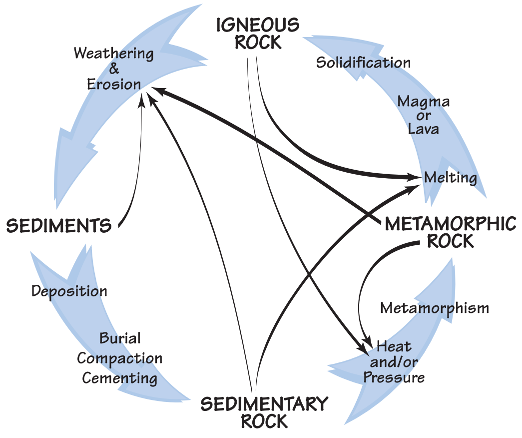
Chapter 2:
Rocks of the Western US

Approximately 200 million years ago, the western edge of what is now North America contained only Nevada and a small sliver of Washington State. As the supercontinent **Pangaea** split up, the western edge of the continent became an **active plate boundary**. The Western States were built by violent eruptions, **subductions**, collisions, and accretions as well as by the processes of **erosion**, deposition, and **lithification**. As a result, there are a wide variety of rocks to be found throughout the Western US (*Figure 2.1*).

Igneous Rocks of the West

rhyolite
obsidian
pumice
andesite
basalt
peridotite
granite
tuff
diorite
dacite
gabbro
pyroclastic rocks



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

Metamorphic Rocks of the West
schist
slate
gneiss
phyllite
quartzite
marble
serpentine

Sedimentary Rocks of the West

conglomerate
greywacke
shale
travertine
gypsum
sandstone
siltstone
limestone
tufa
chert
halite (rock salt)

Figure 2.1: The rock cycle.

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

active plate boundary • *the boundary between two plates of the Earth's crust that are colliding, pulling apart, or moving past each other.*

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

erosion • *the transport of weathered materials.*

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

CHAPTER AUTHORS

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2

Rocks

Igneous Rock Classification

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

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

As rocks at the Earth's surface erode and **weather**, the sediment that forms can be compacted and **cemented** into **sedimentary rock**. Generally, these sediments are transported by **wind**, water, or ice to a depositional environment such as a lakebed or ocean floor; here they build up, burying and compacting

Metamorphic Rock Classification

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

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

Review

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

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

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

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

Sedimentary Rock Classification

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

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

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

lower layers. As water permeates the sediment, dissolved minerals may precipitate out, filling the spaces between particles and cementing them together. Sedimentary rocks can also **accrete** from fragments of the shells or skeletal material of marine organisms such as clams and coral.

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

Review

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.*

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

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

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.*

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

Review

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

granite • *a common and widely occurring type of igneous rock.*

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

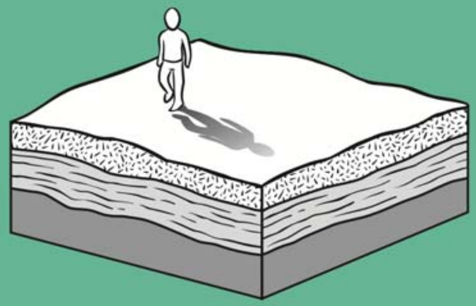
schist • *a medium grade metamorphic rock with sheet-like crystals flattened in one plane.*

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

stromatolite • *regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats.*

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

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



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

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

When rocks are folded or tilted, the person walking across the surface sees several layers of rock exposed.

Rocks 2

Rocks of the Basin and Range

Region 1

While the formation of the Basin and Range province is a recent event that began only 30 million years ago, the bedrock that makes up the up-thrust ranges and down-dropped basins is very old. Since its formation, the bedrock of the basins has been covered by young deposits such as loose sediment washed down from the mountains and **evaporite** deposits from dried- out lakes. The ranges, however, expose rocks whose ages span from **Precambrian** to **Cenozoic**. Many of the sedimentary rock layers exposed in the mountains of the Basin and Range are the same as the rocks exposed by the Colorado River in the Grand Canyon, such as the Coconino Sandstone, Hermit Shale, and Kaibab Limestone, all of which are **Permian** in age.

Unless rock layers are overturned, older rocks are found at the bottom and younger rocks are found at the top of a sedimentary sequence. This is known as the *Law of Superposition*.

The oldest rocks in the Basin and Range can be found in southern Nevada and the eastern Mojave Desert of California. They include **granite** as well as 1.7-billion-year-old metamorphic rocks such as **gneiss**, **schist**, and **marble**. The Pahrump group of rocks in Death Valley and nearby Nevada contains limestone in which **stromatolites** may be found.

See Chapter 1: Geologic History for a geologic time scale on which you can reference the time periods described throughout this chapter.

An excellent place to see both **Paleozoic** and **Mesozoic** rock is near Las Vegas, Nevada. The dark gray limestone of the Bonanza King Formation formed in the **Cambrian** sea during a time period when the land that is now the Western States was still completely submerged—or not even yet part of North America. Today, the Paleozoic limestone has been thrust over the younger **Jurassic** Aztec Sandstone along a reverse **fault** that was created in the Mesozoic when the western edge of North America became a **convergent plate boundary**. The red Aztec Sandstone gives Red Rock Canyon its name (*Figure 2.2*). The **sand** that makes up this stone was deposited as sand dunes, which is evident from the **cross-bedded** layers that result from sand sliding down the side of a dune.

See Chapter 1: Geologic History for more details about the position and formation of the Western states during the Paleozoic.

Region 1

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.*

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

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

cross-bedding • *layering within a bed in a series of rock strata that does not run parallel to the plane of stratification.*

cyanobacteria • *a group of bacteria, also called "blue-green algae," that obtain their energy through photosynthesis.*

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

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

Stromatolites

Stromatolites are regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats (especially photosynthetic *cyanobacteria*). Cyanobacteria emit a sticky substance that binds settling clay grains and creates a chemical environment that leads to the precipitation of *calcium carbonate*. The calcium carbonate then hardens the underlying layers of bacterial mats, while the living bacteria move upward so that they are not buried. Over time, this cycle of growth combined with sediment capture creates a rounded structure filled with banded layers.

Stromatolites peaked in abundance around 1.25 billion years ago, and likely declined due to predation by grazing organisms. Today, stromatolites exist in only a few locations worldwide, such as Shark Bay, Australia. Modern stromatolites form thick layers only in stressful environments, such as very salty water, that exclude animal grazers. Even though there are still modern stromatolites, the term is often used to refer specifically to fossils. For more information, see the Fossils chapter in this Guide.

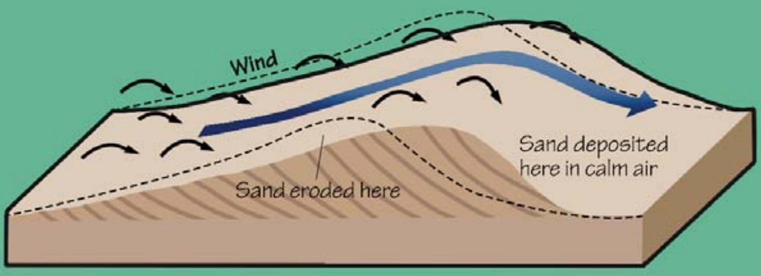
During the Mesozoic, subduction occurred along the western coast. The resulting volcanoes are long since gone, but the granite that formed beneath those volcanoes remains, especially in the western parts of the Basin and Range. The stacked towers of granitic boulders found in Joshua Tree National Park (*Figure 2.3*), the Granite Mountains of the eastern Mojave, and Granite Peak in Nevada are all examples of granitic **intrusions** that formed during the Mesozoic.

The formation of the San Andreas Fault around 30 million years ago ended the compression of southern California and Nevada, and a period of extension

Figure 2.2: The Aztec Sandstone in Nevada.

Cross-bedded Sand Dunes

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



Region 1

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

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

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

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

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

Figure 2.3: "Giant Marbles" in Joshua Tree National Park.

began, leading to the wide-spread formation of basins and ranges. The extensional forces thinned the **crust**, allowing magma to reach the surface, which resulted in a period of intense volcanism This volcanic activity continues to the present day. In addition to creating the faults that make up the fault-block mountains of the Basin and Range, the tension resulted in a period of intense volcanism, which still continues today.

This volcanic activity gave rise to a wide variety of igneous materials. Hole in the Wall and Wild Horse Mesa of the eastern Mojave National Park provide evidence for an explosive eruption of **rhyolitic** ash, which created an ash-flow **tuff** (*Figure 2.4*). Ash-flow tuffs are the result of pyroclastic flows—explosions that contain pulverized rock and superheated gases, which can reach temperatures of up to 1000 °C (1830 °F). The violent expansion of hot gas shreds the erupting magma into tiny particles that cool in the air to form dense clouds of **volcanic ash**. The tremendous explosions that are necessary to create ash-flow tuffs are caused by rhyolitic magma, which is **felsic** in nature. High **silica** content makes the magma quite viscous, preventing gas bubbles from easily escaping, thus leading to pressure build-ups that are released by explosive eruptions. The ash flows from these violent explosions tend to hug the ground, eventually solidifying into tuffs. Tuffs and other pyroclastic materials are **vesicular** (porous) due to gases expanding within the material as it cools.

The largest deposit of ash-flow tuff in the West is the Bishop Tuff from California's Long Valley Caldera eruption

See Region 2: Rocks of the Columbia Plateau in this chapter for more details about columnar jointing.

Understanding Volcanism

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

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

Prior to eruption, magma ascends from the mantle to a relatively shallow (1–10 kilometers [0.5–6 miles]) magma chamber. Upward movement reduces the pressure on the magma until it is low enough to permit dissolved gas to exsolve (come out of solution and form bubbles). All eruptions are driven by the exsolution of dissolved gas. As the gas forms bubbles, it expands in volume and forces the magma out of the vent/chamber system onto the surface. The combination of magma viscosity and gas content can produce a range of eruptive styles, from gentle, effusive eruptions to violent explosions.

760,000 years ago. The Bishop Tuff is pink in color, vesicular, and contains pieces of **pumice** (*Figure 2.5*). Along the Owens Gorge, just north of Bishop, California, the Bishop Tuff can be found in **columnar joints**.

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

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

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

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

Figure 2.4: Hole in the Wall ash-flow tuff.

Figure 2.5: Bishop Tuff.

