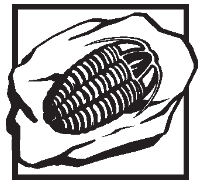


Chapter 3: Fossils of the Western US

Fossils (from the Latin word *fossilis*, meaning "dug up") are the remains or traces of organisms that lived in the geologic past (older than the last 10,000 years), now preserved in the Earth's **crust**. Most organisms never become fossils, but instead decompose after death, and any hard parts are broken into tiny fragments. In order to become fossilized, an organism must be buried quickly before it is destroyed by **erosion** or eaten by other organisms. This is why fossils are found almost exclusively in sediment and **sedimentary rocks**. **Igneous rocks**, which form from cooling **magma** or **lava**, and **metamorphic rocks**, which have been altered by **heat** and pressure, are unlikely to contain fossils (but may, under special circumstances).

Since rapid burial in sediment is important for the formation of fossils, most fossils form in marine environments, where sediments are more likely to accumulate. Fossils come in many types. Those that consist of an actual part of an organism, such as a bone, shell, or leaf, are known as **body fossils**; those that record the actions of organisms, such as footprints and burrows, are called **trace fossils**. Body fossils may be preserved in a number of ways. These include preservation of the original **mineral** skeleton of an organism, mineral **replacement** (chemical replacement of the material making up a shell by a more stable mineral), **recrystallization** (replacement by a different **crystal form** of the same chemical compound), **permineralization** (filling of empty spaces in a bone or shell by minerals), and molds and casts, which show impressions of the exterior or interior of a shell. **Chemical fossils** are chemicals produced by an organism that leave behind an identifiable trace in the geologic record. Chemical fossils provide some of the oldest evidence for life on Earth.

Paleontologists use fossils as a record of the history of life. Fossils are also extremely useful for understanding the ancient environment that existed in an area when they were alive. The study of the relationships of fossil organisms to one another and their environment is called **paleoecology**.

Fossils are also the most important tool for dating the rocks in which they are preserved. Because species only exist for a certain amount

***Index fossils* are used to determine the age of many deposits that cannot be dated radiometrically. An ideal index fossil lived during a short period of time, was geographically and environmentally widespread, and is easy to identify. Some of the most useful index fossils are hard-shelled organisms that were once part of the marine plankton.**

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

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

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

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

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

***crystal form* •** *a physical property of minerals, describing the shape of the mineral's crystal structure.*

CHAPTER AUTHORS

Brendan M. Anderson
Alexandra Moore
Gary Lewis
Warren D. Allmon

3

Fossils

Review

amber • *a yellow or yellowish-brown hard translucent fossil resin that sometimes preserves small soft-bodied organisms inside.*

echinoderm • *a member of the Phylum Echinodermata, which includes starfish, sea urchins, and crinoids.*

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

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

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

Cambrian • *a geologic time period lasting from 541 to 485 million years ago.*

Lagerstätte

The "soft" tissues of an organism, such as skin, muscles, and internal organs, are typically not preserved as fossils. Exceptions to this rule occur when conditions favor rapid burial and mineralization or very slow decay. The absence of oxygen and limited disruption of the sediment by burrowing are both important for limiting decay in those deposits where soft tissues are preserved. Examples of such exceptional preservation, also called *Lagerstätte*, from the West include leaves and insects preserved in *amber*, and bones and insects preserved in asphalt at the La Brea Tar Pits. Another recently discovered example is the Indian Springs Lagerstätte exposed in the northern part of the Montezuma Range, in Esmeralda County, Nevada. This fossil assemblage includes the remains of many animals with hard (mineralized) skeletons, such as *echinoderms* and brachiopods, but many of these fossils also preserve non-mineralized parts, such as tentacles, gut tracts, and soft appendages.

of time before going **extinct**, their fossils only occur in rocks of a certain age. The relative age of such fossils is determined by their order in the stacks of layered rocks that make up the **stratigraphic** record (older rocks are on the bottom and younger rocks on the top—a principle called the **Law of Superposition**). Such fossils are known as **index fossils.** The most useful index fossils are abundant, widely distributed, easy to recognize, and occur only during a narrow time span.

Fossils also have helped geologists piece together the complicated geology of North America's northwest coast. Fossils were one of the most important pieces of evidence that **terranes** had moved to assemble the edge of the continent as we now know it. For example, similar-aged but very different fossils that are now found in close geographic proximity can be explained by their host rocks having moved from their original locations. This is called **paleobiogeography**.

See Chapter 1: Geologic History to learn more about accreted terranes.

Ancient Biodiversity

Since life began on Earth more than 3.7 billion years ago, it has continuously become more abundant and complex. It wasn't until the beginning of the **Cambrian** period, around 543 million years ago, that *complex life*—living things

Discovering Ancient Environments

The kinds of animals and plants living in a particular place depend on the local environment. The fossil record preserves not only fossil organisms, but also evidence of what their environments were like. By studying the geological and biological information recorded in a rock that contains a fossil, scientists can determine some aspects of the paleoenvironment.

***Grain size and composition of the rock* can tell us what type of sediment surface the animal lived on, what the water flow was like, or whether it was transported in a current. Grain size also tells us about the clarity of the water. Fine-grained rocks such as *shales* are made of tiny particles of *silt* or *clay* that easily remain suspended in water. Thus, a fossil found in shale might have lived in muddy or very quiet water. Filter-feeding organisms, such as clams or corals, are not usually found in muddy water because the suspended sediment can clog their filters.**

***Sedimentary structures,* such as asymmetrical ripples and *cross-beds*, can indicate that the organism lived in moving water. Mud cracks or symmetrical ripples are characteristic of shoreline or *intertidal* environments.**

Broken shells or concentrated layers of shells may indicate transportation and accumulation by waves or currents.

***Color of the rock* may indicate the amount of oxygen in the water. If there is not enough oxygen in the water, organic material (carbon) in sediments will not decompose, and the rock formed will be dark gray or black in color.**

with cells that are differentiated for different tasks—became predominant. The diversity of life has, in general, increased through time since then. Measurements of the number of different kinds of organisms—for example, estimating the number of species alive at a given time—attempt to describe Earth's **biodiversity**. With a few significant exceptions, the rate at which new species evolve is significantly greater than the rate of extinction.

Review

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

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

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

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

intertidal • *areas that are above water during low tide and below water during high tide.*

biodiversity • *the number of kinds of organisms at any given time and place.*

3 Fossils

Review

mass extinction • *the extinction of a large percentage of the Earth's species over a relatively short span of geologic time.*

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

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

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.*

sponge • *a marine invertebrate belonging to the Phylum Porifera, and characterized by a soft shape with many pores and channels for water flow.*

Ordovician • *a geologic time period spanning from 485 to 443 million years ago.*

