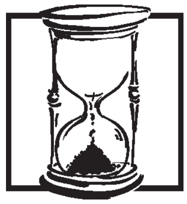

Chapter 1: Geologic History of the Northwest Central US: Reconstructing the Geologic Past

Geologic history is the key to this Guide and to understanding the story recorded in the rocks of the Northwest Central US. By knowing more about the geologic history of your area, you can better understand the types of rocks that are in your backyard and why they are there. In this chapter, we will look at the history of the Northwest Central as it unfolded: as a series of major events that created and shaped the area over the past one billion years. These events will act as the framework for the topics in the chapters to follow and will shed light on why our region looks the way it does!

The shape and position of North America has changed dramatically over the last billion years, and geologic processes continue these changes today. The Earth's outer layer—the **crust**—is dynamic, consisting of constantly moving **plates** that are made of a rigid continental and oceanic **lithosphere** overlying a churning, plastically flowing **asthenosphere**—part of the Earth's **mantle** (*Figure 1.1*). These plates are slowly pulling apart, colliding, or sliding past one another with great force, creating strings of **volcanic islands**, new ocean floor, **earthquakes**, and mountains. The continents are likewise continuously shifting position relative to each other. This not only shapes the land, but 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. By studying rocks, **fossils**, and other geologic features, however, scientists can still reconstruct a great deal of what the ancient Earth might have looked like.

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 the history of molten rock, both below the surface (**plutonism**) and at the surface (**volcanism**). Likewise, **metamorphic rocks**, created when sediment is subjected to intense **heat** and pressure, provide important clues about 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

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.*

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

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

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

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

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

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

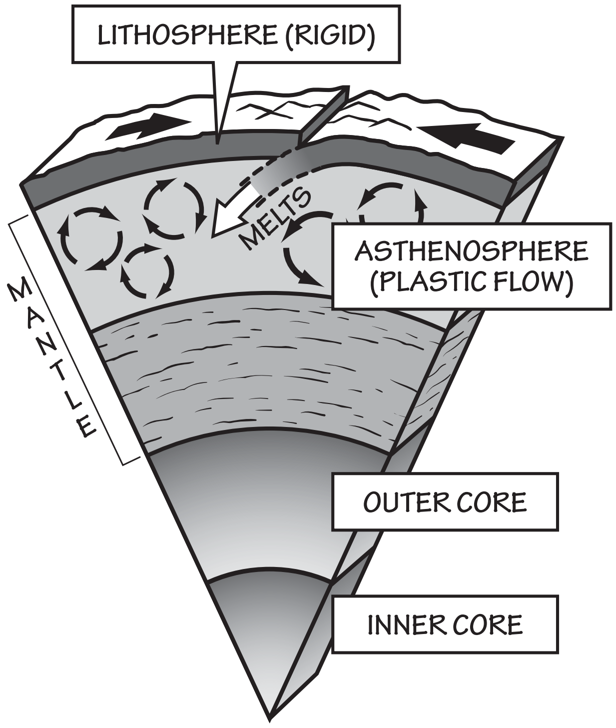

Figure 1.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

Lithosphere and Asthenosphere: What's the difference?

The difference between crust and mantle is mainly chemical: the lithosphere's composition typically varies between basalt in oceanic crust and diorite or *gabbro* in continental crust, while the mantle is composed of homogenous *ultramafic* material. The boundary between rigid lithosphere and flowing asthenosphere is usually found *within* the mantle, and is largely a result of temperature increase with depth beneath the surface. In tectonically active regions of extension such as the Basin and Range, where temperature rises rapidly with depth compared to in more tectonically stable regions, the asthenosphere begins nearly at the base of the crust.

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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 Northwest Central.

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 ancient 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 can be easily preserved as fossils, and many environments do not lend themselves to preserving organisms as fossils. As a result, the clues that fossils give us provide only incomplete glimpses of the ancient world, with many important details missing.

See Chapter 3: Fossils for more information about the Northwest Central'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 transported 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 landscape of the Northwest Central States.

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 do, the Earth's recent history is better known than its ancient past. Although preserved geologic clues are indeed fragmentary, geologists have become increasingly skilled at interpreting them and constructing ever more detailed pictures of the Earth's past.

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

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

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.*

ripple marks • *surface features created when sediment deposits are agitated, typically by water currents or wind.*

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

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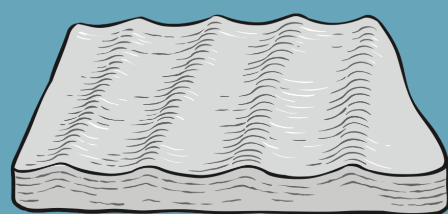
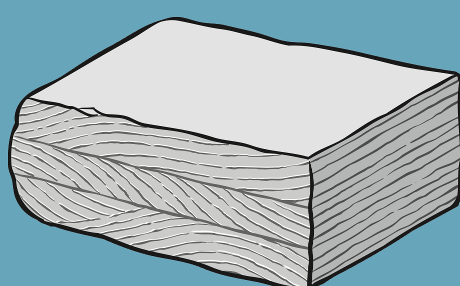
geologic time scale • *a standard timeline used to describe the age of rocks and fossils, and the events that formed them.*

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.

The **geologic time scale** (*Figure 1.2*) is an important tool used to portray the history of the Earth—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 separated into four principle divisions.

The first of these four divisions, the **Precambrian**, extends from the beginning of the Earth, around 4.6 billion years ago, to the beginning of the **Cambrian** period, around 541 million years ago. The Precambrian is subdivided into two sections: the **Archean** (before 2.5 billion years ago) and the **Proterozoic** (2.5 billion to 541 million years ago). Less is known about the Earth during the Precambrian than during later parts of its history, since relatively few fossils

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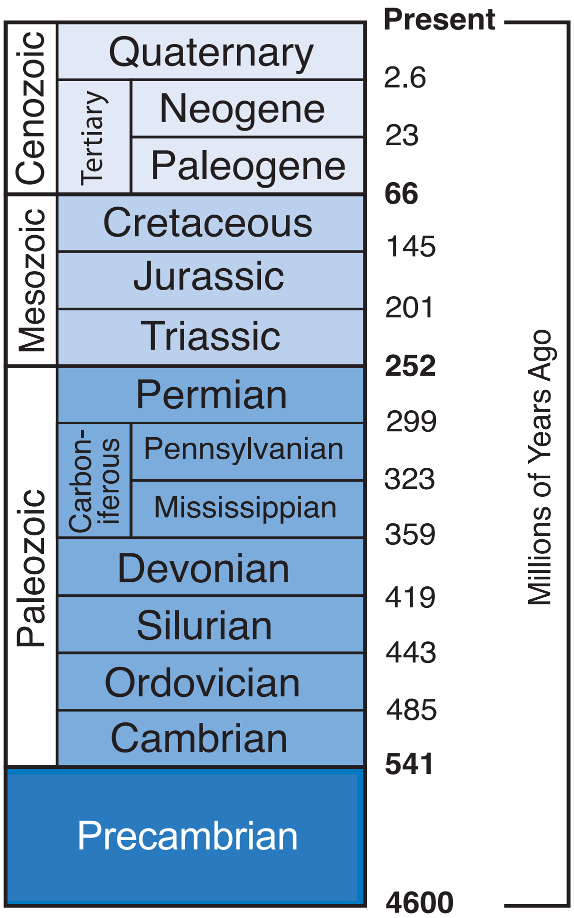


Figure 1.2: The Geologic Time Scale (spacing of units not to scale).

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 found 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.*

Geologic Time

How did geologists come up with the timeline for the history of the Earth? The geologic time scale was developed over the course of many years and through the combined work of geologists around the world. 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 Silurese of England and Wales, from which the "*Silurian*" period was derived.

1 Geologic History

Big Picture

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.*

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

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

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

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

natural hazards *• events that result from natural processes and that have significant impacts on human beings.*

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

or unaltered rocks have survived. Nevertheless, the evidence that has been preserved and discovered reveals much about the planet's first several billion years, including clear evidence that life first appeared on the planet some 3.9 billion years ago in the form of single-celled organisms.

The second division, the **Paleozoic**, extends from 541 to 252 million years ago. Geological evidence shows that during this time period, continents moved, mountains formed, and 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.

Pangaea, meaning "all Earth," began to assemble over 300 million years ago and lasted for almost 150 million years. All of the Earth's continents were joined as one to form a giant supercontinent.

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 much more diverse and abundant. We humans didn'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!

The Northwest Central States

The Big Picture

The geologic history of the Northwest Central United States is a story of the repeated assembly and disassembly of a large continental mass. By around 600 million years ago, the core of what would eventually become most of North America was a separate continental block. Over the next several hundred million years this continent was mostly tectonically stable and flat, and was repeatedly flooded and exposed by rising and falling sea level. Around 300 million years ago, episodes of tectonic activity and volcanism added land to the continent along what would become the West Coast. Major mountain building did not begin until around 100 million years ago, and reached its peak around 65 million years ago, at the very end of the Mesozoic era. These episodes of **orogenic** activity formed the Rocky Mountains, which have dominated the geology and landscape of western North America ever since. At the same time that the Rockies were rising, globally high sea level caused an enormous shallow sea – the Western Interior Seaway – to form across what is today the Great Plains, from Texas to Alaska. This seaway disappeared in the early Cenozoic era, and was replaced by a changing landscape of forest and grasslands filled with an amazing diversity of life, especially mammals, which replaced dinosaurs in most of the ecological niches for large terrestrial vertebrates.

In this volume, the Northwest Central States are divided up into five different geologic provinces or regions (*Figure 1.3*): the Central Lowland (1), Great Plains (2), Rocky Mountains (3), Columbia Plateau (4), and the Basin and Range (5). Each of these regions has a different geological history and thus varies in rocks, fossils, **topography**, mineral resources, **soils**, and **natural hazards**.

