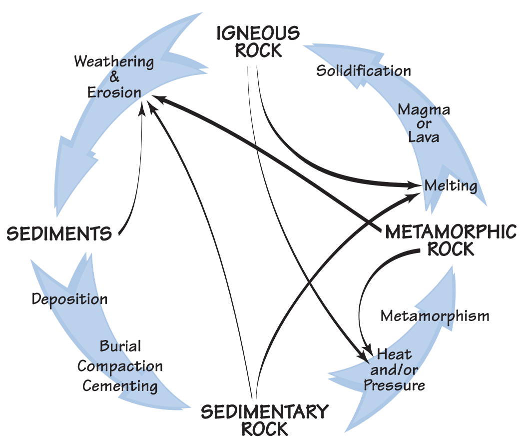
Chapter 2: Rocks of the Southwestern US

The amazingly diverse rocks in the Southwest span a wide range of ages and types, and they are also well exposed and accessible to the public. For geologists, rockhounds, and people who simply enjoy the outdoors, the Southwestern US is a wonderland filled with an interesting and beautiful array of rocks. Colliding **plates**, rifting, **inland seas**, deposition, **erosion**, igneous and metamorphic activity, and recent **glacial** processes are all part of this story. The Southwest'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 Southwest

rhyolite	granite	basalt
trachyte	tuff	pumice
minette	andesite	breccia
dacite	pyroclastic rocks	

Sediments of the Southwest (not consolidated into rocks)
- gravel
- sand
- silt
- clay



Metamorphic Rocks of the Southwest
- gneiss
- marble
- quartzite
- schist
- slate

Sedimentary Rocks of the Southwest

arkose	limestone
conglomerate	mudstone
dolomite	sandstone
gypsum	shale
halite (rock salt)	siltstone

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

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

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

erosion • *the transport of weathered materials.*

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

topography • *the landscape of an area, including the presence or absence of hills and the slopes between high and low areas.*

fossil • *preserved evidence of ancient life.*

CHAPTER AUTHORS

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2 Rocks

Review

mineral *• a naturally occurring solid with a specific chemical composition and crystalline structure.*

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

plate tectonics *• the process by which the plates of the Earth's crust move and interact with one another at their boundaries.*

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

lithification *• the process of creating sedimentary rock through the compaction or sementation of soft sediment.*

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

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

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 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.

Sediment size (decreasing size)	Sedimentary rock	Environment of deposition
gravel	conglomerate	river beds, mountains
sand	sandstone	beaches, river sand bars, sand dunes
sand, silt, clay	graywacke	continental shelf
silt	siltstone	quiet water
clay	shale	very quiet water, lakes, swamps, shallow oceans

Mineral Content	Sedimentary Rock	Environment of Deposition
calcium carbonate skeletons of marine organisms	limestone	tropical reefs, beaches, warm shallow seas
precipitated calcium carbonate	travertine, tufa	hot spings, playas (dry lake beds), drying seas
gypsum	rock gypsum	playas, dryng seas
halite	rock salt	playas, drying seas

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 from 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.

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 rock that would have revealed its previous history, transforming it into an entirely

Igneous Rock Classification

Igneous rocks differ not only in 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, such as basalt, are low in silica and high in iron and magnesium. They are dark in color and are called *mafic*.

Crystal size	Felsic	Intermediate	Mafic	Ultramafic
large (plutonic)	granite	diorite	gabbro	peridotite
small (volcanic)	rhyolite	andesite	basalt	--
none (glassy)	obsidian, tuff, pumice	obsidian	obsidian	--

Review

cementation *• the precipitation of minerals that binds together particles of rock, bones, etc., to form a solid mass of sedimentary rock.*

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

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

conglomerate *• a sedimentary rock composed of multiple large and rounded fragments that have been cemented together in a fine-grained matrix.*

calcium carbonate *• a chemical compound with the formula $CaCO_3$, commonly found in rocks in the mineral forms calcite and aragonite, as well as the shells and skeletons of marine organisms.*

limestone *• a sedimentary rock composed of calcium carbonate ($CaCO_3$).*

dolostone *• a rock primarily composed of dolomite, a carbonate mineral.*

Review

compression *• flattening or squeezing as a result of forces acting on an object from all or most directions.*

protolith *• the original parent rock from which a metamorphosed rock is formed.*

crust *• the uppermost, rigid outer layer of the Earth.*

intrusive rock *• a plutonic igneous rock formed when magma from within the Earth's crust escapes into overlying strata.*

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 come from very deep burial or from contact with magma.

Metamorphic Rock Classification

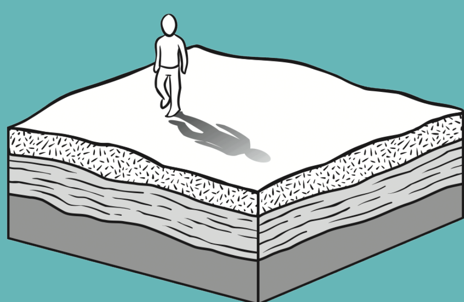
Metamorphic rocks are classified differently depending on the *protolith* (parent rock) they are made from. The following chart shows common rocks and the metamorphic rocks that they can become.

Parent rock	Metamorphic rocks
shale	slate, phyllite, schist, gneiss (in order of increasing heat and pressure)
granite	gneiss
sandstone	quartzite
limestone	marble
peridotite	serpentinite

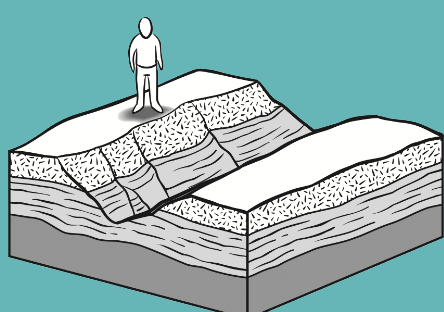
As you read through this chapter, keep in mind that once you understand the geologic events that have affected a given region, you should be able to predict the type of rocks found in that area. For example, when plates collide, compression and friction melt the **crust**. The rising magma forms igneous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

Why do we see different kinds of rocks at the surface?

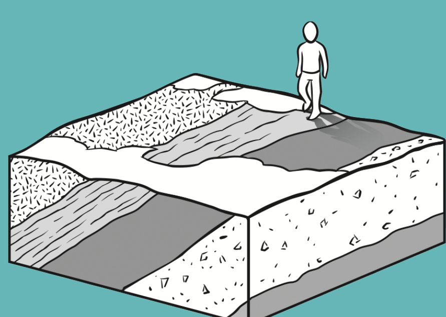
As you walk across the surface of the Earth, you will observe an amazing variety of rock types. If all rocks were flat-lying layers and there was no erosion, then we would only see one type of rock exposed on the surface. Often, however, rocks have been worn away (eroded), and the underlying layers are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

2 Rocks

Region 1

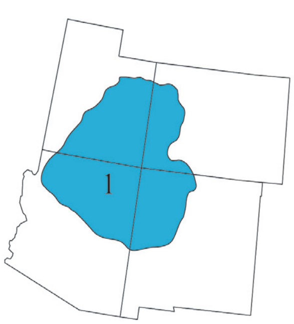
Cenozoic *• the geologic time period spanning from 66 million years ago to the present.*

epeirogenic *• large-scale crustal uplift caused by hot or upwelling mantle underlying the surface.*

uplift *• upward movement of the crust due to compression, subduction, or mountain building.*

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

basement rocks *• the foundation that underlies the surface geology of an area, generally composed of igneous or metamorphic crystalline rock.*



Rocks of the Colorado Plateau
Region 1

The Colorado Plateau is an arid region that developed as a stable crustal block. It was not significantly affected by either the compressional forces that gave rise to the Rockies or by the **Cenozoic** extensional forces that produced the Basin and Range. Between eight and five million years ago, an **epeirogenic** (vertical) **uplift** raised the entire region as a single block to its present elevation of 610–4000 meters (2000–13,000 feet). Despite its name, the Colorado Plateau is not a flat area, but rather a landscape of contrasting features and colors, including dramatic sheer-walled canyons, wind- and water-sculpted formations, towering monoliths, and flat-topped mesas. The region embodies the quintessential Old West, and includes many of the landscape features so often seen in the backdrop of films and books. Interesting rocks and breathtaking vistas can be found almost anywhere on the plateau, which has the highest density of national parks and monuments in the country (*Figure 2.2*). The Colorado Plateau was also home to the ancient Native American culture known as the Anasazi, or Ancestral Puebloan people.

Epeirogenic uplift refers to large-scale crustal uplift caused by hot or upwelling mantle underlying the whole region, which buoys up the overlying crust but does not significantly fold or fault the rocks.

See Chapter 4: Topography for more about the spectacular erosive landscape of the Colorado Plateau.

The Colorado Plateau is underlain by **Precambrian basement rock**, which is exposed in the deep gorge of Arizona's Grand Canyon as well as at the edge of Colorado's San Juan Mountains. The **schists** and **gneisses** found in the Needle Mountains (a subrange of the San Juan Mountains), and at the base of the Grand Canyon, are 1.9 to 1.7 billion years old and comprise metamorphosed volcanic and marine sedimentary rocks. These rocks are the product of plate tectonic activity from the collision and **accretion** of a **volcanic island** arc, the Yavapai **terrane**, with what was then a much smaller North American continent. Igneous rock bodies, such as the Zoroaster Granite,

Terranes are fragments of crustal material that have been broken off from one plate and accreted to a different piece of crust through tectonic forces. Each fragment in a large grouping of accreted terranes shows a distinct geologic history.

See Chapter 1: Geologic History to learn more about the ancient terranes that formed the basement of the Southwest.

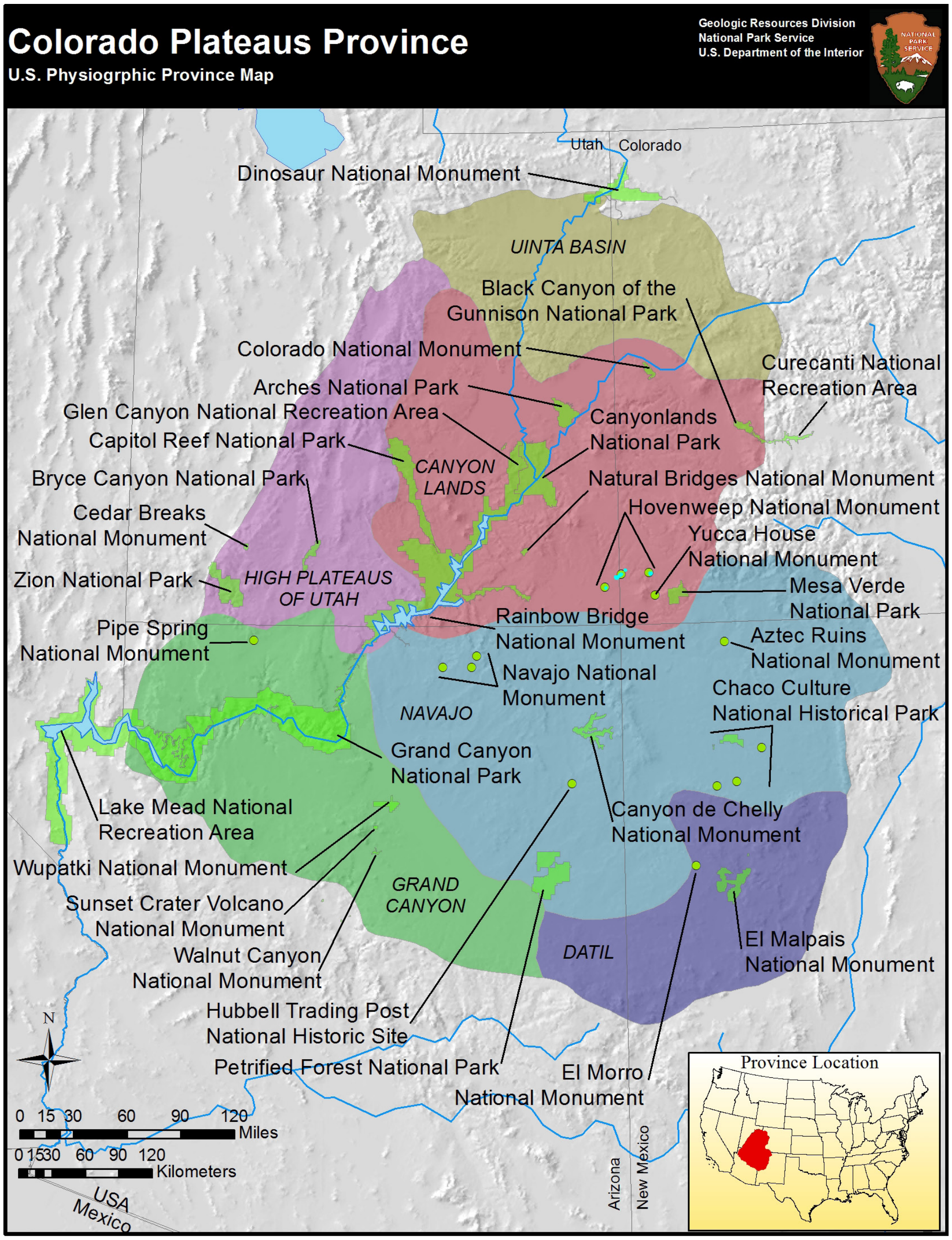


Figure 2.2: Locations of some national parks and monuments in the Colorado Plateau. The region hosts 10 national parks, 27 national monuments, 19 national forests, and 57 state parks. (See TFG website for full-color version.)

were intruded into the plate at approximately the same time. These ancient rocks are overlain by a thick sequence of mildly metamorphosed sedimentary layers known as the **Grand Canyon Supergroup** (*Figure 2.3*), a series of sandstones, shales, and limestones that constitutes one of the most complete middle-to-late **Proterozoic** geologic records in North America. These rocks were generated approximately 1.2 to 1.1 billion years ago during the formation of the supercontinent **Rodinia**, when they were compressed from sedimentary layers originally deposited in **fluvial** and shallow marine environments. Basalt

Region 1

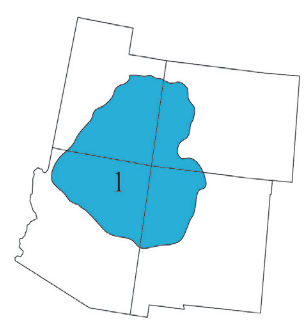
schist *• a medium grade metamorphic rock with sheet-like crystals flattened in one plane.*

gneiss *• a metamorphic rock that may form from granite or layered sedimentary rock such as sandstone or siltstone.*

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.*

volcanic island *• one of a string of islands created when molten rock rises upward through oceanic crust.*

terrane *• a piece of crustal material that has broken off from its parent continent and become attached to another plate.*



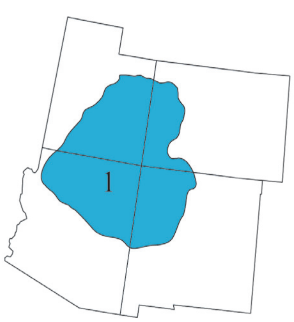
dike • *a sheet of intrusive igneous or sedimentary rock that fills a crack cutting across a pre-existing rock body.*

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

magnetic • *affected by or capable of producing a magnetic field.*

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

seismic waves • *the shock waves or vibrations radiating in all directions from the center of an earthquake or other tectonic event.*



sills and **dikes** were intruded throughout the Grand Canyon Supergroup as a result of volcanic activity during the late Proterozoic (*Figure 2.4*). Overall, these layers record a long history—perhaps 200 million years—between the Precambrian formation of continental crust by terrane accretion and the more familiar events of the **Cambrian** period and later.