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

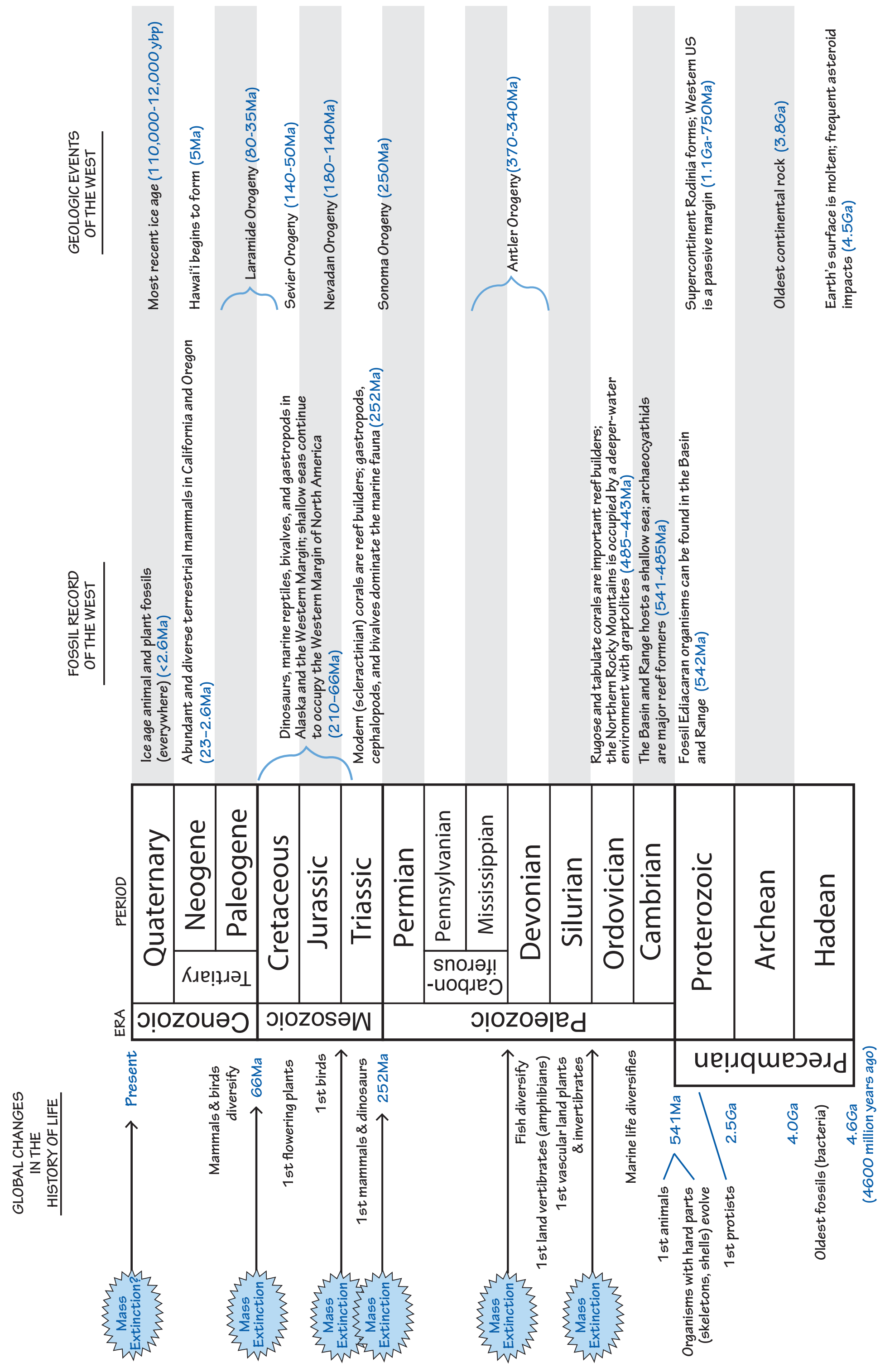


Figure 3.1. The history of life in relation to global and regional geological events and the fossil record of the Western US. (Time scale is not to scale.)

Fossils

3

Most species have a lifespan of several million years; rarely do they exist longer than 10 million years. The extinction of a species is a normal event in the history of life. There are, however, intervals of time during which extinction rates are unusually high, in some cases at a rate of 10 or 100 times the normal rate. These intervals are known as **mass extinctions** (*Figure 3.1*). There were five particularly devastating mass extinctions in geologic history, and these specific mass extinction events have helped to shape life through time. Unfortunately, this is not just a phenomenon of the past—it is estimated that the extinction rate on Earth right now may be as much as 1000 times higher than normal, and that we are currently experiencing a mass extinction event.

Different fossils are found in different regions because of the presence of rocks deposited at different times and in a variety of environments. The availability of fossils from a given time period depends both on the deposition of sedimentary rocks and the preservation of these rocks through time.

Fossils of the Western US

Western rocks preserve an excellent fossil record of the history of life (*Figure 3.1*)—so much so, in fact, that it is impossible to describe all of it here. We will therefore highlight the major types of fossils present in most of the geologic periods represented by rocks in each state. The resources at the end of the chapter should be consulted for details, especially for identifying particular fossils you might find.

Fossils of the Basin and Range

Region 1

During the early **Paleozoic**, the area that is now the Basin and Range was a **passive continental margin** with no tectonic activity, similar to the east coast of the US today. A warm shallow sea flooded what is now Nevada, and **trilobites** were abundant and diverse (*see Figure 3.21,* see box p. 101). During the Cambrian, **reefs** were built by an extinct group of **sponge**-like organisms known as **archaeocyathids** (see box p. 86). During the **Ordovician** and **Silurian**, these were replaced by reefs built by **rugose** and **tabulate corals** (*Figure 3.2,* see box p. 87) along with **brachiopods** (*Figure 3.3,* see box p. 88) and **bryozoans** (colonial **filter-feeding** animals that build **calcium carbonate** skeletons, *Figure 3.4)*. One kind of brachiopod found in **Mississippian** rocks in northern California and Oregon is among the largest brachiopods in the world: *Titanaria* (*Figure 3.5*) reached shell widths (along the hinge line) of more than 35 centimeters (14 inches). In deeper waters, planktonic **graptolites** were common.

The **Triassic** and **Jurassic** rocks of Oregon testify to major global changes in marine life, especially when compared to the Paleozoic. The once-abundant brachiopods on the seafloor are gone, replaced by faunas composed primarily of burrowing **bivalves** and **gastropods**. Tabulate and rugose corals were replaced by **scleractinian** corals, which were building reefs in this region by the mid-Triassic (*see Figure 3.2D*).

Region 1

filter feeder • *an animal that feeds by passing water through a filtering structure that traps food.*

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

Mississippian • *a subperiod of the Carboniferous, spanning from 359 to 323 million years ago.*

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

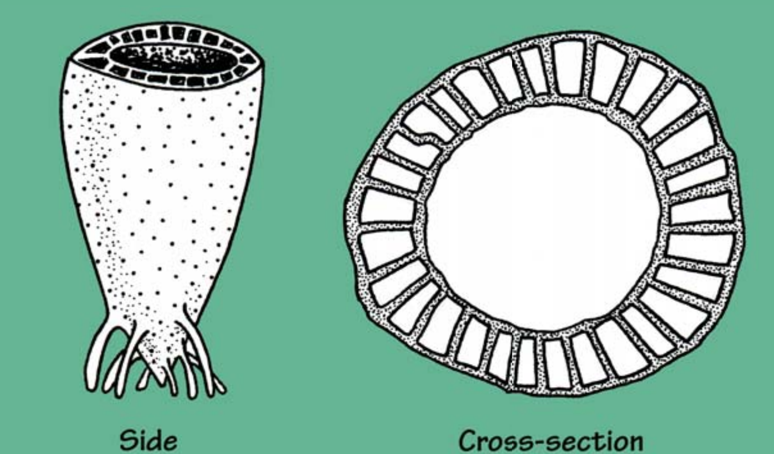
ammonoid • *a member of a group of extinct cephalopods belonging to the Phylum Mollusca, and posessing a spiraling, tightly coiled shell characterized by ridges, or septa.*

cephalopod • *a marine invertebrate animal characterized by a prominent head, arms and tentacles with suckers, and jet propulsion.*

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

Archaeocyathids

Archaeocyathids were the first important animal reef builders, originating in the early Cambrian. These vase-shaped organisms had carbonate skeletons and are generally believed to be sponges. They went extinct in the late Cambrian, but were very diverse. Archeocyathids are often easiest to recognize in limestones by their distinctive cross sections.



Archaeocyathids are found in early Cambrian rocks in northern California and southern Oregon. Their vase-shaped calcite skeletons commonly reached lengths of 5-20 centimeters (2-8 inches).

Ammonoid cephalopods (*Figure 3.6*) also diversified during the Triassic, and their fossils can be found in Oregon, California, and Nevada. Swimming with (and probably feeding on) these ammonoids were marine reptiles called **ichthyosaurs** (*Figure 3.7,* see box p. 92). *Shonisaurus popularis* (*Figure 3.7B*) was an ichthyosaur first discovered in Berlin, Nevada in the mid-1800s. It lived around 217 million years ago, while Nevada was still covered by the ocean. In contrast to Jurassic and **Cretaceous** ichthyosaurs, *Shonisaurus* (along with other early ichthyosaurs) is thought to have lacked dorsal fins. *Shonisaurus* was over 15 meters (50 feet) long and was the largest known ichthyosaur until 2004, when an even larger species was discovered in British Columbia.

