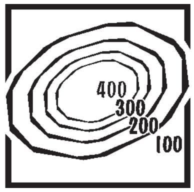

Chapter 4: Topography of the Southwestern US

Does your region have rolling hills? Mountainous areas? Flat land where you never have to bike up a hill? The answers to these questions can help others understand the basic topography of your region. The term **topography** is used to describe the shape of the land surface as measured by how elevation—height above sea level—varies over large and small areas. Over **geologic time**, topography changes as a result of weathering and erosion, as well as the type and structure of the underlying bedrock. It is also a story of **plate tectonics**, volcanoes, folding, **faulting**, **uplift**, and mountain building.

The Southwest's topographic zones are under the influence of the destructive surface processes of weathering and erosion. **Weathering** includes both the mechanical and chemical processes that break down a rock. There are two types of weathering: physical and chemical. Physical weathering describes the physical or mechanical breakdown of a rock, during which the rock is broken into smaller pieces but no chemical changes take place. Water, ice, and **wind** all contribute to physical weathering, sculpting the landscape into characteristic forms determined by the **climate**. In most areas, water is the primary agent of **erosion**. Streams are constantly eroding their way down through bedrock to sea level, creating valleys; Arizona's Grand Canyon provides a dramatic example of this process. Given sufficient time, streams can cut deeply and develop wide flat **floodplains** on valley floors. The pounding action of ocean waves on a coastline contributes to the erosion of coastal rocks and sediments, while the emptying of a river can lead to the formation of a **delta**. Rock material is carried by rivers and streams to the oceans or to an inland lake or basin where it is eventually deposited. In the case of the Basin and Range and parts of the desert in southern New Mexico and Arizona, streams end in basins within the region. The rest of the Southwest is drained by rivers that reach either the Gulf of Mexico (the Platte, Arkansas, Canadian, Pecos, and Rio Grande rivers) or the Gulf of California (the Colorado River and its major tributaries, the Green and San Juan rivers).

Pressure release can also cause rocks to crack. Growing plant roots can exert many pounds per square inch of pressure on rocks—think of **tree** roots uplifting and cracking a sidewalk. Additionally, since rocks buried kilometers (miles) beneath the surface are under considerable pressure, if those rocks become exposed at the Earth's surface (where the rock is under less pressure), the rock may expand and crack in a process called **exfoliation** (*Figure 4.1*). At higher elevations, ice can also change the landscape due to frequent episodes of freezing and thawing, causing both temperature and pressure differentials within a rock. As water trapped in **fractures** within the rock freezes and thaws, the fractures continue to widen (*Figure 4.2*). This alone can induce significant

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

geologic time scale *• a standard timeline used to describe the age of rocks and fossils, and the events that formed them.*

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

fault *• a fracture in the Earth's crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side.*

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

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

CHAPTER AUTHORS

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Review

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

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

igneous rocks • rocks derived from the cooling of magma underground or molten lava on the Earth's surface.

metamorphic rocks • rocks formed by the recrystallization and realignment of minerals in pre-existing sedimentary, igneous, and metamorphic rocks when exposed to high enough temperature and/or pressure.

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

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

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

breakdown of large rock bodies. During the **Quaternary**, ice has been an important agent of erosion throughout the highest parts of the Southwest.

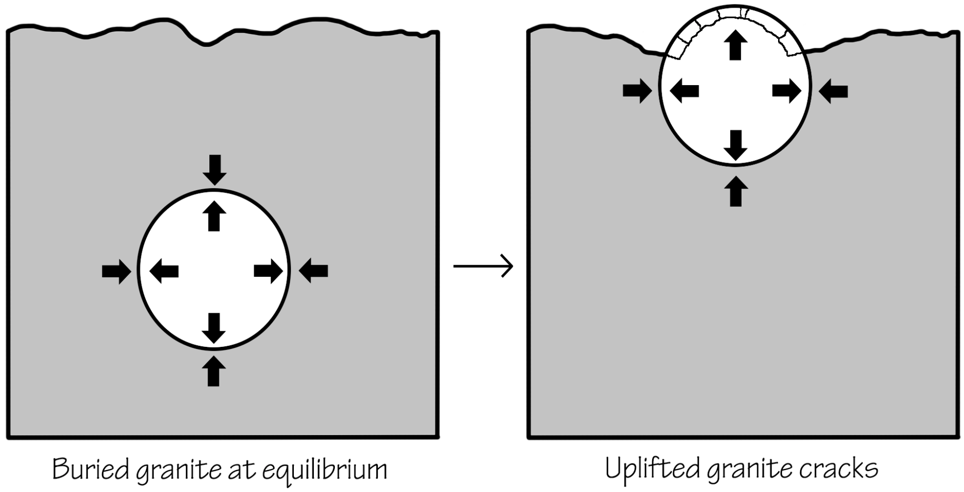


Figure 4.1: Exfoliation as a result of uplift and pressure release.

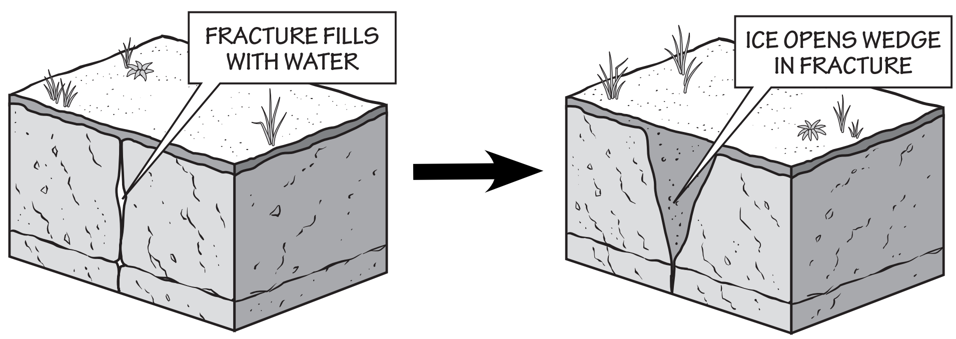


Figure 4.2: Physical weathering from a freeze-thaw cycle.

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

Topography 4

Volcanic activity has shaped the land throughout the Southwest. Although there are no active volcanoes there today, evidence of past activity—such as volcanic cones and craters, **lava** flows, **dikes**, and plugs—can be seen in a variety of locations, including volcanic fields throughout the Basin and Range and along the southern edge of the Colorado Plateau, **tuff** beds in and along the Rio Grande Rift, and the Carrizozo Malpais lava field in New Mexico.

The specific rock type at the surface has an important influence on the topography of a region. Certain rocks are able to resist weathering and erosion more easily than are others; resistant rocks that overlie weaker layers act as caps and form ridges. The great continental seas that advanced across the face of the continent during the **Paleozoic** and **Mesozoic** collected and preserved sediments that became sedimentary rocks, such as the deposits exposed along the walls of the Grand Canyon. Sedimentary rocks weather and erode differently than do crystalline (and generally **harder**) igneous and metamorphic rocks, such as those found at the base of the Grand Canyon and in the Rocky Mountains. **Silica**-rich igneous rocks have a crystalline nature and mineral composition that resists weathering far better than do the cemented grains of a sedimentary rock. The metamorphic equivalents of sedimentary and igneous rocks are often even more resistant than the original unmetamorphosed rocks, due to **recrystallization**. There are exceptions, however, such as **schist**, which is much weaker than its pre-metamorphic limestone or **sandstone** state.

See Chapter 2: Rocks for more information about the igneous, metamorphic, and sedimentary rocks of the Southwest.

The underlying structure of the rock layers also plays an important role in the topography at the surface. In the Southwest, with its semi-arid climates and lack of dense vegetative cover, the rock structures that influence the area's topography are clearly revealed. Sedimentary rocks are originally deposited in flat-lying layers that rest on top of one another. The movement of tectonic **plates** creates stress and tension within the **crust**, especially at plate boundaries. **Intrusions** beneath the surface may also cause deformation of the crust. All these different sources of geological stress can deform flat sediment layers through folding, faulting, or overturning. These terms are collectively used to describe rock structure, and they can also be used to determine which forces have affected rocks in the past. The folding of horizontal rock beds followed by erosion and uplift brings layers of rock to the surface. Tilted rocks expose underlying layers; resistant layers stick out and remain as ridges, while surrounding layers of less resistant rock erode away. Faulting likewise exposes surface layers to erosion, as blocks of crust move and tilt along the fault plane. For example, the Basin and Range formed as a result of normal faulting (*Figure 4.3A*), which occurs due to extensional stresses that create uplifted ranges and downdropped basins. The Rocky Mountains provide another regional example of folding and faulting: this range formed as a result of uplift associated with **subduction** along the western edge of the North American plate. The shallow angle of the subducting plate generated thrust (reverse) faults (*Figure 4.3B*) and the onset of the **Laramide Orogeny**.

Review

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

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

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

volcanism • *the eruption of molten rock onto the surface of the crust.*

lava • *molten rock located on the Earth's surface.*

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

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

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

4 Topography

Review

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

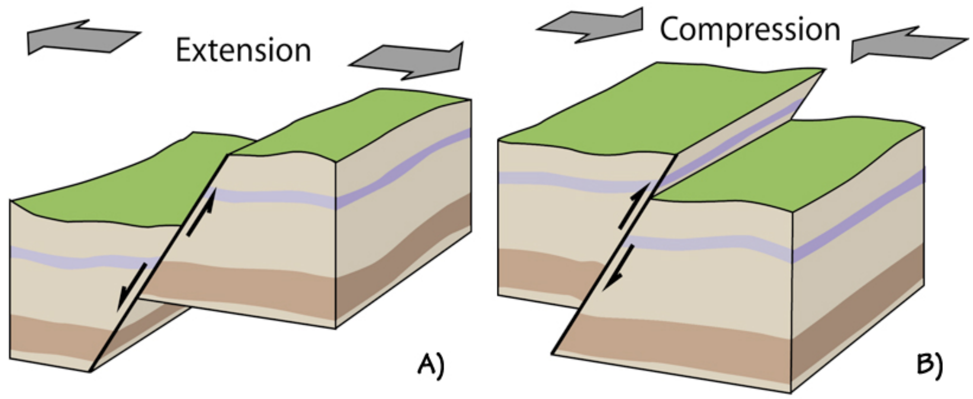


Figure 4.3: A) Normal faulting and B) thrust (reverse) faulting.

Just as we are able to make sense of the type of rocks in an area by knowing the geologic history of the Southwestern US, we are able to make sense of its topography (*Figure 4.4*) based on rocks and structures resulting from past geologic events. Topography is a central element of the broader concepts of geomorphology or **physiography**, which also include consideration of the shape (not just the height) of land forms, as well as the bedrock, soil, water, vegetation, and climate of an area, and how they interacted in the past to form the landscape we see today. A physiographic province is an area in which these features are similar, one in which these features are significantly different from those found in adjacent regions, and/or one that is separated from adjacent regions by major geological features. The "regions" of the Southwest that we use in this book are examples of major physiographic provinces. The topography unique to each region thus provides a set of clues to its extensive geologic history.

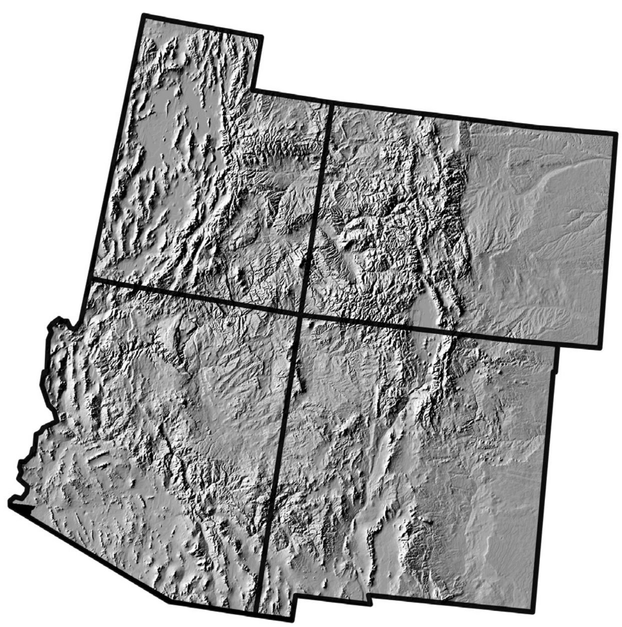


Figure 4.4: Digital shaded relief map of the Southwestern states.

Topography

4

The rocks of the Southwest reach back into the **Precambrian**, but the area's remarkable topography is primarily the result of dramatic Mesozoic and **Cenozoic** plate tectonics. Subduction of the Farallon plate during the late **Cretaceous** and Cenozoic, and the associated **Sevier** and Laramide **orogenies**, shaped the mountains of the Basin and Range as well as uplifiting the Rocky Mountains, Colorado Plateau, and the edge of the Great Plains. Late Cenozoic crustal extension led to faulting and volcanic activity that is most dramatically exhibited in the Basin and Range of Utah and Arizona and the Rio Grande Rift of New Mexico and Colorado. Southwestern topography particularly emphasizes broad **epeirogenic** uplift, one of the more contentious and least understood features of the Earth's topography. In contrast to orogenic (mountain building) uplift, epeirogenic uplift raises the land surface without **compressing** and thus thickening the crust. During the Cenozoic, most of the Southwest was lifted by this process. Today, the elevation of nearly the entire Southwest lies above 1200 meters (4000 feet), except for the southwestern desert in Arizona (*Figure 4.5*). The north-south "backbone" of highest elevation, shown by areas above 1800 meters (6000 feet), stretches from New Mexico through Colorado and into Wyoming. The Rocky Mountains of Colorado define a particularly high area, where elevations exceed 2700 meters (9000 feet) over a large part of the state.