In the Basement

The Precambrian rocks underlying younger surface rocks in any locality are referred to as the "basement." The basement might be fairly shallow beneath thin layers of young sedimentary rocks or even occasionally exposed at the surface, but it often lies thousands of meters (feet) deep beneath thick sequences of overlying sediment. Basement rocks can be identified in several ways, using both direct and indirect methods.

To investigate the underlying geology directly, holes may be drilled down to the top of the basement. Rock samples are then brought to the surface from the bottom of the hole and analyzed. This procedure is common in government geological surveys or in oil and gas exploration.

Indirectly, sensitive readings of *magnetism* and gravity can be measured from planes and satellites. These give very broad estimates of the characteristics of rocks beneath the surface. Recording of sound waves traveling through, and bouncing off of, layers of subsurface rock can give us an indirect measurement of their properties. This "seismic data" comes both from *earthquakes* (seismology) and from surveys performed by artificially creating *seismic waves* (through pounding the Earth or by creating small explosions) at the surface.

Overlying the uppermost layers of the Grand Canyon Supergroup is one of the most conspicuous features of the rocks in the Grand Canyon, an irregular level called "the Great Unconformity" (*Figure 2.5*). This feature preserves a gap in the geological record where stratified layers have been interrupted or destroyed due to erosion or deformation. The **unconformity** separates rocks of Precambrian age from those of the **Paleozoic** era, and is part of a continent-wide feature that extends across the ancient core of North America. The length of time represented by the Great Unconformity varies along its length—in some

Region 1

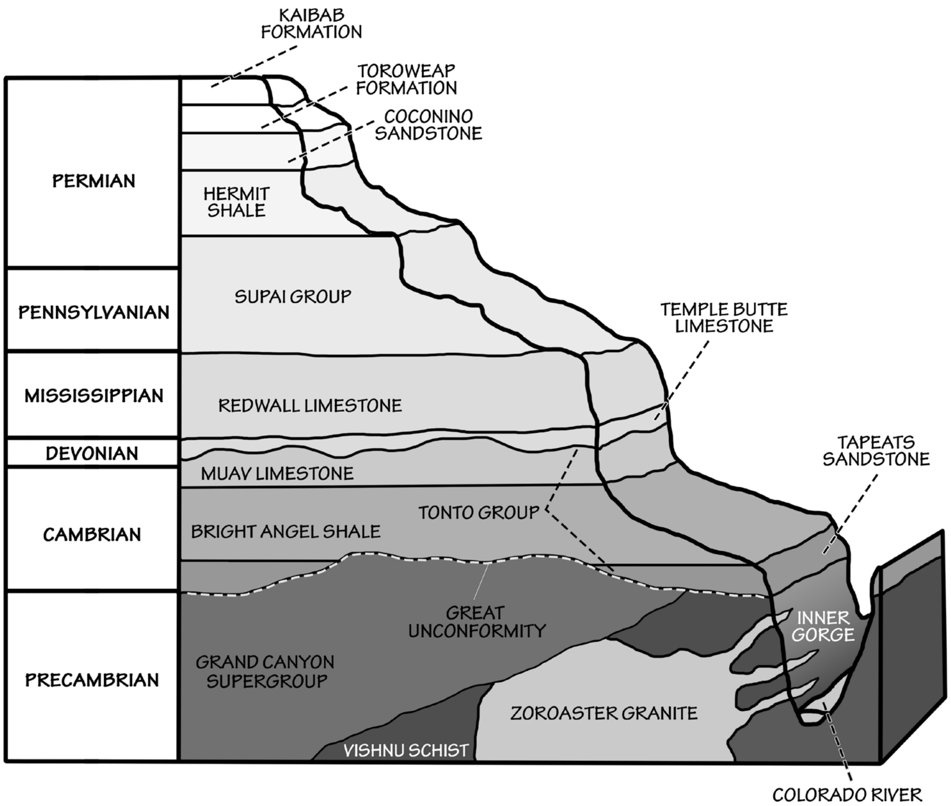
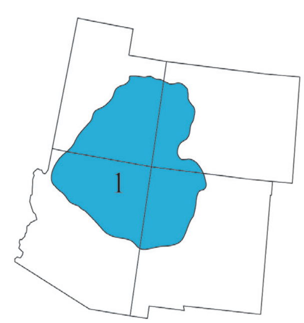


Figure 2.3: Major Paleozoic stratigraphic units of the Grand Canyon and Colorado Plateau.

Figure 2.4: A basalt dike intruded into the orange-red Hakatai Shale, part of the Grand Canyon Supergroup. This exposure is found at Hance Rapid on the Colorado River, Grand Canyon.

unconformity • *the relation between adjacent rock strata for which the time of deposition was separated by a period of nondeposition or erosion.*

Paleozoic • *a geologic time interval that extends from 541 to 252 million years ago.*



stratigraphy *• the branch of geology specifically concerned with the arrangement and age of rock units.*

craton *• the old, underlying portion of a continent that is geologically stable relative to surrounding areas.*

parts of the Grand Canyon, a period of 175 million years is "missing" between the Cambrian Tonto Group sandstones and the Grand Canyon Supergroup. In other places, there is a gap of over 1.2 billion years where the 550-million-year-old Tapeats Sandstone rests on 1.7-billion-year-old basement rock.

The Great Unconformity is one of the most widely recognized and distinctive **stratigraphic** surfaces in the entire rock record. Geologists are still unsure of its exact origin, but it may have been caused by a major episode of continental uplift following the formation of the North American **craton**. This uplift would have exposed the continent—then completely barren of life—to extensive erosion, degrading the rocks for hundreds of millions of years before they were submerged by a shallow sea in the Cambrian.

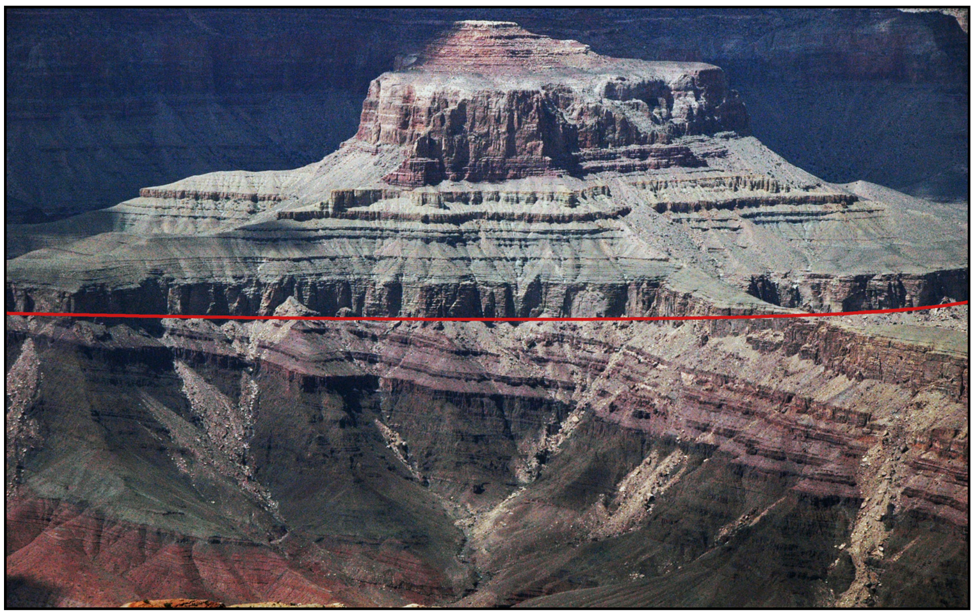
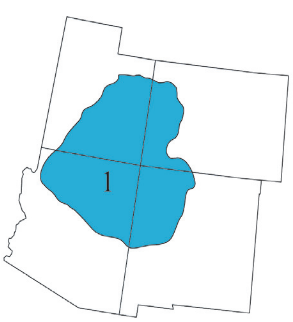


Figure 2.5: The Great Unconformity (marked by the line) in the Grand Canyon, Arizona, where the horizontal Tonto Group (Cambrian) overlies the tilted Grand Canyon Supergroup (Proterozoic). (See TFG website for full-color version.)

The Great Unconformity is one of the most prominent sections of "missing time" in North America, but there are other examples of unconformities throughout the US. The absence of rocks deposited during certain time periods does not mean that no rocks were formed during that time. It may mean, however, that very little sediment was deposited, that the sediment was eroded away, or that the rocks are buried beneath the surface. There is no single place on Earth with a complete sequence of rocks from the Precambrian to the Quaternary. Erosion and weathering over time have removed many meters (feet)—and in some cases kilometers (miles)— of rock from the surface of the Southwest.



The Colorado Plateau is perhaps the best place to examine a nearly continuous sequence of representative Southwestern sedimentary layers (*see Figure 2.3*). From near the bottom of the Grand Canyon, up through younger layers observed farther east, these rocks tell the story of the entire Paleozoic. Cambrian strata of the Tonto Group comprise a sequence of tan, gray, and brown sandstone, mudstone, and limestone that represent an approaching shoreline (Tapeats Sandstone) and offshore mud layers (Bright Angel Shale, Muav Limestone). Late **Devonian** layers of gray and tan limestone are referred to as the Temple Butte Formation, and they were laid down in an environment similar to that of the modern Yucatan. Sea level rose from the **Ordovician** through **Mississippian** periods, and Mississippian rocks are widespread across much of Arizona and New Mexico, where they typically form prominent cliffs that dominate the landscape. **Orogenic** activity to the northwest (in what is now western Nevada) had little effect on Arizona's clear, warm, shallow marine **carbonate** shelf. Here, the Mississippian Redwall Limestone is one of the most conspicuous rock layers, forming towering vertical cliffs in the Grand Canyon (*Figure 2.6*). Although its name implies that the limestone is red, it is actually gray. The visible portions of the Redwall Limestone have been stained red from the erosion of **iron**-rich sediments in the overlying Supai Group and Hermit Formation, which have washed down across the limestone over time and been absorbed into its surface.

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*. The sedimentary rocks of the Grand Canyon are nearly flat lying, and are a textbook example of superposition.

Figure 2.6: The 340-million-year-old Redwall Limestone forms distinct red cliffs up to 240 meters (800 feet) thick. It is a very hard stone, which often causes it to break at harsh angles, creating pillars.

Region 1

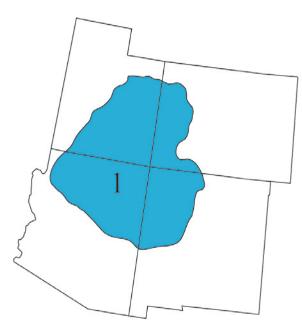
Devonian *• a geologic time period spanning from 419 to 359 million years ago.*

Ordovician *• a geologic time period spanning from 485 to 443 million years ago.*

Mississippian *• a subperiod of the Carboniferous, spanning from 359 to 323 million years ago.*

orogeny *• a mountain-building event generally caused by colliding plates and compression of the edge of the continents.*

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



Region 1

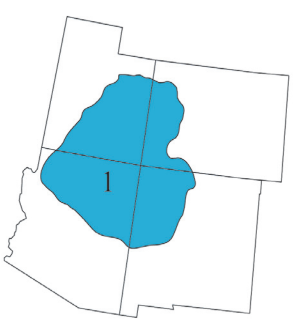
Pennsylvanian *• a subperiod of the Carboniferous, spanning from 323 to 299 million years ago.*

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

karst topography *• a kind of landscape defined by bedrock that has been weathered by dissolution in water, forming features like sinkholes, caves, and cliffs.*

estuary *• a place where freshwater and saltwater mix, created when sea level rises to flood a river valley.*

transgression *• a relative rise in sea level in a particular area, through global sea level rise or subsidence of land.*



The **Pennsylvanian** and **Permian** periods—the last 70 million years of the Paleozoic era—were marked by uplift and falling sea level across the Southwest, both of which led to the expansion of terrestrial environments. The Redwall Limestone was exposed to subaerial erosion, forming **karst topography**. Streams carved valleys into the limestone, and **estuarine** deposits flooded the valleys as fills during subsequent **transgressions**. Uplifted areas shed large volumes of sediment, forming thick deposits in adjacent basins. The heavy influx of **sand** and mud resulted in preservation of these and other continental sediments as red beds (such as the Hermit Shale), **colored** by the **oxidation** of iron minerals. At this time, the region was near the equator, and an arid **climate** led to the widespread formation of sand dunes. Today, extensive coastal, wind-blown (**aeolian**) sand dune fields are preserved as thick beds of sandstone, with large-scale **cross-bedding**. The late Pennsylvanian Manakacha Formation, in the lower Supai Group, documents the earliest influx of aeolian sand onto what later became the Colorado Plateau. Permian dune sands include the Cedar Mesa Sandstone exposed in Natural Bridges National Monument (*Figure 2.7*) the Needles district of Canyonlands National Park, and the bright pale-yellow Coconino Sandstone visible in Arizona and Utah (*Figure 2.8*).

Along the coasts of shrinking inland seas, salt flats grew along arid coastlines. These newly formed **sabhka** environments became sites of abundant deposition for **evaporite** minerals, including salt, **gypsum**, and anhydrite. Thick sequences of alternating evaporites and shales accumulated in basins across the region, as shallow marine water evaporated and deposited layers of salt. The Paradox Basin in southeastern Utah is best known for its salt deposits; it also contains **oil** reserves and **copper**.

See Chapter 5: Mineral Resources for more information about the plentiful resources found in the Paradox Basin.

Figure 2.7: Sipapu Natural Bridge, formed from Cedar Mesa Sandstone in Natural Bridges National Monument, Utah. Note the cross-bedding at lower right.

Figure 2.8: Cross-beds in the Coconino Sandstone at Sedona, Arizona.

By the end of the Permian period, the supercontinent **Pangaea** had formed, and the Southwest was largely a terrestrial environment. The **Mesozoic** era generated a succession of near-shore and continental deposits, mostly sandstones and shales, which form the spectacular cliffs and mesas seen throughout much of the Colorado Plateau. Similarly to the way the entire Paleozoic is exposed at the Grand Canyon, the Mesozoic and part of the Cenozoic are beautifully exposed in the Grand Staircase. This immense sedimentary sequence stretches south from Bryce Canyon National Park in Utah to the edge of the Grand Canyon (*Figure 2.9*).