Nevada's shallow seas persisted into the Jurassic and part of the Cretaceous, and remained inhabited by ammonoids and bivalve mollusks (*Figures 3.8* and *3.13*). In the northernmost part of the Basin and Range (northern California and southern Oregon), bivalves called **rudists** (*Figure 3.9*) frequently formed

Corals

Corals are sessile relatives of jellyfish and sea anemones. They possess stinging tentacles, which they use to feed on small planktonic prey. Each group of coral possesses distinctly shaped "cups" that hold individual animals, or polyps.

Rugose corals were both colonial and solitary (solitary forms are often called "horn corals"). Tabulate corals were exclusively colonial and produced a variety of shapes, including domed and chainlike forms. These corals receive their name from the table-like horizontal partitions within their chambers. Both rugose and tabulate corals went extinct at the end of the Permian. Modern corals, or scleractinians, appeared in the Triassic, and include both solitary and colonial species. Many modern scleractinian corals have photosynthetic symbiotic algae called zooxanthellae in their tissues. These algae provide nutrition to the coral polyps, helping them to grow more rapidly.

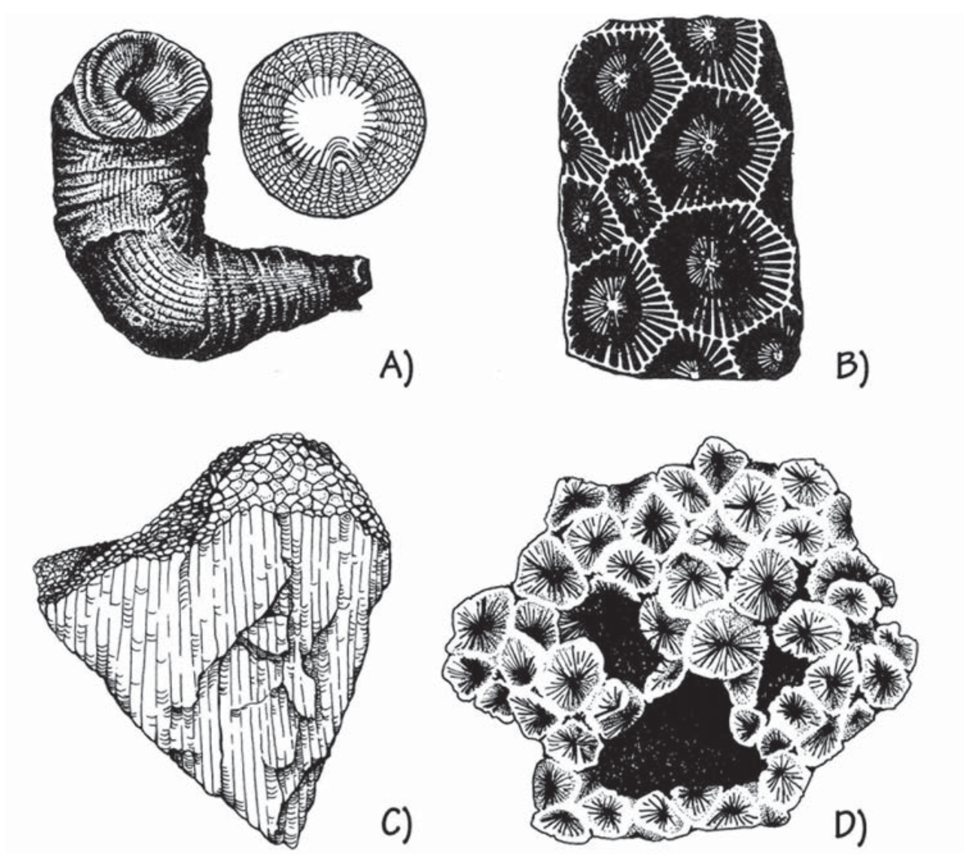


Figure 3.2: Corals. A) Solitary rugose ("horn") coral, Campophyllum, *up to 20 centimeters (8 inches) long, Devonian. B) Colonial rugose coral,* Lithostrotion, *Carboniferous. C) Tabulate coral,* Favosites, *Devonian. D) Colonial scleractinian coral,* Kompsasteria, *Triassic, Alaska.*

3 Fossils

Region 1

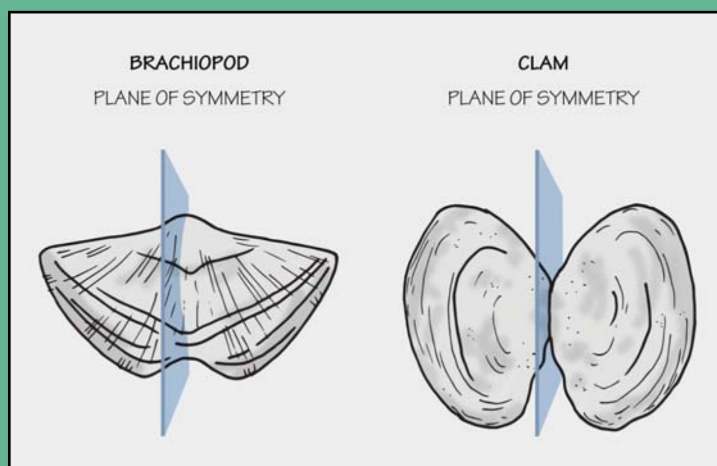
dinosaur *• a member of a group of terrestrial reptiles with a common ancestor and thus certain anatomical similarities, including long ankle bones and erect limbs.*

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

mammoth *• an extinct terrestrial vertebrate animal belonging to the Order Proboscidea, from the same line that gave rise to African and Asian elephants.*

Brachiopods

Brachiopods are filter-feeding animals that have two shells and are superficially similar to bivalves (such as clams). Instead of being mirror images *between* shells (symmetrical like your hands), brachiopod shells are mirror images across each shell (symmetrical like your face). Internally, brachiopods are substantially different from bivalves, with a lophophore (filter-feeding organ made of thousands of tiny tentacles) and a small and simple gut and other organs. Bivalves, in contrast, have a fleshier body and collect their food with large gills.



The difference between the shells of a typical brachiopod (left) and a typical bivalve mollusk (right). Most brachiopods have a plane of symmetry across the valves (shells), while most bivalves have a plane of symmetry between the valves.

reef-like mounds. Rudists became extinct with the **dinosaurs** and many other species at the end of the Cretaceous.

The sea retreated during the late Cretaceous, and the Basin and Range became entirely terrestrial. During the **Cenozoic** era, the region was home to diverse and abundant mammals such as camels, **mammoths**, and rhinoceroses. Freshwater lakes dotted the area and were inhabited by fish such as sticklebacks, Nevada killifish, and topminnows.

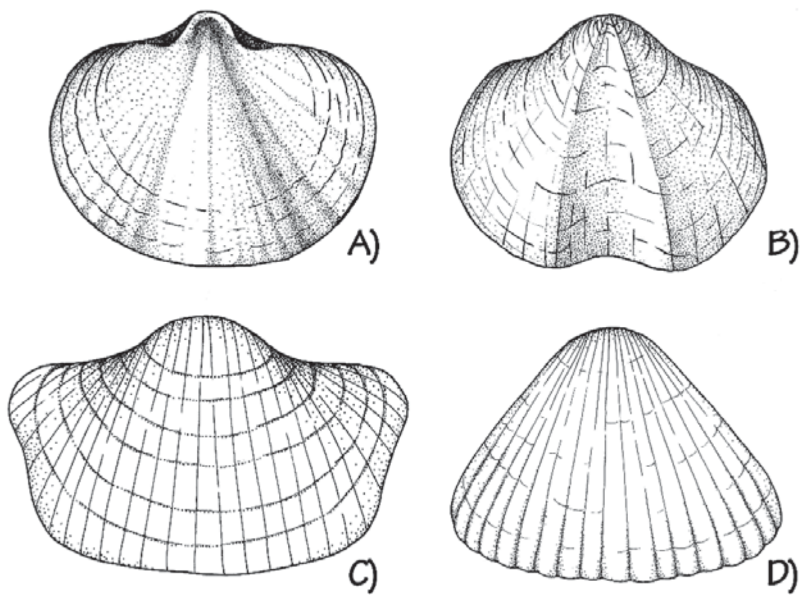


Figure 3.3: Paleozoic brachiopods. A) Strophatrypa*, Silurian of Alaska, about 1 centimeter (inches 0.4 inches). B)* Warrenella*, Devonian of Oregon, about 2 centimeters (1 inch). C)* Retzia compressa*, Carboniferous of California, about 3 centimeters (1.2 inches). D)* Kirkidium alaskense*, Silurian of southeastern Alaska, about 8 centimeters (3 inches).*

