



Chapter 1: Geologic History of the Western US: Reconstructing the Geologic Past

We often wonder: What will the places we live in look like a millennium from now? A vision of “what might be” is critical for making the big decisions that will shape our future and that of our descendants. But to look forward, we have to first look back in time.

The shape and position of North America has changed dramatically over the last billion years, and geologic processes continue these changes today. The Earth is estimated to be approximately 4.6 billion years old. The oldest rocks known are located in northern Quebec and date to 4.3 billion years ago. These are part of Canada’s **Precambrian** shield, the ancient core of the North American continental landmass. Rocks more than 3.5 billion years old are found on every continent.

The *oldest rocks found on Earth* are 4.3-billion-year-old greenstone beds found along the eastern shore of Hudson Bay in northern Quebec. The oldest known materials are 4.4-billion-year-old zircons from Western Australia.

The Earth is dynamic, consisting of constantly moving **plates** that are made of rigid continental and oceanic **lithosphere** overlying a churning, plastically flowing **asthenosphere** (Figure 1.1). These plates pull apart, collide, or slide past one another with great force, creating strings of volcanic islands, new ocean floor, **earthquakes**, and mountains. The continents likewise continuously

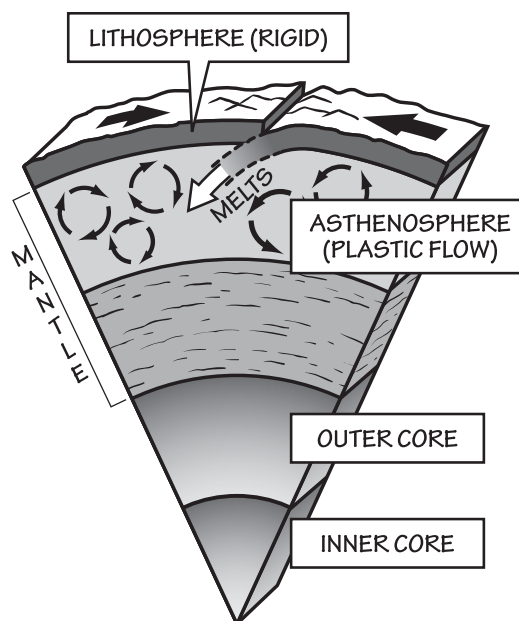


Figure 1.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

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

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

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

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

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

CHAPTER AUTHORS

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

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).

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

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

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

shift position because they are part of the moving plates. This not only shapes the land over time, but it also affects the distribution of rocks and **minerals**, natural resources, **climate**, and life.

Reconstructing the past is a lot like solving a mystery. Geologists use scraps of evidence to piece together events they have not personally observed, but to do so they must contend with two major complications. First, the overwhelming majority of geologic history occurred long before there were any human witnesses. Second, much of the evidence for the older events is highly fragmented.

- **Rocks and sediments** are indicators of past geologic processes and the environments in which those processes took place. In general, **igneous rocks**, created through tectonic activity, reflect past volcanism. By looking at both their texture and chemistry we can determine the tectonic setting and whether or not the rocks formed at the surface or deep underground. Likewise, **metamorphic rocks**, created when sediment is subjected to intense **heat** and pressure, provide important clues of past mountain-building events, and geologists often use them to map the extent of now-vanished mountain ranges. **Sedimentary rocks** tell perhaps the most comprehensive story of the Earth's history, as they record characteristics of far-away mountain ranges, river systems that transported the sediments, and the final environment in which the sediments accumulated and **lithified**. The size and shape of sediments in sedimentary rocks, as well as the presence of **fossils** and the architecture of sedimentary rock layers (sedimentary structures), can help us infer how the sediments were transported and where they were finally deposited. However, because rocks are often reformed into different rock types, ancient information is lost as the rocks cycle through the igneous, metamorphic, and sedimentary stages.

See Chapter 2: Rocks to learn more about different rocks found in the West.

- **Fossils** indicate both the type of life that once flourished in an area and the kind of climate in which that life existed. Paleontologists use groups of fossils found in the same place to construct pictures of entire ecosystems. These ecosystems of the past are matched to similar present-day ecosystems, whose climate conditions are then used to infer what sort of climate the fossilized organisms lived in. Unfortunately, few organisms are easily preserved as fossils, and many environments also do not lend themselves to preserving organisms as fossils. As a result, the clues that fossils give provide only glimpses of the ancient world, with many important details missing.

See Chapter 3: Fossils for more information about the West's prehistoric life.

- **Landscapes and geologic structures** are also indicators of past geologic processes and the environments in which they occurred. For instance, the shape of a valley reflects the forces that carved it. Valleys with V-shaped

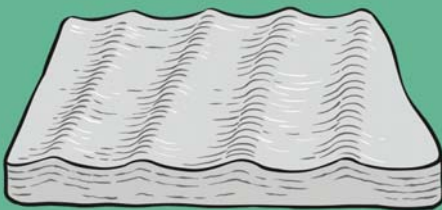


profiles tend to be the products of stream **erosion**, whereas U-shaped valleys are more likely to have been carved by **glaciers**. Layers of intensely folded rock indicate a violent past of tectonic plate collisions and mountain building. Sedimentary structures, such as **ripple marks** or **cross-bedding**, can demonstrate the direction and energy level of the water that moved the sediment. Although landscapes tell us much about the geologic processes that created them, they inevitably change over time, and information from the distant past is overwhelmed by the forces of the more recent past.

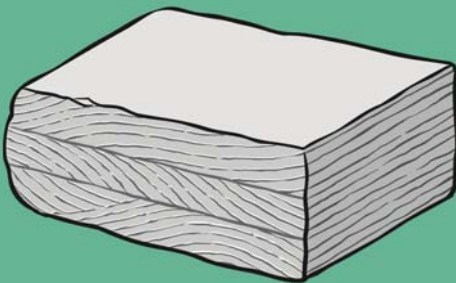
See Chapter 4: Topography for more detail about the landscapes found in the Western States.

Sedimentary Structures

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



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



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

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

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

fossil • preserved evidence of ancient life, including, for example, preserved skeletal or tissue material, molds or casts, and traces of behavior.

erosion • the transport of weathered materials.

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

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Geologic History

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

paleogeographic maps • maps that portray the estimated ancient geography of the Earth.

dinosaur • a member of a group of terrestrial reptiles with a common ancestor and thus certain anatomical similarities, including long ankle bones and erect limbs.

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

About the Time Scale:
The time scale in The Teacher-Friendly Guides™ follows that of the International Commission on Stratigraphy (ICS). The Tertiary period, though it was officially phased out in 2008 by the ICS, remains on the scale in the Guides, since “Tertiary” is present extensively in past literature. In contrast, the Carboniferous and Pennsylvanian & Mississippian periods all enjoy official status, with the latter pair being more commonly used in the US.

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

Organizing and Presenting the Case

There are two important tools that geologists use to portray the history of the Earth: the **geologic time scale** and **paleogeographic maps**.

The geologic time scale is a standard timeline used to describe the age of rocks and fossils, and the events that formed them. It spans Earth’s entire history and is typically divided into four principle divisions.

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

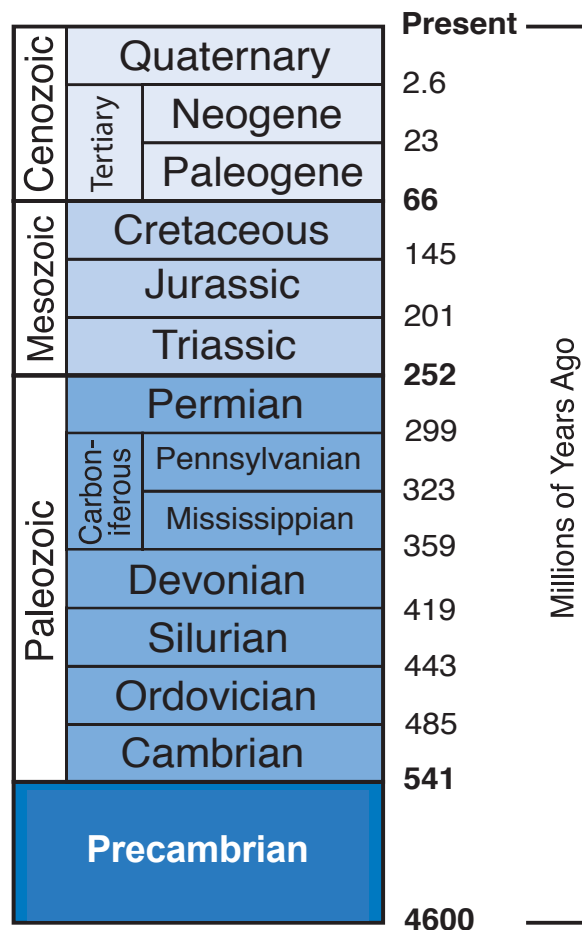


Figure 1.2: The Geologic Time Scale (spacing of units not to scale).