See Chapter 1: Geologic History for more information about the tectonics and mountain building that shaped the Southwest.

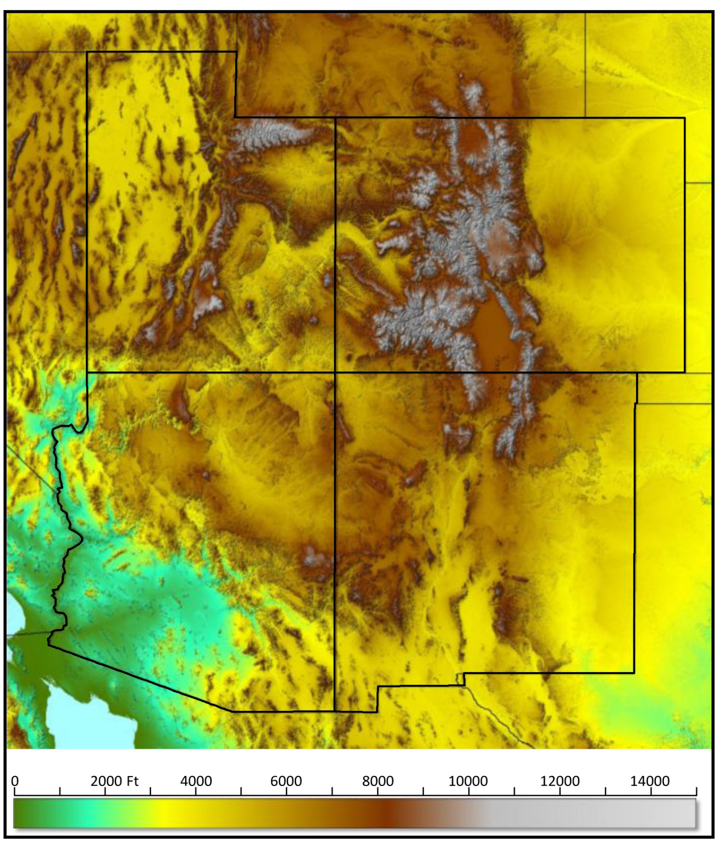


Figure 4.5: Elevation map of the Southwest (See TFG website for full-color version).

Review

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).*

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

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

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

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

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

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

4 Topography

Region 1

anticline • *a layer of rock folded (bent) along an axis, concave side down (i.e., in an upside down "u" or "v" shape).*

Topography of the Colorado Plateau
Region 1

The Colorado Plateau covers an area of approximately 335,000 square kilometers (130,000 square miles) close to the center of the Southwest. It is the one region located in all four states, whose borders intersect at the "four corners" near the center of the plateau. It is bordered by the Colorado Rockies in the northeast, the Uinta Mountains in the northwest, and the Basin and Range (including the Rio Grande Rift) along the west, southwest, and southeast. Although the Colorado Plateau is largely semi-arid, the Colorado River and its tributaries access considerable runoff from snowmelt and rain in the Rocky Mountains to the north and east. These rivers and streams have carved numerous canyons throughout the region, culminating in the grandest of canyons on Earth. The Colorado River defines the lowest elevation on the plateau, near 330 meters (1100 feet) where it exits into Lake Mead, but most of the plateau is higher, with an average elevation of approximately 2000 meters (6500 feet) and elevations mainly in the range of 1200 to 2400 meters (4000 to 8000 feet). Higher elevations up to 3300 meters (11,000 feet) are located in the High Plateaus of Utah and the volcanic fields of the Navajo section (*Figure 4.6*).

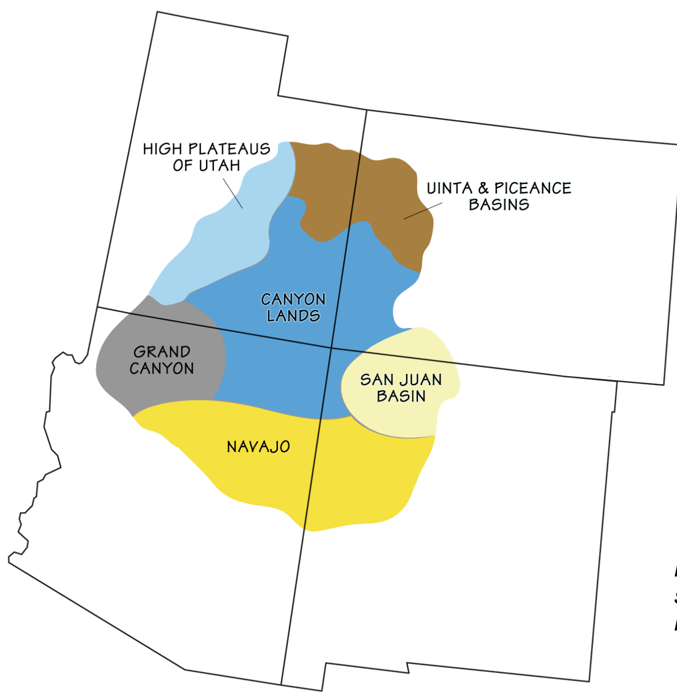
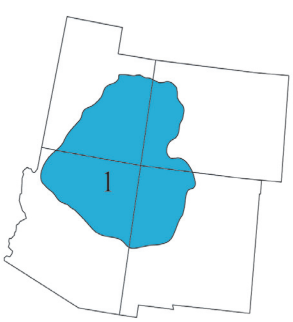


Figure 4.6: Physiographic subdivisions of the Colorado Plateau.



The outstanding and unusual topographic scenery of the Colorado Plateau is a main theme for the 8 National Parks and 25 National Monuments located there. Initially, this topography was shaped when the Laramide Orogeny deformed the thick sequence of Paleozoic and Mesozoic strata that had previously been lying flat near sea level beneath the Western Interior Seaway. The broad arches (**anticlines**), monoclines, domes, and basins formed by the Laramide

Orogeny are beautifully preserved in the plateau as textbook examples of geologic structures. During the Cenozoic, the margins of the plateau were also affected by Basin and Range faulting and **magmatism**. Second, erosion of the plateau, especially during the late Cenozoic, has mostly occurred in a semi-arid environment. This has allowed a dramatic display of both the unique forms of semi-arid erosion (driven by flash floods, frost, and intermittent rain) and the structural features generated by past geologic deformation.

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

Canyon Lands

The Canyon Lands (or Canyonlands), encompassing the central portion of the Colorado Plateau, are a scenic wonderland where erosion has sculpted some of the most beautiful and geologically fascinating landscapes on Earth. The semi-arid climate prevailing over the plateau during much of the Cenozoic has interacted with the area's mildly deformed layer cake of sedimentary strata to produce fantastic erosional forms. The strata's variation in thickness and erodibility led to the formation of plateaus, mesas, **buttes**, and chimneys, all fringed by cliffs or a staircase of cliffs and slopes topped with more resistant **caprocks**. The slopes between cliffs are formed from eroded rock debris. As plateaus continue to erode, they leave behind progressively smaller remnants, including arches, natural bridges, windows, tents, spires, needles, hoodoos, balanced rocks, fins, and pinnacles that appear in stunning displays (*Figures 4.7-4.9*). The differing patterns of vertical **joints** in the rocks are a major factor in the production of this variety of bizarre features. In thick massive sandstones such as the Navajo Formation exposed in Zion National Park, erosion of vertical joints has produced deep and narrow canyons with up to 600 meters (2000 feet) of **relief** on nearly vertical canyon walls. The same type of erosion has created thousands of spectacular hoodoos in Bryce Canyon.

Figure 4.7: Weathered rock spires in the Needles district of Canyonlands National Park, Utah.

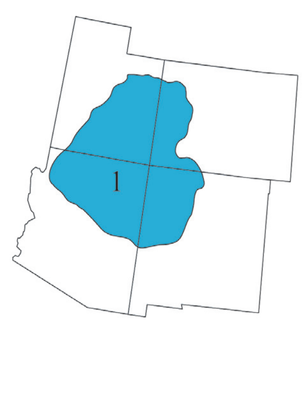
magma *• molten rock located below the surface of the Earth.*

butte *• an isolated hill with steep, often vertical sides and a small, relatively flat top.*

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

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

relief *• the change in elevation over a distance.*



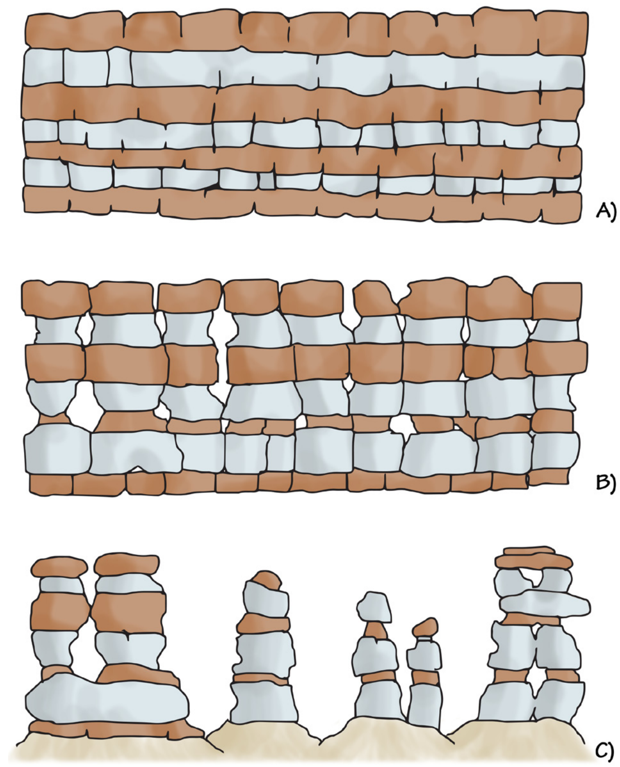
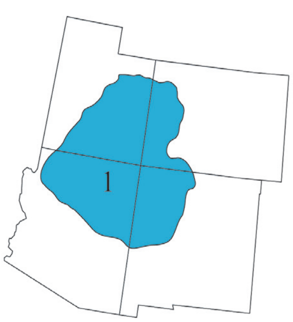


Figure 4.8: Erosive processes in the Colorado Plateau. A) Solid sedimentary strata contain fractures, joints, and other points of weakness. B) Weathering from rain and frost eats away at the sedimentary rock along its weak points. C) Progressively smaller remnants are left behind as erosion continues over time. More resistant rock layers cap the spires.

Figure 4.9: Delicate Arch, Arches National Park, Utah. The La Sal Mountains are visible in the background.

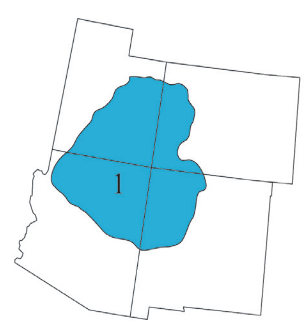


In spite of the plateau's generally semi-arid climate, erosion of such features is aided by localized, intense thunderstorms that produce very energetic (and dangerous) flash floods, transporting considerable masses of rock debris. The gorges, slots, and chasms of the Canyon Lands are a particularly prominent example of the erosive actions of flash floods. The area boasts the highest concentration of slot canyons in the world—these features are formed by the wear of water rushing through rock, and are extremely tall and narrow. Antelope Canyon, a slot canyon located approximately 10 kilometers (6 miles) southwest of the town of Page, Arizona, near the Glen Canyon Dam, is over 30 meters (100 feet) deep but measures only a few meters (yards) in width (*Figure 4.10*) The Upper and Lower Antelope canyons are carved in a 300-meter-long (1000-foot-long) section of Navajo Sandstone that partially blocks Antelope Creek, a stream that flows north to join the Colorado River. During flash floods, water fills the upstream basin, forcing mud- and **sand**-saturated water through a crack in the obstruction. The combination of turbulent flow interacting with the sand dune structures of the Navajo Sandstone has produced intricately carved and incredibly beautiful slot canyons.

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

See Chapter 2: Rocks for more information about the Navajo Sandstone and other Jurassic sand dune deposits.

Figure 4.10: Lower Antelope Canyon (The Corkscrew), Arizona, a slot canyon characterized by the flowing spiral shape of its walls. The canyon was formed by erosion of the Navajo Sandstone due to flash flooding.