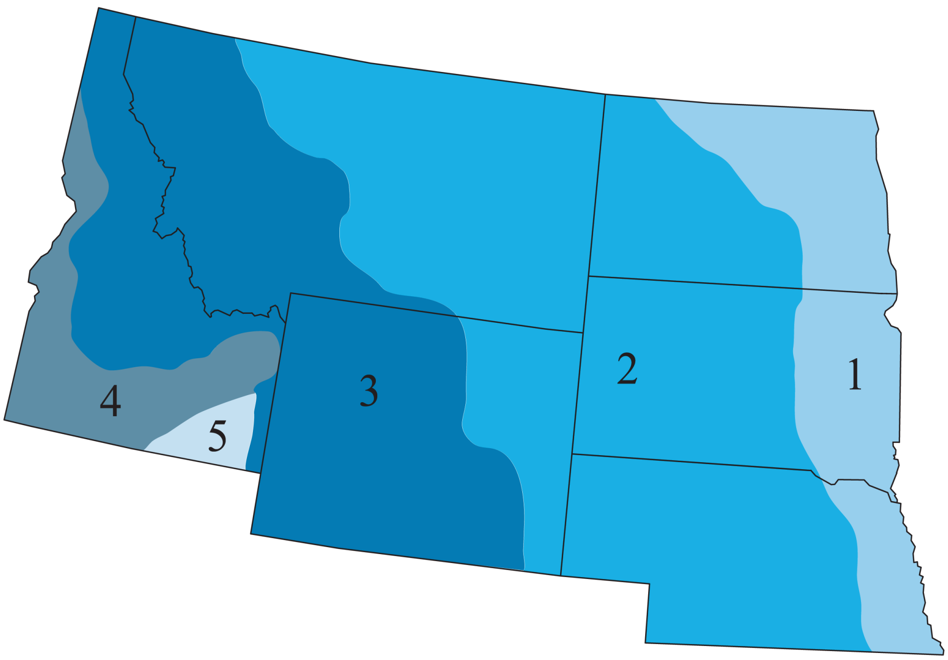


Figure 1.3: Geologic regions of the Northwest Central.

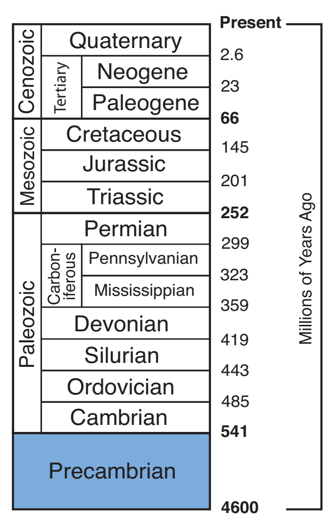
Canadian Shield *• the stable core of the North American continental landmass, containing some of the oldest rocks on Earth.*

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.*

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

Precambrian Beginnings
Roots of the Northwest Central

The Earth is estimated to be approximately 4.6 billion years old—an age obtained by dating **meteorites**. Rocks dating to around four billion years old are found on almost every continent, but the oldest rocks known on Earth are 4.3 billion-year-old rocks found along the eastern shore of Hudson Bay in northern Quebec. These are part of the **Canadian Shield**, the ancient core of the North American continental landmass, which has experienced very little tectonic activity (**faulting** and folding) for millions of years. Shields, or **cratons**, are the stable cores of all continents and are often covered by layers of younger sediments. They formed and grew during pulses of **magmatic** activity, as bodies of molten rock deep in the Earth's crust contributed to form new crust. In the Northwest Central US, the main cratonic elements are referred to as the Wyoming Province (Wyoming



1 Geologic History

Precambrian

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

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.*

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

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

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

and eastern Montana), the Medicine Hat Block (northwestern Montana), and the Superior Province (Dakotas, Minnesota, Wisconsin, and Michigan) (*Figure 1.4*). Outcrops of these rocks are exposed mainly as **uplifted** blocks in mountain ranges throughout Wyoming, Montana, and South Dakota. The oldest rocks identified so far in the Northwest Central US are 3.6– to 3.8-billion-year-old **granitic gneisses** found in Wyoming's Wind River Mountains.

The oldest known materials in the world are 4.4-billion-year-old zircons from rocks in Western Australia.

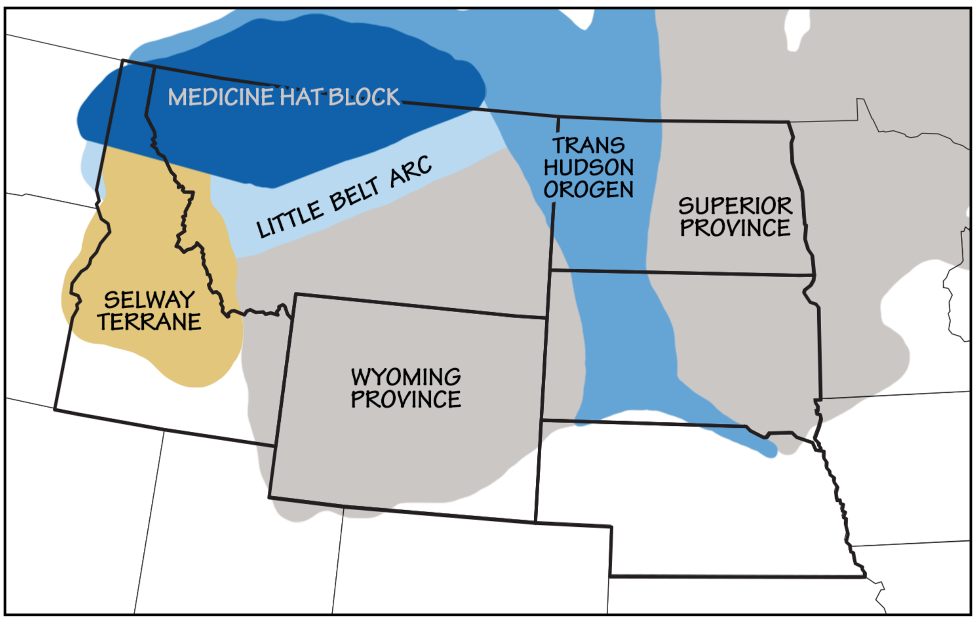


Figure 1.4: Cratonic elements and belts of deformation. (See TFG website for full-color version.)

The shape and position of North America has changed dramatically over the last billion years, and geologic processes continue these changes today. **Compression** from colliding plates, tension from plates pulling apart, the addition of land to North America, **weathering**, uplift, and erosion have combined to slowly sculpt the form of the continent. As such, it is very difficult to reconstruct the size, shape, and position of continents during the Precambrian. Fewer rocks are preserved from this time, and those that remain have been highly altered. Nevertheless, available evidence suggests that the proto-North American continent, also called Laurentia, had its Precambrian beginnings in a supercontinent that existed around 2.6 billion years ago. From this proto-North America, sediment was eroded and transported by rivers and streams across the ancient continental margins and then into the adjacent oceans. The sediment deposited in the ocean waters on the western margin of Laurentia can be found today in southern Wyoming's 2.2– to 2.4-billion-year-old Snowy Range Supergroup, where thick sequences of **sandstone**, **conglomerate**, and **limestone** were deposited near what is now the southern margin of Wyoming.

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These sediments contain 2.3-billion-year-old **stromatolites** (mounds of sediment formed by mats of photosynthetic **cyanobacteria**), indicating that they were deposited in a continental shelf environment. During this time period, at least two episodes of glaciation occurred, represented by rocks formed from glacially derived sediments (**tillites**) found in Idaho and Montana.

See Chapter 2: Rocks to learn more about stromatolites.

Around two billion years ago, a second supercontinent, often called columbia or Nuna, began to assemble from major cratons and other fragments of land. In the Northwest Central, the zones of collision between the cratons and fragments are preserved as deformed metamorphic rocks in the Little Belt Arc of northern Idaho and Montana, the Selway Terrane of southern Idaho, and the Trans-Hudson Orogen of the Dakotas and Canada (*see Figure 1.4*). The breakup of this supercontinent began around 1.5 billion years ago.

The remainder of the Precambrian period saw the formation of a third supercontinent, which geologists call **Rodinia,** about 1.1 billion years ago (*Figure 1.5*), and its eventual breakup about 750 million years ago. Preserved remnants of the continental collisions that formed this supercontinent are found widely across modern North America, but very few of these elements are recognizable in the Northwest Central US.

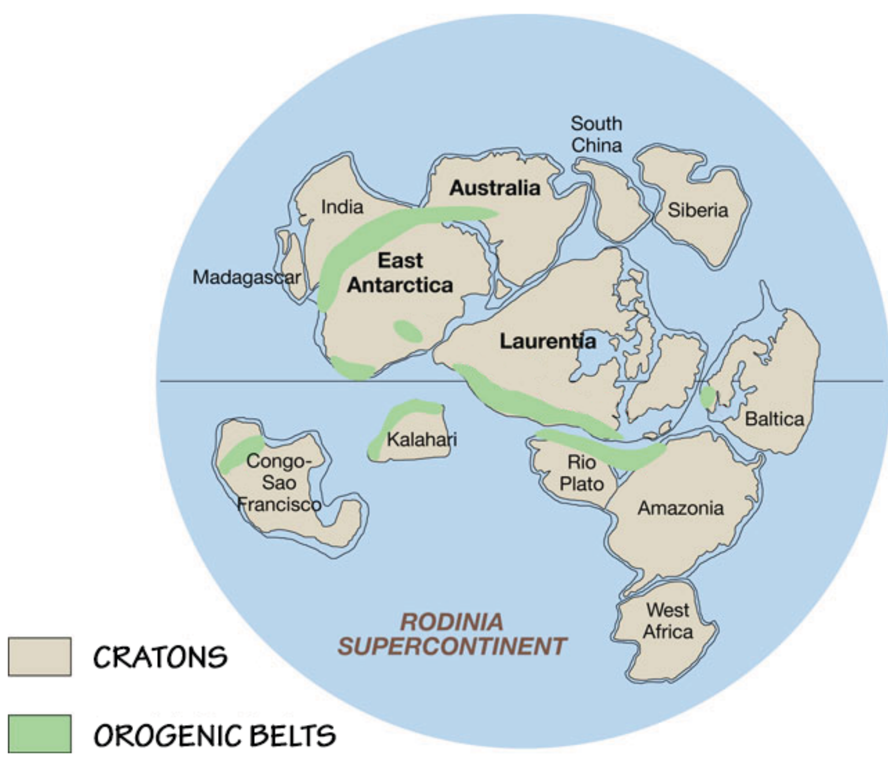


Figure 1.5: The supercontinent Rodinia, circa 1.1 billion years ago. Laurentia represents proto-North America. (See TFG website for full-color version.)