Not all volcanic rocks of the Basin and Range were created under such explosive conditions. **Mafic** magmas, which create rocks such as basalt, are less viscous and therefore can flow more easily. These gentler, effusive eruptions create features such as cinder cones and basalt flows. Lunar Crater in Nevada

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

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

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

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

contains cinder cones and basalt lava flows that date from the **Miocene** to the **Pleistocene**, 20,000 years ago. Amboy Crater, Pisgah Crater, and the Cima Volcanic fields of the eastern Mojave also produced **basalt** and **scoria.**

In addition to the ancient stromatolites preserved in **limestone**, the Basin and Range also contains younger sedimentary rocks. Because the region is part of the Great Basin, water does not flow to the ocean, but instead evaporates from many **playa lakes** in the basins. At Mono Lake, a large playa lake located in Mono County, California, bubbling hot springs create a spongy limestone called **tufa**, which composes the strange towers that can now be seen since the water level of the lake has fallen (*Figure 2.6*).

Figure 2.6: Tufa towers at Mono Lake, California.

Rocks of the Columbia Plateau
Region 2

The Columbia Plateau, also known as the Columbia Basin, is the site of one of the largest outpourings of lava that the world has ever seen. Between 15 and 6 million years ago, basaltic lava flooded approximately 163,000 square kilometers (63,000 square miles), covering large parts of Washington, Oregon, and Idaho (*Figure 2.7*). The thickness of the lava flows reached 1800 meters (6000 feet), burying almost all of the older rock in the area.

scoria • *a highly vesicular form of basalt. It tends to form as cinders in the early stages of a volcanic eruption, when gas bubbles are still caught up in the frothy erupting magma.*

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

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

tufa • *a carbonate sedimentary rock, formed by evaporation of water around the mouth of a hot spring or other seep, causing calcium carbonate to precipitate out of solution.*

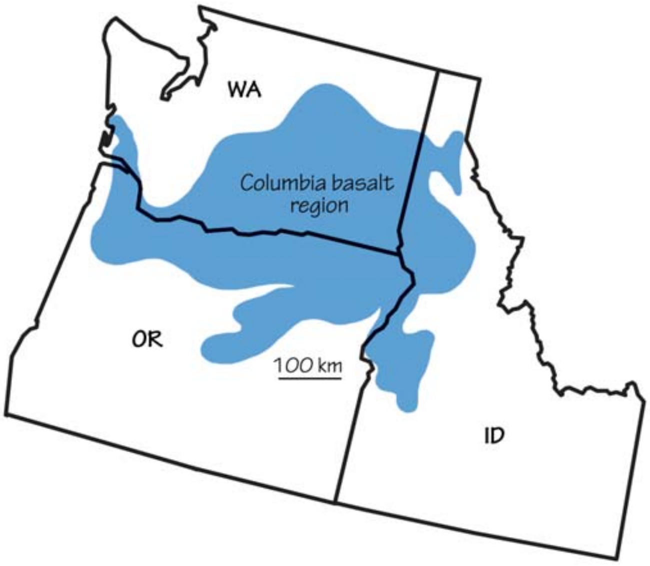


Figure 2.7: Extent of Columbia Basin Flood Basalt.

The Columbia River has eroded deep into the lava flows of the Columbia Plateau, revealing layers of columnar jointed basalt. Layers of these jointed lava flows have been exposed at the Moses Coulee in Douglas County, Washington (*Figure 2.8*). The rhyolitic ash flows of the Bishop Tuff in California and Devil's Tower (an igneous intrusion) in Wyoming (*Figure 2.9*) also exhibit columnar jointing.

Basaltic magmas are produced by partial melting of the upper mantle. Materials melt when we increase their temperature, but a second way to melt a solid is to decrease the pressure. In the interior of the Earth this second mechanism—decompression—is far more important. When pressure on the mantle is released as it is forced up through the crust due to subduction, it becomes basaltic magma.

Figure 2.8 Moses Coulee exposure of lava flows in Douglas County, Washington.

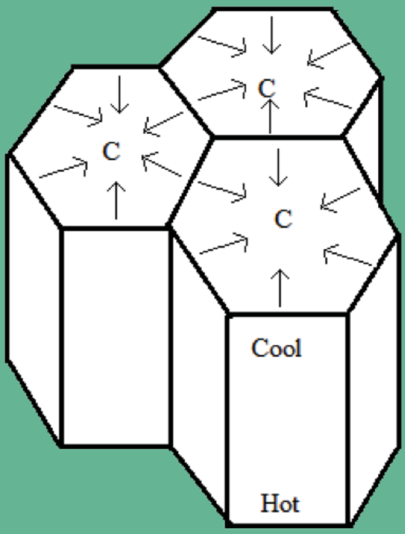
Figure 2.9: Devil's Tower National Monument in Wyoming.

Regions 2–3

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

Columnar Jointing

As a lava flow cools, it contracts, and the resulting force may cause the rock to crack. These cracks continue down to the bottom of the flow, resulting in five- or six-sided columns. Columnar joints are not restricted to basalt flows and can form in ashflow tuffs as well as shallow intrusions. The columns are generally vertical, but may also be slightly curved.



Rocks of the Northern Rocky Mountains

Region 3

The oldest rocks of Washington State can be found in the Northeastern Highlands, which contain the Northern Rocky Mountains as well as the Kootenay Arc and the Okanogan Highlands (*Figure 2.10*). The Northern Rocky Mountains defined the ancient edge of the North American continent during the Precambrian. The oldest rocks are granite, gneiss, and schist of the ancient continental crust. Above them lies the **Belt Supergroup**, a 1.45-billion-year-old series of sedimentary rocks that contains **sandstones** and mudstones.

Region 3

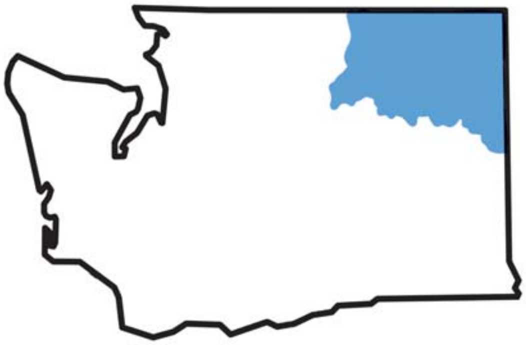


Figure 2.10: Washington State with highlighted Northeastern Highlands region.

For millions of years, the edge of the continent deposited sediments onto its continental shelf. About 200 million years ago the Okanogan micro-continent, an island about the size of California, slammed into the coast, folding and compressing the coastal sediments. The resulting sedimentary rocks, known as the Kootenay Arc, were compressed like an accordion, so that today they lie nearly vertical. They can be viewed between Chewelah and Kettle Falls, Washington. Kettle Falls, now below Franklin D. Roosevelt Lake, marks the **suture** line between the sedimentary rocks of the Kootenay Arc and the granites and gneisses of the Okanogan micro-continent.

The Belt Supergroup is of particular note due to its age and excellent preservation. It is extremely rare for sedimentary rocks of over a billion years in age to not have been warped, tilted, metamorphosed, or otherwise altered. The Belt Supergroup is also famous for its abundant and well-preserved stromatolites.

Granite can also be found throughout the Northeastern Highlands, due to Mesozoic-era magmatic intrusions that cooled at depth. These intrusions are notable for their uranium content, and uranium mines operated in the region between the 1950s and 1980s.

During the early **Paleogene** (50–66 million years ago), the Okanogan Highlands were subjected to further volcanic and tectonic events, resulting in the development of gneiss domes. As the granitic rocks of the highlands were subjected to heat and stress, they melted and rose, dragging underlying gneiss up with them to form the domes. During the same time period, massive **ore** deposits formed as igneous intrusions. Significant deposits of **gold** and **silver** can be found in the Okanogan area. In addition, Mt. Tolman near Keller, Washington holds one of the largest **molybdenum** reserves in the United States, containing over 2.4 billion tons of ore.

See Chapter 5: Mineral Resources to learn more about valuable ores found in the Western States.

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

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

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

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

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

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

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

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).

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

Rocks of the Cascade-Sierra Mountains

Region 4

The rocks of the Cascades and the Sierra Nevada are primarily igneous, since they resulted from melting above a subduction zone. The Cascades are younger mountains, having first appeared 36 million years ago, and are still forming today. In contrast, the plutonic core of the Sierra Nevada began to form over 200 million years ago during the Nevadan **Orogeny**. Oceanic **lithosphere** at the edge of the North American continent melted while subducting at a steep angle, and the magma rose back through the continental crust to form a volcanic arc. While these volcanoes ruptured the surface, massive bodies of magma slowly cooled deep below, creating a huge granite **batholith**. During the **Laramide Orogeny** in the late **Cretaceous** (70–80 million years ago), the angle of subduction became shallower, possibly due to an increased rate of plate convergence. As a result of this shallow subduction angle, volcanism slowed and the North American plate was heavily **uplifted**. The original volcanoes are long since worn away, and their sediments can now be found in the Central Valley of California.

Part 1: The Sierra Nevada

The Sierra Nevada that we see today is composed of the once-deep granite batholith, uplifted with the North American plate and exposed by erosion. The uplifted granitic intrusion is 640 kilometers (400 miles) in length, and lies mostly within California, although one small spur resides in Nevada (*Figure 2.11*). The Sierra Nevada batholith is composed of over 100 different plutons. Each pluton has a slightly different chemistry, but all of the rock is made up of some form of granite. The White Mountains and the Alabama Hills are considered part of the same batholith, but they have been separated from the main body by faulting.

Figure 2.11: Extent of the Sierra Nevada range.

Region 4

Mt. Whitney and the other high peaks of the Sierra experience frequent freezing and thawing, which creates a process called **frost wedging**. At these high elevations, water seeps into cracks in the rocks and then freezes, expanding as it transitions from liquid to solid. This forces the cracks to widen, and the process is repeated as temperatures rise and fall, finally shattering the rocks (*Figure 2.12*).

Figure 2.12: On Mt. Whitney, frost wedging causes rocks to crack in sharp patterns.

The rounded rocks of the Alabama Hills appear markedly different from the jagged granite peaks of Mt. Whitney above them, not because they are made of a different rock, but because they weather differently (*Figure 2.13*). At lower elevations where freezing is infrequent, the granite experiences **spheroidal weathering.** The rough edges of the rock wear away evenly, gradually revealing a smooth surface. The rocks tend to look browner because chemical weathering**,** which is enhanced at warmer temperatures**,** produces **iron** oxides, or rust.

A different weathering process, known as **exfoliation**, formed the impressive rounded granite domes of Yosemite National Park. Although granite is under tremendous pressure when it forms deep underground, it is at equilibrium with the surrounding rock because the pressure is equal in every direction. However, when it is uplifted*,* there is no longer any significant downward pressure on it, so it expands towards the surface. This expansion causes **joints**, or cracks, to form parallel to the surface, producing slabs that resemble the curved layers of an onion (*Figures 2.14 and 2.15*). The most famous example of an exfoliation dome is Half Dome of Yosemite (*Figure 2.16*).