4 Topography

Region 1

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

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

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

laccolith *• an intrusive igneous rock body that forms from magma that has, through pressure, been forced between two sedimentary layers.*

In places, the Colorado Plateau has been deformed by sharp, fault-cored folds called monoclines. These geologic landforms are step-like folds in rock strata, where an otherwise horizontal rock sequence dips steeply. The Waterpocket Fold, a monocline that defines Capitol Reef National Park, extends for nearly 160 kilometers (100 miles) across the Canyon Lands of central Utah. It formed between 70 and 50 million years ago, when the Laramide Orogeny activated a buried fault. The overlying rock layers on the fold's west side were lifted more than 2100 meters (7000 feet) higher than those on the east side (*Figure 4.11*). Today, the erosion of these tilted rock layers, which dip sharply downwards to the east, has resulted in colorful cliffs with fantastical domes, spires, and monoliths. Capitol Reef National Park is named for its white domes of Navajo Sandstone, which resemble the dome of the Capitol Building (*Figure 4.12*).

In addition to monoclines, compression during the Laramide Orogeny also formed convex uplifted domes, or anticlines (*Figure 4.13*). The San Rafael Swell of central Utah is a 120-kilometer-long (75-mile-long) sandstone anticline that was pushed up during the **Paleocene**. Today, its sedimentary rocks have eroded into valleys, canyons, and mesas, exposing the **Jurassic** Navajo and Wingate sandstones and the **Permian** Coconino and Kaibab formations. I-70 cuts across this area, exposing the rock strata and providing beautiful vistas.

Cenozoic magmatic activity has also left major imprints on the Colorado Plateau's topography. During the Laramide Orogeny, magma intruded into the region's sedimentary strata and spread out, creating **laccoliths**—domed intrusions of magma injected into the sedimentary rock layers like jelly in a jelly donut. The laccoliths pushed up overlying sediment, which later eroded away to expose the igneous rock below. The Henry, La Sal, Abajo, and Carrizo mountains, as well as the Sleeping Ute and Lone Cone peaks, are all examples of laccolithic mountain ranges in the Canyon Lands.

Figure 4.11: A view south along the Waterpocket Fold, Utah, which slopes steeply down across the white Navajo Sandstone. The formation is named for its "waterpockets," small depressions that form when rain erodes the sandstone.

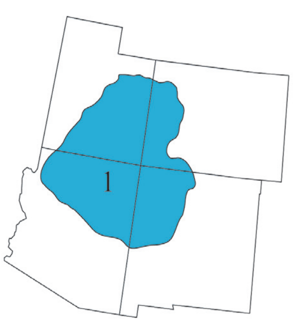


Figure 4.12: Capitol Dome and other white domes of Navajo Sandstone are common geologic features in Capitol Reef National Park, Utah.

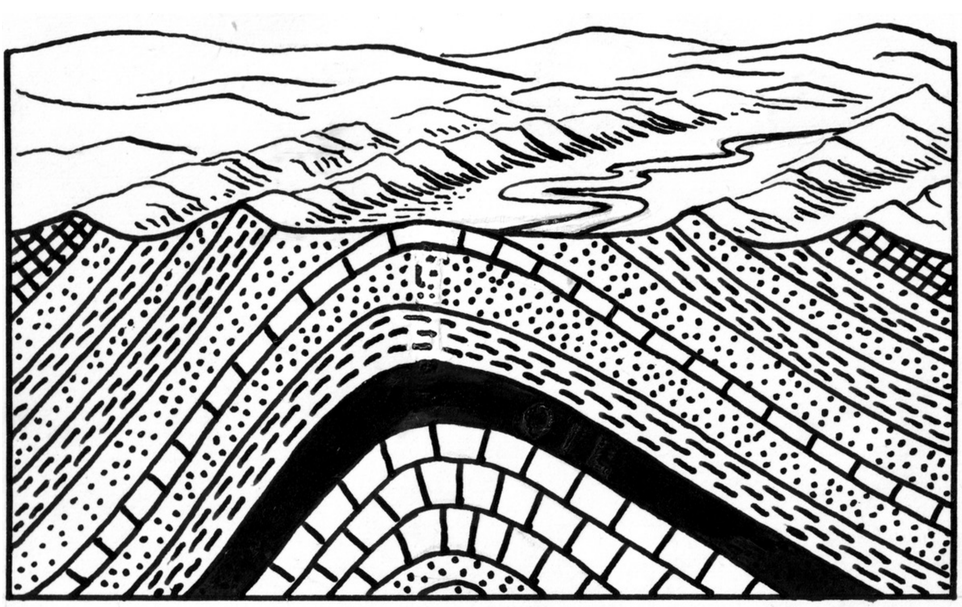
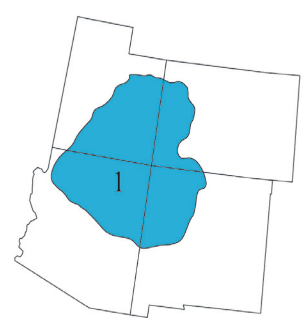


Figure 4.13: An anticline, an upward fold in layered rocks.



4 Topography

Region 1

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

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

Grand Canyon

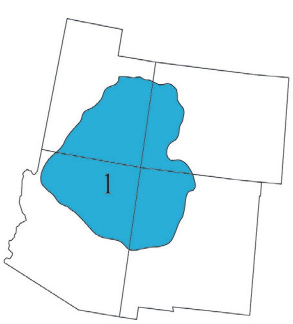
The most extensive erosion anywhere on the Colorado Plateau has taken place at the region's southwest corner, in the area of the Grand Canyon. Permian-aged strata are found at much of the surface, revealing the extensive erosion that has taken place during the Cenozoic. An entire section of Mesozoic strata, estimated to be perhaps 450 meters (1500 feet) thick, has been eroded from the Plateau's southwest corner.

It is at the Grand Canyon itself that the erosional power of water is so dramatically demonstrated (*Figure 4.14*). The Colorado River has incised through all of the area's Mesozoic and Paleozoic strata, reaching the Precambrian metamorphic and igneous **basement rock**. This process has formed a canyon with dramatic topographic relief—the river's elevation is over a kilometer (nearly a mile) lower than the south rim of the canyon, and two kilometers (over a mile) lower than the north rim. An enormous array of tributary canyons is also visible from the canyon's rims. These tributaries exhibit remnant mesas and chimneys, and a step-like erosional pattern of cliffs, flats, and steep piles of rock rubble, resulting from variations in the rock layers' resistance to erosion. In contrast, in areas where the river has incised into the very hard Precambrian basement rock, the cross-section becomes V-shaped. V-shaped streambeds form in areas where rivers cut downwards into rock that is relatively uniform in resistance.

The rise of the Colorado Plateau is closely connected to the formation of the Grand Canyon. How and when this gigantic example of **fluvial** erosion occurred has remained hotly debated since geologist John Wesley Powell's trip by boat through the canyon in 1867. Many generations of geologists have questioned whether the canyon is very old, dating back to or before the Laramide Orogeny, or is geologically relatively young. Much of the literature available in past years and in tourist guides speaks of "hundreds of millions of years" as the time it took to carve the canyon, but this is incorrect. In fact, major portions of the Grand Canyon were downcut in response to the region's uplift, starting eight million years ago, in possible combination with a lower base elevation associated with Basin and Range crustal stretching.

The Colorado River does, however, have a complex ancestry that extends further back in time. Rivers have been running through the Grand Canyon area for the tens of millions of years it has been above sea level, and some initially carved their own canyons through normal erosional processes. One such canyon on the western side, Hurricane Canyon, may have been formed by a river that flowed northwest 70 to 50 million years ago; another on the eastern side may have formed approximately 25 to 15 million years ago. Segments of the Grand Canyon probably did develop to perhaps half their current depth during an early- and mid-Cenozoic time frame. The westernmost portion upstream from Lake Mead, and the northernmost segment, Marble Canyon, formed in just the past six million years. As these young river segments integrated with older ones, they formed the modern Colorado River that widened and deepened the Grand Canyon we know today.

The entire series of Mesozoic and Cenozoic strata is preserved farther north and east of the Grand Canyon, and is progressively revealed along the Grand Staircase. Here, successively younger strata each form higher steps. South-

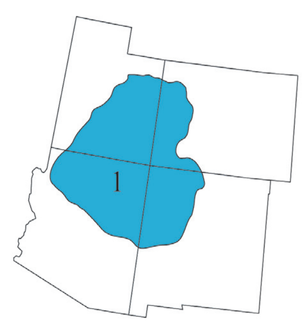


color (mineral) • *a physical property determined by the presence and intensity of certain elements within the mineral.*

Figure 4.14: A view of the Colorado River flowing through the Grand Canyon, from Pima Point, Arizona.

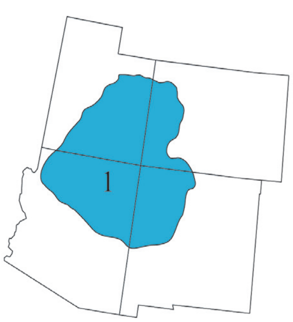
ward facing risers—the more sloping or vertical parts between the steps, also known as scarps—are formed by south-facing cliffs (cuestas) of the northward dipping strata. The cliffs have names describing their **colors**, including Chocolate, Vermillion, White, Gray, and Pink cliffs (*Figure 4.15*).

See Chapter 2: Rocks for more on the stratigraphy of the Grand Staircase and Grand Canyon.



4 Topography

Region 1



The Colorado River

The Colorado River and its tributaries drain most of the Colorado Plateau, as well as the Uinta Mountains, the southwestern Wind River Mountains, the eastern Wyoming Range, and the western Rockies. The river exits the plateau into the lower elevation desert of Arizona and southern Nevada and then travels southwards, as the boundary between Arizona and California, to the Gulf of California. The river descends steeply through the Grand Canyon from Lees Ferry, at an elevation of 940 meters (3100 feet), to about 330 meters (1100 feet), where it flows into Lake Mead.

The Colorado River and its tributaries.

Region 1

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

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

ice cap • *an ice field that lies over the tops of mountains.*

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

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.*

Figure 4.15: Colorful mesas of the Vermillion Cliffs near Para, Utah, in the Grand Staircase-Escalante National Recreation Area.

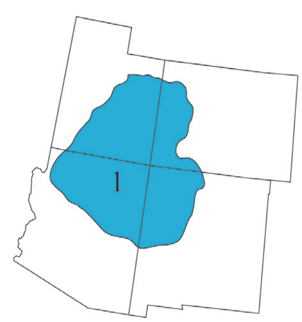
The Uinkaret Volcanic Field, which includes numerous Quaternary **basaltic cinder** cones and flows, is located near and on the northern rim of the western Grand Canyon. The age of these flows has provided key data for estimating the Grand Canyon's incision rates during the past 100 to 600 thousand years. The most recent eruption in Uinkaret occurred approximately 1000 years ago; some of the lava flows spilled into the gorge and temporarily dammed the Colorado River.

High Plateaus of Utah

North of the Grand Canyon lie the High Plateaus of Utah, a part of the Colorado Plateau where extensive volcanism has covered much of the landscape. The plateaus, separated by north-south trending normal faults, form a transition zone between the Colorado Plateau and the more fully developed extensional structures of the Basin and Range. The Marysvale Volcanic Field, which arose in the mid- and late Cenozoic, forms the caprocks of the High Plateaus in this area.

See Chapter 2: Rocks to learn more about volcanic fields in the Southwest.

On the easternmost Aquarius Plateau, the highest forested plateau in North America, Boulder Mountain forms a high elevation mesa with a volcanic cap protecting the more erodible Mesozoic sediments beneath. The Boulder Mountain mesa, at an elevation of approximately 3350 meters (11,000 feet), had a small **ice cap** and **glaciers** during the last **ice age**. A combination of Quaternary glaciation and the susceptibility of the underlying sedimentary rocks to erosion has produced remarkable **landslides** around much of the mesa.



4 Topography

Region 1

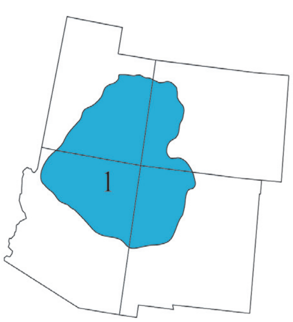
oil *• See petroleum: a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface and consisting primarily of hydrocarbons*

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

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

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

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



Uinta and Piceance Basins

The Uinta and Piceance basins encompass a diverse landscape of forests, canyons, and high mountains, which overlie deep basins formed in association with the Laramide basement uplift of the Rocky Mountains. The Uinta and Piceance basins are two parts of an ancient east-west trending basin that developed across the Utah-Colorado state boundary during the late Cretaceous. They are known for their accumulation of **oil shale** from the deep parts of the basin, and **coal** beds from the basin edges. Nearly the entire sequence of Mesozoic and Cenozoic strata, through the late Cenozoic, is preserved in this area.

See Chapter 6: Energy to learn more about the extraction of oil in the Uinta and Piceance Basins.

San Juan Basin

The San Juan Basin is an area of rugged plains and valleys, covering approximately 12,000 square kilometers (4600 square miles) of northwestern New Mexico and southeast Colorado. The basin encompasses a large, **downwarped** area of Mesozoic and Cenozoic rocks, formed in association with the Laramide Orogeny, and it is an important reservoir for oil and gas. Countless archaeological sites of the Ancestral Puebloan people can also be found throughout the San Juan's sandstone canyons. The landscape is punctuated by buttes, mesas, and **badlands**, including Chacra Mesa, Fajada Butte, and the Bisti Badlands (*Figure 4.16*).