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

The third division, the **Mesozoic** (from 252 to 66 million years ago), is also called the “age of reptiles” since **dinosaurs** and other reptiles dominated both marine and terrestrial ecosystems. It is also noteworthy that during this time the last of the earth’s major supercontinents, **Pangaea**, formed and later broke up, producing the Earth’s current geography (more about this later).

The last and current division, the **Cenozoic**, extends from the **extinction** of the dinosaurs, nearly 66 million years ago, to the present. With the demise of the dinosaurs, mammals became dominant and, subsequently,



Geologic Time

How did geologists come up with the timeline for the history of the Earth? Over the course of many years and through the combined work of geologists around the world, the geologic time scale was developed (*Figure 1.2*). No rock record in any one place contains the complete sequence of rocks from Precambrian to present. Geology as a science grew as geologists studied individual sections of rock. Gradually, evolutionary successions of fossils were discovered that helped geologists determine the relative ages of groups of rocks. Rock units were then correlated with similarly aged rock units from around the world. The names you see for the different periods on the geologic time scale have diverse origins. Time periods were named after dominant rock types, geography, mountain ranges, and even ancient tribes like the Silures of England and Wales, from which the *Silurian* period was derived.

more diverse and highly developed. We humans don't come into the picture until the last two million years. To get some perspective on this, if the entire geologic time scale were reduced to 24 hours, we wouldn't come onto the stage until two seconds before midnight!

Paleogeographic maps portray the probable ancient geography of the Earth. They often appear in sequences designed to show the geologic development of a region. The process of constructing these maps is based on first looking at the rocks and landscapes to develop the geologic history of a specific area. Then, by comparing the histories of neighboring areas, geologists can determine how much of an area experienced a similar history. Because an enormous amount of data is required to construct even a small paleogeographic map, completed sections often show only general details and are frequently subject to considerable debate. Maps of the distant past are particularly difficult to piece together since the important clues are so fragmented.

Reconstructing

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

Silurian • a geologic time period spanning from 443 to 419 million years ago.



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

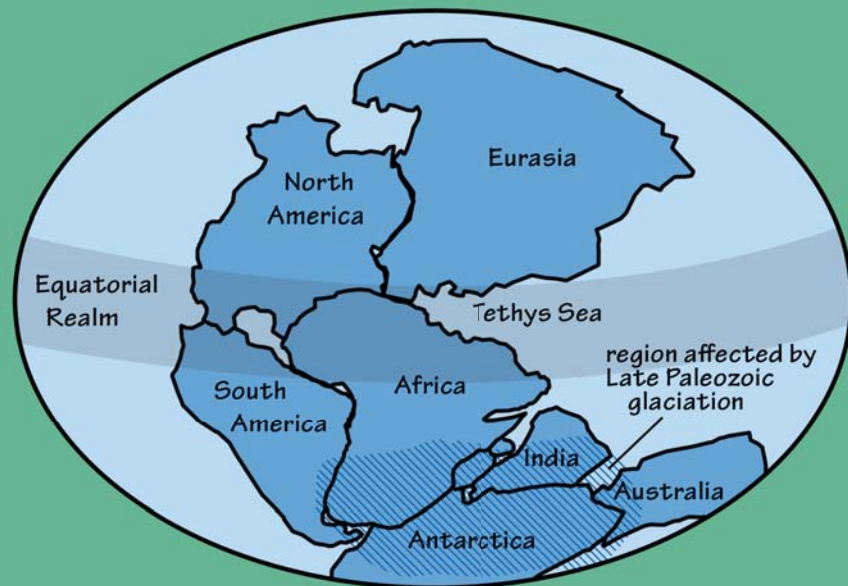
plate tectonics • the way by which the plates of the Earth's crust move and interact with one another at their boundaries.

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

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

Evidence for Pangaea

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



Pangaea during the late Paleozoic era



The Western States: The Big Picture

The geologic history of the Western United States is a saga of moving continents and climate change that produced shifting coastlines, rising and eroding mountain chains, and ever-changing ecosystems. Though much of it is geologically young, its rocks and landscapes record over half a billion years of Earth history. Furthermore, it is a place where nearly all the processes that shaped it are still visible at some level.

The Western States are divided up into seven different geologic provinces (*Figure 1.3*): The Basin and Range (1), Columbia Plateau (2), Northern Rocky Mountains (3), Cascade-Sierra Mountains (4), Pacific Border (5), Alaska (6), and Hawai'i (7).

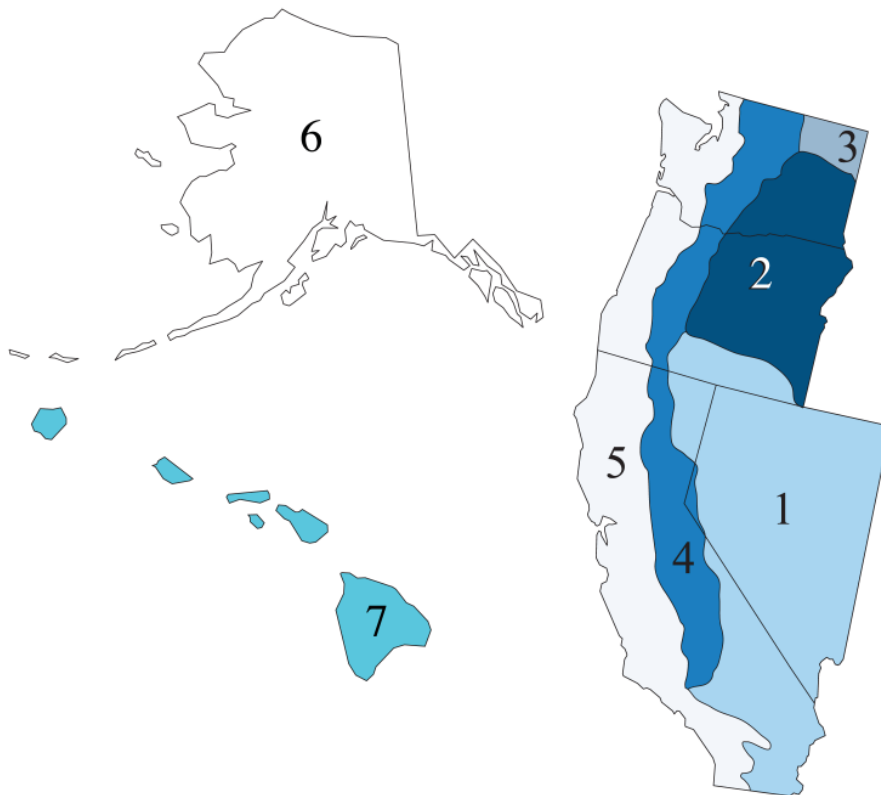


Figure 1.3: Geologic regions of the West.

With the exception of Hawai'i (which will be handled separately at the end of this chapter), the Western States are all on **active plate margins** (*Figure 1.4*). In the case of Alaska, Oregon, and Washington, thin oceanic **crust** is colliding with the thicker continental crust of the North American plate. As it does so, sediment, sedimentary rock, and even bits of the oceanic crust itself are scraped off the descending crustal plate and pushed onto the overlying

Big Picture

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

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

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Big Picture

plate. Just as a rug develops folds when pushed from the side, these rocks are wrinkled up into mountains like the Coast Range of Oregon and the Olympic Mountains of Washington in a process known as **accretion** (Figure 1.5).