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

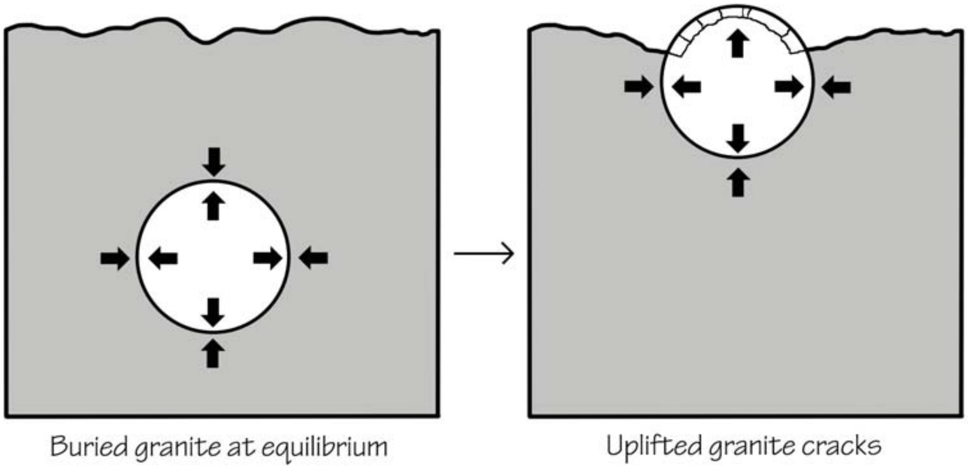
frost wedging • *weathering that occurs when water freezes and expands in cracks.*

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

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

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

Figure 2.13: Rounded Granite of the Alabama Hills with the Sierra Nevada in the background.



Buried granite at equilibrium

Uplifted granite cracks

Figure 2.14: Exfoliation process diagram.

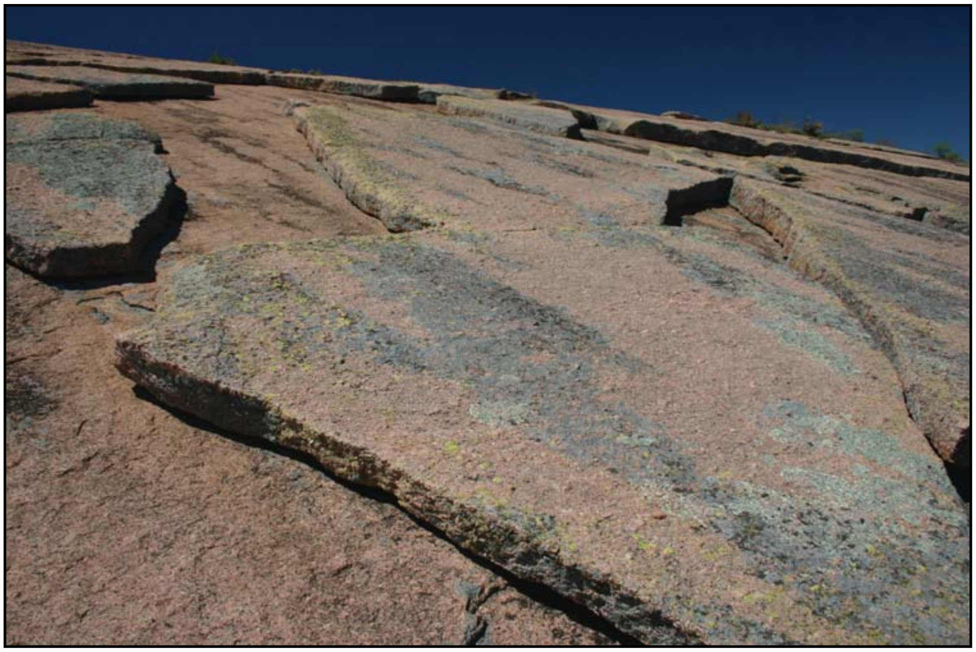


Figure 2.15: Exfoliation joints on granite dome.

Figure 2.16: Half Dome of Yosemite.

Region 4

The superheated intrusions of granitic magma that formed the Sierra batholith also affected the surrounding rocks. One classic example is called a **roof pendant**, which forms when the intruding magma turns the surrounding sedimentary **basement rock** into metamorphic rock through the process of **contact metamorphism**. After uplift and erosion, the remnant of the metamorphic rock hangs above the granitic intrusion (*Figure 2.17*).

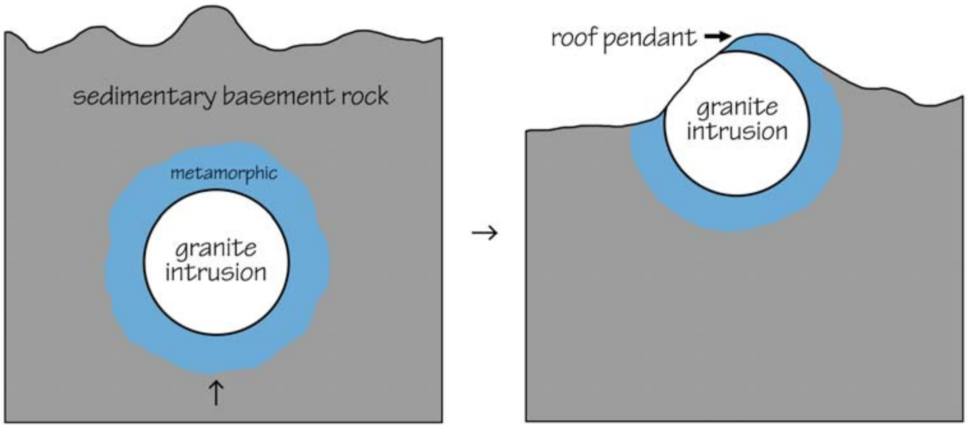


Figure 2.17: Formation of a roof pendant. (See TFG website for full-color version.)

Besides the famous felsic granite of the Sierra Nevada, there are prominent mafic rocks as well, particularly in the Tehachapi Mountains at the southern end of the range. These mountains contain plutonic igneous and metamorphic rocks that are highly mafic due to their iron and magnesium content. The most abundant rock is mafic gneiss. Sometimes this dark rock can be found as **inclusions** within the lighter granite of the Sierra, indicating the presence of older rock enveloped by a newly hardening intrusion.

Several parts of the Sierra Nevada are composed of accreted **terranes** from the subducting Farallon plate along the western continental margin. The Western Foothills contain highly metamorphic rock that is the result of terranes colliding. The rocks here include serpentinite from the subduction zone as well as **hydrothermally** formed veins of **quartz** that contain gold. The Klamath Mountains, also composed of accreted terranes, are oldest in the east and youngest in the west, representing the continuing accretion of island arcs and continental fragments from the Pacific Ocean. The rocks of the eastern Klamath are Cambrian to **Triassic** in age, and are mostly metamorphic and **ultramafic**. The western Klamath, located along the California-Oregon coast, is formed of marble. These rocks began as a limestone **reef** in a shallow ocean. After they accreted onto the edge of the continent, they were

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

roof pendant • *a downward projection of metamorphosed basement rock that hangs exposed above an uplifted igneous intrusion.*

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

contact metamorphism • *a metamorphic rock that has been altered by direct contact with magma.*

inclusion • *a fragment of older rock located within a body of igneous rock.*

hydrothermal solution • *hot, salty water moving through rocks.*

Region 4

ultramafic rocks • *igneous rocks with very low silica content (< 45%), which are composed of usually greater than 90% mafic minerals.*

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

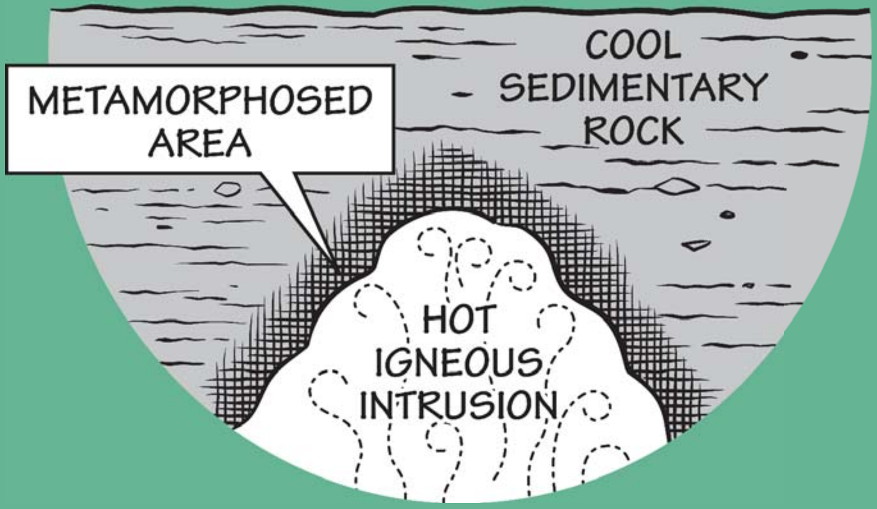
Triassic • *a geologic time period that spans from 252 to 201 million years ago.*

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.*

What happens to a rock when it is metamorphosed?

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

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



Regional or *dynamic metamorphism* describes a metamorphic rock that has been altered due to deep burial and great pressure. This type of metamorphic rock tends to occur in long belts. Different types of metamorphic rock are created depending on the gradients of heat and pressure applied.

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

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

***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.**

finally metamorphosed into marble by the heat from intruding magma during the Mesozoic. The intrusions cooled into granite and diorite, which are visible at the Oregon Caves National Monument.

See Chapter 5: Mineral Resources to learn more about Alaskan gold.

Part 2: The Cascades

The Cascade Range extends all the way from southern British Columbia to northern California, and is made up of a series of volcanoes that have built up a large platform of volcanic debris (*Figure 2.18*). These volcanoes, the Cascade Volcanic Arc, arose due to the subduction of the Pacific plate beneath North America. As long as subduction continues, the Cascades will remain volcanically active.