Figure 4.16: Sandstone hoodoos in the Ah-Shi-Sle-Pah Wilderness Study Area, San Juan County, New Mexico. A hoodoo forms when weathering erodes a softer material out from underneath a mass of harder capstone, leading to "mushroom" formations.

Navajo

The Navajo section, along the southern edge of the Colorado Plateau in Arizona and New Mexico, is dominated by Cenozoic volcanism. The San Francisco, Hopi Buttes, Springerville-Red Hill, Zuni-Bandera, and Mount Taylor volcanic fields are all located in this part of the region. Volcanism in this area of the Colorado Plateau is related to tectonic activity that stretched the neighboring Basin and Range region.

The San Francisco Volcanic Field, a young volcanic field dating from six million years ago to the **Holocene**, is located between the Grand Canyon and Flagstaff, Arizona. The field is dotted with 600 large and small volcanic cinder cones; most are basaltic cinder cones, but the largest edifice is an eroded **stratovolcano** that forms the San Francisco Peaks (*Figure 4.17*). An **aquifer** that supplies much of Flagstaff's water is located within the volcano's ancient **caldera**. The San Francisco Peaks contain the six highest peaks in Arizona, including Humphreys Peak (the highest point in Arizona at 3851 meters [12,633 feet]), and the mountain range is a popular site for hiking and skiing. The most recent eruption within the San Francisco Volcanic Field occurred between the years 1064 and 1180, forming Sunset Crater—the focus of the Sunset Crater Volcano National Monument—and nearby smaller cones and flows.

Figure 4.17: The San Francisco Peaks of north central Arizona are a remnant of San Francisco Mountain, a former stratovolcano that collapsed around 200,000 years ago.

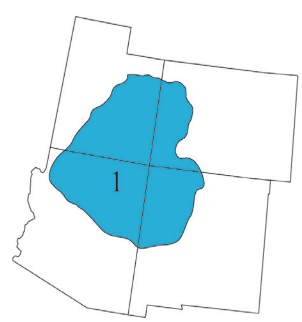
There are striking remains of volcanic **maars**, craters left by volcanic explosions, in the Hopi Buttes Volcanic Field. The maars are approximately 80 kilometers (50 miles) east of the San Francisco Volcanic Field, in the Navajo Reservation near the town of Dilkon, Arizona. The volcanism there is older than the San Francisco field and has been dated to seven million years ago. Erosion at Hopi Buttes exposes approximately 300 deep vertical volcanic pipes called **diatremes** and their associated maars. These exposures of diatremes and maars have become a mecca for geologists studying monogenetic volcanism—locations where many small volcanoes erupt only a single time each.

Holocene *• the most recent portion of the Quaternary, beginning about 11,700 years ago and continuing to the present.*

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

aquifer *• a water-bearing formation of gravel, permeable rock, or sand that is capable of providing water, in usable quantities, to springs or wells.*

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



4 Topography

Region 1

Scattered cones and basaltic flows of late Cenozoic age leave their topographic imprint in a zone trending northeast along the southern border of the Colorado Plateau including the Springerville–Red Hill, Zuni-Bandera, and Mount Taylor volcanic fields. These areas, similar to the San Francisco Volcanic Field, are characterized by basaltic flows and cinder cones plus a large eroded stratovolcano, Mount Taylor. Cabezon Peak, a prominent feature in the northwestern New Mexico landscape, is a volcanic plug—the solidified remains of magma trapped in the neck of a volcano—that is also part of the Mount Taylor Volcanic Field (*Figure 4.18*).

Figure 4.18: Cabezon Peak, a basalt volcanic plug that rises to 2373 meters (7785 feet) in elevation. It is part of the Mount Taylor Volcanic Field in New Mexico.

The Springerville–Red Hill Volcanic Field is another large area of numerous **Pliocene**-**Pleistocene** cinder cones and flows. It is located close to the southern border of the Colorado Plateau, approximately 160 kilometers (100 miles) south-southeast of the Hopi Buttes. Just to the south of this field is Mount Baldy, a deeply eroded **shield volcano** of late Cenozoic age.

Approximately 55 kilometers (35 miles) east of Flagstaff is a small topographic feature that at first glance might be mistaken for a volcanic feature, such as a maar. This crater, approximately 1200 meters (3900 feet) in diameter and 45 meters (148 feet) deep, is in fact the result of a **meteorite** impact. It is, appropriately, called Meteor Crater (*Figure 4.19*). A **nickel**-**iron** meteorite generated the crater approximately 50,000 years ago; it is estimated to have been approximately 45 meters (150 feet) across and was mostly vaporized upon impact. The largest recovered fragment is called the Holsinger Meteorite and is exhibited at the crater's visitor center. It weighs 639 kilograms (1409 pounds) and is approximately 1.2 meters (4 feet) long.

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

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

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.*

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

nickel *• a ductile, silvery-white metallic element (Ni) generally found in combination with iron.*

iron *• a metallic chemical element (Fe).*

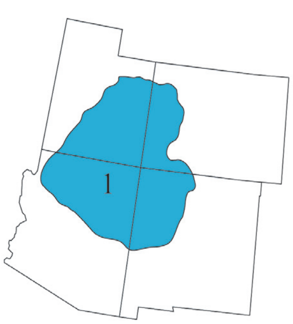


Figure 4.19: Meteor Crater (also called Barringer Crater), Coconino County, Arizona.

Topography of the Basin and Range
Region 2

In the Southwest, the Basin and Range stretches along the western sides of Utah and Arizona as well as the southern parts of Arizona and New Mexico (*Figure 4.20*). The entire Basin and Range region covers a massive expanse of land, stretching from Idaho and southeastern Oregon through all of Nevada, southeastern California, and extending into western Texas and Mexico.

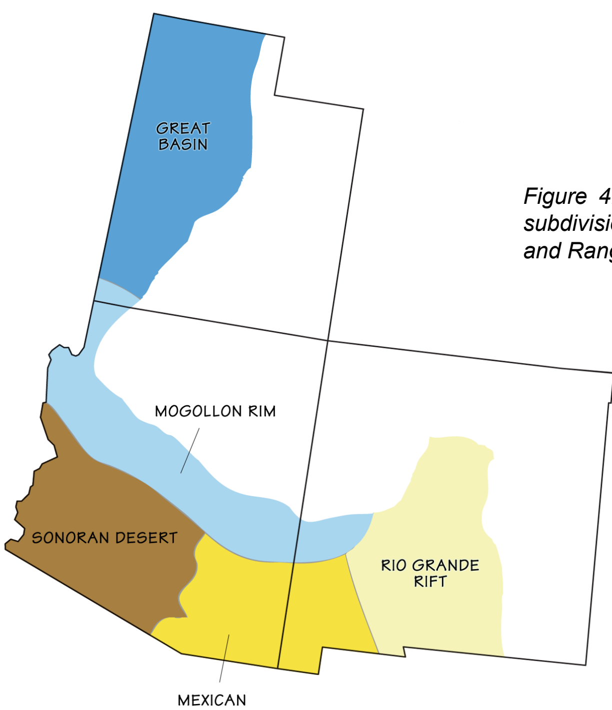
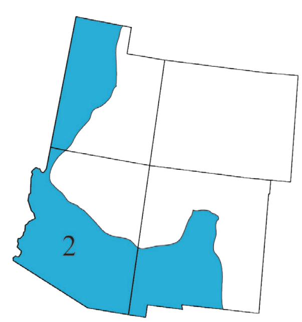


Figure 4.20: Physiographic subdivisions of the Basin and Range.



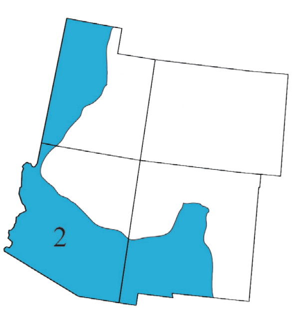
Topography

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

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

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

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



The Basin and Range is characterized by rapid changes in elevation alternating from flat and dry basins to narrow, faulted mountains. This pattern of many parallel, north-south mountain ranges found throughout the region inspired geologist Clarence Dutton to famously observe that the topography of the Basin and range appeared “like an army of caterpillars crawling northward.” The formation of this topography is directly related to tectonic forces that led to crustal extension (pulling of the crust in opposite directions). After the Laramide Orogeny ended in the **Paleogene**, tectonic processes stretched and broke the crust as California's San Andreas fault **system** began to develop, and the upward movement of magma weakened the **lithosphere** from underneath. Approximately 20 million years ago, the crust along the Basin and Range stretched, thinned, and faulted into some 400 mountain blocks. The pressure of the **mantle** below uplifted some blocks, creating elongated peaks and leaving the lower blocks below to form down-dropped valleys. The boundaries between the mountains and valleys are very sharp, both because of the straight faults between them and because many of those faults are still active.

These peaks and valleys are also called horst and graben landscapes (*Figure 4.21*). Such landscapes frequently appear in areas where crustal extension occurs, and the Basin and Range is often cited as a classic example thereof. In the Basin and Range, the crust has been stretched by up to 100% of its original width. The distance between the Sierra Mountains of California and the Colorado Plateau increased by over 320 kilometers (200 miles) as a result of this crustal extension. Due to the stretching, the average crustal thickness of the Basin and Range is 30–35 kilometers (19–22 miles), compared with a worldwide average of approximately 40 kilometers (25 miles).

There is a marked change in elevation between the northern and southern portions of the Basin and Range. In Utah, the Great Basin is in the range of 1200 to 2100 meters (4000 to 7000 feet) in elevation, while the Sonoran Desert in Arizona is mostly 150 to 600 meters (500 to 2000 feet) above sea level.

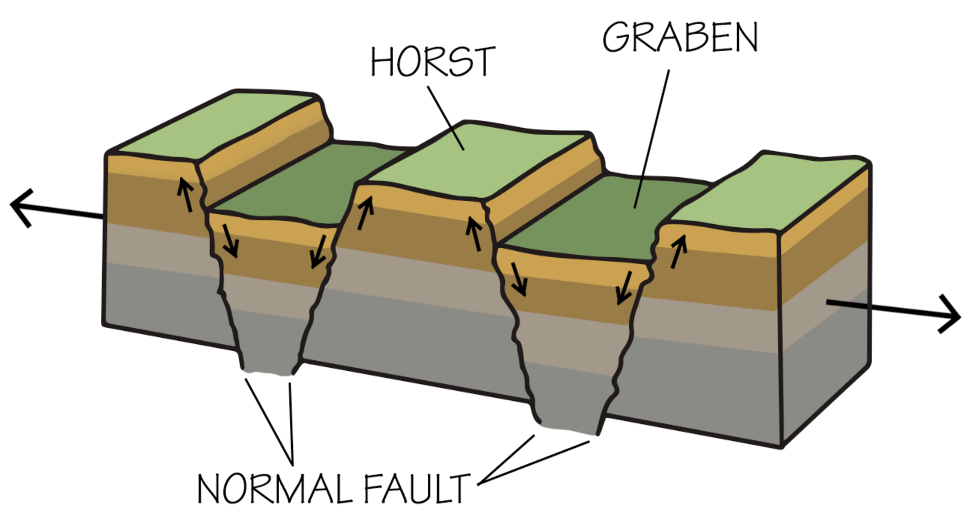


Figure 4.21: A horst and graben landscape occurs when the crust stretches, creating blocks of lithosphere that are uplifted at angled fault lines.

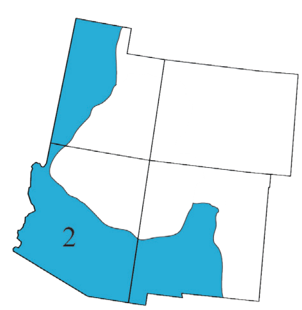
Region 2

Great Basin

Utah's western half is part of the Great Basin, an area that spans most of Nevada and reaches into California, Oregon, and Idaho (*Figure 4.22*). The Great Basin is bounded on all sides by topographical features—the Wasatch Range in Utah, the Sierra Nevada and Cascades in California, and the Snake River Basin to the north—that prevent it from having any outlet to the ocean. As such, the Basin drains internally; that is, all water in the region evaporates, flows into lakes, or sinks underground. Because there are no flow outlets and water typically leaves lakes via evaporation (allowing minerals to concentrate), many of the area's lakes are saline.

In Utah, the Great Basin largely drains into the Great Salt Lake, which receives considerable runoff from the Wasatch Range. Today, the Great Salt Lake is the largest saltwater lake in the Western Hemisphere and the largest remnant of

Figure 4.22: The extent of the Great Basin.



