays, bicarbonate, and calcium ions. Silica weathering occurs relatively slowly, taking place on large scale in the weathering and erosion of mountain ranges, and it may have an impact on atmospheric carbon dioxide levels on time scales of tens or hundreds of millions of years. On the other hand, carbonate rocks weather (in this case, dissolve) quickly, relative to silicates. In both cases, the products of weathering often end up in sea water, where they may be used in the calcium carbonate skeletons of marine organisms or taken up during photosynthesis. Skeletal material and organic matter often sink to the sea floor and become buried, effectively removing carbon from the global carbon cycle (and thereby the atmosphere) for many millions of years.

Past–Present

mastodon • an extinct terrestrial mammal belonging to the Order Proboscidea, characterized by an elephant-like shape and size, and massive molar teeth with conical projections.

mammoth • an extinct terrestrial mammal belonging to the Order Proboscidea, from the same line that gave rise to African and Asian elephants.

delta • a typically wedge-shaped deposit formed as sediment is eroded from mountains and transported by streams across lower elevations.

alluvial • a thick layer of river-deposited sediment.

scouring • erosion resulting from glacial abrasion on the landscape.

tornado • a vertical funnel-shaped storm with a visible horizontal rotation.

hurricane • a rapidly rotating storm system with heavy winds, a low-pressure center, and a spiral arrangement of thunderstorms.
The Köppen Climate Map

Wladimir Köppen developed a commonly used system of climate categorization based on the kinds of vegetation areas sustain. He defined 12 climate types, many of which are familiar: rainforest, monsoon, tropical savanna, humid subtropical, humid continental, oceanic, Mediterranean, steppe, subarctic, tundra, polar ice cap, and desert. Updated by Rudolf Geiger, it has been refined to five groups, each with two to four subgroups.

(See TFG website for full-color version.)

Today, the South Central lies at the intersection of several distinct climate zones, with much of the region characterized as warm temperate (represented by “C” in the Köppen system). Northern Missouri and northern Kansas are characterized as continental (represented by “D”), and the eastern parts of Kansas and Texas are arid (represented by “B”).
Average temperatures in the South Central tend to decrease northward, which is simply the influence of latitude: lower latitudes receive more heat from the sun over the course of a year. The warmest temperatures are found in Louisiana and Texas, and the coolest found in Missouri and Kansas (Figure 9.8). The South Central’s overall average high temperature of 20ºC (68ºF) and average low of 9ºC (49ºF) are indicative, on the whole, of a more uniform climate than that found in most other regions of the United States. By comparison, the average high and low temperatures for the entire United States are 17ºC (63ºF) and 5ºC (41ºF), respectively. Another factor besides latitude that influences temperature in the South Central is proximity to the ocean, which has a moderating influence: air masses that have passed the Gulf of Mexico rarely get either extremely hot or extremely cold. Thus the most extreme temperatures in the South Central are found toward the center of the continent: record high and low temperatures are both held by Kansas, which has experienced a high of 49ºC (121ºF) and a low of -40ºC (-40ºF).

<table>
<thead>
<tr>
<th></th>
<th>Combined (ºC [ºF])</th>
<th>Low (ºC [ºF])</th>
<th>High (ºC [ºF])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Louisiana</td>
<td>19.2 (66.6)</td>
<td>13.2 (55.7)</td>
<td>22.1 (71.8)</td>
</tr>
<tr>
<td>Texas</td>
<td>18.7 (65.6)</td>
<td>11.8 (53.3)</td>
<td>23.2 (73.7)</td>
</tr>
<tr>
<td>Arkansas</td>
<td>15.8 (60.5)</td>
<td>9.6 (49.3)</td>
<td>22.1 (71.8)</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>15.7 (60.2)</td>
<td>8.8 (47.8)</td>
<td>20.9 (69.6)</td>
</tr>
<tr>
<td>Missouri</td>
<td>12.8 (55.0)</td>
<td>6.5 (43.7)</td>
<td>17.3 (63.2)</td>
</tr>
<tr>
<td>Kansas</td>
<td>12.6 (54.7)</td>
<td>5.6 (42.1)</td>
<td>16.7 (62.1)</td>
</tr>
</tbody>
</table>

The average amount of precipitation for the United States is 85.6 centimeters (33.7 inches). In the South Central, however, average precipitation ranges from 146.3 centimeters (57.6 inches) in Louisiana to 74.4 centimeters (29.3 inches) in Kansas (Figure 9.9), demonstrating the impact of moisture carried inland from the adjacent Gulf of Mexico.

The geography and climate of the South Central are nearly ideal for the formation of thunderstorms. Storms occur when there is strong convection in the atmosphere. Because warm air can hold more moisture than cool air can, convective mixing with cool air forces moisture to condense out of warm air, as vapor (clouds) and precipitation. It is hypothesized that the formation of precipitation causes the electrical charging that produces lightning. Of course, air cannot mix without moving, and that movement is caused by the wind.

A strong temperature difference at different heights creates instability—the warmer the air near the surface is relative to the air above it, the more potential energy it has to move up. The South Central receives warm, moist air moving north from the Gulf of Mexico, and cold, dry air moving in from the Rocky Mountains and the northern US. Where these air masses

See Chapter 10: Earth Hazards to learn more about tornados and hurricanes.
meet, vigorous mixing causes storms. Typically, a storm blows itself out once the warm air has moved up and the cool air down—a vertical column turning over as a unit. But because the lower air from the Gulf is moving north while air higher up is moving west, more heat and moisture is constantly added to the system, allowing the storm to persist and strengthen. This movement in different directions is also the reason for the South Central’s unusually high incidence of powerful tornados.

During the summer months, rainfall increases in southeastern Louisiana, where moist tropical air arriving from the Gulf of Mexico results in almost daily showers. The state is also commonly in the path of tropical storms and hurricanes moving northward off of the Gulf. Louisiana is south of the path of many winter storm centers, which travel from the northwest, but the northern parts of the state are susceptible. For this reason, Louisiana’s winter precipitation pattern is reversed from the summer, with the heaviest precipitation found in the state’s north.
Arkansas’ climate is influenced by its **topography** as well as its relative proximity to the Gulf of Mexico. The state’s winters, like those of Louisiana, are short, while its summers are hot and humid, with heavy precipitation. Arkansas is often subject to heavy rainfall from the remnants of tropical storms that arrive from the Gulf; the state is known for its extreme weather and abundant storms, including thunderstorms and tornados. The Ouachita Mountains, running northeast through southern Arkansas, are high enough to influence the state’s climate as well. Due to a minor rain shadow effect (Figure 9.10), the land north of the mountain chain is drier than that to the south, as the mountains block northward-moving precipitation. Snow does fall in the winters, but it is primarily restricted to the northwest section of the state.

In Oklahoma, summers are long and warm, and winters are shorter than in other states of the Great Plains. Because of moist warm air moving northward from the Gulf, rainfall increases dramatically toward the state’s eastern
Climate

Present

Portion, with an average of 43 centimeters (17 inches) in the west and 142 centimeters (56 inches) in the far southeast. In the winter, snowfall follows the reverse pattern, with more snow in the west than in the east, due to the state’s elevation gradient. This same pattern is also present in Kansas, where the annual average precipitation ranges from 107 centimeters (42 inches) in the southeast to 51 centimeters (20 inches) in the west, and the annual average snowfall ranges from 38 to 102 centimeters (15 to 40 inches) along the same gradient. With its low topographic relief, Kansas is also commonly home to tornados and dust storms.

Figure 9.10: The rain shadow effect occurs when moisture-laden air rises up the windward side of a mountain, only to release this moisture as precipitation due to cooling and condensation. Once the air reaches the leeward side, it warms and expands, promoting evaporation (and a lack of precipitation).

Missouri’s location in the US interior, and the absence of nearby large bodies of water or mountain ranges that would moderate the state’s climate, means that it is subject to major temperature extremes. The warm moist air of the Gulf influences summer precipitation, while Arctic air from the north affects the winters. Missouri experiences a temperature fluctuation of approximately 17 to 22 degrees Celsius (30 to 40 degrees Fahrenheit) in any 24-hour period.

Covering nearly 700,000 square kilometers (270,000 square miles), Texas is the second largest state, and encompasses a wide variety of climate regions. The rugged terrain of western Texas receives little rainfall and ranges from desert to semi-arid climate conditions, although the area’s highest peaks do receive significant snowfall in the winter. Texas’ central and eastern areas possess significantly less complicated topography, with the terrain descending from northwest to southeast. In areas where the terrain drops abruptly, such as in the Caprock Escarpment, topography has a greater effect on local climate, enhancing precipitation and promoting the formation of thunderstorms. Overall,
precipitation along Texas’ topographic gradient ranges from near-desert conditions in the west to annual accumulations close to 152 centimeters (60 inches) along the coast thanks to moisture from the Gulf. Although the humid air amplifies summer heat, the Gulf’s waters cool during the winter, moderating coastal temperatures during the spring. Texas’ coastal area is prone to severe thunderstorms and tornados, and it is also vulnerable to the occasional hurricane.

Future Climate of the South Central

By using some of the techniques that help to reconstruct past climates, and by tracking trends in the present, we can predict how current climates might change. Overall, the world is warming, yet, because we are still in an ice age, eventually the current interglacial period should end, allowing glaciers to advance towards the equator again (although likely not for about 100,000 years). However, because the Earth is already getting warmer, the effects of anthropogenic warming are amplified through feedback. Some scientists worry that, if not curbed, human activity could actually disrupt the cycle and knock the planet entirely out of the interglacial period, melting all the ice on Earth.

Causes of Change

While astronomical and tectonic forces will continue to cause climatic shifts, they act so slowly that they will be overshadowed in the near term by human-induced effects. In 1956, NOAA established the Mauna Loa Observatory (MLO) in Hawai’i to measure a variety of atmospheric parameters, including carbon dioxide concentration. The CO$_2$ record extends from 1958 to present, and it shows the influence of both natural and anthropogenic processes (Figure 9.11). The zigzag pattern is the result of seasonal photosynthesis in the northern hemisphere. In spring and summer, the growth and increased photosynthetic activity of plants draws CO$_2$ out of the atmosphere. Conversely, it accumulates in the atmosphere during fall and winter when plants are dormant. The overall upward trend is caused by human activity. Industrialization, fossil fuel combustion, and deforestation all contribute CO$_2$ to the atmosphere, adding it at a rate much faster than natural processes can remove it. Analyses of ancient atmosphere samples preserved in glacial ice cores show CO$_2$ levels to be 180 parts per million (ppm) at the height of the last ice age and 280 ppm at its end. The amount of CO$_2$ in the atmosphere has been increasing at a rapid rate since the start of the industrial revolution, and it has accelerated since the end of World War II. In May 2013, measurements at MLO reached 400 ppm CO$_2$ for the first time.
While some atmospheric CO$_2$ is necessary to keep Earth warm enough to be a habitable planet, the unprecedentedly rapid input of CO$_2$ to the atmosphere by human beings is cause for concern. Everything we know about atmospheric physics and chemistry tells us that increased CO$_2$ leads to a warmer planet. Multiple paleoclimate data sets verify this conclusion, and modern measurements confirm that we are living in an increasingly warmer world. The increasing heat is causing glaciers and sea ice around the globe to melt, and as the ground and ocean they covered is exposed, these darker surfaces absorb and re-radiate increasing amounts of heat.

As permafrost in high latitudes melts, carbon in the soil will become free to enter the atmosphere and, worse, to be converted by bacteria into the even more potent greenhouse gas, methane. Less directly, higher temperatures lead to more frequent and severe droughts, which, in turn, lead to more wildfires that release carbon and aerosols into the atmosphere. Aerosols can have a cooling effect as they reflect away radiation from the sun, but they can also pose a public health hazard.

Water is extremely good at absorbing heat: water vapor is actually the most effective greenhouse gas. Higher temperatures increase evaporation and allow the air to retain more water. While water vapor feedback is the most significant reinforcer of climate warming, water tends to move out of the atmosphere in a matter of weeks—other greenhouse gases, such as carbon dioxide and methane, linger in the atmosphere for years.
The South Central contributes significantly to climate change. The population of any industrialized and particularly wealthy country produces pollution. The 48 million residents of the South Central use electricity, transportation, and products that come from carbon-rich fossil fuels. Burning fossil fuels releases carbon into the atmosphere, which warms the Earth. Of the South Central States, Texas emits by far the most greenhouse gases. The highest greenhouse gas emitter in the nation, Texas releases nearly 656 million metric tons of CO\textsubscript{2} per year, nearly double that of California, the second largest emitter. The majority of these emissions come from the use of petroleum.

On the other hand, South Central States are making changes to reduce human impact on the climate. Texas’ emissions have decreased by 65 metric tons (64 standard tons) in the last decade, the greatest absolute reduction in of any state over that time period. The city of Dallas was an early adopter of the 2030 Challenge, an effort by cities to reduce fossil fuel use in buildings so that both new and renovated buildings would qualify as carbon neutral by the year 2030. Additionally, many states are stepping up their use and production of renewable energy. Missouri ranks 17th in the nation for renewable energy use, most of which it produces from biomass.

**Trends and Predictions**

Studies show that the South Central’s climate is changing right now, and that change has accelerated in the latter part of the 20th century. These changes include the following:

- The number of days with temperatures above 35°C (95°F) has been steadily increasing for the last 25 years (*Figure 9.12*).

- The city of St. Louis experiences about four heat waves lasting three days or longer each summer—a number which has doubled over the last 60 years.

- Locations along the Gulf of Mexico have experienced over 8 inches of sea level rise in the last 50 years.

- In 2011, Texas experienced the worst one-year drought in state history, exacerbated by temperatures almost 3°C (5°F) above normal. The drought cost the state $7.6 billion in agricultural losses.

- The Ogalalla Aquifer, which provides fresh water to much of the South Central, has been depleted by more than 40% in some areas, thanks to years of decreased rainfall.

- Altered flowering patterns due to more frost-free days have increased the South Central’s pollen season for ragweed, a potent allergen, by 16 days since 1995.

See Chapter 10: Earth Hazards for more information on how drought is affecting the Ogalalla Aquifer.
Climate models predict that the South Central will continue to warm, and that the average annual temperature will continue to increase for the foreseeable future—likely a 3°C (5°F) increase by 2100. Summer temperatures in Oklahoma, for example, are expected to increase by 3 to 6°C (6 to 10°F) by 2100. These increased temperatures lead to a whole host of other effects, including drier soils from more evaporation, and the increased likelihood of drought and fires. Texas, which contains the largest acreage of crop-, pasture-, and rangeland in the United States, could be severely impacted by these changes. Because higher temperatures mean greater evaporation and warmer air can hold more water, precipitation will occur in greater amounts at a time, but less frequently (Figure 9.13). During the cooler spring this will lead to flooding, while in hot summers, droughts will become more frequent. These drier summers and wetter winters and springs could have significant adverse impacts on agriculture.

Water supply is a critical issue in the South Central, and communities will need to adapt to changes in precipitation, snowmelt, and runoff as the climate changes. Drier days and higher temperatures will amplify evaporation, increasing the desertification of already arid areas and affecting natural ecosystems as well as increasing pressure on the water supply for agriculture and cities (Figure 9.14).
Figure 9.13: Changes in heavy precipitation events from the 1900s to the 2000s. Each event is defined as a two-day precipitation total that is exceeded, on average, only once every five years. The occurrence of such events has become increasingly common.

Figure 9.14: Dead fish rot on the cracked lakebed of the O.C. Fisher Reservoir at San Angelo State Park, Texas. The lake, which once spanned more than 2200 hectares (5400 acres), was once an important source of drinking water as well as a recreational fishing area. It is now completely dry due to severe drought conditions.
The causes of specific weather events such as hurricanes and severe thunderstorms are incredibly complex, although climate change has enhanced some correlated factors, such as increased wind speed and an unstable atmosphere. Higher atmospheric moisture content has also been correlated with an increased incidence of tornados and winter storms. However, although climate change is predicted to enhance the intensity of severe weather, there is currently no way to calculate what effect climate change will have on the frequency of specific storm events—for example, we might see more powerful tornados, but we do not know if we will see more of them.

More than 50% of the American population currently lives in coastal regions. With increased global warming, sea-level rise and the likelihood of increased incidences of extreme weather are expected, including an increase in hurricane intensity and associated storm surge. Sea level rise from melting glaciers and the thermal expansion of a warmer ocean will be a concern for populated coastal areas, including major cities such as New Orleans (Figure 9.15) and Houston. Regional studies project that by 2030, climate change could cause $4.6 billion in damages to coastal property and assets on the Gulf Coast alone.

Figure 9.15: Land loss in coastal Louisiana between 2010 and 2060, according to projections consistent with a sea level rise of 27 centimeters (10.6 inches) (left) and 80 centimeters (31.5 inches) (right). (See TFG website for full-color version.)
Resources

Books


Websites: General Resources on Climate


Regional Climate Trends and Scenarios for the US National Climate Assessment, National Oceanographic and Atmospheric Administration. [http://www.nesdis.noaa.gov/technical_reports/142_Climate_Scenarios.html](http://www.nesdis.noaa.gov/technical_reports/142_Climate_Scenarios.html).


**Websites: State- or Region-specific Climate Resources**

*Climates of the States, Climatography of the United States No. 60, US Climate Normals, NOAA Satellite and Information Service.* [http://hurricane.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl?directive=prod_select2&amp;prodtype=CLIM60&amp;subrnum=](http://hurricane.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl?directive=prod_select2&amp;prodtype=CLIM60&amp;subrnum=)


Chapter 10: Earth Hazards of the South Central US

Natural hazards are events or processes that have significant impacts on human beings and the environment. Extreme weather conditions or geologic activity can cause substantial short-term or long-term changes to our environment. These changes can influence many aspects of the world around us, including crops, homes, infrastructure, and the atmosphere. The 4.6-billion-year-old Earth has experienced many naturally generated hazards, while other events are byproducts of human activities, created during mineral and energy extraction or in construction practices that modify the landscape.

The South Central is subject to a variety of earth hazards. Most famously, the area happens to have just the right combination of conditions for tornados that cross the region and hurricanes that impact the Gulf Coastal Plain. Modifications of the Mississippi River and its mouth, as well as the Gulf coastline, have exacerbated the impacts of storms and floods. Limestone, gypsum, and salt deposits are responsible for significant areas of karst topography and sinkholes. Like many parts of the country, landslides from expansive soils and exposure to radioactivity from radon are present, depending upon the nature of the local bedrock. Perhaps most surprisingly, despite being far from a plate boundary, certain areas of the South Central are at risk from large earthquakes due to occasional movement along large ancient faults, and from smaller earthquakes associated with injection of wastewater into the Earth that promotes movement along smaller faults.

Earthquakes

Earthquakes occur when a critical amount of stress is applied to the Earth’s crust. According to the elastic rebound theory, rocks can bend elastically up to a point, until they finally break. The rocks then snap apart, releasing energy in the form of seismic waves (Figure 10.1). The plane defined by the rupture is known as a fault, and the rock layers become offset along it.

Many earthquakes, including most of those that occur in the South Central US, arise along ancient, pre-existing faults. In cases such as these, stress may accumulate from lateral compressive pressure, as the rocks are temporarily locked in position by friction and other constraints, until sufficient strain energy has built up to cause sudden slippage along the fault (i.e., an earthquake).

There are two common ways to measure the size of earthquakes: magnitude and intensity. Magnitude (M) is the measure of the energy released by the earthquake, whereas the intensity is what people actually experience.
first scale used to measure magnitude was the Richter scale, which measures the amplitude of a seismic wave at a defined distance from the earthquake. Unfortunately, the Richter scale proved incapable of accurately measuring large earthquakes, so the Moment Magnitude scale ($M_w$) was introduced in 1979 as an alternative. Both the Richter and Moment Magnitude scales may appear to reach maximum values of 10 (since the largest recorded earthquakes are slightly greater than 9), but technically there is no upper limit. The United States Geological Survey (USGS) describes earthquakes as minor (M3.0–3.9), light (M4.0–4.9), moderate (M5.0–5.9), strong (M6.0–6.9), major (M7.0–7.9) and great (M8.0 or higher). The scales are logarithmic, meaning that an M9.0 earthquake has 10 times the amplitude, and releases 32 times the energy, of an M8.0 earthquake. Accordingly, an M9.0 quake would have 100 times the amplitude and 1024 times the energy of a M7.0 earthquake. The largest recorded earthquake in US history was the 1964 Alaskan earthquake, which had an $M_w$ of 9.2. By comparison, the largest recorded earthquakes in the South Central were a cluster of four M7.5-M7.0 earthquakes that were centered around the New Madrid fault region in Missouri and Arkansas.
The magnitude of an earthquake, however, does not tell us how much damage is done by the seismic waves in a particular area. The amount of shaking and damage is known as the earthquake's intensity, and it can be measured by the Modified Mercalli Intensity (MMI) scale. This scale uses the Roman numerals I–XII to describe the effects of the earthquake in a particular location. For example, near the epicenter of a small earthquake, or at a location far from a large earthquake, the intensity may be described with an MMI of II: "Felt only by a few persons at rest, especially on the upper floors of buildings. Delicately suspended objects may swing." Unlike the Moment Magnitude scale, the MMI scale is a subjective gauge, and the USGS has attempted to improve the accuracy of MMI shake maps by soliciting data from the public. Figure 10.2 shows the intensities felt in surrounding areas after the 1931 Earthquake in Valentine, Texas, which is the largest earthquake known to have occurred in the state.

Earthquakes have occurred in each of the South Central states (Figure 10.3), but the greatest hazard potential is in the area of the New Madrid seismic zone (NMSZ), a 240-kilometer (150-mile) set of subsurface faults thought to have formed during the breakup of the supercontinent Rodinia in the late Precambrian (about 750 million years ago). Although this rift did not split the continent, it remains an underground weak point. The bedrock that makes up most of the central US is colder, drier, and less fractured than rocks on the East or West Coast. As a result, the earthquakes here can release the same amount of energy as other earthquakes, but the shaking affects a much larger area because the seismic waves travel through denser, more solid bedrock.

**See Chapter 1: Geologic History to learn more about Rodinia and other supercontinents.**
Four of the largest earthquakes in North American history—the New Madrid Sequence—occurred in the NMSZ on three days over a period of three months: December 16, 1811, January 23, 1812, and February 7, 1812. The quakes, with estimated magnitudes between 7.0 and 8.0, occurred along the Mississippi River in southeastern Missouri and northern Arkansas, and shook the Mississippi Valley and much of the eastern United States. The tremors destroyed buildings and warped the ground, causing landslides along the Mississippi River bluffs and ground subsidence brought on by soil liquefaction across the Mississippi River flood plain. Shaking was felt as far away as New Orleans and Boston, where it is said to have caused church bells to ring, and the waters of the Mississippi River appeared to flow backwards for several days due to local uplift and waves flowing upstream. Hundreds of aftershocks followed for a period of a several years, and were felt regularly until 1817.

The next largest quake to have occurred along the NMSZ was a 6.6-magnitude quake that occurred on October 31, 1895. The quake, centered in Charleston, Missouri, damaged almost every building in the city. Even today, areas in the NMSZ continue to experience earthquake activity, which is closely monitored.
by seismologists. There are ancient, seismically inactive subsurface faults in many other parts of the country, and it is unclear why seismic activity remains so high along the faults in the NMSZ, which are now far from North America’s plate margins. Most of the dozens of annual earthquakes that occur in the NMSZ (Figure 10.4) are very small—too small to notice except with sensitive equipment. If a major earthquake were to occur there, it could be expected to produce landslides, fissures, soil liquefaction, and bridge and road failures. Interstate 55 in Arkansas could become impassable; flooding of farmland could contaminate rivers and streams with mud, sand and agricultural chemicals; and the failure of levees and riverbanks could make the Mississippi River and its tributaries difficult to navigate for many weeks.

Another area that presents modest seismic risk is the Nemaha Uplift in northern Oklahoma and eastern Kansas (Figure 10.5). The seismic activity around the Nemaha Uplift is associated with faulting known as the Humboldt fault zone, which, like the NMSZ, lies along a Precambrian basement and ancient rift system.

Recently, Oklahoma has experienced an unusual amount of earthquake activity, with numerous earthquakes of magnitude 3 or 4 and a few above magnitude 5 (Figure 10.6). Only 89 earthquakes occurred in the state between 1970 and 2009, but since then the incidence has increased dramatically, rising from 48 earthquakes in 2010 to 611 in 2014 alone. The seismic activity in these instances has been linked to the high-pressure injection of wastewater from oil and gas extraction operations into the ground. The pressure of the water increases the likelihood that a rupture might occur along an otherwise locked fault. Concerns exist that additional activity along offshoot faults from the Nemaha Uplift near Oklahoma City might be even more serious. Similar instances of induced seismic
activity have occurred elsewhere in the South Central, perhaps most famously with cases associated with injection wells near Dallas-Fort Worth. These wells have been used to dispose of wastewater from the extraction of natural gas in the Barnett Shale.

Networks of seismograph stations have improved geologists’ ability to detect and accurately locate earthquake hazards (Figure 10.7), and specific fault zones are being studied throughout the South Central. This information on earthquake risk can lead to better designs for high-risk infrastructure like dams, high-rise buildings, and power plants—and it can also be used to inform the public of potential hazards to lives and property.

See Chapter 7: Energy Hazards to learn more about oil and gas extraction.
Landslides

The term “landslide” refers to a wide range of mass wasting events that result in rock, soil, or fill moving downhill under the influence of gravity (Figure 10.8). Landslides may be triggered by high rainfall, earthquakes, erosion, deforestation, groundwater pumping, or volcanic eruptions. They may occur rapidly, such as in some mud and debris flows, or they can be as slow as soil creep: slow land movement that usually does not cause loss of life, but can still destroy roads and buildings.

Landslides and slumps are common problems in parts of the South Central that have a wetter climate and/or the presence of steep slopes, such as west Texas, the Central Lowland, and the Interior Highlands, but they can also occur in areas with low relief (Figures 10.9 and 10.10). Heavy rain, snowmelt, groundwater percolation, and water level changes along coastlines, earthen
Earth Hazards

Earthquakes

Oklahoma Area Seismicity (1970 - 1/20/2015)

Explanation

Time Period
- Pre 2009
- 2009 - 2010
- 2011 - 2012
- 2013 - 2014
- 2015

Magnitude
- 2.0 - 2.9
- 3.0 - 3.9
- 4.0 - 4.9
- 5.0 - 5.9
- 6.0 - 6.9
- 7.0

Figure 10.6: Seismic activity in Oklahoma. Greatly increased seismic activity in 2013–2015 has been linked to injection wells. (See TFG website for full-color version.)

Figure 10.7: Seismic hazard map of the South Central US, based on data in 2014. (See TFG website for full-color version.)
dams, and the banks of water bodies are conditions under which landslides can occur. These flood-related conditions are associated with precipitation, runoff, and saturation of the ground. Hazards occur from mudflows themselves, but also from backwater flooding, dam failure, and debris that rushes downstream and causes further erosion.

In northern Arkansas, there is a risk of potential landslides associated with earthquakes in the New Madrid seismic zone. Steep slopes in this area increase the likelihood that landslides will occur when the ground shakes or when water rapidly infiltrates the soil during an earthquake, though, as mentioned earlier, steep slopes are not always necessary for a landslide to occur. In low-lying areas of the Coastal Plain, saturated soils and heavy rains can combine to cause soil liquefaction, which can result in laterally moving mudslides. This can be triggered by storm runoff or by rapid earth movement during an earthquake.
Figure 10.9: A landslide on the steep walls of Palo Duro Canyon in West Texas.

Figure 10.10: Landslide incidence and risk in the South Central US. (See TFG website for full-color version.)
Damage to life and property can be reduced by avoiding landslide hazard areas or by restricting access to known landslide zones. Hazard reduction is possible by avoiding construction on steep slopes or by stabilizing the slopes. There are two main ways to accomplish stabilization: 1) preventing water from entering the landslide zone through runoff, flooding, or irrigation and 2) stabilizing the slope by placing natural or manmade materials at the toe (bottom) of the landslide zone or by removing mass from the top of the slope.

**Expansive Soils**

Soils that weather from shale, volcanic ash, or bentonite are rich in clay, which may contain minerals that can absorb water and swell up to 1.5 to 2 times their original volume. That amount of expansion can exert enough force to cause damage, such as cracked foundations, floors, and basement walls (*Figure 10.11*). An estimated nine billion dollars of damage to infrastructure built on expansive clays occurs each year in the United States. See Chapter 8: Soils for more information about Vertisols, soils rich in swelling clays.

![Figure 10.11: Expansive soils caused cracks to form in the wall of this house in Austin, Texas.](image)

Soil creep is a slow kind of landslide that occurs when certain types of clay in the soil on a hillside absorb water, expanding and causing the soil to swell. As the clay dries and contracts, the particles settle slightly in the downhill direction. This process can cause fences and telephone poles to lean downhill, while trees adjust by bending uphill (*Figures 10.12 and 10.13*).
Landslides

Figure 10.12: Some influences of soil creep on surface topography.

Figure 10.13: Soil creep affects telephone poles and fence posts on a hillside in Toronto, Kansas.
While soils can swell by absorbing water, they will also shrink when they dry out, resulting in subsidence that damages landforms and infrastructure. Fissures may develop in the soil, allowing for the deep penetration of water when floods or runoff occurs. This produces a cycle of shrinkage and swelling that puts repeated stress on rock layers and human structures. While expansive soils can be found all over the US, every state in the South Central has bedrock units or soil layers that are possible sources, with Louisiana’s coastal plain and Oklahoma’s Cretaceous shales being the most susceptible (Figure 10.14).
Significant or repeated changes in moisture, which can occur in concert with other geologic hazards such as earthquakes, floods, or landslides, greatly increase the hazard potential of expansive soils. The key to reducing this hazard is to keep the water content of the soil constant. There are also chemical stabilizers, including lime, potassium, and ionic agents, that can reduce the potential for soil volume changes by increasing the clay’s structural stability.