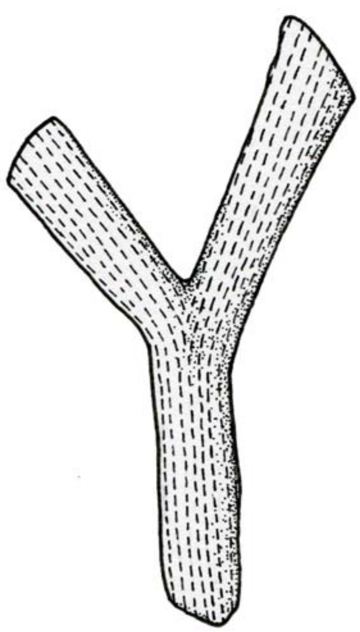


Figure 3.4: A branching bryozoan colony. Some bryozoans had skeletons resembling branching corals, but with smaller cavities for the individual organisms. About 2–5 centimeters (1–2 inches) tall.

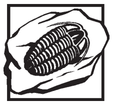
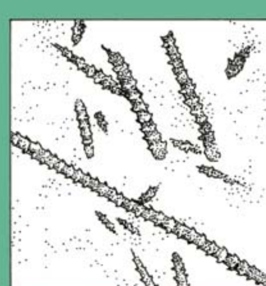


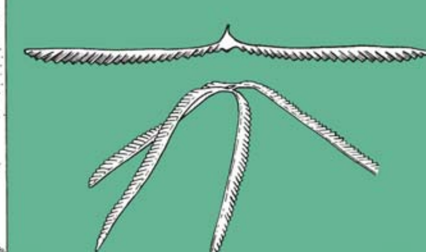
Figure 3.5: Specimen of the giant brachiopod Titanaria*, from the Mississippian of Oregon. The specimen is slightly broken; the dotted line shows its reconstructed size and shape. This specimen, from the collections of the National Museum of Natural History, Smithsonian Institution, in Washington, DC, is one of the largest brachiopod fossils in the world.*

Graptolites

Graptolites (meaning "rock writing") are an extinct group of colonial, free-floating organisms. They lived from the Cambrian to the Carboniferous, and were relatives of modern hemichordates such as acorn worms. Graptolites are frequently preserved as thin black sawblade-like streaks across black shale; tiny cups along these structures held individual animals. Graptolites are often useful as index fossils.



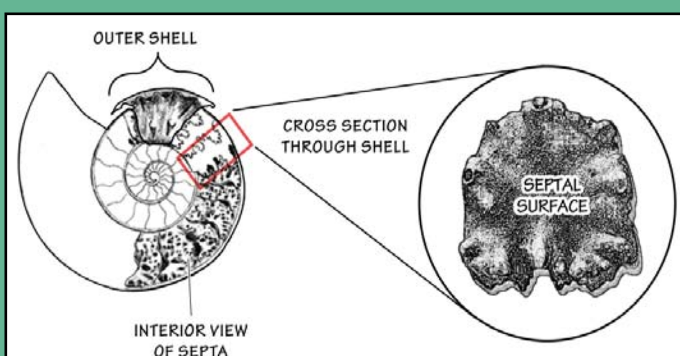
Rock with many fragments of* Climacograptus *colonies.



Restoration of what graptolite colonies may have looked like when they were alive, floating in the water.

Ammonoids

Ammonoids are a major group of cephalopods that lived from the Devonian to the end of the Cretaceous. Both nautiloids (the group that today contains the chambered nautilus) and ammonoids have chambered shells subdivided by walls, or septa (plural of septum). These shells are frequently, but not always, coiled. The term "ammonoid" refers to the larger group of these extinct cephalopods, distinguished by complex folded septa. Within ammonoids, "ammonites" is a smaller sub-group, distinguished by the extremely complex form of their septa. Ammonites were restricted to the Jurassic and Cretaceous periods. The form of the septa in nautiloids and ammonoids is not visible in a complete shell; it is most often seen in the trace of the intersection between the septum and the external shell. This trace is called a suture. Sutures are usually visible in fossils when sediment has filled the chambers of a shell, and the external shell has been broken or eroded away.



Ammonite shell break-away cross section; surface plane of a septum and sediment-filled chamber.

Figure 3.6: Triassic ammonite, Harpoceras, *about 15 centimeters (6 inches) in diameter.*

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

Ichthyosaurs

Ichthyosaurs are an extinct group of Mesozoic marine reptiles that evolved in the Triassic and went extinct in the late Cretaceous. They superficially resembled dolphins with long, toothed snouts, dorsal fins, and vertical tail fins. These animals were descended from land-dwelling reptiles, and evolved dorsal fins and vertical tails independently from other animal groups. These structures were not bony and are only known due to a few exceptionally preserved specimens that show outlines of the entire animal. Ichthyosaurs are known to have given live birth, and some may have been warm-blooded.

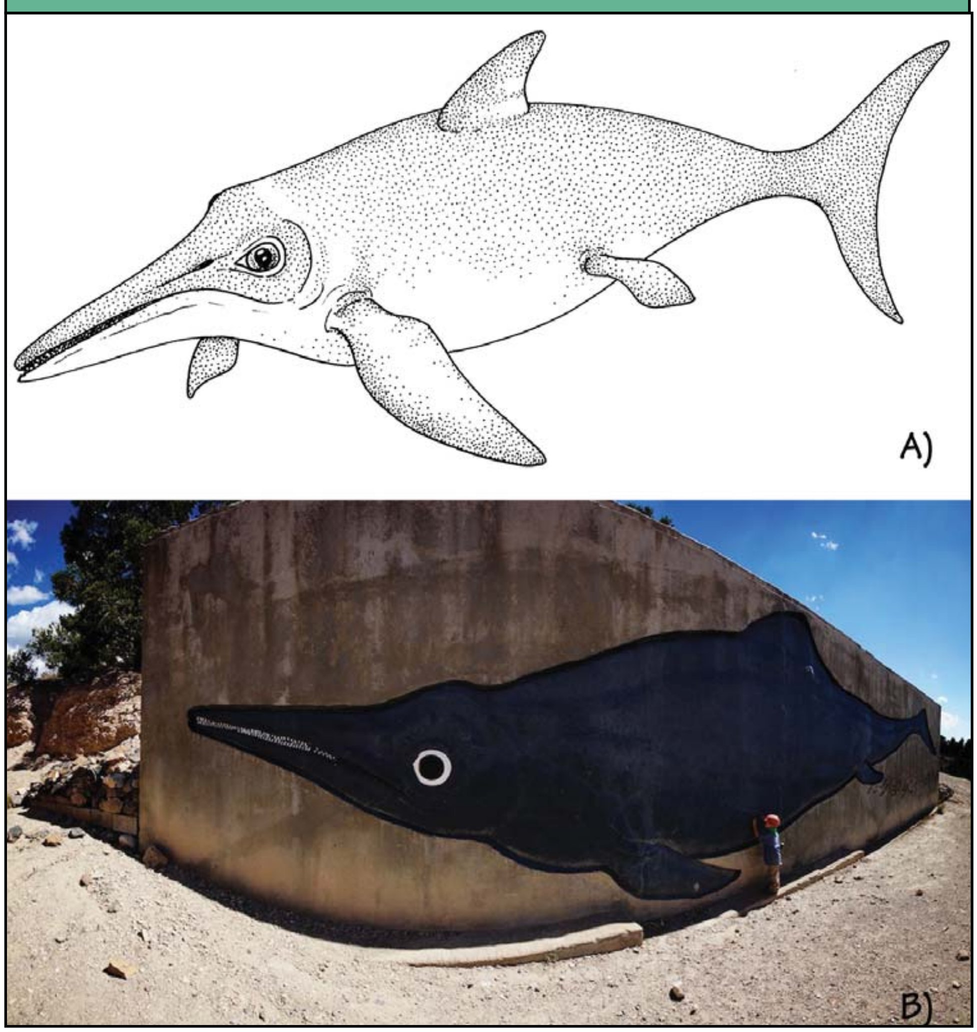


Figure 3.7: Ichthyosaurs. A) A typical ichthyosaur, as it might have looked in life. B) Shonisaurus, *the largest known ichthyosaur, from the Triassic of Nevada. Painting at Ichthyosaur State Park, Nevada.*