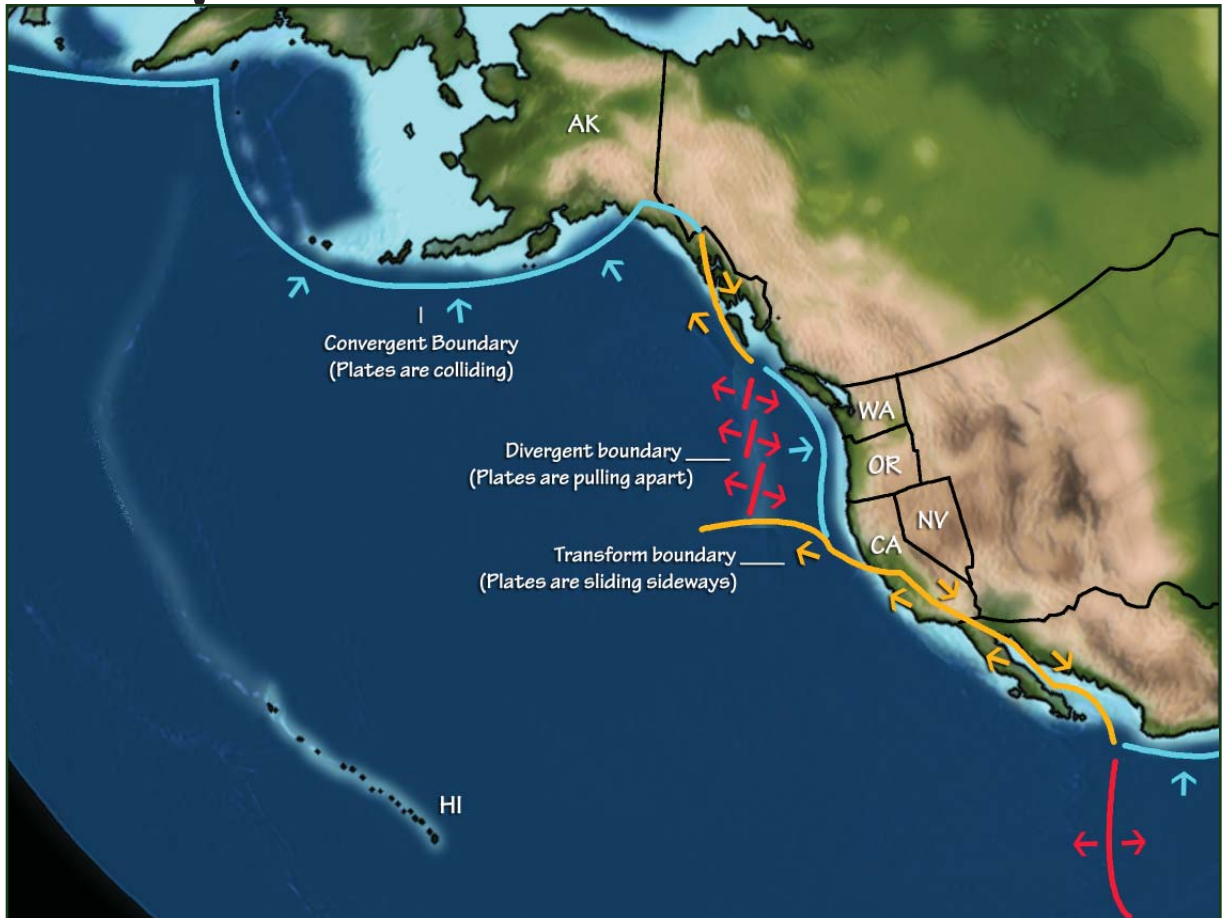


Figure 1.4: Active plate margins of western North America. (See TFG website for full-color version.)

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.

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

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

Farther inland, as the oceanic crust descends deep into the upper **mantle**, the rock above the descending crust melts and forms a line of volcanoes on the surface. This process, called **subduction**, is responsible for creating the Cascades of Oregon and Washington as well as the Aleutian Islands and Wrangell Mountains of southern Alaska. Though they are also located on an active margin, the crustal plates in California are moving sideways past one another rather than colliding. This **transform boundary**, which includes the San Andreas Fault, is in reality a wide zone of north-south oriented **faults** with frequent and destructive earthquakes. Although **volcanic** activity is rare in this area, long, straight mountain ranges and troughs, such as Bodega Bay in northern California, are formed as blocks of crust are wrenched sideways.

In addition to tectonic activity, climate is a major player in the West's geologic history. The past two million years, a time span called the **Quaternary**, have



been a time of radical shifts in the Earth's climate. Though we are currently in a period of rising global temperatures, much of the Quaternary has been characterized by **ice ages** in which glaciers repeatedly expanded to cover the northern half of North America, Europe, and Asia. During the most recent

Big picture

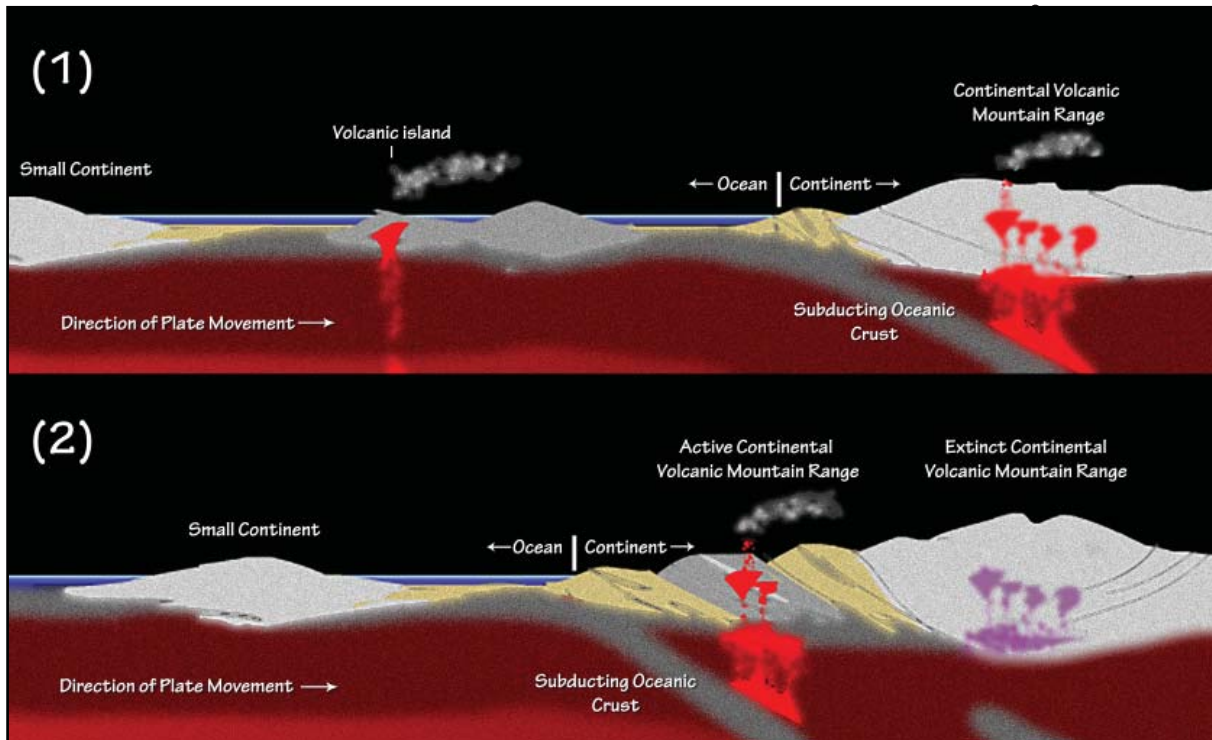


Figure 1.5: An idealized cross section of an active margin where an island arc (1) is added to the edge of a continent (2). (See TFG website for full-color version.)

glacial advance, approximately 20,000 years ago, portions of the **Cordilleran Ice Sheet** buried southern Alaska and northern Washington under a mile of ice, carving deep **fjords** and glacial valleys. This **ice sheet** deposited huge quantities of glacial sediment in low-lying areas such as Puget Sound and also carved rugged mountain landscapes (Figure 1.6). Farther to the south, what are now modest mountain glaciers grew to become **ice caps** covering entire mountain ranges such as the Sierra Nevada and the Blue Mountains of Oregon. Even Hawai'i, which is now ice-free, saw small glaciers on the summit of Mauna Kea, its highest peak.

See Chapter 6: Glaciers to learn more about how glaciers have sculpted Western landscapes.

During each ice age, sea level dropped as more and more seawater became locked up in glacial ice. As the oceans fell, coastlines moved farther out to sea. Later, as the climate warmed and sea level rose, the former coastal lands were flooded, drowning river valleys, glacial valleys, and coastal plains.

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.

fjord • a deep, narrow, glacially scoured valley that is flooded by ocean water.

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



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Continental and Oceanic Crust

The lithosphere has two types of crust: continental and oceanic. Continental crust is less dense but significantly thicker than oceanic crust. The higher density of the oceanic crust means that when continental crust collides with oceanic crust, the more dense oceanic crust will be dragged (or subducted) under the buoyant continental crust. Although mountains are created at these oceanic/continental crust collisions due to the compression of the two plates, much taller ranges are produced by continental/continental collisions. When two buoyant continental crusts collide, there is nowhere for the crust to go but up! The modern Himalayas, at the collision site of the Asian and Indian plates, are a good example of very tall mountains formed by a collision between two continental crusts.