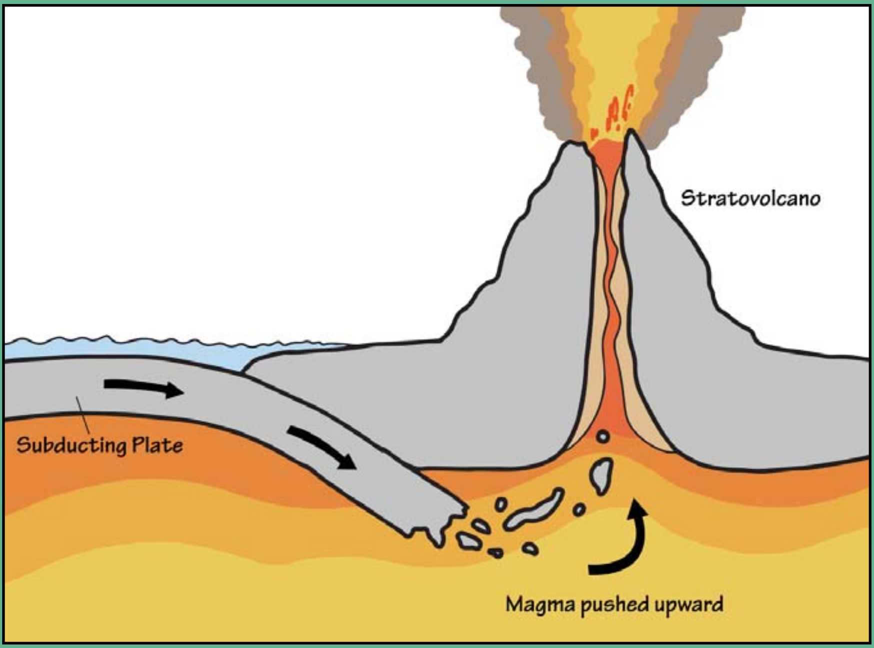
Figure 2.18: The Cascade Range. (See TFG website for full-color version.)

The Cascades are primarily composed of volcanic igneous rock, the youngest of which is found in the active volcanoes of the High Cascades—strikingly large **stratovolcanoes** that rise high above the landscape of the range. The tallest of the High Cascades is Mt. Rainier, which rises to 4392 meters (14,410 feet) above sea level. The most common rock produced by these volcanoes is **andesite**, a fine-grained rock of intermediate silica content. Another common rock is **dacite**, a gray volcanic rock that lies between andesite and rhyolite in terms of its silica content.

The Cascades also contain a few ancient **shield volcanoes.** A shield volcano has a low profile and gradual slope because it is made of lava flows that were more fluid than the "sticky" silica-rich lavas that build up stratovolcanoes. Newberry Volcano in Oregon is the widest volcano of the Cascades, with a

Stratovolcanoes

A *stratovolcano* is a conical volcano made up of many lava flows as well as layers of ash and breccia from explosive eruptions. In fact, stratovolcanoes are often characterized by their periodic violent eruptions, which occur due to their presence at subduction zones. While young stratovolcanoes tend to have steep cone shapes, the symmetrical conical shape is readily disfigured by massive eruptions, such as at Mt. Saint Helens in 1980. Older stratovolcanoes like Mt. Rainier further lose their symmetry due to erosion, especially because volcanoes are inherently unstable mountains. Many older stratovolcanoes contain collapsed craters called *calderas*.



diameter of 32 kilometers (20 miles). This broad shield volcano emitted a wide range of flows, ranging from basalt to rhyolite. The volcano's caldera is thought to have first formed 500,000 years ago, when the original cone collapsed following a particularly large eruption that emptied the underlying magma chamber. Today, the caldera forms a lake that contains a few smaller volcanic

obsidian • *a glassy volcanic rock, formed when felsic lava cools rapidly.*

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

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

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

gabbro • *a usually coarse-grained, mafic and intrusive igneous rock.*

cones as well as the Big Obsidian Flow (*Figure 2.19*), a 1300-year-old patch of volcanic glass that covers about 10 square kilometers (4 square miles). The **obsidian** from this flow was commonly used to make tools, and it has been traced to Native American sites all over the region.

See Region 7: Hawai‘i in this chapter for more information about shield volcanoes.

Figure 2.19: Newberry Caldera showing the lake, central cones, and the Big Obsidian Flow.

Belknap Crater in Oregon (*Figure 2.20*) is another large shield volcano. It produced basaltic lava flows 3000 years ago, but its last eruption, 1500 years ago, produced **basaltic andesite** lava flows. Overall, the flows from Belknap Crater—and its sister craters, Little Belknap and Yapoah—cover nearly 200 square kilometers (77 square miles) of the surrounding area.

The Western Cascades are made up of old, extinct, and highly eroded volcanoes. The oldest outcrops, 18–40 million years old, contain many pyroclastic rocks. The old volcanic remnants of the Western Cascades provide us with a glimpse of what the current High Cascades will look like in about 18 million years.

The North Cascade Range, although it has a few prominent volcanoes, is predominantly an uplifted block of accreted terranes. The collision that accreted these terranes created intense pressure, leading to metamorphic conditions that formed rocks such as **slate**, **phyllite**, schist, gneiss, and marble. Numerous magmatic intrusions left behind intrusive rocks such as granite, diorite, and **gabbro**, as well as causing contact metamorphism. The volcanoes of the North Cascades, such as Mt. Baker and Glacier Peak, are

Figure 2.20: Belknap Crater.

made of basalt and andesite as well as volcanic **breccia**, a pyroclastic rock composed of volcanic fragments from an explosive eruption. There are some sedimentary rocks in the North Cascades as well; the Methow Valley contains a thick layer of Cretaceous sedimentary rocks such as **shale**, sandstone, and **conglomerate**.

Rocks of the Pacific Border

Region 5

Stretching from Mexico to Alaska, the Pacific Border is a chaotic jumble of compressed land and ocean sediments, subducted plate scrapings, accreted terranes, and even errant pieces of ocean plate plastered against the western edge of the continent. Many different parts of the range contain a wide variety of rocks, but all of the ranges share one thing in common: they are the leading edge of an active plate boundary.

Southern California lost its subducting plate boundary 20 million years ago. The junction between the subducting Farallon plate and North America has been shifting northward, leaving the Pacific plate directly next to the North American plate. This new boundary is defined by the San Andreas Fault, a **transform boundary** (*Figure 2.21*).

Evidence of past subduction can be found along the California coast in what is called the Franciscan Assemblage (or formation). Some parts of it are called a **mélange**, a mixture of fragmented rocks produced in a subduction zone. Approximately 90% of the Franciscan Assemblage is composed of **greywacke**, a form of sandstone deposited in deep marine basins by submarine landslides called **turbidity currents**. This dark-colored rock has layers that transition from

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

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

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

greywacke • *a variety of dark-colored sandstone that contains angular grains of quartz and feldspar embedded in clay.*

coarse grains to fine grains as a result of the submarine turbidity currents coming to rest. The Franciscan Assemblage has also been intruded by **serpentinite**, a metamorphic rock formed when **peridotite** from the subducting plate reacts with water, producing a light, slippery, green rock.

The rocks of the Franciscan Assemblage stand in stark contrast to the Salinian block, a terrane that contains granite as well as metamorphic rocks such as gneiss, schist, **quartzite**, and marble. The Salinian block is a segment of the

serpentinite *• a metamorphic rock formed when peridotite from a subducting plate reacts with water, producing a light, slippery, green rock.*

peridotite *• a coarse-grained plutonic rock containing minerals, such as olivine, which make up the Earth's mantle.*

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

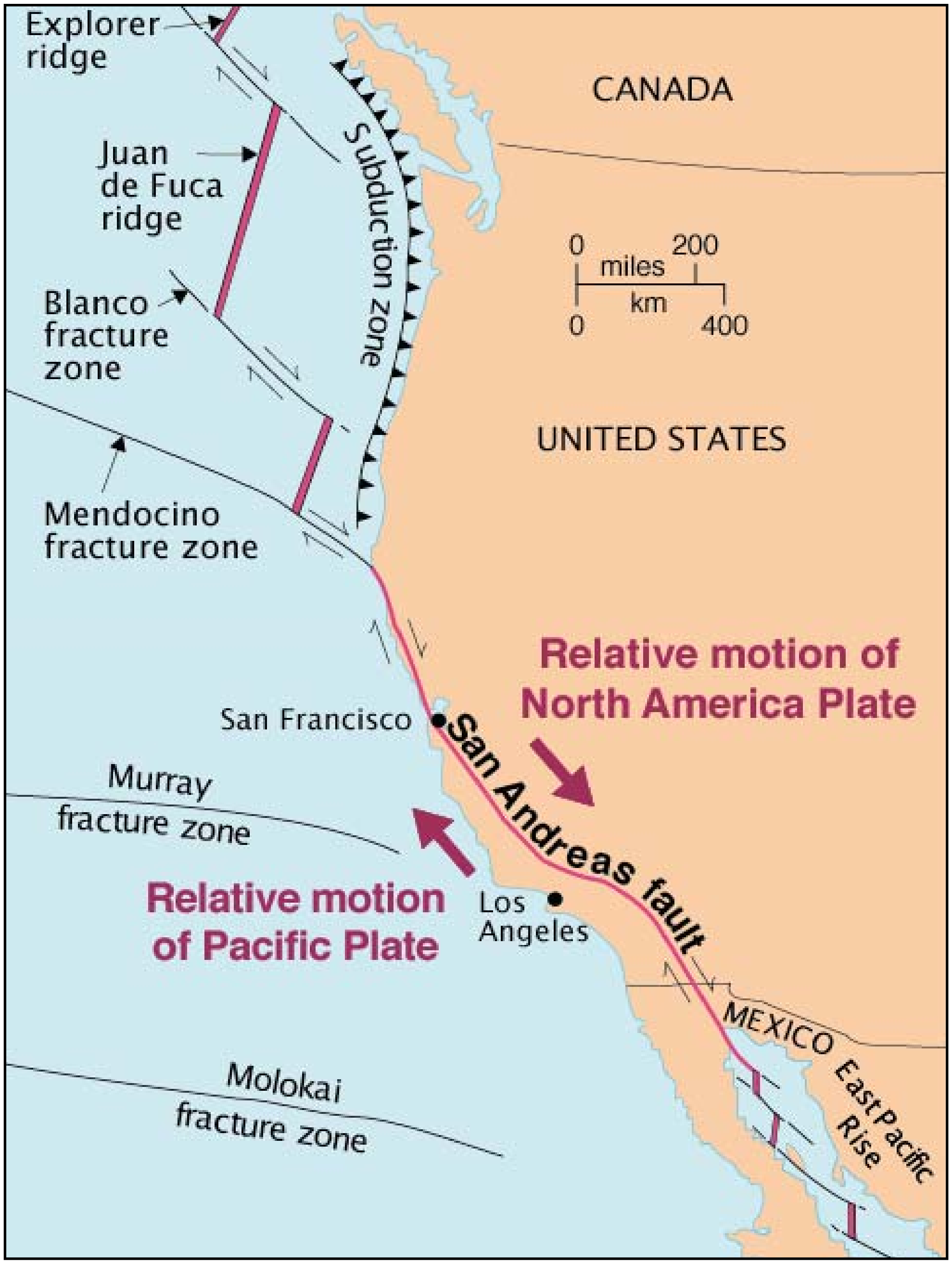
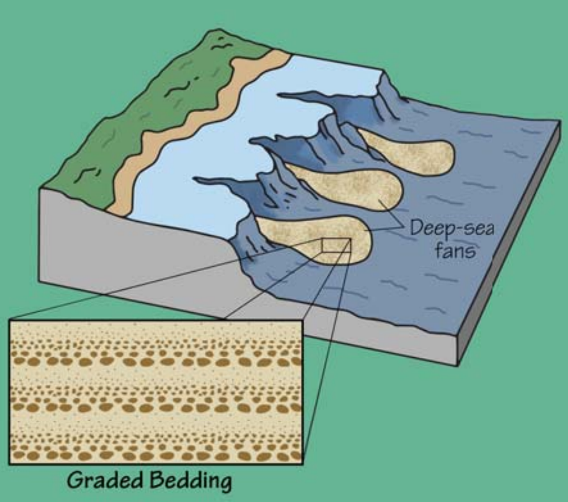


Figure 2.21: Plate boundaries of the West Coast. (See TFG website for full-color version.)