Many Mesozoic sandstones, especially those from the **Triassic**, have a reddish color caused by the oxidation of iron within the rock (*Figure 2.10*). For example, the Triassic Moenkopi Formation consists of reddish-brown, fine-grained sandstone and mudstone. It represents both shallow marine and near-shore terrestrial environments. Terrestrial features of the Moenkopi, such as **ripple marks**, mud cracks, and scour marks, point to an arid environment prone to flash floods. Stream channels, flood plains, fresh or brackish ponds, **playas**, and shallow marine environments can also create similar traces.

Above the Moenkopi, the Chinle Formation consists of diverse sandstones, mudstones, and conglomerates deposited in a somewhat wetter environment—low-**relief** rivers and lakes. The Chinle is famous for its colors, ranging from various shades of reds, blues, and pinks to grays, tans, and browns (*Figure 2.11*). It is also famous for its fossils, which include abundant **trees** (e.g., Petrified Forest National Park) and **dinosaurs**.

See Chapter 3: Fossils to learn more about dinosaurs and tetrapods of the Chinle Formation.

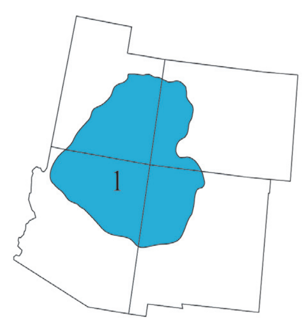
Region 1

sand • *granular sediment most commonly composed of weathered grains of quartz and feldspar, of grain diameter 1/16 to 2 millimeters.*

color (mineral) • *a physical property determined by the presence and intensity of certain elements within the mineral.*

oxidation • *a chemical reaction involving the loss of at least one electron when two substances interact.*

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).*



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

braided stream *• a stream consisting of multiple, small, shallow channels that divide and recombine numerous times, forming a pattern resembling strands of braided hair.*

erg *• an area of desert, greater than 125 square kilometers (48 square miles), covered by wind-blown sand.*

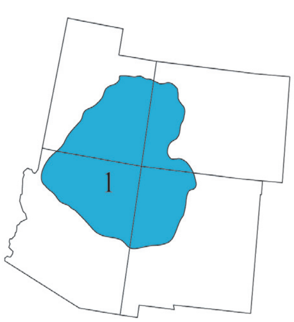
Colors of Sedimentary Rocks
What do they tell us about the environment?

The color of a rock can be an important indicator of the environment in which it formed. The red-brown color so common throughout the Southwest results from oxidized (rusted) iron within the rock. This is most common in sediments deposited in a seasonally hot and dry climate on land, where the iron could be exposed to the air. Red sedimentary rock is also found in the Southwest's Permian rocks, reflecting a time when ocean floor sediments were exposed above water. Red clays may also form in well-oxygenated, deep marine conditions. In some marine environments, however, where iron is reduced rather than oxidized, rocks may take on a greenish hue. Likewise, some greenish sedimentary rocks may indicate the presence of the mineral glauconite, which is found only in marine environments.

In contrast, many shales are gray or black in color, reflecting the abundance of carbon-rich organic material that can accumulate in quiet-water settings. The darker the shale, the more organic material that is preserved within. Shales are most commonly formed in quiet waters where tiny particles have time to settle out onto the sea or lake floor.

Pangaea began to break up during the early **Jurassic**. At this time, vast sand dune fields covered much of the Southwestern US, forming thick cross-bedded layers of sandstone. The early Jurassic sediments of the Colorado Plateau represent some of the world's best geological records from this time interval. These sediments are collectively called the Glen Canyon Group, which includes (from older to younger) the Wingate/Moenave, Kayenta, and Navajo formations. The Moenave and Navajo represent aeolian sediments, while the Kayenta, sandwiched in between them, consists of siltstones and sandstones that were deposited in **braided** and meandering streams.

The Jurassic dune-forming environment (called a "sand sea" or **erg**) is best seen in the Navajo Sandstone, which is exposed widely across northern Arizona and southern Utah (*Figure 2.12*). The Navajo, together with the Nugget and Aztec sandstones to the north and southwest, represents one of the largest ancient sand dune deposits on Earth, covering more than 150,000 square kilometers (58,000 square miles)—an area approximately the size of Illinois (*Figure 2.13*).



Rocks 2

Region 1

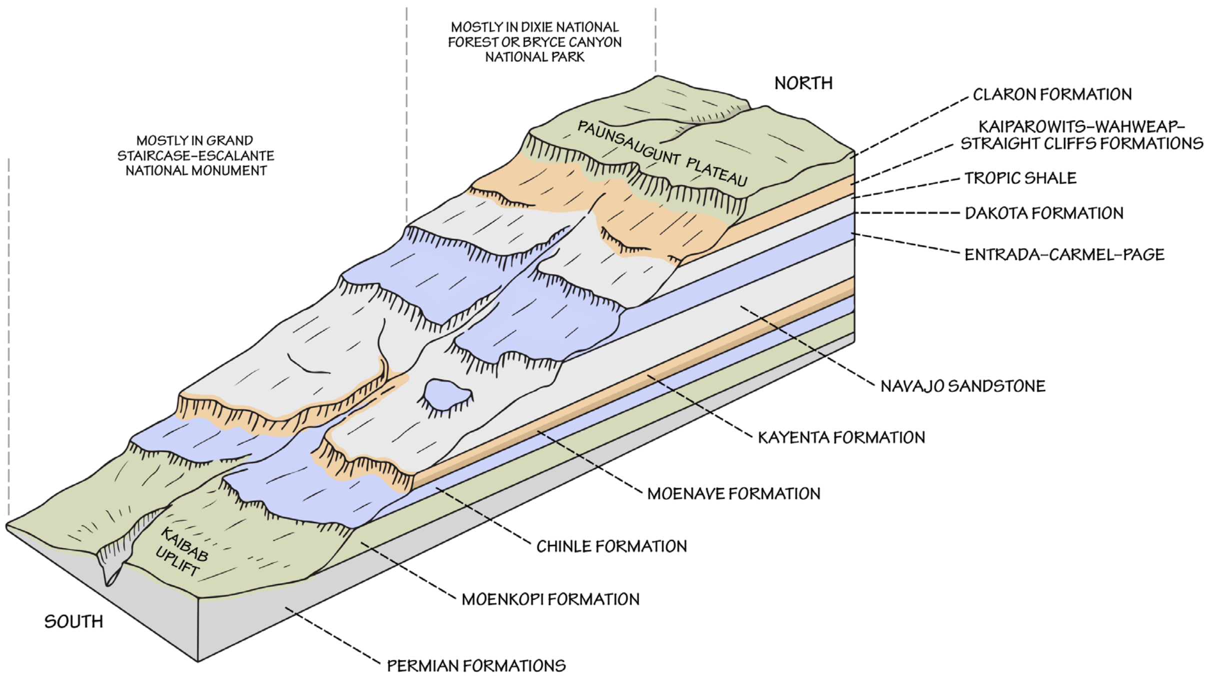
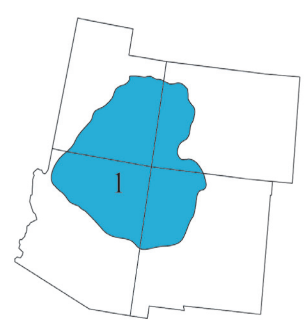


Figure 2.9: Major Mesozoic and Cenozoic stratigraphic units of the Grand Staircase and Colorado Plateau. (See TFG website for full-color version.)

Figure 2.10: Triassic sediments at The Castle, Capitol Reef National Park, Utah. Three strata are visible here: the Wingate Sandstone (top), the Chinle Formation (middle), and the Moenkopi Formation (bottom).

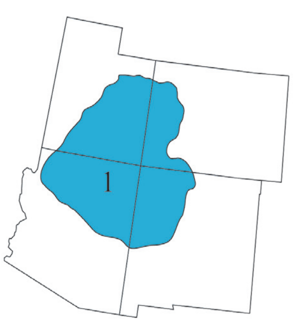


2 Rocks

Region 1

Figure 2.11: The Painted Desert in northern Arizona showcases the Chinle Formation's spectacular colors.

Figure 2.12: The Wave, a series of intersecting U-shaped troughs eroded into Jurassic Navajo Sandstone within the Paria Canyon-Vermilion Cliffs Wilderness, Arizona. The cycling layers in the sandstone represent changes in the direction of prevailing winds as large sand dunes migrated across the desert.



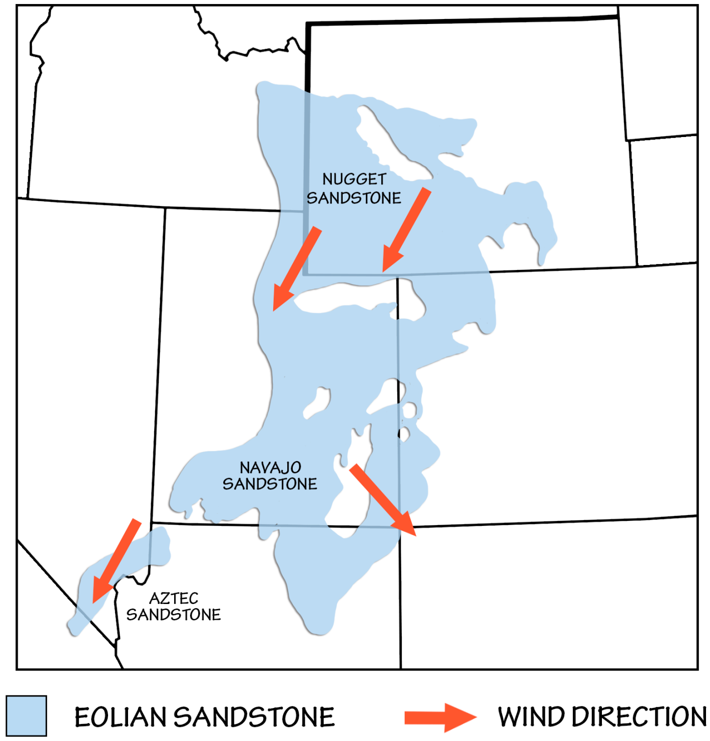
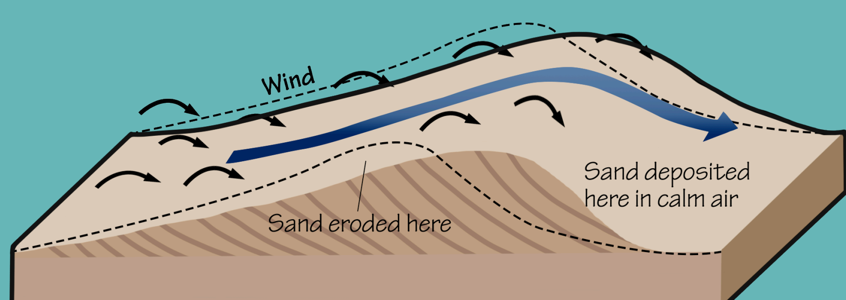
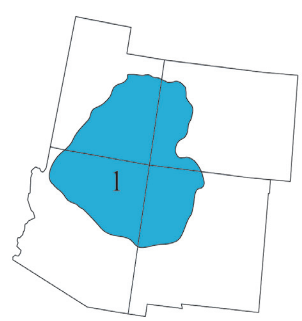


Figure 2.13: Extent of the Navajo, Nugget, and Aztec sandstones, with arrows showing the direction of wind in the dune-forming environment.

Cross-bedded Sand Dunes

Cross-bedded sand dunes form as air movement pushes sediment downwind, 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.





2 Rocks

Region 1

floodplain *• the land around a river that is prone to flooding.*

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

downwarp *• a segment of the Earth's crust that is broadly bent downward.*

lithosphere *• the outermost layer of the Earth, comprising a rigid crust and upper mantle broken up into many plates.*

Laramide Orogeny *• a period of mountain building that began in the Late Cretaceous, and is responsible for the formation of the Rocky Mountains.*

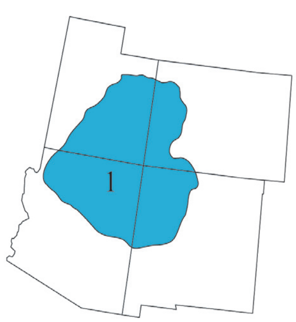
By the late Jurassic, the Colorado Plateau contained a complex environment of coastlines, rivers, lakes, marshes, ponds, **floodplains**, and dunes. The Morrison Formation, a series of variegated mudstones and shales, was deposited in mixed mud flats, river channels, and lakes. Dinosaur bones and trackways are often found in the Morrison's relict stream channels. During the **Cretaceous** period, the interior of North America was **downwarped** by tectonic processes associated with the **subduction** of oceanic **lithosphere** along the western edge of the continent. As the **Laramide** and **Sevier orogenies** occurred to the west, the North American interior was flooded by a particularly vast inland sea called the Western Interior Seaway (*Figure 2.14*). The Dakota Sandstone, formed from beach sand, signals the onset of this sea. Ripple marks created by currents or waves are common in these sediments, indicating wave action at or near a beach (*Figure 2.15*). In Colorado, at Morrison and along the Purgatoire River, spectacular dinosaur **trackways** are preserved in these sandstones.

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.

As the water deepened, thick sequences of shale (the Mancos Shale) were deposited. When the sea again retreated at the end of the Cretaceous, more sandstones (the Mesaverde Formation) were laid down. During the 12th and 13th centuries, the Ancestral Puebloan peoples of Colorado carved massive, elaborate dwellings and other structures into these sandstones (*Figure 2.16*).

Throughout the Cenozoic era, mountains that had formed during the Sevier and Laramide orogenies experienced significant erosion. Cobbles, sand, and mud were carried by streams and deposited into rivers and lakes, forming conglomerate, sandstone, mudstone, and shale. Large basins— areas of the crust that slowly **subside**, or sink—on the Colorado Plateau received thick layers of sediment that became sources and reservoirs for oil and gas. Swamps and lowlands on basin margins formed widespread **coal** beds. During the **Eocene** period, sediment accumulated in floodplains, shallow lakes, rivers, and **soils** to form the Claron Formation, a set of varied conglomerates, sandstones, mudstones, and carbonates stained by iron to produce a distinctive pinkish hue. These layers alternate

See Chapter 6: Energy for more information about fossil fuel deposits in the Southwest's sedimentary basins.



Region 1

Figure 2.14: The Western Interior Seaway.

Figure 2.15: Ripple marks in the Dakota Sandstone of Dinosaur Ridge, Colorado.