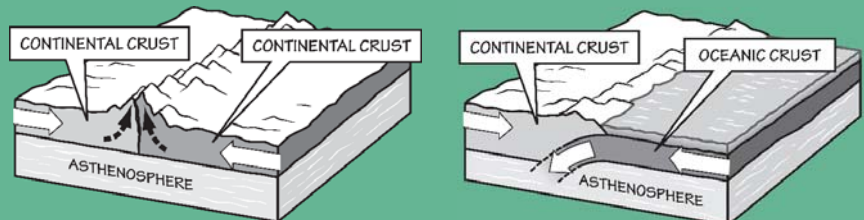


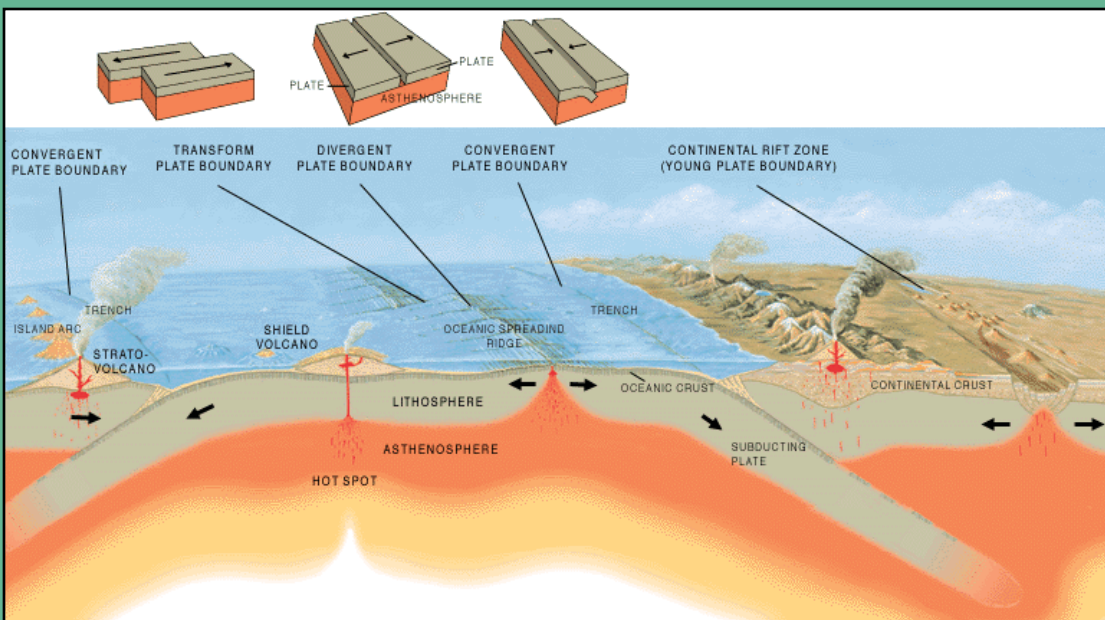
Figure 1.6: Continental glaciers originating in Canada spread across North America, including Alaska and Washington, during the Quaternary period.



Understanding Plate Boundaries

Active plate margins are the boundaries between two plates of the Earth's crust that are colliding, pulling apart, or moving past each other as they move over the mantle.

When one plate slides beneath another, it is called a *convergent boundary* or subduction zone. When two plates pull apart from each other, it is known as a *divergent boundary* or *rift margin*. When the plates slip past each other in opposite directions, it is called a *transform boundary*.



(See TFG website for full-color version.)

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Paleozoic

passive margin • a tectonically quiet continental edge where crustal collision or rifting is not occurring.

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

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

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

The Paleozoic and Precambrian: Looking to the Distant Past

Over 600 million years ago, the entirety of what is now the Western States was either underwater or had not yet become part of North America. Seafloor sedimentary rocks found in the Klamath Mountains, the Sierra Nevada, the Basin and Range, and the central mountains of Alaska indicate that the entire region was underwater during the early Paleozoic and that the coastline of ancient North America was somewhere to the east, near Arizona, Utah, and Idaho (Figure 1.7).

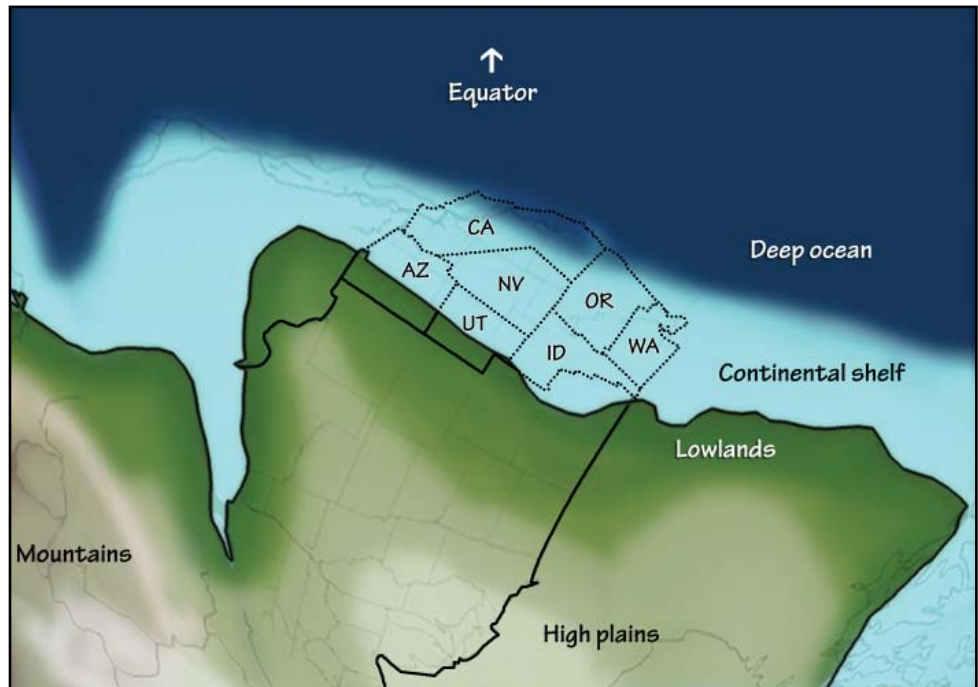
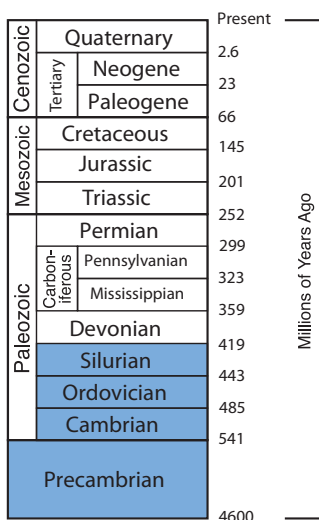


Figure 1.7: The Western United States at 600 million years ago. The entire region is located in the southern hemisphere. (See TFG website for full-color version.)

In the early Paleozoic, about 500 million years ago, what is now the west coast of North America was a **passive margin**—little or no volcanic activity, earthquakes, large mountain ranges, or plate boundaries were found in the Western States at that time. As the Earth's continents began moving towards one another to eventually form the supercontinent Pangaea, the Western States became an active subduction zone, which began **uplifting** new mountains. Subduction also led to accretion, adding **volcanic islands** and seafloor sediment to the edge of the continent. One such episode created much of the present-day **basement rock** in Nevada and southern Oregon. Other periods of accretion created the Okanogan Highlands and sections of Alaska's central mountains. By 400 million years ago, large mountain ranges had risen in parts of Alaska and the Basin and Range of Nevada and Oregon. As accretion continued over



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time, the coastline moved farther seaward. The landmass also began to rotate, moving the North American plate into a more modern orientation.

The Mesozoic

For much of the Mesozoic, large sections of the Western States were underwater. Around 300 million years ago, the Western States were part of the continental margin surrounding the supercontinent Pangaea. However, that changed once Pangaea began splitting apart 250 million years ago. As the supercontinent **rifted** apart, subduction, volcanism, and accretion in the Western States accelerated, adding more land to the continental margin (*Figure 1.8*). Land did not build up continuously—accretion in these states delivered packages of rock known as accreted or exotic **terrane**s. Each terrane consists of sedimentary rock made from former seafloor sediment, slabs of oceanic crust (**ophiolites**, *Figure 1.9*), the remains of volcanic islands, and, in some instances, shards of continental crust. The terrane is pressed against the edge of the continent in a process sometimes described as “docking.”



Figure 1.8: The Western United States at 135 million years ago. The terrane contains an island arc in the process of docking with the Western States. This arc will eventually become part of Alaska and British Columbia. (See TFG website for full-color version.)

In general, accretion was accompanied by volcanism, which resulted in several major **orogenies** (episodes of mountain building). During the Mesozoic, three such episodes were particularly important in the development of western North

Mesozoic

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

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

ophiolite • a section of the Earth's oceanic crust and the underlying upper mantle that has been uplifted and exposed above sea level and often thrust onto continental crustal rocks.

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

		Present	Millions of Years Ago		
Cenozoic	Quaternary	2.6			
		Tertiary		Neogene	23
				Paleogene	66
Mesozoic	Cretaceous	145			
	Jurassic	201			
	Triassic	252			
Paleozoic	Carboniferous	Permian		299	
		Pennsylvanian		323	
		Mississippian		359	
	Devonian	419			
	Silurian	443			
	Ordovician	485			
	Cambrian	541			
	Precambrian	4600			

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Mesozoic

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

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

bathymetry • the topography of an underwater landscape.