Karst, Sinkholes, and Salt Dissolution

Karst topography forms in areas where the underlying bedrock is composed of material that can be slowly dissolved by water. Examples of this type of sedimentary rock include carbonate rocks such as limestone, halite, gypsum, dolomite, and anhydrite. Carbonate rocks may develop karst and other dissolution features due to the effects of circulating groundwater that has been made slightly acidic through the presence of dissolved carbon dioxide (which creates carbonic acid that reacts with the rock, dissolving it). Sinkholes and caverns can form, creating potential hazards (i.e., the land surface could subside or collapse into the underground openings). This may principally occur in areas where cavities filled with water are emptied through groundwater withdrawal or other natural processes, resulting in the cavities being filled with air and reducing support for the overlying rock. Much of the South Central is underlain by karst and carbonates (see Figure 10.17).

Central and southern Missouri, including the Ozark Mountains and their extensions into northern Arkansas and northeastern Oklahoma, are famous for caves and karst in Ordovician and Carboniferous limestone and dolomite. Missouri is home to over 6000 limestone caverns, many of which are prominent tourist attractions (Figure 10.16). In Missouri, karst is also associated with exceptionally large springs such as Big Spring, Greer Spring, and Maramec Spring (Figure 10.17). Other karst formations are found in the Arbuckle Mountains of south central Oklahoma and the Limestone Hills in southwestern Oklahoma. Soluble gypsum and salt deposits near the surface in western Oklahoma and the Texas panhandle can also cause karst and dissolution problems.

Because karst terrain is very porous and fractures easily, groundwater pollution can be a serious problem. Contaminants that might otherwise be filtered through the sedimentary rock are quickly transported into aquifers by runoff. The hazards of pollution are increased by rampant industrial, agricultural, and residential development over karst features. This is occurring rapidly in northwest Arkansas and in Missouri, where 59% of the state sits atop thick layers of carbonate rock (Figure 10.17).
Earth Hazards

Figure 10.15: Meramec Caverns, a 7.4-kilometer (4.6-mile) limestone cave system near Stanton, Missouri, is the most visited cave in the state. Meramec Caverns was introduced as a tourist attraction in 1935; advertisements for the location involved one of the earliest uses of the bumper sticker.

Figure 10.16: Maramec Spring, located in the east-central Ozarks, has an average daily discharge of 360 million liters (100 million gallons) of water. The spring’s opening is underwater, at the base of the dolomite overhang.
Figure 10.17: Areas of karst in the continental US, associated with carbonate and evaporate rocks. See Key on facing page. (See TFG website for full-color version.)
Earth Hazards

**Karst**

See Chapter 4: Topography for a karst map of the South Central.
The Coastal Plain of eastern Texas and Louisiana is dotted with many Jurassic subsurface salt domes that can collapse if salt is removed. For example, the Bayou Corne sinkhole in Assumption Parish, Louisiana, is a site where an underground salt dome collapsed in 2012 (Figure 10.18). Before its collapse, the Bayou Corne sinkhole was preceded by months of seismic activity and the release of methane bubbles. It originally spanned one hectare (2.5 acres) but has since grown to over 10 hectares (26 acres). It is still growing, swallowing surrounding cypress swamp and endangering the nearby community, from which many of the residents have been evacuated. Scientists believe the sinkhole was created by the salt dome cavern being excavated too close to the massive salt deposit’s outer face, making it incapable of maintaining pressure. A similar event occurred in Daisetta, Texas, a town also located on the edge of a major salt dome. In May 2008, a 330-meter-wide (1080-foot-wide) sinkhole caused by partial collapse of the dome swallowed a parking lot, construction equipment, and a small stand of trees over the course of a single day before filling with water (Figure 10.19). These types of situations present a growing hazard that will be studied by geoscientists for years to come.

Salt karst can also be a hazard through its association with pathways for fluids, such as the flow of natural gas, which is sometimes stored in salt caverns. For example, in 2001, the Yaggy storage field—consisting of dozens of caverns in the Permian-age salt deposits near Hutchinson, Kansas—leaked 4 million cubic meters (143 million cubic feet) of natural gas, leading to multiple large-
scale explosions within and around the city. In this case, the leak was associated with drilling errors as well as with faults and fractures in rocks overlying the salt formation.

**Radon**

Radon is a naturally occurring radioactive, colorless, odorless gas. It is the leading cause of lung cancer in non-smokers and the second leading cause of lung cancer overall. It can collect in homes, buildings, and even in the water supply. Radon gas is formed naturally when uranium-238 undergoes radioactive decay, producing energy and several radioactive products such as radon-222.
and thorium-232. The thorium later decays to emit energy and radon-220. Radon is more commonly found where uranium is relatively abundant in bedrock at the surface, often in granite, shale, and limestone. The EPA produced a map of the US showing geographic variation in radon concentrations, divided into three levels of risk: low, medium, and high (Figure 10.20).

In the South Central US, the highest radon concentrations are generally associated with black, organic-rich Pennsylvanian shales in northeastern Kansas and the northwest corner of Missouri, and black Cretaceous shales in north-central Kansas. Radon risk in western Kansas is associated with Neogene sandstones containing volcanic ash layers. (Figure 10.21). Volcanic ash can be high in uranium that eventually decays to radon. Water moving through the ash into the surrounding sandy layers carried with it uranium-rich dissolved silica that precipitated between the grains of the sandstone.

Radon is chemically inert, meaning that it does not react or combine with elements in the ground, and it can move up through rocks and soil into the atmosphere. It is dangerous primarily when it accumulates indoors, creating a health hazard.
Earth Hazards

Figures 10.21: Radon risk levels at the surface in the South Central US.

similar to that of secondhand smoke. Radon gas finds its way through cracks in basement foundations, sump pump wells, dirt floor crawlspace, and basement floor drains. It can also be found in well and municipal water. Since radon is more easily released from warm water than from cold water, one of the greatest forms of exposure likely occurs while showering in water with high radon levels.

Radon cannot be detected by sight or smell, so there is no way that the body can sense its presence. Fortunately, with proper monitoring and mitigation (reduction) techniques, radon gas can be easily reduced to low levels. One technique that is often used in homes involves sealing cracks in the basement floor, covering drains, and installing ventilation systems. A well-ventilated space will prevent the radon from accumulating and will reduce the risk of exposure. Most states have licensed radon mitigation specialists who are trained in the proper testing and mitigation of radon levels in buildings. The EPA has also published a homebuyer’s guide designed to help citizens make informed decisions about radon gas. For radon in water, filtration systems can be installed to mitigate exposure in the home.

Floods

Floods are controlled by the rate of precipitation, run-off, stream flow, and shape of the land surface. They may occur as water overflows the banks of a standing water body (such as a lake) or flowing water (such as a stream), or when rainwater accumulates in an area that normally has neither standing nor flowing water. Areas near rivers, tributaries, creeks, and streams are likely to experience flooding during periods of heavy rainfall.
Floods are areas adjacent to rivers and streams that occasionally flood but are normally dry, sometimes for many years. When storms produce more runoff than a stream can carry in its channel, waters rise and flood adjacent lowlands, leaving behind layers of settled sediment. Significant damage and sometimes loss of human life may occur when buildings and other human infrastructure are built on floodplains, under the assumption that future floods may never occur or will only occur in the distant future. Floods can occur at any time, but major floods are more frequent in spring and fall after periods of heavy or sustained rains when stream levels rise rapidly.

In the South Central US, the greatest human impact from flooding is related to events along the banks of major rivers. Historically, there have been a number of record-setting floods along the Mississippi River (in 1927, 1937, 1945, and 1993), which runs along the eastern edge of the South Central. Many South Central floods have also involved major tributaries of the Mississippi, such as the Missouri River, which intersects the Mississippi near St. Louis, and the Kansas River, which intersects the Missouri near Kansas City. The Great Mississippi and Missouri Rivers Flood of 1993 (Figure 10.22) was preceded by a wet fall and a winter with heavy snowfall, followed by a series of precipitation events in roughly the same locations through the spring and summer of 1993. Many locations near St. Louis were flooded for over half a year. Dozens of individuals lost their lives and costs are estimated to have been in the $15–20 billion range. However, even with the massive damage sustained from this flooding event, the impact could have been even worse were it not for a series of levees and reservoirs built in response to a large flood of the Kansas River in 1951—an event called “one of the worst [disasters] this country has ever suffered from water,” by President Truman.

Flash floods—rapid flooding of low-lying areas—are often associated with heavy rain, which can quickly waterlog soil and lead to mudslides on steep terrain, resulting in damage to roads and property. In areas of lower elevation, flash floods can be produced when slow-moving or multiple thunderstorms occur over the same area. When storms move more quickly through an area, flash flooding is less likely. Flash floods can also occur in conjunction with a dam break or levee failure. A special case of flooding due to a failed levee occurred in fall 2005, when Hurricane Katrina forced water over and through the levee holding seawater back from New Orleans, part of which is built below sea level (see the “Storms” segment later in this chapter for more information). In this case, flooding came not from precipitation, but from a “storm surge,” where seawater was transported high onto shore through a combination of low atmospheric pressure and powerful winds (Figure 10.23).

While floods are always considered a hazard to life and property, they present a compound threat when they trigger mudslides or contribute to the conditions that cause expansive soils and karst topography. While there is no way to completely avoid the destructive impacts of flooding, good community planning and informed decision-making can greatly reduce the safety concerns and economic impacts of these events. The Federal Emergency Management Agency (FEMA) provides guidelines for communities that are planning mitigation strategies designed to minimize the impacts of natural hazards such as flooding.
Figure 10.22: Confluence of the Mississippi and Missouri rivers, near St. Louis. A) 2002, during non-flooding. B) 1993, during the Great Mississippi and Missouri Rivers Flood.

Figure 10.23: This house in New Orleans was destroyed when it floated off its foundation during the 2005 flood.
Sea Level Rise, Coastal Erosion, and Subsidence

Coastal erosion has been occurring along Louisiana’s Gulf Coast since its formation as an alluvial plain deposit of the Mississippi River. It is a natural process in which currents and waves remove sediment in some areas and deposit it in others, but the natural accretion and replenishment processes have been disrupted by levees along the Mississippi River, as well as by dams along the river’s length. Simply put, the river carries about half the amount of sediment that it did when it built the Coastal Plain. Because the primary substrate (“bedrock”) is soft alluvium rather than rock, erosion rates tend to be higher than deposition rates (Figure 10.24). About 40% of US wetlands are in Louisiana, but about 80% of US wetlands-loss occurs there as well. The dramatic increase in Louisiana’s coastal erosion in recent decades is due to a number of different factors, including natural erosional processes and human activities such as dredging and development. This trend is expected to continue as sea level rises and storm frequency and severity increase. Barrier island and beach erosion is expected to occur in large bursts during storm events as a result of increased wave height and storm intensity.

The Coastal Plain is threatened by the triple risk of coastal erosion, sea level rise, and subsidence, with subsidence exacerbating the effects of the first two. Compaction of sediment, extraction of water and minerals from the soil, and

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**Sea Level Rise**

- **alluvial**: a thick layer of river-deposited sediment.
- **accretion**: the process by which a body of rock increases in size due to the addition of further sedimentary particles or of large chunks of land.

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See Chapter 4: Topography to learn more about how the Mississippi Delta was formed.
collapse along fault lines are combining to increase the rate of subsidence. A combination of coastal erosion, sea level rise, subsidence, and increased storm intensity could have catastrophic impacts on the Coastal Plain region. Since the 1930s, Louisiana has lost 4870 square kilometers (1880 square miles) of coastline, and it is predicted that an additional 4530 square kilometers (1750 square miles) could be lost by 2100, at least partially due to rising sea levels caused by glacial melting associated with climate change.

New Orleans, which is subsiding five centimeters (two inches) per decade, is of special concern. The city’s topography and that of the surrounding coastal zone reflects the negative effects of river levees and subsidence along faults. One study places significant blame for recent subsidence on the Michoud Fault, which trends beneath the eastern portion of New Orleans, where a portion of the city known as “Michoud” has an unusually high subsidence rate. New Orleans is the largest urban area in the US that has been affected by subsidence—over 35 square kilometers (13.5 square miles) of the city are now below sea level and must be kept dry by use of a series of levees and pumps. With sea level rise and the loss of nearby protective wetlands, the impacts of coastal storms, hurricanes, and associated storm surges may become increasingly devastating.

Weather Hazards

Weather is the measure of short-term atmospheric conditions such as temperature, wind speed, and humidity. The South Central is among the most active locations on Earth for two very different kinds of high-energy atmospheric events: tornados and hurricanes. It also experiences a variety of other weather hazards, including high temperatures and drought.

Storms, Tornadoes, and Derechos

Rainstorms occur where colder air from higher latitudes abruptly meets warmer air. This often happens in the mid-latitudes (particularly in the South Central US) where air may warm up as it passes over flat open spaces or when warm, moist air is delivered off the Gulf of Mexico. At the boundary between warmer and cooler air, buoyant warm air rises, and then cools because air pressure decreases with increasing height in the atmosphere. As the air cools, it becomes saturated with water vapor; condensation occurs and clouds begin to form. Because liquid water droplets in the clouds must be very small to remain suspended in the air, a significant amount of condensation causes small water droplets to come together, eventually becoming too large to remain suspended. Sufficient moisture and energy can lead to dramatic rainstorms. Because warm air has a lower pressure relative to cold air, and the movement of air from areas of high pressure to areas of low pressure generates wind,
the significant difference in air pressure associated with these boundaries and rainstorms also generates strong winds. Flat regions, such as the Great Plains, allow winds to move unimpeded by topography, and are often subject to severe thunderstorms.

While severe thunderstorms are common in some parts of the South Central, two less common storm hazards have the potential to cause serious property damage and endanger lives: derechos and tornados. Both of these storm events are associated with wind shear, which occurs when the wind’s speed or direction changes with increasing height in the atmosphere. Wind shear can happen when a cold front moves rapidly into an area with very warm air. There, the condensing water droplets mix with the cooler, drier air in the upper atmosphere to cause a downdraft. When these downdrafts are very powerful, they can cause a derecho, or a set of powerful straight-line winds that exceed 94 kilometers per hour (kph) (58 miles per hour [mph]) and can often approach 160 kph (100 mph). These powerful windstorms can travel over 400 kilometers (250 miles) and cause substantial wind damage, knocking down trees and causing widespread power outages. The lightning associated with these intense storms can cause both forest fires and house fires. Approximately one derecho every year or two will occur in Arkansas, eastern Oklahoma, and southern Missouri (Figure 10.25), but they do occur with decreasing frequency through most of the remaining parts of the South Central US.

The differences between tornados and derechos are indicated in their names: derecho is the Spanish word for straight ahead, while the word tornado has its roots in the Spanish word tonar, which means to turn. Both types of storm...
events can be associated with the same major cold front boundary because they require similar conditions to get started. However, tornado formation is more complicated. At the frontal boundary, warm, moist air rapidly rises as cooler, dry air descends; in the meantime, the pressure differences between the warm and cold air masses cause strong winds. Clouds with a visible horizontal rotation can appear, appearing to roll like waves crashing on the shore of a beach. This horizontal motion can tilt, lifting the rotating cloud vertically, and the rolling cloud will form a tornado. Most tornados will last a few seconds to several minutes. During that time, many tornado-prone areas will use tornado sirens to alert residents of the danger. A smaller tornado might generate flying debris that can cause injury or damage to buildings, while larger tornados can cause buildings and houses to be completely broken apart. Tornados are classified by their ranking on the Enhanced Fujita scale, or EF scale. These classifications are estimates of wind speeds based on the type of damage that is observed following the storm.

**Measuring Tornado Intensity**

Tornado intensity is measured on the Fujita scale, or simply F-scale, based on the amount of damage that a tornado can cause. The scale ranges from F0 to F5. The scale was modified recently to more accurately reflect specific wind speeds; this newer scale is known as the “Enhanced Fujita scale” and is labeled EF0 to EF5.

<table>
<thead>
<tr>
<th>EF Scale</th>
<th>Estimated Wind Speed (kph)</th>
<th>Estimated Wind Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF0</td>
<td>104–137</td>
<td>65–85</td>
</tr>
<tr>
<td>EF1</td>
<td>138–177</td>
<td>86–110</td>
</tr>
<tr>
<td>EF2</td>
<td>178–217</td>
<td>111–135</td>
</tr>
<tr>
<td>EF3</td>
<td>218–266</td>
<td>136–165</td>
</tr>
<tr>
<td>EF4</td>
<td>267–322</td>
<td>166–200</td>
</tr>
<tr>
<td>EF5</td>
<td>&gt; 322</td>
<td>&gt; 200</td>
</tr>
</tbody>
</table>

“Tornado Alley” is the nickname for an area, extending from Texas to Minnesota, that experiences a high number of exceptionally strong tornados due to its flatter topography and high incidence of severe thunderstorms. Most of the South Central resides within Tornado Alley, leading to more tornados in this part of the United States than in any other (Figure 10.26). From 1991 to 2010, for example, an annual average of 115, 62, and 96 tornados occurred in Texas, Oklahoma, and Kansas, respectively. To the east of Tornado Alley, far fewer tornado strikes occur, with an annual average of 37, 39, and 45 striking Louisiana, Arkansas,
and Missouri, respectively. The boundaries of Tornado Alley vary in application, depending on whether the frequency, intensity, or number of events per location are used to determine the area’s borders. Some people apply the name “Dixie Alley” to the adjacent tornado-prone area from Louisiana and Arkansas east to Florida.

Although specific tornado paths are not predictable, the conditions that produce them are used to alert people so that they can seek shelter. The National Weather Service issues a *watch*, if the conditions are right for a type of storm event, or a *warning*, if the conditions are occurring or imminent for the storm event. The National Weather Service is part of the National Oceanographic and Atmospheric Administration, which maintains a US map of all current watches and warnings. Since the atmospheric conditions can change very quickly, an important factor in preventing loss of human life is getting the public to act upon the severe weather alerts. One recent attempt to improve public response to warnings is through a tornado alert index that helps people evaluate the risk of a local tornado. The Tor:Con index used by the Weather Channel provides a number from 1 to 10 that represents the probability of a tornado occurring. Meteorologists evaluate the atmospheric conditions associated with a storm and assign a score. For example, a 4 on the Tor:Con index would indicate a 40%, or moderate, chance of a tornado forming in a particular area.

*Figure 10.26: Annual tornado reports per 29,500 square kilometers (10,000 square miles) in the continental US, between 1950 and 1995. (See TFG website for full-color version.)*
Earth Hazards

Weather

Hurricanes

Hurricanes occur when a warm, moist, low-pressure air mass forms over the Atlantic Ocean south and east of Florida. These storms gather strength as warm surface ocean water evaporates in the summer, yielding humid, low-pressure air that rises; the moisture condenses into water droplets that form clouds, releasing latent heat, and thereby providing energy for even greater evaporation of warm ocean water. This positive feedback cycle continues until the low-pressure center moves over land. These storms are considered tropical depressions when wind speeds are below 63 kph (39 mph). As the storm grows, it develops a more organized structure, with warm air rising in the center and somewhat discrete bands of rain being formed. It becomes known as a tropical storm when its wind speeds reach the 63–117 kph (39–73 mph) range, and it is called a hurricane once winds have reached 119 kph (74 mph). The western Atlantic, Caribbean, and Gulf of Mexico area is one of the world’s most active for hurricanes, though they also occur in areas of the western Pacific, where they are known as typhoons, and in the South Pacific to Indian Ocean, where they are called cyclones.

Measuring Hurricane Intensity

Hurricanes are ranked in the Saffir-Simpson scale from category 1 to 5, with 5 being the highest, based on wind speed. Category 5 hurricanes occur on average only about once every three years in the Atlantic and Gulf of Mexico.

<table>
<thead>
<tr>
<th>Saffir-Simpson Hurricane Scale</th>
<th>Wind Speed (kph)</th>
<th>Wind Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>119–153</td>
<td>74–95</td>
</tr>
<tr>
<td>Category 2</td>
<td>154–177</td>
<td>96–110</td>
</tr>
<tr>
<td>Category 3</td>
<td>178–208</td>
<td>111–129</td>
</tr>
<tr>
<td>Category 4</td>
<td>209–251</td>
<td>130–156</td>
</tr>
<tr>
<td>Category 5</td>
<td>≥ 252</td>
<td>≥ 157</td>
</tr>
</tbody>
</table>

In an average year, about a dozen hurricanes travel through the western Atlantic and sometimes the Gulf of Mexico. Of these, roughly one a year hits the Texas and/or Louisiana coast, though these occurrences vary considerably. The peak month is September, followed by August and October. More rarely, hurricanes may hit the coast in June, July, or November. The 2005 hurricane season was the most active in recorded history, with a record number of 15 hurricanes, 7 of which strengthened into major (category 3 or greater) hurricanes (Figure 10.27). Two of these—Katrina and Rita—were category 5 hurricanes that did
substantial damage to the Gulf Coast. Katrina (*Figure 10.28*) destroyed large parts of New Orleans and other areas along eastern Louisiana, while Rita did substantial damage in southwest Louisiana and went ashore at Sabine Pass, Texas. More recently, Category 4 Ike (2008) caused damage along the Louisiana coast and made landfall at Galveston, Texas.

*Figure 10.27: Tracks of all Atlantic hurricanes during the 2005 season. Warmer colors indicate higher maximum sustained wind speeds. (See TFG website for full-color version.)*

*Figure 10.28: Satellite image of Hurricane Katrina as it approached the Louisiana coastline.*
Earth Hazards

Once hurricanes reach land, they lose energy rapidly, though they typically continue to deliver substantial precipitation and somewhat high winds for hundreds of miles onshore. Hurricane tracks over eastern Texas and Louisiana generally veer north to northeast, heading across eastern Texas and Louisiana to eastern Oklahoma, Arkansas, and southeast Missouri.

Extreme Temperature and Drought
Extreme temperatures can create dangerous conditions for people and may lead to property damage. Heat waves are periods of excessively hot weather that may also accompany high humidity. Temperatures of just 3°C (6°F) to 6°C (11°F) above normal are enough to reclassify a warm period as a heat wave. Under these conditions, the mechanism of sweating does little to cool people down because the humidity prevents sweat from evaporating and cooling off the skin. Heat waves have different impacts on rural and urban settings. In rural settings, agriculture and livestock can be greatly affected. Heat stress recommendations are issued to help farmers protect their animals, particularly pigs and poultry, which, unlike cattle, do not have sweat glands.

The impacts of heat waves on urban settings include a combination of the natural conditions of excessive heat and the social conditions of living in a densely populated space. Cities contain a considerable amount of pavement, which absorbs and gives off more heat than vegetation-covered land does. Air conditioning units that cool down the inside of buildings produce heat that is released outside. Pollution from cars and industry also serve to elevate the outdoor temperatures in cities. This phenomenon, in which cities experience higher temperatures than surrounding rural communities, is known as the heat island effect. Other social conditions can increase the hazards associated with heat waves in urban areas. People who are in poor health, live in apartment buildings with no air conditioning, or are unable to leave their houses are at greatest risk of death during heat waves. In 2011, the South Central experienced the nation’s hottest summer heat wave in 75 years, with temperatures reaching upwards of 55°C (131°F) during a period of four months (Figure 10.29). Texas, Oklahoma, and Arkansas took the brunt of the extreme heat, which contributed to severe drought, amplified heat-based health emergencies, and caused a heavy spike in electricity usage (related to increased air conditioning use) that generated a record-breaking demand on the power grid and led to increased energy prices.

While high temperatures can be directly dangerous, a larger scale hazard arises when these temperatures are coupled with lack of precipitation in an extended drought period. Many significant droughts have occurred in the South Central states. Most famously, high temperature and drought in the 1930s, combined with deep plowing that removed moisture-trapping grasses, led to the Dust Bowl—dust storms that carried vast clouds of black dust across the Midwest and eastern US, greatly damaging both the ecology and agriculture across that portion of the country (Figure 10.30). The Dust Bowl, which was most intense in the panhandles of Texas and Oklahoma and also affected adjoining parts of Kansas, New Mexico, and Colorado, displaced 3.5 million people.

Texas experienced a seven-year record drought in the 1950s, and the lowest average statewide rainfall record was set in Texas as recently as 2011. That year, nearly the entire state was categorized as experiencing “exceptional drought,” the
Figure 10.29: Number of days with temperatures reaching above 100°F during the year 2011. (See TFG website for full-color version.)

Figure 10.30: A dust storm approaching the town of Stratford, Texas during the Dust Bowl in 1935.
highest of the five drought levels recognized by NOAA’s US Drought Monitor. Today, much of the South Central is still experiencing moderate to extreme drought, with exceptional drought still occurring in some areas of Texas and Oklahoma (Figure 10.31).

![Drought Intensity Map](image)

**Figure 10.31: Drought severity in the South Central, as of March 2015.**

**Climate Change**

It is important to understand that most of the extreme climate change in Earth’s history occurred before humans existed. That being said, the rapid release of carbon dioxide into the atmosphere from human activity is currently causing a **global warming** event. The warmest overall average state summer temperatures in the US are generally found in the South Central (primarily in Oklahoma, Texas, Louisiana, and Arkansas), with the warmest years averaging 28 to 30°C (83 to 86°F) and occasional weeks with maximum temperatures above 37.8°C (100°F). For the last 25 years, these temperature averages have been steadily rising. This seemingly slight increase has been accompanied by more frequent heat waves, shorter winters, and an increased likelihood of drought and wildfires.

The South Central is currently experiencing significant drought throughout, with the worst effects occurring in Texas and Oklahoma (see Figure 10.31). Increased dryness contributes to fire risk—in March 2015, the area northeast...
of Woodward, Oklahoma experienced a wildfire that consumed more than 9600 hectares (23,000 acres) of land and forced over 125 people to evacuate from their homes. During the major drought and heat wave of 2011, more than 31,000 separate wildfires raged through central Texas, burning a cumulative 1,559,446 hectares (3,853,475 acres) of land and destroying almost 6000 structures.

Water supply is also a critical issue for the South Central states. Much of the area obtains its agricultural and drinking water from aquifers, underground layers of permeable rock. The Ogallalla aquifer, part of the High Plains aquifer system, supplies vast quantities of groundwater to Texas, Oklahoma, Kansas, and Nebraska. As drought intensifies and temperature rises, the amount of water drawn from the aquifer (especially for agricultural irrigation) has increased, while the rate at which the aquifer refills has decreased. The aquifer’s average water level has dropped by about 4 meters (13 feet) since 1950, and in some areas of heavy use, the decrease is as high as 76 meters (250 feet) (Figure 10.32). However, the aquifer only replenishes at a rate no greater than 150 millimeters (6 inches) per year. Some estimates indicate that at its current rate of use, the entire Ogallalla aquifer could be depleted by as early as 2028, threatening human lives, our food supply, and the entire Great Plains ecosystem.

Increasing temperatures also allow certain pests, such as ticks and mosquitoes, to live longer, thereby increasing the risk of contracting the diseases they carry. In addition, invasive organisms that damage ecosystems, such as the hydrilla plant in Louisiana, have a better chance to multiply and outcompete native organisms because increased temperatures stress local ecosystems and create an environment more favorable to invasive species.

Another concern regarding hazards exacerbated by climate change in the South Central is whether or not there has been or will be an increase in the number or severity of storms, such as hurricanes and tornados. According to NASA, the present data is inconclusive in terms of whether hurricanes are already more severe, but there is a greater than 66% chance that global warming will cause more intense hurricanes in the 21st century. Since climate is a measure of weather averaged over decades, it might take many years to determine that a change has occurred with respect to these types of storms. Scientists are certain that the conditions necessary to form such storms are becoming more favorable due to global warming.

The Union of Concerned Scientists has created an infographic that demonstrates the relative strength of the evidence that various hazards are increasing as a result of climate change (Figure 10.33).
Figure 10.32: Water level change in the Ogallala aquifer between 1950 and 2005. (See TFG website for full-color version.)
Figure 10.33: The strength of evidence supporting an increase in different types of extreme weather events caused by climate change.
Resources

Earth Hazards

General Resources


NASA Earth Observatory Natural Hazards map. (Monthly images of Earth hazards occurring globally.) [http://earthobservatory.nasa.gov/NaturalHazards/](http://earthobservatory.nasa.gov/NaturalHazards/).

General Resources for Specific Areas of the South Central US


Hurricanes

*Geology and Hurricane-protection Strategies in the Greater New Orleans Area, Louisiana Geological Survey,* Public Information Series No. 11, 32 pp.


Coastal Hazards and Processes

*Coastal Hazards,* Gulf of Mexico Coastal Ocean Observing System (GCOOS).
[http://gcoos.tamu.edu/?page_id=5041](http://gcoos.tamu.edu/?page_id=5041).

*Losing Louisiana: Our Land Keeps Sinking Because of Subsidence, While the Gulf is Rising Due to Global Warming,* 2008, The Times-Picayune Greater New Orleans.

Earth Hazards

Resources

Louisiana Coastal Wetlands: A Resource At Risk, USGS Coastal and Marine Geology Program. [http://pubs.usgs.gov/fs/la-wetlands/]

StormSmart Coasts. (Resource for coastal decision makers.) [http://stormsmartcoasts.org]


Floods


Tornados


Expansive Soils

Damage to Foundations from Expansive Soils, J. D. Rogers, R. Olshansky, & R. B. Rogers, Missouri University of Science and Technology. [http://web.mst.edu/~rogersda/expansive-soils/DAMAGE%20TO%20FOUNDATIONS%20FROM%20EXPANSIVE%20SOILS.pdf]


Landslides


Earthquakes


Incorporated Research Institutions for Seismology (IRIS) education and public outreach. [http://www.iris.edu/hq/programs.epo]


Earth Hazards


Radon Information, Environmental Protection Agency (EPA). [http://www.epa.gov/radon/].