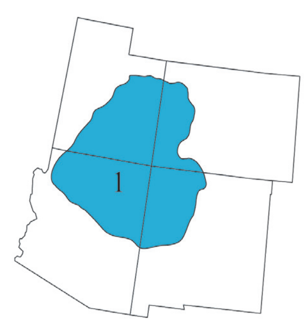
Sevier Orogeny • *a mountain-building event resulting from subduction along the western edge of North America, occurring mainly during the Cretaceous.*

subsidence • *the sinking of an area of the land surface.*

trackway • *a set of impressions in soft sediment, usually a set of footprints, left by an animal.*

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

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



badlands • *a type of eroded topography that forms in semi-arid areas experiencing occasional periods of heavy rainfall.*

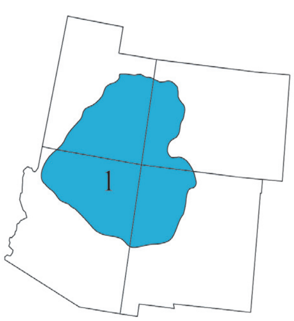
capstone • *a harder, more resistant rock type that overlies a softer, less resistant rock.*

Neogene • *the geologic time period extending from 23 to 2.6 million years ago.*

suture • *the area where two continental plates have joined together through continental collision.*

trachyte • *a fine-grained extrusive igneous rock, with a composition high in alkali feldspar.*

tuff • *a pyroclastic rock made of consolidated volcanic ash.*



between less and more resistant rocks, such that weathering produces wavy vertical profiles leading to hoodoos and **badlands** topography (*Figure 2.17*). Hoodoos form when weathering erodes a softer material out from underneath a mass of harder **capstone**, leading to "mushroom" formations.

See Chapter 4: Topography for more on hoodoos in the Southwest.

Figure 2.16: Cliff Palace, the largest cliff dwelling in North America, at Mesa Verde National Park, Colorado.

Many of the Colorado Plateau's volcanic rocks occur around the region's edges, and are attributed to Cenozoic volcanism spurred by the formation of the Basin and Range. For example, the southeast margin of the Plateau, in New Mexico, is covered by **Neogene** volcanic rocks that erupted along an ancient **suture** zone called the Jemez Lineament (*Figure 2.18*). The Mt. Taylor volcanic field in New Mexico, part of this igneous zone, contains **trachyte**, **tuff**, **pumice**, **rhyolite**, basalt, and other volcanic flows and deposits. The field is scattered with volcanic necks, the solidifed erosional remnants of volcanoes. The Valles Caldera, a small **supervolcano** also located along the Jemez Lineament, erupted several times between 1.5 million and 60,000 years ago, forming thick layers of solidified **volcanic ash** and tuff. Supervolcanoes—volcanoes capable of producing more than 1000 cubic kilometers (240 cubic miles) of ejecta—can occur when magma rises under the crust from a hot spot, but is unable to break through. Eventually, the crust ruptures when it can no longer contain the built-up pressure. The ashfall from the eruption 1.2 million years ago blanketed an area roughly 800 by 1300 kilometers (500 by 800 miles) in extent (*Figure*

2.19). The Bandelier Tuff is one such layer, formed as extremely hot dust and ash poured out of the Valles Caldera and flowed down its side in thick layers of tuff (*Figure 2.20*). The ancient Ancestral Pueblo peoples built pueblos and dwellings against these cliffs, and also carved rooms from the soft rock.

Figure 2.17: The Claron Formation is prominently exposed in the cliffs and hoodoos (tall skinny spires of rock) of Bryce Canyon, Arizona. Vertical joints through the rocks have become weathered through frost wedging, leading to the formation of hoodoos.

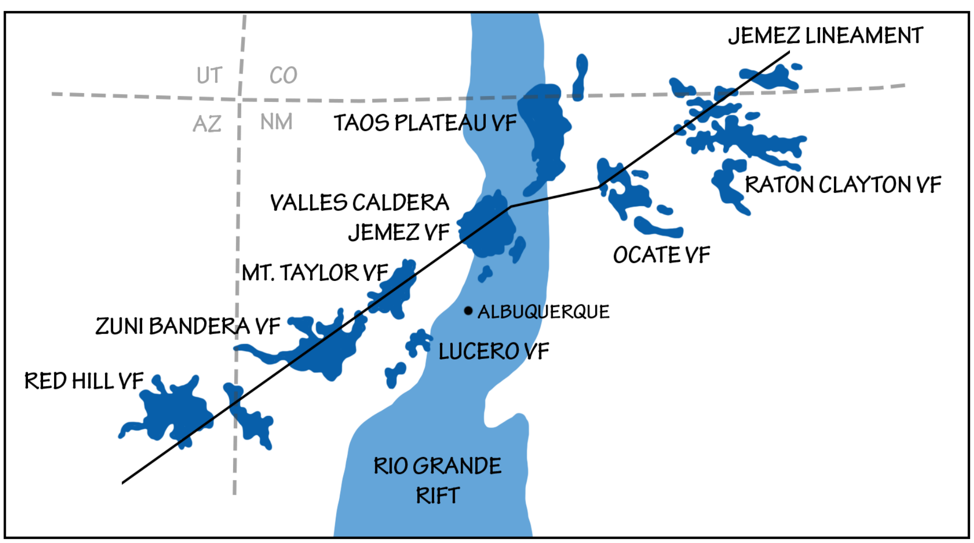


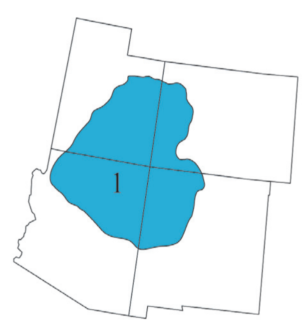
Figure 2.18: The Jemez Lineament and associated volcanic fields.

pumice • *a pyroclastic rock that forms as frothing and sputtering magmatic foam cools and solidifies.*

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

supervolcano • *an explosive volcano capable of producing more than 1000 cubic kilometers (240 cubic miles) of ejecta.*

volcanic ash • *fine, unconsolidated pyroclastic grains under 2 millimeters (0.08 inches) in diameter.*



Region 1

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

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

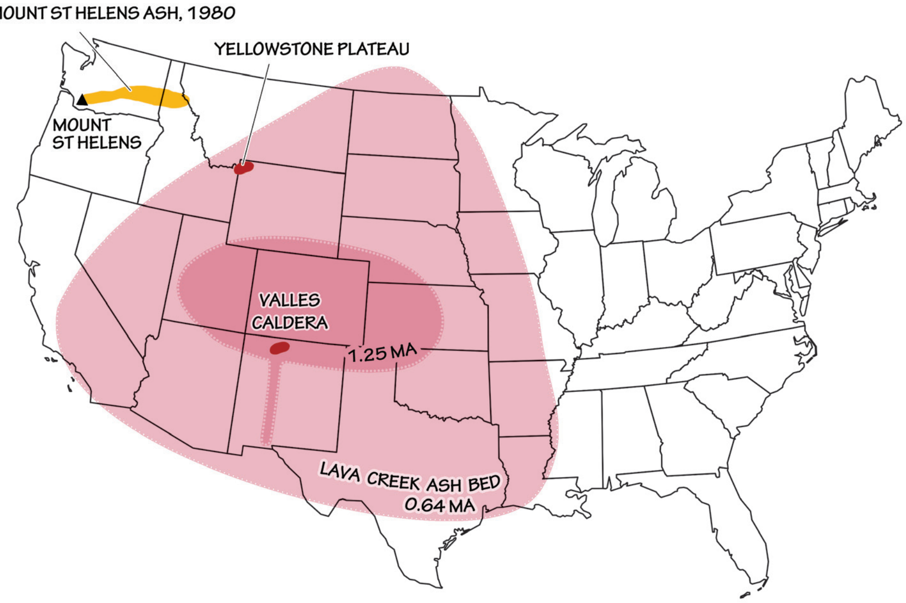
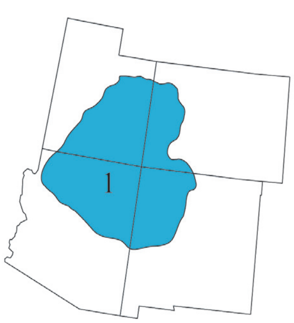


Figure 2.19: Extent of ashfall from the Valles Caldera, as compared to the Lava Creek Ash Bed from Yellowstone and the eruption of Mt. St. Helens. (See TFG website for full-color version.)

Figure 2.20: The Bandelier Tuff, a Pleistocene-aged mixture of volcanic tuff and pumice, at Bandelier National Monument in New Mexico.



A few notable volcanic deposits are located more centrally within the Colorado Plateau, mainly in the form of volcanic fields. The Navajo Volcanic Field includes over 80 **Oligocene** to **Miocene** volcanoes (approximately 28 to 19 million years old) and associated intrusive igneous rocks that are found in an arc across the region. The rocks in the Navajo Volcanic Field are unusual because they are very potassium rich and highly **mafic** (probably forming from **mantle** magma). Many of the rocks are composed of **minette**, which contains biotite (**mica** with potassium) and orthoclase (potassium fieldspar). **Xenoliths**—rocks from older layers incorporated into the magma—are common, and include rocks from both the crust and upper mantle. Uplift and weathering of the Colorado Plateau exposed these volcanic rocks, including dikes, pipes, necks, sills, and other features formed at the base of volcanoes. Differential weathering produced distinctive landforms such as Shiprock, a volcanic neck made of tuff and **breccia** in northwest New Mexico (*Figure 2.21*). The volcanic crater associated with Shiprock may have been as much as a kilometer (0.6 miles) above the current land surface; the rock itself formed nearly 1000 meters (3000 feet) underground and was eventually exposed after millions of years of erosion. The Uinkaret Volcanic Field, on the north rim of the Grand Canyon, is one of the region's youngest volcanic areas, with igneous rock ranging from 1.2 million years to only 1000 years old. Here, massive basalt lava flows cascaded down into the Grand Canyon, occasionally blocking the Colorado River (*Figure 2.22*). Other volcanic deposits inside the Colorado Plateau include **laccoliths**—dome-shaped igneous intrusions—that core the La Sal, Abajo, and Henry mountains of Utah.

See Chapter 4: Topography to learn more about the La Sal mountains and other igneous intrusions that created Southwestern landforms.

Figure 2.21: Shiprock, a volcanic monadnock in San Juan County, New Mexico, rises roughly 483 meters (1583 feet) above the desert plain.

mafic *• igneous rocks that contain a group of dark-colored minerals, with relatively high concentrations of magnesium and iron.*

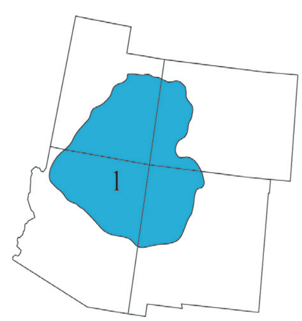
mantle *• the layer of the Earth between the crust and core.*

minette *• an unusual, mafic, fine-grained igneous rock made mostly of the potassium-containing minerals biotite mica and orthoclase.*

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

xenolith *• a chunk of pre-existing rock incorporated into magma that becomes part of an igneous rock body.*

breccia *• a pyroclastic rock composed of volcanic fragments from an explosive eruption.*



Region 1

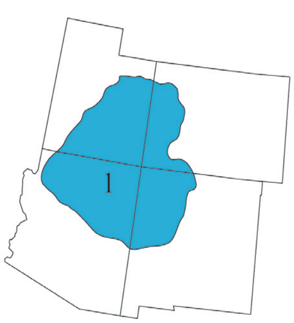
divergent boundary • *an active plate boundary where two tectonic plates are pulling apart from one another, causing the mantle to well up at a rift.*

convergent boundary • *an active plate boundary where two tectonic plates are colliding with one another.*

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

shield volcano • *a volcano with a low profile and gradual slope, so named for its likeness to the profile of an ancient warrior's shield.*

Quaternary • *a geologic time period that extends from 2.6 million years ago to the present.*



Understanding Volcanism

Most volcanic eruptions occur along tectonic plate boundaries. At *divergent boundaries*, the mantle wells up where two plates pull apart, creating new crust. Mid-ocean ridges are the most common type of divergent boundary and are characterized by the eruption of bulbous, pillow-shaped basalt lavas and hydrothermal fluids. Conversely, *convergent plate boundaries* destroy old lithosphere at subduction zones, where the ocean floor descends into the mantle. Volcanism here results from the subduction of seawater and seafloor sediments that descend into the mantle with the subducting slab, which lowers the melting temperature of mantle rocks enough to generate magma. Explosive eruptions characterize subduction zone volcanism and create arrays of cone-shaped stratovolcanoes that mark the position of the convergent boundary.

Volcanism can also occur at a *hot spot*, where superheated magma plumes well up from a point directly underneath the plate. Large *shield volcanoes* are produced as a direct result. The mechanics of hot spot volcanism are still largely unknown.

Prior to eruption, magma ascends from the mantle to a relatively shallow (1- to 10-kilometer [0.5- to 6-mile] deep) 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.

There are few **Quaternary**-age sedimentary deposits on the Colorado Plateau. Most are related to glacial **outwash** from the alpine glaciers in the Rocky Mountains, as well as modern stream deposits and windblown sand and **silt**.

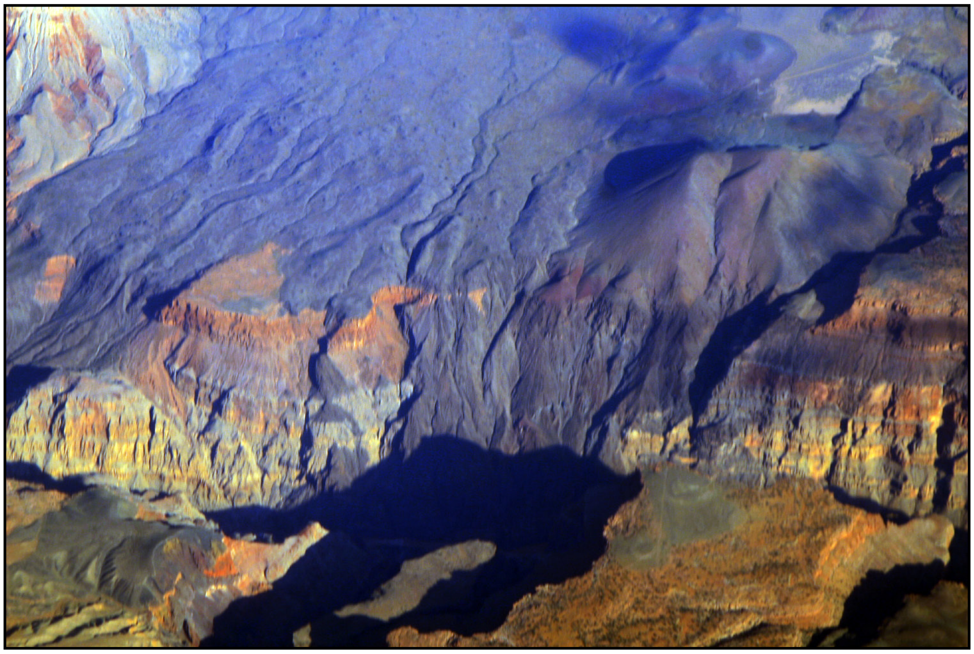


Figure 2.22: In this aerial view, the black basalt of the Uinkaret Volcanic Field is seen preserved where it cascaded over the side of the Grand Canyon at Lava Falls.

