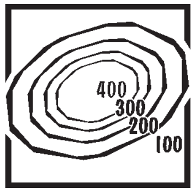

Chapter 4: Topography of the Western US

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 changes in elevation over a particular area and is, generally speaking, the result of two processes: deposition and **erosion**. These processes can happen on an enormous range of timescales. For example, a flash flood can erode away tons of rock in a matter of hours, yet which rock is broken down and which remains can depend on how it was formed hundreds of millions of years ago. In the West, topography is intimately tied to **weathering** and erosion as well as to the type and structure of the underlying bedrock, but it is also a story of **plate tectonics** and its associated folding, **faulting**, and **uplift**.

Weathering includes both the mechanical and chemical processes that break down a rock. **Wind**, water, and ice are the media by which physical weathering and erosion occur. Streams are constantly eroding their way down through bedrock to sea level, creating valleys in the process. With enough 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. Ice also plays a major role in the weathering and erosion of the West's landscape due to frequent episodes of freezing and thawing that occur at high elevations and high latitudes. On a small scale, as water trapped in **fractures** within the rock freezes and thaws, the fractures widen farther and farther (*Figure 4.1*). This alone can induce significant breakdown of large rock bodies. On a larger scale, ice in the form of alpine **glaciers** or continental **ice sheets** can reshape the surface of a continent through mechanical weathering.

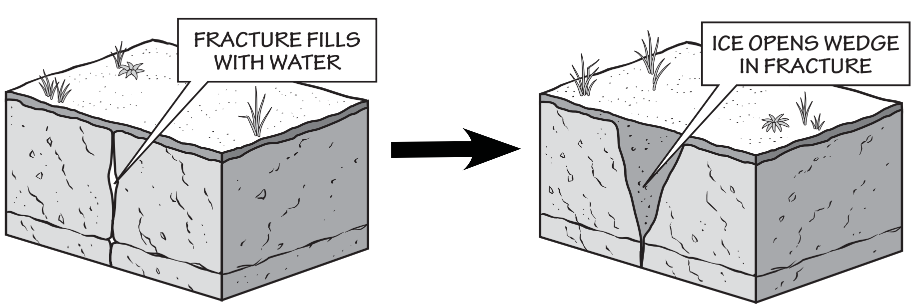

Figure 4.1: Physical weathering from a freeze-thaw cycle.

erosion • *the transport of weathered materials.*

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

plate tectonics • *the way 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.*

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4 Topography

Review

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

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

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

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

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

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

recrystallization • *the change in structure of mineral crystals that make up rocks, or the formation of new mineral crystals within the rock.*

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

See Chapter 2: Rocks to learn more about igneous, metamorphic, and sedimentary rocks.

The specific rock type found 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 inland ocean basins of California's **Jurassic** and **Cretaceous** mountain-building events collected and preserved sediments that eventually became sedimentary rocks. Sedimentary rocks weather and erode differently than do the crystalline, and generally harder, igneous and metamorphic rocks that are more common in the Sierra Nevada. **Silica**-rich igneous rocks have a crystalline nature and mineral composition that resists weathering far better than do the **cemented** grains of a sedimentary rock. The metamorphic equivalents of sedimentary and igneous rocks are often even more resistant due to **recrystallization**. There are exceptions, however, such as **schist**, which is much weaker than its pre-metamorphic limestone or **sandstone** state. Landscapes of unconsolidated sediments, like beaches and **alluvial** fans, are the least resistant to erosion. The limited degree of cement, compaction, and interlocking crystals found in alluvial fan sediments makes it difficult for these types of sediments to stand up to the effects of wind and water, which is why they tend to persist only in arid regions.

See Chapter 1: Geologic History for more information about the mountain-building events that helped to shape the West.

The underlying structure of rock layers also plays an important role in surface topography. Sedimentary rocks are originally deposited in flat-lying layers that rest on top of one another. Movement of tectonic **plates** creates stress and tension within the **crust**, especially at plate boundaries, which often deform the flat layers by folding, faulting, intruding, or overturning them. 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 exposes layers of rock to the surface. Faulting likewise exposes layers at the surface to erosion, due to the movement and tilting of blocks of crust along the fault plane. Tilted rocks expose underlying layers. Resistant layers stick out and remain as ridges, while surrounding layers of less resistant rock erode away.

Ice sheets of the **last glacial maximum**, as well as extensive mountain glaciers, covered part of the West and had a dramatic effect on the area's topography.

Glaciers carved away at the land's surface as they made their way primarily southward, creating a number of U-shaped valleys such as Yosemite and depositional features such as **moraines**. Mountains were sculpted, leaving high peaks and bowl-like **cirques**. As the ice sheet and glaciers melted, other characteristic glacial features were left behind as evidence of the glaciers' former presence, including glacial lakes and polished rock.

See Chapter 6: Glaciers for more about how glaciers influenced Western topography.

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

Topography of the Basin and Range
Region 1

The Basin and Range possesses perhaps the most unique topography of the Western United States. It covers a large area of the US, extending to the Rocky Mountain, Southwestern, and South Central states. Basin and Range topography is characterized by alternating valleys and mountainous areas, oriented in a north-south, linear direction. The entire region, including all of Nevada, southeastern California, and southeastern Oregon, consists of high mountain ranges (mostly running north-south) alternating with low valleys.

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**—the mountain-building event that created the Rockies—ended in the **Paleogene**, tectonic processes stretched and broke the crust, and the upward movement of **magma** weakened the **lithosphere** from underneath. Around 20 million years ago, the crust along the Basin and Range stretched, thinned, and faulted into some 400 mountain blocks. The pressure of the **mantle** below uplifted some blocks, creating elongated peaks and leaving the lower blocks below to form down-dropped valleys. The boundaries between the mountains and valleys are very sharp, both because of the straight faults between them and because many of those faults are still active.

These peaks and valleys are also called horst and graben landscapes (*Figure 4.3*). Such landscapes frequently occur in areas where crustal extension occurs, and the Basin and Range is often cited as a classic example thereof.

Region 1

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

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

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

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

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

4 Topography

Region 1

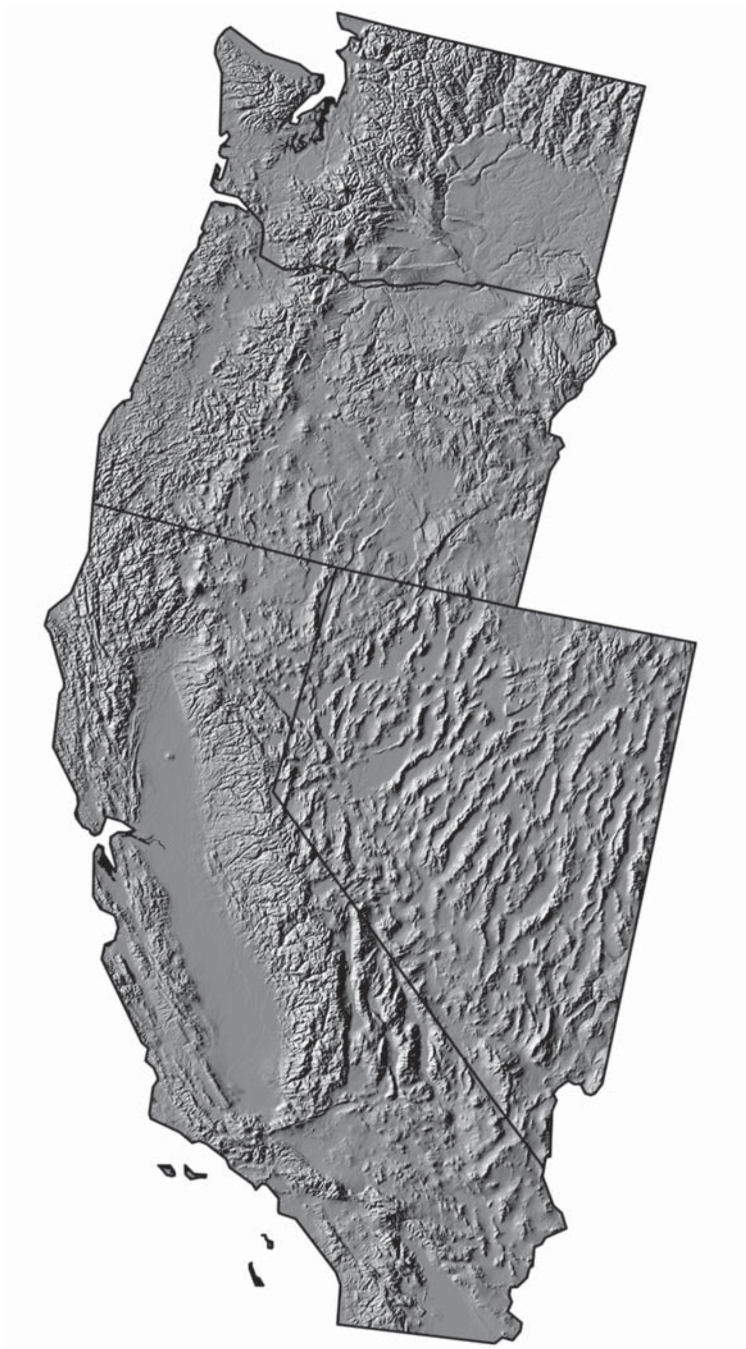
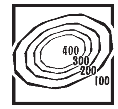


Figure 4.2: Digital shaded relief map of the contiguous Western States.