Sinkholes


Earth Hazards Teaching Resources

Impact of Natural Disasters on the Earth, J. Radke, Hamline University Graduate School of Education MnSTEP Teaching Activity Collection. [http://serc.carleton.edu/sp/mnstep/activities/19789.html].


Teaching Quantitative Concepts in Floods and Flooding, SERC Resources for Undergraduate Students and Faculty. [http://serc.carleton.edu/quantskills/methods/quantlit/floods.html].

Resources


Radon (Rn): Where You Live, United States Environmental Protection Agency (EPA). (State radon maps with county-level data.) [http://www.epa.gov/radon/whereyoulive.html].


All the major topics in The Teacher-Friendly Guides™ were built upon observations of the natural world, and these observations are the clues that scientists use to reconstruct the history of the Earth. Shelly fossils along the Himalayas tell of ancient sea floors that have been uplifted into mountains. Ripple marks that have since turned to stone tell of ancient shorelines. And scratches along the bedrock in Central Park tell of massive glaciers that—some 20,000 years ago—created a skyline much different than the one of steel and glass found in New York today. A number of forces and processes have made seas, forests, deserts, and the life those ecosystems hosted appear and disappear from the landscape over the course of geologic time. Many of these changes left behind hints that we can interpret today when we tell the story of a place. That massive glaciers once advanced as far south as New York is not a conclusion derived from mathematical modeling in a lab; it is instead evidenced by not only those scratches, but also by a host of observed glacial deposits that litter not only New York, but much of northern North America.

The story of a place is written in its landscape, rocks, fossils, and biota; fieldwork investigations help scientists—and students and teachers—tell that story.

Introducing students to the practice of fieldwork can be a tremendous experience. Its central role in the education of geoscientists makes fieldwork a “signature pedagogy” in the preparation of professionals within the field, and fieldwork warrants a larger place in the K-12 curriculum. For these reasons, real and virtual fieldwork practices are well suited for addressing both The Next Generation Science Standards and The Common Core Learning Standards. Fieldwork as a topic is also fundamentally different from the other chapter topics in this guide. Therefore, this chapter is somewhat different in structure and is significantly longer than the other chapters in the Guide. The chapter begins by laying out some of the rationale for engaging in real and virtual fieldwork, and it then addresses some of the nuts-and-bolts issues for planning, carrying out, and documenting fieldwork with your students.

Exploring local natural history through inquiry-based approaches emphasizes critical thinking. And by conducting such investigations, students have taken a tremendous leap: they are not merely learning about science; they are doing science! But getting students into the field can be difficult. An alternative is for the educator to visit the field on his or her own time, returning to the classroom with a series of images and specimens that permit a Virtual Field Experience.
Virtual fieldwork offers the opportunity to explore an area without leaving the classroom, and it allows multiple “visits” to a site. VFEs can also enhance and extend the experience when actual fieldwork is possible. The Earth is a system, after all, and any one site—virtual or real—can display a host of natural phenomena, from simple erosion and deposition to the principles of superposition and faunal succession to the formation of ripple marks or mud cracks. By adding to a VFE year after year, you can also document changes within the environment, such as changes to a stream’s course, the succession of an ecosystem, or the nature of human disturbance. Ideally, virtual fieldwork in the classroom captures the active experience of a scientist examining an area: It provides opportunities to actively explore, discover, ask questions, and make observations that help to answer those questions, ultimately allowing students to develop educated responses to the question “Why does this place look the way it does?”

**Commonalities of Virtual and Actual Fieldwork**

This chapter addresses both actual and virtual fieldwork and the many connections between them. The process of making VFEs, at least in the ways we lay out here, involves doing actual fieldwork. Much of the work of making a VFE involves simply following good fieldwork practices in combination with a heightened attention to sharing the experience with students or other learners. While VFEs can be used in place of actual fieldwork, they can also be used to both prepare for and reflect upon actual fieldwork. Engaging students as partners in the creation of VFEs is an opportunity for teaching through inquiry while also building a resource that is useful to people outside of the school, as well as to future students. What follows addresses all of these possibilities.

We also draw attention to the distinction between fieldwork and field trips. We strive to engage learners in figuring things out, while field trips—whether actual or virtual—are too often characterized by trip leaders pointing things out. Building in the opportunity for genuine discovery is challenging but promises to yield longer-term engagement and understanding.

**Just Go (and Don’t Stop)**

The minimum requirement for conducting fieldwork is your own sweet self. This chapter discusses a wide range of tools and approaches, but doing fieldwork of any (safe) sort that doesn’t damage the site is a key objective. The tools and approaches discussed in this chapter will extend your senses and help you to capture the experience in ways that will make it easier to share with students. Work within your comfort zone (but perhaps at its edge) and at a pace appropriate to what life allows, and gradually build your virtual representation of the local environment over the course of years, increasing student participation in the process as time goes by. Use the local landscape to nurture skills within.
your students that will allow them to read any type of landscape. Through this process, your students can teach members of your community about the story of your site while also creating and extending resources that can teach other learners around the country about where you live. Building a deep understanding of place through VFE development and then comparing your local environment with VFEs created by other teachers and students is an excellent way to use the local environment to understand the global environment.

Whether the fieldwork is real or virtual, it can either involve a single visit or be extended over many, many visits. Scientists may reach points where they have figured out particular pieces of the puzzle when understanding the nature of a site, but they never fully understand all aspects of a place’s story. Fieldwork, therefore, is something that is never “finished.” Whether it is the second or seven-hundreth visit to a site, there is always more to discover. This is part of what makes science fascinating! It connects to the idea that while fieldwork may focus primarily upon a single topic, researchers (whether K-12 students, educators, or professional scientists) who develop a deep understanding of the story of a place must understand the roles of geology, ecology, climatology, anthropology, and more. Of course, this type of understanding will not come from a single class period of fieldwork, or even a single course infused with fieldwork, but the appreciation of this systems idea can be planted and nurtured.

**Start local**

In choosing a field site, whether it is local or distant or for actual or virtual fieldwork, it should be interesting from an Earth systems science perspective. Fortunately, if you know how to look, **every** site is interesting from an Earth system science perspective. Over the grand course of Earth history, the story of any location is a fascinating one that involves myriad changes. The work of telling the story of any environment is a form of rich inquiry. While it would also be fascinating to find a place that hasn’t changed, no such place exists on the surface of Planet Earth!

While VFEs provide the opportunity to study distant or otherwise difficult to access locations, we suggest starting close to home or school, at a location that students are already familiar with or have access to. What is outside your classroom door has more immediate relevance to the lives of your students than anywhere else on Earth. Nearly every unit in an Earth or environmental science course, and most of the units in a biology course, play out in some meaningful way in the local environment, and the local environment can extend the boundaries of the classroom tremendously with little or no cost. Things are only understood in comparison to something else, so comparing sites to one another can deepen one’s understanding of both or even of all sites—but it is still best to start with the local.

Students can use real or virtual field sites to study how all the major topics in their Earth or environmental science curriculum are manifest in the “real world.” In an ideal situation, the classroom is immediately adjacent to a safe, accessible field site, and there is flexibility within the school schedule that allows for in-depth study of the site in ways that cut across disciplinary boundaries. Unfortunately, it’s not always practical to repeatedly visit an actual field site
with 30 students throughout the year or semester. Through virtual fieldwork, students can come to see how the rock types and flora and fauna outside their classroom tell part of the story of that place.

In order to create VFEs, authors must closely study their field sites with an eye toward doing fieldwork with students. VFEs are a stepping-stone to bringing students into the field, even if the field is "only" the schoolyard. VFEs can be used to prepare students for the field and/or to process the fieldwork after visiting the actual site. Ideally, students will participate in the creation and extension of VFEs, but we recognize that getting to this point may take years.

**Connecting to Earth Science Bigger Ideas, the Next Generation Science Standards, and the Common Core**

Fieldwork investigations have the potential to be extended indefinitely in time and can involve the integration of a wide range of science and non-science disciplines. "Why does this place look the way it does?" is a bottomless question, meaning that it can be productively investigated for a very, very long time. Field scientists, be they professionals or fifth graders, will never fully answer this driving question absolutely or at every scale.

The act of VFE creation is a valuable type of professional development (PD) that creates useful evidence of having done the PD. Through the creation and continued use of virtual fieldwork, a teacher can become a true expert on his or her local environment—perhaps the preeminent expert. The process of VFE creation and use can also create evidence of inquiry teaching aligned to relevant standards. The VFE you create or augment can serve as a key piece of a professional portfolio.

The ultimate goal of our instruction is to build understanding of the Earth system and the ways in which science is used to build that understanding. We bring focus through the use of a small set of bigger ideas and overarching questions. These are discussed in detail in the Big Ideas Chapter and are also summarized below.

**Overarching questions:**

- How do we know what we know?
- How does what we know inform our decision making?

**Earth system science bigger ideas:**

- The Earth is a system of systems.
- The flow of energy drives the cycling of matter.
Life, including human life, influences and is influenced by the environment.

Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system.

To understand (deep) time and the scale of space, models and maps are necessary.

Fieldwork should provide the opportunity to explore, describe, and build understanding of these questions and ideas. These ideas and questions map onto the Next Generation Science Standards’ Disciplinary Core Ideas, Crosscutting Concepts, and Science and Engineering Practices. The Crosscutting Concepts and Scientific and Engineering Practices are shown in Table 11.1. As you read through the rest of this chapter, and as you and your students carry out fieldwork, revisit these lists of concepts and practices frequently in order to draw attention to how they connect to the work of reading the landscape.

**Table 11.1: NGSS’s Scientific and Engineering Practices and Crosscutting Concepts. As you and your students engage in fieldwork, consider how the practices and concepts are being used to make sense of the environment. See the Big Ideas Chapter for a more in-depth discussion.**

<table>
<thead>
<tr>
<th>Scientific and Engineering Practices</th>
<th>Crosscutting Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Asking questions and defining problems</td>
<td>1. Patterns</td>
</tr>
<tr>
<td>2. Developing and using models</td>
<td>2. Cause and effect</td>
</tr>
<tr>
<td>3. Planning and carrying out observations</td>
<td>3. Scale, proportion, and quantity</td>
</tr>
<tr>
<td>4. Analyzing and interpreting data</td>
<td>4. Systems and system models</td>
</tr>
<tr>
<td>5. Using mathematics and computational thinking</td>
<td>5. Energy and matter</td>
</tr>
<tr>
<td>7. Engaging in argument from evidence</td>
<td>7. Stability and change</td>
</tr>
<tr>
<td>8. Obtaining, evaluating, and communicating information</td>
<td>8. Interdependence of science, engineering, and technology</td>
</tr>
<tr>
<td></td>
<td>9. Influence of engineering, technology, and science on society and the natural world</td>
</tr>
</tbody>
</table>

**Fieldwork Challenges and Benefits**

Of course, VFEs also allow for some kind of “fieldwork” experience when actual fieldwork is difficult or impossible to carry out. The reasons that actual fieldwork is difficult are fairly obvious:

- **Fieldwork is logistically challenging.** It's hard to fit into a typical class period, or even a double lab period. To go off site requires permission slips, busing, and figuring out how to deal with behavior outside the normal classroom setting.
Challenges

- **It costs money.** Field trip budgets have been slashed, and weren’t even very common at the secondary level before budget cuts.

- **Many teachers have only limited experience doing field science themselves.** Earth science has more teachers teaching out of field than any other science discipline, and fieldwork is not a component of many Earth, biology, or environmental science teacher certification programs. It is intimidating to lead fieldwork if you haven’t been through it yourself.

- **Fieldwork poses safety and behavior concerns different from those in the classroom.** Falling off a cliff has different consequences than falling off a chair.

- **Teaching in the field employs a different set of skills than teaching in the classroom.** The logistics of moving groups of students from place to place and focusing their attention on the goals of the fieldwork takes careful planning, especially if multiple classes are involved.

These issues shouldn’t preclude fieldwork, but they undeniably complicate it. These challenges are not insignificant, but the rewards of doing fieldwork are worth the trouble. Field trips are among the most memorable and most valued school experiences.

**Fieldwork 101: Gathering Information and Creating Your Own VFE**

What follows are recommendations. These recommendations are intended to help prepare you for fieldwork, but they are just guidelines, not steadfast rules. Bringing the field to the classroom at any scale is better than not bringing the field to the classroom at all. The careful attention to detail described here will prove extremely helpful, but avoid being discouraged if your first trip to the field isn’t as productive as you had initially imagined. Scientists of all disciplines continually refine their methods and procedures, leading to more productive and “better” results over time. With time and more fieldwork, your confidence will grow. Get into the field, be safe, and do your best to capture the experience in a way that allows you to best reproduce it for your students!
Before visiting the site: understand the natural history of the region
In order to make sense of a local site, it’s helpful to understand the geologic history of the larger region before your visit. Did inland seas once flood the area? Have mountain-building events shaped the landscape and its rocks? Was it glaciated? Since the reasons that a place looks the way it does are dependent upon more than the geology, you want to pay attention to this concept as well. That being said, since the geology is the base upon which the landscape is built, starting there makes good sense. The Teacher-Friendly Guides™ are an excellent source for discovering the history of a region, as well as that history’s effect on the rocks, fossils, and other features of the area.

Questions to Keep in Mind
When visiting or examining any area, the ultimate question to answer is: Why does this place look the way it does? But to help understand such an overarching concern, it is important to have certain other questions in mind. These questions will guide exploration, and they will help ensure that important information is recorded during your visit:

- What kind(s) of rock(s) are found in the area? How do you know?
- In what environment did these rocks probably form?
- What is the arrangement of the rocks?
- Are fossils preserved in the rocks? If so, what can they tell you about past environments?
- What has happened to this area to make it look the way it does today? (That is, what has happened to the area since the rocks formed?) Why do you think so? (What is the evidence for your claim?)

We have put together a set of questions that build upon the fundamentals listed above and that can be asked of any site. This is a key idea—that there are questions that can be asked productively about any environment. Recognizing that idea is a key step toward being able to take the lessons of one field trip and applying them to the “reading” of any landscape. These questions are included in the graphic organizer in Figure 11.1, and as a checklist in the section entitled Back in the Classroom.
Figure 11.1: This pair of graphic organizers shows various paths of inquiry that stem from the question: Why does this place look the way it does? The top graphic focuses upon the geosciences, and the bottom focuses upon the environmental sciences. The questions within the diagrams are also included as printable checklists in the section “Back in the Classroom.”
Safety and Logistics in the Field

At the Site
Considerations are different for an adult or a group of adults in the field than they are for taking students into the field, but certain measures related to safety are universal. At any field site, safety is the first priority. No photograph, measurement, or fossil is worth the risk of personal injury or death. To ensure safe and productive fieldwork, keep the following thoughts in mind:

- Always carry a small, standard first-aid kit.
- Wearing the proper clothing is very important. Long pants are recommended, as are sturdy boots, which will help prevent twisted ankles as you scurry over uneven or loose surfaces.
- While walking through a valley or next to any outcrop, always be on the lookout for rock falls. Remember, slopes with no vegetation tend to produce more falls.
- If more than one individual is climbing an outcrop, do not climb single file. Rocks dislodged from one climber can quickly tumble down the outcrop and hit the next climber.
- When using your rock hammer, protective eyewear should always be worn. If your hammer possesses a sharp pick opposite the flat surface, always use the flat surface when striking. And if you are working with others, notify all in the vicinity before striking any surface with your hammer.
- Never use one hammer to strike another. Metal chips can be broken off and thrown at high speeds.

Sunscreen, insect repellent, flashlights, food, and water should be considered in relation to environmental conditions and length of the field excursion. Please note that this chapter is written with shorter excursions in mind where substantial supplies will not generally be required. The next section offers more detail on the materials to take with you into the field.

Give appropriate consideration to group management. We suggest taking individual classes into the field for short trips before attempting either longer fieldwork excursions or trips with multiple classes. Managing larger groups or longer trips requires attention to logistics that will not be addressed in depth here. Whether the group is large or small, consider the benefits of a buddy system and measures to keep track of where everyone is—both children and adults. If groups are spread out on the trail, the lead group should stop at trail crossings to make sure everyone follows the intended trail. Younger students should not be left unsupervised for any length of time. Schedules and rendezvous points are important for longer trips and larger groups. All teachers and chaperones should have one another’s cell phone numbers.
Fieldwork

Things You Might Use in the Field

The Essentials and Near Essentials
As noted above, the essential materials for going in the field (besides yourselves) are clothing (especially footwear) that is suited to the weather and trail conditions and a first-aid kit appropriate to the situation. You will likely also want tools or devices to extend your senses, to preserve your observations, to collect materials (where safe and legal), to take photographs, and to store data, all of which will allow for continued observation and analysis after you return from the field. If your fieldwork is on the school grounds, or adjacent to it, you perhaps won’t need anything different than what is needed on a typical class day, at least for the initial visit.

To extend your senses, start with simple things like magnifying loupes and rulers and potentially move on to include more sophisticated tools like probeware (to measure pH, temperature, and dissolved oxygen) or field microscopes. Since tools are used for both extending your senses and for capturing and preserving your observations, the most obvious tools for preserving one’s observations are notebooks, pencils, cameras, GPS units, smartphones, and tablets.

As varied as field science is, a few items should be in every scientist’s gear whether you are investigating rocks, observing streams, or documenting ecology. Even though processes and concepts are universal, each place is also unique, a product of its position on the Earth, its geological and ecological history, and the local human impacts. Making sense of why a place looks the way it does must take that context into account. Further, good science depends upon repeatability of observations: if another scientist (or your next class!) wants to analyze or build upon your observations, he or she must be able to know precisely where your study took place and how you made your observations. It is thus critical to locate the position of your studies on a map as precisely as possible. With modern GPS technology, it has never been easier to record a location to within a few meters, though you can certainly follow good science practices even if you don’t have this capability. Table 11.2 lists equipment and materials that are useful in the field.

Maps and Notebooks
Large-scale maps provide a way to see your field site in the context of other features in the area. At a closer scale they also provide a way to show the position of several sites relative to each other. At still higher resolution, maps provide the medium to store and display spatial information from one site. You will therefore probably want maps at all of these scales.

Large- and medium-scale maps for providing context can be found online. Google Maps and Google Earth are two of the best known interactive sources. If students need help understanding maps and scale, a helpful exercise is to create a “Powers of Ten” map of your schoolyard, starting with an overhead shot of the school yard that students recognize, then zooming out—making each of the new images increase in dimension by ten times—until one can see the site from the perspective of the whole Earth. A video tutorial, inspired

Table 11.2

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by the classic film, is available at http://www.virtualfieldwork.org. It is simple to add your field site to the same Google Earth file containing the Powers of Ten centered on your school. This can help students better understand the location of the field site in relation to the school.

Field scientists typically show information about their field site: the location of observations (such as photographs and specimen collection) and also the scientific data (such as rock type, position of faults, areas of bedrock exposure, water quality information, and much more). For these purposes you may want to have a paper copy of a map you can bring into the field upon which you can make notes. Commonly topographic maps are used as base maps, in part because the contours can help you locate yourself on the map (if it’s not completely flat) and partly because the topography itself is often relevant to Earth and the environmental data being collected. If your field area is larger than about 100 meters (330 feet) on a side, you can create a topographic map tailored to your needs using online software (http://www.gpsvisualizer.com). USGS topographic maps of the entire US are available as free downloads at http://www.usgs.gov/pubprod/. You may wish to download the local map and take an excerpt of the area surrounding your site.

Table 11.2: Materials to take in the field. (Items in bold are highly recommended.)

<table>
<thead>
<tr>
<th>For Safety and Comfort</th>
<th>For Extending the Senses</th>
<th>For Preserving and Extending Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yourself</td>
<td>Ruler or scale card</td>
<td>Notebook</td>
</tr>
<tr>
<td>Appropriate footwear</td>
<td>Measuring tape or meter</td>
<td>Pencil</td>
</tr>
<tr>
<td>First aid supplies</td>
<td>stick</td>
<td>Materials for collecting</td>
</tr>
<tr>
<td>Water</td>
<td>Magnifying loupe or hand</td>
<td>collecting</td>
</tr>
<tr>
<td>Sunscreen</td>
<td>lens (about 10x)</td>
<td>o Baggies</td>
</tr>
<tr>
<td>Insect repellent</td>
<td>magnification</td>
<td>o Specimen labels</td>
</tr>
<tr>
<td>Food</td>
<td>Water test kit</td>
<td>o Sharpies</td>
</tr>
<tr>
<td>Safety goggles</td>
<td>Compass</td>
<td></td>
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<tr>
<td>Flashlight</td>
<td>Clinometer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Field microscope</td>
<td>Rock hammer</td>
</tr>
<tr>
<td></td>
<td>Field guides</td>
<td>Camera</td>
</tr>
</tbody>
</table>

Common sense should be your guide when determining what is needed for a particular visit to the field. Trips that last a class period and are adjacent to the school may require nothing beyond materials for a typical class—a notebook and a pencil.

For Both Extending the Senses and Preserving Observations

- Maps
- Camera (possibly with video)
- Probes and interface (like the Vernier LabQuest)
- Digital field microscope
- GPS unit, smartphone, or tablet
- Apps used in the field might include:
  - GPS
  - Google Earth or other virtual globe
  - Sketch (or other image-annotating app) for adding notes to photos. Sketch also includes a map annotation function.
  - Photosynth or other panorama app
  - Video (the YouTube Capture app allows for basic video editing on your smartphone or tablet)
  - Other specialized photography apps
  - Audio recorder
  - Notes
  - Photo management software, such as Web Albums
Positions of samples, photographs, and observations can be located using GPS. In this case, you can make notes about your GPS locations, and plot the locations on a computer later, or make use of an app like Skitch that allows you to annotate digital maps in the field. Photos taken with smartphones, tablets, and GPS-enabled cameras will include location data with pictures. Those familiar with Geographic Information Systems (GIS) can make elaborate maps using your own sets of coordinates and data. While GPS and GIS technology are now standard in most types of fieldwork, they are not essential for doing good fieldwork. Standard, intuitive tools for measuring are, however, quite helpful. A compass (either traditional or digital) can be helpful in orienting your field site in space, and a ruler and protractor can be helpful when drawing the field site in correct proportions (e.g., the position of samples along a transect or the angle of bedding or faults). Bring a clipboard so that you have a flat surface to write upon in the field—pencils and a good eraser are the best writing implements for drawing and annotating your map.

It is possible in principle to capture all your data electronically, but most field scientists still use a notebook even if they have access to the latest technology. Certain information can be captured very simply in the field with a pencil and paper while it may prove challenging with digital technology, such as when making annotated sketches of the field site and taking written notes. Normally pencil is used, in part because it doesn't smear if it gets wet, but also because it's erasable; while not essential, field scientists who know they may have to work in wet conditions will purchase notebooks with waterproof paper (Rite-in-the-Rain notebooks). An audio recorder (smartphone or standalone digital recorder) is handy when writing a lot of text is impractical, though it does create transcription work at the end of the day. Remember that it is considered a form of "best practice" to make sure that each entry includes the date, time, and locality.

### Documentation and Specimen Collection

#### Photographs
Once at a field site it is easy to immediately begin taking photographs without recording notes to accompany them—a problem experienced by professional and amateur scientists alike. But the lack of proper documentation is perhaps the most common mistake made in the field, especially with digital photography, where it is easy to take tens or even hundreds of photographs at a single site. Also, before you begin photographing it is advisable to first explore the entire location and develop a plan for how you will communicate the site to your students back in the classroom. This plan will guide your photography, and the recorded notes will ensure that every image makes sense long after you’ve visited the site. Proper documentation includes the following steps:
Note the location and orientation of the photographs you take. Recording this information on a map is very helpful.

In each photograph, it is important to have a sense of scale. For smaller structures (like ripple marks or fossils) or close-ups of an outcrop or rock, it is important to show scale by using a common object, such as a penny, rock hammer, an unsharpened pencil, or (ideally) a clearly marked ruler. For larger structures, a really great scale is a person, so feel free to step into the picture! The importance of a scale cannot be overstated, as the proper identification of geologic features in photographs often depends on knowing the feature’s size.

In addition to showing scale within photographs, be sure to pay attention to different scales across the set of photographs you take. That is, include photographs across a wide range of scales, from the smallest fossil or mineral crystal to panoramic shots of the landscape. Maps and virtual globe software, such as Google Earth, can extend scales from the local landscape to a global perspective.

**Drawings**

Although photographs are key, simple sketches or drawings are also useful for documenting a field site. In fact, subtle changes in rock layers, for example, may not be visible in photographs, so to capture such features, drawing may be required. Drawing also forces you (or your students) to observe closely. It will be helpful to use either a Rite in the Rain notebook or a large, clear plastic bag to hold your notebook in case of rain. When drawing, keep in mind that you should document the same type of information that is documented in photographs (location, orientation, and scale). Drawing also requires close study in a way snapping a photograph does not. Louis Agassiz once said that “…a pencil is one of the best of eyes.” While drawing, you have to think about the relationship of the elements you are representing, their scale, and their arrangement.

**Annotating Photographs**

The use of smartphones and tablets in the field allows for a hybrid of photographs and drawings. Many apps allow for captioning photos in the field, and some allow you to draw and write text on photos as you take them. Skitch is one such app, and it also allows for the taking of notes on the maps themselves. Photos taken on smartphones and tablets are also (typically) geo-referenced. This means that they can easily and quickly be included in a Google Earth or other GIS program in the precise location where the image was taken. If you are unable to annotate photographs in the field, or you wish to add more detail than is practical on your electronic device while you are at the field site, the “old fashioned” technique is to take a picture, then make a simple notebook sketch containing labels of key features. Later you can annotate a digital or printed version of the photograph using your field notes. If the conditions are poor for
Fieldwork

note taking either digitally or manually, it may be more practical to record audio notes that you can later match to your picture.

Using Field Guides
Select field guides appropriate to the focus of your work and consider whether or not you wish to bring others. The appropriate field guide might be something as simple as a single sheet with line drawings of the fossils common at your field site, a few pages containing a dichotomous key of common rock types, or a collection of field guides on fossils, birds, mammals, butterflies, rocks, flowering plants, and more. While scientists will come to know by sight the kinds of specimens commonly found at their site, they do not typically set out to memorize them, and uncommon things are sometimes found that send even experts back to their field guides.

Collecting Specimens
Rocks and fossils often provide significant clues for interpreting past environments. Layers of basalt indicate past volcanism, for example, whereas shales bearing trilobite and other fossils indicate deposition in a shallow sea. Collecting specimens from a site provides a wonderful opportunity to take a piece of the field into the classroom, allowing you to engage students in hands-on learning. Collecting specimens also permits further study away from a site where time and field conditions can impose certain limitations. You can and are encouraged to identify rocks, minerals, fossil types, and flora and fauna in the field. So, what do you need to know about collecting specimens?

- You first need to confirm that collecting specimens at the site you are visiting is legal. Typically, collecting is not allowed in parks, so be sure to check.
- Just as you made decisions about photography based on how you plan to communicate the site to students, collect specimens that will help tell the story of the site back in the classroom. If rock types change from area to area, either vertically or horizontally, then specimens of each type are ideal.
- Before collecting a specimen, take a photograph of it in situ, both close up as well as from a distance. Don’t forget to include an object for scale in the photograph!
- Document the location from which the specimen is collected, preferably on a map of the area. Labeling the specimen with a number that corresponds to a number on your map is an effective technique.
- Specimens should be broken directly from the outcrop so the exact source is known. Eroded rocks scattered about on the floor of the site may have originated from multiple locations.
- The weathered surface of rocks often carries a different appearance than a “fresh” break. Ideally, collected specimens
possess one weathered surface but are otherwise not weathered. Rocks broken directly from outcrops will ensure fresh surfaces.

- As specimens are collected, place each in a separate resealable bag, noting on the bag with permanent marker each specimen's location as indicated on your map. Include a specimen label within the bag, including the information shown in Figure 11.2.

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**Back in the Classroom: Virtual Field Experiences (VFEs)**

Following your trip to a field site, perhaps the most critical step after returning to your lab or classroom is to examine all of your photographs, illustrations, specimens, and notes associated with each. Sometimes even the most diligent geologist forgets to record notes that, in hindsight, are critical. It is therefore recommended that one makes sure that his or her notes are legible and complete. Recopy your notes. Such an activity will not only ensure legibility for the future, but it will help indicate any gaps in your note taking. If gaps exist, then it is easiest to fill them in when your memory of the site is fresh.

Once your materials from the site visit are in order, it is time to develop an activity that will allow your students to experience the site much like you did—but in the classroom. VFEs allow you to compile this information in a way that
Fieldwork

VFES

is easy to share with others who wish to learn about the site. Ideally, VFEs provide opportunities for open-ended exploration, just as actual fieldwork does. Scientists in the field are not limited to a single possible way to operate, nor do they have a guide explaining what they see at every turn. In the field, one might pick up a rock and take a closer look, or pull out a magnifying glass and look at a cliff face. Exploration drives inquiry in the field, and inquiry and exploration are key goals of VFEs.

The concept of VFEs can take on multiple forms. For example, kits containing maps, printed photographs, and specimens (with notes on the map indicating where the specimens were collected or where the photographs were taken) can be produced. Or, your digital photographs can be embedded within a PowerPoint or Prezi presentation, a website, or a Google Earth tour with placemarks containing photos, video, or other data in the exact locations where the specimens were collected. Maps can also be overlain. Historic maps can be included, and Google Earth has historical imagery included for much of the world. Many VFEs incorporate more than one technological platform.