Rocks of the Basin and Range
Region 2

A portion of the Basin and Range—a huge **physiographic** region that extends from southeastern Oregon to west-central Mexico—extends into the Southwest, covering most of western Utah, much of Arizona, and large areas of New Mexico. While the formation of the Basin and Range is a recent event that began only 30 million years ago, the bedrock that makes up the region's up-thrust ranges and down-dropped basins is very old. Here, rocks can be found from nearly all periods of the **Phanerozoic**. 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 a bookend is removed from a shelf, the blocks slid against each other as they filled the increased space (*Figure 2.23*).

The Basin and Range is characterized by mostly north-south oriented linear mountain ranges of Precambrian, Paleozoic, and Mesozoic-aged rocks. Since the region's formation, the bedrock of the basins has been covered by young deposits, including loose sediment washed down from the mountains and evaporite deposits left behind in dried-out lakes. The ranges, however, expose

Regions 1-2

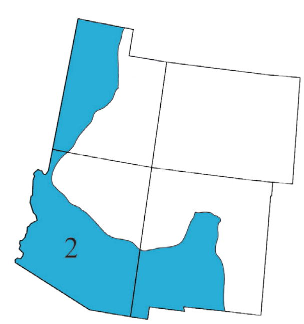
outwash plain *• large, sandy flats created by sediment-laden water deposited when a glacier melts.*

silt *• fine granular sediment most commonly composed of weathered grains of quartz and feldspar crystals, of grain diameter 1/250 to 1/16 millimeters.*

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

Phanerozoic *• a generalized term used to describe the entirety of geological history after the Precambrian, from 541 million years ago to the present.*

Paleogene *• the geologic time period extending from 66 to 23 million years ago.*



Region 2

dolomite *• a carbonate mineral, consisting of calcium magnesium carbonate ($CaMg(CO_3)_2$).*

tillite *• glacial till that has been compacted and lithified into solid rock.*

phosphate *• an inorganic salt of phosphoric acid, and a nutrient vital to biological life.*

far older materials. The region is underlain by Precambrian basement—granitic gneisses and metamorphosed volcanic and sedimentary rocks ranging from 2.5 to 1 billion years in age. The oldest rocks in the Southwest underlie the northern part of Utah, as well as southwestern Utah and northwestern Arizona. Exposures of these rocks are rare, occuring in the cores of uplifted ranges. Most of the Precambrian rocks exposed in the Basin and Range are related to the Grand Canyon Supergroup, produced approximately 1.2 to 1.1 billion years ago during formation of the supercontinent Rodinia. The mildly metamorphosed conglomerate, sandstone, shale, and **dolomite** layers of the Grand Canyon Supergroup are exposed in the Cricket Mountains of west-central Utah. In addition, ancient **tillites** (glacial deposits) found in Utah represent major glaciation events that occurred during the Proterozoic (*Figure 2.24*).

See Chapter 8: Climate to learn about Snowball Earth and other Proterozoic glacial events.

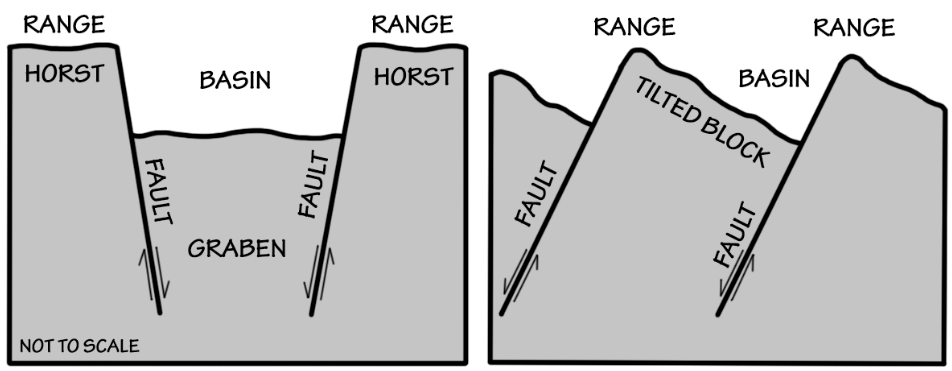
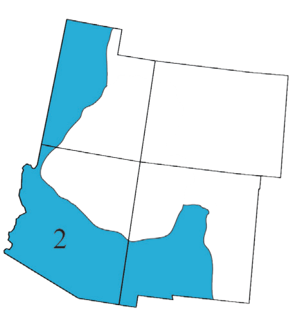


Figure 2.23: Alternating basins and ranges were formed during the past 17 million years by gradual movement along faults. Arrows indicate the relative movement of rocks on either side of a fault.

The Basin and Range's Paleozoic rocks—a succession of sandstones, limestones, and shales—were deposited on the western shore of North America from the Cambrian to the Mississippian. These rocks, like those in the Colorado Plateau, record a story of rising seas and shallow marine environments. Early Ordovician limestones of the El Paso Formation extend from southern Arizona and New Mexico into western Texas; Utah hosts similar limestones, sandstones, and dolomites, with occasional conglomerates formed when tidal currents ripped up newly deposited carbonate layers. This was followed during the Pennsylvanian through the Permian by a transition to shallow and evaporating seas, which deposited sandstones, mudstones, limestones, and **phosphate**-rich rocks. Thick Pennsylvanian sedimentary sequences are present in the Oquirrh Mountains west of Salt Lake City, and in the Sacramento, Robledo, Caballo, and San Andres mountain ranges along the Rio Grande Rift. After the Permian, as receding seas left the continent high and dry, subaerial weathering caused karstic topography to develop in the exposed carbonate rocks. Massive **reefs** became ideal structures for the formation of caves thanks



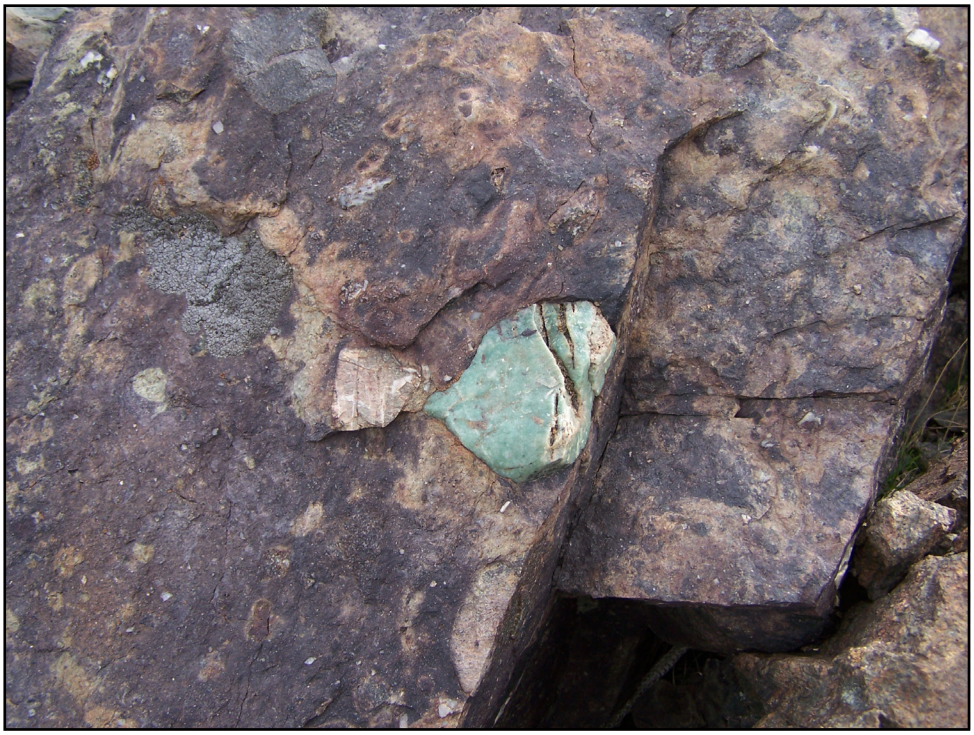


Figure 2.24: A piece of the Mineral Fork Tillite from Antelope Island, Utah. This rock is thought to have been deposited during the "Snowball Earth" Proterozoic glacial period, and is composed of glacial alluvium as well as embedded aventurine quartz.

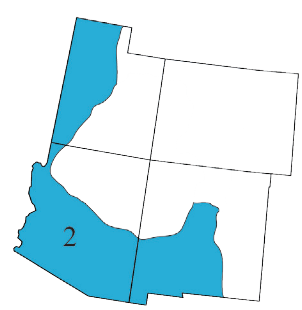
reef • *a feature lying beneath the surface of the water, which is a buildup of sediment or other material built by organisms, and which has positive relief from the sea floor.*

permeability • *a capacity for fluids and gas to move through fractures within a rock, or the spaces between its grains.*

to their **permeability** and soluble nature, allowing groundwater to infiltrate, dissolve, and carry away the calcium carbonate material. The Guadalupe Mountains of southeastern New Mexico expose an enormous Paleozoic reef, the Capitan Reef, which was revealed to the elements during the Permian. Carlsbad Caverns, also in the same area, is a massive limestone cave that developed in the region's carbonate bedrock after the mountains were uplifted (*Figure 2.25*).

Mesozoic rocks in the Basin and Range are represented by the red beds, sandstones, mudstones, and limestones of the Moenkopi Formation and the Navajo Sandstone, which formed as sea level dropped relative to the land. These Paleozoic and Mesozoic sediments form the cores of the region's mountain ranges; they were thrusted during the Sevier Orogeny, then involved in the Basin and Range style of extension during the Paleogene. Valleys and basins formed by this extensional faulting were filled with younger rocks from the Cretaceous and the Cenozoic (*Figure 2.26*). These rocks are mainly conglomerates, sand-stones, and mudstones originating from erosion of the nearby uplifts. Neogene sediments from glacial lakes, modern streams, and volcanic activity are also common.

See Chapter 1: Geologic History for more about the tectonic processes, extension, and faulting that shaped the Southwest.



Region 2

fracture *• a physical property of minerals, formed when a mineral crystal breaks.*

silica *• a chemical compound also known as silicon dioxide (SiO_2).*

cinder *• a type of pyroclastic particle in the form of gas-rich lava droplets that cool as they fall.*

caldera *• a collapsed, cauldron-like volcanic crater formed by the collapse of land following a volcanic eruption.*

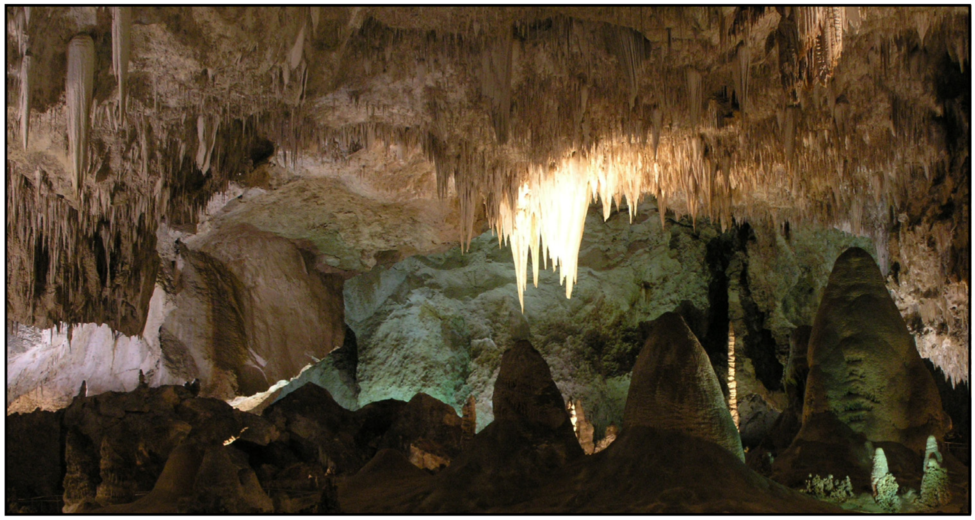


Figure 2.25: Delicate limestone speleothems decorate Carlsbad Caverns, New Mexico, in an array of spectacular formations.

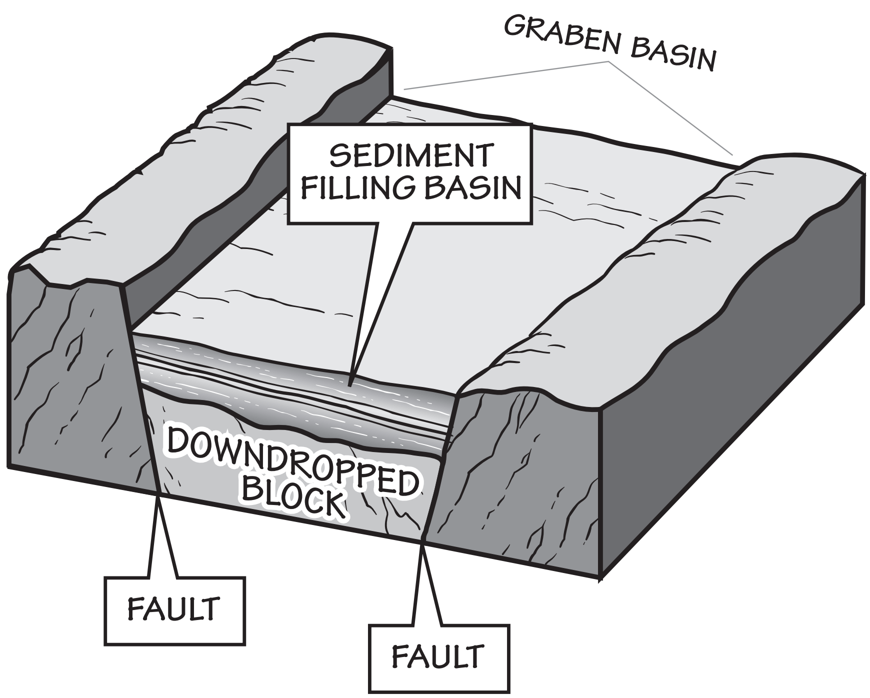
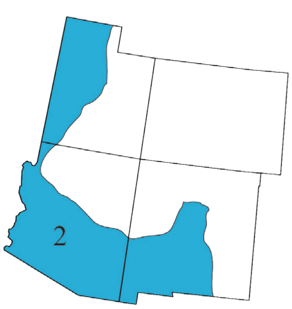


Figure 2.26: Basin fill in the Basin and Range.