4 Topography

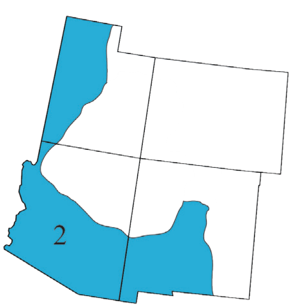
Region 2

pluvial lake • *a landlocked basin that fills with rainwater or meltwater during times of glaciation.*

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

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

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



Lake Bonneville, a large, deep **pluvial lake** that covered much of western Utah during the Pleistocene. As the lake evaporated, **salts** were concentrated in the remaining water, then left behind with the muds as the final water evaporated from low areas. The present day Great Salt Lake has a saline content of approximately 13% (depending on lake level) and contains approximately 4.1 billion metric tons (4.5 billion tons) of salt. Deltas and shoreline deposits from Lake Bonneville remain visible on the slopes of the Wasatch Mountains, and their elevations provide measurements of the area's **isostatic** rebound after the lake receded and the weight of its water was removed from the land. Other, smaller remnants of Lake Bonneville include Rush Lake, Sevier Lake, and Utah Lake, as well as the Bonneville Salt Flats and the Escalante Desert Valley.

See Chapter 8: Climate to learn more about the formation and extent of glacial Lake Bonnevile.

Mogollon Rim

The Mogollon Rim is a major escarpment that forms the southern edge of the Colorado Plateau, extending approximately 320 kilometers (200 miles) through Arizona and into New Mexico. Erosion and faulting have carved dramatic canyons into the rim, and **Carboniferous** and Permian sandstone and limestone form spectacular high cliffs. The Mogollon Rim rises approximately 1200 meters (4000 feet) above the land to the south (*Figure 4.23*).

Escarpments, or "scarps," form when faulting or erosion acts to create a cliff or steep slope that separates two level or gently sloping topographical surfaces.

Figure 4.23: The Mogollon Rim in Coconino National Forest, Arizona.

Isostasy

The elevation of Earth's surface topography, on scales of a few kilometers (miles), may seem to result just from the height of the rigid rock that the crust is made of. However, over hundreds or thousands of kilometers, surface elevation is mainly influenced by how the weight of the thin rigid lithosphere (which includes the crust and uppermost mantle) floats buoyantly on the more fluid-like part of the mantle (the *asthenosphere*). Since this relationship is complex and good data from the deep subsurface are difficult to acquire, it is still not well understood.

The weight of the lithosphere in a unit area is controlled by its thickness and the *density* of its rocks. All else being equal, the heavier the lithosphere, the more it will sink into the mantle. For example, water and sediment may accumulate in a basin, increasing weight and pressing downward, or water may be drained and rocks eroded away. In higher latitudes, Pleistocene continental glaciers pushed the crust downward, and when they melted, the land surface slowly rose again in a process called isostatic rebound. With tectonic movement, the lithosphere may thicken by horizontal compression or thin by extension (as in the Basin and Range). Since the boundary between the lithosphere and asthenosphere is controlled by where rigid rocks become fluid (about 1300°C [2370°F]), the lithosphere's thickness and density are also controlled by how quickly temperature increases with depth. These and yet other factors can make a detailed understanding of Earth's topography remarkably challenging.

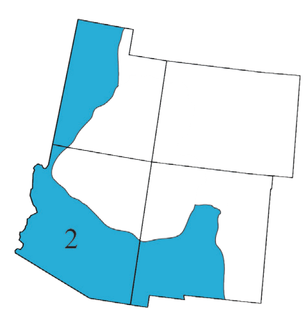
asthenosphere • *a thin semifluid layer of the Earth, below the outer rigid lithosphere, forming much of the upper mantle.*

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

alluvial • *a layer of river-deposited sediment.*

Sonoran Desert

Arizona's southwestern corner is occupied by the Sonoran Desert, the hottest desert in North America. The area is characterized by steep, blocky mountain ranges and intervening flat desert basins, as well as intermittent streams and **alluvial** fans formed when heavy rainstorms transport eroded material. During extension of the Basin and Range in southern Arizona, the overlying sedimentary rocks were stretched so much that underlying metamorphic rocks were exposed. These rocks are called metamorphic core complexes (MCCs), and they consist of metamorphic rock bodies that formed deep in the crust before moving to the surface along low-angle faults. MCCs are usually the



Region 2

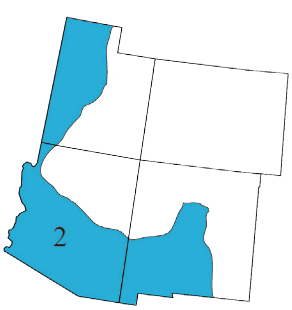
andesite *• a fine-grained extrusive volcanic rock, with a silica content intermediate between that of basalt and dacite.*

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

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

lava tube *• a natural tube formed by lava flowing beneath the hardened surface of a lava flow.*

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



highest topography in the area, but are also domed and frequently do not match the form of other nearby mountains, which have modest relief (300 to 600 meters [1000 to 2000 feet]) and are nearly buried in their eroded detritus. This extremely resistant metamorphic rock, along with patches of volcanics, are responsible for many small mountain ranges that do not follow the mostly north-south pattern of narrow ridges so characteristic of the rest of the Basin and Range. Large intervening basins, filled with eroded sediment from the mountains, are drained by the Gila River into the Colorado River. Saguaro National Park is located close to an especially prominent example, forming the Rincon and Santa Catalina mountains near Tucson (*Figure 4.24*). A band of MCCs stretches from southeastern Arizona to the junction of its borders with California and Nevada (*Figure 4.25*); the pattern continues north through eastern Nevada, then reemerges in Utah's northwestern corner.

Mexican Highlands

The Mexican Highlands, extending from eastern Arizona into western New Mexico, contains Basin and Range structures with higher relief and higher basin elevations, similar to those of the Great Basin. Desert grasslands surround the highlands' isolated mountain ranges, and the area also includes a number of volcanic structures.

The Mogollon-Datil Volcanic Field in southeastern Arizona and southwestern New Mexico includes mid-Cenozoic volcanic **andesites**, tuff, **rhyolites**, and basalts that extend into the complexly faulted area where the Basin and Range melds into the Rio Grande Rift zone. The deeply eroded remains of a number of silicic calderas have been identified, including the Mogollon Mountains whose peaks reach nearly 3350 meters (11,000 feet). This volcanic field includes part of the Continental Divide between the Gila and the Rio Grande rivers.

Rio Grande Rift

The Basin and Range of New Mexico is dominated by the Rio Grande Rift, a zone of extension in the continental crust running from New Mexico north into Colorado. A small amount of true crustal spreading occurred in this narrow area, resulting in an elongate depression bounded by faults, which also controls the course of the Rio Grande River. Magma erupting through the **rift** resulted in adjacent volcanic fields, as well as volcanic fill, that cover the rift valley floor. Faulting of the Rio Grande Rift also reaches into and affects the topography of the Colorado-New Mexico Rocky Mountains.

The Rio Grande Rift began to form approximately 30 million years ago, peaked from 16 to 10 million years ago, and remains tectonically active today. One recent eruption, the 5000-year-old Carrizozo Malpais, resulted in a 75-kilometer-long (47-mile-long) flow of black basalt that filled the Tularosa Basin and contains **lava tubes**, collapse pits, wrinkles, and fissures (*Figure 4.26*). The Carrizozo Malpais is considered to be one of the youngest lava flows in the continental US.

Directly south of the Carrizozo Malpais lies a famous non-volcanic feature, the White Sands National Monument. This is the largest **gypsum** dune field in the world, covering an area of 710 square kilometers (275 square miles) in southern

Figure 4.24: The heavily eroded Santa Catalina Mountains near Tucson, Arizona are surrounded by forests of saguaro cacti. The highest point in these mountains has a relief of 1572 meters (5157 feet) over the surrounding landscape, and the mountains are tall enough to receive snowfall.

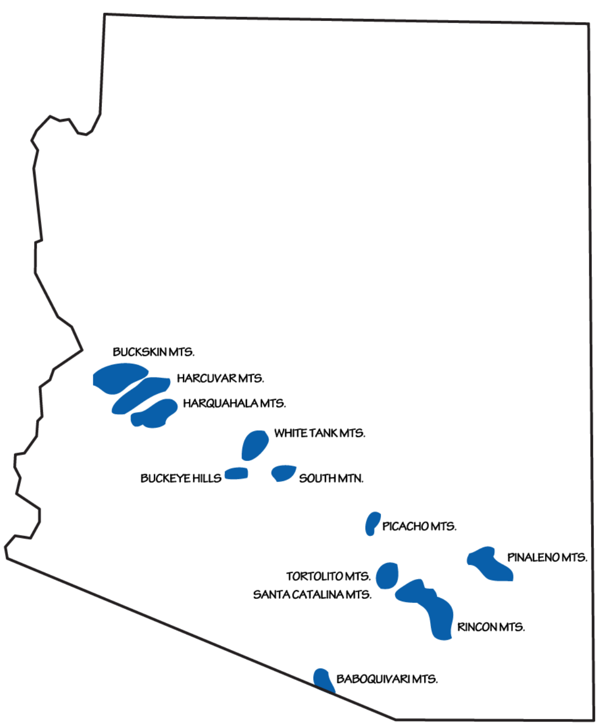
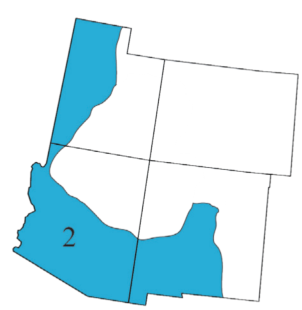


Figure 4.25: Distribution of metamorphic core complexes in Arizona.

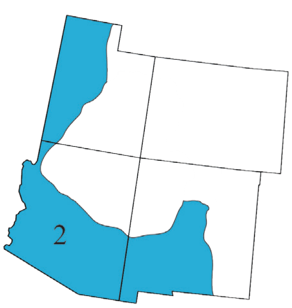


New Mexico (*Figure 4.27*). The dunes are composed of windblown gypsum grains, eroded from Permian Basin **evaporite** deposits in the surrounding San Andres Mountains. Gypsum is water-soluble, and is found in sand form only rarely; White Sands has endured thanks to the area's aridity and the fact that the Tulsarosa Basin has no outlet to the sea.

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

Figure 4.26: A characteristic ropy lava flow covers the ground at the Valley of Fires Recreation Area in New Mexico, directly adjacent to the Carrizozo Malpais.

Figure 4.27: Windblown gypsum dunes of the White Sands National Monument, New Mexico. The dune field began forming 25,000 years ago.



Topography of the Rocky Mountains
Region 3

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

talus • *debris fields found on the sides of steep slopes, common in periglacial environments.*

The Rocky Mountains of the Southwest consist of multiple uplifted ranges resulting from the Sevier and Laramide orogenies, as well as from Cenozoic volcanism and extension. The mountains extend more than 4800 kilometers (3000 miles) from northern British Columbia southward through Alberta, Idaho, Montana, Wyoming, and—in the Southwest—into central and western Colorado, northeastern Utah, and north-central New Mexico (*Figure 4.28*). They include the high and rugged mountain ranges of the Southern Rocky Mountains, located between the Colorado Plateau and the Great Plains; the Uinta Mountains, bordering the northwestern part of the Colorado Plateau; and the Wasatch Mountains, located in Utah along the eastern border of the Basin and Range. Because of their high elevations, all the ranges capture rain and snow, and have been subjected to both fluvial and glacial erosion during the Quaternary. Evidence for this varies from the **cirques** and U-shaped valleys of the Front Range to the massively glaciated San Juan Mountains and their numerous huge rock glaciers (glaciers buried in **talus**).

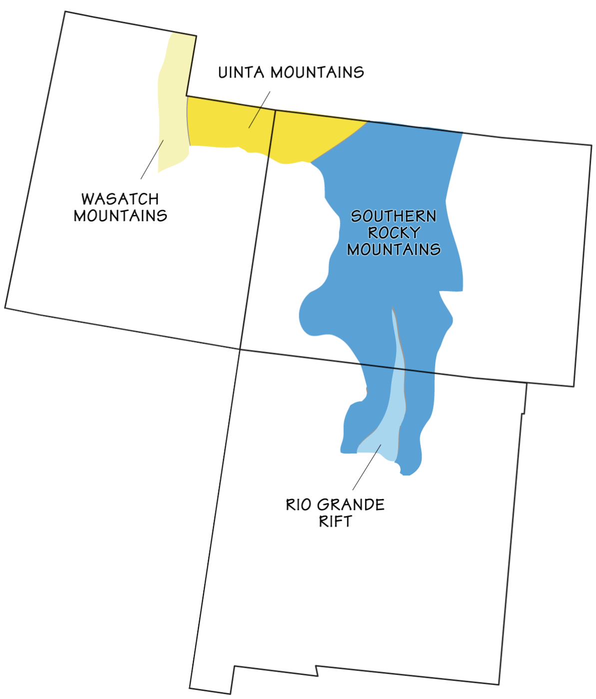


Figure 4.28: Physiographic subdivisions of the Rocky Mountains.

The Rocky Mountains, from the Wyoming border to northern New Mexico, boast 53 peaks over 4200 meters (14,000 feet) high—the "Fourteeners" of mountain climbing fame. The highest part of the Rocky Mountain uplift is centered in Colorado; the state has the highest concentration of mountains over 4200 meters (14,000 feet) high in the continental US, as well as the highest base elevation of any area of the continent. Forty of these peaks are located in Colorado's Sawatch, Sangre de Cristo, and San Juan ranges, and were uplifted by faulting or magmatic activity during the mid- to late Cenozoic.