Turbidity Currents

Turbidity currents are essentially submarine sediment avalanches. These fast-moving currents of sediment are often caused by *earthquakes* or other geological disturbances that loosen sediment on a continental shelf. The sediment rushes down the continental slope, picking up sediment and speed as it moves. The density of the sediment within the current gives it great force; turbidity currents have been reported to move at speeds of 100 kph (62 mph). These massive sediment flows have extreme erosive potential, and often carve out underwater canyons. In 1929, the Grand Banks earthquake off the coast of Newfoundland generated a turbidity current that traveled more than 600 kilometers (370 miles) and snapped twelve different transatlantic cables.

Turbidity currents deposit huge amounts of sediment during their flow; such deposits are called *turbidites*. Turbidite sediments are deposited in a graded pattern, with the largest particles at the bottom (as they are the heaviest, and detach from the flow more quickly) and smaller particles on top. Turbidites commonly form in a shape called an abyssal fan, which spreads out in a wide teardrop shape from the source. Because of the rate at which turbidity currents deposit dense sediments, they are often responsible for the effective preservation of many fossil organisms, which are swept up from shallow marine environments and buried in the deep sea.



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

chert • a sedimentary rock composed of microcrystaline quartz.

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

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

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

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

continental crust that has been moving northwest along the west side of the San Andreas Fault (*Figure 2.22*). It was once an extension of the southern Sierra Nevada, but it was captured by the Pacific plate. It can be clearly seen at Point Reyes National Park, where it is separated from the Franciscan mélange by Tomales Bay.

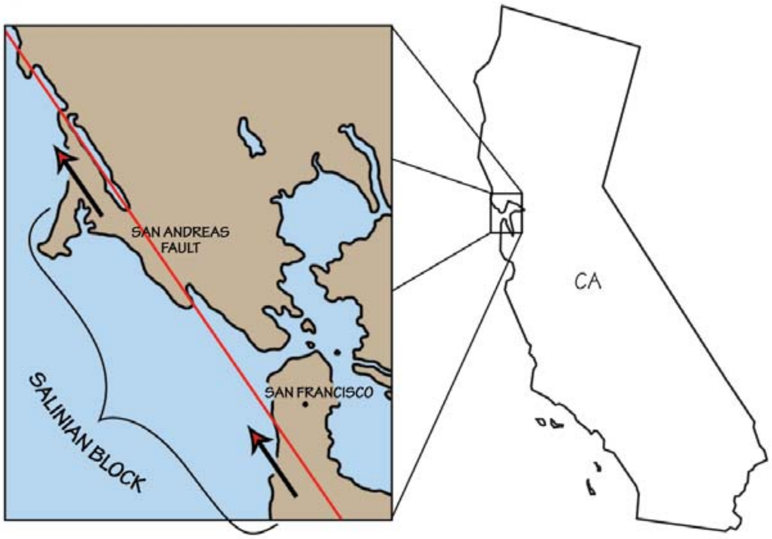


Figure 2.22: Geography of the Salinian block.

Occasionally, a subducting oceanic plate will fracture and leave behind a slice of oceanic crust on land. The resulting rock sequences, called **ophiolites** (*Figure 2.23*), are the most helpful tool we have for studying oceanic crust. The top of the crust contains deep-sea sedimentary rock, such as **chert**. Below that are **pillow basalts** that were **extruded** into the water at a mid-ocean ridge. Below the pillow basalts are intrusions of basalt known as sheeted **dikes**, formed as the mid-ocean ridge pulled apart. Below the basalt is gabbro, the plutonic version of basalt, and finally **peridotite**, the rock that composes the Earth's **mantle**. Ophiolites

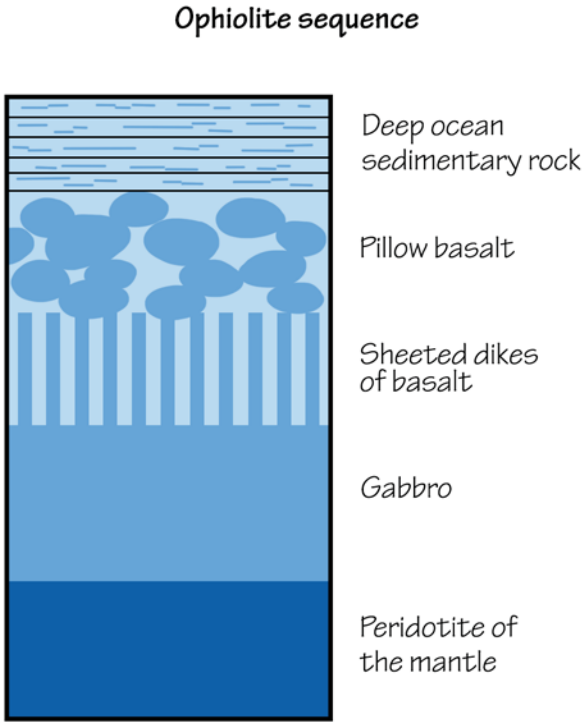


Figure 2.23: Structure of an ophiolite.

are among the only places where mantle rock can be seen on the Earth's surface. Ophiolite sequences can be found exposed at the Golden Gate National Park, Cuesta Ridge (near San Luis Obispo), and in the western Klamath Mountains.

The **Monterey Formation** is a distinctive light-colored sedimentary rock unit that formed in the Miocene seas. Its buff color comes from its high silica content. Outcrops from the Monterey Formation are visible along California's coast and peninsula, and on some of the offshore islands. It is composed primarily of shale, and it is the source rock for most of California's **oil**. Oil shale like this tends to form when deposition occurs on top of thick algal beds—the sediment layers then trap the oil that forms from the decomposing organic matter.

The Juan de Fuca plate is still subducting along Northern California, Washington, and Oregon. The Oregon Coast Range, which overlies this subduction zone, extends for 320 kilometers (200 miles) from the Washington-Oregon border south to the Coquille River (*Figure 2.24*). These mountains began to form 66 million years ago during the Cretaceous, when a series of offshore **volcanic islands** were pushed into the North American plate. The collision forced undersea basalt formations and sediment **terraces** upward, and these deposits now underlie the Southern and Central parts of the Coast Range. During the **Eocene**, the Siletz River Volcanics—basaltic pillow lavas and other lava flows that formed in submarine volcanoes present on the subducting plate—were added to the range. Lastly, basalt from the edge of the Columbia Basin basalt flow added further material to the range.

See Region 2: Rocks of the Columbia Plateau in this chapter for more information about the Columbia Basin basalt flow.

The Northern portion of the Oregon Coast Range, though it still contains the same basaltic core as the range's more southern portions, tells a slightly different geologic story. Portions of this area contain marine sedimentary rock, uplifted by the subducting Juan de Fuca plate. Sandstone, mudstone, siltstone, and shale are common rocks here, and marine **fossils** also appear in some areas. Heavy rainfall has contributed to the erosion of much of the landscape, leading to the formation of steep slopes and deep valleys.

In Washington State, the coastal region is made up of the Olympic Peninsula, a large arm of land that juts out into the Pacific Ocean. The Olympic Mountains, an extension of Oregon's Coast Range, form the Peninsula's core. These mountains formed in the same way as the Coast Range (*Figure 2.25*), and are underlain by a very similar basalt formation called the Crescent Formation. As convergence of the Juan de Fuca plate accelerated in the middle Miocene, a variety of sedimentary, metamorphic, and volcanic rocks accreting to the Olympics were chaotically jumbled to form a mélange called the **Hoh rock assemblage**. These rocks are exposed along 72 kilometers (45 miles) of Washington's Olympic Coast (*Figure 2.26*).

During the Pleistocene, continental **ice sheets** sculpted the Olympic Mountains, leading to the formation of U-shaped valleys and the deposition of many granitic glacial **erratics**.

Region 5

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

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

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

fossil • *preserved evidence of ancient life.*

Hoh rock assemblage • *a mélange formed from a variety of chaotically jumbled sedimentary, metamorphic, and volcanic rocks that accreted to the Olympic Peninsula during the Eocene.*

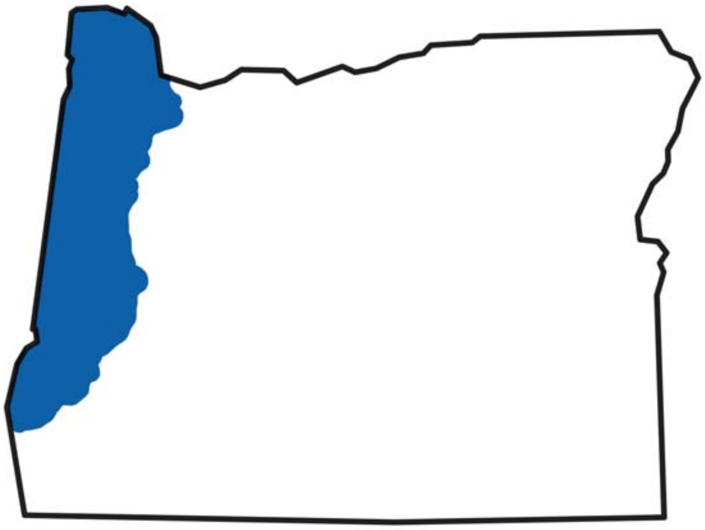


Figure 2.24: Extent of the Oregon Coast Range.

See Chapter 6: Glaciers for more information about the landforms created by glaciers in the Western States.