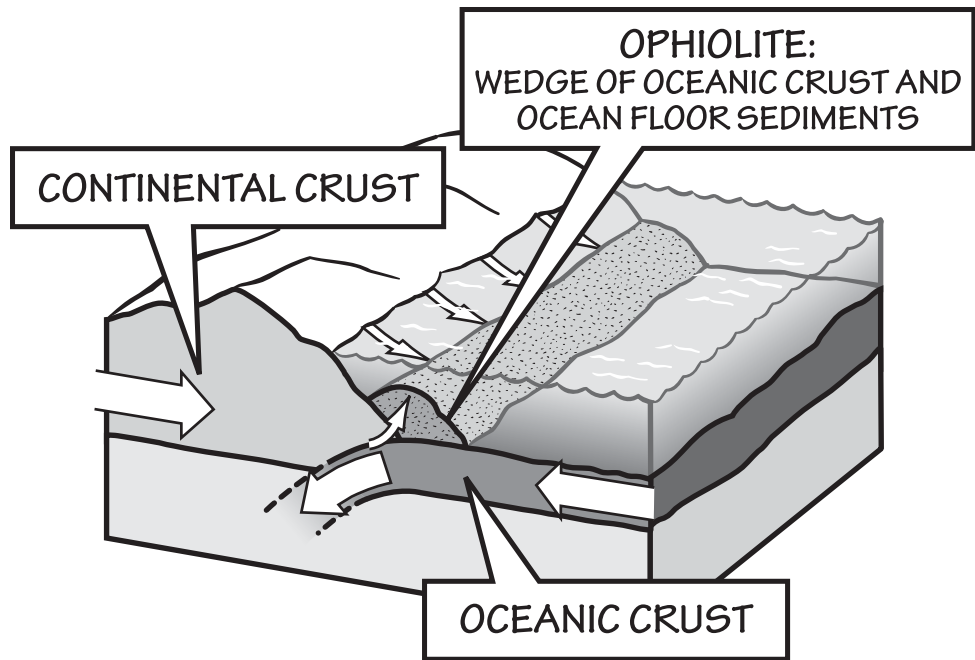
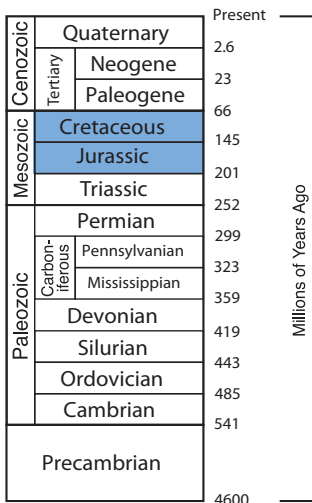


Figure 1.9: Formation of an ophiolite.

America. The Nevadan, Siever, and **Laramide orogenies** took place between 180 and 50 million years ago. The remnants of these mountain-building events can still be seen as bodies of **intrusive rock** embedded in the West's present-day ranges.

While the addition of land to the continental margin was a general theme throughout the Mesozoic, it was by no means a consistent process. Sedimentary rock found in the Midwest indicates that shallow seas episodically inundated the interior of North America, turning major parts of the Western States into a broad isthmus (*Figures 1.10 and 1.11*). The exact reasons for this periodic flooding are not known, but there are two possibilities: sea level rise or a change in the elevation of the continental plain. Although sea level change is often associated with climate change, it can also be driven by changes in the **bathymetry** of the ocean floor. Increased volcanic activity at mid-ocean ridges could have increased the size of the ridges, displacing seawater and causing the sea level to rise. Additionally, as Pangaea began to drift apart, the crust underlying the Interior Plains most likely stretched, causing it to thin and making the land surface drop below sea level.



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Mesozoic

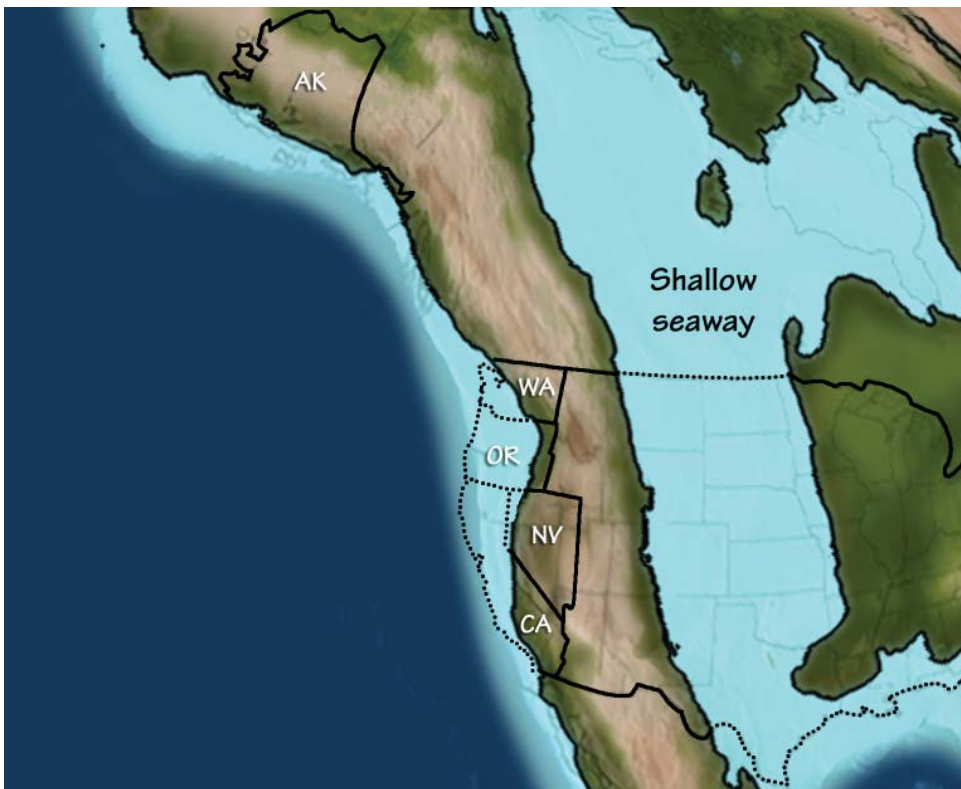


Figure 1.10: North America 90 million years ago. During this time, a shallow seaway covered much of central North America.

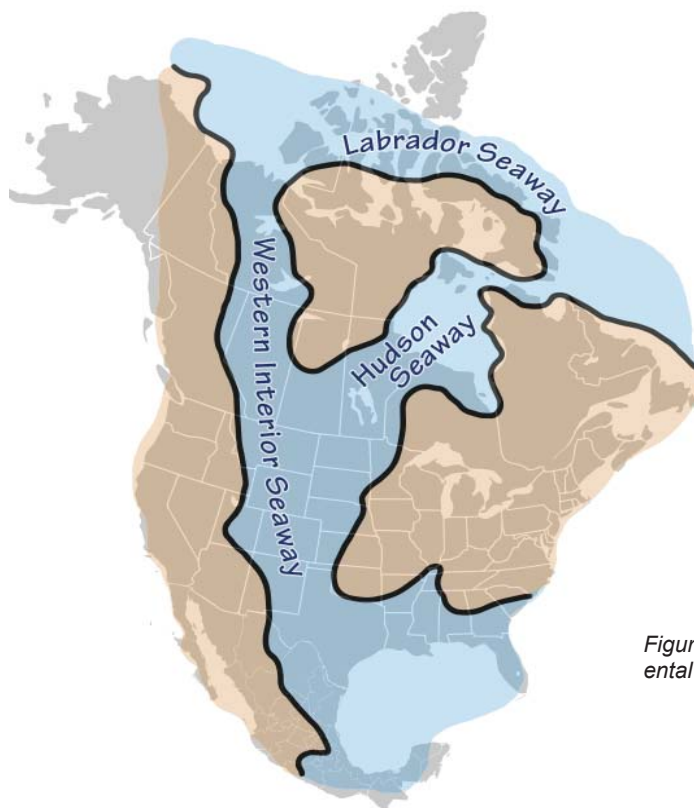


Figure 1.11: Cretaceous continental seas over North America.

Cenozoic	Tertiary	Quaternary	Present
		Neogene	2.6
Paleogene		23	
Mesozoic		Cretaceous	66
		Jurassic	145
		Triassic	201
Paleozoic	Carboniferous	Permian	252
		Pennsylvanian	299
		Mississippian	323
		Devonian	359
		Silurian	419
		Ordovician	443
	Cambrian	485	
		Precambrian	541
			4600

Millions of Years Ago

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Cenozoic

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

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

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

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.

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

The Cenozoic

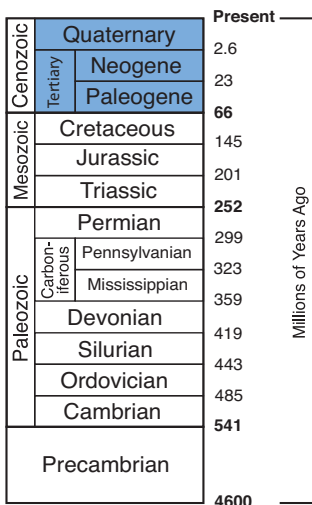
The geography of the Western States became progressively more recognizable during the Cenozoic. Around 66 million years ago, the entire west coast of North America was a **convergent boundary**, where subduction created volcanic mountain ranges. Although some of the volcanic ranges from this time span remain active today, all of the earliest ranges have ceased to erupt, often being replaced by newer ranges farther seaward (see *Figure 1.5*). As more land accreted to the edge of the continent, subduction became increasingly more difficult, until it finally stopped, forming a new convergent boundary farther seaward. When this happened, the source of **magma** for the old volcanic arcs was cut off, and a new arc formed closer to the new boundary. This accretion caused the western edge of North America to expand outward, towards its present configuration (*Figure 1.12*).