In the Basin and Range, the crust has been stretched by up to 100% of its original width. As a result of this extension, the average crustal thickness of the Basin and Range region is 30–35 kilometers (19–22 miles), compared with a worldwide average of around 40 kilometers (25 miles).

Topography



4

Region 1

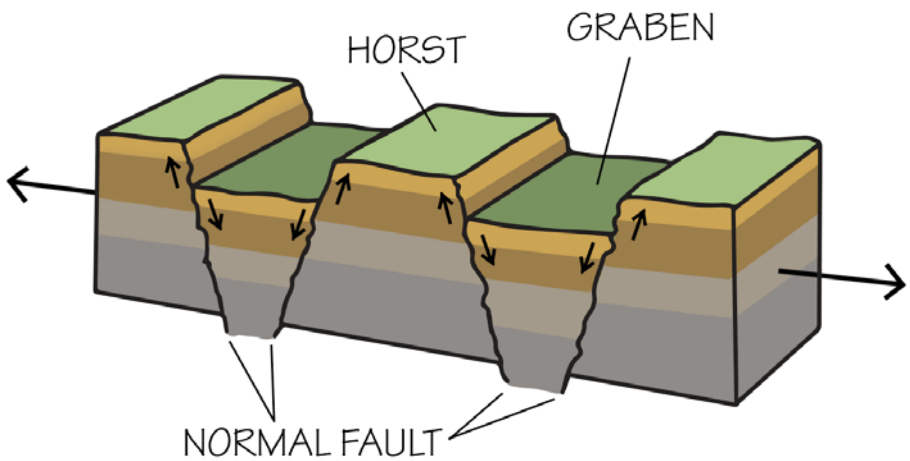


Figure 4.3: A horst and graben landscape occurs when the crust stretches, creating blocks of lithosphere that are uplifted at angled fault lines.

The Basin and Range's arid **climate** contributes to its topography. Erosion is slow, and mechanical weathering is the dominant erosional process, partly because plants, which play a role in chemical weathering, are very sparse. The rugged mountains are fringed by large features called alluvial fans (*Figure 4.4*). These features form when **gravel** and **sand**—and sometimes boulders—are washed out of the mountains by flash floods. The sediment is made up of large, heavy grains, and precipitates out of the water at canyon mouths, where streams lose power as they leave their channels to enter the valleys (*Figure 4.5*).

Plants can contribute to chemical weathering by releasing organic acids from their roots. These acids help dissolve minerals in the rock, providing nutrients to the plant.

If mountain ranges are close together, alluvial fans from opposite sides of the valley will meet in the middle, but where the ranges are farther apart, valley floors will be flat and are often occupied by either **playas** or dune fields.

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

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

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

playa lake • *ephemeral or dry lakebed that occasionally contains only a thin layer of quickly evaporating water.*

4 Topography

Region 1

microcontinent • *a piece of continental crust, usually rifted away from a larger continent.*

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

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

Figure 4.4: Alluvial fans in Death Valley, California.

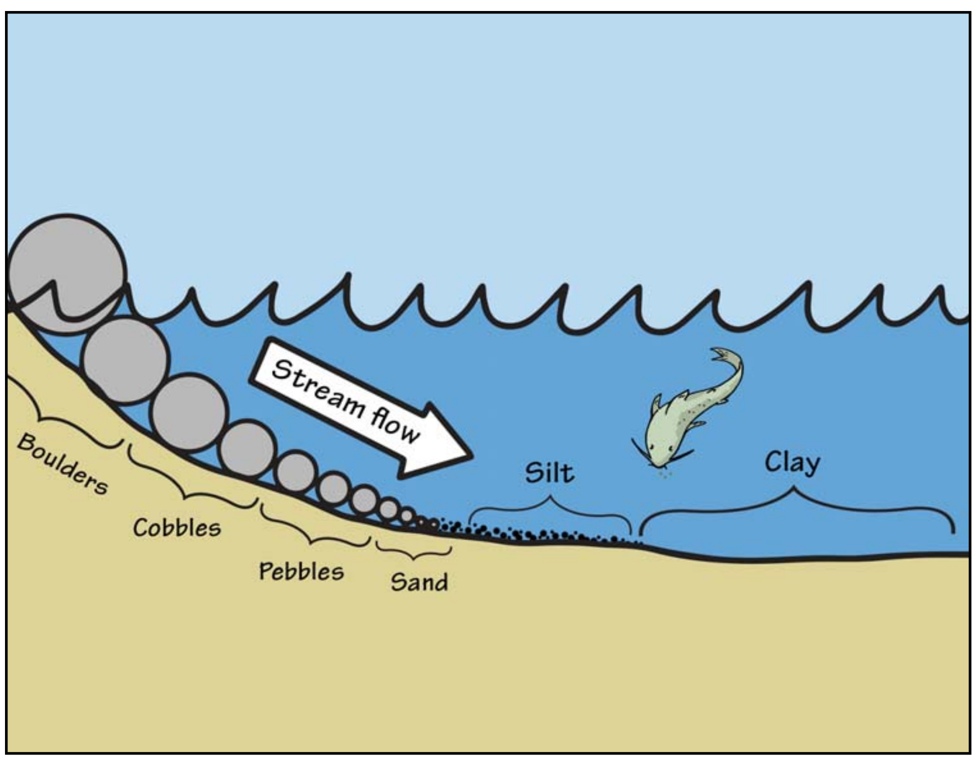


Figure 4.5: Moving water deposits sediments in what is known as a horizontally sorted pattern. As the water slows down (i.e., loses energy), it deposits the larger particles first.

Topography of the Columbia Plateau
Region 2

The interior areas of eastern Washington and central and northeastern Oregon are divided into three major areas: the Blue Mountains, the High Lava Plains, and the Columbia Basin (*Figure 4.6*)

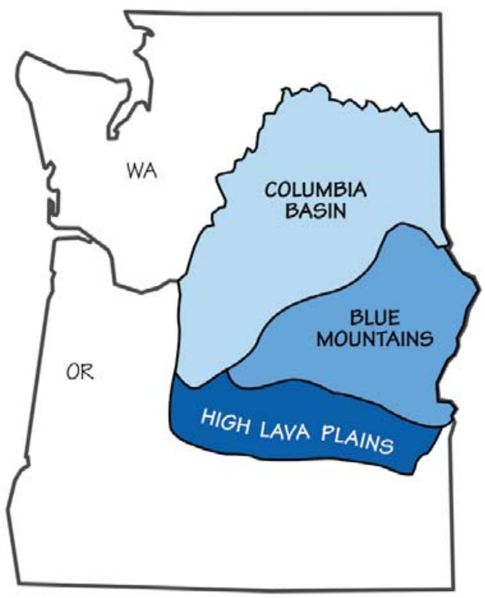


Figure 4.6: The three major divisions of the Columbia Plateau.

The Blue Mountains include the Wallowas, which reach a height of 2999 meters (9838 feet). This area is formed of ancient **microcontinents**, small pieces of continental crust that collided with North America in the Jurassic.

The High Lava Plains are the result of extensive **volcanism** during the **Neogene**. Newberry Volcano, just south of Bend, Oregon, is the westernmost point of eruption for a **hot spot** that is now responsible for the spectacular volcanic features found in Yellowstone. This hot spot, which has existed for over 16 million years, left its trail across southeastern Oregon and southern Idaho.

See Chapter 1: Geologic History to learn more about hot spot volcanism.

The Columbia Plateau, also called the Columbia Basin, is a broad, volcanic plain composed of **basalt**. Basalt solidifies from **lavas** that are very fluid when hot, and the basalt lava in this area erupted along a series of fractures in eastern Oregon, flowing westward. The basalt was so voluminous and fluid that it completely filled the preexisting topography (remnants of which can be seen in hills such as Steptoe Butte [*Figure 4.7*] and Kamiak Butte in easternmost

Region 2

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

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

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

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

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

__silt__ • fine granular sediment most commonly composed of quartz and feldspar crystals.

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

Washington), forming a broad, flat plain that tilts downward to the west. The lava flowed all the way to the Cascades, and even to the ocean, along what is now the Columbia River drainage. In western parts of the plateau, the basalt has been gently folded and faulted by mountain building associated with the uplift of the Cascade Mountains.

Figure 4.7: Steptoe Butte, a 400-million-year-old quartzite mound protruding from the Columbia Plateau and Palouse Hills in Whitman County, Washington. Elevation: 1101 m (3612 feet).

The youngest topographic features in the Northern Interior of Washington formed during the most recent **ice age** when glacial outwash and **loess** was deposited and later cut by the Missoula Floods, which also carved the Grand Coulee (an ancient river bed) and many of the lakes and channels of the central part of the state. In the Palouse area of Washington and Oregon, glacial outwash formed a series of steeply-sloped **silt** dunes, which are agriculturally important today due to their highly fertile **soil** (*Figure 4.8*).

The Missoula Floods swept periodically across eastern Washington at the end of the last ice age. The floods were a result of a rupture in the ice dam that contained Glacial Lake Missoula, a massive glacial lake originally holding 2100 cubic kilometers (500 cubic miles) of water.

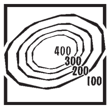
Figure 4.8: The Palouse Hills in southeastern Washington are an important agricultural area.