Keep in mind that these electronic presentations may take on a very linear, directed feel. In that respect, be careful that your VFE does not turn into a Virtual Field Trip. Virtual Field Trips have become increasingly common at many levels of education, but these experiences are typically guided tours rather than opportunities for inquiry. An online search will yield many examples of these tours, as will a search of the Digital Library of Earth System Education (DLESE). Such resources clearly have value, but they are passive experiences for students. VFEs, in contrast, should stress the importance of inquiry; learning for understanding involves students figuring things out. The act of making new, or extending existing, VFEs may be the simplest way to bring inquiry to the use of VFEs.

In considering VFEs as a recurring practice, initial experiences are perhaps more guided than the later experiences; allow a gradual transfer of responsibility from teacher to student. But VFEs ideally offer the same opportunities for exploration as those provided at an actual field site, with occasional moments of discovery that lead to new questions about the site. By asking such questions and then seeking answers, students are doing science. And it is perfectly reasonable to virtually visit a site several times for further data collection, or even to study different concepts at the same site. Scientists, of course, do exactly the same thing.

Prezi and PowerPoint VFE Templates
This section discusses templates intended to simplify VFE production in addition to providing general information on VFE development and use. There are templates in both Prezi and PowerPoint formats, each with a version of the graphic organizer shown in Figure 10.1 as its centerpiece. Questions in the graphic organizers and in the rest of the templates are written generically, so they may be applied to any site. The templates serve as starting tools that are useful for creating an “entry level” VFE. They are available at http://virtualfieldwork.org/Template.html. The template includes graphic organizers
for both Earth and environmental science, with the environmental science organizer embedded within the geoscience organizer.

**How are teachers using virtual fieldwork?**

VFEs might be used as a single, in-class exercise, or they can be explored across an entire year. We hope that teachers who use and develop VFEs will eventually use them across the entire curriculum, but it makes sense to start smaller. There is no single correct approach to using VFEs in the classroom. Here are some examples of ways teachers are using virtual fieldwork:

- Students in a rural community are using Google Earth to create Powers of Ten tours centered on their homes (based on the Eames’ classic film). This helps students to internalize the abstraction that is central to making maps and to build deeper understandings of scale.

- Students are making geologic maps of the local bedrock.

- Students are creating an interpretive guide for a county forest.

- Students are exploring lakes, dams, streams, outcrops, quarries, waterfalls, and more.

For more VFEs, see our growing database at [http://virtualfieldwork.org/](http://virtualfieldwork.org/).

**What do I need to consider as I begin to build my VFE?**

Considerations fall into four categories:

- **Logistical**: What do I have the attitude, time, resources, and skills to do? (Attitude is listed first as it is the most important factor.)

- **Pedagogical**: How do I bring the scientific content together with technologies in a way that best builds enduring understandings of bigger ideas and overarching questions, as well as of the smaller scale ideas and questions I deem important?

- **Technological**: What hardware and software do I need to assemble the materials for the VFE and to make it accessible to my students? This may include traditional scientific tools, like a rock hammer or a compass, as well as the computer technologies discussed in this chapter and on our website.

- **Content**: What scientific knowledge, ideas, processes, and practices do I want my students to understand and be able to do at the end of the experience?

Of course, these categories overlap and interplay substantially—teachers of Earth science use Google Earth in different ways than other Google Earth users do.
Most of the remainder of this chapter is a set of checklists to help you address these different considerations when outlining your VFE design. Take it with you into the field as you collect pictures and other kinds of data for your VFE; use it to identify issues you think are most important for the development of your VFE. Most of the items in the checklists are there to start you thinking about how to address a particular issue. Content is listed last for the sake of readability, as the checklists for the content section are longer than they are for the other categories.

Table 11.3: A checklist of cross-category issues. Many of the questions in the checklist relate to more than one of the categories identified above. Because of this overlap, only the cross-category issues and content sections are of significant length.

<table>
<thead>
<tr>
<th>Question:</th>
<th>Logistical</th>
<th>Pedagogical</th>
<th>Technical</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do I have appropriate safety and first aid equipment and materials?</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What content do I want to address?</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do I have connections in mind to at least a couple of the bigger ideas and overarching questions?</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- The Earth is a system of systems.</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- The flow of energy drives the cycling of matter.</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Life, including human life, influences and is influenced by the environment.</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system.</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- To understand (deep) time and the scale of space, models and maps are necessary.</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- How do we know what we know?</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- How does what we know inform our decision-making?</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How much time do I realistically have to spend on VFE creation?</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How much class time do I want to dedicate to VFEs?</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am I okay with the trade-off between some expected frustration and the pedagogical payback?</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Can I productively engage students in VFE development? Or is that something to aspire to for next year?</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How does the technology I have serve the goals I wish to meet?</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do I have enough batteries for my powered equipment?</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is the site accessible to me? This includes legal, safety and proximity considerations.</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Are my students familiar with the area? If not, is it accessible to all of my students? If the answer to both questions is no, select another site.</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Are the required pedagogical, technological, and content skills and knowledge needed to create the VFE within my reach? Ideally, select challenges that are just within (or just beyond) your reach so that you grow professionally.</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do I have the hardware (including field equipment) and software needed for VFE creation? The bare essentials are an Internet-connected computer, a digital camera, and either PowerPoint or Google Earth.</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Logistical

We hope that VFE development is used to expand teachers’ skills and knowledge. Performing fieldwork for the first time can be overwhelming, but remember that science is a process, and not even professional scientists capture all that they need in one visit. With practice, and the proper attitude, you will become more and more comfortable when visiting the field.
Pedagogical
While most pedagogical questions also address other categories as noted above, there are issues that deserve explicit attention here.

- Does the data you are collecting go toward answering why this place looks the way it does? Or is there a good reason to introduce distracting information?

- If the site is especially striking or unusual, have you considered how to get yourself and your students beyond the “novelty space” of the location? Crudely summarized, novelty space is the idea that you can’t figure out what’s going on at a field site if you’re either awed by its beauty or freaked out by its perceived dangers. This is one of several reasons for choosing a site that is already familiar to the students.

Technological
Most technological issues are also logistical; these are addressed in the table above.

Content
Why does this place look the way it does? The driving question of our work can serve as an entry into any major topic in Earth or environmental science curricula. It also brings relevance to the science since we want to start with sites near the school that are already somewhat familiar to the students. We want students to look at the familiar with new eyes, and to become skilled at reading their local landscape. Ultimately, we want the skills built by reading the local landscape (being able to tell the story of why a place looks the way it does) to be transferable to any landscape.

What scientific content do you want your students to better understand through their work in the VFE? How does this fit into the larger goals of the course? Can you draw, and help your students to draw, connections to bigger ideas and overarching questions? What topics in Earth science can be addressed by doing fieldwork?

Below are questions taken from the geoscience and environmental science graphic organizers. Most teachers will likely use one sheet or the other, but not both. Your VFE likely won’t address all of the questions (on either sheet), but you should be able to strategically select what you minimally wish to address.
Fieldwork

For the Geosciences:

For all of the following questions:
- How do you know? (What evidence is there?)
- What does it tell you about past environments?
- What does it imply about the future?

☐ Describe the shape of the land.
- Are there mountains, valleys, or hills?
- What are the valley shapes?
- What can cause valleys to form?
- What can cause mountains or hills to form?
- Are the mountains or hills young or old?
- What roles does tectonics play in shaping the site?

☐ What effects has water had on the landscape?
- Is water depositing material, eroding material, or both?
- Is the action of water primarily chemical, primarily physical, or both chemical and physical?

☐ What effect has the climate had on the landscape?
- Was the past climate different?
- What factors may have been affected or caused by climate?
- How has fire played a role in shaping the environment?

☐ Describe the ecosystem.
- See the ecosystem graphic organizer and checklist.

☐ What does the arrangement of the rocks and soils indicate about past conditions?
- Do the rocks seem to form a sequence?
- Where would you find the oldest rocks? The youngest rocks?
- Does the rock record include evidence of ancient disturbances? If yes, describe.
- Are there different kinds of rocks at different outcrops?

☐ What types of rock and soils are there and what do they indicate about past conditions?
Sediments and Sedimentary Rocks
- Is the sample clastic or organic/chemical?
- If clastic, what is the grain size?
- If organic, what minerals is it made out of?
- Are there fossils?
Metamorphic
- Is the rock foliated or non-foliated?
- What was the parent rock?
Igneous
- Did the rock form above or below ground?
- Is it felsic or mafic?

☐ What effects has life, including human life, had on the landscape?
- How have plants shaped the landscape?
- How have animals generally, and humans in particular, changed the landscape?
- On what scale?
For the Environmental Sciences:

For all of the following questions:
- How do you know? (What evidence is there?)
- What does it tell you about past environments?
- What does it imply about the future?

☐ Describe how life shapes the land.
- What are the pioneer plants?
- How do pioneer plants impact soil formation?
- How are animals shaping the land?
- Are there invasive species? If yes, what are they, and how are they changing the ecosystem?
- Have disturbances played a role in the introduction of invasives? If yes, describe.
- How are new invasives likely to change the ecosystem over the next century?

☐ Describe the role of water in the ecosystem.
- In what ways does water serve or disturb habitats?
- How does life move, use, and store water?

☐ How has climate shaped the ecosystem?
- How is the climate reflected by living things at the site?
- Describe any microclimates and how they affect life.
- Describe how sun and shadow affect life.
- What roles do fire, hurricanes, or other climate-related disturbances play in shaping this landscape?

☐ Describe the role rocks and soil play in the ecosystem.
- How does life change the rocks and soil at the site?
- How is life dependent upon the rocks and soil at the site?
- Does the rock record include evidence of ancient disturbances? If yes, describe.
- See also the geoscience questions.

☐ Describe the types and arrangements of plants and animals and what they indicate about present and past environments.
- Why do living things in the environment look the way they do?
- What life forms were the earliest to arrive?
- Describe how different life forms are distributed throughout the field site.
- What is the impact of invasive species and other disturbances? See also the Describe how life shapes the land section.

- Plants
  - How have plants shaped the landscape?
  - How has the landscape affected the plants?

- Animals
  - How do animals contribute to plant distribution?
  - How has the landscape affected the animals?

- Other biota
  - What effects have humans had on the landscape?
  - What resources do humans use from here?
  - How have humans changed the landscape?
  - On what scale?
Closing Thoughts

This chapter was written to help get you started in the creation of VFEs and, in a broader sense, to help you learn more about fieldwork. But how do you know when to stop? It may be more productive to think of VFEs or activities involving actual fieldwork as undertakings that are becoming ready for use rather than as finished products. Here is a nice quote from Wendell Berry’s essay “Faustian Economics” that relates to this concept:

It is the artists, not the scientists, who have dealt unremittingly with the problem of limits. A painting, however large, must finally be bounded by a frame or a wall. A composer or playwright must reckon, at a minimum, with the capacity of an audience to sit still and pay attention. A story, once begun, must end somewhere within the limits of the writer’s and the reader’s memory. And of course the arts characteristically impose limits that are artificial: the five acts of a play, or the fourteen lines of a sonnet. Within these limits artists achieve elaborations of pattern, of sustaining relationships of parts with one another and with the whole, that may be astonishingly complex. And probably most of us can name a painting, a piece of music, a poem or play or story that still grows in meaning and remains fresh after many years of familiarity.
Resources

Field Geology Teaching Practices


Guides to Fieldwork
(Mostly focused on post secondary education, but useful as references)


*How to Read a Geologic Map*, Wisconsin Geological and Natural History Survey.
http://wgnhs.uwex.edu/wisconsin-geology/bedrock-geology/read-geologic_map/.


Appendix: The Teacher-Friendly Guides™, Virtual Fieldwork, and the NGSS’s Three-Dimensional Science

The Next Generation Science Standards contain a set of learning goals that define and describe the ideas and practices that we need in order to think scientifically. The NGSS are not a curriculum. They tell teachers not how to teach, but rather, are tools to show what to teach. They also help families know what children are expected to learn, and help schools and teachers know what to assess. So, how do you teach in ways that align with NGSS, if NGSS itself doesn’t tell you? The strategies, tools and resources associated with the ReaL Earth Inquiry project, like this Teacher-Friendly Guide™, are intended to offer a partial answer to that question.

The vision of NGSS differs in a number of important ways from current common practice in schools and classrooms across the country. Teaching about local and regional Earth and environmental science can and has worked well for many teachers under more traditional standards, but by attending to the three dimensions of the NGSS (see below), we believe it can work even better. Deep understandings of why your local environment looks the way it does requires understanding the local environment from multiple disciplinary perspectives, and understanding the connections amongst these different disciplinary ideas. That is, to understand your local environment, a systems perspective is needed. Scientifically accurate meaningful understanding can and does come out of single lessons, single units, and single courses, but these understandings become richer, deeper, and more durable if they are connected across courses. The NGSS vision includes recognition that building a deep understanding of big ideas is both very important and a process that takes years of coordinated effort. Fortunately, the many processes that shape the local environment are part and parcel of existing curricula, and especially for Earth science, biology, and environmental science courses, nearly every unit has central aspects that play out on a human scale just outside the school door. A coordinated approach to the study of the local environment across units within a single course and across grade levels...
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and courses can be a fairly subtle change in each teacher’s daily routines, but it has the potential for big returns in terms of the depth of student understanding. This deeper understanding pertains not only to the local environment and the way course topics are represented within it, but also to systems more generally, to the nature and importance of scale, and to much, much more.

NGSS builds upon the earlier work in the National Science Education Standards (NSES), but brings more of a systems approach not only to its representation of science, but to the standards themselves. NSES defined science not just as a body of ideas, but an evolving body of ideas extended by inquiry. NGSS continues this work by clarifying inquiry and the sciences as a set of relationships amongst three dimensions: Disciplinary Core Ideas (DCIs), Scientific and Engineering Practices and Crosscutting Concepts.” Each of the three dimensions is judged to be of roughly equal importance and they are seen as interdependent. To truly, deeply, understand science and how scientific understandings develop, learners must not only understand each dimension, but how the dimensions are related to one another—the whole is greater than the sum of the parts. By coming to understand these interconnections, teachers and students will also come to better understand the nature of both scientific inquiry and of complex systems.

A Perspective on Science Education Priorities

The bulk of the NGSS is a series of Standards, each a page or two in length, with “Performance Expectations” (PEs) at the top of the first page, followed “Foundation Boxes” and “Connection Boxes” supporting the PEs. It’s tempting to jump into the discussion of NGSS by starting there. It’s also tempting to start with the Disciplinary Core Ideas (DCIs), especially for those who specialize in a particular scientific discipline. But readers shouldn’t do either of those things. Appendix K of NGSS notes, “The goal is not to teach the PEs, but rather to prepare students to be able to perform them by the end of the grade band course sequence.” It’s important to understand the basic three-dimensional structure of the NGSS before looking at the PEs or DCIs. We will give them both their due, but we won’t start with either of them.

If you have a degree in a particular science, and this is the science that makes up the bulk of your teaching load, it’s natural to go straight for your area of expertise in the NGSS, to see how that’s addressed. But don’t do that, or, if you already have, try to imagine that you haven’t. Before considering the concepts and practices essential to being literate in your discipline, consider what you think everyone needs to know about science disciplines outside your area of specialization, and consider the ideas that are broadly applicable across all the sciences. That is, think about the fundamentals of science.

Imagine having magical powers that allowed you to make every American understand six or eight profound scientific ideas – ideas that, if everyone understood them, would help people make the world a better place because
they would make better decisions. Imagine again that this power could also be used to give everyone a small set of well-developed scientific skills. What should these ideas and skills be? Ponder what these ideas and skills are before reading further, perhaps going so far as to put them down on paper. Ask your colleagues, and your former students the same question. What are the most important ideas and skills for everyone to understand or be able to do related to science?

The profound scientific ideas you thought of are likely to be something like NGSS’s Crosscutting Concepts, and the scientific skills are likely to be something like the Scientific and Engineering Practices (Table A.1). In reviewing the NGSS, teachers at the secondary and college levels who specialize in a particular subject are often naturally drawn first to the Disciplinary Core Ideas for their discipline, and when they find a favorite topic that is not addressed to what they consider an appropriate depth, they are upset that NGSS is not providing the content necessary to prepare their students for the future. But, decades of educational practice teaching science courses with thousand-page textbooks and scores of key ideas has not yielded a scientifically literate populace. It is essential to focus on smaller sets of truly big ideas (see also the Big Ideas chapter) and work across grade-levels to build understandings over time. This may mean, however, that your favorite topics are no longer explicitly listed in the learning goals.

Table A.1 contains abbreviated versions of the Concepts, Practices, and Ideas. You can find longer descriptions within the NGSS, and we’ll look at one as an illustrative example. Consider the full description of Crosscutting Concept #3:

*Scale, proportion, and quantity.* In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system’s structure or performance.

It seems likely that most Americans do not have a good and durable understanding of this concept, yet it has relevance to many aspects of their daily lives. The same could be said of most, if not all, of the remaining concepts on the list.

Such understandings are almost certainly more important than knowing particular facts about geologic history or the nature of disease (two topics not given deep attention in the NGSS). Indeed, it’s only possible to understand geologic history or the nature of disease if you also understand these concepts!

While your favorite topics may not be explicitly mentioned in NGSS, that doesn’t necessarily preclude them from being taught. There’s a tremendous amount of content in these Teacher-Friendly Guides™ that are not mentioned in NGSS, yet we believe that all of the contents of the Guides support teaching
Appendix

that is aligned with the NGSS. Different topics, such as glaciers or mineral resources, can serve as our pedagogical partners in building understandings of the Crosscutting Concepts, Scientific and Engineering Practices, and the Disciplinary Core Ideas that make up the NGSS. In other words, we can and should teach these topics, but understanding the particular topic isn’t the primary goal. The primary goal is to use the teaching of these topics as a means to build an understanding of those bigger ideas.

It isn’t clear if K–12 science curricula designed to bring the NGSS’s vision to fruition will be more or less rigorous than today’s common K–12 curricula, but rigor shouldn’t be the goal of education. Education should develop citizens who can reason critically and use evidence to inform their actions. This isn’t to say that schooling shouldn’t be challenging, but rather that its challenges should be in the service of meeting other goals. Building deep and interconnected understandings of the three dimensions of NGSS will not be a simple task, but it has the potential to better prepare for students for citizenships, college, and careers.

Connecting “Why does this place look the way it does?” and Virtual Fieldwork to NGSS

This Teacher-Friendly Guide™ is one part of a large project designed to help educators teach about Regional and Local (ReaL) Earth system science in an inquiry-based way. This ReaL Earth Inquiry Project, and all of its related resources, support educators and students in the investigation of the project’s driving question: “Why does this place look the way it does?” The “place” of the question is anywhere you happen to be, but we hope and expect users of these materials will start by studying areas outside their backdoor or their classroom door. The Fieldwork chapter (Chapter 11) addresses both actual and Virtual Fieldwork, and we believe the coupling of virtual and actual fieldwork is an excellent way to teach and learn, and it’s an approach that is fully three dimensional, in the NGSS’s sense of that term.

Read through the Practices outlined in Table A.1 with an eye towards engaging in and documenting fieldwork. See the graphic organizer and the question list in Chapter 11 and consider how these questions can be asked of any site, and how they can serve to inspire new questions that are site-specific. Then, consider the making of Virtual Fieldwork Experiences (VFEs) to document the site, allowing for continued investigation after leaving the field, and sharing findings with others in the community and beyond. This approach provides opportunities to engage all of the practices. To build rich explanations of the range of processes at play in a field site requires application of all of the Crosscutting Concepts. There are also opportunities for using field sites to build understandings of all of the DCIs, though selected ones from the Life and Earth & Space Sciences have the most direct correspondence. The use of virtual and actual fieldwork is scalable to fit the educational need, so a particular lesson or activity would be
Scientific and Engineering Practices | Crosscutting Concepts
--- | ---
1. Asking Questions and Defining Problems | 1. Patterns
2. Developing and Using Models | 2. Cause and Effect
3. Planning and Carrying Out Investigations | 3. Scale, Proportion, and Quantity
7. Engaging in Argument from Evidence | 7. Stability and Change
8. Obtaining, Evaluating, and Communicating Information | 8. Interdependence of Science, Engineering, and Technology

Disciplinary Core Ideas

<table>
<thead>
<tr>
<th>Physical Sciences</th>
<th>Life Sciences</th>
<th>Earth and Space Sciences</th>
<th>Engineering, Technology, and the Applications of Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS 1: Matter and its interactions</td>
<td>LS 1: From molecules to organisms: Structures and processes</td>
<td>ESS 1: Earth's place in the universe</td>
<td>ETS 1: Engineering design</td>
</tr>
<tr>
<td>PS 2: Motion and stability: Forces and interactions</td>
<td>LS 2: Ecosystems: Interactions, energy, and dynamics</td>
<td>ESS 2: Earth's systems</td>
<td>ETS 2: Links among engineering, technology, science, and society</td>
</tr>
<tr>
<td>PS 3: Energy</td>
<td>LS 3: Heredity: Inheritance and variation of traits</td>
<td>ESS 3: Earth and human activity</td>
<td></td>
</tr>
<tr>
<td>PS 4: Waves and their applications in technologies for information transfer</td>
<td>LS 4: Biological evolution: Unity and diversity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A.1: Summary of NGSS’s Three Dimensions. For more detailed descriptions, see the relevant appendices in The Next Generation Science Standards.

expected to target just one or two, but a program of fieldwork across a course would allow for the addressing of many of the Concepts, Practices, and Ideas.

Look again to the graphic organizers from Chapter 11: Fieldwork. It is easy to see how, especially in Earth science, biology, or environmental science courses, most of the units in these courses play out in some meaningful way outside the classroom door. As the DCIs are akin to umbrellas relative to a course’s units, these too largely play out in meaningful ways outside the classroom door. The
NGSS recognizes that in order to understand big ideas, years of coordinated study are required. The coordinated study of the local and regional environment provides an excellent opportunity for this. A field site can be studied using increasingly sophisticated approaches across the K–12 experience, and for the students, this does not entail repetition, but rather the opportunity to study a site from different disciplinary vantage points across all or part of the K–12 continuum. If such an approach is adopted broadly, kids who move during the course of their schooling can bring in new eyes, and information, to compare and contrast the environment in their new school with the environment where they used to live.

**How to Read the NGSS**

Each standard in the NGSS includes multiple interconnected parts. They have an architecture that can be seen in Figure A.1. This diagram is taken directly from the NGSS website’s page, “How to Read the Next Generation Science Standards.” This page includes a short written overview and an accompanying video as well as links to more detailed information. The standards are designed to be read online, with features like pop-ups, choices for highlighting different parts of the text (the different dimensions) in different colors, and links to related content elsewhere within the NGSS. If you’re not familiar with how they work, you should follow the link above and then explore around the NGSS a bit before reading further.

Know that the appearance of the Standards can be a bit intimidating, with all the abbreviations, acronyms, codes, and different colors, but after a bit of time working with the text, its logic does become understandable.

**Example of ReaL Connections to Performance Expectations**

Earth and Space Science Disciplinary Core Idea #2 is “Earth’s Systems,” and it has five supporting concepts:

- ESS2.A: Earth Materials and Systems
- ESS2.B: Plate Tectonics and Large-Scale System Interactions
- ESS2.C: The Roles of Water in Earth’s Surface Processes
- ESS2.D: Weather and Climate
- ESS2.E: Biogeology

In the middle school grade band of NGSS, there are six performance expectations associated with ESS2. All six are listed below, but not in their complete form. “Clarification Statements” and “Assessment Boundaries” are not included in the full list, but we’ll look at one of the Performance Expectations in greater detail. See the full list (and the full standard) at [http://nextgenscience.org/msess2-earth-systems](http://nextgenscience.org/msess2-earth-systems).
Figure A.1: The architecture of a standard. The NGSS is designed with the web in mind and features of its online architecture make it easier to understand than this diagram might indicate.
Appendix

MS-ESS2 Earth’s Systems (Middle School-Earth System Science 2)
Students who demonstrate understanding can:

MS-ESS2-1. Develop a model to describe the cycling of Earth’s materials and the flow of energy that drives this process.

MS-ESS2-2. Construct an explanation based on evidence for how geoscience processes have changed Earth’s surface at varying time and spatial scales.

MS-ESS2-3. Analyze and interpret data on the distribution of fossils and rocks, continental shapes, and seafloor structures to provide evidence of the past plate motions.

MS-ESS2-4. Develop a model to describe the cycling of water through Earth’s systems driven by energy from the sun and the force of gravity.

MS-ESS2-5. Collect data to provide evidence for how the motions and complex interactions of air masses results in changes in weather conditions.

MS-ESS2-6. Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates.

Each of the six above Performance Expectations (PEs) incorporates aspects of each of the three dimensions. The color-coding helps to reveal some of that. “Science and Engineering Practices” are shown in blue (italics here) and Crosscutting Concepts are shown in green (underlined italics here). Disciplinary Core Ideas are in black. This is one of the color-coding options in the online presentation. Pop-ups (which can be disabled) appear when the different colored parts of the PE are scrolled over with the mouse. Figure A.2 is a screen grab of the first three PEs for ESS2, with a pop-up showing the Crosscutting Concepts related to “MS-ESS2-2.”

All of these Performance Expectations directly aligns with “Why does this place look the way it does?” We’ll take a closer look at MS-ESS2-2, which addresses how geoscience processes have shaped the Earth’s surface at varying time and spatial scales. This Guide coupled with the development of a VFE of a site local to your school, provides rich opportunities for addressing both this particular PE, along with all of the others within this standard. The Clarification Statements often provide helpful examples, and Assessment Boundaries indicate what will not be addressed in the assessments now under development. Importantly, this is not an indication that these topics are out of bounds. These standards represent minimum expectations—exceeding these expectations is often appropriate.
Figure A.2: A screen-grab of part of the middle school standard on Earth Systems: MS-ESS2. Shown here are the first three PEs, with the first partially obscured by a pop-up related to the CC in the second.
Appendix

Figure A.2 only shows a piece of the standard—only the first few Performance Expectations. Like the example in the previous section, this PE also includes Foundation Boxes, which highlight what pieces of each of the three dimensions is addressed in the standard and Connection Boxes, which highlight connections to other disciplines and grade levels. Drawing these connections is important in helping fortify understandings of both the particular content and how that content is contextualized in broader human and natural systems.
Appendix

Resources

Following are some of the most commonly used and cited publications on science education standards and benchmarks.


Common Core State Standards Initiative. (While not focused on science education directly, standards on math and non-fiction reading impact are importantly related.) http://www.corestandards.org.