A major change in the plate boundary along California also contributed to the extinction of the older Cenozoic volcanic arcs. Beginning about 30 million years ago, a mid-ocean ridge called the East Pacific Rise collided with the North American continent. As this ridge subducted, the plate boundary adjacent to California gradually changed, becoming a transform or sideways-moving boundary. As a result, subduction ceased, as did the last of the volcanic activity in what we now know as the Sierra Nevada. An important byproduct of this change in plate motion was that Nevada and southern Oregon began to pull apart, forming the collection of north-south trending mountains and valleys known as the Basin and Range.

Much of the present-day Sierra Nevada is a large exposure of **granite** called a **batholith**—the remains of the magma chambers that previously fueled volcanic mountain ranges that are exposed once the ancestral ranges have been eroded away. In the case of the Sierra Nevada, the stretching of the Basin and Range uplifted the solidified magma chambers of the ancestral range as rivers, **landslides**, and glaciers eroded away the overlying rock. The continued erosion of this rock is the source of much of the **gold-laden gravel** found in the rivers of California's Central Valley.

The present-day Cascade Range, which extends all the way from southern British Columbia to northern California, is made up of a series of volcanoes that have built up a large platform of volcanic debris. These volcanoes, the Cascade Volcanic Arc, began to arise 36 million years ago due to the subduction of the Pacific plate beneath North America. However, the major volcanic peaks that make up what we call the High Cascades today formed more recently, within the **Pleistocene**. As long as subduction continues, the Cascades will remain volcanically active, although there is evidence that the rate of subduction is slowing, and as a result, volcanism in the Cascades will eventually cease.

Farther north, accretion and volcanism continued to add more land to Alaska's coastline. As mountain ranges rose and eroded, sediment washed from the land, mixed with the remains of microscopic marine life, and settled onto the continental shelf fringing the state. As this organic material was buried by even



Geologic History



1



Cenozoic

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

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

Figure 1.12: (A) North America 50 million years ago—the entire west coast of North America is a subduction zone. (B) North America 30 million years ago—the East Pacific Rise is approaching the subduction zone. (C) North America 5 million years ago—by this time California is a transform boundary and the Basin and Range begins stretching. (See TFG website for full-color version.)

Cenozoic	Tertiary	Quaternary	Present
		Neogene	2.6
		Paleogene	23
Mesozoic		Cretaceous	66
		Jurassic	145
		Triassic	201
Paleozoic	Carboniferous	Permian	252
		Pennsylvanian	299
		Mississippian	323
		Devonian	359
		Silurian	419
		Ordovician	443
		Cambrian	485
	Precambrian	541	
		4600	

Millions of Years Ago



Geologic History

Cenozoic

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

greenhouse conditions • time periods when atmospheric greenhouse gas concentrations are high and global temperatures are elevated.

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

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

more sediment, it was slowly converted into the large **petroleum** deposits on which much of Alaska's economy now relies.

Fossils found in Alaska tell us that during parts of the Cenozoic, its climate was temperate, perhaps even subtropical. Although plate motion can account for some of this change—North America has been slowly moving north throughout the Cenozoic—other important factors also played a role in Alaska's changing climate history. The majority of the Cenozoic was characterized by **greenhouse conditions**, during which sea levels are generally higher and glaciers diminish. During periods of changing global climate, polar areas tend to see a greater shift in climate than do areas close to the equator. During a shift to greenhouse conditions, tropical climate zones could have moved into areas that are now temperate or even subpolar.

Geologic History of Hawai'i

Hawai'i is located thousands of kilometers from the nearest plate boundary, but it is volcanically active and geologically very young. The oceanic crust on which the Hawaiian Islands reside is nearly 90 million years old, yet the oldest of these islands was formed a mere 5 million years ago. In fact, the youngest is less than a half million years old. The Hawaiian Islands are the surface expression of a mantle **hot spot**—a place where a large slab of crust rides over the top of a rising plume of hot rock in the underlying mantle. The Hawaiian hot spot has its origin deep within the Earth, near the core-mantle boundary, where an area of anomalously high temperature creates a **thermal plume**: a zone of solid mantle material that moves slowly upward toward the surface. Thermal stress drives the motion of the plume; the hotter material rises because it is less dense and therefore more buoyant than its surroundings. As magma created by the plume erupts onto the seafloor, repeated **lava** flows build a massive volcano that eventually reaches the surface of the ocean and becomes a volcanic island.

The Hawaiian hot spot lies beneath the Pacific plate, where it maintains a relatively fixed position within the mantle. The overlying Pacific plate moves to the northwest at the tectonically rapid rate of 8.5 centimeters per year (3 inches per year). The northwest motion of the plate eventually carries each island away from the hot spot, creating a chain of volcanic islands whose age increases with increasing distance from the hot spot (*Figure 1.13*). The Hawaiian Islands are the southernmost part of a string of islands and undersea mountains stretching from the middle of the North Pacific to the Aleutian Islands of Alaska. The Emperor Seamounts, the northernmost end of these undersea mountains, are the oldest. The youngest islands are currently over the hotspot, and still volcanically active, whereas the older, extinct islands reveal the track of oceanic crust moving over the hotspot.

The Hawaiian hot spot has been active for at least 80 million years, based on the age of the oldest island, Meiji Seamount, now far to the north near the Aleutian trench. The hot spot remains active today, erupting new lava at Kīlauea volcano and the still-submerged Lō'ihi seamount—the youngest volcano in the chain.



Geologic History



1

As each volcano forms above the hot spot and moves away, it undergoes a sequence of constructive and then destructive geological processes. These processes, detailed below, have created a chain of volcanoes that extend 5800 kilometers (3600 miles) from the Hawaiian Islands to the Emperor Seamounts.

Hawai'i

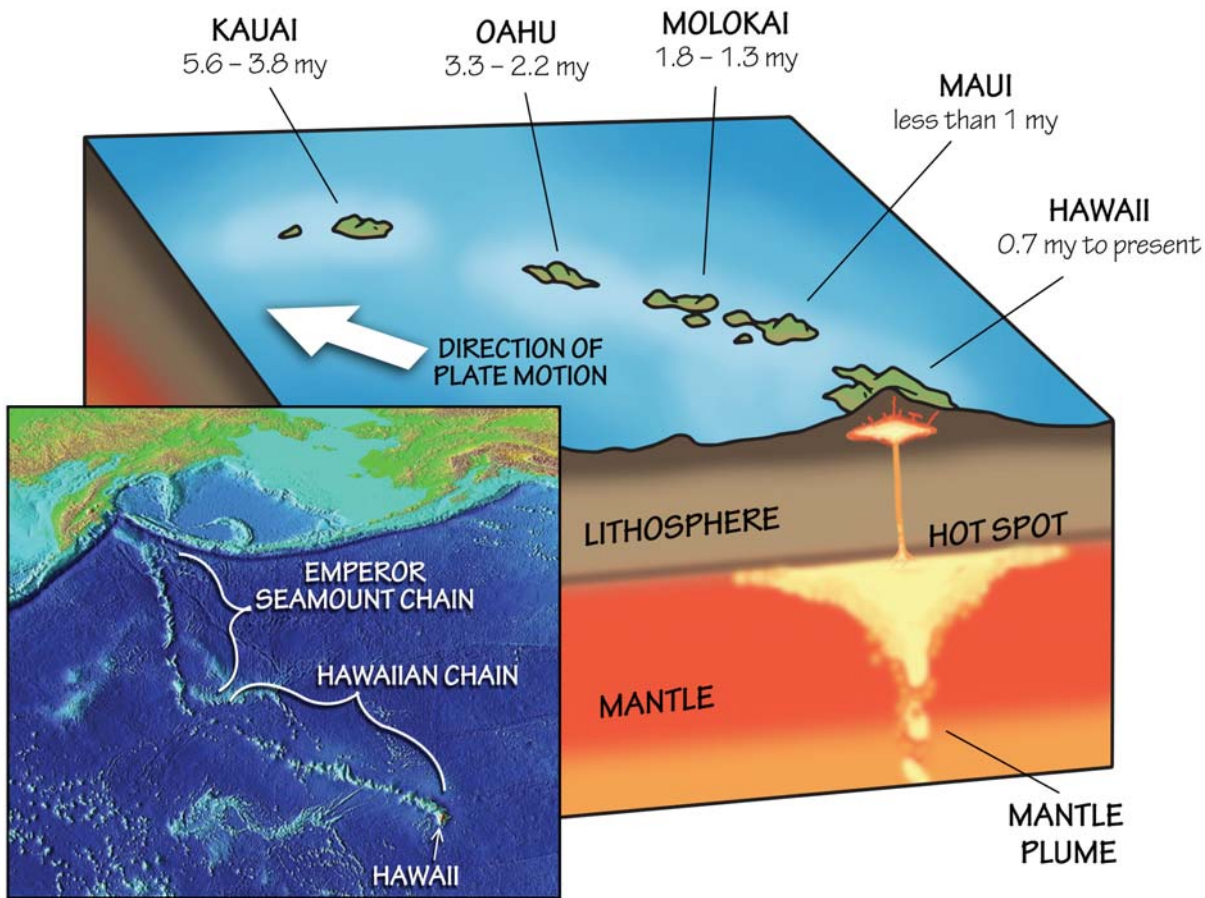


Figure 1.13: Interaction of the Pacific plate and the Hawaiian hot spot produces a chain of volcanic islands that increase in age with increasing distance from the hot spot. The Emperor Seamounts are the continuation of the Hawaiian Islands, and formed while the plate was moving directly north. (See TFG website for full-color version.)