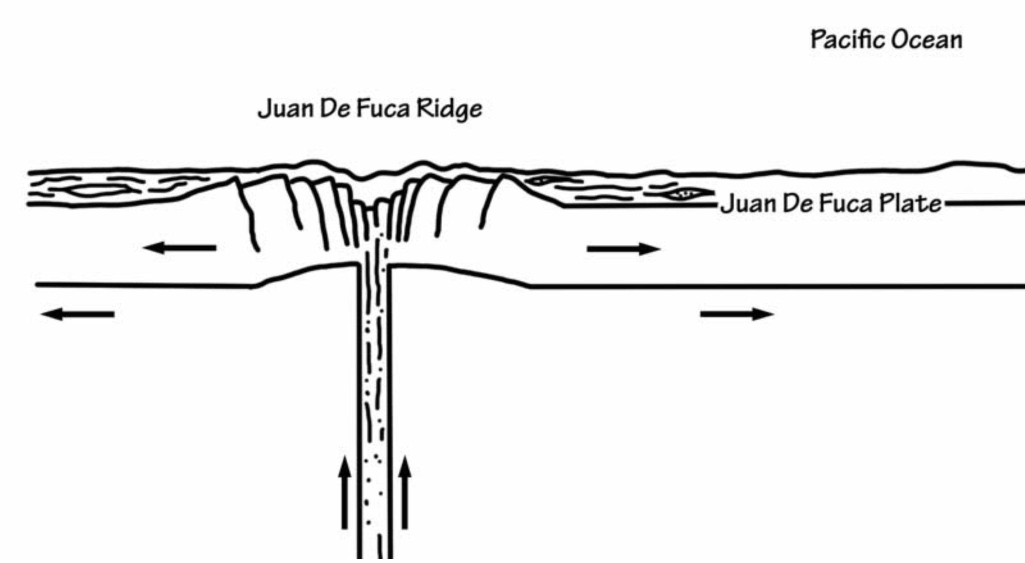
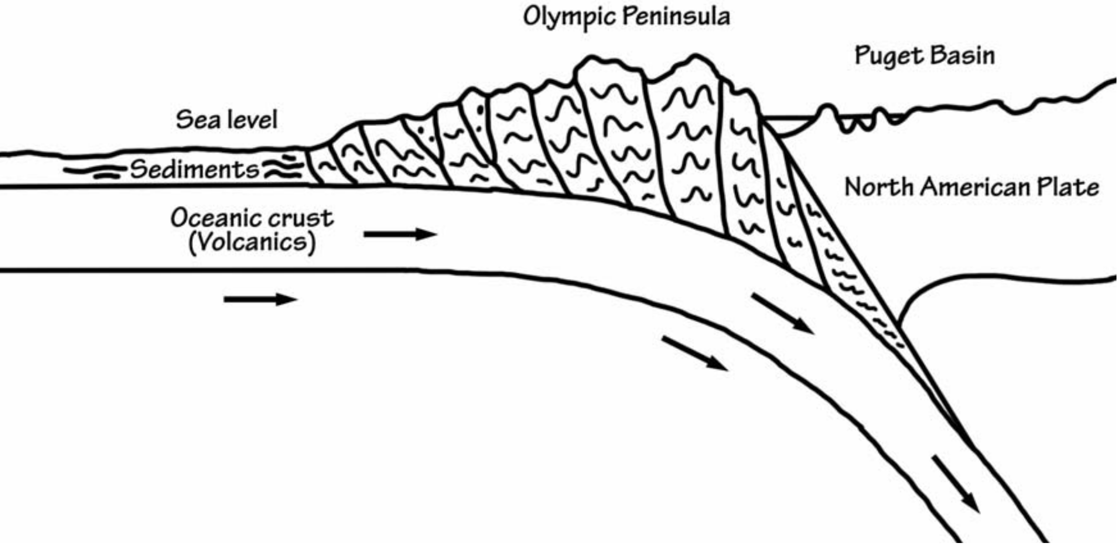


Figure 2.25: Formation of the Olympic Peninsula and Mountains.

Figure 2.26: Hoh assemblage rocks along the Olympic Coast.



Rocks of Alaska

Region 6

Alaska is a mosaic of accreted terranes, each with its own history (*Figure 2.27*). Due to the accretion of these terranes over time, Alaska today showcases a diverse array of mountain ranges and physiographical regions (*Figure 2.28*). The first rocks of Alaska were put in place when the Yukon-Tanana terrane collided with the western edge of North America 200 million years ago. These rocks are late Precambrian in age and are mostly composed of schist. The greenschist and blueschist of the southwestern Brooks Range show clear signs of having been formed at this convergent plate margin, as they contain minerals that form at high pressure but low temperature. The Brooks Range, Alaska's northernmost mountain range, is heavily composed of the Yukon-Tanana's ancient seabed, and contains many ancient marine fossils. Rocks on the northern side of the Alaska Range, Alaska's central mountain chain, have also been correlated with schists from the Yukon-Tanana.

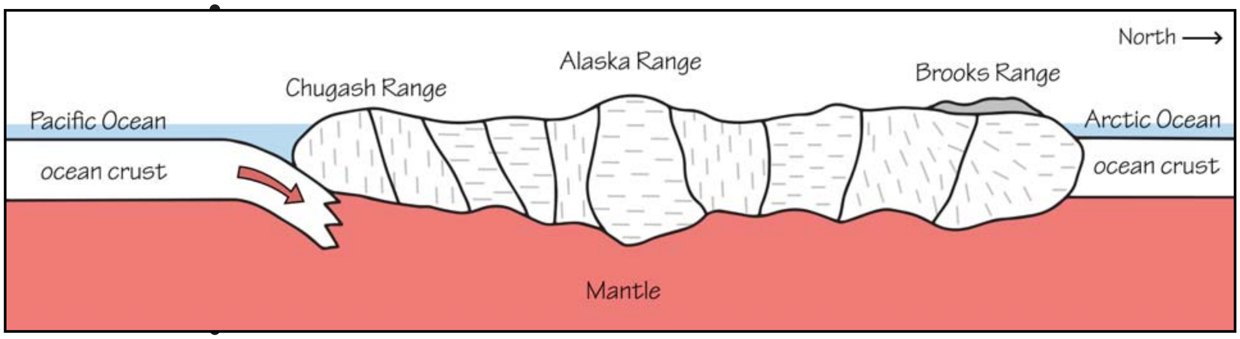


Figure 2.27: A cross-section of Central Alaska. Each section delineates a separate terrane.

Other late Precambrian and Paleozoic rocks of Alaska include gneisses of the Seward Peninsula, which extends from northwest Alaska and is a remnant of the Bering land bridge that connected Alaska to Siberia during the Pleistocene. The Seward

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

Peninsula is actually composed of two terranes: the Seward terrane, which is made up of Precambrian schists, granites, and marbles, and the York terrane, which consists of **Ordovician** through **Mississippian** limestone, **dolostone**, and phyllite. The sedimentary rocks of the York terrane would have originally been deposited in a shallow marine environment before their accretion onto the North American plate. During the Cretaceous, thrust faulting deformed the York terrane, allowing the formation of intrusive granites.

See Chapter 3: Fossils to learn more about Alaska's ancient marine fossils.

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

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

In the late Cambrian to early **Devonian**, undersea volcanism resulted in large quantities of igneous material being mixed with fossiliferous limestone. As these units were transported to finally dock against North America, they accreted as part of the northern Alaska Range, and metamorphism created large quantities of carbonaceous schist.

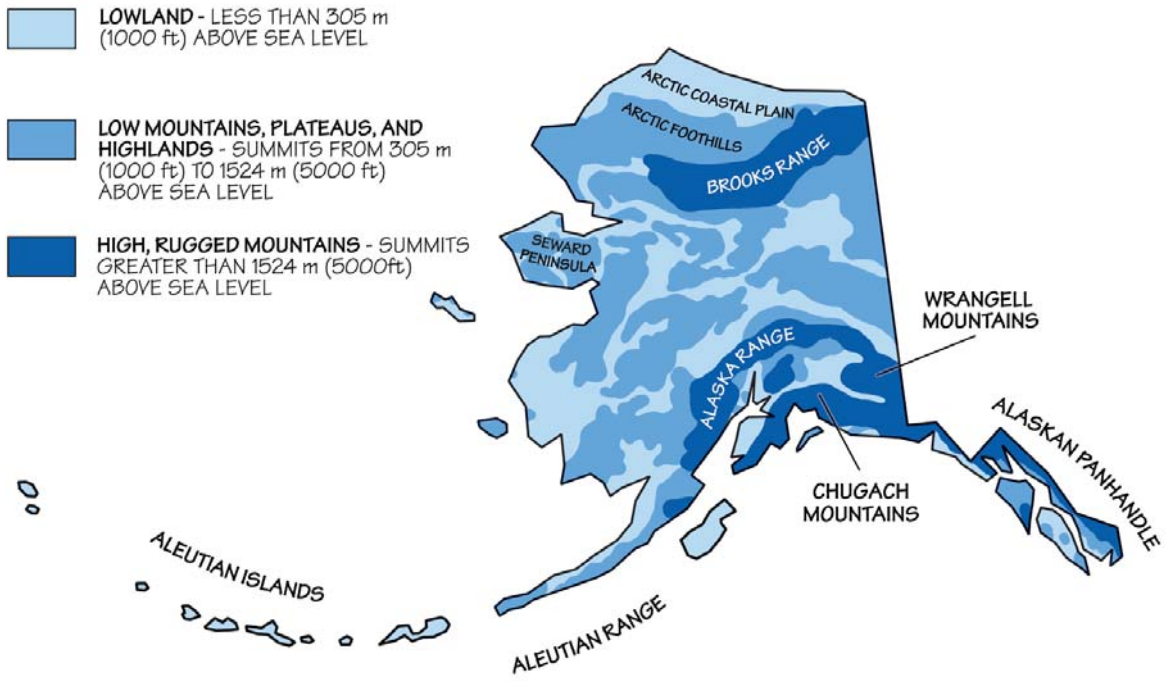


Figure 2.28: Regions and ranges of Alaska. (See TFG website for full-color version.)

The next major terrane, Stikinia, began as a volcanic island arc that formed on the **rifted** margin fragments of the Yukon-Tanana. Its formation would have been similar to the volcanic arc that makes up the islands of Japan today. As this island arc traveled towards a collision with Alaska during the Cretaceous, it scooped up marine shales, sandstones, and limestones that became jumbled up with the volcanic rhyolites, andesites, and basalts that formed the islands. This collection of varied, jumbled rocks eventually became part of the Alaska

Range. The Taku terrane and the Tracy Arm terrane were the next to crash into Alaska, adding more metamorphic rocks such as gneiss, schist, and marble.

The Wrangellia terrane, born near the equator about 300 million years ago, didn't dock with Alaska until 120 million years ago, so it contains rocks that tell a complex story of many years of volcanism, erosion, deposition, sinking, and uplift. Wrangellia's defining unit is a 2500-kilometer (1553-mile) Triassic flood basalt, which would have been extruded onto the terrane's landmass about 230 million years ago. Shallow seas later inundated the region, covering these volcanic rocks with layers of limestone and other marine sediments. Today, these flood basalts and their overlying sediments extend across the southern portion of the Alaska Range and the Wrangell Mountains. As Wrangellia moved toward North America, it also collided with a variety of other smaller terranes, compressing seafloor rocks against it and forming a complex fault system. This fault is expressed today as the Border Ranges Fault, which occurs throughout the Chugach Mountains at the southern edge of Alaska.