Note: Words in **bold font** are also defined in this glossary.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ablation zone</td>
<td>the front part of a <strong>glacier</strong>, where ice is lost due to melting and <strong>calving</strong>.</td>
</tr>
<tr>
<td>acanthodian</td>
<td>member of a class of <strong>extinct</strong> fish, bearing a superficial resemblance to <strong>sharks</strong>, and sharing features with both bony and cartilaginous fish. Acanthodian skin was covered with tiny, spiny scales.</td>
</tr>
<tr>
<td>accretion, accrete</td>
<td>the process by which a body of rock increases in size due to the addition of further <strong>sedimentary</strong> particles or of large chunks of land, such as <strong>terranes</strong>.</td>
</tr>
<tr>
<td>accumulation zone</td>
<td>the highly elevated part of a <strong>glacier</strong>, where annual snow accumulation outpaces snow loss.</td>
</tr>
</tbody>
</table>
| active plate boundary, active plate margin | the boundary between two plates of the Earth's **crust** that are colliding, pulling apart, or moving past each other.  
   See also: convergent boundary, subduction, transform boundary |
| aeolian | pertaining to, caused by, or carried by the **wind**. Aeolian sediments are often polished, giving them a “frosty” appearance.  
   The name comes from Aeolus, the Greek god of wind. |
| aerosol | tiny solid or liquid particles in the air. Examples include dust, smoke, mist, and human-made substances such as particles emitted from factories and cars. |
| agate | a crystalline **silicate** rock with a colorful banded pattern. It is a variety of **chalcedony**. Agates usually occur as nodules in **volcanic** rock. |
| Alfisols | a **soil order**; these are highly fertile and productive agricultural **soils** in which clays often accumulate below the surface. They are found in humid and subhumid **climates**. |
| alluvium, alluvial | a thick layer of river-deposited sediment. |
| aluminum | a metallic chemical element (Al), and the most abundant metal in the Earth's crust.  
   Aluminum has a low **density** and an excellent ability to resist corrosion. Structural components made from the metal and its alloys are commonly used in the aerospace industry, transportation, and household goods. |
<p>| ammonoid, ammonite | a group of <strong>extinct</strong> <strong>cephalopods</strong> belonging to the Phylum Mollusca, and possessing a spiraling, tightly-coiled shell characterized by ridges, or septa. |
| amphibole | a group of dark-colored <strong>silicate minerals</strong>, or either <strong>igneous</strong> or <strong>metamorphic</strong> origin. |
| anapsid | a type of <strong>tetrapod</strong> vertebrate whose skull has no openings near the temple. Anapsids are the most primitive subclass of reptile. |</p>
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>andesite</td>
<td>a fine-grained <strong>extrusive volcanic</strong> rock, with a <strong>silica</strong> content intermediate between that of <strong>basalt</strong> and <strong>dacite</strong>.</td>
</tr>
<tr>
<td>Andisols</td>
<td>a <strong>soil order</strong>; these are highly productive <strong>soils</strong> often formed from <strong>volcanic</strong> materials. They possess very high water- and nutrient-holding capabilities, and are commonly found in cool areas with moderate to high levels of precipitation.</td>
</tr>
<tr>
<td>anthracite</td>
<td>a dense, shiny <strong>coal</strong> that has a high carbon content and little volatile matter. Anthracite is as much as 95% carbon. Found in deformed rocks, anthracite is the cleanest burning of the three types of coal, because it contains the highest amount of pure carbon.</td>
</tr>
<tr>
<td>anthropogenic</td>
<td>caused or created by human activity.</td>
</tr>
<tr>
<td>anticline</td>
<td>a layer of rock folded (bent) along an axis, concave side down (i.e., in an upside down &quot;u&quot; or &quot;v&quot; shape). Thus rocks at the center of the anticline, along the fold (crest), are lifted up relative to the rest of the layer.</td>
</tr>
<tr>
<td>aquifer</td>
<td>a water-bearing formation of <strong>gravel</strong>, <strong>permeable</strong> rock, or <strong>sand</strong> that is capable of providing water, in usable quantities, to springs or wells.</td>
</tr>
<tr>
<td>archaeocyathid</td>
<td>a vase-shaped organism with a carbonate skeleton, generally believed to be a <strong>sponge</strong>. Archaeocyathids were the first important animal <strong>reef</strong> builders, originating in the early <strong>Cambrian</strong>. They were very diverse, but went <strong>extinct</strong> by the end of the Cambrian. Archeocyathids are often easiest to recognize in limestones, by their distinctive cross-section.</td>
</tr>
<tr>
<td>Archean</td>
<td>a <strong>geologic time</strong> period that extends from 4 billion to 2.5 billion years ago. It is part of the <strong>Precambrian</strong>.</td>
</tr>
<tr>
<td>Aridisols</td>
<td>a <strong>soil order</strong>; these are formed in very dry (arid) <strong>climates</strong>. The lack of moisture restricts <strong>weathering</strong> and leaching, resulting in both the accumulation of <strong>salts</strong> and limited subsurface development. Commonly found in deserts.</td>
</tr>
<tr>
<td>arthropod</td>
<td>an invertebrate animal, belonging to the Phylum Arthropoda, and possessing an external skeleton (exoskeleton), body segments, and jointed appendages. Arthropods include crustaceans, arachnids, and insects, and there are over a million described arthropod species living today. <strong>Trilobites</strong> are a major group of <strong>extinct</strong> arthropods.</td>
</tr>
<tr>
<td>asphalt</td>
<td>a black, sticky, semi-solid and viscous form of <strong>petroleum</strong>.</td>
</tr>
<tr>
<td>asthenosphere</td>
<td>a thin semifluid layer of the Earth, below the outer rigid lithosphere, forming the upper part of the <strong>mantle</strong>. The heat and pressure created by the overlying <strong>lithosphere</strong> make the solid rock of the asthenosphere bend and move like metal when heated. The layer is thought to flow vertically and horizontally with circular <strong>convection</strong> currents, enabling sections of lithosphere to subside, rise, and undergo lateral movement.</td>
</tr>
<tr>
<td>atmosphere</td>
<td>a layer of gases surrounding a planet. Earth's atmosphere protects living organisms from damage by solar ultraviolet radiation, and it is mostly composed of nitrogen. Oxygen is used by most organisms for respiration. Carbon dioxide is used by plants, algae and cyanobacteria for photosynthesis.</td>
</tr>
</tbody>
</table>
### Glossary

<table>
<thead>
<tr>
<th><strong>banded iron formation</strong></th>
<th>Rocks with regular, alternating thin layers of iron oxides (e.g., hematite and magnetite) and either shale or silicate minerals (e.g., chert, jasper, and agate). They are a primary source of iron ore.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>barite</strong></td>
<td>A usually white, clear, or yellow mineral found in limestone, clay-rich rocks, and sandstones. Barite (BaSO₄) occurs as flattened blades or in a circular pattern of crystals that looks like a flower and, when colored red by iron stains, is called a “desert rose.” Before federal laws were passed in 1906 to prevent the practice, finely ground barite was often added to flour and other foods to increase the weight.</td>
</tr>
<tr>
<td><strong>basalt</strong></td>
<td>An extrusive igneous rock, and the most common rock type on the surface of the Earth. It forms the upper surface of all oceanic plates, and is the principal rock of ocean/seafloor ridges, oceanic islands, and high-volume continental eruptions. Basalt is fine-grained and mostly dark-colored, although it often weathers to reds and browns because of its high iron content. Basaltic magmas are produced by partial melting of the upper mantle. Materials melt when we increase their temperature, but a second way to melt a solid is to decrease the pressure. In the interior of the Earth this second mechanism—decompression—is far more important. When pressure on the mantle is released as it is forced up through the crust due to subduction, it becomes basaltic magma.</td>
</tr>
<tr>
<td><strong>basement rocks</strong></td>
<td>The foundation that underlies the surface geology of an area, generally composed of igneous or metamorphic crystalline rock. In certain areas, basement rock is exposed at the surface because of uplift or erosion.</td>
</tr>
<tr>
<td><strong>batholith</strong></td>
<td>A large exposed structure of intrusive igneous rock that solidified at depth, and covers an area of over 100 square kilometers (40 square miles). While batholiths may appear uniform, they are actually composed of multiple plutons that converged to form one mass.</td>
</tr>
<tr>
<td><strong>bauxite</strong></td>
<td>A whitish, grayish, brown, yellow, or reddish-brown rock composed of hydrous aluminum oxides and aluminum hydroxides; the principal commercial source of aluminum.</td>
</tr>
<tr>
<td><strong>bentonite</strong></td>
<td>A clay, formed from decomposed volcanic ash, with a high content of the mineral montmorillonite.</td>
</tr>
<tr>
<td><strong>beryl</strong></td>
<td>A white, blue, yellow, green, or pink mineral, found in coarse granites and igneous rocks. It is a source of beryllium and used as a gemstone; the green variety is called emerald, the blue is known as aquamarine.</td>
</tr>
<tr>
<td><strong>biodiversity</strong></td>
<td>The number of kinds of organisms at any given time and place. Global changes in biodiversity through geologic time tells paleontologists that something is happening to the rate of extinction or the rate of origin of new species. Regional changes are influenced by migration, or the number of species supported by available food and space resources.</td>
</tr>
<tr>
<td><strong>biofuel</strong></td>
<td>Carbon-based fuel produced from renewable sources of biomass like plants and garbage. Energy is obtained through combustion, so greenhouse gases are still produced. Because plants get their carbon from the air, burning them for energy and re-releasing it into the air has less effect on climate than fossil fuels, whose carbon is otherwise sequestered away from the atmosphere.</td>
</tr>
<tr>
<td><strong>biomass</strong></td>
<td>Organic material from one or more organisms.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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</tr>
<tr>
<td>biostratigraphy</td>
<td>the branch of geology that uses fossils to determine the relative age of sedimentary layers.</td>
</tr>
<tr>
<td>biota</td>
<td>the organisms living in a given region, including plants, animals, fungi, protists, and bacteria.</td>
</tr>
<tr>
<td>bitumen</td>
<td>any of various flammable mixtures of hydrocarbons and other substances, occurring naturally or obtained by distillation from coal or petroleum, that are a component of asphalt and tar and are used for surfacing roads and for waterproofing.</td>
</tr>
<tr>
<td>bituminous coal</td>
<td>a relatively soft coal containing a tarlike substance called bitumen, which is usually formed as a result of high pressure on lignite.</td>
</tr>
<tr>
<td>bivalve</td>
<td>a marine or freshwater invertebrate animal belonging to the Class Bivalvia (or Pelecypoda) in the Phylum Mollusca. Bivalves are generally called “clams,” but they also include scallops, mussels, cockles, and oysters. Bivalves are characterized by right and left calcareous shells (valves) joined by a hinge. Most are filter feeders, collecting food particles from the water with their gills. During the Paleozoic, bivalves lived mostly on the surface of the ocean floor. In the Mesozoic, bivalves became extremely diverse and some evolved the ability to burrow into ocean floor sediments.</td>
</tr>
<tr>
<td>blastoid</td>
<td>an extinct form of stemmed echinoderm, similar to crinoids. Blastoids possessed a nut-shaped body covered with interlocking plates, which was covered with fine hairlike structures for use in filter-feeding. The body was held above the sea floor by a stalk of stacked disc-shaped plates.</td>
</tr>
<tr>
<td>body fossils</td>
<td>fossils that consist of an actual part of an organism, such as a bone, shell, or leaf.</td>
</tr>
<tr>
<td>boreal</td>
<td>a cold temperate region relating to or characteristic of the sub-Arctic climatic zone, often dominated by conifers, birch, and poplar.</td>
</tr>
<tr>
<td>brachiopod</td>
<td>a marine invertebrate animal belonging to the Phylum Brachiopoda, and characterized by upper and lower calcareous shell valves joined by a hinge, and a crown of tentacles (lophophore) used for filter-feeding and respiration. Brachiopods are the most common fossil in Paleozoic sedimentary rocks. Brachiopods look somewhat similar to the clams that you find at the beach today. Brachiopods and bivalves both have a pair of hinged shells (valves) to protect themselves while feeding. However, the soft parts of modern brachiopods tell us that they are completely unrelated to bivalves. Brachiopods have a special structure formed by tissue with thousands of tiny hair-like tentacles stretched along a coiled piece of internal shell material. These tentacles catch and move small particles towards the mouth. This body plan is very different from that of bivalves, which have a larger fleshy body and collect particles with their gills. To tell the difference between a brachiopod and a bivalve, look for symmetry on the surface of the shell. Bivalve valves are of equal size and mirror image shapes. Brachiopods' bottom valves, however, are slightly bigger and often have a different shape.</td>
</tr>
<tr>
<td>braided stream</td>
<td>a stream consisting of multiple, small, shallow channels that divide and recombine numerous times, forming a pattern resembling strands of braided hair. A braided stream carries more sediment than a typical stream, causing the formation of sandbars and a network of crisscrossing streams.</td>
</tr>
</tbody>
</table>
### Glossary

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</thead>
<tbody>
<tr>
<td><strong>brine</strong></td>
<td>See hydrothermal solution.</td>
</tr>
<tr>
<td><strong>British Thermal Unit (BTU or Btu)</strong></td>
<td>the most commonly used unit for heat energy. One Btu is approximately the amount of heat required to raise one pound of water by one degree Fahrenheit. A Btu is also about the amount of energy released by burning a single wooden match.</td>
</tr>
<tr>
<td><strong>bromine</strong></td>
<td>a liquid chemical element (Br), with corrosive and toxic properties. It is commonly used in pesticides, flame retardants, and as a gasoline additive. Bromine is highly soluble, and it is the fifth most abundant element dissolved in ocean water. It can be extracted from brines, some of which are associated with salt deposits.</td>
</tr>
<tr>
<td><strong>bryozoan</strong></td>
<td>a marine or freshwater, colonial invertebrate animal belonging to the Phylum Bryozoa, and characterized by an encrusting or branching calcareous skeleton from which multiple individuals (zooids) extend from small pores to filter-feed using crowns of tentacles (lophophores). Bryozoans have a long and exemplary fossil record. One of the more common Paleozoic varieties looks like fine mesh cloth with numerous tiny holes in which the individual animals in the colony lived. Although they function somewhat like coral, and are often found in similar environments, bryozoans are more closely related to brachiopods.</td>
</tr>
<tr>
<td><strong>calcite</strong></td>
<td>a carbonate mineral, consisting of calcium carbonate (CaCO₃). Calcite is a common constituent of sedimentary rocks, particularly limestone.</td>
</tr>
<tr>
<td><strong>calcium carbonate</strong></td>
<td>a chemical compound with the formula CaCO₃, commonly found in rocks in the mineral forms calcite and aragonite, as well as the shells and skeletons of marine organisms.</td>
</tr>
<tr>
<td><strong>caldera</strong></td>
<td>a collapsed, cauldron-like volcanic crater formed by the collapse of land following a volcanic eruption.</td>
</tr>
<tr>
<td><strong>caliche</strong></td>
<td>a zone of cemented material within soil, formed when water infiltrates the soil, dissolves soluble materials, and evaporates, leaving behind precipitates (particularly calcium carbonate) in the pore space between soil grains. Layers of caliche accumulate to tens of feet in some locations. Caliche is commonly collected for use as an additive in cement.</td>
</tr>
<tr>
<td><strong>calving</strong></td>
<td>the process by which ice breaks off from the end of a glacier (sometimes into a lake or ocean, sometimes over the edge of a cliff).</td>
</tr>
<tr>
<td><strong>calyx</strong></td>
<td>the head of a crinoid.</td>
</tr>
<tr>
<td><strong>Cambrian</strong></td>
<td>a geologic time period lasting from 541 to 485 million years ago. During the Cambrian, multicellular marine organisms became increasingly diverse, as did their mineralized fossils. The Cambrian is part of the Paleozoic Era.</td>
</tr>
<tr>
<td><strong>Canadian Shield</strong></td>
<td>the stable core of the North American continental landmass, containing some of the oldest rocks on Earth. The shield has experienced very little tectonic activity (faulting or folding) for millions of years. As the stable cores of all continents, shields are often covered by layers of younger material.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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</tr>
<tr>
<td>capstone, caprock</td>
<td>a harder, more resistant rock type that overlies a softer, less resistant rock. The harder rock typically helps to control the rate of erosion.</td>
</tr>
<tr>
<td>carbonate rocks</td>
<td>rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms such as corals, clams, snails, bryozoans, and brachiopods. These organisms thrive in warm, clear shallow waters common to tropical areas, therefore modern carbonate rocks are observed forming in places such as the Florida Keys and the Bahamas. They are also one of the dominant rock forms of the bottom of the ocean, where sediments form from the skeletons of planktonic organisms such as foraminifera. Carbonate rocks include limestone and dolostone.</td>
</tr>
<tr>
<td>Carboniferous</td>
<td>a geologic time period that extends from 359 to 299 million years ago. It is divided into two subperiods, the Mississippian and the Pennsylvanian. By the Carboniferous, terrestrial life had become well established. The name Carboniferous means &quot;coal-bearing,&quot; and it is during this time that many of today's coal beds were formed. The Carboniferous is part of the Paleozoic.</td>
</tr>
<tr>
<td>cementation</td>
<td>the precipitation of minerals, such as silica and calcite, that binds together particles of rock, bones, etc., to form a solid mass of sedimentary rock.</td>
</tr>
<tr>
<td>Cenozoic</td>
<td>the geologic time period spanning from 66 million years ago to the present. The Cenozoic is also known as the age of mammals, since extinction of the large reptiles at the end of the Mesozoic allowed mammals to diversify. The Cenozoic includes the Paleogene, Neogene, and Quaternary periods.</td>
</tr>
<tr>
<td>cephalopod</td>
<td>a marine invertebrate animal belonging to the Class Cephalopoda in the Phylum Mollusca, and characterized by a prominent head, arms and tentacles with suckers, and jet propulsion locomotion. Cephalopods are swimming predators with beak-shaped mouthparts. The shells of cephalopods range from long straight cones to spirals, but some have internal shells or no significant shell at all, like the octopus. The group includes belemnites, ammonoids, nautilus, squid, and octopuses. A mass extinction between the Cretaceous and Paleogene eliminated many varieties of cephalopods.</td>
</tr>
<tr>
<td>chalcedony</td>
<td>a crystalline silicate mineral that occurs in a wide range of varieties.</td>
</tr>
<tr>
<td>chalcopyrite</td>
<td>a yellow mineral consisting of a copper-iron sulfide (CuFeS$_2$). Chalcopyrite is the most common and important source of copper, and can also be called copper pyrite.</td>
</tr>
<tr>
<td>chalk</td>
<td>a soft, fine-grained, easily pulverized, white-to-grayish variety of limestone, composed of the shells of minute planktonic single-celled algae.</td>
</tr>
<tr>
<td>chemical fossils</td>
<td>chemicals produced by an organism that leave behind an identifiable record in the geologic record. Chemical fossils provide some of the oldest evidence for life on Earth.</td>
</tr>
</tbody>
</table>
### Glossary

<table>
<thead>
<tr>
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<th>Definition/description</th>
</tr>
</thead>
<tbody>
<tr>
<td>chemical reaction</td>
<td>a process that involves changes in the structure and energy content of atoms, molecules, or ions but not their nuclei.</td>
</tr>
<tr>
<td>chert</td>
<td>a sedimentary rock composed of microcrystalline quartz. It is often found as nodules or concretions in limestone and other marine sedimentary rocks. As these rocks form, water moving through them transports small amounts of silicon dioxide that accumulate into clumps of microscopic crystals. The resulting rocks are extremely hard and have no planes of weakness. For thousands of years, humans exploited these qualities, breaking chert nodules into blades and other tools.</td>
</tr>
<tr>
<td>chordate</td>
<td>an animal that possesses the following five traits during at least one stage of its development: a notochord (the flexible rod that, in vertebrates, becomes the backbone), a hollow dorsal nerve cord, pharyngeal gill slits, an endostyle (precursor to the thyroid gland), and a post-anal tail</td>
</tr>
<tr>
<td>clay</td>
<td>the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet. Chemically, clays are hydrous aluminum silicates.</td>
</tr>
<tr>
<td>cleavage</td>
<td>a physical property of minerals. Cleavage occurs when a mineral breaks in a characteristic way along a specific plane of weakness. Mica and graphite have very strong cleavage, allowing them to easily break into thin sheets.</td>
</tr>
<tr>
<td>climate</td>
<td>a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30). These factors interact with and are influenced by other parts of the Earth system, including geology, geography, insolation, currents, and living things. The climate of a region represents the average weather over a long period of time.</td>
</tr>
<tr>
<td>climate change</td>
<td>See global warming</td>
</tr>
<tr>
<td>coal</td>
<td>a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation. By far the greatest abundance of coal is located in strata of Carboniferous age.</td>
</tr>
<tr>
<td>coccolithophore</td>
<td>a marine phytoplankton with a skeleton made up of microscopic calcareous disks or rings, and forming much of the content of chalk rocks.</td>
</tr>
<tr>
<td>cold front</td>
<td>the boundary between the warm air and the cold air moving into a region. At this boundary, denser, colder air moves in, making the less dense, warm air rise. This displaced warm air cools as it rises because air pressure decreases with increasing height in the atmosphere. As the air cools, it becomes saturated with water vapor, and condensation begins to occur, eventually leading to dramatic rainstorms.</td>
</tr>
<tr>
<td>color (mineral)</td>
<td>a physical property of minerals. Color is determined by the presence and intensity of certain elements within the mineral.</td>
</tr>
<tr>
<td><strong>Glossary</strong></td>
<td></td>
</tr>
<tr>
<td>---</td>
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</tr>
<tr>
<td><strong>color (soil)</strong></td>
<td>a physical property of <strong>soils</strong>. Soil color is influenced by mineral content, the amount of organic material, and the amount of water it routinely holds. These colors are identified by a standard soil color chart called the Munsell chart.</td>
</tr>
<tr>
<td><strong>columnar joint</strong></td>
<td>five- or six-sided columns that form as cooling <strong>lava</strong> contracts and cracks. Columnar joints are often found in <strong>basalt</strong> flows, but can also form in ashflow <strong>tuffs</strong> as well as shallow <strong>intrusions</strong>. The columns are generally vertical, but may also be slightly curved.</td>
</tr>
<tr>
<td><strong>commodity</strong></td>
<td>a good for which there is demand, but which is treated as equivalent across all markets, no matter who produces it.</td>
</tr>
<tr>
<td><strong>compression, compressional force</strong></td>
<td>forces acting on an object from all or most directions, resulting in compression (flattening or squeezing). Compressional forces occur by pushing objects together.</td>
</tr>
<tr>
<td><strong>concretion</strong></td>
<td>a hard, compact mass, usually of spherical or oval shape, found in <strong>sedimentary rock</strong> or <strong>soil</strong>. Concretions form when <strong>minerals</strong> precipitate around a particulate nucleus within the sediment.</td>
</tr>
<tr>
<td><strong>conglomerate</strong></td>
<td>a <strong>sedimentary rock</strong> composed of multiple large and rounded fragments that have been cemented together in a fine-grained <strong>matrix</strong>. The fragments that make up a conglomerate must be larger than grains of <strong>sand</strong>.</td>
</tr>
<tr>
<td><strong>conifer</strong></td>
<td>a woody plant (tree) of the division Coniferophyta. Conifers bear cones that contain their seeds.</td>
</tr>
<tr>
<td><strong>conodont</strong></td>
<td>an extinct, eel-shaped animal classified in the class Conodonta and thought to be related to primitive <strong>chordates</strong>. Originally, conodonts were only known from small phosphatic tooth-like microfossils, which have been widely used for <strong>biostratigraphy</strong>. Knowledge about their soft tissues still remains limited.</td>
</tr>
<tr>
<td><strong>Conservation of Energy</strong></td>
<td>a principle stating that <strong>energy</strong> is neither created nor destroyed, but can be altered from one form to another.</td>
</tr>
<tr>
<td><strong>contact metamorphism</strong></td>
<td>the process by which a <strong>metamorphic rock</strong> is formed through direct contact with <strong>magma</strong>. Changes that occur due to contact metamorphism are greatest at the point of contact. The further away the rock is from the point of contact, the less pronounced the change.</td>
</tr>
<tr>
<td><strong>convection</strong></td>
<td>the rise of buoyant material and the sinking of denser material. In the <strong>mantle</strong>, variations in <strong>density</strong> are commonly caused by the melting of <strong>subducting</strong> materials.</td>
</tr>
<tr>
<td><strong>convergent boundary</strong></td>
<td>an <strong>active plate boundary</strong> where two tectonic <strong>plates</strong> are colliding with one another. <strong>Subduction</strong> occurs when an oceanic plate collides with a continental plate or another oceanic plate. If two continental plates collide, mountain building occurs.</td>
</tr>
<tr>
<td><strong>copper</strong></td>
<td>a ductile, malleable, reddish-brown metallic element (Cu). Copper is used extensively as wiring in the electrical industry as well as in alloys such as brass and bronze.</td>
</tr>
</tbody>
</table>
### Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>coquina</strong></td>
<td>a porous, sometimes crumbly <strong>limestone</strong>, composed of fragments of shells and coral, and used as a building material.</td>
</tr>
<tr>
<td><strong>corundum</strong></td>
<td>an <strong>aluminum oxide mineral</strong> (Al₂O₃) that is, after diamond, the hardest known natural substance. Corundum is best known for its gem varieties, ruby (red) and sapphire (blue).</td>
</tr>
<tr>
<td><strong>craton</strong></td>
<td>the old, underlying portion of a continent that is geologically stable relative to surrounding areas. The portion of a craton exposed at the surface is termed a shield, while that overlain by younger layers is often referred to as a platform. A craton can be thought of as the heart of a continent—it is typically the oldest, thickest, and most stable part of the bedrock. It is also usually far from the margins of tectonic plates, where new rock is formed and old destroyed. This rock has usually been <strong>metamorphosed</strong> at some point during its history, making it resistant to <strong>erosion</strong>.</td>
</tr>
<tr>
<td><strong>creep</strong></td>
<td>the slow movement or deformation of a material under the influence of pressure or stress (such as gravity); the slow progression of rock and soil down a slope due to the interacting factors of gravity, vegetation, water absorption, and steepness.</td>
</tr>
<tr>
<td><strong>Cretaceous</strong></td>
<td>a <strong>geologic time</strong> period spanning from 144 to 66 million years ago. It is the youngest period of the <strong>Mesozoic</strong>. The end of the Cretaceous bore witness to the <strong>mass extinction</strong> event that resulted in the demise of the dinosaurs. “Cretaceous” is derived from the Latin word, “creta” or “chalk.” The white (chalk) cliffs of Dover on the southeastern coast of England are a famous example of Cretaceous chalk deposits.</td>
</tr>
<tr>
<td><strong>crevasse</strong></td>
<td>a deep crack in an <strong>ice sheet</strong> or <strong>glacier</strong>, which forms as a result of shear stress between different sections of the moving ice.</td>
</tr>
<tr>
<td><strong>crinoid</strong></td>
<td>a marine invertebrate animal belonging to the Class Crinoidea of the Phylum Echinodermata, and characterized by a head (<strong>calyx</strong>) with a mouth on the top surface surrounded by feeding arms. Several groups of stemmed <strong>echinoderms</strong> appeared in the early <strong>Paleozoic</strong>, including crinoids, <strong>blastoids</strong>, and <strong>cystoids</strong>. Crinoids have five-fold symmetry and feathery arms (sometimes held off the sea floor on a stem) that collect organic particles from the water. The stems, the most often preserved part, are made of a series of stacked discs. Upon death, these stems often fall apart and the individual discs are preserved separately in the rock. The crinoid’s feathery arms make it look something like a flower on a stem. Thus, crinoids are commonly called “sea lilies,” although they are animals, not plants.</td>
</tr>
<tr>
<td><strong>cross-bedding</strong></td>
<td>layering within a bed in a series of rock strata that does not run parallel to the plane of stratification. Cross-beds form as flowing water or wind pushes sediment downcurrent, creating thin beds that slope gently in the direction of the flow as migrating ripples. The downstream slope of the ripple may be preserved as a thin layer dipping in the direction of the current, across the natural flat-lying repose of the beds. Another migrating ripple will form an additional layer on top of the previous one.</td>
</tr>
<tr>
<td>Glossary Term</td>
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<tr>
<td>crust</td>
<td>the uppermost, rigid outer layer of the Earth, composed of tectonic plates. Two types of crust make up the lithosphere. Oceanic crust is denser but significantly thinner than continental crust, while continental crust is much thicker but less dense (and therefore buoyant). When continental crust collides with oceanic crust, the denser oceanic crust will be dragged (subducted) under the buoyant continental crust. Although mountains are created by these oceanic/continental crust collisions due to the compression of the two plates, much taller ranges are produced by continental/continental collisions. When two buoyant continental crusts collide, there is nowhere for the crust to go but up! The modern Himalayas, at the collision site of the Asian and Indian plates, are a good example of very tall mountains formed by a collision between two continental crusts.</td>
</tr>
<tr>
<td>Cryogenian</td>
<td>a geologic period lasting from 850 to 635 million years ago, during the Precambrian. During this period, the Earth was subject to a 200-million-year-long ice age.</td>
</tr>
<tr>
<td>crystal form</td>
<td>a physical property of minerals, describing the shape of the mineral's crystal structure (not to be confused with cleavage). A mineral might be cubic, rhomboidal, hexagonal, or polyhedral.</td>
</tr>
<tr>
<td>cyclothem</td>
<td>alternating sequences of marine and non-marine sedimentary rocks, usually including coal, and characterized by their light and dark colors.</td>
</tr>
<tr>
<td>cystoid</td>
<td>extinct, stalked echinoderms related to crinoids, but with an ovoid body and triangular pore openings.</td>
</tr>
<tr>
<td>dacite</td>
<td>a fine-grained extrusive igneous rock, with a silica content intermediate between that of andesite and rhyolite.</td>
</tr>
<tr>
<td>debris flow</td>
<td>a dangerous mixture of water, mud, rocks, trees, and other debris that can move quickly down valleys. Such flows can result from sudden rainstorms or snowmelt that create flash floods. Areas that have experienced a recent wildfire are particularly vulnerable to debris flows, since there is no vegetation to hold the soil.</td>
</tr>
<tr>
<td>degrade (energy)</td>
<td>the transformation of energy into a form in which it is less available for doing work, such as heat.</td>
</tr>
<tr>
<td>delta, deltaic</td>
<td>a typically wedge-shaped deposit formed as sediment is eroded from mountains and transported by streams across lower elevations. The Mississippi Delta is a modern delta containing sediment being transferred from the Mississippi River into the Gulf of Mexico.</td>
</tr>
<tr>
<td>density</td>
<td>a physical property of minerals, describing the mineral's mass per volume.</td>
</tr>
<tr>
<td>derecho</td>
<td>a set of powerful straight-line winds that exceed 94 kilometers per hour (58 miles per hour) and can often approach 160 kilometers per hour (100 miles per hour). These powerful windstorms can travel over 400 kilometers (250 miles) and cause substantial wind damage, knocking down trees and causing widespread power outages. The lightning associated with these intense storms can cause both forest fires and house fires. <em>Derecho is the Spanish word for &quot;straight ahead.&quot;</em></td>
</tr>
<tr>
<td>Glossary Item</td>
<td>Description</td>
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<tr>
<td>derrick</td>
<td>a lifting device in the form of a framework steel tower that is built over a deep drill hole, typically an oil well. An oil derrick is composed of machinery for hoisting and lowering tools required during the drilling process, and readying the well for extraction of petroleum.</td>
</tr>
<tr>
<td>Devonian</td>
<td>a geologic time period spanning from 419 to 359 million years ago. The Devonian is also called the “age of fishes” due to the diversity of fish that radiated during this time. On land, seed-bearing plants appeared and terrestrial arthropods became established. The Devonian is part of the Paleozoic.</td>
</tr>
<tr>
<td>diamond</td>
<td>a mineral form of carbon, with the highest hardness of any material. Most natural diamonds are formed at high temperature and pressure deep in the Earth’s mantle.</td>
</tr>
<tr>
<td>diapsid</td>
<td>a vertebrate animal possessing two holes behind the orbit (eye hole) in each side of its skull. Diapsids are extremely diverse; they arose in the late Carboniferous, and include all dinosaurs, birds, lizards, snakes, crocodiles, and the tuatara.</td>
</tr>
<tr>
<td>dike</td>
<td>a sheet of intrusive igneous or sedimentary rock that fills a crack in a pre-existing rock body.</td>
</tr>
<tr>
<td>dimension stone</td>
<td>the commercial term applied to quarried blocks of rock cut to specific dimensions and used for buildings, monuments, facing, and curbing.</td>
</tr>
<tr>
<td>dinosaur</td>
<td>a member of a group of terrestrial reptiles with a common ancestor and thus certain anatomical similarities, including long ankle bones and erect limbs. All of the large reptile groups, including the dinosaurs, disappeared at or before the mass extinction at the end of the Cretaceous.</td>
</tr>
<tr>
<td>dolomite</td>
<td>a carbonate mineral, consisting of calcium magnesium carbonate (CaMg(CO₃)₂). Dolomite is an important reservoir rock for petroleum, and also commonly hosts large ore deposits.</td>
</tr>
<tr>
<td>dolostone</td>
<td>a rock (also known as dolomitic limestone and once called magnesian limestone) primarily composed of dolomite, a carbonate mineral. It is normally formed when magnesium bonds with calcium carbonate in limestone, forming dolomite.</td>
</tr>
<tr>
<td>double refraction</td>
<td>the result of light passing through a material that splits it into two polarized sets of rays, doubling images viewed through that material. For example, a single line on a sheet of paper will appear as two parallel lines when viewed through a clear calcite crystal.</td>
</tr>
<tr>
<td>downwarp</td>
<td>a segment of the Earth’s crust that is broadly bent downward.</td>
</tr>
<tr>
<td>drift</td>
<td>unconsolidated debris transported and deposited by a glacier.</td>
</tr>
<tr>
<td>drumlin</td>
<td>a teardrop-shaped hill of till that was trapped beneath a glacier and streamlined in the direction of the flow of the ice moving over it. The elongation of a drumlin is an excellent clue to the direction of flow during an ice sheet’s most recent advance.</td>
</tr>
<tr>
<td>dynamic metamorphism</td>
<td>See regional metamorphism</td>
</tr>
</tbody>
</table>
### Glossary

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<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td>earthquake</td>
<td>A sudden release of energy in the Earth’s crust that creates <em>seismic waves</em>. Earthquakes are common at <strong>active plate boundaries</strong>.</td>
</tr>
<tr>
<td>echinoderm</td>
<td>A member of the Phylum Echinodermata, which includes starfish, sea urchins, and <strong>crinoids</strong>. Echinoderms have radial symmetry (which is usually five-fold), and a remarkable ability to regenerate lost body parts.</td>
</tr>
<tr>
<td>effervesce</td>
<td>To foam or fizz while releasing gas. <strong>Carbonate minerals</strong> will effervesce when exposed to hydrochloric acid.</td>
</tr>
<tr>
<td>efficiency</td>
<td>The use of a relatively small amount of <strong>energy</strong> for a given task, purpose, or service; achieving a specific output with less energy input.</td>
</tr>
<tr>
<td>energy</td>
<td>The power derived from the use of physical or chemical resources. Everything we do depends upon energy—without it there would be no civilization, no sunlight, no food and no life. Energy moves people and goods, produces electricity, heats our homes and businesses, and is used in manufacturing and other industrial processes.</td>
</tr>
<tr>
<td>energy carrier</td>
<td>A source of <strong>energy</strong>, such as electricity, that has been subject to human-induced energy transfers or transformations.</td>
</tr>
<tr>
<td>Entisols</td>
<td>A <strong>soil order</strong>; these are <strong>soils</strong> of relatively recent origin with little or no <strong>horizon</strong> development. They are commonly found in areas where <strong>erosion</strong> or deposition rates outstrip rates of soil development, such as <strong>floodplains</strong>, mountains, and badland areas.</td>
</tr>
<tr>
<td>Eocene</td>
<td>A <strong>geologic time</strong> period extending from 56 to 33 million years ago. The Eocene is an epoch of the <strong>Paleogene</strong> period.</td>
</tr>
<tr>
<td>erosion</td>
<td>The transport of <strong>weathered</strong> materials. Rocks are worn down and broken apart into finer grains by <strong>wind</strong>, rivers, wave action, freezing and thawing, and chemical breakdown.</td>
</tr>
<tr>
<td>erratic, glacial erratic</td>
<td>A piece of rock that differs from the type of rock native to the area in which it rests, carried there by <strong>glaciers</strong> often over long distances.</td>
</tr>
<tr>
<td>esker</td>
<td>A sinuous, elongated ridge of <strong>sand</strong> and <strong>gravel</strong>. Most eskers formed within ice-walled tunnels carved by streams flowing beneath a <strong>glacier</strong>. After the ice melted away, the stream deposits remained as long winding ridges.</td>
</tr>
</tbody>
</table>

Over millions of years, weathering and erosion can reduce a mighty mountain range to low rolling hills. Some rocks wear down relatively quickly, while others can withstand the power of erosion for much longer. Softer, weaker rocks such as **shale** and poorly cemented **sandstone** and **limestone** are much more easily worn than hard, crystalline **igneous** and **metamorphic rocks**, or well-cemented sandstone and limestone. Harder rocks are often left standing as ridges because the surrounding softer, less resistant rocks were more quickly worn away.