Lifecycle of Hawaiian Volcanoes

For more than 50 years, geologists have recognized that Hawaiian volcanoes exhibit a relatively consistent set of features reflecting events in the island's lifecycle. These events are typically divided into nine stages, although (as with all natural processes) there may be overlap and gradation between them. Over time, the volcanoes exhibit changes in morphology and behavior, as well as chemical changes in the lavas they erupt. Early lavas are derived from near the edge of the thermal plume, a magmatic source that is chemically different from lavas derived from the center of the plume.





Geologic History

Hawai'i

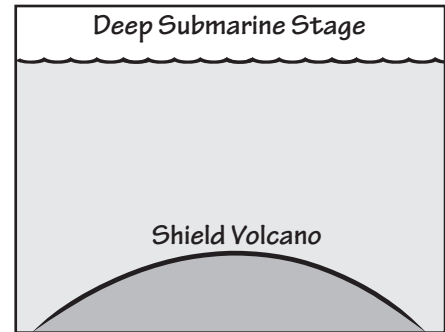
system • a set of connected things or parts forming a complex whole.

silica • a chemical compound also known as silicon dioxide (SiO₂).

As one of the best-developed examples of an oceanic hot spot **system**, the Hawaiian Islands provide a unique window into geologic processes—a time machine through which we can look either forward or backward at the creation and evolution of the islands.

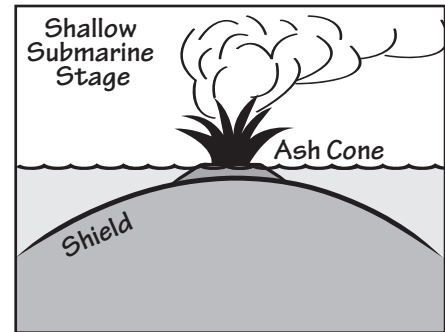
(1) Deep Submarine Stage

While not all Hawaiian volcanoes go through every stage of development described here, we assume that all volcanoes begin with a deep submarine stage, where magma erupts through the seafloor and solidifies. During the deep submarine stage of volcano formation, the magma is made up of **alkalic basalt**, which is derived from the edge of the thermal plume. Alkalic basalts contain around 47% **silicates**, and are relatively high in sodium and potassium. On the seafloor, they erupt as dense lava flows form the initial volcanic shield. Lō'ihi, currently forming off the south coast of Hawai'i Island, is an example of the deep submarine stage.



(2) Shallow Submarine/Early Shield Stage

After layers of early dense lava flows have accumulated, they create a broad submarine shield. When lavas erupt on the deep sea floor, the pressure of the overlying water column keeps gases like oxygen, carbon dioxide, and hydrogen sulfide dissolved in the magma. However, as the growing volcanic shield approaches the ocean surface, the gases begin to form bubbles in the magma, or **exsolve**. These bubbles can be preserved in the chilled lava as **vesicles**. The exsolving gasses can also contribute to a more violent style of eruption. When the summit of the growing volcano approaches the sea surface, the interaction of seawater with the erupting magma can be quite spectacular, characterized by jets of steam, shattered rock, and vaporized lava. No eruptions of this type occur in modern Hawai'i, although from similar eruptions observed in Iceland and elsewhere in the Pacific, we hypothesize that they must have been part of Hawai'i's past.



(3) Subaerial Shield-Building Stage

The submarine and subaerial shield-building stages are the main constructive phases of Hawaiian volcanism. By the time the volcano has emerged above sea level, the lavas have undergone a change in chemistry. Movement over the center of the hot spot produces lavas with fewer alkali elements and more silicates, creating **tholeiitic basalt**, the second major type of Hawaiian lava. This highly fluid lava erupts voluminously over 0.5–1 million years, continuing to build a classic shield-shaped volcano. These volcanoes erupt from shallow

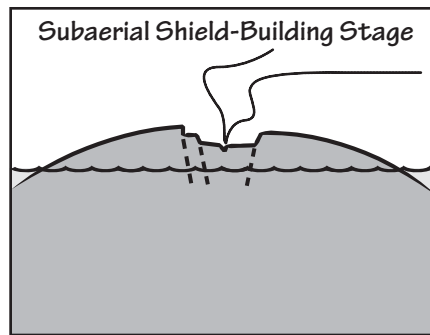


Geologic History



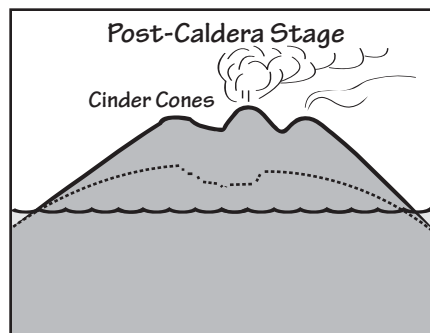
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magma reservoirs located a few kilometers beneath their summits, and also from radial rift zones that channel magma lower onto the flanks of the active volcano. High-volume eruptions that rapidly empty the magma reservoir often lead to summit collapse and the formation of a volcanic **caldera**: the large steep-walled crater that crowns many **shield volcanoes**. While a summit caldera is characteristic of the shield-building stage, some volcanoes do not appear to have one (e.g. Hualālai, West Moloka'i), and the well-developed summit caldera on Lō'ihi shows that caldera formation may also occur earlier in the life cycle of a volcano. Mauna Loa and Kīlauea, which both have large summit calderas, are examples of volcanoes in the subaerial shield-building stage.



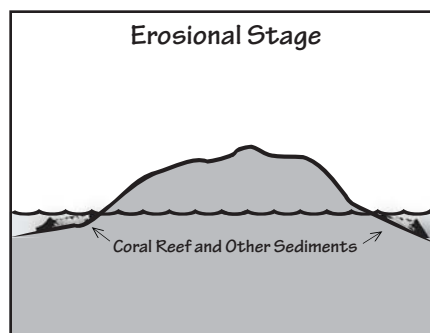
(4) Post-Caldera Stage

Most summit calderas are eventually filled and buried by continuing eruptions of tholeiitic lavas. As the volcano moves away from the center of the hot spot, the eruptions change composition again, returning to alkalic basalt. These later eruptions cap the older shield, and their slightly more explosive nature gives rise to lava fountains that produce **cinder** cones on the summits and flanks of the volcanoes. These cones give older volcanoes a bumpy profile, in contrast to the smooth, younger shield. Alkalic cap lavas often contain numerous **phenocrysts**: early-formed crystals that are entrained in the magma as it erupts. The growth of crystals changes the composition of the remaining liquid magma, and late-stage eruptions can sometimes produce unusual lavas that are so silica-rich they are no longer called **basalts**. Mauna Kea and Hualālai are in the post-caldera stage, and the Pu'u Wa'awa'a cinder cone on Hualālai's north flank produces high-silica eruptions called **trachyte**.



(5) Erosional Stage

While the first four stages in the volcanic life cycle are predominantly constructional, it is important to recognize that erosional processes begin as soon as a volcano rises above the sea floor. Submarine landslides that drape the flanks of Lō'ihi, and prominent **fault scarps** (*pali* in Hawaiian) on Kīlauea and Mauna Loa are evidence that even young volcanoes begin to experience gravitational collapse. Once eruptive



Hawai'i

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.

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

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

fault scarp • an escarpment directly beside a fault line, where the ground on one side of the fault has moved vertically with respect to the other side, creating step-like topography.



1



Geologic History

Hawai'i

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

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

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

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.

leeward • downwind; facing away from the wind.