Topography of the Northern Rocky Mountains
Region 3

Extreme northeastern Washington has a history that is quite different from that of the other regions to the south and west. Although the rocks here contain both metamorphic and sedimentary structures, they share a similar degree of hardness. This means the region has been resistant to erosion, and, even though they are very old, these rocks remain exposed. Since this region was covered with ice during the last ice age, the mountains have been rounded by glaciation (*Figure 4.9*). Deep valleys were carved by glaciers flowing from the ice sheet.

Figure 4.9: Rounded topography of the Okanogan Highlands, Washington. This type of topography occurs on all scales, from these hill-sized outcrops to the region's mountains.

4 Topography



Region 4

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

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

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

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

Topography of the Cascade-Sierra Mountains

Region 4

The highest mountains in the western continental US are uniformly about 177 kilometers (110 miles) west of the Pacific coastline but are actually made up of two different mountain ranges, the Sierra Nevada and the Cascades, with the Klamath Mountains of northwestern California sandwiched in between.

The Sierra Nevada are composed almost entirely of **granodiorite** and highly metamorphosed sedimentary and volcanic rocks. This granodiorite makes up the Sierra Nevada **batholith**, which is one of the largest in the US; it is composed of a series of **plutons**, large bodies of molten rock that intruded the crust and cooled, only to be revealed by erosion millions of years later (*Figure 4.10*). Because plutons are extremely resistant to weathering and the mountains in this region are so young, the Sierra Nevada are home to some of the highest peaks in the United States. In fact, Mt. Whitney, at 4421 meters (14,505 feet), is the highest mountain in the continental US and has the most extreme **relief**. The town of Lone Pine, less than 21 kilometers (13 miles) away, lies at 987 meters (3237 feet), a drop of more than 163 meters per kilometer (866 feet per mile)!

See Chapter 2: Rocks to learn more about the Sierra Nevada.

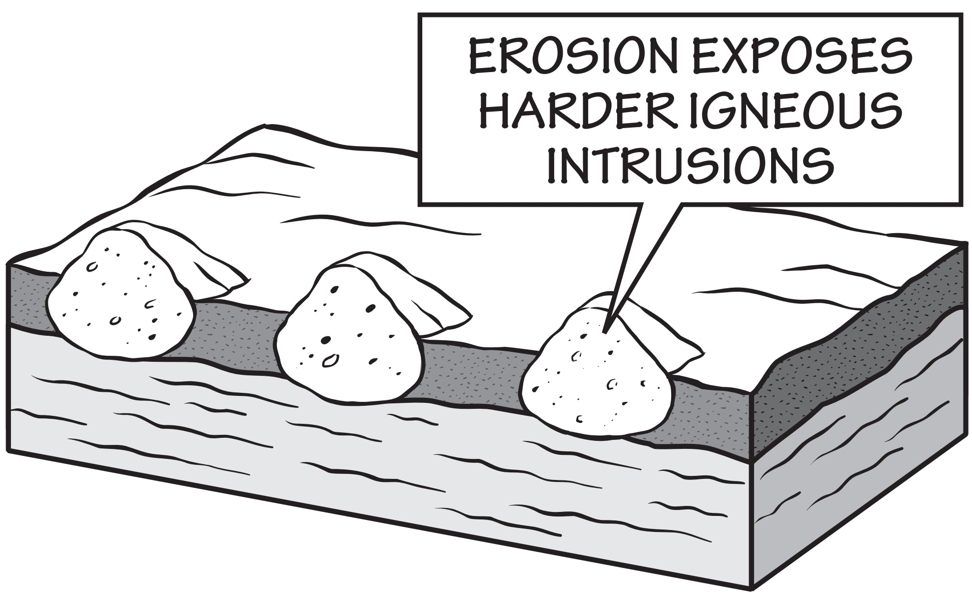


Figure 4.10: Igneous intrusions (plutons) are exposed after millions of years of erosion.

The Sierra Nevada were originally thought to have been uplifted to their current height around 10 million years ago, but more recent work has provided evidence that the initial uplift occurred much earlier, as early as the Late Cretaceous, and that the Sierra Nevada may at one time have been even higher than they are today. New evidence also shows they are still rising.

The Sierra Nevada are unusual in that they are bounded on the east by an extensive fault system along which most of the uplift has occurred. This means that they are very steep on the eastern side but slope gently to the Central Valley on the western side. Because of the rain shadow effect (*Figure 4.11*), the climate on the mountains' eastern side is very dry and weathering there is predominantly mechanical, while the western side is wetter and chemical weathering is more prevalent. This weathering concentrated the **placer gold deposits** that were the object of California's mid-1800s gold rush. Gold is completely stable, so when the rock containing it weathered away, the gold remained behind, concentrated in the bottoms of streams.

See Chapter 5: Mineral Resources for more information about gold in the West.

placer deposit • *a mineral deposit occurring in rivers and streams where less dense sediment has been carried downstream but denser minerals such as gold have been left behind.*

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

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

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

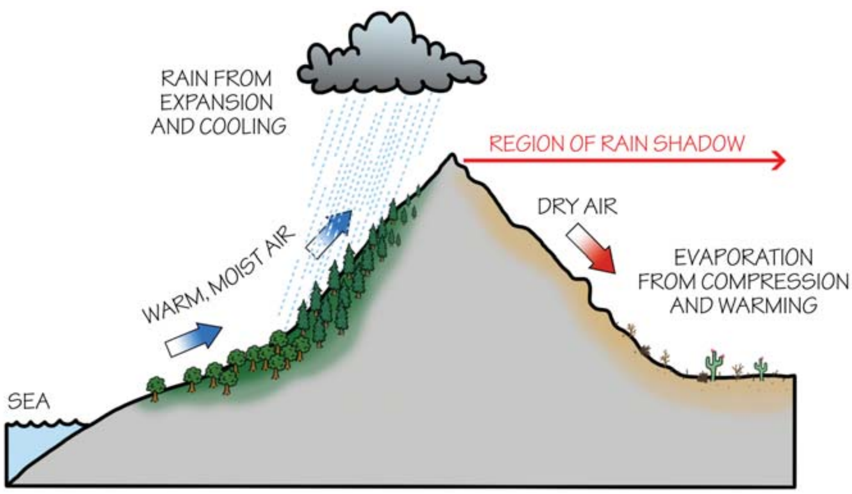


Figure 4.11: The rain shadow effect occurs when moisture-laden air rises up the windward side of a mountain, only to release this moisture as precipitation due to cooling and condensation. Once the air reaches the leeward side, it warms and expands, promoting evaporation (and a lack of precipitation).

The Klamath Mountains are one of the many **terranes** that make up large parts of the West, including much of Alaska and Oregon. The Klamath microcontinent collided with North America in the Jurassic, causing these mountains to rise. In addition, plutonic **intrusions** made the mountains relatively resistant to the weathering caused by the region's heavy winter rains.

The Cascade Mountains have largely been shaped by plate tectonics in the Pacific Ocean. Early in the Paleogene, the Cascades portion of Washington

subduction • *the process by which one plate moves under another, sinking into the mantle.*

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

accretionary prism • *a pile of sediments and ocean crust, scraped off a descending plate during subduction, and piled onto the overlying continental crust.*

transform boundary • *an active plate boundary in which the crustal plates move sideways past one another.*

began as a series of basins and uplifts that formed when several smaller plates, along with their boundaries, were successively **subducted** under North America. Beginning around 37 million years ago, this subduction also created the first volcanoes that pierced the area. The remains of these extinct volcanoes define the landscape—the area that surrounds Mt. Rainier (and extends to the south) contains remnants of the ancient volcanoes themselves, while to the north only their plutonic cores remain.

The topography of the modern Cascades was created during the last seven million years. After a lull in volcanic activity, plate motion shifted, and new subduction created the modern volcanic arc and also uplifted the entire region. The greatest uplift took place in the north.

Topography of the Pacific Border

Region 5

The Pacific Border can be divided into two major areas based entirely on dominant plate tectonic forces. A transform (sideways-moving) boundary between the Pacific plate and North America extends through California. Meanwhile, a **convergent boundary** subducts off the coast of Washington and Oregon, between North America and the remnants of the ancient oceanic Farallon plate. These two areas are separated by the great Mendocino fracture zone off the coast of northernmost California.

Before the formation of the San Andreas Fault system, the area south of the Mendocino fracture zone was a subduction zone. The features of subduction zones can vary, depending on how fast the plates are moving and the angle at which the subducting oceanic crust is traveling. Where the descending plate subducts at a relatively shallow angle, a forearc basin may form oceanward of the volcanic arc (*Figure 4.12*). The Central Valley of California is the forearc basin associated with the volcanic arc that became the Sierra Nevada, and it formed partly due to the weight of the growing mountains on the crust. West of this basin, a pile of sediments and even ocean crust, known as an **accretionary prism** (*Figure 4.12*), was scraped off the subducting oceanic plate and piled higher and higher onto the overlying continental crust. The Coast Ranges of California formed in this way.