Erratics are often distinctive because they are a different type of rock than the bedrock in the area to which they’ve been transported. For example, boulders and pebbles of **igneous** and **metamorphic rocks** are often found in areas where the bedrock is **sedimentary**; it is sometimes possible to locate the origin of an erratic if its composition and textures are highly distinctive.

Eskers are sometimes mined for their well-sorted sand and gravel.
<p>| <strong>eukaryotes</strong> | organisms with complex cells containing a nucleus and organelles. <strong>Protists</strong> and all multicellular organisms are eukaryotes. |
| <strong>evaporite</strong> | a sedimentary rock created by the precipitation of minerals directly from seawater, including gypsum, carbonate, and halite. See also: carbonate, gypsum, mineral, sedimentary rock |
| <strong>exfoliation</strong> | a type of physical <strong>weathering</strong>. When overlying layers are weathered away, the reduction of downward pressure allows the underlying rock to expand toward the surface. This expansion causes <strong>joints</strong>, or cracks, to form parallel to the surface, producing slabs that resemble the curved layers of an onion. |
| <strong>extinction</strong> | the end of species or other taxonomic groups, marked by death of the last living individual. Paleontologists estimate that over 99% of all species that have ever existed are now extinct. The species of modern animals that we study in biology today represent less than 1% of what has lived throughout <strong>geologic time</strong>. |
| <strong>extrusion, extrusive rock</strong> | an <strong>igneous rock</strong> formed by the cooling of <strong>lava</strong> after <strong>magma</strong> escapes onto the surface of the Earth through <strong>volcanic</strong> craters and cracks in the Earth’s <strong>crust</strong>. |
| <strong>fault</strong> | a fracture in the Earth’s <strong>crust</strong> in which the rock on one side of the fracture moves measurably in relation to the rock on the other side. |
| <strong>feldspar</strong> | an extremely common, rock-forming <strong>mineral</strong> found in <strong>igneous</strong>, <strong>metamorphic</strong> and <strong>sedimentary</strong> rocks. There are two groups of feldspar: alkali feldspar (which ranges from potassium-rich to sodium-rich) and plagioclase feldspar (which ranges from sodium-rich to calcium-rich). Potassium feldspars of the alkali group are commonly seen as pink crystals in igneous and metamorphic rocks, or pink grains in sedimentary rocks. Plagioclase feldspars are more abundant than the alkali feldspars, ranging in color from light to dark. Feldspars are commercially used in ceramics and scouring powders. |
| <strong>felsic</strong> | <strong>igneous rocks</strong> with high <strong>silica</strong> content and low <strong>iron</strong> and magnesium content. They are light in color and are typically found in continental <strong>crust</strong>. |
| <strong>filter feeder</strong> | an animal that feeds by passing water through a filtering structure that traps food. The water may then be expelled and the food digested. This strategy is employed by a wide range of animals today, from clams and krill to flamingos and whales. |
| <strong>firn</strong> | compacted <strong>glacial</strong> ice, formed by the weight of snow on top. Individual flakes break down by melting, refreezing, and bonding to the snow around them, eventually forming compacted grains. |
| <strong>flint</strong> | a hard, high-quality form of <strong>chert</strong> that occurs mainly as <strong>nodules</strong> and masses in <strong>sedimentary rock</strong>. Due to its <strong>hardness</strong> and the fact that it splits into thin, sharp flakes, flint was often used to make tools during the Stone Age. Flint will also create sparks when struck against steel, and has been used to ignite gunpowder in more modern times. |</p>
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>floodplain</strong></td>
<td>the land around a river that is prone to flooding. This area can be grassy, but the sediments under the surface are usually deposits from previous floods.</td>
</tr>
<tr>
<td><strong>fluorite, fluorspar</strong></td>
<td>the mineral form of calcium fluoride (CaF$_2$). Fluorite is used in a variety of commercial applications, including as lenses for microscopes, the production of some glass, and the chemical industry. Fluorite lent its name to the phenomenon of fluorescence, which occurs in some fluorites due to impurities in the crystal.</td>
</tr>
<tr>
<td><strong>fluvial</strong></td>
<td>See outwash plain</td>
</tr>
<tr>
<td><strong>foliation</strong></td>
<td>the arrangement of the constituents of a rock in leaflike layers, as in schists. During metamorphism, the weight of overlying rock can cause minerals to realign perpendicularly to the direction of pressure, layering them in a banded pattern.</td>
</tr>
<tr>
<td><strong>foraminifera</strong></td>
<td>a class of aquatic protists that possess a calcareous or siliceous exoskeleton. Foraminifera have an extensive fossil record.</td>
</tr>
<tr>
<td><strong>fossil</strong></td>
<td>preserved evidence of ancient life, including, for example, preserved skeletal or tissue material, molds or casts, and traces of behavior. Fossilization may alter biological material in a variety of ways, including permineralization, replacement, and compression. Remains are often classified as fossils when they are older than 10,000 years, the traditional start of the Holocene (Recent) epoch. However, this date is only a practical guideline—scientists studying successions of plant or animal remains would not recognize any sudden change in the material at 10,000 years, and would typically refer to all material buried in sediments as fossil material. The word fossil is derived from the Latin word fossilis, meaning “dug up.”</td>
</tr>
<tr>
<td><strong>fossil fuels</strong></td>
<td>fuel for human use that is made from the remains of ancient biomass, referring to any hydrocarbon fuel source formed by natural processes from anaerobically decomposed organisms, primarily coal, petroleum, and natural gas (methane). Fossil fuels are non-renewable, meaning that because they take thousands to millions of years to form, the rate of use is far greater than the rate of formation, and eventually we will run out.</td>
</tr>
<tr>
<td><strong>fracture (mineral)</strong></td>
<td>a physical property of minerals, formed when a mineral crystal breaks; also a crack in rocks, sometimes known as a joint.</td>
</tr>
<tr>
<td><strong>frost wedging</strong></td>
<td>weathering that occurs when water freezes and expands in cracks.</td>
</tr>
<tr>
<td><strong>fuel</strong></td>
<td>a material substance that possesses internal energy that can be transferred to the surroundings for specific uses—including are petroleum, coal, and natural gas (the fossil fuels), and other materials, such as uranium, hydrogen, and biofuels.</td>
</tr>
<tr>
<td><strong>gabbro</strong></td>
<td>a usually coarse-grained, mafic and intrusive igneous rock. Most oceanic crust contains gabbro.</td>
</tr>
<tr>
<td><strong>galena</strong></td>
<td>an abundant sulfide mineral with cubic crystals. It is the most important ore of lead, as well as an important source of silver.</td>
</tr>
<tr>
<td><strong>gastropod</strong></td>
<td>a marine, freshwater, or terrestrial invertebrate animal belonging to the class Gastropoda of the Phylum Mollusca, and characterized by a single, coiled, calcareous shell, a muscular foot for gliding, and internal asymmetry caused by an embryonic process (torsion). Gastropods include snails and slugs.</td>
</tr>
<tr>
<td><strong>Gellisols</strong></td>
<td>a soil order; these are weakly weathered soils formed in areas that contain permafrost within the soil profile.</td>
</tr>
<tr>
<td><strong>gem, gemstone</strong></td>
<td>a mineral that has been cut and polished for use as an ornament.</td>
</tr>
<tr>
<td><strong>geologic time scale</strong></td>
<td>a standard timeline used to describe the age of rocks and fossils, and the events that formed them. It spans Earth’s entire history, and is often subdivided into four major time periods: the Precambrian, Paleozoic, Mesozoic, and Cenozoic.</td>
</tr>
<tr>
<td><strong>glacier</strong></td>
<td>a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight. Glaciers form when snow accumulates faster than it melts over many years. As long as melt does not exceed accumulation, the ice and snow pile up and become a self-sustaining system. As glaciers slowly flow, they abrade and <em>erode</em> the landscape around them to create crevasses, moraines, and other distinguishing features. Glaciers form only on land, and are much thicker than ice that forms on the surface of water. 99% of Earth’s glacial ice exists as vast polar <em>ice sheets</em>, but glaciers are also found high in the mountains of every continent except Australia.</td>
</tr>
<tr>
<td><strong>glassy rock</strong></td>
<td>a volcanic rock that cooled almost instantaneously, resulting in a rock with tiny crystals or no crystals at all. Obsidian, tuff, and scoria are examples of glassy rocks.</td>
</tr>
<tr>
<td><strong>global warming</strong></td>
<td>the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere. With the coming of the Industrial Age and exponential increases in human population, large amounts of gases have been released into the atmosphere (especially carbon dioxide) that give rise to global warming. The term “climate change” is preferred because warming contributes to other climatic changes such as precipitation and storm strength.</td>
</tr>
<tr>
<td><strong>gneiss</strong></td>
<td>a metamorphic rock that may form from granite or layered sedimentary rock such as sandstone or siltstone. Parallel bands of light and dark minerals give gneiss its striated texture.</td>
</tr>
<tr>
<td><strong>gold</strong></td>
<td>a soft, yellow, corrosion-resistant element (Au), which is the most malleable and ductile metal on Earth. Gold has an average abundance in the crust of only 0.004 parts per million. It can be profitably mined only where hydrothermal solutions have concentrated it.</td>
</tr>
<tr>
<td><strong>Gondwana, Gondwanaland</strong></td>
<td>the supercontinent of the Southern Hemisphere, composed of Africa, Australia, India, and South America. It combined with the North American continent to form Pangaea during the late Paleozoic.</td>
</tr>
<tr>
<td><strong>granite</strong></td>
<td>a common and widely occurring type of igneous rock. Granite usually has a medium- to coarse-grained texture, and is at least 20% quartz by volume.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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</tr>
<tr>
<td>graphite</td>
<td>a mineral, and the most stable form of carbon. Graphite means &quot;writing stone,&quot; a reference to its use as pencil lead. Graphite occurs in metamorphic rocks, igneous rocks, and meteorites.</td>
</tr>
<tr>
<td>graptolite</td>
<td>an extinct colonial invertebrate animal belonging to the Class Graptolithina of the Phylum Hemichordata, and characterized by individuals housed within a tubular or cup-like structure. The soft parts of a graptolite's body have never been clearly identified.</td>
</tr>
<tr>
<td>gravel</td>
<td>unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).</td>
</tr>
<tr>
<td>greenhouse conditions</td>
<td>climatic conditions when atmospheric greenhouse gas concentrations are high and global temperatures are elevated. Sea levels are generally higher and glaciers diminish during these conditions.</td>
</tr>
<tr>
<td>greenhouse gas</td>
<td>a gas in the atmosphere that absorbs and emits heat. The primary greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone.</td>
</tr>
<tr>
<td>gypsum</td>
<td>a soft sulfate mineral that is widely mined for its use as fertilizer and as a constituent of plaster. Alabaster, a fine-grained light colored variety of gypsum, has been used for sculpture making by many cultures since ancient times.</td>
</tr>
<tr>
<td>halite</td>
<td>See salt</td>
</tr>
<tr>
<td>hardness</td>
<td>a physical property of minerals, specifying how hard the mineral is. Hardness helps us understand why some rocks are more or less resistant to weathering and erosion. See also: Moh's Scale of Hardness</td>
</tr>
<tr>
<td>heat</td>
<td>a form of energy transferred from one body to another as a result of a difference in temperature or a change in phase. Heat is transmitted through solids and fluids by conduction, through fluids by convection, and through empty space by radiation.</td>
</tr>
<tr>
<td>heat island effect</td>
<td>a phenomenon in which cities experience higher temperatures than do surrounding rural communities.</td>
</tr>
<tr>
<td>heat wave</td>
<td>a period of excessively hot weather that may also accompany high humidity. Temperatures of just 3°C (6°F) to 6°C (11°F) above normal are enough to reclassify a warm period as a heat wave. Under high humidity, the mechanism of sweating does little to cool people down because the humidity prevents sweat from evaporating and cooling off the skin.</td>
</tr>
<tr>
<td>hectare</td>
<td>a metric unit of area defined as 10,000 square meters.</td>
</tr>
<tr>
<td>helium</td>
<td>a gaseous chemical element (He), which is the second most abundant and second lightest element in the universe. Helium is used in cryogenics, as a coolant; it is also used in industrial applications including pressurization, welding, and leak detection. Balloons and blimps, although probably the most well-known and visible application of helium, take up less than an eighth of its total use.</td>
</tr>
<tr>
<td>Term</td>
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</tr>
<tr>
<td>hematite</td>
<td>a mineral form of iron oxide (Fe$_2$O$_3$). The name hematite has its origins in the Greek word haimatos, meaning blood. It is very common in Precambrian banded iron formations. Iron from hematite is used in the manufacture of steel. The vivid red pigments that iron lends to the mineral also makes it valuable as a commercial pigment.</td>
</tr>
<tr>
<td>Histosols</td>
<td>a soil order; these are organic-rich soils found along lake coastal areas where poor drainage creates conditions of slow decomposition and peat (or muck) accumulates.</td>
</tr>
<tr>
<td>Holocene</td>
<td>the most recent portion of the Quaternary, beginning about 11,700 years ago and continuing to the present. It is the most recent (and current) interglacial, an interval of glacial retreat. The Holocene also encompasses the global growth and impact of the human species.</td>
</tr>
<tr>
<td>horizon (soil)</td>
<td>a layer in the soil, usually parallel to the surface, which has physical characteristics (usually color and texture) that are different from the layers above and below it. Each type of soil usually contains three or four horizons.</td>
</tr>
<tr>
<td>hornblende</td>
<td>a dark silicate mineral that can occur in a variety of forms. Hornblende is a common constituent of many igneous and metamorphic rocks.</td>
</tr>
<tr>
<td>horsetail</td>
<td>see Sphenopsid</td>
</tr>
<tr>
<td>hot spot</td>
<td>a volcanic region thought to be fed by underlying mantle that is anomalously hot compared with the mantle elsewhere. Hot spots form from plumes of magma rising off the mantle. Magma from the hot spot pushes its way up through the crust, creating an igneous intrusion and sometimes a volcano. Although the hot spot remains fixed, the plates of the lithosphere continue to move above it. As a plate continues to move over the hot spot, the original volcano shifts off of the hot spot and a new intrusion or volcano is formed. This gradually produces a chain of volcanic islands such as the Hawaiian Islands. Erosion of volcanoes may eventually wear down the crust to reveal the igneous intrusions that formed the volcano's magma chamber.</td>
</tr>
<tr>
<td>humus</td>
<td>a soil horizon containing organic matter.</td>
</tr>
<tr>
<td>Huronian glaciation</td>
<td>a glaciation beginning about 2.4 billion years ago, that covered the entire surface of the Earth in ice for as long as 300 million years.</td>
</tr>
<tr>
<td>hurricane</td>
<td>a rapidly rotating storm system with heavy winds, a low-pressure center, and a spiral arrangement of thunderstorms. These storms tend to form over large, warm bodies of water. Once winds have reached 119 kph (74 mph), such a storm is classified as a hurricane. Hurricanes usually develop an eye, which is visible as a small, round, cloud-free area at the center of the storm. The eye is an area of relative calm and low atmospheric pressure. The strongest thunderstorms and winds circulate just outside the eye, in the eyewall.</td>
</tr>
</tbody>
</table>
### Glossary

<table>
<thead>
<tr>
<th>Term</th>
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</thead>
<tbody>
<tr>
<td><strong>hydrothermal solution</strong></td>
<td>hot, <em>salty</em> water moving through rocks. These solutions are always enriched in salts (such as sodium chloride, potassium chloride, and calcium chloride) and thus are called “brines.” The brine is as salty or even saltier than seawater. Salty water can contain minute amounts of dissolved <em>minerals</em> such as <em>gold</em>, <em>lead</em>, <em>copper</em>, and <em>zinc</em>. The presence of salt in the water suppresses the precipitation of the metallic minerals from the brine because the chlorides in the salt preferentially bond with metals. Additionally, because the brine is hot, minerals are more easily dissolved, just as hot tea dissolves sugar more easily than cold tea.</td>
</tr>
<tr>
<td><strong>hyolith</strong></td>
<td>animals with cone-shaped shells that existed throughout the <em>Paleozoic</em>. Their affinities to other animals are uncertain, with some scientists classifying them as mollusks and others placing them in their own phylum.</td>
</tr>
<tr>
<td><strong>hypersaline</strong></td>
<td>of high salinity.</td>
</tr>
<tr>
<td><strong>ice age</strong></td>
<td>a period of global cooling of the Earth's surface and <em>atmosphere</em>, resulting in the presence or expansion of <em>ice sheets</em> and <em>glaciers</em>. Throughout the Earth's history, it has been periodically plunged into ice ages, dependent upon the <em>climate</em> and position of the continents. Over the past 2.6 million years, North America has experienced about 50 glacial advances and retreats. The most recent ice age ended about 12,000 years ago.</td>
</tr>
<tr>
<td><strong>ice cap</strong></td>
<td>an <em>ice field</em> that lies over the tops of mountains.</td>
</tr>
<tr>
<td><strong>ice field</strong></td>
<td>an extensive area of interconnected <em>glaciers</em> spanning less than 50,000 square kilometers (19,305 square miles). Ice fields are usually constrained by an area's <em>topography</em>. Ice fields that lie over the tops of mountains are called <em>ice caps</em>.</td>
</tr>
<tr>
<td><strong>ice sheet</strong></td>
<td>a mass of <em>glacial</em> ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).</td>
</tr>
<tr>
<td><strong>igneous rocks</strong></td>
<td>rocks derived from the cooling of <em>magma</em> underground or molten <em>lava</em> on the Earth’s surface. Igneous rocks differ not only in their cooling rates and subsequent crystal sizes, but also in their chemical compositions. Rocks found in continental <em>crust</em>, such as <em>granite</em>, have high <em>silica</em> content and low <em>iron</em> and magnesium content. They are light in color and are called <em>felsic</em>. Rocks found in oceanic crust, like <em>basalt</em>, are low in silica and high in iron and magnesium. They are dark in color and are called <em>mafic</em>. Although the composition of magma can be the same as lava, the texture of the rocks will be quite different due to different rates of cooling. It is because of this difference in genesis that geologists are able to make the distinction between <em>extrusive</em> and <em>intrusive</em> igneous rocks when encountered at an outcrop at the Earth’s surface.</td>
</tr>
<tr>
<td><strong>Illinoian glaciation</strong></td>
<td>a period of <em>glaciation</em> that occurred during the <em>Pleistocene</em>, 191 to 131 thousand years ago.</td>
</tr>
<tr>
<td><strong>ilmenite</strong></td>
<td>an <em>ore</em> of titanium, produced for use as a white pigment in paint.</td>
</tr>
<tr>
<td><strong>Inceptisols</strong></td>
<td>a <em>soil order</em>; these are <em>soils</em> that exhibit only moderate <em>weathering</em> and development. They are often found on steep (relatively young) <em>topography</em> and overlying <em>erosion</em>-resistant bedrock.</td>
</tr>
<tr>
<td><strong>index fossil</strong></td>
<td>a <em>fossil</em> used to determine the relative age of <em>sedimentary</em> deposits. An ideal index fossil lived during a short period of time, was geographically and environmentally widespread, and is easy to identify. Some of the most useful index fossils are hard-shelled organisms that were once part of the marine plankton.</td>
</tr>
<tr>
<td><strong>inland basin</strong></td>
<td>a depression located inland from the mountains, and formed by the buckling (<em>downwarping</em>) of the Earth’s <em>crust</em>. Basins naturally preserve thick sediment layers because they accumulate eroded sediment and commonly continue to subside under the weight of the sediment.</td>
</tr>
<tr>
<td><strong>inland sea</strong></td>
<td>a shallow sea covering the central area of a continent during periods of high sea level. An inland sea is located on continental <em>crust</em>, while other seas are located on oceanic crust. An inland sea may or may not be connected to the ocean. For example, Hudson Bay is on the North American plate and connects to the Atlantic and Arctic Oceans, while the Caspian Sea is on the European <em>plate</em> but does not drain into any ocean at all.</td>
</tr>
<tr>
<td><strong>intensity (earthquake)</strong></td>
<td>a subjective measurement that classifies the amount of shaking and damage done by an <em>earthquake</em> in a particular area.</td>
</tr>
<tr>
<td><strong>interglacial</strong></td>
<td>a period of geologic time between two successive <em>glacial</em> stages.</td>
</tr>
<tr>
<td><strong>intertidal</strong></td>
<td>areas that are above water during low tide and below water during high tide.</td>
</tr>
<tr>
<td><strong>intrusion, intrusive rock</strong></td>
<td>a <em>plutonic igneous rock</em> formed when <em>magma</em> from within the Earth’s <em>crust</em> escapes into spaces in the overlying strata. As the magma rises, pushing through overlying layers of rock, it begins to cool. The cooling magma can crystallize and harden to become intrusive igneous rock, locked within layers of older rock.</td>
</tr>
<tr>
<td><strong>iodine</strong></td>
<td>a metallic chemical element (I) that is essential in humans for thyroid hormone production. It is found in trace amounts in seawater and is assimilated by seaweeds. Iodine is a lustrous, black, crystalline solid that appears violet in gas form.</td>
</tr>
<tr>
<td><strong>iron</strong></td>
<td>a metallic chemical element (Fe). Iron is most often found in combination with other elements, such as oxygen and <em>sulfur</em>, to form <em>ores</em> like hematite, magnetite, siderite, and pyrite. The ready availability of iron at Earth's surface made it one of the earliest mined <em>mineral</em> resources in the US.</td>
</tr>
<tr>
<td><strong>isostasy</strong></td>
<td>an equilibrium between the weight of the <em>crust</em> and the buoyancy of the <em>mantle</em>.</td>
</tr>
<tr>
<td><strong>jade</strong></td>
<td>a word applied to two green <em>minerals</em> that look similar and have similar properties: jadeite (a kind of <em>pyroxene</em>) and nephrite (a kind of <em>amphibole</em>). Both minerals are formed during <em>metamorphism</em> and are found primarily near <em>subduction</em> zones, which explains why jade is abundant in a variety of locations along active <em>plate boundaries</em>.</td>
</tr>
<tr>
<td><strong>jasper</strong></td>
<td>a speckled or patterned <em>silicate</em> stone that appears in a wide range of colors. It is a variety of chalcedony. Jasper forms when silica precipitates in a fine particulate material such as soft sediment or <em>volcanic ash</em>. The particulates give the stone its color and patterns.</td>
</tr>
<tr>
<td><strong>joint</strong></td>
<td>a surface or plane of fracture within a rock.</td>
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</tr>
<tr>
<td><strong>joule (J)</strong></td>
<td>the <strong>energy</strong> expended (or work done) to apply a force of one newton over a distance of one meter.</td>
</tr>
<tr>
<td><strong>Jurassic</strong></td>
<td>the <strong>geologic time</strong> period lasting from 201 to 145 million years ago. During the Jurassic, <strong>dinosaurs</strong> dominated the landscape and the first birds appeared. The Jurassic is the middle period of the <strong>Mesozoic</strong>.</td>
</tr>
<tr>
<td><strong>kame</strong></td>
<td>an irregularly shaped mound made up of sediment that accumulated in a depression on a retreating <strong>glacier</strong>. The mound-like deposits of sorted sediment are then deposited on the land after the glacier retreats.</td>
</tr>
<tr>
<td><strong>kaolinite</strong></td>
<td>a <strong>silicate clay mineral</strong>, also known as china clay. Kaolinite is the main ingredient in fine china dishes such as Wedgewood.</td>
</tr>
<tr>
<td><strong>karst topography</strong></td>
<td>a kind of landscape defined by bedrock that has been <strong>weathered</strong> by dissolution in water, forming features like sinkholes, caves, and cliffs. Karst <strong>topography</strong> primarily forms in <strong>limestone</strong> bedrock.</td>
</tr>
<tr>
<td><strong>kettle</strong></td>
<td>a lake formed where a large, isolated block of ice became separated from the retreating <strong>ice sheet</strong>. The weight of the ice leaves a shallow depression in the landscape that persists as a small lake.</td>
</tr>
<tr>
<td><strong>kinetic energy</strong></td>
<td>the <strong>energy</strong> of a body in motion (e.g., via friction).</td>
</tr>
<tr>
<td><strong>Köppen system</strong></td>
<td>a commonly used system of climate categorization developed by Russian climatologist Wladimir Köppen. It is based on the kinds of vegetation that areas sustain, and defines 12 <strong>climate</strong> types: rainforest, monsoon, tropical savanna, humid subtropical, humid continental, oceanic, Mediterranean, steppe, subarctic, tundra, polar ice cap, and desert. Updated by Rudolf Geiger, it has been refined to five groups each with two to four subgroups.</td>
</tr>
<tr>
<td><strong>Lagerstätte (pl. Lagerstätten)</strong></td>
<td><strong>fossil</strong> deposit containing animals or plants that are preserved unusually well, sometimes even including the soft organic tissues. Lagerstätten form in chemical environments that slow decay of organic tissues or enhance preservation through mineralization. Also, quick burial of the organism leaves no opportunity for disturbance of the fossils. Lagerstätten are important for the information they provide about soft-bodied organisms that we otherwise would know nothing about.</td>
</tr>
<tr>
<td><strong>lamproite</strong></td>
<td>an <strong>ultramafic volcanic</strong> (<strong>extrusive</strong>) rock with high levels of potassium and magnesium that contains coarse crystals. <strong>Diamonds</strong> can occur in lamproites.</td>
</tr>
<tr>
<td><strong>landslide</strong></td>
<td>the rapid slipping of a mass of earth or rock from a higher elevation to a lower level under the influence of gravity and water lubrication. Landslides include rock falls, avalanches, <strong>debris flows</strong>, mudflows, and the <strong>slumping</strong> of rock layers or sediment. See also: mass wasting</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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</tr>
<tr>
<td>Laramide Orogeny</td>
<td>a period of mountain building that began in the late Cretaceous, and is responsible for the formation of the Rocky Mountains. See also: orogeny</td>
</tr>
<tr>
<td>Last glacial maximum</td>
<td>the most recent time the ice sheets reached their largest size and extended farthest towards the equator, about 26,000 to 19,000 years ago. Ice sheets over North America melted back until about 10,000 years ago—they have been relatively stable since that time.</td>
</tr>
<tr>
<td>Laurentide Ice Sheet</td>
<td>an ice sheet that covered most of Canada during the last major glaciation. In its prime, the Laurentide was more than 5 kilometers (3.1 miles) thick at its thickest point on what is now the Hudson Bay. The sheet began to melt about 13,000 years ago.</td>
</tr>
<tr>
<td>Lava</td>
<td>molten rock located on the Earth's surface. When magma rises to the surface, typically through a volcano or rift, it becomes lava. Lava cools much more quickly than magma because it is at the surface, exposed to the atmosphere or ocean water where temperatures are much cooler. Such rocks, with little time to crystallize, have small or no crystals.</td>
</tr>
<tr>
<td>Law of Superposition</td>
<td>the geological principle that states that unless rock layers have been overturned or intruded, older rocks are found at the bottom and younger rocks are found at the top of a sedimentary sequence. See also: stratigraphy</td>
</tr>
<tr>
<td>Lead</td>
<td>a metallic chemical element (Pb). Lead was one of the first metals mined in North America, where it was sought after especially for making shot. It is used in batteries, communication systems, and building construction.</td>
</tr>
<tr>
<td>Leeward</td>
<td>downwind; facing away from the wind (not subject to orographic precipitation, and thus dryer).</td>
</tr>
<tr>
<td>Lignite</td>
<td>a soft, brownish-black coal in which the alteration of plant matter has proceeded farther than in peat but not as far as in bituminous coal.</td>
</tr>
<tr>
<td>Limestone</td>
<td>a sedimentary rock composed of calcium carbonate (CaCO₃). Most limestones are formed by the deposition and consolidation of the skeletons of marine invertebrates; a few originate in chemical precipitation from solution. Limestone is ordinarily white but can be colored by impurities such as iron oxide (making it brown, yellow, or red), or organic carbon (making it blue, black, or gray). The rock's texture varies from coarse to fine.</td>
</tr>
<tr>
<td>Lithification</td>
<td>the process of creating sedimentary rock through the compaction or sementation of soft sediment. The word comes from the Greek lithos, meaning “rock.”</td>
</tr>
<tr>
<td>Lithosphere</td>
<td>the outermost layer of the Earth, comprising a rigid crust and upper mantle broken up into many plates. The plates of the lithosphere move with the underlying asthenosphere, on average about 5 centimeters (2 inches) per year and as much as 18 centimeters (7 inches) per year.</td>
</tr>
<tr>
<td>Term</td>
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<tr>
<td>loam</td>
<td>a soil containing equal amounts of clay, silt, and sand.</td>
</tr>
<tr>
<td>loess</td>
<td>very fine grained, wind-blown sediment, usually rock flour left behind by the grinding action of flowing glaciers.</td>
</tr>
<tr>
<td>luminescence</td>
<td>the emission of light.</td>
</tr>
<tr>
<td>luster</td>
<td>a physical property of minerals, describing the appearance of the mineral's surface in reflected light, and how brilliant or dull it is. Luster can range from metallic and reflective to opaque, vitreous like glass, translucent, or dull and earthy.</td>
</tr>
<tr>
<td>lycopod</td>
<td>an extinct, terrestrial tree belonging to the plant division Lycopodiophyta, and characterized by a tall, thick trunk covered with a pattern of diamond-shaped leaf scars, and a crown of branches with simple leaves. Lycopods, or &quot;scale trees,&quot; grew up to 98 feet (30 meters) high in Mississippian and Pennsylvanian forests. The plant division Lycopodiophyta survives today but only as very small plants on the forest floor, sometimes called “ground pines.”</td>
</tr>
<tr>
<td>mafic</td>
<td>igneous rocks that contain a group of dark-colored minerals, with relatively high concentrations of magnesium and iron compared to felsic igneous rocks.</td>
</tr>
<tr>
<td>magma</td>
<td>molten rock located below the surface of the Earth. Magma can cool beneath the surface to form intrusive igneous rocks. However, if magma rises to the surface without cooling enough to crystallize, it might break through the crust at the surface to form lava.</td>
</tr>
<tr>
<td>magnetic</td>
<td>affected by or capable of producing a magnetic field.</td>
</tr>
<tr>
<td>magnetite</td>
<td>a mineral form of iron oxide (Fe₂O₃). It is the most magnetic naturally occurring mineral. The molecules in magnetite align with the North and South Poles when rocks containing magnetite ore are formed. By examining the alignment today, scientists can reconstruct how the rocks have moved since their formation, giving them clues about the previous arrangement of the continents. Magnetite lodestones were used as an early form of compass. Huge deposits of magnetite have been found in Precambrian banded iron formations.</td>
</tr>
<tr>
<td>magnitude (earthquake)</td>
<td>a logarithmic scale used to measure the seismic energy released by an earthquake. Magnitudes range from 1 to 10, with M3 earthquakes classed as minor and earthquakes of M8 or greater being classified as great.</td>
</tr>
<tr>
<td>mammoth</td>
<td>an extinct terrestrial vertebrate animal belonging to the Order Proboscidea of the Class Mammalia. Mammoths are from the same line of proboscideans that gave rise to African and Asian elephants. They had tall bodies with a rather high “domed” skull, and teeth with numerous parallel rows of ridges. Mammoths are among the most common Pleistocene vertebrate fossils in North America, Europe, and Asia.</td>
</tr>
<tr>
<td>manganese</td>
<td>a metallic chemical element (Mn). Manganese is used in the production of steel.</td>
</tr>
</tbody>
</table>