Precambrian

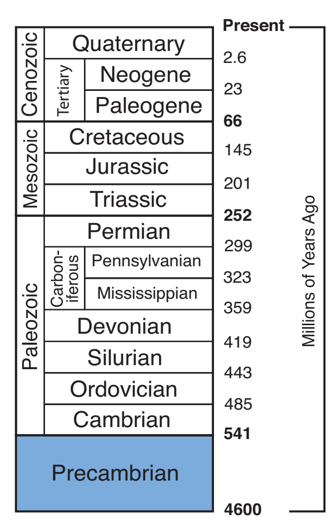
sandstone • *sedimentary rock formed by cementing together grains of sand.*

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

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

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

Rodinia • *a supercontinent that contained most or all of Earth's landmass, between 1.1 billion and 750 million years ago, during the Precambrian.*



Paleozoic

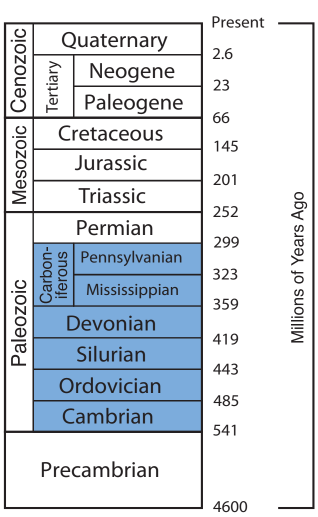
***rift** • a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates.*

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

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

***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.*

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



The breakup of Rodinia was associated with the formation of **rifts** throughout North America, with igneous activity occurring in rifted zones and continuing slowly and irregularly until about 600 million years ago. North America's rifted edges formed **passive margins**, where sediments were deposited on continental shelves into the early Paleozoic era.

A rift occurs when tectonic plates move away from each other. Magma rises up into the margin, cooling to produce new oceanic crust. The resulting action is similar to two conveyor belts moving away from each other. A failed rift occurs when the existing crust is stretched thin and magma begins to well up, but the plate is never completely broken.

The Paleozoic:
Formation of a Continent

At the beginning of the Paleozoic, during the Cambrian, the area that is now the states of California, Oregon, Washington, Idaho, and Nevada did not yet exist as part of the North American continent. The edge of North America's continental shelf was located at approximately the Arizona-Utah-Nevada-Idaho line (*Figure 1.6*). In the late **Devonian** (370 million years ago), a portion of the continental shelf adjacent to present-day Idaho and Nevada transitioned from quiet passive margin to an active **subduction** zone, where oceanic crust plunged beneath the continent. Here, as oceanic crust descended deep into the upper mantle, the rock above the descending crust melted to form a line of volcanoes on the surface. Subduction also led to **accretion**—sediment, sedimentary rock, and even bits of the oceanic crust itself were scraped off the descending crustal plate and pushed onto the overlying plate (*Figure 1.7*). Just as a rug develops folds when pushed from the side, these rocks were wrinkled up into mountains. Volcanic islands carried along by the subducting plate also accreted to the edge of the continent. The landmass began to rotate, moving the North American plate into a more modern orientation.

During the **Carboniferous**, **plate tectonics** led to the initial stages of Pangaea's assembly. As North America began to collide with **Gondwana**, forces from the collision began to affect the continent's topography. During the **Mississippian** (340 million years ago), most of the West Coast had transformed into a subduction zone. A series of exotic **terranes**, consisting of sedimentary rock made from former seafloor sediment, slabs of volcanic and granitic rock, and the remains of volcanic islands, collided with and accreted to western North America. These collisions deformed and elevated the continent's topography, generating two major mountain-building events: the **Antler Orogeny** (340 million years ago) and the **Sonoman Orogeny** (245 million years ago).

During the **Pennsylvanian** (300 million years ago), compressional forces from the collision and tension from coastal subduction combined to deform the continent's interior, buckling

Geologic History 1

Paleozoic

Gondwana • the supercontinent of the Southern Hemisphere, composed of Africa, Australia, India, and South America.

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

Antler Orogeny • a period of mountain building that deformed rocks in a belt extending from the California–Nevada border northward into Idaho.

Sonoman Orogeny • a period of mountain building along the western edge of North America, in what is now Nevada and eastern Oregon.

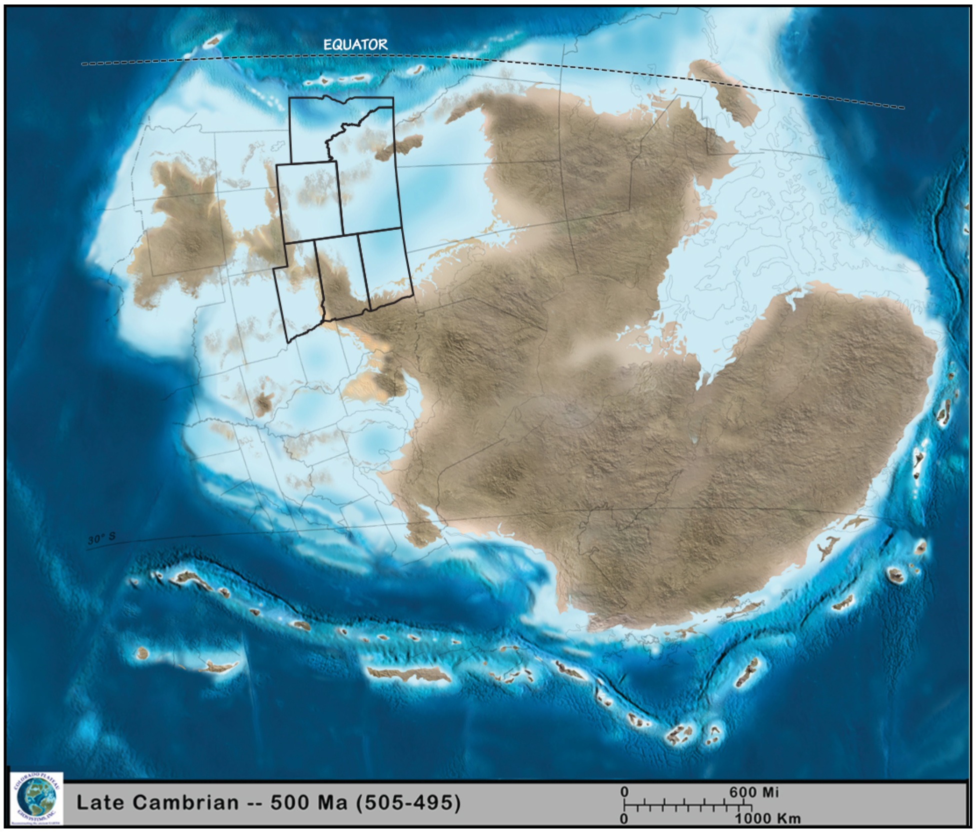


Figure 1.6: The Northwest Central US during the late Cambrian, approximately 500 million years ago. The entire region is located in the southern hemisphere—note the position of the equator.

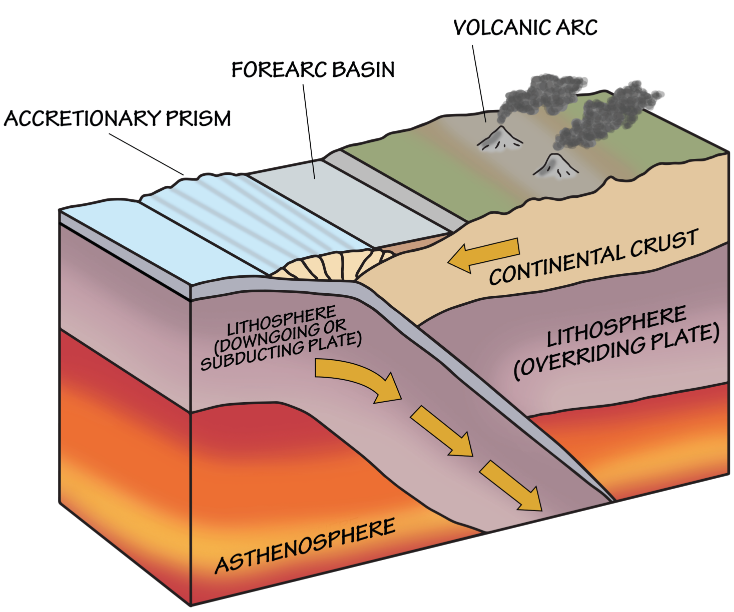
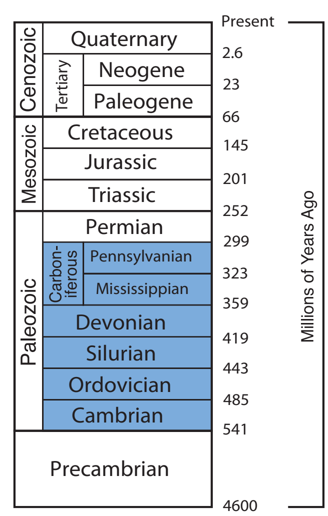


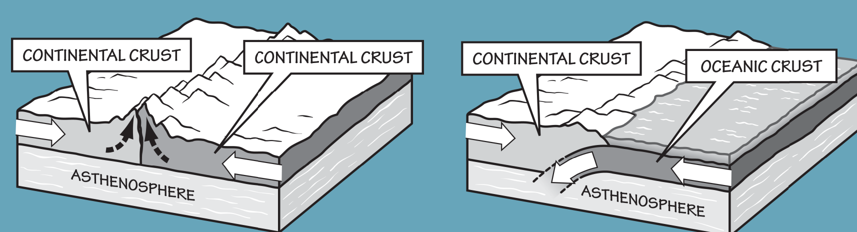
Figure 1.7: Subduction along the western edge of the North American plate.