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

ice field • *an extensive area of interconnected glaciers spanning less than 50,000 square kilometers (19,305 square miles).*

Wasatch Mountains

The Wasatch Mountains, located at the western edge of the Rockies in between the Basin and Range and the Colorado Plateau, stretch approximately 260 kilometers (160 miles) south from the Utah-Idaho border. This mountain range owes its current high relief mainly to faulting that encroached into the Colorado Plateau during the Cenozoic. Normal faulting is still active along the Wasatch Fault today, posing **seismic** risks to Salt Lake City.

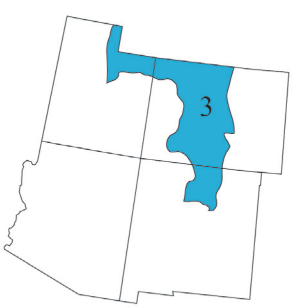
See Chapter 9: Earth Hazards to learn more about earthquakes along the Wasatch Fault.

There are no exposures of Precambrian basement rock in the Wasatch Range, except for a small area near the westward extension of the Uinta uplift—the mountains are largely made up of Paleozoic strata. The mountain range is punctuated by valleys, into which it drops steeply on its western side and more gently to the east. Much of the Wasatch Range exhibits glacially sculpted landforms (*Figure 4.29*).

Figure 4.29: Mount Timpanogos in Utah's Wasatch Range displays the sculpting power of moving ice. Alpine glaciers shaped the mountain's knife-edge ridges and its wide U-shaped amphitheaters.

Uinta Mountains

The Uinta Mountains are the only the only part of the Rockies where the mountains run east-west instead of generally north-south. This range is a classic example of Laramide uplift, when the Precambrian basement rock and its cover of Paleozoic and Mesozoic sedimentary strata were pushed up to form an anticline bounded on either side by low-angle thrust faults. The faults dipped beneath the Precambrian basement and thrust it above sedimentary cover, deforming the strata into basins adjacent to the mountain range. During and subsequent to these crustal deformations, erosion removed the entire series of Paleozoic and Mesozoic strata above the uplift, exposing the more resistant Precambrian rocks beneath. The exposed Precambrian block eroded slowly, forming relatively smooth relief during the Cenozoic, and was nearly buried by the accumulation of eroded sediments. During glaciation in the Quaternary, the highest parts of the Uinta Mountains were covered by an **ice field**. High peaks poked through the ice as isolated points called "nunataks," while glaciers moving down on either side carved cirques and U-shaped valleys, generating the alpine ruggedness we are familiar with today.



During the mid- to late Cenozoic, the eastern part of the Uinta uplift played a key role in shaping the flow of the Colorado River. In the mid-Cenozoic, the ancestral Green River flowed south from the Wind River Mountains in northern Wyoming and then east towards the Great Plains. After the Laramide Orogeny ended, faulting in the low-elevation and sediment-covered eastern segment of the Uintas led to a complex series of stream captures that eventually connected the southward flow of the Green River to the then-northern headwaters of the Colorado River. With this added contribution of water from the Wind River and Wyoming ranges and the northern slopes of the Uintas, the connection cut through the sedimentary cover to carve the dramatic Lodore Canyon into the Precambrian core of the Uinta uplift (*Figure 4.30*).

Figure 4.30: The Green River flows through the Gates of Lodore near Dinosaur National Monument, Colorado.

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

Southern Rocky Mountains

The Rocky Mountains of Colorado and New Mexico have a complex topographical history. Their high relief is a product of four components: uplift of the late Paleozoic Ancestral Rockies, compressional uplift of Precambrian basement rock during the Laramide Orogeny, igneous activity during the mid- to late Cenozoic, and extensional tectonics associated with the Rio Grande Rift. The effects of volcanism and the Rio Grande Rift were most important at the region's southern end, where the rift dominates the landscape.

The Ancestral Rockies date to the **Pennsylvanian**, during which time thrust faulting uplifted the Precambrian basement rock in Colorado and northern New Mexico. These ancient mountains were covered beneath the Western Interior Seaway during the Mesozoic, but they generated weaknesses in the crust that led to greater faulting during the Laramide Orogeny. During the late Cretaceous

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

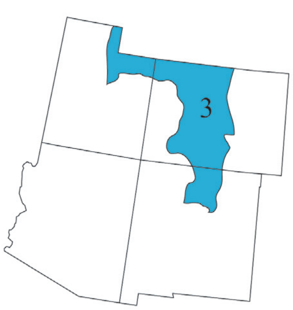
terrace • *a flat or gently sloped embankment or ridge occurring on a hillside, and often along the margin of (or slightly above) a body of water, representing a previous water level.*

pluton • *a body of intrusive igneous rock that formed under the Earth's surface through the slow crystallization of magma.*

and early Cenozoic, the Rockies were rejuvenated by compressional uplift, and erosion began anew, cutting stream valleys and leaving the more resistant rock as topographic highs. Alpine glaciers later carved cirques into the high peaks, leaving the rugged sharp peaks we see today. This is best exhibited in the northern Colorado Rockies, including the Front Range north of Colorado Springs (*Figure 4.31*), the Gore Range near Vail, and the Park Range, which extends north into Wyoming. In between these ranges lie the North Park and Middle Park basins, which are broad, lower areas of relatively low relief floored by Precambrian basement rocks. Meltwater from glaciers deposited **outwash plains** and **terraces** downstream—Rocky Mountain National Park in northern Colorado contains spectacular examples of these features.

Figure 4.31: The view from Mount Evans, one of the highest points in Colorado's Front Range at 4350 meters (14,271 feet).

Farther south, the Rocky Mountains become increasingly affected by Cenozoic faulting and volcanism associated with the Rio Grande Rift. On the western side of the rift, the Elk, Sawatch, and Mosquito ranges are cut by a rift valley (graben) bordered by normal faults between the Sawatch and Mosquito ranges. The valley forms the headwaters of the West Arkansas River. The Nacimiento Mountains are another example of Laramide-aged basement uplift; their Precambrian rocks thrust towards the west. The northern part of the range includes the San Pedro Parks Wilderness Area, which has the highest elevation of the mountain range, reaching up to approximately 3230 meters (10,600 feet). The area's high relief is due to the resistance of its Precambrian **plutonic** rocks. The San Juan Mountains, also located on the rift's western side, are primarily mid-Cenozoic volcanoes that are now deeply eroded into rugged mountains. The ruggedness of the terrain, especially in contrast to mountains formed from Precambrian metamorphics, highlights the difference in erodability between the two types of rocks.



East of the rift across the South Park Basin, uplifted Precambrian basement rocks of the Rampart Range and Pikes Peak Massif face the Great Plains. Exposures of uplifted Precambrian rocks continue in the Wet Mountain Range and the long, narrow Sangre de Cristo Range, which ends south of Santa Fe, New Mexico. The Sangre de Cristo Mountains were uplifted in the mid- to late Cenozoic through a process similar to Basin and Range extension. South of the Sangre de Cristo Range, the mountains are slightly lower in elevation. The Sierra Blanca Mountains are the eroded remains of a large mid-Cenozoic volcano with peak elevation reaching nearly 3700 meters (12,000 feet). The Sandia Mountains, reaching peak elevations just under 3000 meters (10,000 feet), comprise uplifted late Paleozoic and Mesozoic strata.

Rio Grande Rift

The Rio Grande Rift is a zone of extension that reaches from New Mexico's Basin and Range up through the Rocky Mountains to central Colorado, near Leadville. Recent studies indicate traces of the rift may extend farther north, almost to the Wyoming border. Cenozoic volcanic activity within the rift had a major impact on the topography of the surrounding Rocky Mountains, including the flow of the Rio Grande River. When the rift formed, it captured the river, which initially began as a stream trickling from the mountains near Leadville.

The Jemez Lineament in northern New Mexico is thought to be an elongate, ancient crustal weakness through which magmas erupted as part of the Basin and Range extension. Where the Jemez Lineament crosses the Rio Grande Rift, more intense volcanism occurred, forming the Jemez Volcanic Field. This area includes the Valles Caldera, a **supervolcano** that last erupted approximately 1.5 and 1.2 million years ago. Its crater measures approximately 19 by 24 kilometers (12 by 15 miles) across; the younger caldera, 22 kilometers (14 miles) wide, partially buried the older. The supervolcano eruptions produced thick tuffs (i.e., the Bandelier Formation), which cover the eastern side of the caldera and form the Pajarito Plateau. The tuffs slope gently eastward, and are eroded into narrow, vertically walled canyons with relief of up to 240 meters (800 feet). Hoodoos, such as those found at the Kasha-Katuwe Tent Rocks National Monument in Sandoval County, New Mexico, are also common formations found in Jemez **pyroclastic** flows. The northeast trend of late Cenozoic volcanism continues farther across the Rio Grande Rift and into the Great Plains. This linear movement has been attributed to a **hot spot** track, but the dates of the eruptions do not travel in a line from oldest to youngest, as do those associated with other well-known hot spots such as Yellowstone or Hawai‘i.

See Chapter 2: Rocks to learn more about the Jemez Lineament, supervolcanoes, and volcanic fields in the Southwest.

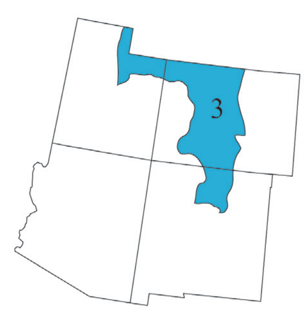
The Rio Grande Rift is also occupied by a series of high-altitude basins: the upper Arkansas graben and San Luis Basin in Colorado, and the Espanola, Albuquerque, and Socorro basins in New Mexico. Each basin is filled with sediment eroded from the nearby mountains and interbedded with **volcanic ash** and lava. The San Luis Valley covers approximately 21,000 square kilometers (8000 square miles) of Colorado and a small portion of New Mexico.

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

pyroclastic rocks *• rocks that form during explosive volcanic eruptions, and are composed from a variety of different volcanic ejecta.*

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

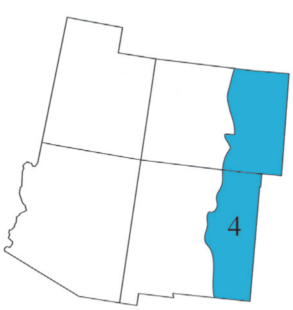
volcanic ash *• fine, unconsolidated pyroclastic grains under 2 millimeters (0.08 inches) in diameter.*



One of the valley's most prominent features is the Great Sand Dunes National Park and Preserve, which contains the tallest sand dunes in North America (*Figure 4.32*). The sand in these dunes formed from Cenozoic deposits left by the Rio Grande and its tributaries, which flow through the valley. The dunes rise approximately 230 meters (750 feet) from the valley floor, near the western base of the Sangre de Cristo Range.

Figure 4.32: Great Sand Dunes National Park and Preserve, at the foot of the Sangre de Cristo Mountains, Colorado.

Topography of the Great Plains
Region 4



The Great Plains is a lowland area underlain by flat-lying sedimentary rocks, and it extends in a north-south band across the entire United States from Montana and North Dakota to Texas and New Mexico. In the Southwest, the Great Plains lie along the eastern margins of Colorado and New Mexico (*Figure 4.33*). The region has a basement of flat-lying Precambrian metamorphic and igneous rocks, overlain by Paleozoic and Mesozoic sedimentary rocks. The Mesozoic sediments consist largely of materials eroded from the Rocky Mountains and deposited in the Western Interior Seaway, which covered this area during the Cretaceous. The Laramide uplift that affected the Colorado Plateau and Rocky Mountains also raised the western Great Plains, but did not significantly buckle or disturb the sedimentary layers. For this reason, the Great Plains region is not entirely flat, but changes in elevation from 1830 meters (6000 feet) on its western edge to 460 meters (1500 feet) on its eastern edge. During much of the Cenozoic, the Great Plains' gentle eastward slope has received sediments deposited by streams issuing from the western highlands. The top of that sequence of continental strata is the Ogallala Formation, deposited between 15 and 5 million years ago in the **Miocene**. This formation houses the famous Ogallala (or High Plains) Aquifer, which supplies water for most of the Great Plains.

See Chapter 9: Earth Hazards to learn about drought's impact on the Ogalalla Aquifer.

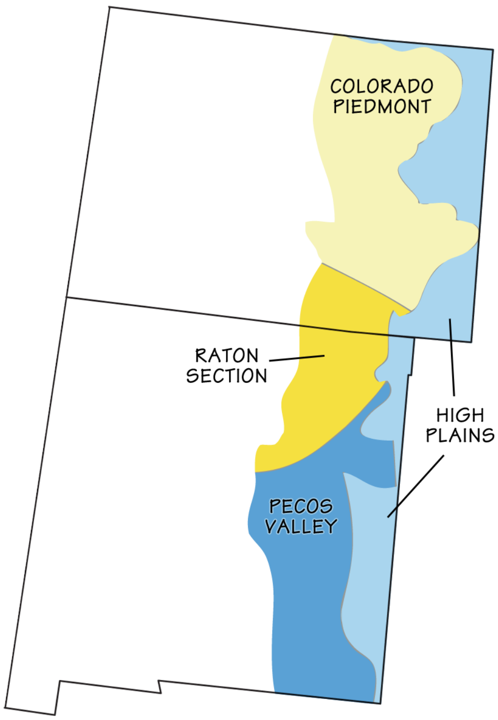


Figure 4.33: Physiographic subdivisions of the Great Plains.