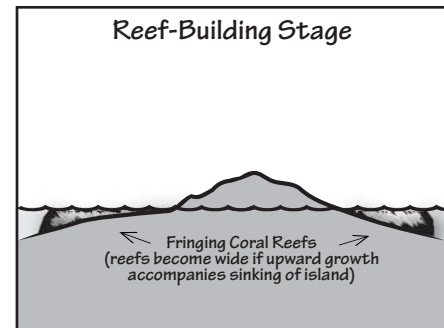


Figure 1.14: Sunrise view of Hawai'i Island from the summit of Haleakalā, Maui. Four of Hawai'i's five subaerial volcanoes are visible. On the leftmost side is Mauna Kea, in the post-caldera stage, and smaller, eroded Kohala peeks through the clouds directly in front. Mauna Loa, a giant shield volcano is on the right, and on its flank is smaller Hualālai, also a post-caldera volcano. Although the topography appears gentle and subdued, both Mauna Kea and Mauna Loa rise more than 4,000 meters (13,100 feet) above sea level.

activity slows, erosion and **weathering** become dominant forces in shaping the evolution of the islands. **Soils** form, and streams—absent on very young volcanoes—begin to incise the surface of the shield. Hawaiian volcanoes are also subject to episodic, catastrophic, erosional events, when mega-landslides rip apart the unsupported seaward flanks of the islands. These landslides scatter enormous blocks of material for hundreds of kilometers (miles) across the seafloor and generate **tsunamis** with local run-up heights up to 300 meters (980 feet) above sea level. Kohala and Haleakalā are examples of erosional stage volcanoes.

(6) Reef-Building Stage

Hawai'i's tropical latitude permits the growth of **reef**-building corals. The reefs are found principally on the **leeward** side of each island where there is little river runoff and thus very clear water. Many of these corals live at or near sea level, making the reefs excellent indicators of sea level rise and fall. As the islands age, the coral reefs expand, eventually encircling each island. Volcanoes as



Geologic History

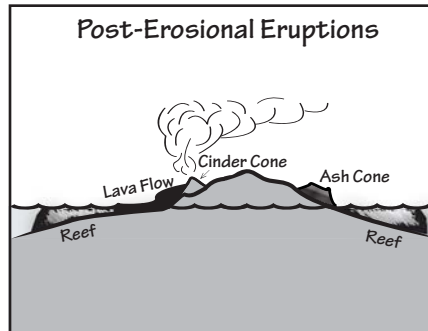


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young as Mauna Loa are host to incipient reefs, while the older islands of O'ahu and Kaua'i have extensive, well-developed fringing reefs.

(7) Rejuvenated Post-Erosional Eruptions

After a long period of quiescence, most Hawaiian volcanoes experience a final episode of eruptive activity. This rejuvenated stage typically produces cinder cones and associated **volcanic ash** deposits. Many of the cinder cones are located near the shoreline. One hypothesis for the origin of these late-stage eruptions is that mass loss due to erosion decompresses the magma below, triggering further melting and eruption. Rejuvenated volcanism is found on all islands except Hawai'i.

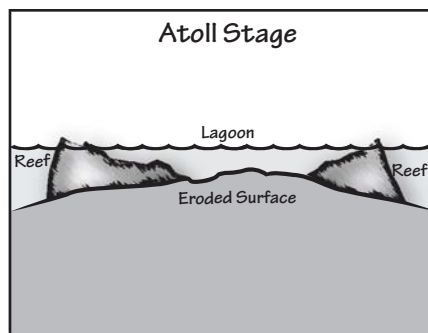


volcanic ash • fine, unconsolidated pyroclastic grains under 2 mm (0.08 inches) in diameter.

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

(8) Atoll Stage

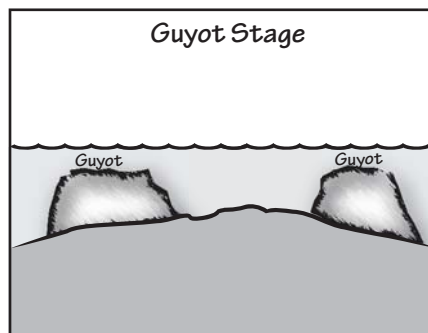
As the volcanoes drift farther from their hot spot origin, they cool and eventually become extinct. The lithosphere on which the islands sit also cools, becoming denser. This leads to a gradual subsidence of the volcanic ridge, causing the islands to slowly sink. As subsidence drags the islands down from below, erosion by waves, streams, and **mass wasting** works to diminish the islands from above. Fringing reefs expand to encircle the eroded volcano. Ultimately, the volcanic edifice is eroded to sea level and only the circular reef remains, forming an **atoll**. Many of the Northwestern Hawaiian Islands are in the atoll stage.



atoll • a circular or horseshoe-shaped coral reef, surrounded by deep water and enclosing a shallow lagoon.

(9) Guyot Stage

Continued subsidence pulls even the coral atolls below sea level. Eventually, the living coral reefs literally "drown," becoming flat-topped seamounts called **guyots**. The Emperor Seamounts exemplify this final stage in the life cycle of Hawaiian volcanoes. Ultimately, each of the Emperor Seamount and Hawaiian islands will return to the mantle via subduction at an active plate boundary, millions of years in the future.





Hawai'i

Hot Spot Volcanoes and Hawaiian Tradition

Some changes that occur as hot spot volcanoes evolve through their life cycle—for example, the transition from alkalic to tholeiitic lavas—are evident only by conducting chemical tests. But many other changes are visible to the naked eye. Smooth volcanic shields are dissected by erosion, large canyons are carved through the landscape, and the size of the islands decreases with increasing age. The original inhabitants of the Hawaiian Islands were acute observers of nature. Their survival in the isolated islands depended on their understanding of natural phenomena, and their cosmology reflected what they saw in the world around them. The ancient Hawaiian story of Pele, the goddess of fire and volcanoes, describes her arrival on the islands of Kaua'i and Ni'ihau: the oldest of the eight main Hawaiian Islands. Pele found these islands to be unsuitable for her fiery temperament, as they were dominated by her sibling rival, Nāmaka, goddess of the ocean. Pele traveled to O'ahu, the next youngest island, but here too she could not escape the influence of her sister. Pele moved from island to island, to Moloka'i, Lāna'i, and on to Maui, where she thought she might be safe. But she was forced to flee even from the giant volcano Haleakalā, coming at last to Hawai'i Island and Kīlauea. On Kīlauea she searched the earth with her digging stick and found a fire that Nāmaka could not extinguish. Here, within the youngest volcano, Pele made her home. This oral tradition accurately reflects the age progression of Hawaiian volcanoes, passing along the islands' geologic history through a colorful narrative.



Resources

Resources

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Geologic History

Resources

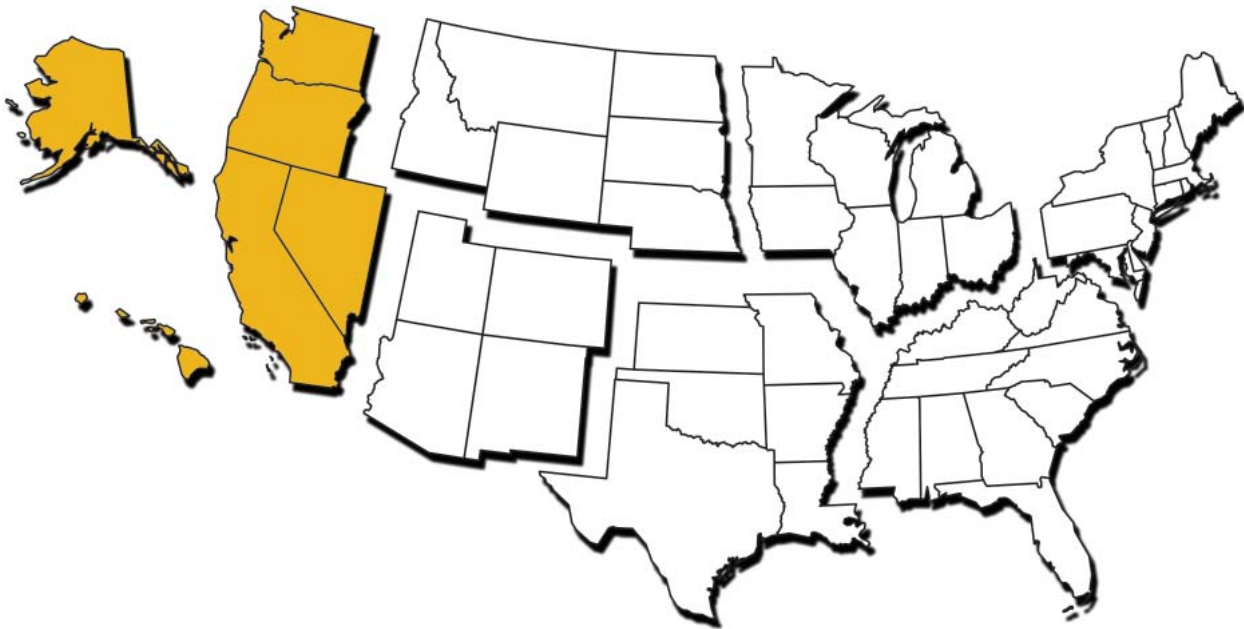
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On the back cover: Blended geologic and digital elevation map of the Western US. Each color represents the age of the bedrock at the surface. Adapted from Barton, K. E., D. G. Howell, & J. F. Vigil, *The North America Tapestry of Time and Terrain*,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