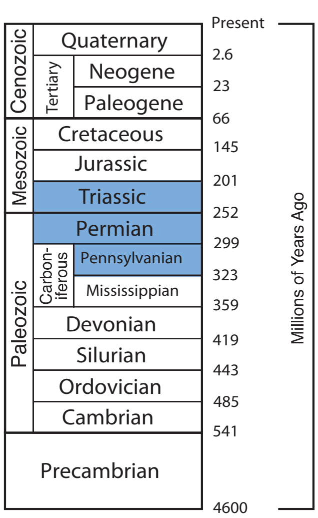


Paleozoic

Continental and Oceanic Crust

The lithosphere includes 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 denser 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.





the crust and creating deep basins between uplifted blocks. Shallow **inland seas** spread across the interior of the continent, covering parts of North America's Precambrian shield (*Figure 1.8*). Uplift formed a mountain range, known as the Ancestral Rocky Mountains, in Wyoming, Colorado, and New Mexico, and land was also raised above sea level in Canada, Montana, and the Dakotas. Sediments that eroded from this range and other uplifted areas were transported to the inland sea and the continental margins, forming deposits of conglomerates, sandstones, **shales**, limestones, and **evaporite** minerals. Although the Ancestral Rocky Mountains has long since eroded away, remnants of its core remain, and can be seen today in Colorado and Utah. As accretion continued over time, the coastline moved farther seaward (*Figure 1.9*). Sea level fell in the late Paleozoic, during the Pennsylvanian and **Permian**, as continental collisions progressed to form the supercontinent Pangaea.

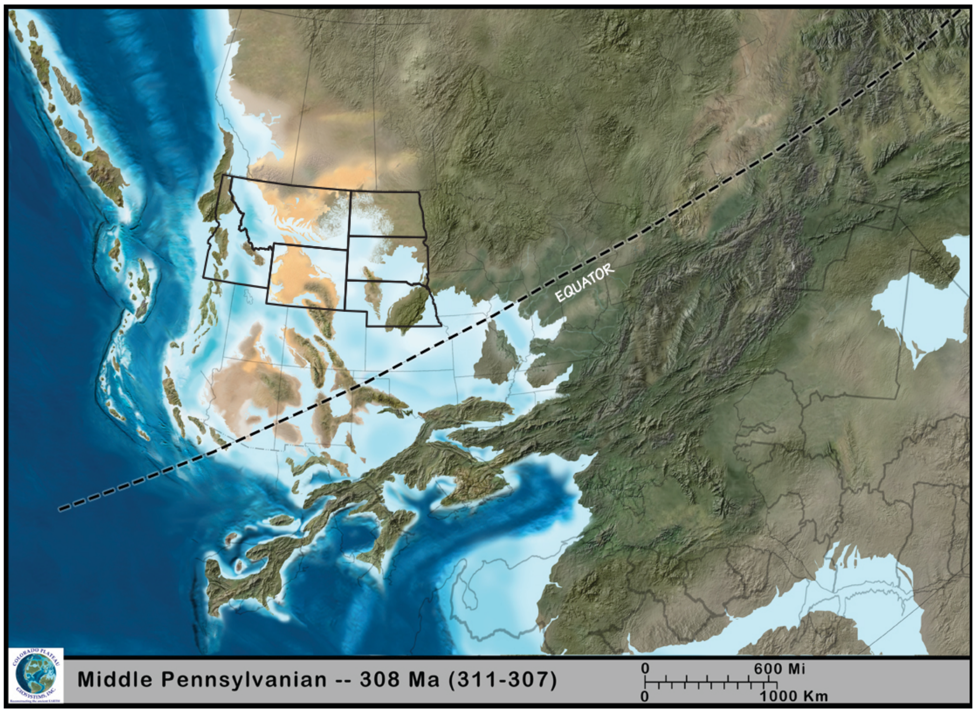


Figure 1.8: The Northwest Central US during the Pennsylvanian, approximately 208 million years ago.

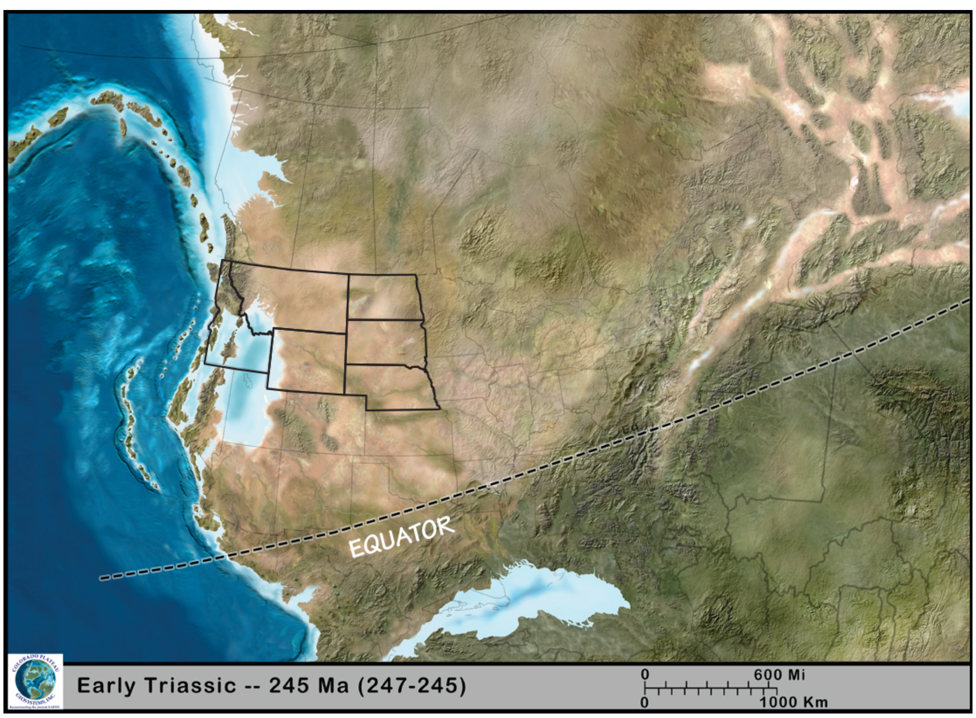


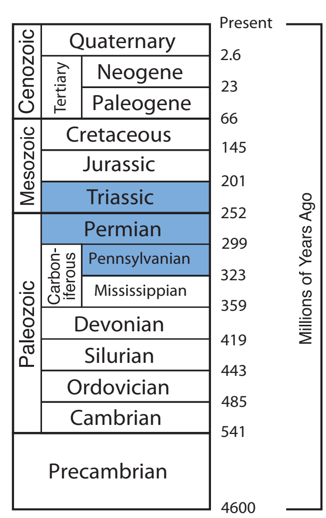
Figure 1.9: The Northwest Central US during the early Triassic, approximately 245 million years ago.

Paleozoic

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

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

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



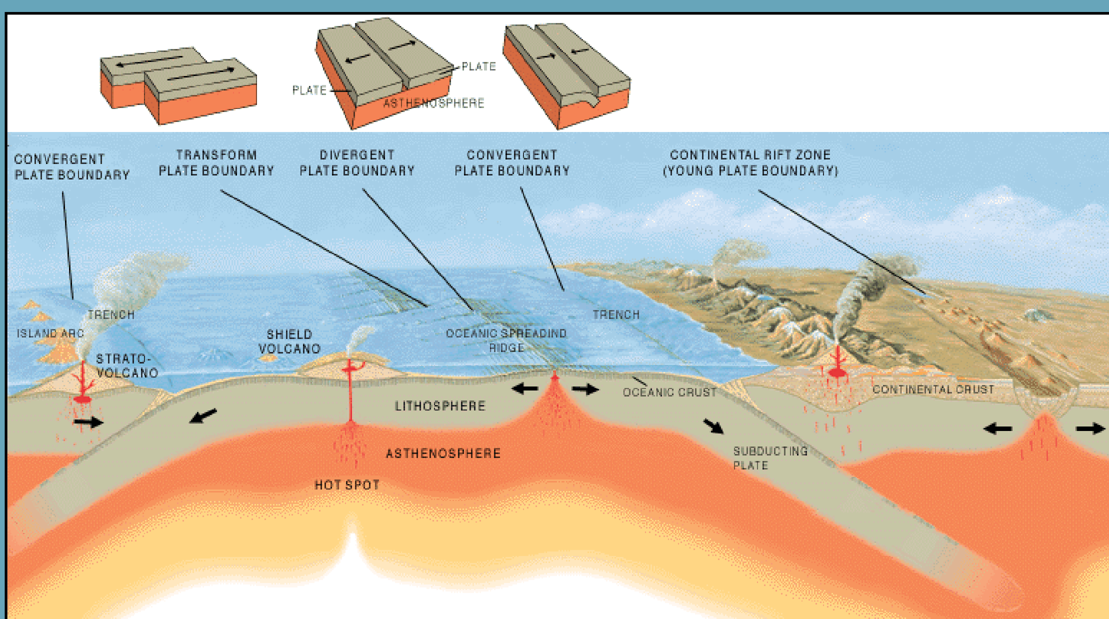
1 Geologic History

Paleozoic

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.)

The Mesozoic:
A Story of Mountains and Seas

The Mesozoic era is frequently known as the Age of the Dinosaurs or Age of Reptiles, but many other life forms evolved and thrived during this time, including marine invertebrates, flowering plants, birds, and mammals. The Mesozoic was also a time of major geologic change during which great thicknesses of rocks were deposited across the western US.