About 30 million years ago, a mid-ocean ridge called the East Pacific Rise collided with and subducted beneath North America. As this ridge subducted, the plate boundary adjacent to California gradually changed, becoming the **transform boundary** that formed the San Andreas Fault system. At this time, the accretionary prism that formed the Coast Ranges stopped growing. Since the fault is not a straight line but rather a system of faults, a lot of tectonic jostling, pushing, and pulling occurs in this part of California. Movement along these faults is responsible for the formation of hills and valleys, and sometimes of broad basins such as the western part of the Mojave Desert. The Transverse Ranges, Tehachapi Mountains, and southern Coast Ranges all owe much of their topography to movement along the San Andreas Fault system. In fact,

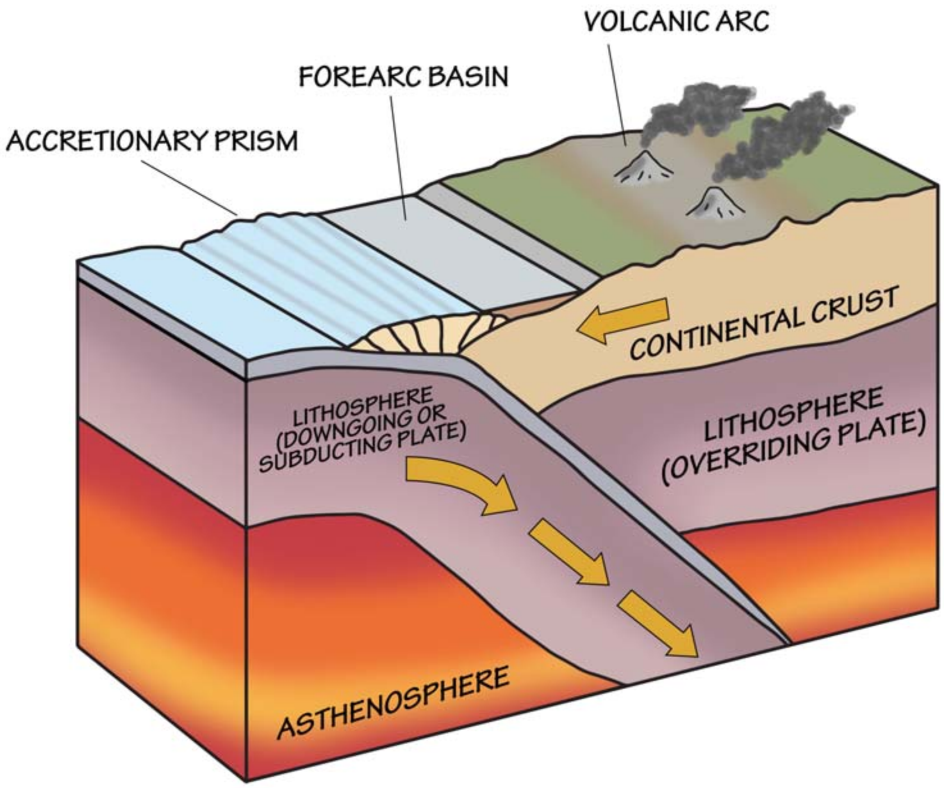


Figure 4.12: Some of the features associated with subduction zones.

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

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

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.*

the Transverse Ranges have been rotated as much as 110 degrees from their original position! The southern end of the fault system lies just north of the Gulf of California, where it terminates in a **rift** zone. The rifting is responsible for the formation of the Imperial Valley, one of the lowest spots in North America. Despite the overall translational motion of the San Andreas Fault system, there is a small **compressional** component, and this has resulted in uplift along parts of the coastline during the last three million years. This uplift can be seen in a series of wave-cut **terraces** that now lie well above the modern shoreline (*Figure 4.13*).

See Chapter 1: Geologic History to learn more about changing plate boundaries off the West coast of North America.

The San Andreas Fault travels off the coastline north of San Francisco, eventually meeting up with the Mendocino fracture zone. The Klamath Mountains, which lie directly east of the fracture zone, are part of an accretionary wedge that has been substantially uplifted.

The subduction zone north of the Mendocino fracture zone is responsible for the formation of the Oregon Coast Range and the Olympic Mountains. These mountains are part of a 66-million-year-old accretionary wedge associated with the subduction zone. In Oregon, the wedge is composed largely of an ancient

volcanic arc, which was carried to the coast of Oregon on an older subducting slab. The Oregon Coast Range is lower in altitude than the coastal ranges north and south, partly because of slower uplift and partly because the wet climate of western Oregon quickly erodes the rock. Despite these conditions, marine terraces similar to those in California are found in this area. The Olympics were uplifted during the **Miocene**, around the same time as the most recent uplift in the northern Cascades.

Like the Central Valley of California, the Willamette Valley in Oregon and Puget Sound in Washington are parts of a forearc basin, but in this case they are associated with an active volcanic arc—the Cascades.

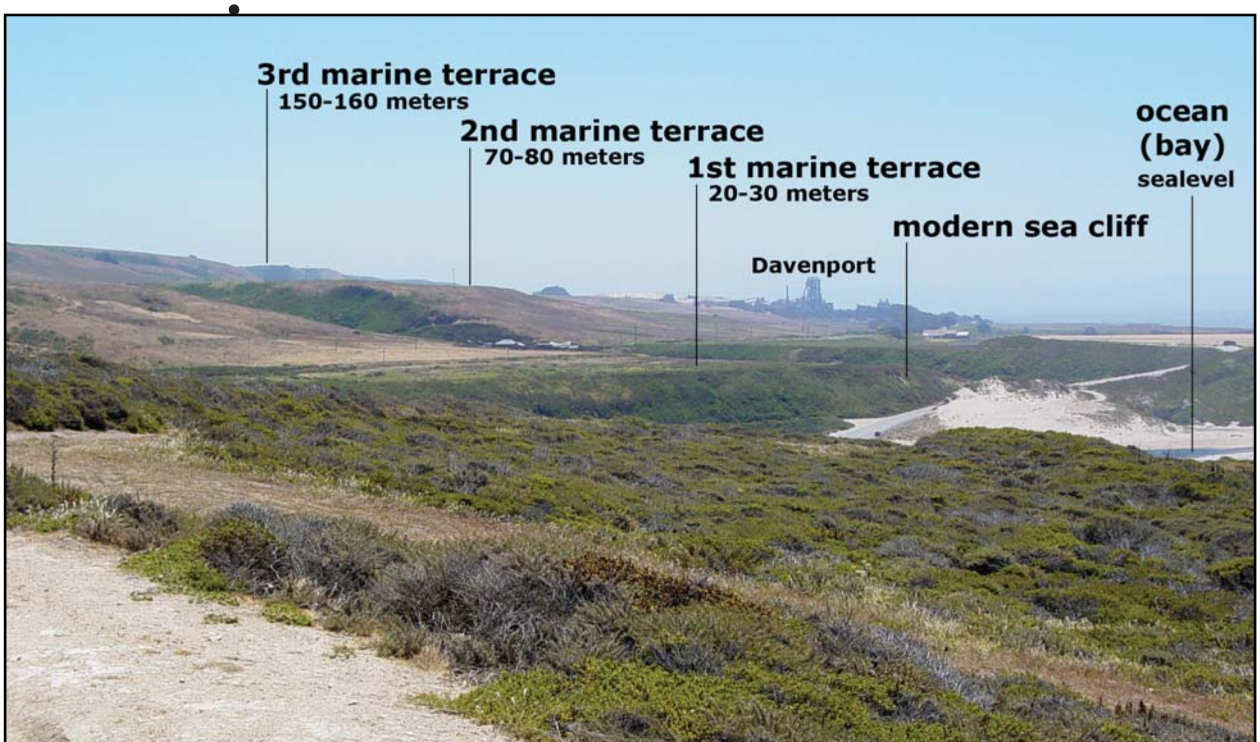


Figure 4.13: Marine terraces north of Santa Cruz, California. The third terrace is the oldest; the first is the youngest. These terraces indicate that the coastline has continued to rise, even though the predominant plate tectonic motion is translational.

Topography of Alaska
Region 6

Alaska is one of the most mountainous states in the US, and, along with California, has the highest relief (*Figure 4.14*). Mt. McKinley, at 6194 meters (20,322 feet), is commonly accessed by climbers and other tourists from the nearby town of Talkeetna (elevation 106 meters [348 feet]). This represents a difference of more than 6000 meters (almost 20,000 feet) within less than

96 kilometers (60 miles). There are, however, two non-mountainous areas of Alaska as well—the North Slope and the Interior. Much of Alaska's topography can be explained by its odd origins: continental Alaska is made up almost entirely of **accreted** terranes—bits and pieces of microcontinents and island arcs that collided together over geologic time.

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

accretion *• the process by which a body of rock increases in size due to the addition of further sedimentary particles or of large chunks of land.*

North Slope, Brooks Range, and Seward Peninsula

The Yukon-Tanana terrane was responsible for the formation of the North Slope and Brooks Range when it collided with a part of Arctic Canada that rifted away,

Figure 4.14: Digital relief map of Alaska.

rotating counterclockwise into its present position. The forward edge of the Yukon-Tanana's ancient seabed was uplifted, forming the Brooks Range, while the trailing edge subsided. The rising Brooks Range shed copious amounts of sediment northward toward the Arctic Ocean, and the combination of subsidence and accumulation of sediment formed the coastal plain we call the North Slope. The Brooks Range is highest in the east because it consists

See Chapter 2: Rocks to learn more about the terranes that formed Alaska.

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

Triassic • *a geologic time period that spans from 252 to 201 million years ago.*

mainly of thrust sheets: giant slabs of rock that were piled on top of each other due to compressional forces acting on the rotating crust (*Figure 4.15*).