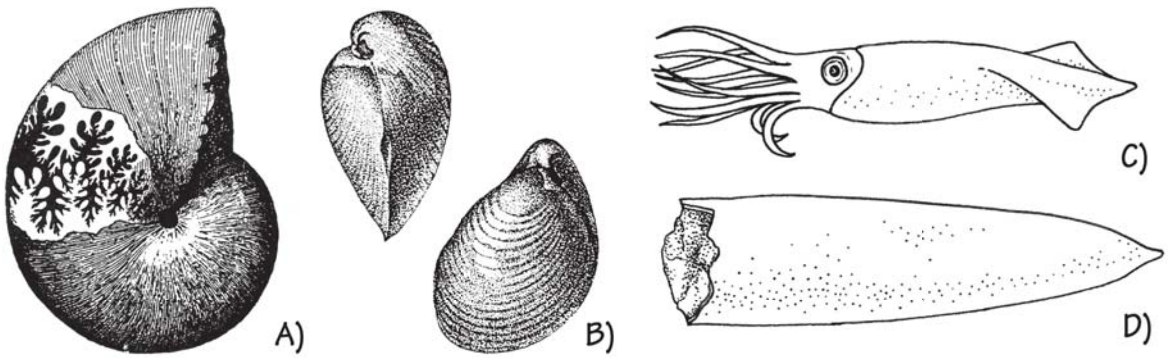


Figure 3.8: Jurassic marine mollusks. A) Ammonite, Phylloceras*, about 15 centimeters (6 inches) in diameter. B) Bivalve,* Buchia piochii*, about 5 centimeters (2 inches) in diameter. C. Reconstruction of a typical belemnite as it appeared alive. D) Belemnite internal shell; most are 5–10 centimeters (2.5–5 inches) long.*

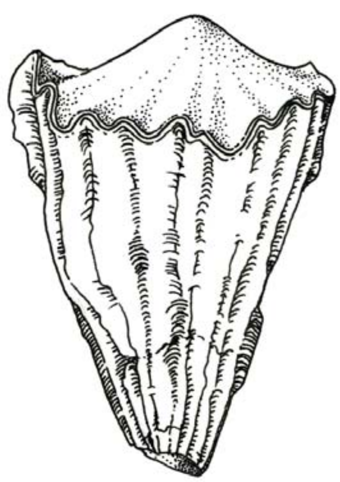


Figure 3.9: Rudists were unusual cone- or cylinder-shaped bivalves that clustered together in reef-like structures and went extinct at the end of the Mesozoic era. They ranged in size from a few centmeters to more than 50 centmeters (1.5 feet) tall.

During the last glacial period (**Pleistocene**), southern Oregon was home to many species of large and now-extinct mammals, including *Arctodus,* the giant short-faced bear, which was 1.8 meters (6 feet) tall at the shoulder with 25-centimeter-long (10-inch-long) paws (*Figure 3.10*). Alongside these massive mammals lived *Teratornis,* a giant vulture with a wingspan of up to 3.8 meters (12.5 feet)—the modern California condor, in comparison, has only a 2.7-meter (9-foot) wingspan (*Figures 3.11* and *3.12*).

Region 1

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

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

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

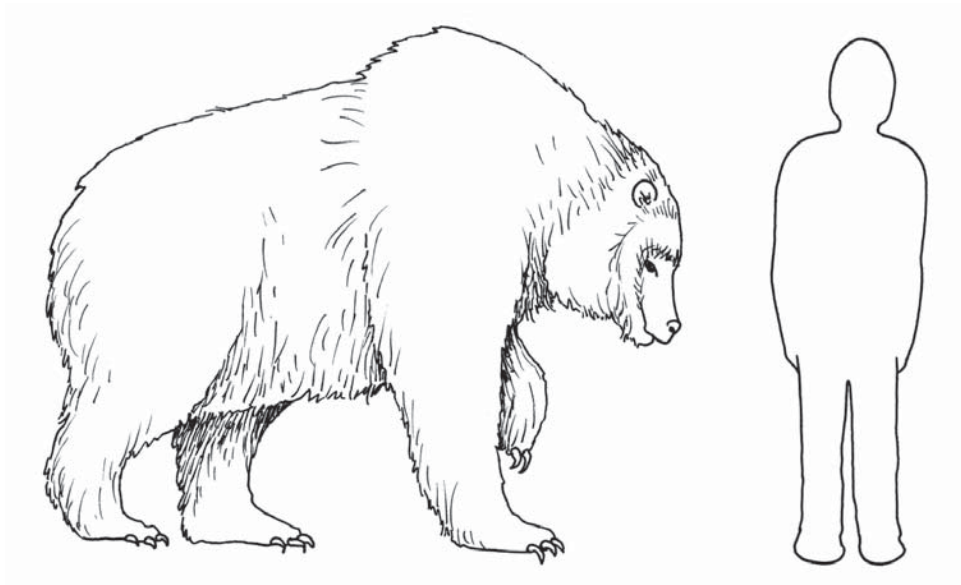


Figure 3.10: Reconstruction of the giant short-faced bear Arctodus, *compared to a six-foot human.*

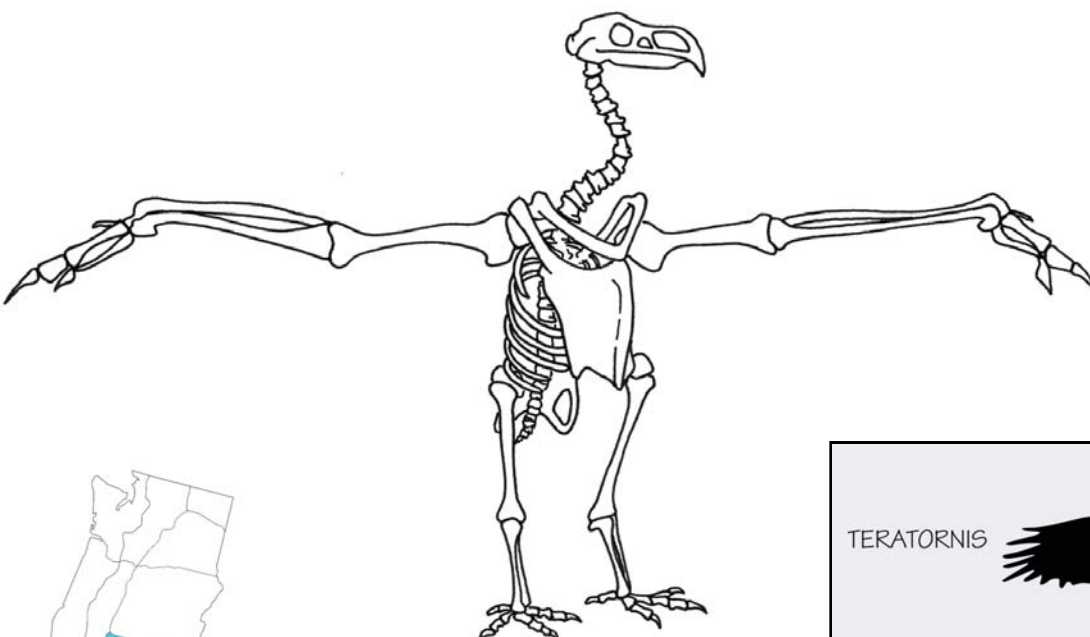


Figure 3.11: Skeleton of Teratornis, *a giant predatory/scavenging bird similar to a modern condor.*

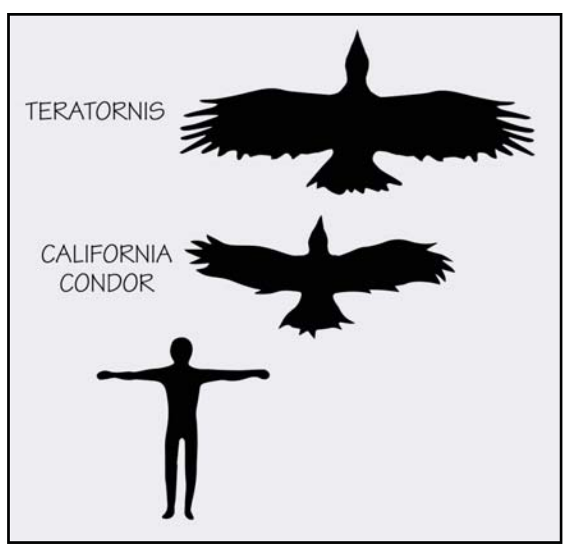


Figure 3.12: Teratornis *size comparisons.*

Fossils of the Columbia Plateau

Region 2

During the Jurassic and part of the Cretaceous, ammonoid cephalopods and bivalves were abundant and diverse in the shallow sea that covered this region (*Figure 3.13*).