The supercontinent Pangaea was in place by the end of the Permian period, and global sea level was probably at its lowest of any time during the past 600 million years. During the **Triassic** and **Jurassic**, sea levels rose, and a shallow arm of the sea reached from Canada through Montana and parts of Wyoming (*Figure 1.10*). **Iron**-rich limestones, sandstones, and mudstones laid down in this sea were **oxidized**, giving a distinctive and characteristic red color to the rocks, which are appropriately called "red beds." During the Jurassic, mudstone and sandstones were also deposited in lowland areas and river channels throughout the Rocky Mountains and **Colorado Plateau**; these formed the Morrison Formation, which is famous for its abundant dinosaur fossils.

See Chapter 3: Fossils to learn about the Morrison Formation and other fossil-rich rock formations.

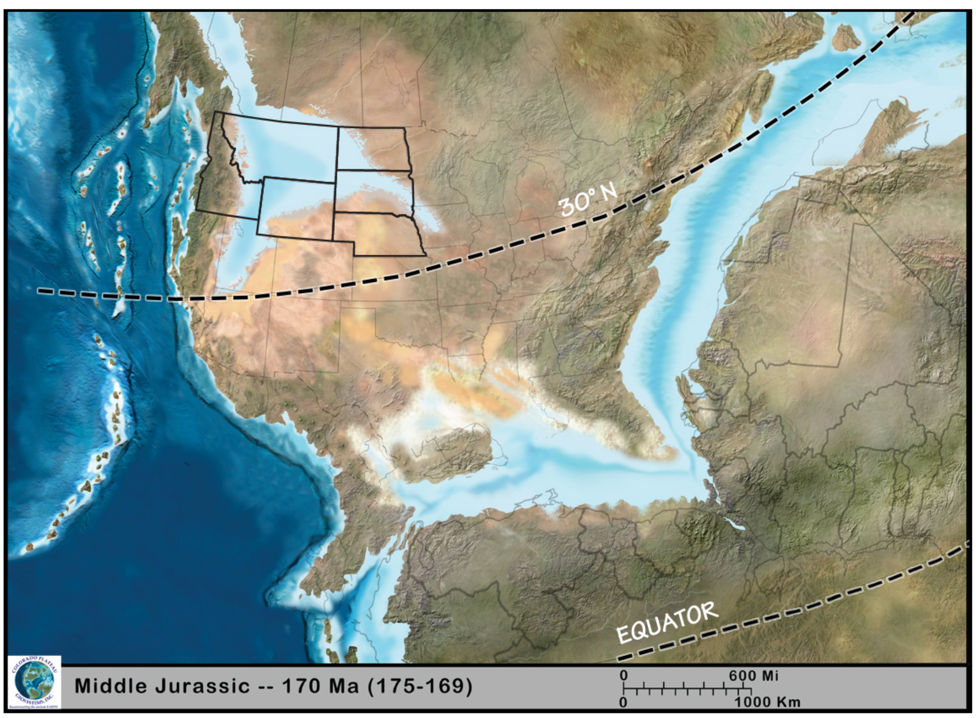
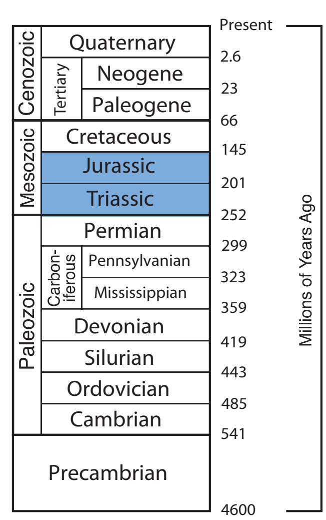


Figure 1.10: The Northwest Central US during the Jurassic, approximately 170 million years ago.

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

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

Colorado Plateau • *a physiographic region that covers an area of 337,000 square kilometers (130,000 square miles) of desert and forest within Colorado, New Mexico, Arizona, and Utah.*



1 Geologic History

Mesozoic

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

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

During the early **Cretaceous**, Pangaea entered its final stages of breakup (*Figure 1.11*). Far to the west, oceanic crust (the Farallon plate) had been subducting under western North America for tens of millions of years, causing a series of volcanic island complexes to collide with and become accreted to that margin of the continent, forming the Sierra Nevada of California. As the new Atlantic Ocean widened, sea levels began to rise. Around 85 million years ago, when the Farallon plate began to subduct at an unusually shallow angle, it slid farther inland beneath western North America before finally sinking into the asthenosphere. This **downwarped** the center of the continent and created a basin that allowed the waters of the Gulf of Mexico to meet with those in the north, forming the Western Interior Seaway (*Figure 1.12*), which inundated a 1000-kilometer (620-mile) wide swath from Mexico to Alaska. During the very latest stages of the Cretaceous period, around 70 million years ago, the Western Interior Seaway was displaced by slow uplift of the continent.

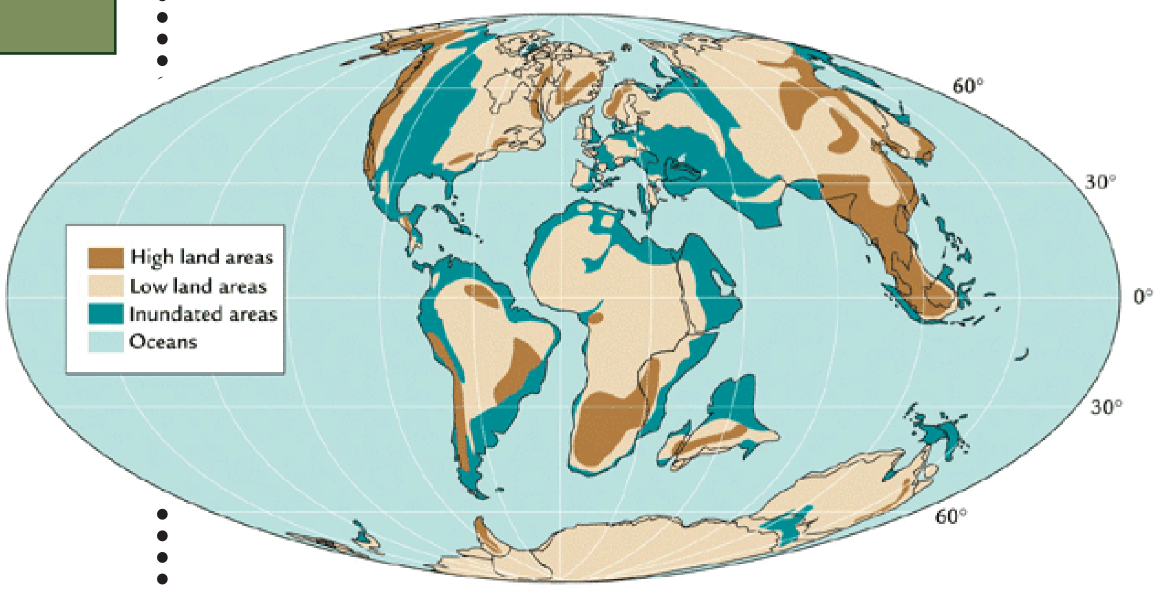
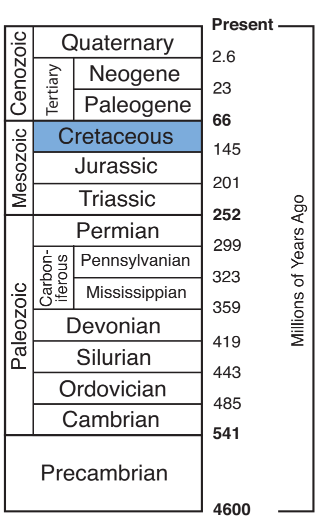


Figure 1.11: Landmasses following the breakup of Pangaea. (See TFG website for full-color version.)

The Farallon plate continued to collide with western North America, thrusting layers of rock up over each other and causing increasing volcanism to the west of the Western Interior Seaway. The compressional forces of subduction faulted the crustal rocks of western North America and uplifted the Rocky Mountains in two major pulses. The **Sevier Orogeny** (100–72 million years ago) raised the portion of the Rocky Mountains in Montana, Wyoming, and Utah known as the "Overthrust Belt." The second event, the **Laramide Orogeny**, peaked around 68–65 million years ago, when the angle of the subducting plate became shallower, uplifting the Rocky Mountains in Colorado and New Mexico. While most of the magmatic activity at this time occurred on the western edge of the continent in the volcanic arc of the Sierra Nevada, some did take place farther inland. The largest and most important evidence of this is the Idaho Batholith—three major lobes of granitic material **intruded** beneath large areas of Idaho



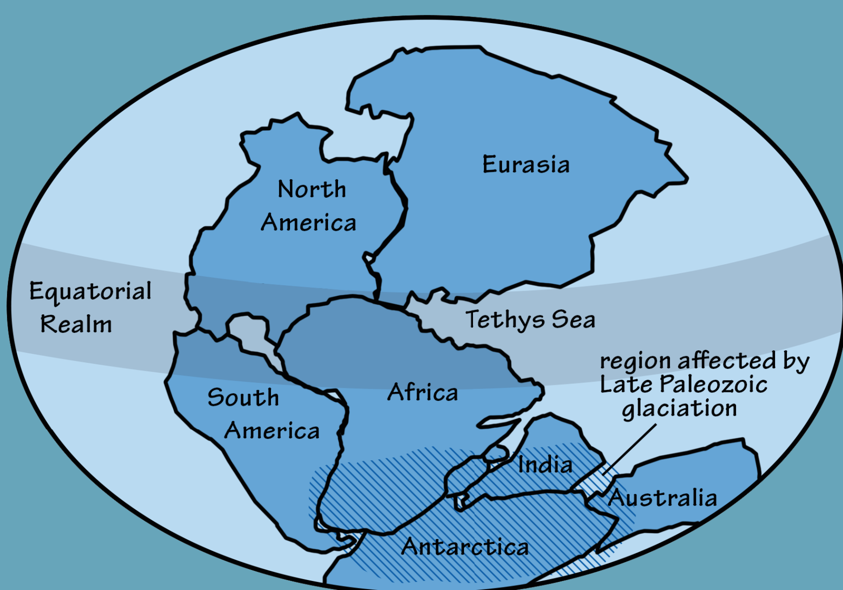
Mesozoic

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

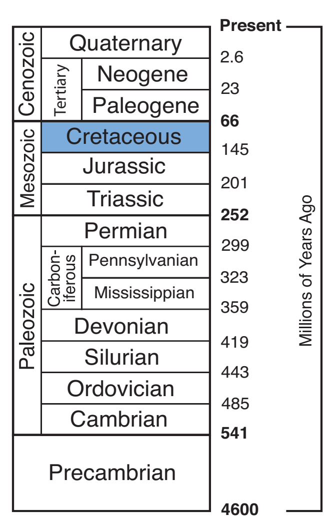
intrusive rock • *a plutonic igneous rock formed when magma from within the Earth's crust escapes into spaces in the overlying strata.*

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, which slowly moved toward their present-day positions over the following 150 million years.