During the Cenozoic, the Southwest experienced significant active volcanism and plutonism. The Paleogene saw magma well up from the mantle from approximately 50 to 45 million years ago, intruding into the existing rock layers. By approximately 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 a rugged landscape, created numerous igneous intrusions, and fed the region's volcanoes. The partial melting of deeper



crust produced large volumes of magma that was both emplaced in the crust and erupted on the surface (for example, plutonic granite and volcanic rhyolite). Many of these rocks host mineral deposits, ranging from precious metals to uranium to industrial materials such as perlite. Most of the Southwest's larger volcanic fields can be found within the Basin and Range, especially around the region's border with the Colorado Plateau.

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 Pluto, the Roman god of the underworld.

The Marysvale Volcanic Field in western Utah is one of the largest volcanic fields in the western United States. During the Oligocene and Miocene, it and the neighboring Pioche Belt erupted large volumes of **silicic** magma, basalt, and ash, producing a variety of volcanic features that included **cinder** cones, lava domes, and **calderas**. The Boot Heel Volcanic Field, covering an area of more than 24,000 square kilometers (9300 square miles) across New Mexico, Arizona, and Mexico, includes nine calderas, **extrusive** flows (rhyolite, basalt, **andesite**, and tuff), and intrusive granite (*Figure 2.27*). The San Francisco Volcanic Field in Arizona contains the San Francisco Peaks—the eroded remnants of an enormous **stratovolcano**—and cinder cones such as the Sunset Crater, a 340-meter-high (1120-foot-high) cone of **basaltic andesite** that last erupted only 1000 years ago. Other Cenozoic volcanic fields in the Basin and Range include the Ajo (Arizona), the Black Rock Desert (Utah), and the Mogollon-Datil (New Mexico). Igneous rocks in the Basin and Range may also appear outside of volcanic fields, such as the exposures of **jointed** basalt found in Utah's geologically complex Traverse Range (*Figure 2.28*).

Figure 2.27: The Organ Mountains, an exposure of granite and rhyolite in New Mexico's Boot Heel Volcanic Field.

Region 2

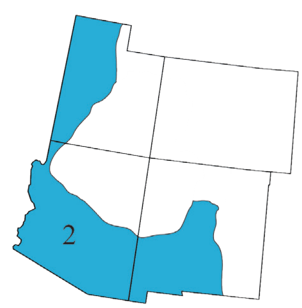
extrusion • *an igneous rock formed by the cooling of lava after magma escapes onto the surface of the Earth through volcanic craters and cracks in the Earth's crust.*

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

stratovolcano • *a conical volcano made up of many lava flows as well as layers of ash and breccia from explosive eruptions.*

basaltic andesite • *a dark, fine-grained rock that is intermediate between basalt and andesite in silica content.*

joint • *a surface or plane of fracture within a rock.*



Region 2

columnar joint • *five- or six-sided columns that form as cooling lava contracts and cracks.*

quartz • *the second most abundant mineral in the Earth's continental crust (after the feldspars), made up of silicon and oxygen (SiO_2).*

aluminum • *a metallic chemical element (Al), and the most abundant metal in the Earth's crust.*

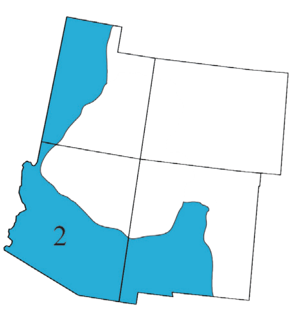
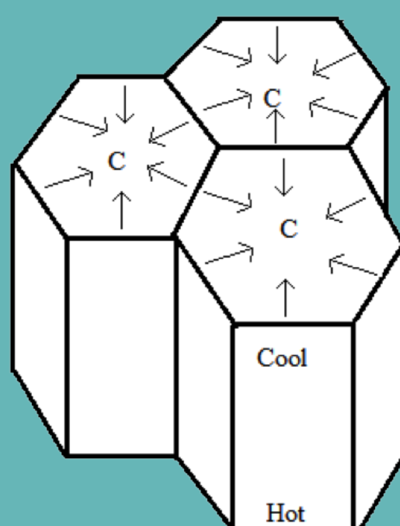


Figure 2.28: Step Mountain, in the Traverse Range, Utah, is composed of overturned basalt that exhibits columnar jointing.

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 in shallow intrusions. The columns are generally vertical, but may also be slightly curved.



Rhyolite and Basalt

Both rhyolite and basalt are lavas, but they behave differently due to their varied densities and melt structures. Rhyolite is composed of felsic minerals including *quartz*, orthoclase, and biotite, and is high in silica and *aluminum*. This composition results in a very viscous magma. The lavas in volcanoes with felsic (rhyolitic) compositions are too viscous to flow easily; pressure builds up beneath them until they erupt explosively. The most explosive volcanoes form calderas, and the ash from such an explosion can travel many kilometers (miles).

Basalt is composed of the mafic minerals plagioclase and *pyroxene*, and may contain *olivine*. These minerals are high in iron and magnesium, and produce a very fluid magma. Volcanoes with mafic or basaltic compositions tend to produce fluid lava flows comparable to those associated with the eruptions presently seen in Hawai'i.

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. Quaternary deposits in the Basin and Range are primarily composed of glacial outwash from rivers, streams, and glacial lakes. These sediments were derived from alpine glaciers in the Rocky Mountains, and were also produced by the **Cordilleran Ice Sheet** during the **ice age**. Windblown sand and dust, both **Pleistocene** and modern, are also common components of the region's Quaternary deposits.

Rocks of the Rocky Mountains
Region 3

The Rocky Mountains of the Southwest consist of multiple mountain ranges resulting from both the Sevier and Laramide orogenies, which uplifted numerous discrete blocks of terrain along thrust faults that accommodated compressional shortening and thickening of the crust. The overlying sediments were

See Chapter 1: Geologic History to learn more about mountain building during the Laramide and Sevier orogenies.

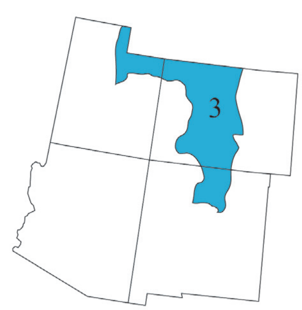
pyroxene • *dark-colored rock-forming silicate minerals containing iron and magnesium.*

olivine • *an iron-magnesium silicate mineral* $((Mg,Fe)_2SiO_4)$ *that is a common constituent of magnesium-rich, silica-poor igneous rocks.*

Cordilleran Ice Sheet • *one of two continental glaciers that covered Canada and parts of the Western US during the last major Pleistocene ice age.*

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

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



***pillow basalt** • basaltic lava that forms in a characteristic "pillow" shape due to its extrusion underwater.*

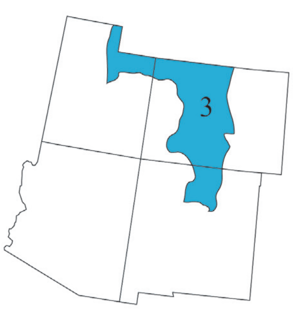
***quartzite** • a hard metamorphic rock that was originally sandstone.*

***slate** • a fine-grained, foliated metamorphic rock derived from a shale composed of volcanic ash or clay.*

subsequently eroded to expose deeper Precambrian rock as well as Paleozoic and Mesozoic sedimentary formations. The thrust-faulted uplift also produced adjacent basins, which subsequently accumulated sediments eroded from the surrounding mountains. In the Southwest, the Rockies are located in central and western Colorado, north-central New Mexico, and northeastern Utah.

Precambrian rocks are well exposed in the Rocky Mountains, where 1.9- to 1.6-billion-year-old metamorphosed volcanic and sedimentary rocks represent the accretion of an ancient terrane to this portion of the North American continent. These ancient rocks are typically metamorphosed and deformed, but occasionally some of the original sedimentary and volcanic textures can still be observed, including bedding, cross-bedding, and **pillow** lavas. Coarse-grained, dark-colored metamorphic rocks are ubiquitous. Many of these Precambrian rock units can be seen in exposures along roads that wind through the mountains. For example, the Uinta Mountains, an east-west segment of the southern Rockies in northeastern Utah, are made of uplifted and metamorphosed sedimentary rocks deposited in a shallow marine basin over 700 million years ago. The rocks at the mountains' peaks include reddish **quartzite** and sandstones, **slate**, and shale. These are part of a thick (4- to 7-kilometer [13,000- to 24,000-foot]) sequence of rocks known as the Uinta Mountain Group that were uplifted during the Laramide Orogeny (*Figure 2.29*).

Figure 2.29: King's Peak, the highest peak in Utah's Uinta Mountains, is composed primarily of Neoproterozoic sandstone, siltstone, and shale.

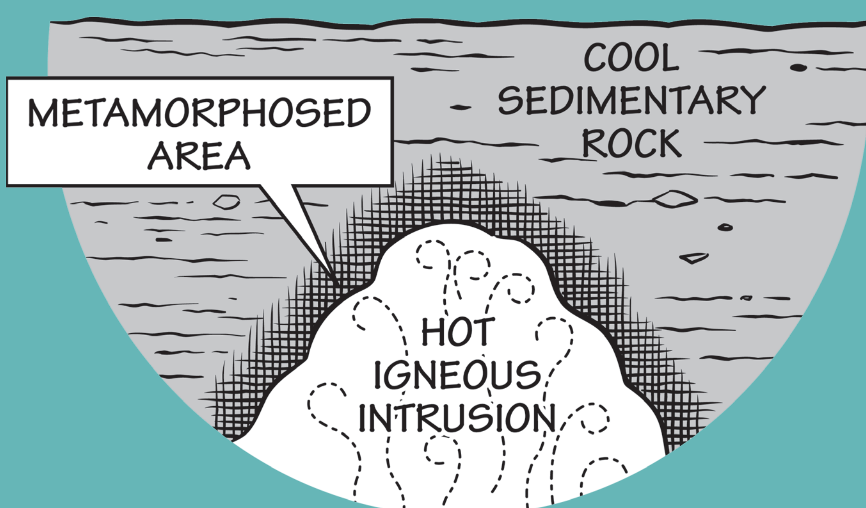


Colorado's Precambrian rocks are primarily metamorphosed volcanics with intermixed sedimentary units. Schist—metamorphosed sediment—is fairly common in the Rocky Mountains, and can be found throughout the region. It is usually composed of shale and siltstone that have been compressed to

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. Individual grains reform as interlocking crystals, making the resulting metamorphic rock much harder than its parent rock.

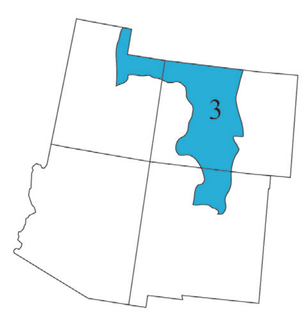
Contact metamorphism describes a metamorphic rock that has been altered by direct contact with magma. Changes that occur due to contact metamorphism are greatest at the point of contact. The farther away the rock is from the point of contact, the less pronounced the change.



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.

foliation • *the arrangement of the constituents of a rock in leaflike layers.*

regional (dynamic) metamorphism • *a metamorphic rock that has been altered due to deep burial and great pressure.*



chemical reaction *• a process that involves changes in the structure and energy content of atoms, molecules, or ions but not their nuclei.*

shearing *• the process by which compressive stress causes the fracturing and faulting of brittle rocks.*

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).*

pegmatite *• a very coarse-grained igneous rock that formed below the surface.*

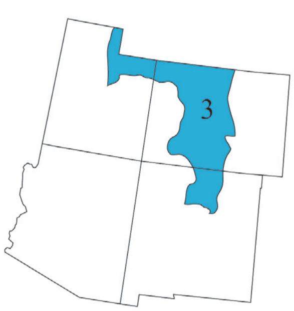
form relatively large crystals (especially micas) that are layered into sheet-like structures. Gneisses—metamorphosed rhyolite or granite—are common in the Colorado Rockies (*Figure 2.30*). In contrast, the Precambrian rocks of New Mexico have a higher ratio of sedimentary units, including more quartzite and conglomerate, than is found in Colorado. Quartzite—metamorphosed sandstone—is very resistant to erosion, so it forms steep slopes and is often found at the core of ridges or mountains. This rock ranges in color from white and gray to pink and purple, depending on the amounts of iron and other minor minerals that were deposited with the sand grains. The Picuris Range near Taos in New Mexico contains more Precambrian quartzite than do the mountains of Colorado. (The best quartzite outcrops in Colorado are south of Boulder in El Dorado State Park, and in Coal Creek Canyon, along Highway 72.)

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.

Three major igneous intrusions followed the original deposition of these rocks, forming large granitic **batholiths** approximately 1.8, 1.4, and 1.1 billion years ago. These batholiths are more resistant to erosion than the surrounding rocks are, and form many high mountain peaks including Pike's Peak, Mount Evans, and Long's Peak in the Colorado Front Range. The Pike's Peak granite (1.8 billion years old) is well known for its **pegmatites** (*Figure 2.31*). Although they have essentially the same composition as the surrounding granite, pegmatites are composed of much larger crystals and may also yield rare, potentially valuable, minerals.

See Chapter 5: Mineral Resources to learn about rhodochrosite, diamonds, and other rare Rocky Mountain minerals.

The Rocky Mountains, like other regions of the Southwest, contain a succession of Paleozoic sandstone, limestone, and shale. Between the Cambrian and Mississippian, these rocks were deposited in shallow marine environments on what was then the western shore of North America. Early Paleozoic rock units can be found in the canyons of Utah's Wasatch Mountains, at the edge of the Sawatch Range in Colorado, and along the deep gorge of the Colorado River, where thick layers of Cambrian and Ordovician sediments overlie the Precambrian basement (*Figure 2.32*).



Region 3

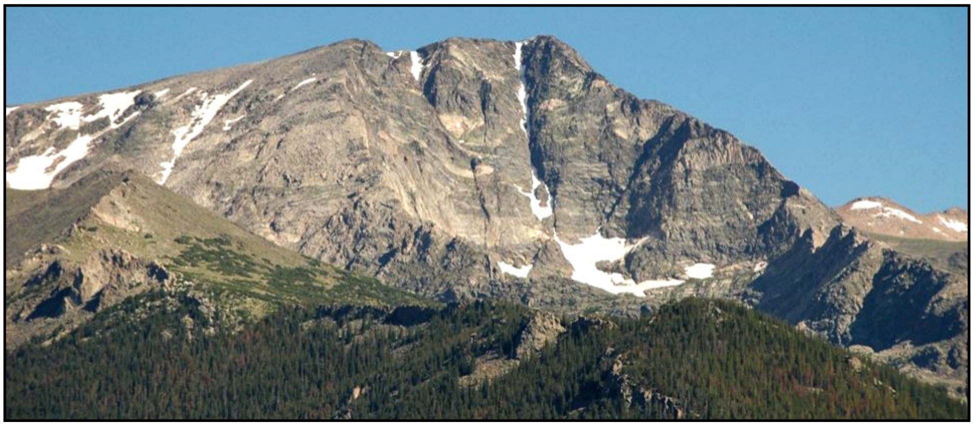


Figure 2.30: Ypsilon Mountain in the Mummy Range of northern Colorado is principally composed of 1.7-billion-year-old biotite schists and gneisses.