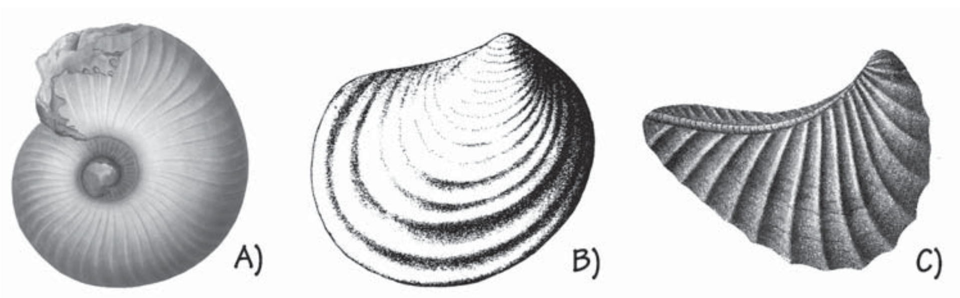


Figure 3.13: Cretaceous marine mollusks. A) Ammonite, Canadoceras newberryanum*, Cretaceous of California, about 15 centimeters (6 inches) in diameter. B) Inoceramid bivalve, Cretaceous of Oregon, about 12 centimeters (5 inches). C. Bivalve,* Trigonia*, Cretaceous of California, about 6 centimeters (2 inches).*

Several sites in Oregon and Washington preserve abundant Cenozoic terrestrial fossils, especially plants and mammals, as a result of widespread **volcanic** activity in the area. During the **Neogene**, the Columbia Plateau was covered in large volcanic outflows of flood **basalt**. These outflows are associated with the same **hot spot** that now heats Yellowstone National Park. Some of these lava flows overran forests, leaving behind empty molds of **trees**. At some localities (such as Ginkgo Petrified Forest State Park in Washington) petrified (permineralized) wood has been preserved either by burial within lake sediments or in volcanic mudflows (*Figure 3.14*). Tree species thus preserved include swamp cypresses, hemlock, spruce, oak, and **ginkgo**.

See Chapter 2: Rocks to learn more about the Columbia flood basalts.

A *tree* is any woody perennial plant with a central trunk. Not all trees are closely related; different kinds of plants have evolved the tree form through geological time. For example, the trees of the Paleozoic were more closely related to club mosses or ferns than they are to today's trees.

The **Eocene** Clarno Formation, exposed at several sites in central Oregon, consists of a series of **volcanic ash** deposits, which quickly buried plants and animals and protected them from decomposition. The resulting spectacular fossils include hundreds of kinds

Region 2

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

***ginkgo** • a terrestrial tree belonging to the plant division Ginkgophyta, and characterized by broad fan-shaped leaves, large seeds without protective coatings, and no flowers.*

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

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

Region 2

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).*

Figure 3.14: A petrified log at the Ginkgo Petrified Forest State Park, central Washington. About 0.6 meters (2 feet) in diameter.

of leaves and seeds, as well as insects, mammals, and other animals. The famous Clarno "nut beds" exposed in Wheeler County in north-central Oregon have yielded more than 170 species of fossil seeds (*Figure 3.15*). Clarno fossil leaves include palms, bananas, and many other flowering tree species (*Figure 3.16*). These fossils indicate that between 50 and 44 million years ago, the **climate** of what is now the Pacific Northwest was warm and humid.

Figure 3.15: Fossil seeds from the Clarno "nut beds": A) Walnut (Juglans), *about 2 centimeters (0.8 inches). B) Oak acorn* (Quercus), *about 2.5 centimeters (1 inch).*

The Oligocene John Day Formation is another series of volcanic ash layers rich in fossil plants and animals, which formed between 35 and 25 million years ago. The climate was cooler, but species diversity is still high. Fossils found in the John Day include more than 60 species of plants—including the "dawn

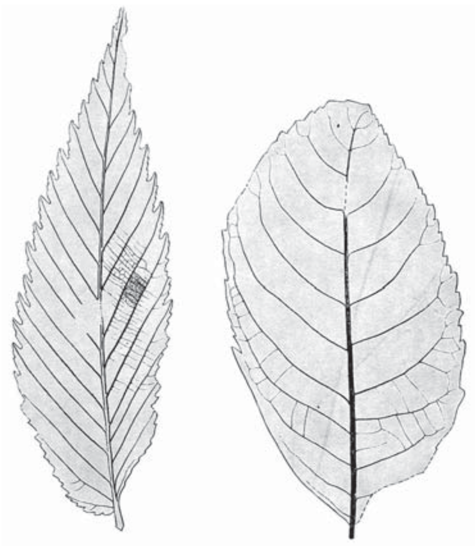


Figure 3.16: Fossil leaves of broadleaf (flowering) trees, from the Clarno Formation. Leaves are about 5 centimeters (2 inches) long.

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

***oreodont** • an extinct ungulate (hoofed animal) related to modern camels.*

redwood" *Metasequoia* (*Figure 3.17*), a relative of sequoias that was believed to have gone extinct in the **Miocene**, until living specimens were discovered in China. *Metasequoia* differs from *Sequoia* (the giant redwood) in that it is deciduous. Living *Metasequoia* leaves are identical to late Cretaceous fossils, indicating that this species has retained much the same form for over 65 million years. The John Day Formation also contains more than 100 species of mammals, including **oreodonts**, saber-toothed cats, horses, camels, and rodents (*Figure 3.18*).

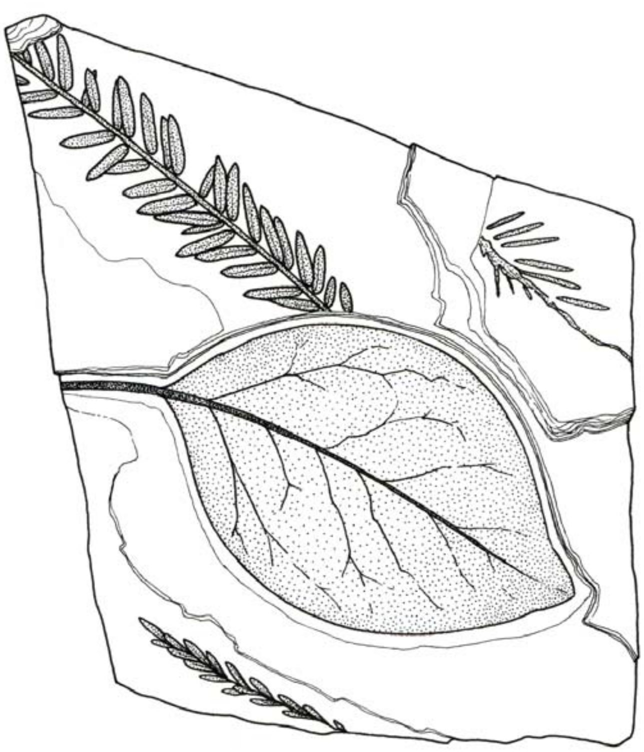


Figure 3.17: The "dawn redwood," Metasequoia *(top) with an unidentified broadleaf angiosperm. Slab is about 5 centimeters (2 inches) wide.*