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Glossary

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<table>
<thead>
<tr>
<th><strong>Glossary</strong></th>
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<tbody>
<tr>
<td><strong>mantle</strong></td>
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<tr>
<td><strong>marble</strong></td>
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<tr>
<td><strong>marl</strong></td>
</tr>
</tbody>
</table>
| **mass extinction** | the extinction of a large percentage of the Earth’s species over a relatively short span of **geologic time**.  
Unfortunately, this is not just a phenomenon of the past: it is estimated that the extinction rate on Earth right now may be as much as 1000 times higher than normal, and that we are currently experiencing a mass extinction event. |
| **mass wasting** | a process in which **soil** and rock move down a slope in a large mass. This can occur both on land (such as a **landslide**) or underwater (such as a **turbidity current**). |
| **mastodon** | an **extinct** terrestrial vertebrate animal belonging to the Order Proboscidea of the Class Mammalia, and characterized by an elephant-like shape and size, and massive molar teeth with conical projections. Mastodons are among the most common **Pleistocene** vertebrate **fossils** in North America. |
| **matrix** | a fine-grained mass of material around and embedding larger grains or crystals. The term **matrix** can also describe sediment or rock in which a **fossil** is embedded. |
| **Mesozoic** | a **geologic time** period that spans from 252 to 66 million years ago. This period is also called the “age of reptiles” since dinosaurs and other reptiles dominated both marine and terrestrial ecosystems. During this time, the last of the Earth’s major supercontinents, **Pangaea**, formed and later broke up, producing the Earth’s current geography.  
The Mesozoic contains the **Triassic**, **Jurassic**, and **Cretaceous** periods. |
| **metamorphism, metamorphic rocks** | rocks formed by the recrystallization and realignment of **minerals** in pre-existing **sedimentary**, **igneous**, and **metamorphic rocks** when exposed to high enough temperature and/or pressure. This can be a result of **plate** movements, very deep burial, or contact with molten rock or superheated water. This process destroys many features in the rock that would have revealed its previous history, transforming it into an entirely new form.  
Tectonic forces can cause minerals to realign perpendicularly to the direction of pressure, layering them in a pattern called **foliation**, as exemplified in **gneiss** and **schist**. **Recrystallization**, as seen in **marble** and **quartzite**, results as rock is heated to high temperatures, and individual grains reform as interlocking crystals, making the resulting metamorphic rock harder than its parent rock. |
<p>| <strong>mica</strong> | a large group of sheetlike <strong>silicate minerals</strong>. |
| <strong>microcontinent</strong> | a piece of continental <strong>crust</strong>, usually <strong>rifled</strong> away from a larger continent. Microcontinents and other smaller fragments of continental crust (<strong>terranes</strong>) each had their own, often complex, geologic history before they were tacked onto the margin of another continent. |</p>
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Milankovitch Cycles</strong></td>
<td>Cyclical changes in the amount of heat received from the sun, associated with how the Earth's orbit, tilt, and wobble alter its position with respect to the sun. These changes affect the global climate, most notably alterations of glacial and interglacial intervals.</td>
</tr>
<tr>
<td><strong>mineral</strong></td>
<td>A naturally occurring solid with a specific chemical composition and crystalline structure. Minerals are identified based on their physical properties, including hardness, luster, color, crystal form, cleavage, density, and streak. There are over 4900 identified minerals. However, the number of common rock-forming minerals is much smaller. The most common minerals that form igneous, metamorphic, and sedimentary rocks include quartz, feldspar, mica, pyroxenes, and amphiboles.</td>
</tr>
<tr>
<td><strong>mineralogy</strong></td>
<td>The branch of geology that studies the chemical and physical properties and formation of minerals.</td>
</tr>
<tr>
<td><strong>Miocene</strong></td>
<td>A geological time unit extending from 23 to 5 million years ago. During the Miocene, the Earth experienced a series of ice ages, and hominin species diversified. The Miocene is the first epoch of the Neogene period.</td>
</tr>
<tr>
<td><strong>Mississippi Embayment</strong></td>
<td>A topographically low-lying basin in the south-central United States, stretching from Illinois to Louisiana. The Mississippi Embayment originated as far back as the Precambrian, during the breakup of Rodinia. During this time, many smaller rifts in the crust formed adjacent to the major rift that split away North America—one of these smaller rifts is located beneath the modern day Mississippi Embayment. During the breakup of Pangaea, the area subsided, forming a trough that was flooded during the Cretaceous. When sea level fell, the Mississippi River was born. Thousands of meters of Cretaceous to Recent sediment were deposited in the river valley. Recurrent activity along faults associated with the deeply buried ancient rifts beneath the embayment caused the 1811-1812 New Madrid Earthquakes, one of the largest earthquakes ever recorded in North America.</td>
</tr>
<tr>
<td><strong>Missippian</strong></td>
<td>A subperiod of the Carboniferous, spanning from 359 to 323 million years ago.</td>
</tr>
<tr>
<td><strong>Mohs Scale of Hardness</strong></td>
<td>The scale of relative hardness of minerals, developed by the Austrian mineralologist, Frederick Mohs, in 1824. The scale is very useful as a means for identifying minerals or quickly determining hardness. A piece of glass has a hardness of approximately 5 on the scale; our fingernails are just over 2; a knife blade is just over 5. Diamond ranks at 10 as the hardest mineral.</td>
</tr>
<tr>
<td><strong>Mollisols</strong></td>
<td>A soil order; these are agricultural soils made highly productive due to a very fertile, organic-rich surface layer.</td>
</tr>
<tr>
<td><strong>molybdenum</strong></td>
<td>A metallic chemical element (Mo) which has the sixth-highest melting point of any element at 2623°C (4753°F). Molybdenum is mainly used in the creation of alloys, such as stainless steel and cast iron, and its strong ability to withstand heat makes it useful in applications that utilize extreme heat, such as the manufacture of motors and aircraft parts.</td>
</tr>
<tr>
<td><strong>monoplacophoran</strong></td>
<td>Any mollusk belonging to the class Monoplacophora, characterized by serially repeating organs and roughly bilateral symmetry. Once known only from fossils of the Paleozoic era, living monoplacophorans were discovered in 1952. They are typically found in the deep ocean.</td>
</tr>
<tr>
<td><strong>moraine</strong></td>
<td>an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions, such as those areas acted upon by a past ice age. The debris is scraped from the ground and pushed forward by the glacier, to be left behind when the ice melts. Thus, many moraines mark the terminus or edge of a glacier. Lateral moraines can also occur in between and at the sides of glaciers or ice lobes.</td>
</tr>
<tr>
<td><strong>mosasaur</strong></td>
<td>an extinct, carnivorous, marine vertebrate reptile. Mosasours were characterized by a streamlined body for swimming, a powerful fluked tail, and reduced, paddle-like limbs. They were common in Cretaceous seas and were were powerful swimmers, reaching 12–18 meters (40–59 feet) in length.</td>
</tr>
</tbody>
</table>
| **natural gas** | a hydrocarbon gas mixture composed primarily of methane (CH\textsubscript{4}), but also small quantities of hydrocarbons such as ethane and propane.  
See also: fossil fuel |
| **natural hazard** | events that result from natural processes and that have significant impacts on human beings. |
| **Neogene** | the geologic time period extending from 23 to 2.6 million years ago. During the Neogene, global climate cooled, the continents moved close to their current positions, mammals and birds continued to evolve, and the first hominins appeared.  
The Neogene is a portion of the Cenozoic. |
| **nickel** | a ductile, silvery-white metallic element (Ni). Nickel in its pure form is rarely found on Earth's surface; large quantities of nickel are typically found in meteorites. On Earth, nickel is generally found in combination with iron.  
Nickel is resistant to corrosion and is commonly used to plate metals, coat chemistry equipment, and manufacture alloys such as electrum. |
| **nodule** | a small, irregular or rounded mineral deposit that has a different composition from the sedimentary rock that encloses it. Nodules typically form when minerals precipitate from a supersaturated solution within or around features such as biotic remains. |
| **nuclear** | pertaining to a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus. |
| **obsidian** | a glassy volcanic rock, formed when felsic lava cools rapidly. Although obsidian is dark in color, it is composed mainly of silicon dioxide (SiO\textsubscript{2}), and its dark color is a result of the rapid cooling process.  
Obsidian is extremely brittle and breaks with very sharp edges. It was valuable to Stone Age cultures for its use as cutting implements or arrowheads. |
<p>| <strong>oil</strong> | See petroleum |
| <strong>Oligocene</strong> | a geologic time interval spanning from about 34 to 23 million years ago. It is an epoch of the Paleogene. |</p>
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>olivine</td>
<td>an iron-magnesium silicate mineral ((\text{Mg},\text{Fe})_2\text{SiO}_4) that is a common constituent of magnesium-rich, silica-poor igneous rocks.</td>
</tr>
<tr>
<td>Ordovician</td>
<td>a geologic time period spanning from 485 to 443 million years ago. During the Ordovician, invertebrates dominated the oceans and fish began to diversify. The Ordovician is part of the Paleozoic.</td>
</tr>
<tr>
<td>ore</td>
<td>a type of rock that contains minerals with valuable elements, including metals, that are economically viable to extract.</td>
</tr>
<tr>
<td>orogeny</td>
<td>a mountain-building event generally caused by colliding plates and compression of the edge of the continents. Orogeny is derived from the Greek word oro, meaning mountain.</td>
</tr>
<tr>
<td>orographic precipitation</td>
<td>rainfall caused when wind pushes a mass of humid air up the side of an elevated land formation like a mountain. As the air rises, it cools, and the moisture precipitates out.</td>
</tr>
<tr>
<td>Ouachita Orogeny</td>
<td>the late Paleozoic mountain building event that resulted in the folding and faulting of strata currently exposed in the Ouachita Mountains. The mountain range extends through Arkansas, Oklahoma, and the Marathon uplift region of West Texas. See also: orogeny</td>
</tr>
<tr>
<td>outwash plain</td>
<td>large sandy flats created by sediment-laden water deposited when a glacier melts. Outwash sediments are also called fluvial material.</td>
</tr>
<tr>
<td>oxidation, oxide</td>
<td>a chemical reaction involving the loss of at least one electron when two substances interact; most often used to describe the interaction between oxygen molecules and the substances they come into contact with. Oxidation causes effects such as rust and cut apples turning brown.</td>
</tr>
<tr>
<td>Oxisols</td>
<td>a soil order; these are very old, extremely leached and weathered soils with a subsurface accumulation of iron and aluminum oxides. Commonly found in humid, tropical environments.</td>
</tr>
<tr>
<td>Paleocene</td>
<td>a geologic time interval spanning from about 66 to 56 million years ago. It is an epoch of the Paleogene period.</td>
</tr>
<tr>
<td>paleoecology</td>
<td>the study of the relationships of fossil organisms to one another and their environment.</td>
</tr>
<tr>
<td>Paleogene</td>
<td>the geologic time interval extending from 66 to 23 million years ago. During the Paleogene, mammals and birds diversified into many of the niches that had previously been held by dinosaurs. The Paleogene is the first part of the Cenozoic.</td>
</tr>
<tr>
<td>Paleozoic</td>
<td>a geologic time period that extends from 541 to 252 million years ago. Fossil evidence shows that during this time period, life evolved in the oceans and gradually colonized the land. The Paleozoic includes the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian periods.</td>
</tr>
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<tbody>
<tr>
<td><strong>Pangaea</strong></td>
<td>supercontinent, meaning “all Earth,” which formed over 250 million years ago and lasted for almost 100 million years. All of the Earth’s continents were joined in a giant supercontinent. Pangaea eventually rifted apart and separated into the continents in their current configuration.</td>
</tr>
<tr>
<td><strong>parent material</strong></td>
<td>the original geologic material from which soil formed. This can be bedrock, preexisting soils, or other materials such as till or loess.</td>
</tr>
<tr>
<td><strong>passive margin</strong></td>
<td>a tectonically quiet continental edge, such as the eastern margin of North America, where crustal collision or rifting is not occurring.</td>
</tr>
<tr>
<td><strong>patterned ground</strong></td>
<td>patterns and sorting in the soil caused by repeated freezing and thawing, which causes repeated heaving upwards and settling of the rocks and pebbles in the soil.</td>
</tr>
<tr>
<td><strong>peat</strong></td>
<td>an accumulation of partially decayed plant matter. Under proper heat and pressure, it will turn into lignite coal over geologic periods of time. As much as 9 meters (30 feet) of peat might need to accumulate to produce an economically profitable coal seam. By the time that a peat bed has been turned into a layer of anthracite, the layer is one-tenth its original thickness.</td>
</tr>
<tr>
<td><strong>peds</strong></td>
<td>clumps of soil, identified by their shape, which may take the form of balls, blocks, columns, and plates. These structures are easiest to see in recently plowed fields, where the soil is often granular and loose or lumpy.</td>
</tr>
<tr>
<td><strong>pegmatite</strong></td>
<td>a very coarse-grained igneous rock that formed below the surface, usually rich in quartz, feldspar, and mica. Pegmatite magmas are very rich in water, carbon dioxide, silicon, aluminum, and potassium, and form as the last fluids to crystallize from magma or the first minerals to melt at high temperatures during metamorphism.</td>
</tr>
<tr>
<td><strong>pelagic</strong></td>
<td>free-swimming; of or in a zone of open water that is neither close to the bottom nor near the shore.</td>
</tr>
<tr>
<td><strong>Pennsylvanian</strong></td>
<td>a subperiod of the Carboniferous, spanning from 323 to 299 million years ago.</td>
</tr>
<tr>
<td><strong>perennial</strong></td>
<td>continuous; year-round or occurring on a yearly basis.</td>
</tr>
<tr>
<td><strong>periglacial zone</strong></td>
<td>a region directly next to an ice sheet, which, although it was never covered or scoured by ice, has its own distinctive landscape and features because it was next to the ice margin. The average annual air temperature in a periglacial area is between -12° and 3°C (10° and 37°F). Though the surface of the ground may melt in the summer, it refreezes in the winter.</td>
</tr>
<tr>
<td><strong>permafrost</strong></td>
<td>a layer of soil below the surface that remains frozen all year round. Its thickness can range from tens of centimeters to a few meters. Permafrost is typically defined as any soil that has remained at a temperature below the freezing point of water for at least two years.</td>
</tr>
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<tr>
<td><strong>permeable, permeability</strong></td>
<td>A capacity for fluids and gas (such as water, oil, and natural gas) to move through fractures within a rock, or the spaces between its grains.</td>
</tr>
<tr>
<td><strong>Sandstone, limestone</strong></td>
<td>Sandstone, limestone, and fractured rocks of any kind generally are permeable. Shale, on the other hand, is usually impermeable because the small, flat clay particles that make up the rock are tightly packed into a dense rock with very little space between particles. Poorly sorted sedimentary rocks can also be impermeable because smaller grains fill in the spaces between the bigger grains, restricting the movement of fluids.</td>
</tr>
<tr>
<td><strong>Permian</strong></td>
<td>The geologic time period lasting from 299 to 252 million years ago. During the Permian, the world’s landmass was combined into the supercontinent Pangaea. The Permian is the last period of the Paleozoic. It ended with the largest mass extinction in Earth’s history, which wiped out 70% of terrestrial animal species and 90% of all marine animal species.</td>
</tr>
<tr>
<td><strong>permineralization</strong></td>
<td>A fossilization method in which empty spaces (such as in a bone or shell) are filled by minerals.</td>
</tr>
<tr>
<td><strong>petroleum</strong></td>
<td>A naturally occurring, flammable liquid found in geologic formations beneath the Earth’s surface and consisting primarily of hydrocarbons. Petroleum, also called oil, is a fossil fuel, formed when large masses of dead organisms (usually algae or plankton) are buried underneath sediments and subjected to intense heat and pressure. Today, petroleum is used to manufacture a wide variety of materials, and it is commonly refined into various types of fuels. It is estimated that 90 million barrels are consumed globally every day.</td>
</tr>
<tr>
<td><strong>Phanerozoic</strong></td>
<td>A generalized term used to describe the entirety of geological history after the Precambrian, from 541 million years ago to the present.</td>
</tr>
<tr>
<td><strong>phenocryst</strong></td>
<td>A large and generally conspicuous crystal which has been enclosed in a much finer-grained igneous rock. Phenocrysts may occur in all types of igneous rock, but are most common in felsic rocks.</td>
</tr>
<tr>
<td><strong>phyllite</strong></td>
<td>A metamorphic rock that is intermediate in grade between slate and schist.</td>
</tr>
<tr>
<td><strong>physiography</strong></td>
<td>A subfield of geography that studies the Earth’s physical processes and patterns, including consideration of the shape (not just the height) of land forms, as well as the bedrock, soil, water, vegetation, and climate of an area, and how they interacted in the past to form the landscape we see today.</td>
</tr>
<tr>
<td><strong>phytosaur</strong></td>
<td>An extinct reptile from the late Triassic period. Phytosaurs were semi-aquatic relatives of the crocodile with heavily armored bodies. Their fossils have been found in North America, Europe, and India.</td>
</tr>
<tr>
<td><strong>placer deposit</strong></td>
<td>A mineral deposit occurring in rivers and streams where less dense sediment has been carried downstream but denser minerals such as gold have been left behind.</td>
</tr>
<tr>
<td><strong>plate tectonics</strong></td>
<td>The process by which the plates of the Earth’s crust move and interact with one another at their boundaries. The Earth is dynamic, consisting of constantly moving plates that are made of rigid continental and oceanic lithosphere overlying a churning, plastically flowing asthenosphere. These plates are slowly pulling apart, colliding, or sliding past one another with great force, creating strings of volcanic islands, new ocean floor, earthquakes, and mountains.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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</tr>
<tr>
<td>plates</td>
<td>large, rigid pieces of the Earth’s crust and upper mantle, which move and interact with one another at their boundaries. See also: plate tectonics</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>a subset of the Quaternary, lasting from 2.5 million to about 11,700 years ago. During the Pleistocene, continental ice sheets advanced south and retreated north several dozen times.</td>
</tr>
<tr>
<td>plesiosaur</td>
<td>a member of a group of extinct long-necked Mesozoic marine reptiles.</td>
</tr>
<tr>
<td>Pliocene</td>
<td>a geologic time interval extending from roughly 5 to 2.5 million years ago. The Pliocene epoch is a subdivision of the Neogene period, and is the time period directly preceding the onset of Pleistocene glaciations.</td>
</tr>
<tr>
<td>plucking</td>
<td>process in which a glacier &quot;plucks&quot; sediments and larger chunks of rock from the bedrock. The flowing ice cracks and breaks rock as it passes over, pieces of which become incorporated into the sheet or bulldozed forward, in front of the glacier’s margin.</td>
</tr>
<tr>
<td>plunge pool</td>
<td>a stream pool, lake, or pond that is small in diameter, but deep.</td>
</tr>
<tr>
<td>pluton, plutonic rock</td>
<td>a large body of intrusive igneous rock that formed under the Earth’s surface through the slow crystallization of magma. The term comes from the name of Pluto, Roman god of the underworld.</td>
</tr>
<tr>
<td>porosity</td>
<td>the percentage of openings in a body of rock such as pores, joints, channels, and other cavities, in which gases or liquids may be trapped or migrate through.</td>
</tr>
<tr>
<td>potash</td>
<td>a name used for a variety of salts containing potassium, with mined potash being primarily potassium chloride (KCl). The majority of potash is used as fertilizer, but an increasing amount is being used in a variety of other ways: water softening, snow melting, a variety of industrial processes, as a medicine, and to produce potassium carbonate (K₂CO₃).</td>
</tr>
<tr>
<td>pothole</td>
<td>a shallow, rounded depression eroded in bedrock by a glacier.</td>
</tr>
<tr>
<td>power (energy)</td>
<td>the rate at which energy is transferred, usually measured in watts or, less frequently, horsepower.</td>
</tr>
<tr>
<td>Precambrian</td>
<td>a geologic time period that spans from the formation of Earth (4.6 billion years ago) to the beginning of the Cambrian (541 million years ago). Relatively little is known about this time period since very few fossils or unaltered rocks have survived. What few clues exist indicate that life first appeared on the planet as long as 3.9 billion years ago in the form of single-celled organisms. The Precambrian contains the Hadean, Archean and Proterozoic eons.</td>
</tr>
<tr>
<td>Pre-Illinoian glaciation</td>
<td>a grouping of the Midwestern glacial periods that occurred before the Wisconsinian and Illinoian glaciations.</td>
</tr>
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<tbody>
<tr>
<td><strong>primary energy source</strong></td>
<td>A source of <strong>energy</strong> found in nature, that has not been subject to any human-induced energy transfers or transformations (like conversion to electricity). Examples include <strong>fossil fuels</strong>, solar, wind, and hydropower.</td>
</tr>
<tr>
<td><strong>progradation</strong></td>
<td>Outward building of strata toward the sea in the form of a beach, fan, or <strong>delta</strong>, caused by continuous deposition of sediment by rivers, or by the progressive accumulation of material thrown up by waves or other shoreline processes.</td>
</tr>
<tr>
<td><strong>Proterozoic</strong></td>
<td>A <strong>geologic time</strong> interval that extends from 2.5 billion to 541 million years ago. It is part of the <strong>Precambrian</strong>. During this eon, the Earth transitioned to an oxygenated atmosphere and eukaryotic cells, including fungi, plants, and animals, originated.</td>
</tr>
<tr>
<td><strong>protists</strong></td>
<td>A diverse group of single-celled <strong>eukaryotes</strong>. See also: eukaryote</td>
</tr>
<tr>
<td><strong>protolith</strong></td>
<td>The original parent rock from which a <strong>metamorphosed</strong> rock is formed.</td>
</tr>
<tr>
<td><strong>pterosaurs</strong></td>
<td>Extinct flying reptiles with wingspans of up to 15 meters. They lived during the same time as the <strong>dinosaurs</strong>.</td>
</tr>
<tr>
<td><strong>pyrite</strong></td>
<td>An <strong>iron sulfide mineral</strong> (FeS₂). Pyrite’s superficial resemblance to gold has led to the common nickname “fool’s gold.”</td>
</tr>
<tr>
<td><strong>pyroclastic rocks</strong></td>
<td>Rocks that form during explosive <strong>volcanic</strong> eruptions, and are composed from a variety of different volcanic ejecta. The term comes from Greek, and means “broken fire.” Pyroclastic debris of all types is known as tephra.</td>
</tr>
<tr>
<td><strong>pyroxene</strong></td>
<td>Dark-colored rock-forming <strong>silicate minerals</strong> containing <strong>iron</strong> and magnesium, found in many <strong>igneous</strong> and <strong>metamorphic rocks</strong>. They are often present in <strong>volcanic</strong> rocks.</td>
</tr>
<tr>
<td><strong>quartz</strong></td>
<td>The second most abundant <strong>mineral</strong> in the Earth’s continental <strong>crust</strong> (after feldspar), made up of <strong>silicon</strong> and oxygen (SiO₂). It makes up more than 10% of the crust by mass. There are a wide variety of types of quartz: onyx, <strong>agate</strong>, and petrified wood are fibrous, microcrystalline varieties collectively known as <strong>chalcedony</strong>. Although agate is naturally banded with layers of different colors and porosity, commercial varieties of agate are often artificially colored. <strong>Flint</strong>, <strong>chert</strong>, and <strong>jasper</strong> are granular microcrystalline varieties of quartz, with the bright red color of jasper due to the inclusion of small amounts of <strong>iron</strong> within the mineral structure. The most common, coarsely crystalline varieties include massive quartz veins, the distinct, well formed crystals of “rock crystal”, and an array of colored quartz, including amethyst (purple), rose quartz (pink), smoky quartz (gray), citrine (orange), and milky quartz (white).</td>
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<tr>
<td><strong>quartzite</strong></td>
<td>A hard metamorphic rock that was originally sandstone. Quartzite usually forms from sandstone that was metamorphosed through tectonic compression within orogenic belts. Quartzite is quarried for use as a building and decorative stone.</td>
</tr>
<tr>
<td><strong>Quaternary</strong></td>
<td>A geologic time period that extends from 2.6 million years ago to the present. This period is largely defined by the periodic advance and retreat of continental glaciers. The Quaternary is part of the Cenozoic.</td>
</tr>
<tr>
<td><strong>radioactivity</strong></td>
<td>The process by which an unstable atom loses energy by emitting radiation.</td>
</tr>
<tr>
<td><strong>radon</strong></td>
<td>A naturally occurring radioactive, colorless, odorless gas. It is one of the products of decay from the breakdown of radioactive elements in soil, rock, and water, released by weathering.</td>
</tr>
<tr>
<td><strong>recrystallization</strong></td>
<td>The change in structure of mineral crystals that make up rocks, or the formation of new mineral crystals within the rock. Recrystallization commonly occurs during metamorphism. When rocks are metamorphosed, individual grains that make up the original rock are melted slightly and recrystallize. The pressure allows crystals to grow into a tighter, interlocking arrangement than in an unmetamorphosed rock.</td>
</tr>
<tr>
<td><strong>reef</strong></td>
<td>A feature lying beneath the surface of the water, which is a buildup of sediment or other material built by organisms, and which has positive relief from the sea floor. While some reefs result from abiotic processes such as deposition or wave action, the best-known reefs are built by corals and other marine organisms.</td>
</tr>
<tr>
<td><strong>regional metamorphism</strong></td>
<td>A metamorphic rock that has been altered due to deep burial and great pressure. This type of metamorphic rock tends to occur in long belts at the center of mountain ranges. Different types of metamorphic rock are created depending on the gradients of heat and pressure applied.</td>
</tr>
<tr>
<td><strong>regression</strong></td>
<td>A drop in sea level.</td>
</tr>
<tr>
<td><strong>relief (topography)</strong></td>
<td>The change in elevation over a distance.</td>
</tr>
<tr>
<td><strong>renewable energy, renewable resource</strong></td>
<td>Energy obtained from sources that are virtually inexhaustible (defined in terms of comparison to the lifetime of the Sun) and replenish naturally over small time scales relative to human life spans.</td>
</tr>
<tr>
<td><strong>replacement</strong></td>
<td>A fossilization method by which the original material is chemically replaced by a more stable mineral.</td>
</tr>
<tr>
<td><strong>residual weathering deposit</strong></td>
<td>A mineral deposit formed through the concentration of a weathering-resistant mineral, in which the other minerals around it have been weathered away.</td>
</tr>
<tr>
<td><strong>rhyolite, rhyolitic</strong></td>
<td>A felsic volcanic rock high in abundance of quartz and feldspar.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>rift</td>
<td>a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates.</td>
</tr>
<tr>
<td>ripple marks</td>
<td>surface features created when sediment deposits are agitated, typically by water currents or wind. The crests and troughs formed by this agitation are occasionally lithified and preserved, providing information about the flow of water or wind in the paleoenvironment.</td>
</tr>
<tr>
<td>rock flour</td>
<td>very fine sediments and clay resulting from the grinding action of glaciers.</td>
</tr>
<tr>
<td>Rodinia</td>
<td>a supercontinent that contained most or all of Earth’s landmass, between 1.1 billion and 750 million years ago, during the Precambrian. Geologists are not sure of the exact size and shape of Rodinia. It was analogous to but not the same supercontinent as Pangaea, which formed was assembled several hundred million years later during the Permian.</td>
</tr>
<tr>
<td>rudist</td>
<td>an extinct group of box- or tube-shaped bivalves that arose during the Jurassic. They were major reef-formers, but went extinct at the end of the Cretaceous.</td>
</tr>
<tr>
<td>rugose coral</td>
<td>an extinct group of corals that were prevalent from the Ordovician through the Permian. Solitary forms were most common; these were horn-shaped, leading to their common name, “horn corals.”</td>
</tr>
<tr>
<td>salt</td>
<td>a mineral composed primarily of sodium chloride (NaCl). In its natural form, it is called rock salt or halite.</td>
</tr>
<tr>
<td>Salt is essential for animal life, and is a necessary part of the diet. In addition, salt is used for de-icing roads in winter and is also an important part of the chemical industry.</td>
<td></td>
</tr>
<tr>
<td>salt dome</td>
<td>a largely subsurface geologic structure, consisting of a vertical cylinder of salt embedded in horizontal or inclined sedimentary strata. Salt buried under thousands of feet of overlying sediment often deforms plastically. Because it is less dense than the rocks above it, it flows upward toward areas of lower pressure, forming geological structures named for their shapes (e.g., domes, canopies, tables, and lenses).</td>
</tr>
<tr>
<td>sand</td>
<td>rock material in the form of loose, rounded, or angular grains, and formed as a result of the weathering and decomposition of rocks. Particles of sand are between 0.05-2 millimeters in diameter.</td>
</tr>
<tr>
<td>sandstone</td>
<td>sedimentary rock formed by cementing together grains of sand.</td>
</tr>
<tr>
<td>schist</td>
<td>a medium grade metamorphic rock with sheet-like crystals flattened in one plane. The flattened crystals are often muscovite or biotite mica, but they can also be talc, graphite, or hornblende.</td>
</tr>
<tr>
<td><strong>scleractinian coral</strong></td>
<td>a modern &quot;stony&quot; coral; a colonial or solitary marine invertebrate animal belonging to the Order Scleractinia in the Class Anthozoa of the Phylum Cnidaria, and characterized by an encrusting calcareous skeleton from which multiple individuals (polyps) extend from small pores to capture prey with small tentacles equipped with stinging cells (nematocysts). Although scleractinians look somewhat similar to extinct rugose and tabulate corals, each group possesses distinctive features in the shape of the skeletal cup holding the individual polyps. Modern scleractinians host commensal algae (zooxanthellae) whose photosynthetic activities supply the coral with energy.</td>
</tr>
<tr>
<td><strong>scoria</strong></td>
<td>a highly vesicular form of basalt. It tends to form as cinders in the early stages of a volcanic eruption, when gas bubbles are still caught up in the frothy erupting magma. Once the gas has escaped, the remaining magma can flow out, creating basalt lava flows that spread out over the landscape.</td>
</tr>
<tr>
<td><strong>scour, scouring</strong></td>
<td>erosion resulting from glacial abrasion on the landscape.</td>
</tr>
<tr>
<td><strong>sedimentary rocks</strong></td>
<td>rocks formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter. Sediment that forms from weathering is transported by wind or water to a depositional environment such as a lakebed or ocean floor; here they build up, burying and compacting lower layers. As water permeates the sediment, dissolved minerals may precipitate out, filling the spaces between particles and cementing them together. Sedimentary rocks may also accrete from fragments of the shells or skeletal material of marine organisms like clams and coral. Sedimentary rocks are classified by their sediment size or their mineral content. Each one reveals the story of the depositional environment where its sediments accumulated and the history of its lithification.</td>
</tr>
<tr>
<td><strong>seismic waves</strong></td>
<td>the shock waves or vibrations radiating in all directions from the center of an earthquake or other tectonic event.</td>
</tr>
<tr>
<td><strong>seismic zone</strong></td>
<td>a regional zone that encompasses areas prone to seismic hazards, such as earthquakes or landslides.</td>
</tr>
<tr>
<td><strong>selenite</strong></td>
<td>a variety of the mineral gypsum that is most often colorless. Like all gypsum, selenite displays a distinct crystalline structure that is easily cleavable, and occurs on every continent. See also: cleavage, gypsum, mineral</td>
</tr>
<tr>
<td><strong>sessile</strong></td>
<td>unable to move, as in an organism that is permanently attached to its substrate.</td>
</tr>
<tr>
<td><strong>shale</strong></td>
<td>a dark, fine-grained, laminated sedimentary rock formed by the compression of successive layers of silt- and clay-rich sediment. Shale is weak and often breaks along thin layers. Shale that is especially rich in unoxidized carbon is dark grey or black. These organic-rich black shales are often source rocks for petroleum and natural gas.</td>
</tr>
<tr>
<td><strong>shark</strong></td>
<td>a large fish characterized by a cartilaginous skeleton and five to seven gill slits on the side of the head. Sharks first appeared 420 million years ago, and have since diversified to over 470 species.</td>
</tr>
</tbody>
</table>
### Glossary