Figure 4.15: A massive thrust sheet in Gates of the Arctic National Park, Central Brooks Range, Alaska.

The Seward Peninsula extends from northwest Alaska and is a remnant of the Bering land bridge that connected Alaska to Siberia during the **Pleistocene**. The Seward Peninsula is actually composed of two terranes: the Seward terrane, which contains predominantly metamorphic rock, and the York terrane, made up of sedimentary rocks that were originally deposited in a shallow marine environment before their accretion onto the North American plate. These sedimentary rocks were deformed by thrust faulting during the Cretaceous.

Although Alaska was never buried under an ice sheet, as were much of Canada and the northern continental US, glaciation was extensive in the Brooks Range during the ice ages. The effects of these glaciers can be seen in the range's sharp peaks and U-shaped valleys.

Interior

The Interior is an expanse of flat, swampy areas and low, rolling hills. The geological origin of this area is murky because so little of its bedrock is exposed, but we do know it contains fragments of what was once ocean floor. Such rocks can be very vulnerable to erosion because the minerals they contain are more easily weathered. The area's low topography probably results from a combination of easily weathered rocks and an incomplete collision between the Brooks Range and terranes south of the Interior. The basin has also been filled with copious amounts of sediment from the Brooks Range, Alaska Range, and the Yukon River.

Southern Alaska

Southern Alaska comprises numerous terranes that have been added to North America since the Late **Triassic** (about 230 million years ago). In addition to colliding with one another, the terranes were progressively pulled apart by major faults that formed due to changing plate motions between North America and the Pacific plate.

The Wrangell-St. Elias Mountains are mostly composed of a large terrane called Wrangellia, which collided with North America in the Cretaceous and has also been cut by large faults. This terrane makes up most of the Coast Range in southeastern Alaska, parts of the Alaska Range, and part of the Alaska Peninsula. It is still being rearranged, as witnessed by the frequent, large **earthquakes** along the Denali Fault system.

Some terranes have an extremely complex geology, and geologists have lumped them into composites made up of pieces with similar tectonic histories. The Mertie Mountains east of Fairbanks are included in the Yukon composite terrane, which was in place by the Late Jurassic. The Kuskokwim Mountains in southwestern Alaska include pieces of several composite terranes that were not assembled until much later, in the Paleogene. The Alaska Range, which includes Mt. McKinley, also comprises at least two terranes that were brought together by the Denali Fault system during the Late Cretaceous. The addition and movement of the Southern Margin composite terrane built the Fairweather, Chugach, and Kenai mountains; these ranges are part of an accretionary prism (*See Figure 4.12*). Subduction is still occurring along the Aleutian Trench, resulting in the formation of the Aleutian Islands. The subduction creates **stratovolcanoes** and plutonic igneous intrusions along the entire Aleutian Range, where some of the highest mountains are young volcanoes that erupt periodically.

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

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

mass wasting *• a process in which soil and rock move down a slope in a large mass.*

Topography of Hawai‘i

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The topography of the Hawaiian Islands changes systematically as a function of age. The eight major islands and 129 minor islands are generally larger and taller in their youth, decreasing in size and height as they age (*Figure 4.16*). The smooth, gently-sloping shield of a young volcano becomes progressively carved and steeper over time. These changes arise from several factors: constructive volcanic processes that dominate the early history of each island, **mass wasting** that occurs throughout the volcano's life cycle, and the erosion and weathering that dominate once volcanism ceases.

See Chapter 1: Geologic History for more detail on the stages of Hawaiian volcano-building.

It is often said that the volcanoes of Hawai‘i are the largest mountains on Earth, and this is true, depending on how one measures size. The peak of Mauna Kea is 4205 meters (13,796 feet) above sea level, while Mauna Loa rises to 4169 meters (13,677 feet). The base of the volcanic edifice extends another 5000 meters (16,400 feet) to the sea floor. Additionally, the weight of the volcanoes depresses the seafloor downward into the mantle for another 8000 meters (26,000 feet). As

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

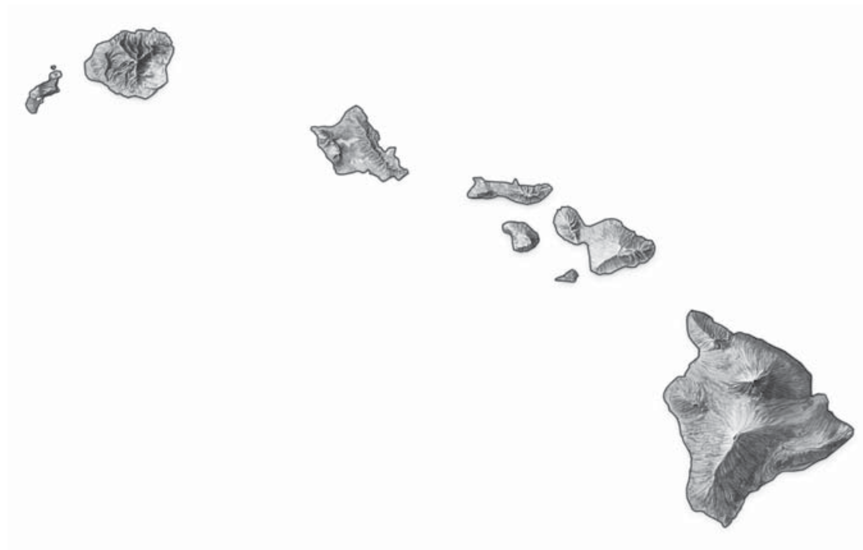

Figure 4.16: Digital relief map of Hawai'i.

a result, the total height of both Mauna Kea and Mauna Loa is nearly 17,200 meters (56,420 feet) (*Figure 4.17*).

Once a volcano grows large enough to emerge from the ocean, its terrestrial surface begins to reflect the interaction of several processes. Overall, lava flows create a smooth surface at a low angle (3˚ in the case of Mauna Loa). However,

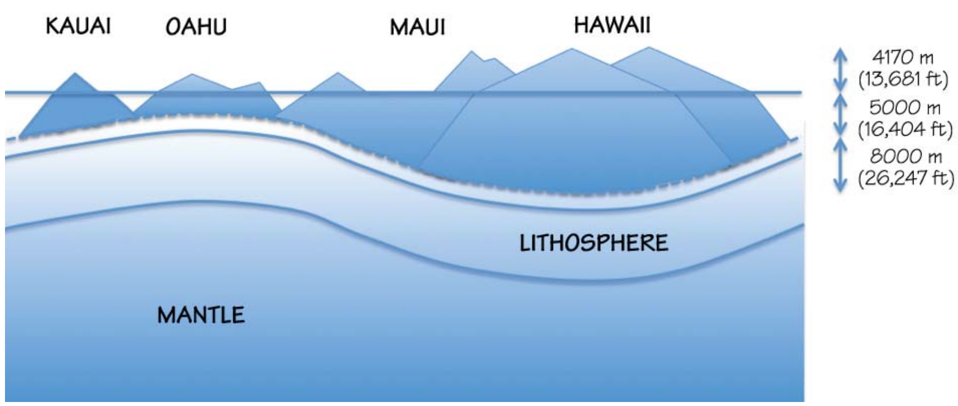

Figure 4.17: The weight of the Hawaiian Islands depresses the lithosphere into the underlying mantle. The total height of Mauna Loa is 4170 meters (13,681 feet) above sea level plus an additional 13,000 meters (42,651 feet) to the top of the oceanic plate on which it sits.

small-scale topography (tens of meters [yards] in size) is superimposed on the smooth slope as weathering and **seismic** activity affect the landscape. While the shield topography sets the basic form of the original volcanic surface, local variations can be important for the later development of stream valleys and other features.

Mass Wasting

Dramatic mass wasting events, known as **flank collapses**, remove huge amounts of volcanic rock from the islands and leave behind giant scarps. Some of Hawai‘i’s most dramatic topographic features are the huge sea cliffs found on many of the islands as a result of these collapses (*Figure 4.18*). The cliffs in Kohala, Hawai‘i drop 125 meters (400 feet), while cliffs on Moloka‘i plunge 800 meters (2600 feet) into the ocean. When a flank collapse occurs on the **windward** side of an island, it creates a steep escarpment, which tends to enhance rainfall, maintaining high erosion rates and steepening dramatic cliffs in places like the Na Pali coast on Kaua‘i (*Figure 4.19*), the Ko‘olau range on O‘ahu, and the Waipi‘o area on Hawai‘i. On the **leeward** (dry) sides, incision and relief are notably less pronounced.