Each terrane was brought to Alaska on a subducting plate, and subduction is still occurring along the Aleutian Trench, resulting in the formation of the Aleutian Islands. The subduction creates stratovolcanoes and plutonic igneous intrusions (*Figure 2.29*) along the entire Aleutian Range. The stratovolcanoes produce rocks that tend to be intermediate in silica content, so andesite and dacite are common. Pyroclastic rocks from explosive events are also quite common. One spectacular example is found at Novarupta in Katmai National Park, where a volcanic eruption thirty times as large as Mt. St. Helens occurred in 1912. Geologists who investigated the aftermath of the eruption were awe-

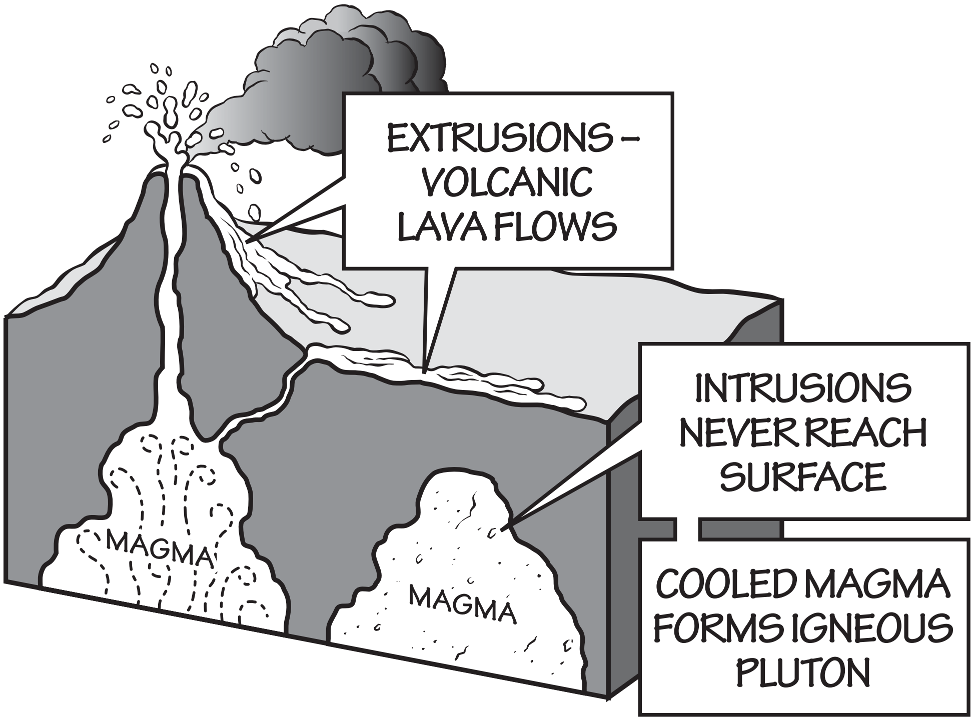


Figure 2.29: Intrusive and extrusive igneous features.

struck by the still-smoking tuff that covered the surrounding area, and named it the Valley of Ten Thousand Smokes (*Figure 2.30*).

Today, the Yakutat Block is the terrane currently accreting to Alaska, along the state's south-central coast. Its convergence with Alaska is responsible for the volcanism evident in the Wrangell Mountains today. The largest volcano in the range, Mt. Wrangell, is unusual because it formed from massive andesitic lava flows that gave it a shield shape rather than the cone shape of a typical stratovolcano. The process that allowed andesite to form a shield volcano is poorly understood, but is likely related to the volume of ejected magma. Besides these andesitic lava flows, the rocks of the Wrangell Mountains include scattered cinder cones and rhyolite domes (*Figure 2.31*).

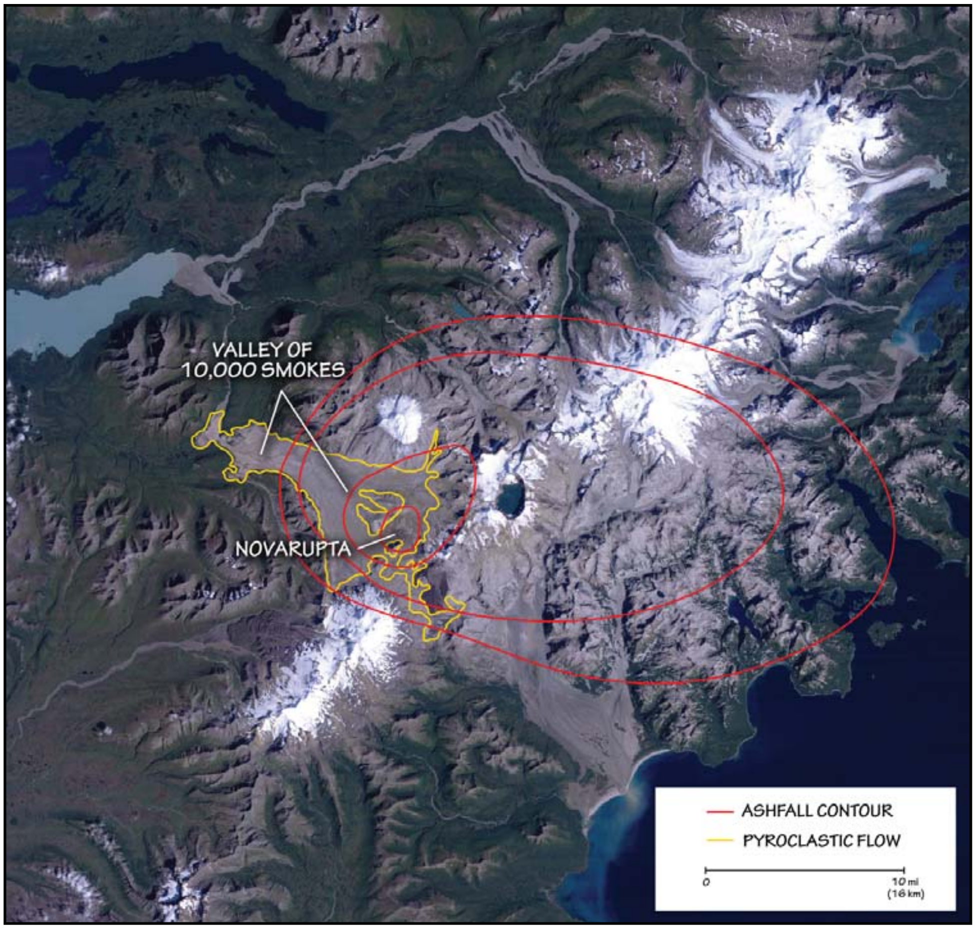


Figure 2.30: Novarupta Volcano in the Aleutian Range. (See TFG website for full-color version.)

During the late Jurassic and early Cretaceous, rotation of the North American plate caused basins to open up in the Arctic, creating shallow seas that filled with sediments eroded from the Brooks Range. Today, these sediments form the upper source rocks of the Arctic Foothills and Arctic Coastal Plain, north of

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

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

Figure 2.31: The Wrangell Mountains, showing (left to right) Mt. Drum, Mt. Blackburn, and Mt. Wrangell.

the Brooks Range. The shales here are rich with oil, formed as the sediments were deposited in a marine environment with high biological activity. Prudhoe Bay, at the edge of the Coastal Plain, is estimated to hold nearly 25 billion barrels of oil.

Southeastern Alaska, also known as the Alaskan Panhandle, expresses a slightly different geologic history than does the main body of the state. The core of the Coast Mountains is a granitic batholith, parts of which have been deformed by metamorphism to form schist, gneiss, and marble. The region contains a large fault system, which has increased uplift in many areas to expose more metamorphic rock. In addition, a jumble of marine sedimentary rock and conglomerates was accreted to the southeastern coastal area as terranes continued to dock and subduct.

Rocks of Hawai‘i

Region 7

In Hawai‘i, younger igneous rocks dominate the landscape, and basaltic lava flows are part of almost any vista. On the eight main Hawaiian Islands, the oldest exposed flows are approximately five million years old, still within the **Pliocene** epoch. The uniform lithology and young age of Hawaiian rocks are fascinating, particularly since the processes that create these rocks and shape the islands are both active and visible.

Hawaiian volcanism occurs far from any plate boundary—the Hawaiian Islands sit above a mantle **hot spot** located beneath the Pacific plate. The eruptive behavior that has created the Hawaiian volcanoes is quite different from either mid-ocean ridge or subduction zone volcanism.

Hawaiian eruptions produce high-temperature, low-viscosity, basaltic lavas. Repeated eruptions build large, gently sloping shield volcanoes, so named for their likeness to the profile of an ancient warrior's shield. The low-viscosity magma under shield volcanoes flows quickly, resulting in the typical expansive size and gentle slopes of the volcano. Shield volcanoes can erupt from a summit vent, or through vents on the volcano's flanks. Typically, a volcano will have one or more rift zones: linear arrays of vents extending away from the summit. Magma can migrate away from the summit vent through a series of **fractures** that create the rifts.

See Chapter 1: Geologic History for more information about hot spots.

Oceanic hot spot eruptions are characterized by lava fountains that feed subsequent lava flows. Lava fountains are spectacular, but on the scale of global volcanism, they are considered gentle and effusive (*Figure 2.32*).

See Chapter 1: Geologic History to learn more about stages in the formation of a hot spot shield volcano.

Figure 2.32: A flank eruption on Kīlauea. The vent erupts a fountain of lava that feeds a channelized lava flow. The dark color of the flow in the lower portion of the photo shows how quickly the surface of the molten lava freezes when in contact with air, while liquid lava continues to flow beneath the chilled crust.

During the fountaining phase of an eruption, various types of pyroclastic particles form. Lava fountains produce abundant **cinders**: gas-rich lava droplets that cool as they fall. Well-formed glassy droplets of cooled lava are known as Pele's tears, after the Hawaiian goddess of fire and volcanoes (*Figure 2.33*). Larger blobs can cool into aerodynamic shapes called bombs. Molten lava can be spun into windblown

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

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

tephra • *fragmented material produced by a volcanic eruption.*

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

threads called Pele’s hair (*Figure 2.34*). Pele’s tears, Pele’s hair, cinders, and bombs are common **tephra** forms found near Kīlauea volcano.

Basaltic lavas have two characteristic modes of motion that produce two very different textures after the flows harden. These textures are controlled by the eruption and effusion rate of the lava, as well as by its viscosity (controlled by temperature and gas content) and strain rate (usually controlled by **topography**).