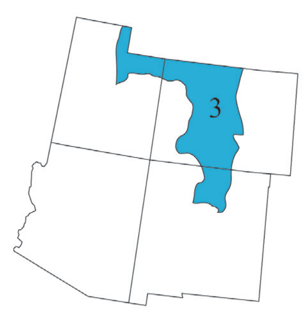
Figure 2.31: Coarsely crystalline granite (approximately 1.8 billion years old) from the Pike's Peak batholith in central Colorado. This pegmatite is dominated by feldspar, quartz, and mica.

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

alluvial • a layer of river-deposited sediment.

arkose • sandstone that is > 25% feldspar, reflecting its relative lack of transport and weathering.

Erosion during the **Carboniferous** deposited sediments on both the east and west sides of the mountains. This resulted in the formation of **alluvial** fans along the mountain flanks, and bedded sediments in lower areas. Mississippian rocks are generally gray limestone and dolomite; Cave of the Winds near Manitou Springs, Colorado is a cavern system developed in Mississippian limestone. The Pennsylvanian Fountain Formation along the eastern flank of the Colorado Front Range was deposited as a series of alluvial fans—wedge-shaped deposits of sediment formed when sediment was deposited at the mouths of ancient streams coming out of the mountains. It is composed of **arkose** covered by conglomerate and thin layers of mud and siltstone (*Figure 2.33*). By the Permian, erosion had leveled the ranges and the area was flooded by shallow and evaporating seas, which deposited marine sandstone, mudstone, limestone, and phosphate-rich rocks (in the deeper zones). Today, these sedimentary layers are best seen around the edges of the Rocky Mountains, where beds

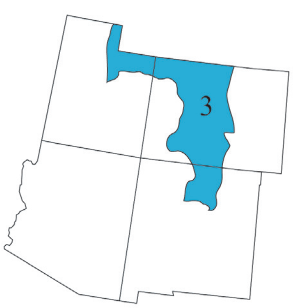


have been tilted and pushed upward by mountain building processes. Fossils of marine invertebrates are common in these Paleozoic rocks.

Figure 2.32: Cambrian and Ordovician strata are exposed in Glenwood Canyon, Colorado, where Interstate Highway I-70 follows the Colorado River.

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 out.



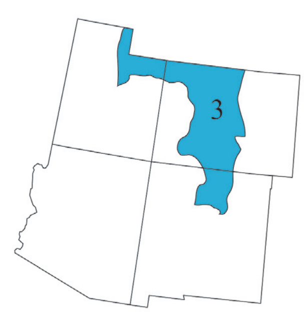
Why are there different sedimentary rocks in different environments? (continued)

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.

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

foraminifera • *a class of aquatic protists that possess a calcareous or siliceous exoskeleton.*

Mesozoic rock units in the Rocky Mountains contain abundant fossils, especially those of dinosaurs and other vertebrates. The region's Triassic and Jurassic rocks were deposited in terrestrial settings, and include red beds, sandstone, mudstone, and limestone. Triassic red beds are composed of iron-rich sandstone or siltstone, while the Jurassic Morrison Formation is a striking variegated siltstone and shale colored in red, purple, gray, tan, and green. The Morrison includes lenses of sandstone, which often contain dinosaur bones that were deposited in streambeds. During the Cretaceous, marine shale and sandstone formed when the epicontinental Western Interior Seaway flooded the area, and coal formed along coasts and swamps. The Cretaceous Dakota Group is a



Region 3

weather *• the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity.*

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

felsic *• igneous rocks with high silica content and low iron and magnesium content.*

vesicular *• porous or pitted with vesicles (cavities).*

rift *• a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates.*

yellow sandstone, often bearing ripple marks formed in beach or tidal zones (*see Figure 2.15*). Dinosaur bones and trackways are present in several places. Cretaceous shale units have thick layers of black, gray, or tan, and often weather into badlands topography. The Dakota Hogback (*Figure 2.34*) is located along the edge of the Front Range just west of Denver, Colorado. This area preserves an important stratigraphic section that includes the Pennsylvanian Fountain Formation (*see Figure 2.33*), Permian Lyons Formation, Permo-Triassic Lykins Formation, Jurassic Ralston Creek Formation and dinosaur fossil-bearing Morrison Formation, Cretaceous Dakota Group, and various Cenozoic formations that are exposed at the edge of the Denver Basin. The modern Rocky Mountains rose near the end of the Cretaceous—earlier in eastern Utah during the Sevier Orogeny, and later in Colorado and New Mexico during the Laramide Orogeny.

See Chapter 3: Fossils for more about the vast array of dinosurs found in the Morrison Formation.

Cenozoic rocks in the Rocky Mountains are mainly sandstones, shales, conglomerates, and mixed sediments that formed when eroding sediment from the uplifted Rocky Mountains was deposited by rivers onto alluvial fans, and into lakes, basins, and swamps. Where they are adjacent to volcanic areas, some stream sediments carry cobbles of volcanic rocks. Thick wedges of Cenozoic sediments were deposited on the flanks of uplifted ranges, and sedimentary basins and lakes were centers for the deposition of thick layers of shale and mudstone. Cenozoic deposits differ from one basin to another, reflecting local differences in **weather** and erosion.

The San Juan Volcanic Field is in the San Juan Mountains of southwestern Colorado and consists mostly of Oligocene lavas and breccias, and Miocene and **Pliocene** basalts. These rocks represent stratovolcano deposits, and include numerous calderas and ash flows, which contain rhyolite tuffs (**felsic**) and andesite (intermediate in composition). The field's largest known caldera, La Garita, is associated with its largest known ash flow deposit. During the Oligocene, this caldera deposited thick layers of coarse volcanic tuff. Ash-flow tuffs are the result of pyroclastic flows—explosions that contain pulverized rock and superheated gases, which can reach temperatures of up to 1000°C (1830°F). 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 in nature. 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. The Wheeler Geologic Area in the La Garita Mountains in southern Colorado is recognized for the unusual jagged shape of its terrain due to the erosion of these tuffs, forming striking hoodoos (*Figure 2.35*). By the Miocene, volcanism in the area had become more mafic, representing a tectonic change to **rifting** during crustal extension.

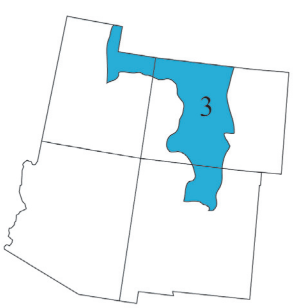


Figure 2.33: Red Rocks Park is nestled within the towering Fountain Formation in Morrison, Colorado. The formation is composed of a sedimentary rock called arkose, which is red in color due to the presence of oxidized iron and a large number of pink feldspar and quartz grains.

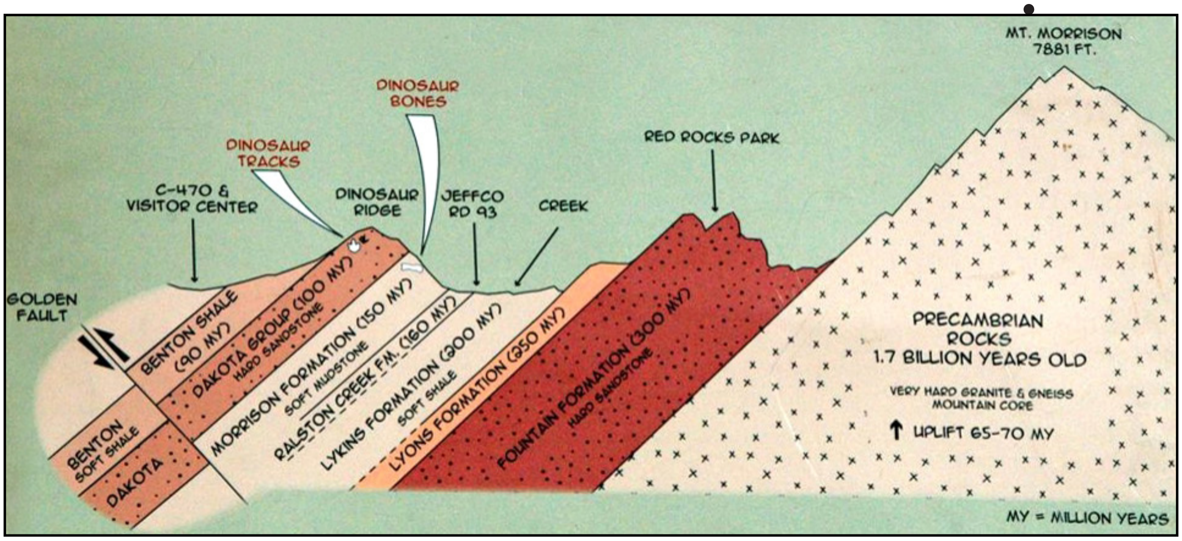
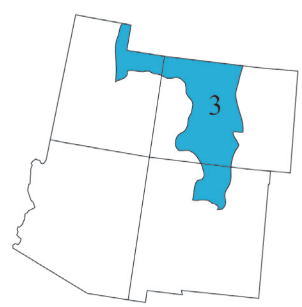


Figure 2.34: Stratigraphic units of the Dakota Hogback, a north-south trending ridge of eastward-dipping Mesozoic sedimentary rocks in north-central Colorado.



Region 3

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

gold *• a soft, yellow, corrosion-resistant element (Au), which is the most malleable and ductile metal on Earth.*

silver *• a metallic chemical element (Ag).*

hydrothermal solution *• hot, mineral-rich water moving through rocks.*

contact metamorphism *• the process by which a metamorphic rock is formed through direct contact with magma.*

calcite *• a carbonate mineral, consisting of calcium carbonate ($CaCO_3$).*

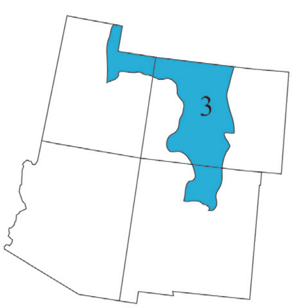


Figure 2.35: The Wheeler Geologic Area in Mineral County, southern Colorado, is a highly eroded outcropping of Oligocene volcanic ash.

Other than the volcanic fields at the edge of the Colorado Plateau and Great Plains, Phanerozoic volcanic and plutonic rocks are minor in the Rocky Mountain region. There are, however, a few notable exceptions. The Colorado Mineral Belt is a structural weakness in the Precambrian crust through which multiple igneous rock bodies were emplaced or erupted during the **Paleocene** (approximately 65 to 60 million years ago). The accompanying fluids carried **gold**, **silver**, other metals, and uranium, many of which have been mined for profit. (This was the primary source of gold during the Gold Rush of 1859.) In addition to deposits emplaced by **hydrothermal solutions**, **contact metamorphism** from the heat of Paleogene igneous activity altered the surrounding rock to form deposits such as the Yule Marble. This metamorphosed Mississippian limestone was transformed into a distinctive, smooth, white stone that is 99.5% pure **calcite**. Thanks to its smooth texture and pure white appearance, the Yule Marble has been used to cover the exterior of a variety of buildings and monuments including the Tomb of the Unknown Soldier and the Lincoln Memorial (*Figure 2.36*)

See Chapter 5: Mineral Resources for more detail about mineral extraction in the Colorado Mineral Belt.

Other Cenozoic-aged volcanic and intrusive activity can be found at Cripple Creek, Colorado (host of another large gold deposit); Questa, New Mexico

molybdenum *• a metallic chemical element (Mo) which has the sixth-highest melting point of any element.*

ice sheet *• a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).*

cirque *• a large bowl-shaped depression carved by glacial erosion and located in mountainous regions.*

moraine *• an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions.*

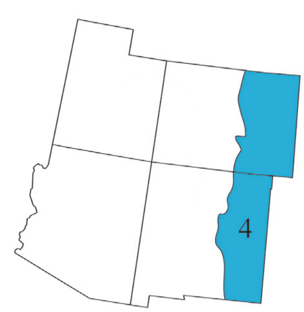
Figure 2.36: The Lincoln Memorial's brilliant white exterior is faced with Yule Marble.

(host of a **molybdenum** deposit); Thirty-Nine-Mile Volcanic Field southwest of Denver; and in various volcanic rocks near Steamboat Springs and North Park, Colorado. Near Gunnison, Colorado, there is an unusual igneous rock known as a carbonatite, a carbonate intrusive rock that does not possess the usual silicate composition. Some of the youngest volcanic activity in the region includes a basaltic cone and lava flow at Dotsero, Colorado, dated at approximately 2200 BCE. Interstate Highway I-70 actually crosses the foot of the flow.

Pleistocene glaciation produced glacial **till** and outwash material in the mountains and basins. Alpine glaciers, rather than continental **ice sheets**, carved **cirques** and deposited **moraines** in mountain valleys. Modern stream sediments are still deposited today.

Rocks of the Great Plains
Region 4

Only the western margin of the Great Plains lies within the Southwestern US, along the eastern border of Colorado and New Mexico. 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. In general, rocks found at the surface of the Great Plains are young sediments (predominantly Cenozoic with some Cretaceous). Erosional processes along the Platte and Arkansas rivers in



Region 4

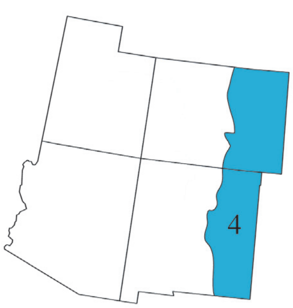
clay • the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet.

rare earth elements • a set of 17 heavy, lustrous elements with similar properties, some of which have technological applications.

kaolinite • a silicate clay mineral, also known as china clay.

meteorite • a stony or metallic mass of matter that has fallen to the Earth's surface from outer space.

mass extinction • the extinction of a large percentage of the Earth's species over a relatively short span of geologic time.



Colorado, and the Canadian and Pecos rivers in New Mexico, have cut into the gently eastward-sloping land surface. Outcrops on the plains are usually exposed by stream erosion, in dissected terrain, or in quarries.

Throughout much of the Paleozoic era until the early stages of the Carboniferous, the Great Plains region was submerged in a shallow sea. During the Paleozoic and Mesozoic, thick sequences of rocks were deposited across the region in environments that varied from marine and coastal to lake, stream, and alluvial. Layers of limestone and shale were deposited when shallow seas repeatedly flooded the area, while sandstones accumulated from sandy beaches were left behind as the seas retreated. 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. The resulting rocks are sandstones, shales, limestones, mudstones, conglomerates, and some evaporites, deposited in beds buried beneath the surface of the plains. Although they are not exposed at the surface, many of these buried rocks are well studied from the cores of numerous oil and gas drillholes throughout the region.