There are deep sedimentary basins in the Great Plains, which have **subsided** throughout most of the **Phanerozoic** while at the same time collecting thick layers of sediment. The Denver Basin covers northeastern and eastern Colorado, into Wyoming, Nebraska, and Kansas. The Raton Basin spans southeastern Colorado and northeastern New Mexico, and the Permian Basin is located in southeastern New Mexico and into west Texas. Multiple strata in these sedimentary basins are important for oil and gas, and certain sandstones contain uranium deposits.

See Chapter 6: Energy for more information about the Southwest's sedimentary basins and major sources of fossil fuels.

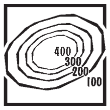
Colorado Piedmont

The Colorado Piedmont, which runs along the foothills of the Front Range in the Rocky Mountains, is a broad hilly valley that serves as the locus of Colorado's urban and agricultural activity. The area hosts the South Platte and Arkansas rivers and their tributaries, which have cut deeply into the Paleogene

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

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

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



Region 4

dendritic drainage • *a drainage pattern where many smaller streams join and contribute to ever larger streams.*

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

sediments deposited after the uplift of the Rocky Mountains. A less eroded segment between the river valleys is located east of Pikes Peak. Here, the middle Cenozoic Castle Rock Conglomerate is preserved in many locations, forming the resistant, protective cap seen on mesas and buttes. Along the eastern edge of the Rockies, older limestones and sandstones upturned during the Laramide Orogeny form a series of hogback ridges and flatirons (steeply sloping triangular landforms) that run parallel to the great mountain chain (*Figure 4.34*).

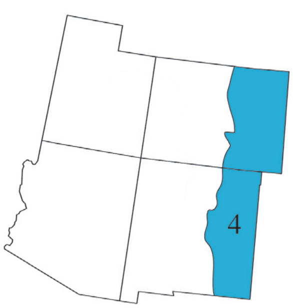
Figure 4.34: The Flatirons rise from the hilly grasslands of the Colorado Piedmont near Boulder, Colorado.

Raton

South of the Colorado Piedmont, the Raton section comprises a less eroded, higher segment between the Arkansas and Canadian Rivers. The area borders the southern end of the Rockies and exhibits interesting erosional and igneous topography.

The Park Plateau is formed from the surface outcrop of the Raton Formation, deposited from material eroded off the Sangre de Cristo Range during Laramide mountain building. The area covered by the formation straddles the divide between the Arkansas and Canadian Rivers and the border between Colorado and New Mexico. The tributaries of the two rivers have eroded the landscape in an intricate **dendritic** pattern, forming a finely dissected hilly area with a relief of approximately 100 meters (330 feet) between hills and valleys. The formation is also of great interest because it includes an iridium-rich **clay**

See Chapter 3: Fossils to learn more about the Cretaceous-Paleogene extinction.



unit that marks the great meteor impact at the Cretaceous-Cenozoic boundary. The Spanish Peaks, a 27- to 14-million-year-old intrusion, are located in south-central Colorado just east of the Sangre de Cristo Range at the northern edge of the Raton Formation. These eroded igneous plutons lie at the border between the Great Plains and Rocky Mountains, forming two large, high peaks with elevations of 4153 meters (13,626 feet) and 3866 meters (12,683 feet). A set of radial dikes extends out from the main body of rock, along with various shapes and sizes of intruding igneous rocks. The dikes range from 1 meter (3 feet) to 30 meters (100 feet) wide, and are kilometers (miles) long.

On the eastern edge of the Park Plateau are topographic expressions of late Cenozoic volcanic flows and eruptions. The Raton-Clayton Volcanic Field is located within a southwest-northeast trending zone, termed the Jemez Lineament, that stretches from the Basin and Range across the Rio Grande Rift and into the Great Plains. The age of volcanism in the area ranges from Capulin Mountain, a cinder cone that erupted nearly 60,000 years ago (*Figure 4.35*), to eruptions and lava flows that occurred between eight and two million years ago. Quaternary basaltic flows can be found farther east, extending almost to the borders of Oklahoma and Texas. In some cases where the flows filled older streambeds, subsequent erosion preserved the flow while removing the surrounding strata to produce what is termed a "**topographic inversion.**"

__topographic inversion__ • a landscape with features that have reversed their elevation relative to other features, most often occurring when low areas become filled with lava or sediment that hardens into material that is more resistant to erosion than the material that surrounds it.

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

Figure 4.35: Capulin Mountain at Capulin Volcano National Monument, New Mexico. The volcanic field surrounding the monument contains more than 100 recognizable volcanoes.

The Raton section also includes landforms related to the submergence of the Great Plains by the Western Interior Seaway during the Cretaceous. Methane seeps are vents on the seafloor through which hydrocarbons emanate, producing cements that **lithify** the surrounding rocks and are thus elevated above the surrounding seafloor. Seeps of this type formed just west of Boone, Colorado during the late Cretaceous, approximately 79 to 69 million years ago.

4 Topography

Region 4

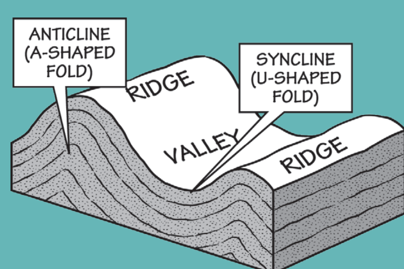
weather *• the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity.*

fossil *• preserved evidence of ancient life.*

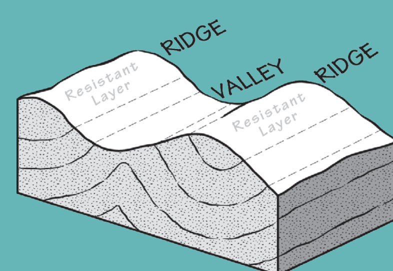
craton *• the old, underlying portion of a continent that is geologically stable relative to surrounding areas.*

Topographic Inversions

Typically, synclines (U-shaped folds) form valleys and anticlines (A-shaped folds) form ridges. However, the reverse can also be true. In a phenomenon called topographic inversion, topographic lows (valleys) may form from the structural high (top of an anticline)—the term "structure" refers to the form of the rock layers. At the top of the anticline, a layer may erode away because of cracks caused by bending of the rock at the top of the fold. Fracturing at the top of the fold allows increased water penetration, and topographic highs are subjected to more severe weather. Once exposed, the less resistant layers below the eroded top quickly *weather* away to form a valley. The limbs of the resistant layer, however, are generally still intact. This leaves two ridges of resistant rock on either side of a valley floored by softer, less resistant layers.

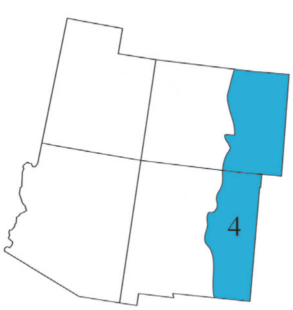


Normal erosion of a fold.



Topographic inversion.

They are referred to as the Tepee Buttes, and they form a linear belt extending in a northeast-southwest direction. The buttes are approximately 10 meters (30 feet) high and are composed of well-cemented **fossiliferous** limestone surrounded by Cretaceous gray shales of the Pierre Formation.



High Plains

The High Plains is an area of flat relief that reflects 500 million years of **cratonic** stability in the continent's interior. Much of this area was submerged by the Cretaceous Western Interior Seaway, leading to the deposition of sediment eroded from the mountains to the west. As such, the Ogallala Formation—a series of porous Miocene strata—defines the extent of the High Plains. The western limits of the Ogallala Formation are located 80 to 240 kilometers (50 to 150 miles) east of the Rocky Mountains because approximately five million years ago, rivers flowing eastwards from the mountains began to erode rather than deposit material in the Great Plains. This drastic change removed the Ogallala and much of the region's older Cenozoic strata in swaths around major east-flowing streams—the North Platte, South Platte, Arkansas, and Canadian rivers. From the rim of the High Plains, the Ogallala caprock dips eastward to form the Llano Estacado or Staked Plains of Texas and New Mexico— a large area of dry, treeless, nearly flat, high prairie.

Pecos Valley

The Pecos Valley is a broad valley formed by erosion driven by the Pecos River, a tributary of the Rio Grande, which drains the area. The valley follows the river from the Sangre de Cristo Mountains of New Mexico southward through the Edwards Plateau to join the Rio Grande River in Texas. The Pecos Valley is relatively flat, and is distinguished by the Ogallala Formation on its eastern side, where it forms a rim rock at the top of the Mescalero escarpment.

At the northern end of the Pecos Valley lies another field of late Cenozoic basalt flows, the Ocate Volcanic Field, which is also a part of the Jemez Lineament. The mesa-capping flows in this field have been dated and reveal a pattern of ages similar to those of the Raton-Clayton Volcanic Field. Flows at higher elevations are older than those found at lower elevations. This pattern can be explained by progressive erosion that lowered the elevation of the sedimentary strata upon which younger flows were deposited.

There is an extensive amount of **karst topography** throughout the Pecos Valley, leading to the formation of some of New Mexico's most spectacular caves (including Carlsbad Caverns, Fort Stanton Cave, Torgac Cave, and Lechuguilla Cave) (*Figure 4.36*). Though most karst is formed when weak carbonic acid in rain or groundwater dissolves the sedimentary bedrock, New Mexico's caverns have been shaped through a unique process called **sulfuric** acid dissolution. In this process, deep sources of hydrogen sulfide—usually derived from gas and oil reservoirs—interact with ground or rainwater to form sulfuric acid, a strong acid that is able to aggressively dissolve large cave passages out of the limestone.

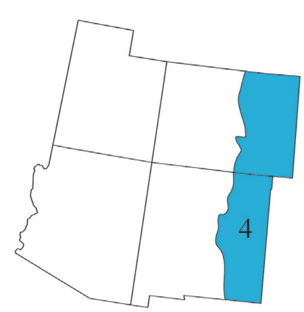
Karst Topography

Karst topography refers to a region where the landscape's features are largely the result of chemical weathering by water, resulting in caves, sinkholes, disappearing and reappearing streams, cliffs, and steep-sided hills called towers. These structures typically form when water picks up carbon dioxide from the *atmosphere* and ground to form carbonic acid. Even this fairly weak and dilute acid dissolves carbonate rocks (such as limestone) relatively easily, resulting in dramatic features while other rock is comparatively unaffected. Karst is found in every state except Hawai‘i, and as an aquifer it is the source of a significant amount of our drinking water.

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

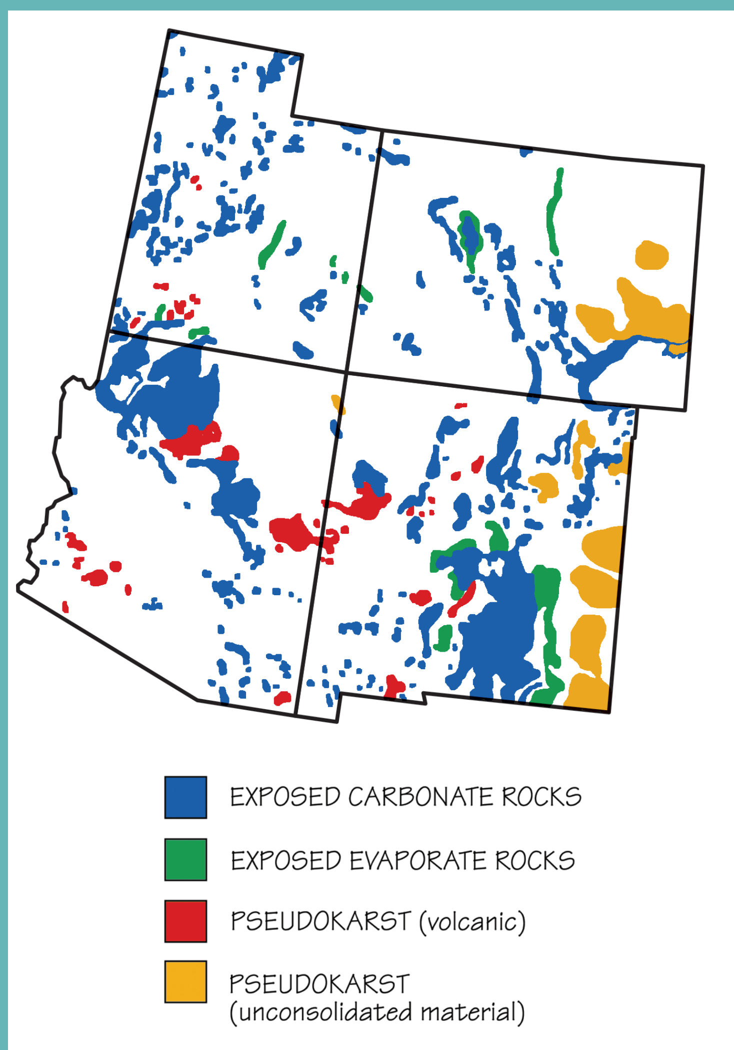
sulfur • *a bright yellow chemical element (S) that is essential to life.*

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

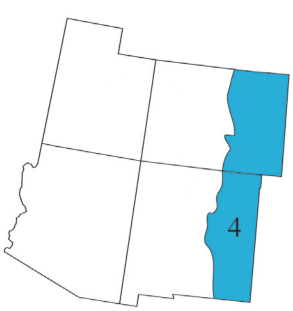


Karst Topography (continued)

While common, karst is not always easily identifiable since it is often not expressed at the surface or its topography has been affected by other factors. Karst topography is a relatively mature type of landscape, taking many tens of thousands of years to develop, and it can indicate that a region has been free of other forms of erosion or deposition for an extended period. Karst topography in the Southwest is present wherever water has eroded the limestone bedrock, especially in the southern Great Plains and around the Grand Canyon. In addition, some karst in the Southwest is generated by the action of sulfuric acid.