Pangaea during the late Paleozoic era



inland basin *• a depression located inland from the mountains, and formed by the buckling (downwarping) of the Earth's crust.*

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.*

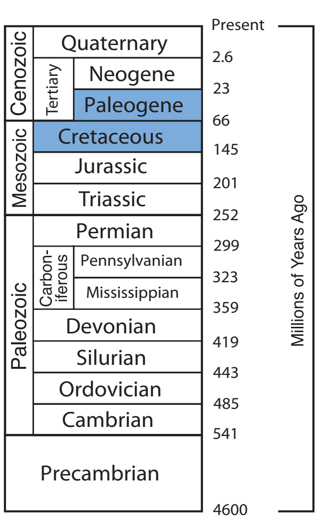
fluvial *• see outwash plain: large sandy flats created by sediment-laden water deposited when a glacier melts.*

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

Figure 1.12: The Western Interior Seaway.

between 100 and 65 million years ago. The rising ancestral Rocky Mountains provided sediment that filled the seaway, and uplift from the ongoing orogeny finally caused the water to split in the Dakotas and retreat south.

Because the crust flexes or breaks under compression, several **inland basins** formed between the mountain ranges, and the eroding mountains shed thick layers of sediment into these basins, forming conglomerates, sandstones, and mudstones. The Colorado Plateau remained stable during this time of compression, and persisted during the subsequent episode of extension that followed from the **Paleogene** period to the present day.



Geologic History 1

The Cenozoic
Volcanism and Tectonism

The Cenozoic era (consisting of the Paleogene and **Neogene** periods, 66 million years ago to present) was an age of diversification and evolution of mammals, birds, insects, flowering plants, and coral **reefs**. The continents continued to spread apart to reach their present day positions. Sea levels rose and fell, affecting the coastline, but the interior of North America remained relatively high. Sediment deposition, for the most part, occurred as **fluvial** and lake deposits. This was also a time of active volcanism in western North America. The Cenozoic geology of western North America is dominated by three large-scale processes: erosion, subduction and extension, and volcanic activity.

Erosion of the mountains and highlands that had formed during the Mesozoic produced thick layers of conglomerates, sandstones, and mudstones across much of the Northwest Central. **Volcanic ash** is commonly interlayered with these sediments. Many of these sedimentary layers were deposited by rivers, or in **alluvial** fans coming from the mountain systems. Several such layers are now important **aquifers**, including the enormous Ogallala Aquifer (*Figure 1.13*) which today supplies water for farming and communities across much of the Great Plains. Due to crustal deformation during the Mesozoic, several basins formed inland lakes or depressions into which sediments were deposited. The best-known example is the Green River Basin of western Wyoming, which is famous for its well-preserved fossils found in lakebed shales and mudstones.

See Chapter 3: Fossils for more information about the Green River fauna.

Subduction at the West Coast ceased with the development of the San Andreas Fault System. Due to the complex interplay of plate motions, the portion of the subducting plate beneath the Southwest US overrode hot, upwelling mantle. This, in turn, caused a number of major changes. In the early Paleogene, melting of the lower crust resulted in the emplacement of numerous granitic bodies and volcanic eruptions across the western US, including the Absaroka Range in Wyoming and Montana and the Challis Volcanic Field in Idaho. These large packages of volcanic rocks also host important mineral deposits. Ash from these eruptions fell long distances from its source, and is a major component of terrestrial sediment on the Great Plains, much of which is abundantly fossiliferous.

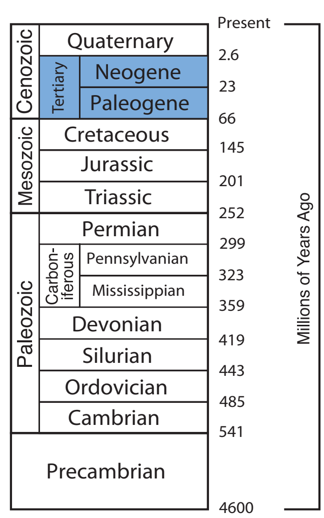
By the Neogene, the Farallon plate lay shallowly under the North American plate for hundreds of kilometers eastward of the West Coast. Now situated more fully beneath what are now the South Central, Southwestern, and Northwest Central States, this extra layer of crust caused uplift and extension of the region, as the added thickness of buoyant rock (relative to the mantle) caused the entire area to rise **isostatically**. The Farallon plate was subjected to increasing temperatures as it subducted, causing it to expand. As heat dissipated to the overlying North

Cenozoic

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

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

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



1 Geologic History

Cenozoic

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

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

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

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

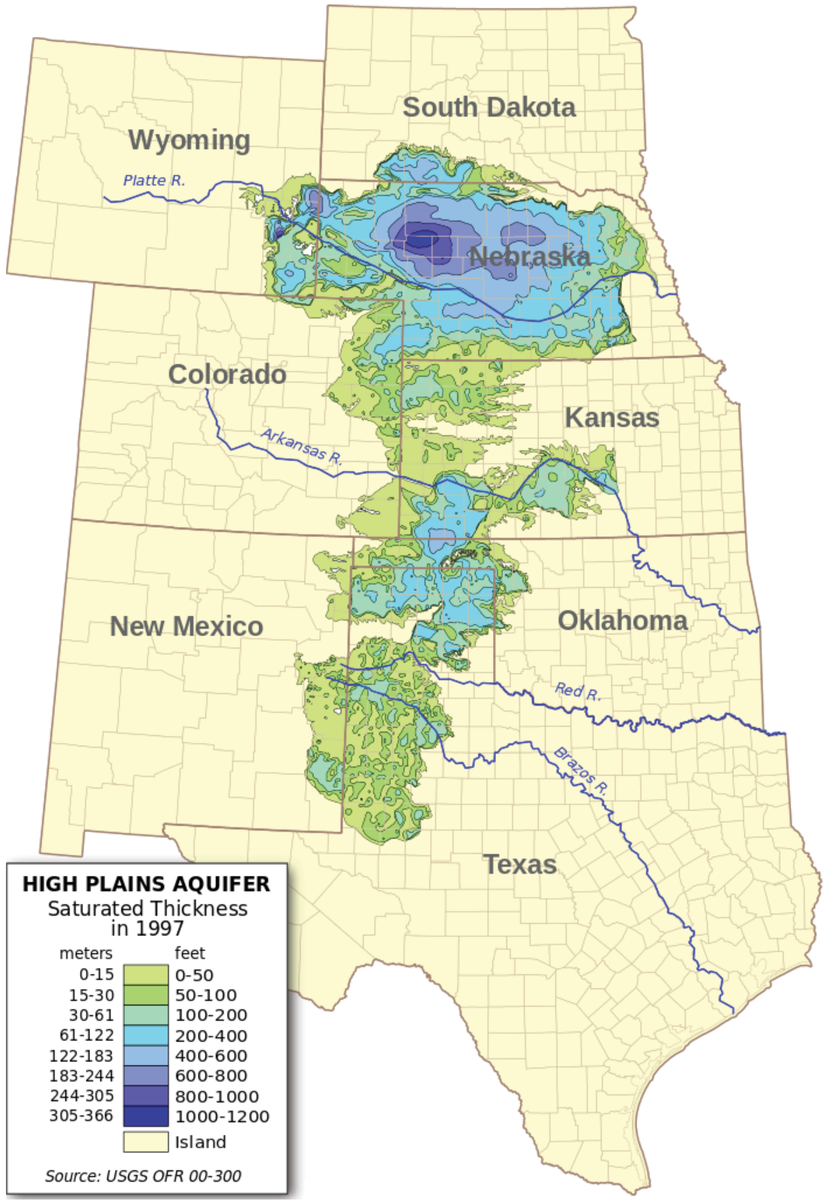
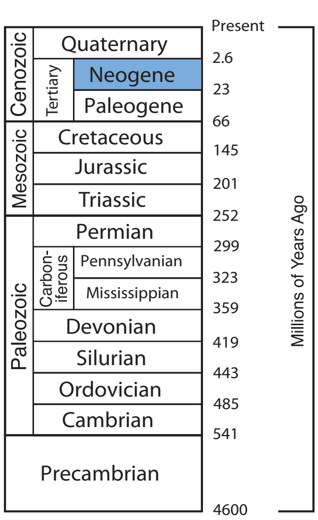


Figure 1.13: Extent and saturated thickness of the Ogalalla Aquifer. (See TFG website for full-color version.)

American plate, that rock expanded as well. Finally, the high temperatures in the upper mantle caused the Farallon plate to melt, and the resulting magma was injected into the North American plate, destabilizing it. These processes caused the surface of the North American plate to pull apart and fault into the mountainous blocks of the huge Basin and Range province that stretches from Idaho, Nevada and Utah into California, Arizona, New Mexico, and Texas.

See Chapter 4: Topography to learn more about the Basin and Range.