Flank collapses result from gravitational stress on the massive volcanic shield. Some of this stress is directed outward, and the stresses cause the development of fractures dipping away from the summit. These faults can slip rapidly, resulting in a massive collapse into the ocean. As well as altering the topography and size of the islands, these mega-**landslides** leave huge debris fields on the sea floor that can extend more than 100 kilometers (60 miles) away from the islands. Studies have shown that at least 15 giant landslides—among the largest ever found on Earth—dissected the Hawaiian Islands (*Figure 4.20*). These flank collapses have left all of the islands with their distinctive coastal cliffs (*pali* in Hawaiian), and at least some of the landslides appear to have

Figure 4.18: Cliffs on windward Kohala, Hawai‘i, viewed looking SE from Pololū valley. Most Hawaiian sea cliffs are the head scarps of mega-landslides.

flank collapse *• a dramatic mass wasting event that occurs when the flank of a shield volcano collapses under its own weight.*

windward *• upwind; facing into the prevailing winds, and thus subject to orographic precipitation.*

leeward *• downwind; facing away from the wind.*

landslide *• the rapid slipping of a mass of earth or rock from a higher elevation to a lower level under the influence of gravity and water lubrication.*

tsunami *• a series of ocean waves that are generated by sudden displacement of water, usually caused by an earthquake, landslide, or volcanic explosions.*

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

perennial *• continuous; year-round or occurring on a yearly basis.*

hanging valley *• a tributary valley that drops abruptly into a much larger and deeper valley.*

Figure 4.19: The Na Pali coast, Kaua'i, Hawai'i

generated massive **tsunamis**. There is evidence across the Hawaiian Islands that rock and coral materials were deposited over 300 meters (1000 feet) above sea level by these events.

Examples of extensional collapse can be observed today—GPS measurements confirm that blocks of land on the flanks of Kīlauea are moving seaward at around 10 centimeters (4 inches) per year. This slow slip is punctuated by larger events that cause earthquakes. Flank collapse, first identified in Hawai'i, has since been recognized as a feature of other high oceanic **volcanic islands**, such as Tenerife in the Canary Islands and Réunion in the Indian Ocean. The last major flank collapse in Hawai'i occurred about 120,000 years ago, so we do not have a detailed picture of what one of these events looks like, nor of the warning signals that may occur prior to a large-scale failure.

Erosion and Valley Formation

Erosion in Hawai'i is primarily driven by water. Erosion is concentrated on the windward slopes of each volcano, where higher precipitation forms **perennial** streams. On young islands nearly all leeward streams are intermittent, and thus have only episodic erosive power.

Stream erosion incises the islands' surfaces and modifies **hanging valleys** left by flank collapses. Tall waterfalls are found where collapse generates steep topography more quickly than stream incision can wear it away (*Figure 4.21*). Stream valleys cut back into the flanks of the volcano, aided by pre-existing faults and underlying structures within the volcanic edifice.

The number and size of stream valleys provides a clear indication of the age of the volcano on which they form. For example, on Hawai'i Island, active Kīlauea

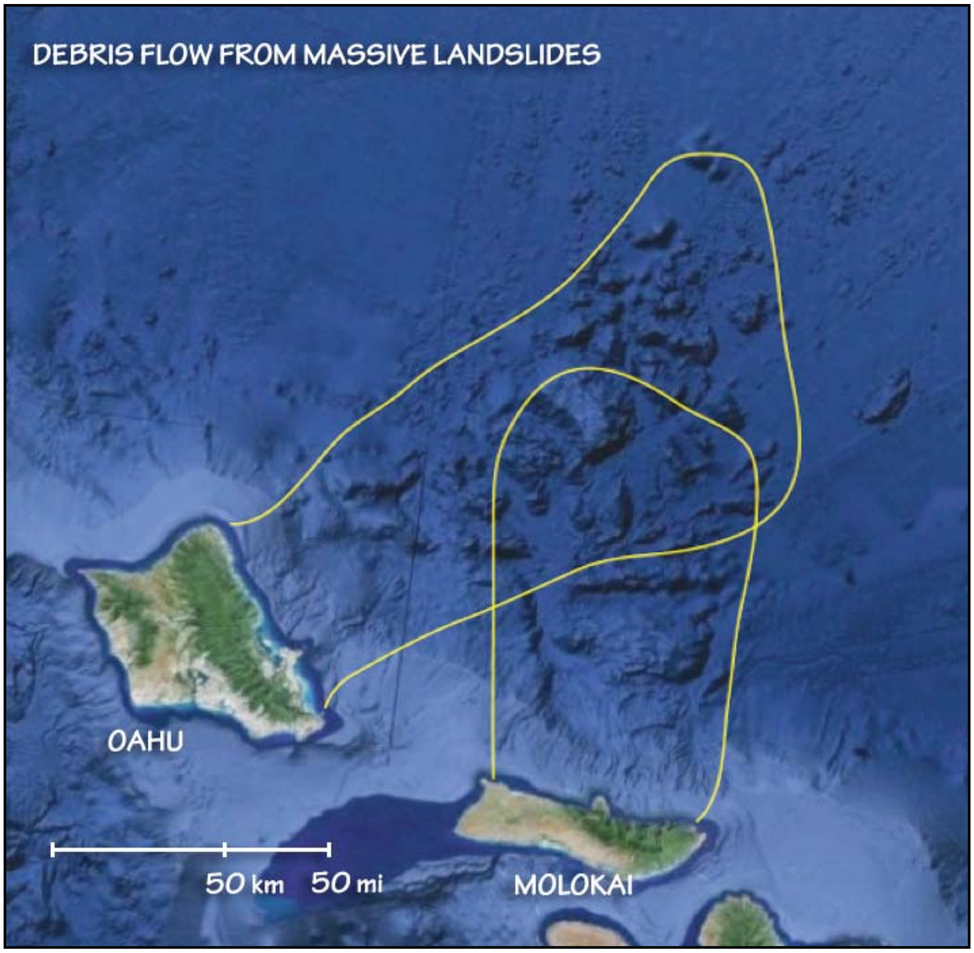

Figure 4.20: Debris flow fields from massive landslides off O'ahu and Moloka'i.

and Mauna Loa show very little incision, while dormant Mauna Kea has a considerable number of deep, yet narrow, river gulches on its windward side. The oldest volcano, Kohala (extinct), has spectacular erosional valleys on the windward side. On older islands, such as O'ahu and Kaua'i, the original shape of the volcano is difficult to see, as most of it has been removed.

Examination of the topographic map of Kohala Mountain shows frequent sharp bends in the upper reaches of windward streams (especially upper Waipi'o Valley). These bends mark the location of buried faults. Waipi'o Valley itself is eroded into the contact between Kohala and Mauna Kea volcanoes (*Figure 4.22*). Similarly, on Kaua'i, Waimea Canyon is located along an ancient fault system. Waimea Canyon is 16 kilometers (10 miles) long and up to 900 meters (3000 feet) deep, making it the largest canyon in the Hawaiian Islands (*Figure 4.23*). A similar fault dropped the east side of the island down relative to the west, creating the low-elevation plain of east Kaua'i.

Cinder Cones and Littoral Cones

The sequence of constructive volcanism accompanied by erosion and catastrophic landslides is overlain by the addition of late-stage eruptions. These

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glassy rock • *a volcanic rock that cooled almost instantaneously, resulting in a rock with tiny crystals or no crystals at all.*

littoral cone • *a volcanic ash or tuff cone formed when a lava flow runs into a body of water.*

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

glassy rock • *a volcanic rock that cooled almost instantaneously, resulting in a rock with tiny crystals or no crystals at all.*