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

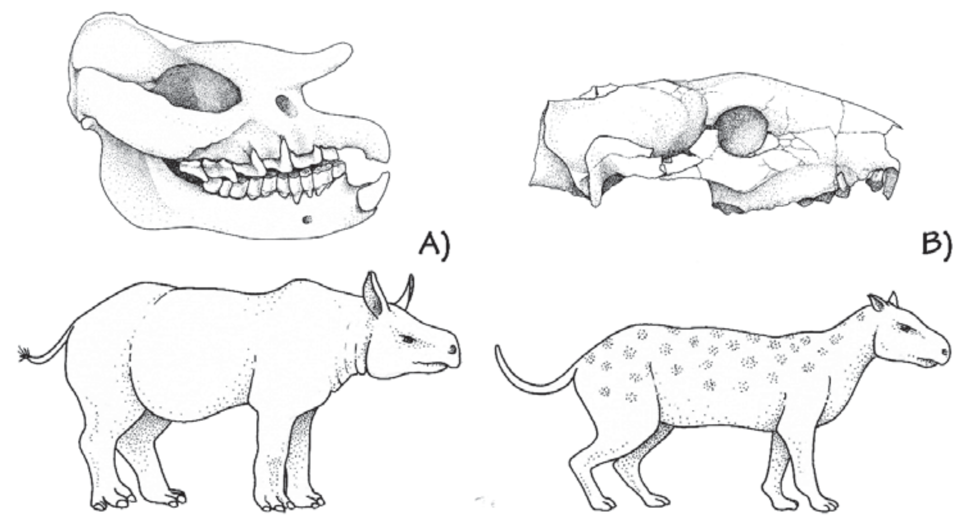


Figure 3.18: Mammal fossils from the John Day beds of Oregon. A) A hornless rhinoceros, Teletoceras*; skull is roughly 20 centimeters (10 inches) long. B) A small sheep-like herbivorous mammal called an oreodont,* Eporedon*; skull is about 12 centimeters (5 inches) long.*

Following the eruption of the Columbia River Basalt flows, between 17 and 12 million years ago, further ashfalls from eruptions in the Cascades formed the Mascall Formation, which includes another diverse assemblage of mammals (including horses, camels, rhinoceroses, bears, pronghorn, deer, weasels, raccoons, and cats). The Mascall's plant fossils, including oak, sycamore, maple, ginkgo, and elms, reflect the region's cooling climate during this time period.

The flood basalts also contain one of the world's most unusual fossils—the "Blue Lake Rhino," in Grant County, Washington (*Figure 3.19*). It is an external mold of a rhinoceros, which lived around 14.5 million years ago. It apparently formed when lava flowed into the water, forming pillows. These were still hot enough to be soft but not hot enough to completely burn away the body.

The Clarno, John Day, and Mascall formations are collectively known as the John Day Fossil Beds. They span over 40 million years and can be best seen in and around John Day Fossil Beds National Monument in Wheeler and Grant Counties in north-central Oregon.

Large mammals, including woolly mammoths and camels dating from the **Quaternary**, have been found in a variety of locations representing ancient riverbanks and lakes. The oldest known **mastodon** (another relative of modern elephants) in North America comes from the Ringold Formation at White Bluffs in south-central Washington (*Figure 3.20*).

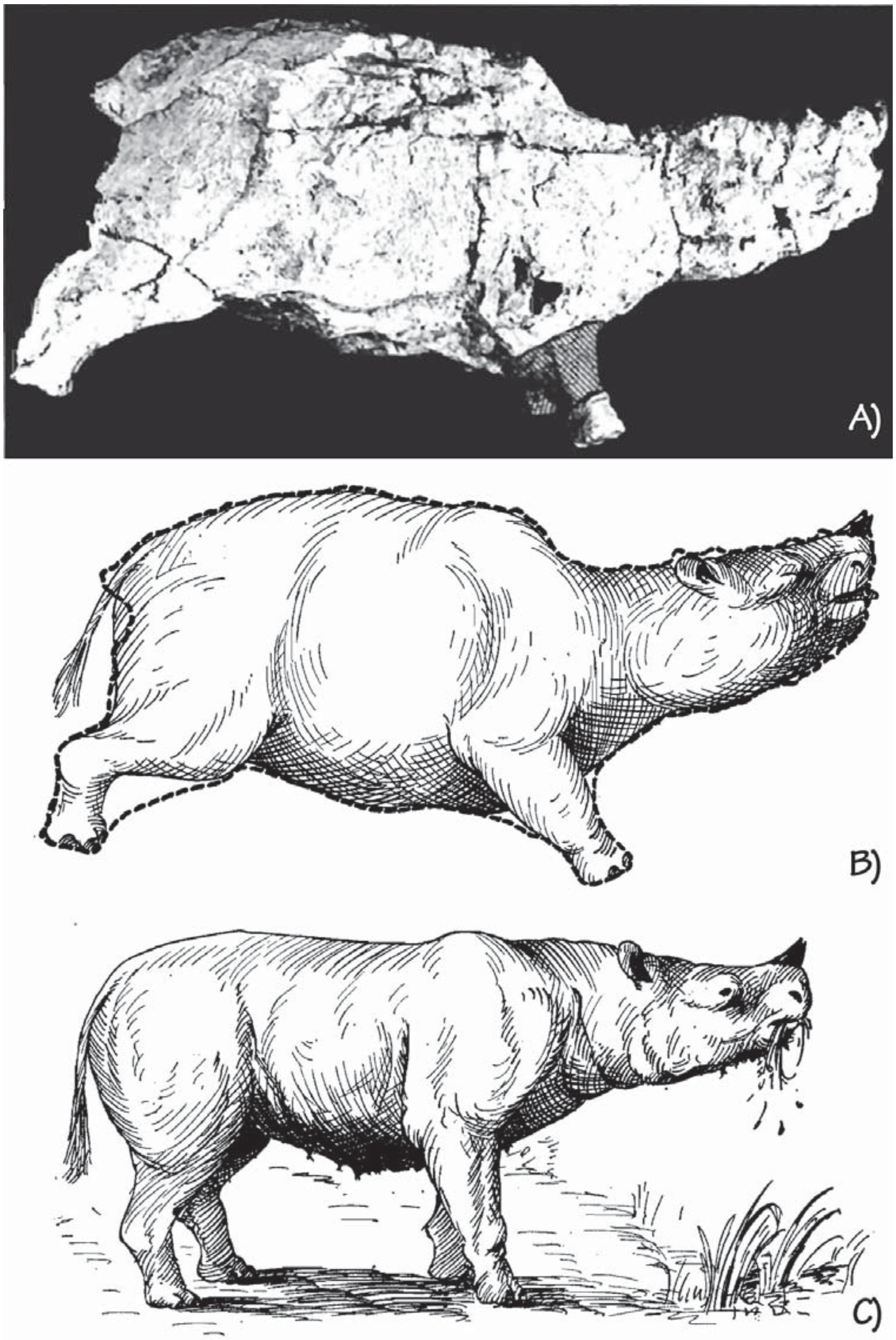
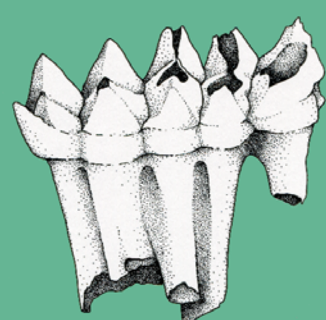


Figure 3.19: The "Blue Lake Rhino," probably Diceratherium. *A) External cast made by applying plaster-soaked burlap to the sides of the hollow natural mold of the body, and then removing it in sections. Total length about 2.4 meters (7 feet). B) What the carcass may have looked like before it was covered with lava. C) Reconstruction of the living animal.*

Mastodons and Mammoths

People frequently confuse these two kinds of ancient elephants (or, more technically, proboscideans). Both were common during the Pleistocene, but they had different ecological niches and are usually found separately. Mammoths are from the same line of proboscideans that gave rise to African and Asian elephants; mastodons are from a separate line of proboscideans that branched off from the modern elephant line in the Miocene. Mastodons have a shorter, stockier build and longer body; mammoths are taller and thinner, with a rather high "domed" skull. In skeletal details, the quickest way to tell the difference is with the teeth: mastodons have teeth with conical ridges, a bit like the bottom of an egg carton; mammoths, in contrast, have teeth with numerous parallel rows of ridges. The teeth are indicative of the two species' ecological differences. Mastodons preferred to bite off soft twigs and leaves, while mammoths preferred tough siliceous grasses. Thus, mastodon teeth are more suitable for cutting, while mammoth teeth are more suitable for grinding.