<table>
<thead>
<tr>
<th><strong>shield</strong></th>
<th>See craton</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>silica, silicon, silicate</strong></td>
<td>a chemical compound also known as silicon dioxide ($\text{SiO}_2$). Silica is most commonly found as quartz, and is also secreted as skeletal material in various organisms. It is one of the most abundant materials in the crust.</td>
</tr>
<tr>
<td><strong>silt</strong></td>
<td>granular sediment most commonly composed of quartz and feldspar crystals. Particles of silt have diameters of less than 0.074 millimeters.</td>
</tr>
<tr>
<td><strong>Silurian</strong></td>
<td>a geologic time period spanning from 443 to 419 million years ago. During the Silurian, jawed and bony fish diversified, and life first began to appear on land. The Silurian is part of the Paleozoic.</td>
</tr>
<tr>
<td><strong>silver</strong></td>
<td>a metallic chemical element (Ag). Silver is used in photographic film emulsions, utensils and other tableware, and electronic equipment.</td>
</tr>
<tr>
<td><strong>slate</strong></td>
<td>a fine-grained, foliated metamorphic rock derived from a shale composed of volcanic ash or clay.</td>
</tr>
<tr>
<td><strong>slump</strong></td>
<td>a slow-moving landslide in which loosely consolidated rock or soil layers move a short distance down a slope. See also: mass wasting</td>
</tr>
<tr>
<td><strong>snail</strong></td>
<td>See gastropod</td>
</tr>
<tr>
<td><strong>soapstone</strong></td>
<td>a metamorphic schistose rock composed mostly of talc. Soapstone has a flaky texture and a greasy or soapy feel, and is an effective medium for carving.</td>
</tr>
<tr>
<td><strong>soil</strong></td>
<td>the collection of natural materials that collect on Earth's surface, above the bedrock. Soil consists of layers (horizons) of two key ingredients: plant litter, such as dead grasses, leaves, and fallen debris, and sediment derived from the weathering of rock. Both of these components can influence the texture and consistency of the soil, as well as the minerals available for consumption by plants. The word is derived from the Latin &quot;solum,&quot; which means “floor” or “ground.”</td>
</tr>
<tr>
<td><strong>soil orders</strong></td>
<td>the twelve major units of soil taxonomy, which are defined by diagnostic horizons, composition, soil structures, and other characteristics. Soil orders depend mainly on climate and the organisms within the soil. These orders are further broken down into 64 suborders based on properties that influence soil development and plant growth, with the most important property being how wet the soil is throughout the year.</td>
</tr>
<tr>
<td><strong>soil taxonomy</strong></td>
<td>The system used to classify soils based on their properties.</td>
</tr>
<tr>
<td><strong>solifluction</strong></td>
<td>a type of <strong>mass wasting</strong> where waterlogged sediment moves slowly downslope, over impermeable material. Solifluction is similar to a <strong>landslide</strong> or mudslide.</td>
</tr>
<tr>
<td><strong>solution mining</strong></td>
<td>the extraction of soluble <strong>minerals</strong> from subsurface strata by the injection of fluids, and the controlled removal of mineral-laden solutions.</td>
</tr>
<tr>
<td><strong>sphenopsid</strong></td>
<td>a terrestrial plant belonging to the Family Equisetaceae in the plant division Pteridophyta, and characterized by hollow, jointed stems with reduced, unbranched leaves at the nodes. Sphenopsids, or horsetails, reached over 33 feet (10 meters) high during the <strong>Pennsylvanian</strong>.</td>
</tr>
<tr>
<td><strong>spheroidal weathering</strong></td>
<td>a type of chemical <strong>weathering</strong> in which the rough edges of a rock wear away evenly, gradually revealing a smooth, rounded surface. This type of weathering often occurs at lower elevations where freezing is infrequent, and is similar to <strong>exfoliation</strong> (which is a form of mechanical weathering).</td>
</tr>
<tr>
<td><strong>Spodosols</strong></td>
<td>a <strong>soil</strong> order; these are acidic <strong>soils</strong> in which <strong>aluminum</strong> and <strong>iron oxides</strong> accumulate below the surface. They typically form under pine vegetation and sandy parent material.</td>
</tr>
<tr>
<td><strong>sponge</strong></td>
<td>a marine invertebrate belonging to the Phylum Porifera, and characterized by a soft shape with many pores and channels for water flow. Because they have no nervous, digestive, or circulatory systems, some consider them to be colonies of specialized single cells. Sponges come in a variety of shapes and body forms, and have been around at least since the <strong>Cambrian</strong>. Entire sponges are rarely preserved, but their tiny skeletal pieces (spicules) are common in <strong>sedimentary rocks</strong>. See also: archaeocyathid</td>
</tr>
<tr>
<td><strong>stratigraphy, stratigraphic</strong></td>
<td>the branch of geology specifically concerned with the arrangement and age of rock units. See also: Law of Superposition</td>
</tr>
<tr>
<td><strong>streak</strong></td>
<td>a physical property of <strong>minerals</strong>, obtained by dragging the mineral across a porcelain plate and effectively powdering it. During identification, the color of the powder eliminates the confounding variables of external <strong>weathering</strong>, <strong>crystal form</strong>, or impurities.</td>
</tr>
<tr>
<td><strong>subduction</strong></td>
<td>the process by which one <strong>plate</strong> moves under another, sinking into the <strong>mantle</strong>. This usually occurs at <strong>convergent plate boundaries</strong>. <strong>Denser</strong> plates are more likely to subduct under more buoyant plates, as when oceanic <strong>crust</strong> sinks beneath continental crust.</td>
</tr>
<tr>
<td><strong>subsidence</strong></td>
<td>the sinking of an area of the land surface.</td>
</tr>
<tr>
<td><strong>sulfur</strong></td>
<td>a bright yellow chemical element (S) that is essential to life. It acts as an <strong>oxidizing</strong> or reducing agent, and occurs commonly in raw form as well as in <strong>minerals</strong>.</td>
</tr>
<tr>
<td><strong>sustainable</strong></td>
<td>able to be maintained at a steady level without exhausting natural resources or causing severe ecological damage, as in a behavior or practice.</td>
</tr>
<tr>
<td><strong>suture</strong></td>
<td>the area where two <strong>continental plates</strong> have joined together through continental collision. See also: convergent boundary, plate tectonics</td>
</tr>
<tr>
<td><strong>synapsid</strong></td>
<td>A group of tetrapod vertebrates possessing one opening in the skull behind each orbit (eye hole), and a bony arch beneath. All mammals are synapsids.</td>
</tr>
<tr>
<td><strong>system</strong></td>
<td>A set of connected things or parts forming a complex whole - in particular, a set of things working together as parts of a mechanism or an interconnecting network.</td>
</tr>
<tr>
<td><strong>tabulate coral</strong></td>
<td>An extinct form of colonial coral that often formed honeycomb-shaped colonies of hexagonal cells.</td>
</tr>
<tr>
<td><strong>talc</strong></td>
<td>Hydrated magnesium silicate, formed during hydrothermal alteration accompanying metamorphism. Talc can be formed from calcite, dolomite, silica, and some ultramafic rocks.</td>
</tr>
<tr>
<td><strong>talus</strong></td>
<td>Debris fields found on the sides of steep slopes, common in periglacial environments.</td>
</tr>
<tr>
<td><strong>terrace</strong></td>
<td>A flat or gently sloped embankment or ridge occurring on a hillside, and often along the margin of (or slightly above) a body of water, representing a previous water level.</td>
</tr>
<tr>
<td><strong>terrane</strong></td>
<td>A piece of crustal material that has broken off from its parent continent and become attached to another plate. Due to their disparate origins, terranes have distinctly different geologic characteristics than the surrounding rocks. Florida is a good example of an exotic terrane, originating as part of the supercontinent Gondwana. Parts of the western coast of North America (including Alaska and the Northeastern US) are also terranes that have been sutured onto the coast.</td>
</tr>
<tr>
<td><strong>Tertiary</strong></td>
<td>An unofficial but still commonly used term for the time period spanning from 66 million to 2.5 million years ago, including the Paleogene, Neogene, and part of the Pleistocene. Although the Tertiary period was officially phased out in 2008 by the International Commission on Stratigraphy, it can still be found in scientific literature. (In contrast, the Carboniferous and Pennsylvanian &amp; Mississippian periods all enjoy official status, with the latter pair being more commonly used in the US.)</td>
</tr>
<tr>
<td><strong>tetrapod</strong></td>
<td>The first four-limbed animals (early land vertebrates) and all of their descendants, including all amphibians, reptile groups (including birds), and synapsids (including mammals). Although most tetrapods today have four limbs, some, such as snakes and whales, have secondarily lost limbs.</td>
</tr>
<tr>
<td><strong>till</strong></td>
<td>Unconsolidated sediment that is eroded from the bedrock, then carried and eventually deposited by glaciers as they recede. Till may include a mixture of clay, sand, gravel, and even boulders. The term originated with farmers living in glaciated areas who were constantly removing rocks from their fields while breaking the soil for planting, a process known as tilling.</td>
</tr>
<tr>
<td><strong>titanium</strong></td>
<td>A metallic chemical element (Ti). Titanium is important because of its lightweight nature, strength and resistance to corrosion.</td>
</tr>
<tr>
<td><strong>topographic inversion</strong></td>
<td>A landscape with features that have reversed their elevation relative to other features, most often occurring when low areas become filled with lava or sediment that hardens into material that is more resistant to erosion than the material that surrounds it.</td>
</tr>
</tbody>
</table>
**Glossary**

<table>
<thead>
<tr>
<th>term</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>topography</strong></td>
<td>the landscape of an area, including the presence or absence of hills and the slopes between high and low areas. These changes in elevation over a particular area are generally the result of a combination of deposition, erosion, uplift and subsidence. These processes that can happen over an enormous range of timescales.</td>
</tr>
<tr>
<td><strong>topsoil</strong></td>
<td>the surface or upper layer of soil, as distinct from the subsoil, and usually containing organic matter.</td>
</tr>
<tr>
<td><strong>tornado</strong></td>
<td>a vertical funnel-shaped storm with a visible horizontal rotation. The word tornado has its roots in the Spanish word <em>tonar</em>, which means “to turn.”</td>
</tr>
<tr>
<td><strong>trace fossils</strong></td>
<td>fossils that record the actions of organisms, such as footprints, trails, trackways, and burrows. Trace fossils cannot always be associated at least with a group of organisms or way of life. The first trace fossils appear a couple hundred million years before the first animal (body) fossils.</td>
</tr>
<tr>
<td><strong>trackway</strong></td>
<td>a set of impressions in soft sediment, usually a set of footprints, left by an animal. Trackways preserved as fossils are known as trace fossils.</td>
</tr>
<tr>
<td><strong>transform boundary</strong></td>
<td>an active plate boundary in which the crustal plates move sideways past one another.</td>
</tr>
<tr>
<td><strong>transgression</strong></td>
<td>a relative rise in sea level in a particular area, through global sea level rise or subsidence of land.</td>
</tr>
<tr>
<td><strong>tree</strong></td>
<td>any woody perennial plant with a central trunk. Not all trees are closely related; different kinds of plants have evolved the tree form through geological time. The trees of the Paleozoic were more closely related to club mosses or ferns than they were to today’s trees.</td>
</tr>
<tr>
<td><strong>Triassic</strong></td>
<td>a geologic time period that spans from 252 to 201 million years ago. During this period, dinosaurs, pterosaurs, and the first mammals appear and begin to diversify. The Triassic begins directly after the Permian-Triassic mass extinction event, and is the first period of the Mesozoic.</td>
</tr>
<tr>
<td><strong>trilobite</strong></td>
<td>an extinct marine invertebrate animal belonging to the Class Trilobita of the Phylum Arthropoda, and characterized by a three-part body and a chitinous exoskeleton divided longitudinally into three lobes. Trilobites have been extinct since the end of the Paleozoic. Trilobites were primitive arthropods distantly related to horseshoe crabs. As bottom dwellers, they were present in a variety of environments. Like crabs and lobsters, trilobites molted their exoskeletons when they grew. Most fossils of trilobites are actually molts, broken as they were shed off the trilobite. Thus, it is common to find only parts of trilobites, such as the head, mid-section, or tail.</td>
</tr>
<tr>
<td><strong>tripoli</strong></td>
<td>a porous, usually brittle, siliceous sedimentary rock that is commonly used as filler for paints, plastics, and rubber, and can also be used as an abrasive or polish. Tripoli is also known as “rotten stone.”</td>
</tr>
<tr>
<td><strong>tropical depression</strong></td>
<td>An organized, rotating system of clouds and thunderstorms. A tropical storm has wind speeds of less than 63 kph (39 mph). It has no eye, and lacks the shape and organization of a more powerful hurricane.</td>
</tr>
<tr>
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<tr>
<td><strong>tuff</strong></td>
<td>A pyroclastic rock made of consolidated volcanic ash. Tuff is the result of pyroclastic flows, in which the violent expansion of hot gas shreds the erupting magma into tiny particles that cool in the air to form dense clouds of volcanic ash. The tremendous explosions that are necessary to create ash-flow tuffs are caused by rhyolitic magma, which is felsic. High silica content makes the magma quite viscous, preventing gas bubbles from easily escaping, thus leading to pressure build-ups that are released by explosive eruptions. The ash flows from these violent explosions tend to hug the ground, eventually solidifying into tuffs. Tuffs and other pyroclastic materials are vesicular (porous) due to gases expanding within the material as it cools.</td>
</tr>
<tr>
<td><strong>turbidity current</strong></td>
<td>A submarine sediment avalanche. These fast-moving currents of sediment are often caused by earthquakes or other geological disturbances that loosen sediment on a continental shelf. These massive sediment flows have extreme erosive potential, and often carve out underwater canyons. Turbidity currents deposit huge amounts of sediment during flow; such deposits are called turbidites. Because of the rate at which turbidity currents deposit dense sediments, they are often responsible for the effective preservation of many fossil organisms, which are swept up from shallow marine environments and buried in the deep sea.</td>
</tr>
<tr>
<td><strong>Ultisols</strong></td>
<td>A soil order; these are soils with subsurface clay accumulations that possess low native fertility and are often red hued (due to the presence of iron oxides). They are found in humid tropical and subtropical climates.</td>
</tr>
<tr>
<td><strong>uplift</strong></td>
<td>Upward movement of the crust due to compression, subduction, or mountain building. Uplift can also occur as a rebounding effect after the removal of an ice sheet reduces the amount of weight pressing on the crust.</td>
</tr>
<tr>
<td><strong>Vertisols</strong></td>
<td>A soil order; these are clayey soils with a high moisture capacity. During dry periods, these soils shrink and develop wide cracks; during wet periods, they swell with moisture.</td>
</tr>
<tr>
<td><strong>vesicular</strong></td>
<td>Porous or pitted with vesicles (cavities). Some extrusive igneous rocks have a vesicular texture.</td>
</tr>
<tr>
<td><strong>volcanic ash</strong></td>
<td>Fine, unconsolidated pyroclastic grains under 2 millimeters (0.08 inches) in diameter. Consolidated ash becomes tuff.</td>
</tr>
<tr>
<td><strong>volcanic islands</strong></td>
<td>A string of islands created when molten rock rises upwards through oceanic crust. Volcanic islands are common in several contexts, including at subduction zones between colliding oceanic plates, above oceanic hot spots, and along mid-ocean ridges. At subduction zones, the friction between the plates generates enough heat and pressure to melt some of the crust. In the case of hot spots, islands form as magma from the mantle breaks through the sea floor.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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</tr>
<tr>
<td>volcanic, volcanism</td>
<td>the eruption of molten rock onto the surface of the crust. Most volcanic eruptions occur along tectonic plate boundaries, but may also occur at hot spots. Rocks that form from molten rock on the surface are also called volcanic.</td>
</tr>
<tr>
<td>Prior to eruption, magma</td>
<td>ascends from the mantle to a relatively shallow (1–10 kilometers / 0.5–6 miles) magma chamber. Upward movement reduces the pressure on the magma until it is low enough to permit dissolved gas to exsolve (come out of solution and form bubbles). All eruptions are driven by the exsolution of dissolved gas. As the gas forms bubbles, it expands in volume and forces the magma out of the vent/chamber system onto the surface. The combination of magma viscosity and gas content can produce a range of eruptive styles, from gentle, effusive eruptions to violent explosions.</td>
</tr>
<tr>
<td>water table</td>
<td>the upper surface of groundwater, that is, the underground level at which groundwater is accessible.</td>
</tr>
<tr>
<td>watershed</td>
<td>an area of land from which all water under or on it drains to the same location.</td>
</tr>
<tr>
<td>watt</td>
<td>a unit of power measuring the rate of energy conversion or transfer designated by the International System of Units as one joule per second.</td>
</tr>
<tr>
<td>weather</td>
<td>the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity. These conditions vary with the time of day, the season, and yearly or multi-year cycles.</td>
</tr>
<tr>
<td>weathering</td>
<td>the breakdown of rocks by physical or chemical means. Rocks are constantly being worn down and broken apart into finer and finer grains by wind, rivers, wave action, freezing and thawing, and chemical breakdown.</td>
</tr>
<tr>
<td>Over millions of years, weathering and erosion can reduce a mighty mountain range to low rolling hills. Some rocks wear down relatively quickly, while others can withstand the power of erosion for much longer. Softer, weaker rocks such as shale and poorly cemented sandstone and limestone are much more easily worn away than hard, crystalline igneous and metamorphic rocks, or well-cemented sandstone and limestone. Harder rocks are often left standing alone as ridges because surrounding softer, less resistant rocks were more quickly worn away.</td>
<td></td>
</tr>
<tr>
<td>wind</td>
<td>the movement of air from areas of high pressure to areas of low pressure. The greater the temperature difference, the greater the air pressure difference and, consequently, the greater the speed at which the air will move.</td>
</tr>
<tr>
<td>wind shear</td>
<td>when wind speed and/or direction changes with increasing height in the atmosphere. Wind shear can happen when a cold front moves rapidly into an area with very warm air. There, the condensing water droplets mix with the cooler, drier air in the upper atmosphere to cause a downdraft.</td>
</tr>
<tr>
<td>windward</td>
<td>upwind; facing into the prevailing winds, and thus subject to orographic precipitation.</td>
</tr>
<tr>
<td>Wisconsinian glaciation</td>
<td>the most recent interval of glaciation, which occurred during the Pleistocene, 85,000 to 11,000 years ago.</td>
</tr>
</tbody>
</table>
### Zeolites

Porous aluminosilicate minerals, often formed some time after sedimentary layers have been deposited, or where volcanic rocks and ash react with alkaline groundwater. Zeolites are often used as catalysts and water softeners, and their microporous surface structure makes them useful in concentrating and condensing molecular substances.

### Zinc

A metallic chemical element (Zn). Zinc is typically used in metal alloys and galvanized steel.
General Resources

On the Earth System Science of North America

Books

Maps (printed)

Maps (online)

Geologic Time Resources
Janke, P. R. 2013. Correlated History of the Earth Chart (laminated), vol. 8, Pan Terra, Hill City, SD.
The Paleontology Portal, paleoportal.org.

Dictionaries

Earth System Science Organizations
General Earth Science Education Resources

Websites
- Science in Your Backyard, US Geological Survey. (State-by-state compilation of Earth science-related data, most of which will need to be adapted for education uses.) http://www.usgs.gov/state/.
- SERC (The Science Education Resource Center) K-12 Resources. (Hundreds of classroom activities organized by grade level and topic as well as guidance on effective teaching.) http://serc.carleton.edu/k12/index.html.
- SERC Earth Exploration Toolbook. (Collection of online Earth system science activities introducing scientific data sets and analysis tools.) http://serc.carleton.edu/eet/index.html.

Science Education Organizations
- National Association of Geoscience Teachers. (Focused on undergraduate geoscience education, but includes active secondary school educators.) http://nagt.org.
**Resources by State**


**Arkansas**

**Books, articles, and maps**


**Websites**


**Kansas**

**Books and articles**


**Websites**

*Geology [of Kansas]*, Kansas Geological Survey. [http://www.kgs.ku.edu/General/geologyIndex.html](http://www.kgs.ku.edu/General/geologyIndex.html).

**Louisiana**

**Books and articles**


**Missouri**

**Books and articles**


Oklahoma

Books and articles

Websites
Oklahoma Geological Survey. (A wide variety of resources on, e.g., energy, geology, earthquakes, and mapping.) http://www ogs ou edu/homepage php.

Texas

Books and articles

Websites
Geology of Texas, Texas Almanac—The Source for All Things Texan Since 1857. http://www texasalmanac com/topics/environment/geology-texas 0.
Acknowledgments

We are grateful to the following reviewers, each of whom reviewed one or more chapters of the The Teacher-Friendly GuideTM to the Earth Science of the South Central US: Warren Allmon, Jayne Aubele, Don Duggan-Haas, Allen Macfarlane, Judith Parrish, Art Waterman, Thomas Yancey, and Ingrid Zabel. Thanks to Jessica Cundiff, Philip Perkins, Catherine Weisel, Robert Elias, and David Meyer for help with Chapter 3: Fossils.

Richard Kissel managed early content development of the Guide, and was aided in content research by Sara Auer Perry. The glossary was developed by Paula Mikkelsen and Andrielle Swaby.

Funding for this Guide came from National Science Foundation DR K-12 grant DRL-0733303 to the Paleontological Research Institution. Funding to start The Teacher-Friendly GuideTM series was provided by the Arthur Vining Davis Foundations. Jane (Ansley) Picconi did page layout for the first Guide in the series, The Teacher-Friendly GuideTM to the Geology of the Northeastern US (Paleontological Research Institution special publication 24, 2000), many features of which have been adopted for this Guide.
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Appendix

A.1–A.3: Next Generation Science Standards