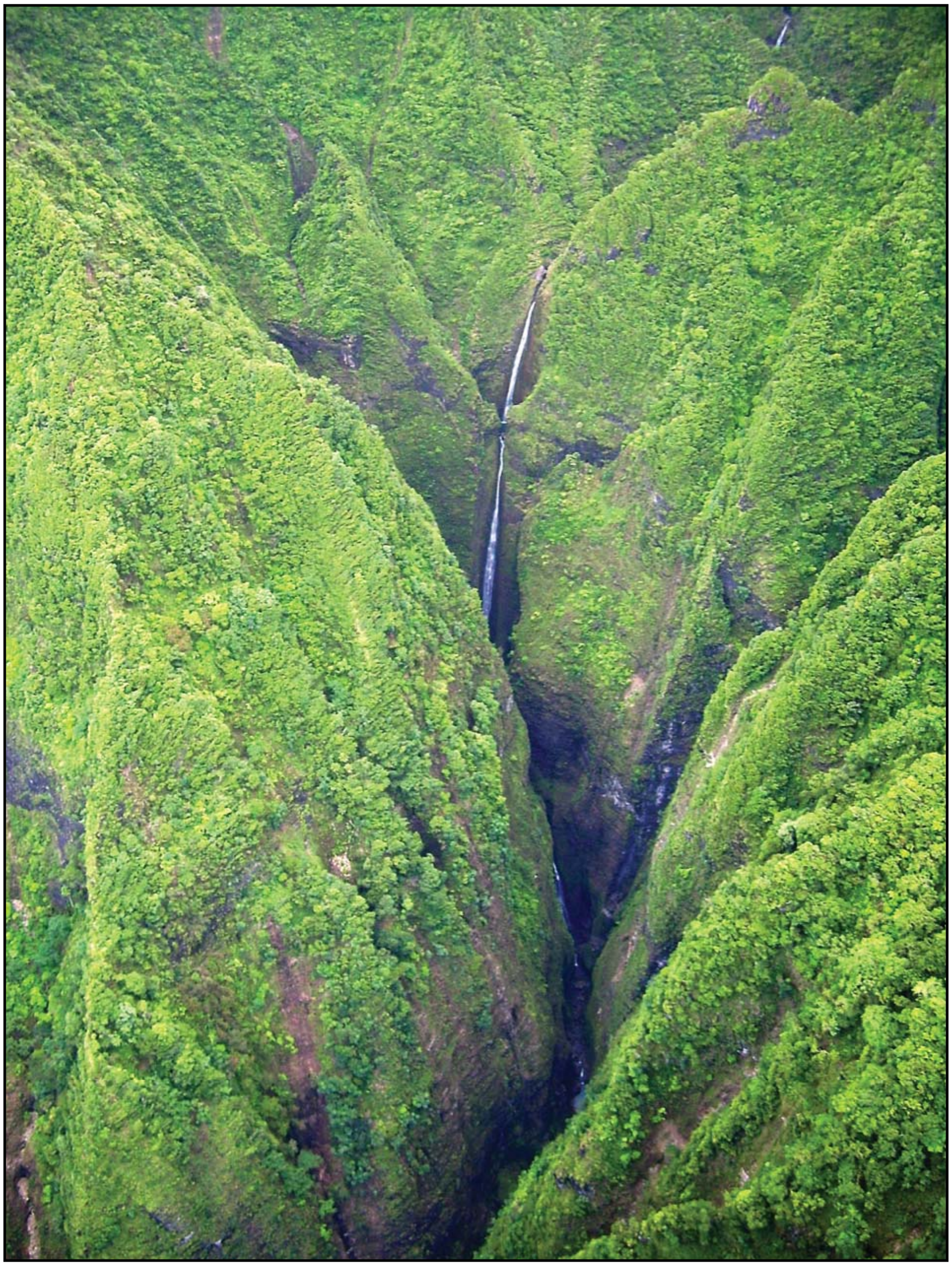

Figure 4.21: Sacred Falls State Park, Oʻahu. Streams on the windward sides of all islands cut rapidly down through easily eroded basalts.

eruptions add topographic highs to the eroded flanks of older volcanoes and can create distinctive hills or *puʻu*. Cinder and **littoral cones** form some of the most iconic landscapes of Hawaiʻi—such as Diamond Head on Oʻahu and the Haleakalā summit area on Maui (*Figure 4.24*).

Where active volcanoes touch the sea, large volumes of lava travel through **lava tube** systems into the ocean. The lava reacts explosively with the seawater, creating a steam-driven eruption that can throw blocks of hot rock a

hundred meters (330 feet) into the air and generate large quantities of **glassy** ash (*Figure 4.25*). The debris can readily build up into littoral cones, dozens of which formed in this way on the coastal stretches of the younger islands. Littoral cones are subject to vigorous wave erosion, which often cuts into the cone to form a protected bay (*Figure 4.26*).

Cinder cones erupt during all subaerial phases of volcanism; however, those formed during earlier shield building are generally covered by later eruptions.

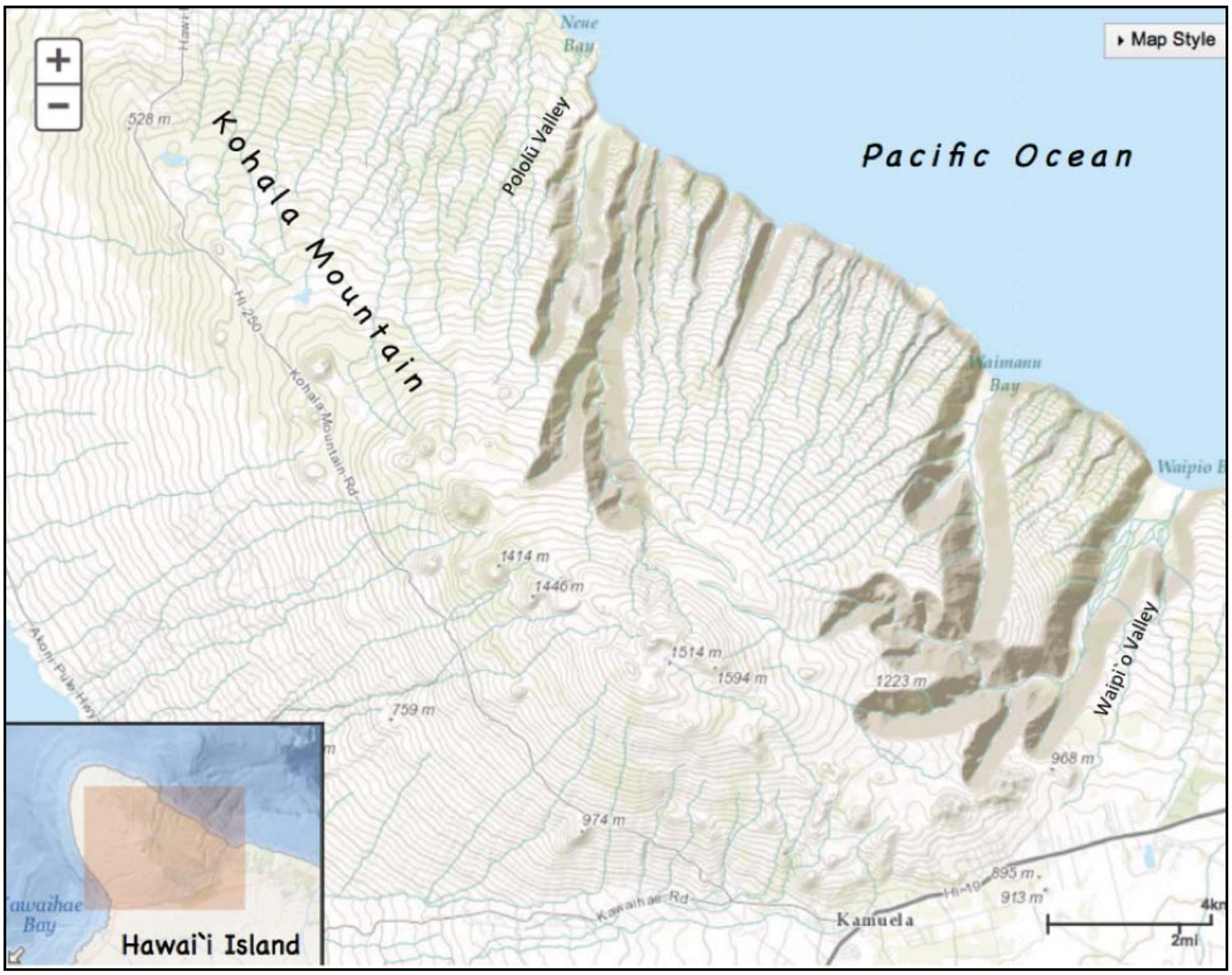

Figure 4.22: Topographic map of Kohala Mountain, Hawai'i Island. The windward side of Kohala is deeply incised by perennial streams while the leeward side remains mostly undissected. The line of cinder cones extending NW-SE across the summit of the mountain marks Kohala's ancient rift zone.

Cinder cones that form during the post-shield stage of volcanism, as well as in the later post-erosional stage, are prominent landscape features. Volcanic rift zones are often marked by linear arrays of cinder cones. Post-erosional eruptions sometimes take place in shallow water where the mix of water and magma adds to the explosive nature of these events. Diamond Head on O'ahu is an example of how lava-seawater interactions can build a substantial edifice composed of layered **cinders** and **volcanic ash** that also contains blocks of basalt and coral fragmented by steam explosions. Another example on O‘ahu is at Haunama Bay, where the cone was later breached by wave erosion and subsequently came to support a protected **reef** ecosystem (*Figure 4.27*).

See Chapter 1: Geologic History for more detail on the stages of Hawaiian volcanism.

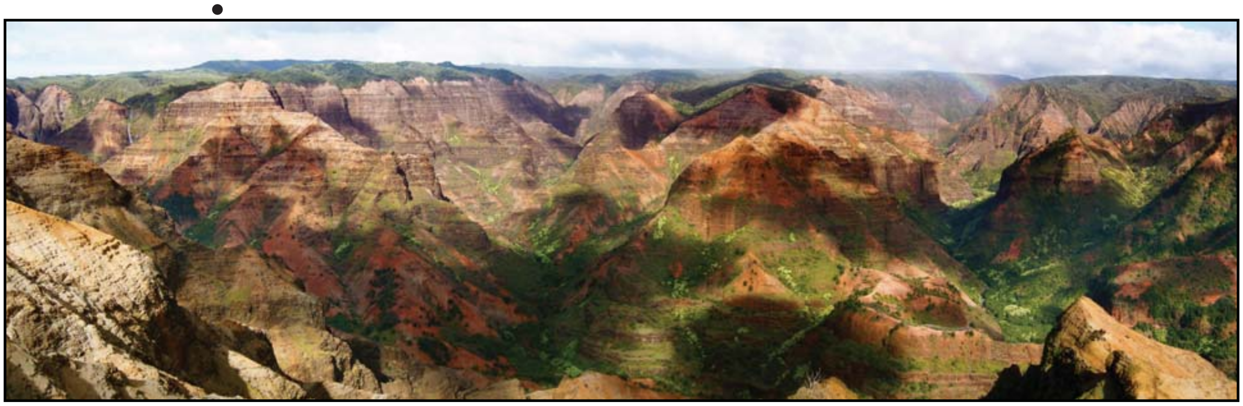

Figure 4.23: Waimea Canyon, Kaua‘i.

Figure 4.24: Haleakalā, Maui. The summit "crater" of Haleakalā formed by erosional—not volcanic—processes. Two headward-eroding valleys were carved into the sides of the volcano and were later covered by the younger cinder cones seen today.

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Figure 4.25: At Kīlauea a lava tube empties into the ocean creating a jet of ash and steam. Repeated interaction of lava and seawater can form littoral cones.