The Great Plains overlie the Raton, Denver, and Permian basins, which are downwarped areas that formed due to tectonic compression in the late Paleozoic. During the Permian period, these basins were carbonate marine environments where reefs grew in the shallows. Deposition of marine sandstone, shale, limestone, and then evaporites (salts and related minerals) eventually ceased as sea level dropped, the basins closed, and the remaining seawater evaporated. The Raton Basin exposes a well-preserved sequence of rock spanning the Cretaceous-Paleogene (K-Pg) boundary. A common characteristic of the K-Pg boundary is the presence of a thin, millimeter-scale layer of **clay** containing a number of **rare earth elements**, including iridium. This layer is represented in the basin by a sheet of compact **kaolinite** clay (*Figure 2.37*). The iridium is thought by most geologists to have come from the impact of a large comet or **bolide**, which was likely a primary cause of the **mass extinction** that marks

Figure 2.37: The Cretaceous-Paleogene (K-Pg) boundary layer is clearly visible in this roadcut along Long Canyon Road near Trinidad Lake, Colorado.

the end of the Cretaceous period. The Denver Basin contains a 55-million-year-old formation of coarse sandstone and conglomerate called the Dawson Arkose, a collection of fluvial and alluvial sediments eroded from the Rockies and deposited at their base during the late Cretaceous and early Paleogene. The Dawson Arkose is beautifully exposed at the Paint Mines Interpretive Park near Colorado Springs, where pastel hoodoos and badlands topography are eroded into the landscape (*Figure 2.38*).

Gravel, sand, and mud dominate the surface of the Great Plains, with progressively younger sediment located farther from the western mountains. Eroded material eventually filled stream valleys and covered hills, creating a massive, gently sloping plain that was in place by five million years ago. Except in river valleys where Mesozoic rocks are exposed, the surface is blanketed by thick soils, **caliche**, windblown sand and silt, and playa lakes. These sediments overlie the Paleogene sediments of 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.

See Chapter 9: Earth Hazards to find out more about the effect of drought on the Ogallala Aquifer.

Volcanic features are less common in the Great Plains, and are generally found along or near the region's western edge. Castlewood Canyon State Park, near Castle Rock, Colorado, provides evidence for an explosive eruption of rhyolitic ash, which created an ash-flow tuff. This welded rhyolite tuff was formed during

Figure 2.38: Ancient cultures and early settlers mined the brightly colored clays seen at the Paint Mines Interpretive Park, Colorado for use as pigment.

Region 4

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

caliche *• a zone of cemented material within soil, formed when water infiltrates the soil, dissolves soluble materials, and evaporates, leaving behind precipitates in the pore space between soil grains.*

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.*

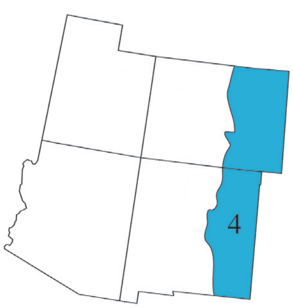
Region 4

granodiorite • *a coarse-grained, plutonic rock rich in the elements sodium and calcium, and in the minerals potassium feldspar and quartz.*

syenite • *a durable, coarse-grained, intrusive igneous rock, which is similar to granite but contains less quartz.*

dacite • *a fine-grained, extrusive igneous rock, with a silica content intermediate between that of andesite and rhyolite.*

loess • *very fine-grained, wind-blown sediment, usually rock flour left behind by the grinding action of flowing glaciers.*



a tremendous volcanic eruption during the Eocene, approximately 36 million years ago, which filled the air with superheated ash and rock that solidified as it hit the ground. The resulting attractive pink rock has been mined near Castle Rock for use as a decorative stone for over a century; it has been used as a building stone in several Denver buildings, including the historic Trinity Presbyterian Church in downtown Denver, parts of the Capitol Building, and buildings on the University of Denver campus.

The Spanish Peaks, a 27- to 14-million-year-old igneous intrusion, are located in south-central Colorado near the towns of Walsenburg and Trinidad. The peaks are formed from a varied set of rocks, including granite, **granodiorite**, **syenite**, monzonite, and lamprophyre. In northeastern New Mexico, the 20,700-square-kilometer (8000-square-mile) Raton-Clayton Volcanic Field contains over 100 recognizable volcanoes, which erupted during the Neogene (likely as a result of crustal extension). For example, Capulin Volcano, an extinct cinder cone that rises steeply from the surrounding grasslands, blanketed the surrounding area with more than 39 square kilometers (15 square miles) of lava. Loose cinders, ash, and rock debris piled up to form a conical mountain, while lava erupted from fissures and vents closer to the volcano's base. Lava-capped mesas throughout the volcanic field, including the Barella, Johnson, and Raton mesas, bear witness to these powerful eruptions. Lava and rocks in the area have a wide range of compositions, including felsic rhyolite, intermediate **dacite** and andesite (*Figure 2.39*), and mafic basalt.

Many Quaternary deposits on the Great Plains of eastern Colorado and northeastern New Mexico are partly related to glacial processes. In the Southwest, glacial activity during the ice age was dominated by alpine glaciers in the mountains west of the Plains. Glacial erosion in the mountains resulted

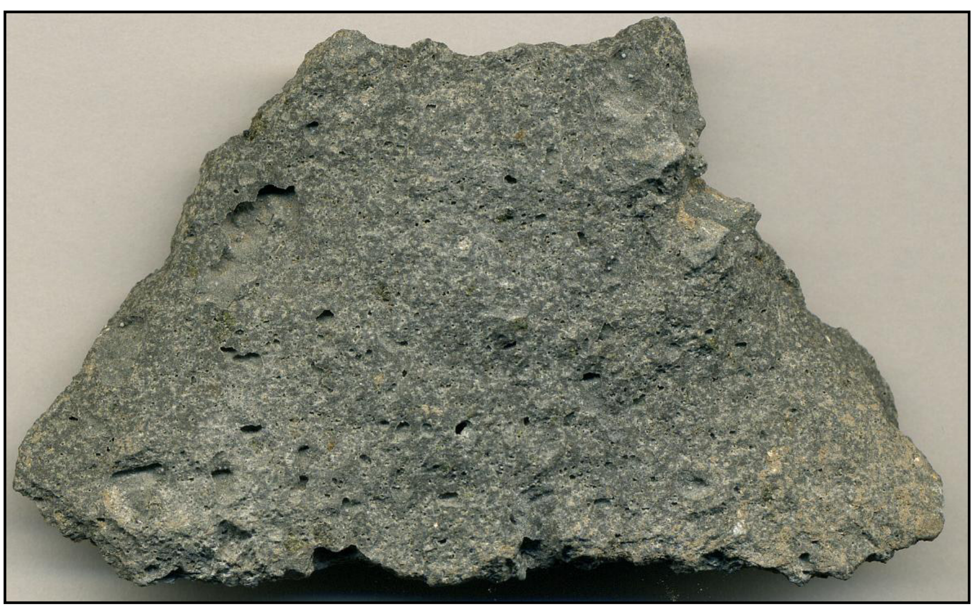


Figure 2.39: A piece of vesicular andesite from the flank of the Sierra Grande shield volcano, the largest peak in New Mexico's Raton-Clayton Volcanic Field. Specimen is 7.3 centimeters (2.9 inches) wide.

in vast amounts of fine- to medium-sized sediment being carried onto the Great Plains by rivers such as the Platte in Colorado. Finer sediment known as glacial flour, the product of glaciers grinding over rock, was picked up by the wind and deposited across large swaths of the region in layers called **loess**.

State Rocks, Minerals, and Gems

Arizona

Arizona has no state rock.

State mineral: copper
Copper mining has been a major industry in Arizona since the 19th century. The state has six of the 10 largest copper mines in the US, including the Morenci mine in Greenlee County, Arizona, which is the largest in the country. In 2007, Arizona produced 60% of the country's copper.

State **gem**: turquoise
Arizona is a major producer of turquoise, an opaque, blue-green mineral that has been popular in jewelry since Native American times. It contains copper and is often found in abundance near copper deposits. Arizona is currently the leading US state for turquoise production.

Colorado

State rock: Yule Marble
Yule Marble is found in the Yule Creek Valley in the West Elk Mountains of Colorado. This white, crystalline **marble** is composed of 99.5% calcite. It has been used in the construction of a number of prominent buildings and monuments.

State mineral: rhodochrosite
Rhodochrosite is a deep red to rose pink carbonate mineral found in association with Colorado's gold, silver, **lead**, **zinc**, and molybdenum **ores**. The world's largest rhodochrosite crystal is on display at the Denver Museum of Nature and Science. Because rhodochrosite is so specifically associated with Colorado, it was chosen as the state mineral over other common minerals such as gold and silver.

State gem: aquamarine
Aquamarine is a blue-colored variety of the mineral **beryl**. It was first discovered in 1881 on Mount Antero, in the Rockies of central Colorado. The state continues to be a major producer of gem-quality aquamarine.

State Rocks

gem *• a mineral that has aesthetic value and is often cut and polished for use as an ornament.*

marble *• a metamorphic rock composed of recrystallized carbonate minerals, most commonly calcite or dolomite.*

lead *• a metallic chemical element (Pb).*

zinc *• a metallic chemical element (Zn, atomic number 30).*

ore *• a type of rock that contains minerals with valuable elements, including metals, that are economically viable to extract.*

beryl *• a white, blue, yellow, green, or pink mineral, found in coarse granites and igneous rocks.*

Rocks

State Rocks

bituminous coal *• a relatively soft coal containing a tarlike substance called bitumen, which is usually formed as a result of high pressure on lignite.*

hardness *• a physical property of minerals, specifying how hard the mineral is, and its resistance to scratching.*

opal *• a silicate gemstone lacking a rigid crystalline structure.*

New Mexico

New Mexico has no state rock or mineral.

State gem: turquoise

Large turquoise deposits in New Mexico are present in the metamorphosed volcanics of the Los Cerillos Mountains, where they have been mined since prehistoric times. Due to the processes under which it formed, this turquoise developed in over 75 different colors. New Mexico was the largest US producer of turquoise until the 1920s; Arizona and Nevada have since become larger producers.

Utah

State rock: coal

Coal is found in 17 of Utah's 29 counties, but coal mining is primarily concentrated in Emery and Carbon counties, where coals formed in the Uinta Basin. Most coal mined in Utah is **bituminous**.

State mineral: copper

The Kennecott's Bingham Canyon mine in the Oquirrh Mountains is the world's largest open-pit copper mine. Copper is a versatile metal widely valued for its capacity to conduct heat and electricity, and is used in electronics, transportation, plumbing, and alloys, among many other areas.

State gem: topaz

Topaz is a **hard,** semiprecious gem that is found in Beaver, Juab, and Tooele counties in Utah. At Topaz Mountain, which is in the Thomas Mountain Range in Juab County, topaz and other minerals such as beryl and **opal** are found in relatively high abundance in the cavities of Neogene-aged rhyolites.

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Mitchell, J., 2008, *The Rockhound's Handbook, revised edition*, Gem Guides Book Company, Baldwin Park, CA, 299 pp.
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Prinz, M., G. Harlow, & J. Peters, eds., 1978, *Simon & Schuster's Guide to Rocks & Minerals*, Simon and Schuster, New York, 607 pp.

For additional resources on minerals, see the resources section in Chapter 5: Mineral Resources.

General Books and Websites on Rocks

Atlas of Igneous and Metamorphic Rocks, Minerals and Textures, University of North Carolina Geology Department, http://leggeo.unc.edu/Petunia/IgMetAtlas/mainmenu.html.
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Books, Articles, and Websites on Rocks of Specific Areas of the Southwest

Multistate areas

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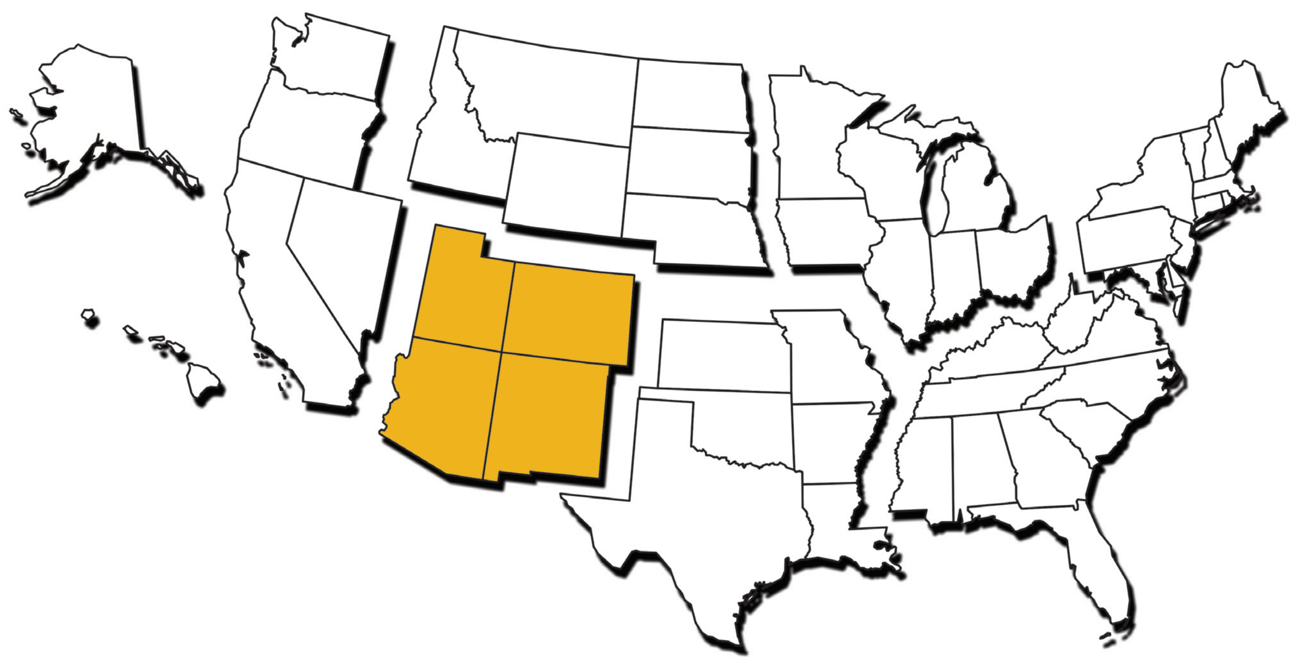
The *Teacher-Friendly* Guide™

to the Earth Science of the Southwestern US



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On the back cover: Blended geologic and digital elevation map of the Southwestern US. Each color represents the age of the bedrock at the surface. Adapted from Barton, K.E., Howell, D.G., Vigil, J.F., *The North America Tapestry of Time and Terrain*, US Geological Survey Geologic Investigations Series I-2781, http://pubs.usgs.gov/imap/i2781.