(See TFG website for full-color version.)



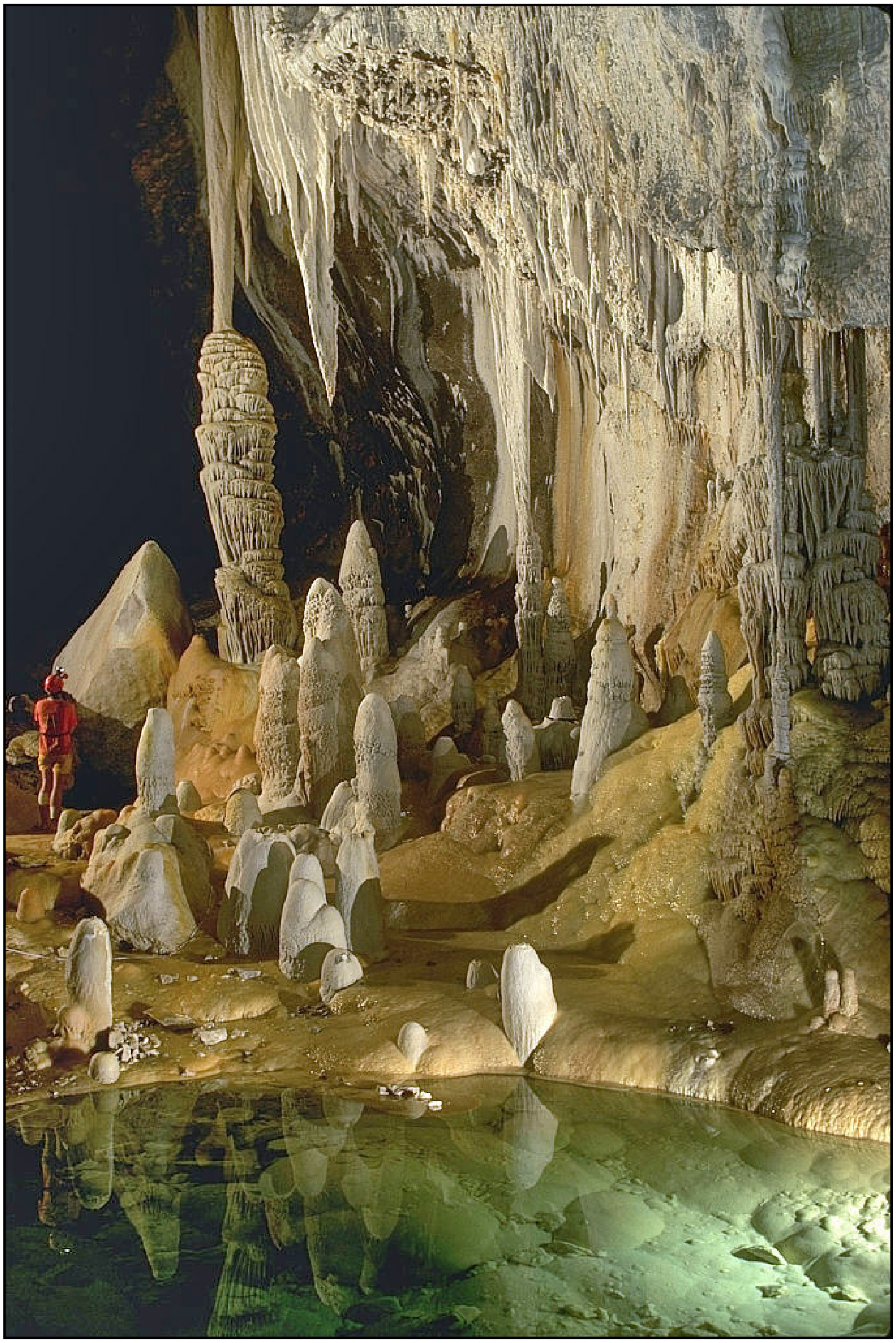
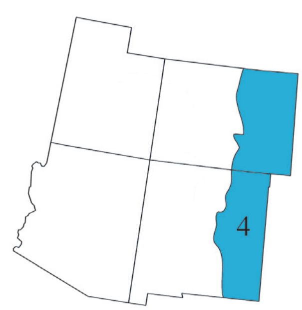


Figure 4.36: Stalagmites, stalactites, and speleothems in Lechuguilla Cave, Eddy County, New Mexico. It is the deepest cave in the continental US.



Highest and Lowest Elevations by State

Arizona

Arizona's highest point is Humphreys Peak, a 3852-meter-high (12,637-foot-high) mountain in the Kachina Peaks Wilderness 18 kilometers (11 miles) north of Flagstaff. It is the highest of the San Francisco Peaks, remnants of an extinct stratovolcano. The state's lowest point is along the Colorado River near San Luis, which lies at only 22 meters (72 feet) above sea level.

Colorado

Mount Elbert, rising 4401 meters (14,440 feet) above sea level, is Colorado's highest point as well as the highest summit in the North American Rockies. The mountain, located 19 kilometers (12 miles) southwest of Leadville, is also the second-highest summit in the continental United States. The lowest point in Colorado is found on the Arikaree River where it flows into Kansas, at an elevation of 1011 meters (3317 feet). This spot is also the highest low point of any US state.

New Mexico

The Sangre de Cristo Mountains are home to Wheeler Peak, New Mexico's highest mountain. At 4011 meters (13,161 feet), the mountain is a popular hiking and climbing destination. It was named in honor of George Montague Wheeler, an American pioneering explorer and naturalist. New Mexico's lowest point is the Red Bluff Reservoir on the Pecos River, with an elevation of 866 meters (2842 feet).

Utah

At 4125 meters (13,534 feet), Kings Peak is Utah's highest point, located in the Uinta Mountains of north-central Duchesne County. The peak is regarded as the hardest state high point to climb without special rock climbing skills or a guide; the easiest trail to the summit requires a 47-kilometer (29-mile) round-trip hike. Beaver Dam Wash, at the Utah-Arizona state line in Washington County, is the lowest point in the state at 664 meters (2178 feet) above sea level.

Elevations


Kings Peak
(4125 m)
Utah
Mount Elbert
(4401 m)
Colorado
Humphreys
Peak
(3852 m)
Arizona
Wheeler Peak
(4011 m)
New Mexico

Resources

Books on Topography

de Blij, H. J., P. O. Muller, J. E. Burt, & J. A. Mason, 2013, *Physical Geography of the Global Environment*, Oxford University Press, New York, 626 pp.
Trimble, D.E., 1980, *The Geologic Story of the Great Plains*, Geological Survey Bulletin 1493, US Government Printing Office, Washington, D.C., http://library.ndsu.edu/exhibits/text/greatplains/text.html.
Wyckoff, J., 1999, *Reading the Earth: Landforms in the Making*, Adastra West, Mahwah, NJ, 352 pp.

Topographic Maps

Color Landform Atlas of the US, http://fermi.jhuapl.edu/states/states.html. (Low resolution shaded relief maps of each state.)
Topoquest, https://www.topoquest.com/.

Websites on Topography

OpenLandform Catalog, Education Resources, OpenTopography. [High resolution topographic images that may be useful in teaching.] http://www.opentopography.org/index.php/resources/lidarlandforms.
Physiographic Provinces, in: Earth Science Concepts: Geology by Region, National Park Service, http://www.nature.nps.gov/geology/education/concepts/concepts_regional_geology.cfm.
Teaching Geomorphology in the 21st Century, On the Cutting Edge, Strong Undergraduate Geoscience Teaching, SERC. [A set of resources for college level, some of which may be adaptable to secondary education.] http://serc.carleton.edu/NAGTWorkshops/geomorph/index.html.
Teaching with Google Earth, On the Cutting Edge, Starting Point: Teaching Entry Level Geoscience, SERC, http://serc.carleton.edu/introgeo/google_earth/index.html.
United States Geography, by S.S. Birdsall & J. Florin, http://countrystudies.us/united-states/geography.htm.
US Geography: The Land Geography, Landscape, and Landforms of the US, 50 State Guide, eReference Desk. [Includes state-by-state information on geography.] http://www.ereferencedesk.com/resources/state-geography/.

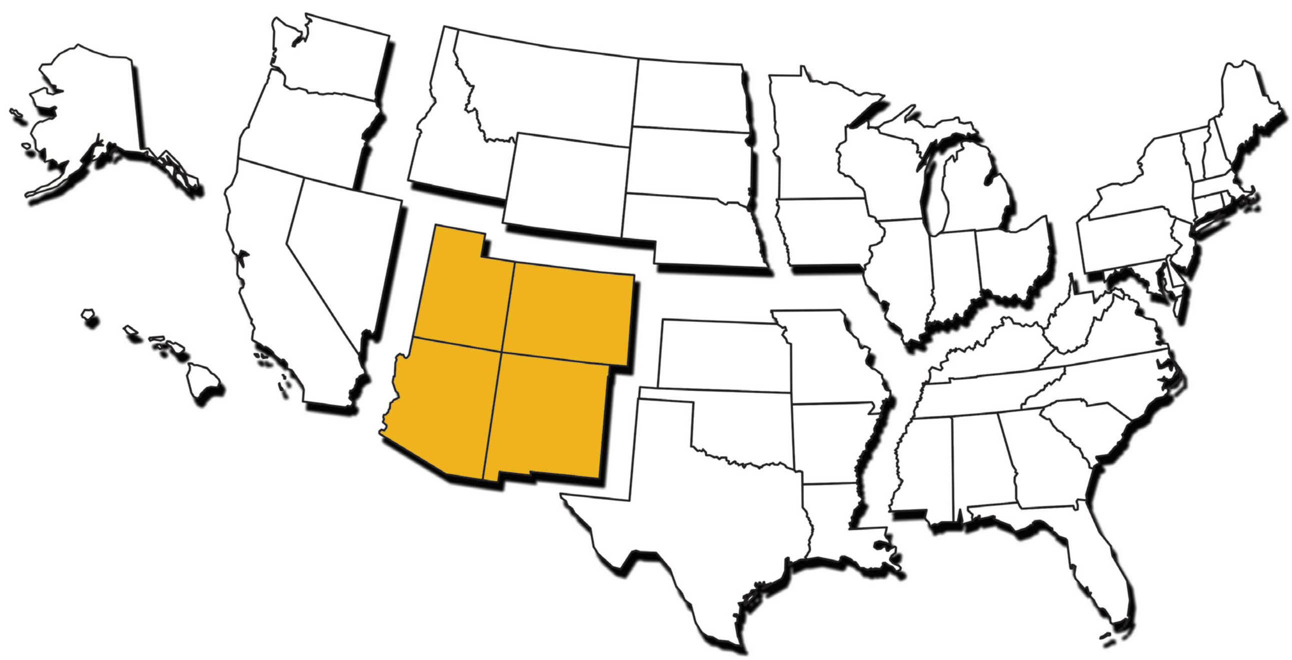
Topography Resources for the Southwest

Davis, W., 2013, *River Notes: a Natural and Human History of the Colorado*, Island Press, Washington, D.C., 176 pp.
Owen, D., 2015, Where the river runs dry: the Colorado and America's water crisis, *The New Yorker* (May 25, 2015), http://www.newyorker.com/magazine/2015/05/25/the-disappearing-river.
Physiographic Provinces, Virtual Geologic Tour of New Mexico, New Mexico Bureau of Geology and Mineralogical Resources, http://geoinfo.nmt.edu/tour/provinces/home.html.
Sand Dunes of the Southwest, by Peter Olsen, http://sand.xboltz.net/.

For additional resources relevant to topography, see the section "General Geology Resources by State" at the end of this volume.

The **Teacher-Friendly** Guide™

to the Earth Science of the Southwestern US



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The interactive online version of this *Teacher-Friendly Guide*™ (including downloadable pdfs) can be found at http://teacherfriendlyguide.org. Web version by Brian Gollands.

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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.