At the end of the Neogene, around eight million years ago, epeirogenic uplift (resulting from upwelling mantle heat pushing the crust upwards) began, raising the Rocky Mountains and Colorado Plateau to its current "mile-high" elevation and initiating the downcutting of the Grand Canyon in Arizona. Another example of downcutting is the more recent development, 500,000 years ago, of the Badlands in South Dakota, where Cretaceous and Cenozoic sedimentary rocks are eroded into **badland** topography.

The development of the Yellowstone **hot spot** appears to have begun with the eruption of the voluminous Columbia Plateau flood **basalts** in present-day Washington and Oregon around 14 million years ago. As the North American plate traveled over this mantle plume, the crust melted and produced a trail of volcanic rock that crosses southern Idaho, forming the Snake River Plain and ending at Yellowstone National Park in northwestern Wyoming (*Figure 1.14*). The trail of volcanic eruptions from the hot spot works its way east along this path, with major explosive **caldera** eruptions occurring on a cycle of around 600,000 years. Multiple minor eruptions occur between the larger explosions; for example, Craters of the Moon National Mounment in southern Idaho is a recent (15,000 to 2000 years old) volcanic flow associated with rift zones formed by the Yellowstone hot spot. The latest caldera at Yellowstone National Park is 630,000 years old, and contains many younger minor volcanic flows and domes. The recent geological history of volcanism at Yellowstone has led the area to be classified as a **supervolcano**. While there is concern that the hot spot could generate another violent eruption, researchers using **seismic tomography** have not observed large volumes of melt below the area that could result in a large eruption. The hot spot has now reached a boundary of thicker overlying crust, which will significantly affect the amount and timing of the melt it produces, and the odds of an explosive eruption occurring during the next several thousand years are very low.

See Chapter 2: Rocks for more about the products of past and present volcanism at the Yellowstone hot spot.

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

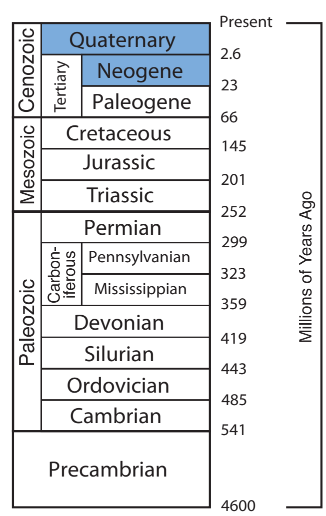
seismic tomography *• a technique for imaging Earth's sub-surface characteristics, in which the velocity of seismic waves is analyzed in an effort to understand deep geologic structure.*

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).*

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

The Quaternary
Mountains of Ice

At the start of the **Quaternary** period, about 2.5 million years ago, continental **ice sheets** began to form in northernmost Canada. Throughout this period, the northern half of North America has been periodically covered by continental glaciers that originated in northern Canada (*Figure 1.15*). The Quaternary period is divided into two epochs: the **Pleistocene** and **Holocene**. During the Pleistocene, ice sheets advanced south and retreated north several dozen times, reaching their maximum extent most recently 25,000–18,000 years ago. The Holocene epoch is the most recent (and current) period of retreat, and is referred to as an **interglacial** interval. The beginning of the Holocene is considered to be 11,700 years ago, or about 9700 BCE.



Quaternary

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.*

Laurentide Ice Sheet *• an ice sheet that covered most of Canada during the last major glaciation.*

Great Lakes *• the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border.*

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

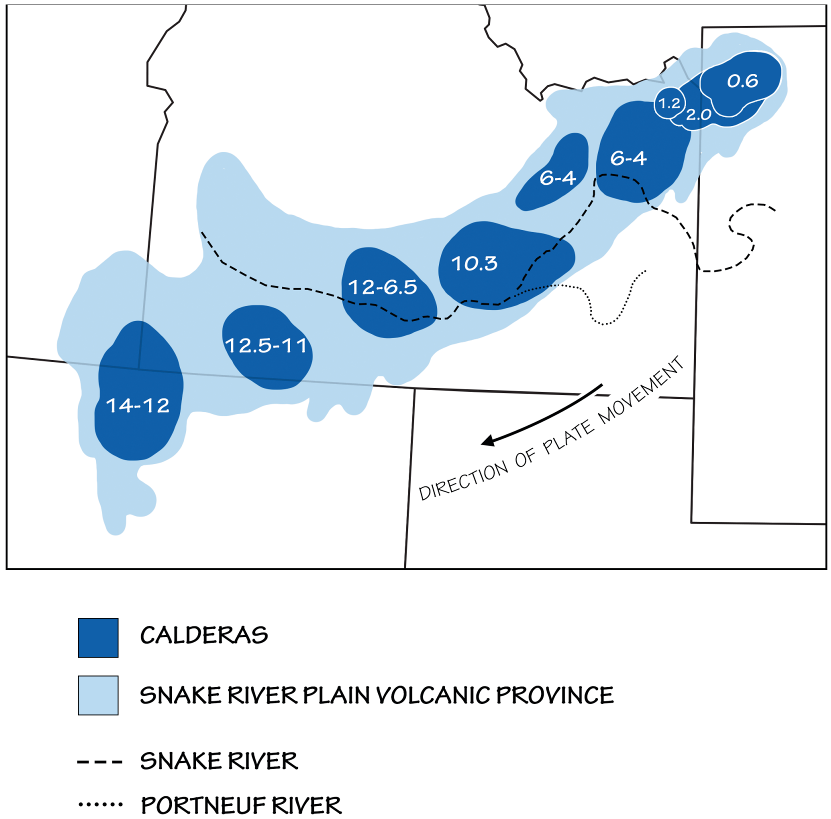
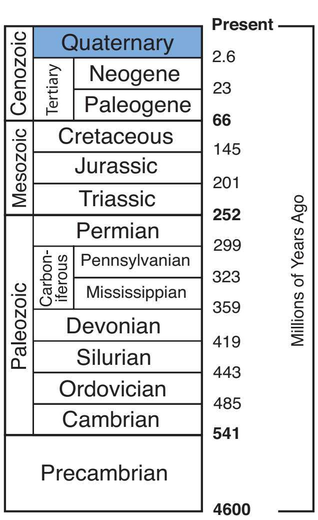


Figure 1.14: The path of the Yellowstone hot spot over the past 16 million years, including the Snake River Plain (part of the Columbia Plateau region) and Yellowstone National Park.

The entire United States was affected by the cooling climate during the most recent **ice age**. A cooling climate contributes to the growth of continental glaciers: as more snow falls in the winter than melts in the summer, the snow packs into dense glacial ice. In this case, as snow and ice continued to accumulate on the glacier, the ice began to move under its own weight and pressure. The older ice on the bottom was pushed out horizontally by the weight of the overlying younger ice and snow. Glacial ice then radiated out from a central point, flowing laterally in every direction away from the origin (*Figure 1.16*). As a result, the continental glacier that originated in Canada migrated southwards toward the United States. During this time, the **Laurentide Ice Sheet** reached into Montana, the Dakotas, Nebraska, Kansas, and east into the **Great Lakes**. The **Cordilleran Ice Sheet** reached into Washington, Idaho, and western Montana. Alpine glaciers covered the mountain heights in Idaho, Montana, Wyoming, Utah, Colorado, and New Mexico, as well as the Cascades and Sierra Nevada in the western states.

Glacial lakes formed in low areas between or in front of glaciers, and also during times between glacial advances. These lakes included Lake Missoula in Montana and Lake Agassiz in south-central Canada, Minnesota, and North Dakota. The catastrophic release of an ice dam on Lake Missoula carved the Channeled Scablands in northern Idaho and eastern Washington. (*Figure 1.17*)



Quaternary

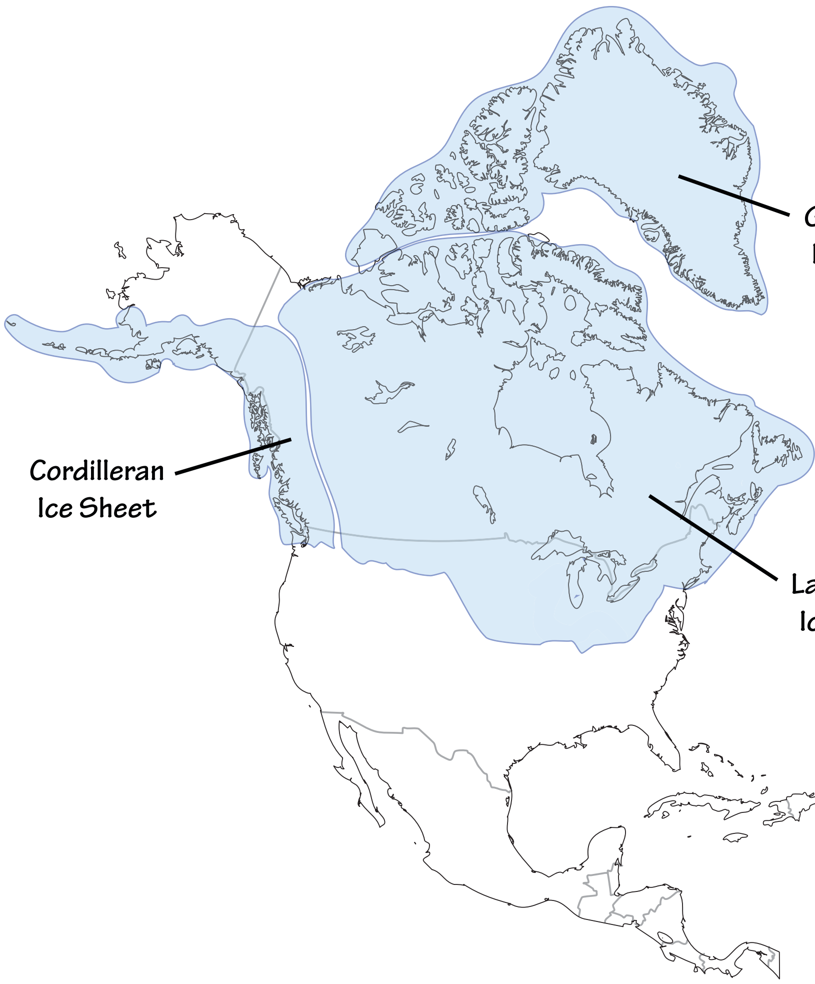


Figure 1.15: Extent of glaciation over North America during the Quaternary.