Figure 4.26: Mahana littoral cone on Hawai‘i Island, now breached by the ocean. The tephra here contains abundant olivine crystals that erode to form a “green sand beach.”

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

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

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

4 Topography

Elevations

Figure 4.27: Hanauma Bay—a breached rejuvenation cone on O'ahu.

Highest and Lowest Elevations (by state)

Alaska

Mt. McKinley, with an elevation of 6168 meters (20,237 feet), is the highest mountain in North America as well as Alaska. The mountain is located in Denali National Park, in the south-central part of the state, and it is considered the third most prominent peak in the world after Mt. Everest in the Himalayas and Aconcagua in the Andes. Alaska's lowest points are along its coastlines, where the shore is at sea level.

California

California's highest point—and also the highest point in the contiguous 48 states—is Mt. Whitney, at 4421 meters (14,505 feet) in elevation. Mt. Whitney is located at the southeastern end of the Sierra Nevada. Interestingly, it is only 85 miles northwest from Badwater Basin in Death Valley, which at 86 meters (282 feet) *below* sea level is the lowest point in all of North America.

Hawai'i

Mauna Kea, a dormant **shield volcano** on the island of Hawai'i, is the state's highest point at 4207 meters (13,803 feet) above sea level. A product of hot spot volcanism, much of this volcano's bulk is below sea level—when measured from the ocean floor, its total height is actually 10,100 meters (33,100 feet). The lowest points in Hawai'i are found at sea level along its coastlines, where the shoreline meets the Pacific Ocean.

Elevations

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.*

Nevada

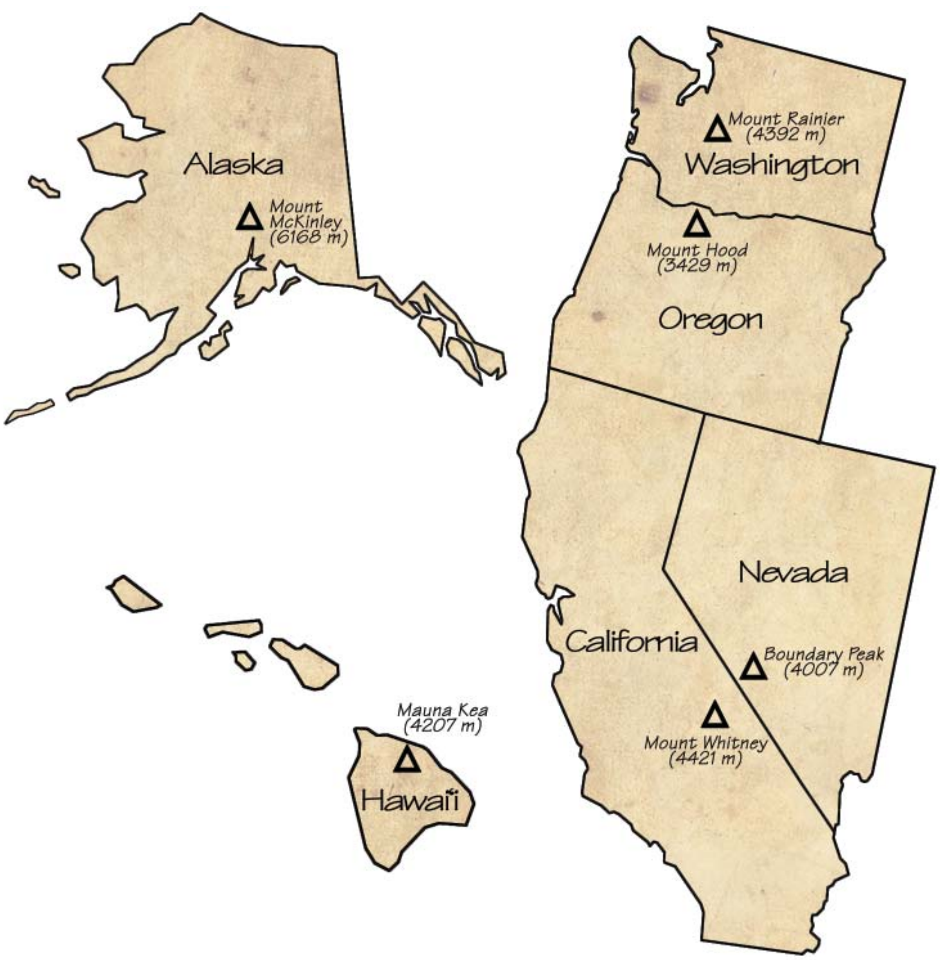
At 4007 meters (13,147 feet) above sea level, Boundary Peak is Nevada's highest point, located less than 2 kilometers (1 mile) from the California border. Nevada's extreme southern border with California, on the Colorado River, is the state's lowest point at 147 meters (481 feet).

Oregon

Mt. Hood, about 80 kilometers (50 miles) east of Portland, is Oregon's highest point at 3429 meters (11,249 feet). A dormant volcano, Mt. Hood is the fourth highest peak in the Cascade Range. Oregon's lowest points are found at sea level along the coast, where the shoreline meets the Pacific Ocean.

Washington

Located 87 kilometers (54 miles) southeast of Seattle, the massive stratovolcano Mt. Rainier is Washington's highest point at 4392 meters (14,411 feet) in elevation. As well as being the highest peak in the Cascade Range, Mt. Ranier is considered one of the world's deadliest volcanoes due to its proximity to highly populated areas. Washington's lowest points are found at sea level along the coast, where the shoreline meets the Pacific Ocean.



Resources

Books

Wyckoff, J., 1999, *Reading the Earth: Landforms in the Making*. Adastra West, Mahwah, NJ, 352 pp.

Sawyer, J. O., 2006, *Northwest California: A Natural History.* University of California, Berkeley, CA, 247 pp. (Chapter 1, The Klamath: Land of Mountains and Canyons, http://www.ucpress.edu/content/pages/9691/9691.ch01.pdf.)

Websites

The Cascade Episode: Evolution of the modern Pacific Northwest, Burke Museum, http://www.burkemuseum.org/static/geo_history_wa/Cascade%20Episode.htm.

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

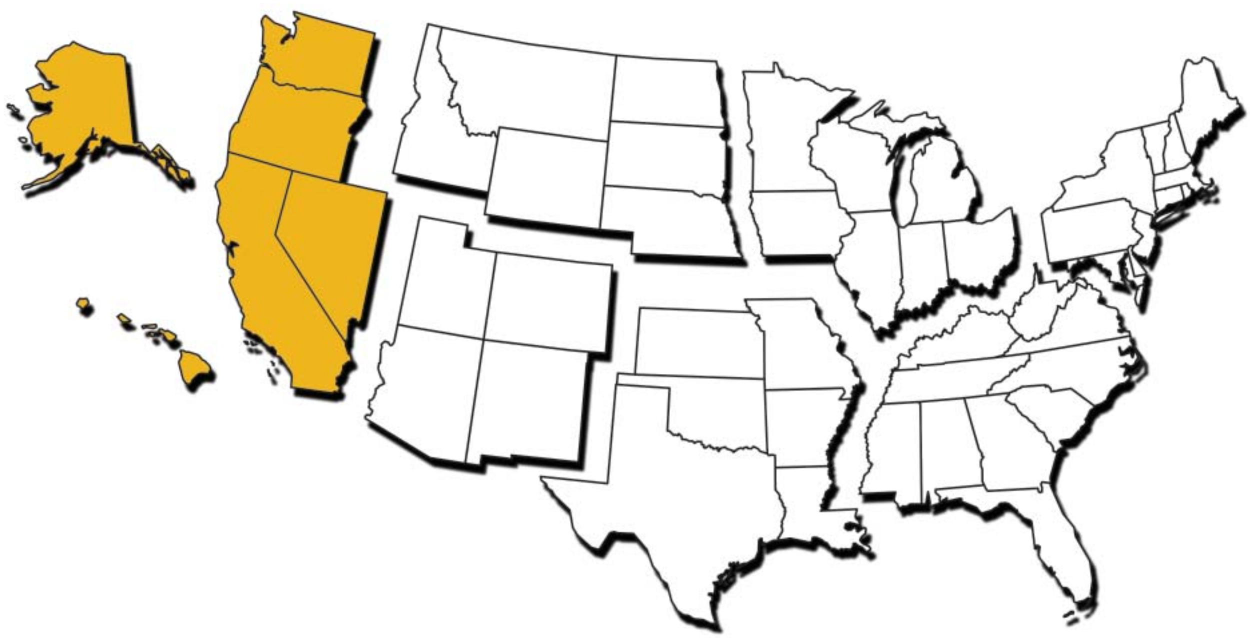
OpenLandform Catalog, Education Resources, OpenTopography, http://www.opentopography.org/index.php/resources/lidarlandforms. (High resolution topographic images that may be useful in teaching.)

Teaching Geomorphology in the 21st Century, On the Cutting Edge—Strong Undergraduate Geoscience Teaching, SERC, http://serc.carleton.edu/NAGTWorkshops/geomorph/index.html. (A set of resources for college level, some of which may be adaptable to secondary education.)

Teaching with Google Earth, On the Cutting Edge—Starting Point: Teaching Entry Level Geoscience, SERC, http://serc.carleton.edu/introgeo/google_earth/index.html.

The **Teacher-Friendly** Guide™

to the Earth Science of the Western US



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