Figure 2.33: Two examples of Pele’s tears, ~1 centimeter (0.39 inches) in diameter.

Figure 2.34: Windblown accumulation of Pele’s hair.

Pahoehoe results from the rapid motion of highly fluid basalt. It cools into smooth glassy flows, or can form fantastic, twisted, ropey shapes (*Figure 2.35*). Pahoehoe is formed from lava that has a low viscosity and strain rate, as well as a low rate of gas effusion.

Figure 2.35: The skin on a pahoehoe flow is deformed by the motion of the underlying molten lava. The resulting texture is ropey and lumpy.

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

‘A‘a flows are dense and blocky, and advance as a more massive front of hardened fragments. Cooled ‘a‘a is a jagged landscape of sharp lava rubble (*Figure 2.36*). ‘A‘a is produced by lava that has a high viscosity and strain rate, as well as high gas effusion.

Both ‘a‘a and pahoehoe have the same basic chemistry, and one type of flow can transition to the other during an eruption (*Figure 2.37*).

Highly fluid lava can move as a broad flow with many advancing pahoehoe fingers, or it may channelize in a narrow lava river. Since the ambient air temperature is hundreds of degrees lower than the temperature of the flow (1100°C [2000°F]) the flow forms a skin of cooled lava almost immediately after leaving the vent. As long as lava is supplied from the vent, however, the flow will continue to advance beneath the cooled skin. A broad, slow-moving pahoehoe flow will advance by inflating the surface from beneath until molten lava spills out below the frozen skin. Alternately, a narrow lava river creates a well-defined **lava tube** through which fast-moving lava can flow—often over

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

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

Figure 2.36: An ʻaʻa flow showing its jagged surface and massive molten interior.

Figure 2.37: Juxtaposition of pahoehoe (left) and ʻaʻa flows (right).

distances of tens of kilometers (miles). The cooled skin is an excellent insulator for the lava flowing beneath, so basaltic lava flows can quickly advance from the volcano summit to the sea. When the eruption ceases, lava will drain out of the tube, leaving behind an empty chamber. Lava tubes are a common feature of the Hawaiian landscape, and they occur on all scales, from large tubes tens of kilometers (miles) long, to the very small, ubiquitous tubes seen in every roadcut.

Although Hawaiian volcanoes are known for their effusive eruptions, there are also occasional episodes of more violent explosive behavior. When

groundwater interacts with a magma chamber, the high temperatures cause water to flash into steam, initiating an explosive eruption. In this case the energy of the eruption shatters the lava into tiny particles of **volcanic ash**. Layers of ash are widespread and are found in volcanic **stratigraphy** across the islands (*Figure 2.38*). On Hawai‘i Island the distribution of Kīlauea’s ash deposits clearly indicates that some eruptions were powerful enough to blast ash above the **trade wind inversion** into the west winds of the **jet stream**. Closer to the volcanic vent wall, rocks can be blasted from the caldera or vent wall itself.

Figure 2.38: Ash from an explosive eruption of Kīlauea.

trade wind inversion • *a reversal of the typical atmospheric situation directly above the Earth’s surface, where air temperature decreases with altitude.*

jet stream • *a fast-flowing, narrow air current found in the atmosphere.*

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

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

Non-Igneous Rocks

Metamorphic rocks are uncommon in Hawai‘i and are represented by only a few occurrences of contact metamorphism. Sedimentary rocks are more widespread. Conglomerates and **alluvial** deposits can be found in stream valleys, but the most common sedimentary rocks are marine limestone and calcareous sandstone.

Colonial coral polyps build calcareous skeletons that create Hawai‘i’s beautiful reef ecosystems. Because corals live close to the ocean surface, reefs are highly susceptible to changes in sea level. Both relative and absolute sea level changes can leave reefs quite literally high and dry. Wind and wave action erode the exposed reef to form large quantities of **carbonate** sand and dunes. During times of particularly high sea level, water movement pushes these dunes inland where they are lithified and preserved (*Figure 2.39*). These **aeolian** (wind-

extinction • *the end of species or other taxonomic groups, marked by death of the last living individual.*

formed) sandstones are most extensive on the older islands but can occur even on young Maui. The ancient dunes are highly fossiliferous and record the range and variation of Hawai‘i’s **extinct** flora and fauna.

See Chapter 3: Fossils for more information about Hawai‘i’s fossil record.

Figure 2.39: Sedimentary rocks on Kaua‘i. These lithified dunes range in age from 4000–350,000 years before present.

State Rocks, Minerals, and Gems

Alaska

State mineral: gold
Gold can be found and mined throughout Alaska, and has always been a major state industry and force for exploration.

State **gem**: nephrite jade
Large deposits of this green metamorphic stone are found throughout the Seward Peninsula. It formed during accretion of the area's terranes.

California

State mineral: gold
California's nickname is the "Golden State." Its early population expansion and modern development, including roads and infrastructure, can be traced back to the discovery of gold there in 1848 and the ensuing gold rush.

State rock: serpentine
This green metamorphic rock is found throughout California's Coast Ranges, Klamath Mountains, and Sierra Nevada foothills. It formed through the metamorphism of oceanic peridotite during subduction.

State gem: benitoite
Benitoite is a rare blue fluorescent mineral formed when serpentine undergoes metamorphism.

Hawai'i

Hawai'i has no state rock. The designated state "gem" is black coral.

Nevada

State mineral: silver
Nevada's nickname is the "Silver State," dating back to the silver rush of the mid-1800s. In some areas, silver had weathered out of desert rocks over millions of years, and could often be shoveled right off the ground. Within a few decades, the desert had been picked clean of these silver deposits.

State rock: sandstone
Sandstone is found throughout the entire state of Nevada and makes up some of its most spectacular scenery. The State Capitol Building is even built of sandstone.

State gem: black fire **opal**
These gems are found in layers of **clay** that formed when a volcanic eruption filled an ancient lake. Silica in the ashfall replaced the cells and cavities in buried wood, hardening over time into opal.

gem *• a mineral that has been cut and polished for use as an ornament.*

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

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

State Rocks

Oregon

State rock: **geode**

These geodes, locally called “thunder-eggs,” are found in Eocene-age rhyolite lava flows, having formed within gas pockets that served as molds.

State gem: Oregon sunstone

This type of translucent **feldspar** formed as large crystals in basaltic lava flows.

Washington

Washington has no state rock. The designated state “gem” is petrified wood.

geode • *a hollow, roughly spherical node of crystal that forms when minerals precipitate within hardened vesicles (gas bubbles) in volcanic rocks.*

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

Resources

Rock and Mineral Field Guides

Brown, V., D. Allan, & J. Stark, 1987, *Rocks and Minerals of California, 3rd revised edition*, Nautregraph Publishers, Happy Camp, CA, 200 pp.
Chesterman, C. W., 1979, *National Audubon Society Field Guide to North American Rocks and Minerals,* Knopf, New York, 850 pp.
Dixon, D., & R. L. Bernor, 1992, *The Practical Geologist: The Introductory Guide to the Basics of Geology and to Collecting and Identifying Rocks,* Simon and Schuster, New York, 160 pp.
Johnsen, O., 2002, *Minerals of the World,* Princeton University Press, Princeton, NJ, 439 pp.
Mitchell, J., 2008, *The Rockhound's Handbook, revised editioin,* Gem Guides Book Company, Baldwin Park, CA, 299 pp.
Pellant, C., 2002, *Rocks & Minerals*, Dorling Kindersley (Smithsonian Handbooks), New York, 256 pp.
Prinz, M., G. Harlow, & J. Peters, eds., 1978, *Simon & Schuster's Guide to Rocks & Minerals,* Simon and Schuster, New York, 607 pp.

Books

Vernon, R. H., 2000, *Beneath Our Feet: The Rocks of Planet Earth,* Cambridge University Press, Cambridge, UK, 216 pp.

Websites

Atlas of Igneous and Metamorphic Rocks, Minerals and Textures, University of North Carolina Geology Department, http://leggeo.unc.edu/Petunia/IgMetAtlas/mainmenu.html. (Older but still useful resource.)

The
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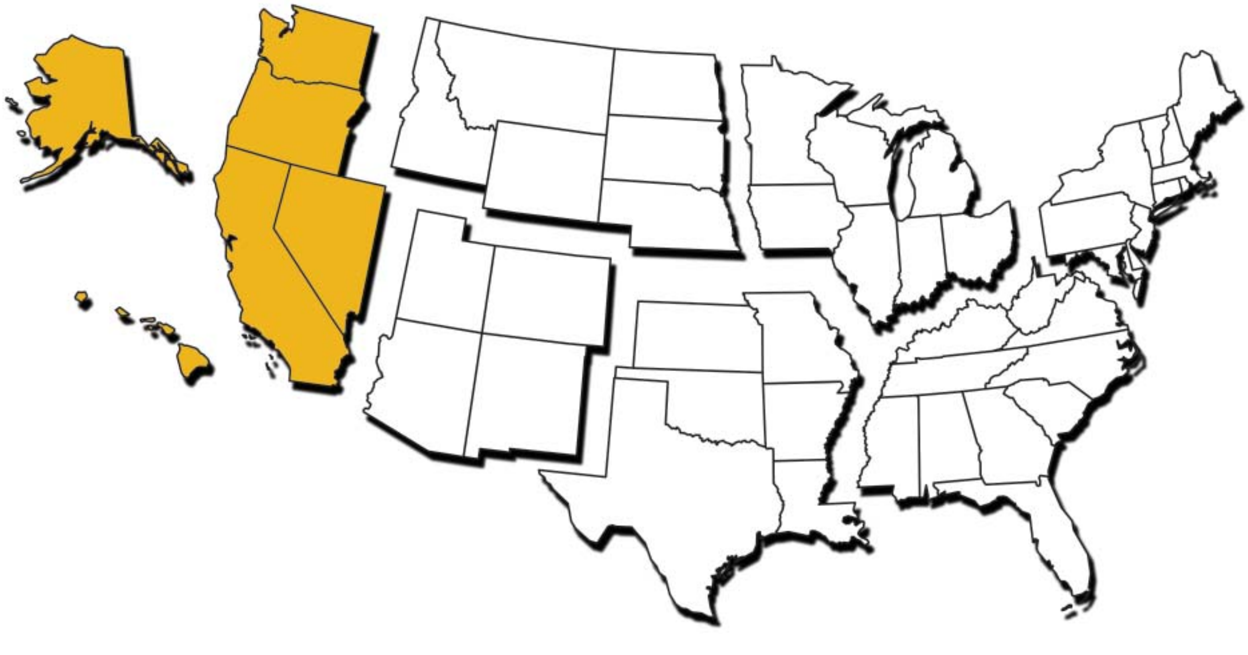

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