Figure 1.16: Continental glaciers originating in Canada spread across North America, including the northern portion of the Northwest Central, during the Quaternary period.

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

1 Geologic History

Quaternary

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

till *• unconsolidated sediment that is eroded from the bedrock, then carried and eventually deposited by glaciers as they recede.*

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

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

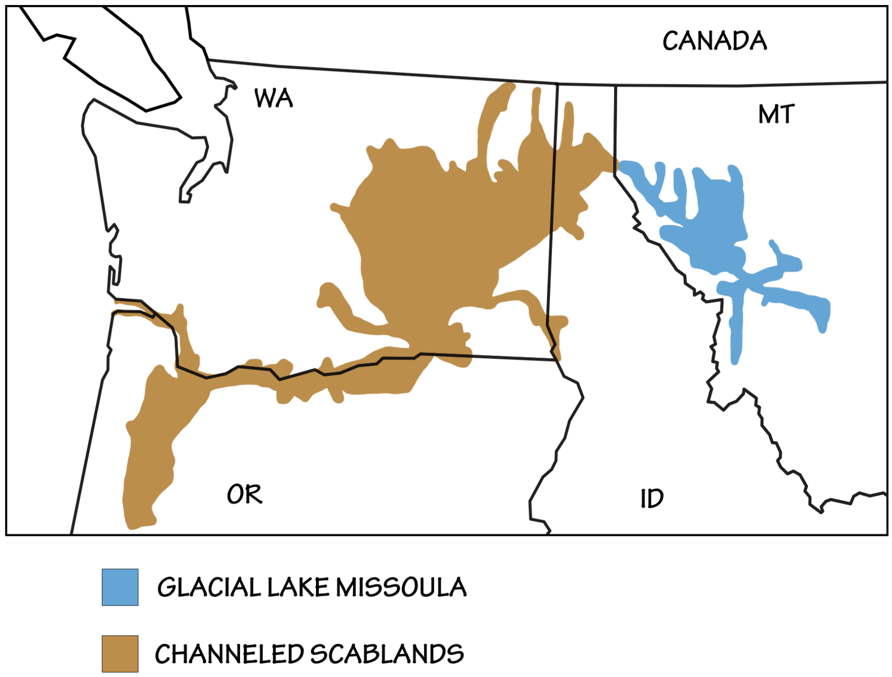


Figure 1.17: The extent of ancient Lake Missoula between 15,000 and 13,000 years ago, and the modern Channeled Scablands, carved by the lake's outburst flood. (See TFG website for full-color version.)

Effects of glaciation on the Northwest Central's landscape include carved glacial **cirques** and valleys, and deposits of glacial **till** in **moraines** and **outwash plains**. Glacier National Park in Montana contains many good examples of these features. Fine **silt** from glacier-ground rock was picked up from the glacial outwash by wind and deposited in thick layers of **loess** across large areas of the midcontinental US. **Sand** dunes, formed where a supply of outwash sand was picked up and blown by the wind, include the Sandhills of Nebraska and Killpecker Sand Dunes in Wyoming.

See Chapter 4: Topography for more on sand dunes in the Northwest Central.

The ice age continues today, but the Earth is in an interglacial stage, since the ice sheets have retreated for now. The current interglacial period has slowed both erosional and depositional processes in the South Central—this and a higher, more stable sea level allowed coastal features such as barrier islands and lagoons to form, resulting in the landscape we know today. The glacial-interglacial cycling of ice ages indicates that the world will return to a glacial stage in the future, that is unless the impacts of human-induced **climate change** radically shift these natural cycles.

See Chapter 9: Climate to learn more about how climate change affects the environment.

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

Geologic History 1

Quaternary

Why was there an ice age?

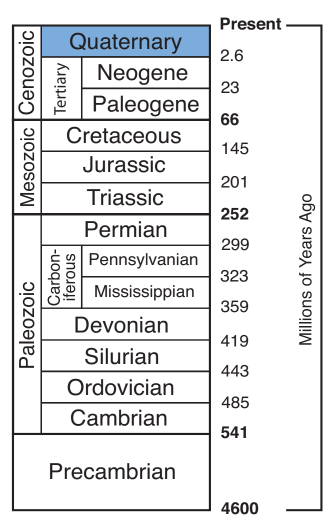
What led to the formation of large continental glaciers in the Northern Hemisphere between 3.5 and 2.5 million years ago? Movement of the Earth's tectonic plates may have been a direct or indirect cause of the glaciation. As plates shifted, continents moved together and apart, changing the size and shape of the ocean basins, and altering ocean currents that transported heat from the equator to the poles. Sufficient precipitation in northern Asia and North America also enabled continental glaciers to grow and flow outward. The rise of the Himalayas exposed new rock that trapped carbon dioxide through chemical weathering; in turn, the decreased levels of carbon dioxide led to a global cooling. Finally, and surprisingly, the formation of the Central American Isthmus, which connects North and South America in what is now Panama, likely had a major effect on climate. Ocean currents than had once flowed east to west through the Central American Seaway were now diverted northward into the Gulf of Mexico and ultimately into the Gulf Stream in the western Atlantic. This strengthened Gulf Stream transported more moisture to high northern latitudes, causing more snow, which eventually formed glaciers.

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

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

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

climate change *• See global warming: the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere.*



Resources

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Powell, J., 2001, *Mysteries of Terra Firma: The Age and Evolution of the Earth*, Free Press, New York, 256 pp.

Winchester, S., and S. Vannithone, 2001, *The Map That Changed the World: William Smith and the Birth of Modern Geology*, HarperCollins, New York, 329 pp.

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Color-coded Continents!, US Geological Survey, http://geomaps.wr.usgs.gov/parks/pltec/ scplseqai.html. (Reconstructions of color-coded continental motions from 620 million years ago through the present; maps from C. Scotese.)

Earth Viewer, by BioInteractive at Howard Hughes Medical Institute, http://www.hhmi.org/ biointeractive/earthviewer. (Free iPad app; an interactive paleo-geographic atlas of the world; state and country overlays allows tracking the development of the Western States.)

Geologic Maps of the 50 United States, by Andrew Alden, http://geology.about.com/od/maps/ig/stategeomaps/.

North America During the Last 150,000 Years, compiled by J. Adams, http://www.esd.ornl.gov/projects/qen/nercNORTHAMERICA.html.

The Paleomap Project, by C. R. Scotese, http://www.scotese.com.

Paleogeography, by R. Blakey, https://www2.nau.edu/rcb7/RCB.html. (The older, but free, version of the site.)

Reconstructing the Ancient Earth, Colorado Plateau Geosystems, http://cpgeosystems.com/index.html. (R. Blakey, updated site.)

Tour of Geologic Time, University of California Museum of Paleontology, http://www.ucmp.berkeley.edu/help/timeform.php. (Online interactive geologic calendar exhibit.)

Geologic History of the Northwest Central

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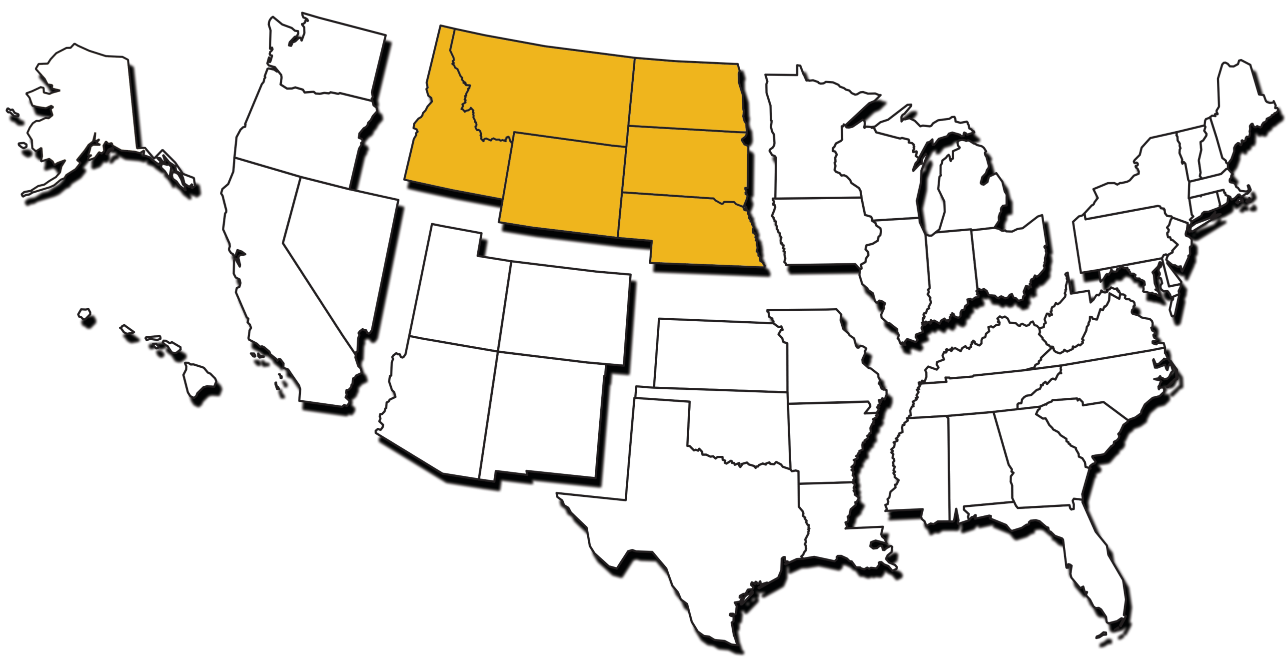
The *Teacher-Friendly* Guide™

to the Earth Science of the Northwest Central US



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