A mastodon tooth, suitable for chewing twigs and tree leaves. About 20 centimeters (8–9 inches) long.

A mammoth tooth, suitable for grinding grass and softer vegetation. About 25 centimeters (almost 1 foot) long.

Regions 2–3

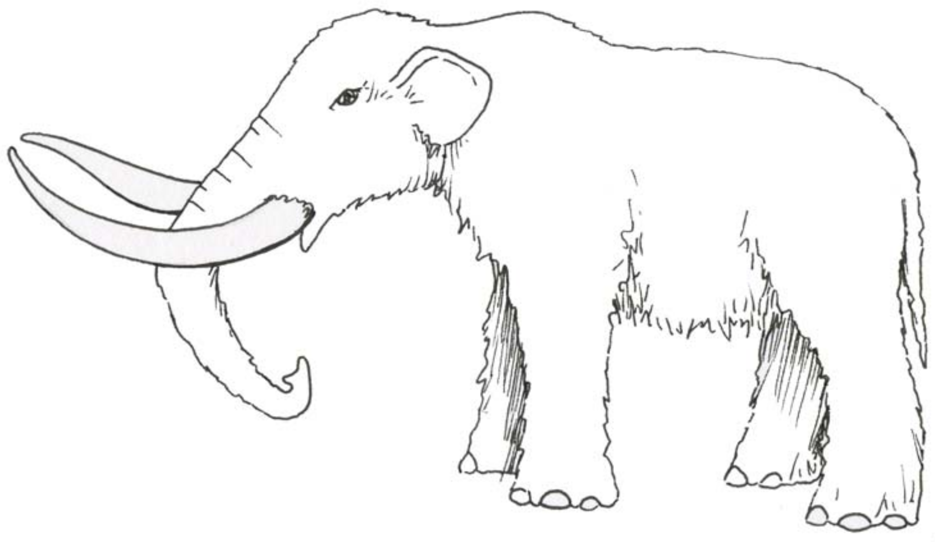


Figure 3.20: A Pleistocene mastodon, Mammut americanum.

Fossils of the Northern Rocky Mountains
Region 3

The region that is now northeastern Washington State has few unmetamorphosed sedimentary deposits. Stevens and Pend Oreille Counties in Washington contain some Cambrian rocks that hold trilobites (*Figure 3.21*) and brachiopods. On rare occasions, these rocks also yield sponges. There are also Ordovician **slates** containing fossil graptolites and **conodonts**, indicating that a deep-water marine community was present during at least part of this time.

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

conodont • *an extinct, eel-shaped animal classified in the class Conodonta and thought to be related to primitive chordates.*

arthropod • *an invertebrate animal, belonging to the Phylum Arthropoda, and posessing an external skeleton (exoskeleton), body segments, and jointed appendages.*

Trilobites

Trilobites are iconic Paleozoic fossils, but were more common in the Cambrian and Ordovician than in later periods. They were *arthropods*, and had well-defined head, tail, and thoracic (leg-bearing) segments. Most had large compound eyes, often with lenses visible to the naked eye. In life, they had antennae like many other arthropods, but since these were not mineralized, they only fossilize under exceptional circumstances. Many could roll up for protection, and several species also had large spines.

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

foraminifera • *a class of aquatic protists that possess a calcareous or siliceous exoskeleton.*

Figure 3.21: Cambrian trilobite Olenellus. *These and similar forms occur in Cambrian rocks in California and Nevada. They are typically 5–10 centimeters (3–6 inches) long.*

Fossils of the Cascade-Sierra Mountains
Region 4

Permian-age rocks in the northern Cascades contain gastropods and corals, along with fusulinid **foraminifera** shells (*Figure 3.22*). Fusulinids are the rice-sized shells of single-celled, amoeba-like organisms that lived in huge numbers on the sea floor during the late Paleozoic.

Late Triassic rocks found in the Cascades and Sierra Nevada contain abundant ammonoids and nautiloids, as well as brachiopods and oysters. Jurassic rocks exposed in Stanislaus and San Joaquin Counties in central California indicate

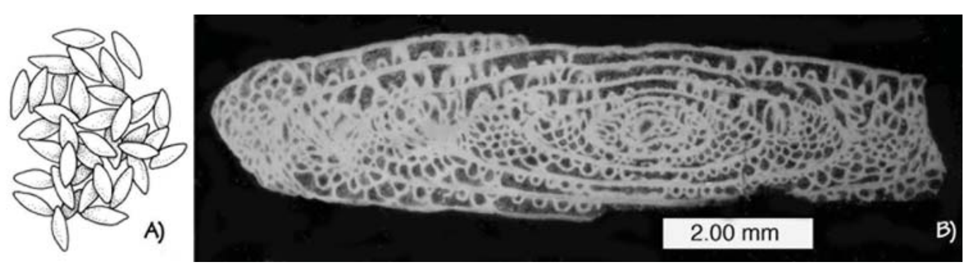


Figure 3.22: One-celled fusulinid shells from the Permian. A) A cluster of shells, the size and shape of large rice grains. B) Photograph of a cross section through a single fusulinid, as seen through a microscope.

a coastal marine environment, with marine fossils including sea urchins, ammonoids, and bivalves. Terrestrial fossils are primarily plants such as **cycads** and ginkgos.

cycad *• a palm-like, terrestrial seed plant (tree) characterized by a woody trunk, a crown of stiff evergreen leaves, seeds without protective coatings, and no flowers.*

Most Neogene fossils from the Cascades represent terrestrial forest and grassland communities. Fossil plants include petrified wood from willow, yew, swamp cypresses (*Figure 3.23*), and *Metasequoia* (*see Figure 3.17*). Fossil vertebrates are less common, but include rabbits, beavers, camels, and the extinct horses *Parahippus, Archaeohippus,* and *Merychippus* (*Figure 3.24*). *Merychippus* was about 90 centimeters (3 feet) tall and had three toes, as opposed to the single toe found in modern horses. It is also the first horse known to have primarily grazed on grasses, rather than to have browsed on shrubs, as earlier horses did.

Figure 3.23: Cross section of the per-mineralized trunk of a species of cypress (Taxodium) *from the Miocene of Washington. About 0.3 meters (1 foot) in diameter.*

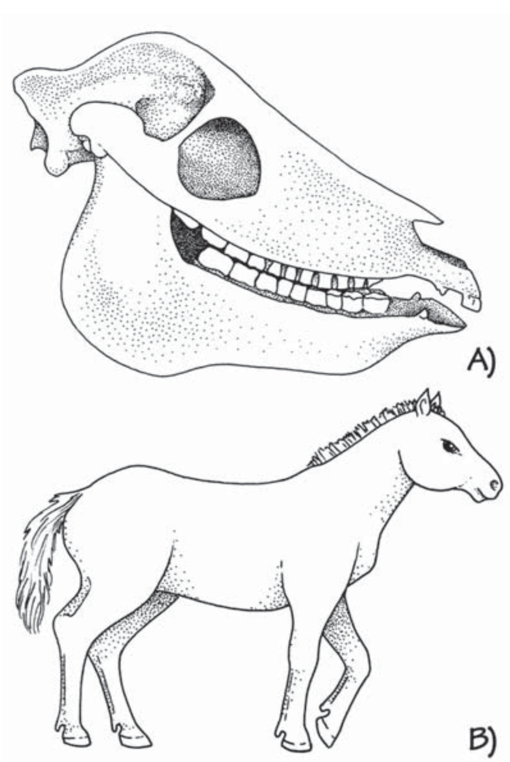


Figure 3.24: A primitive horse, Merychippus*. A) Skull, about 40 centimeters (16 inches) long. B) Reconstruction.*

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.*

plesiosaur • *a member of group of extinct long-necked Mesozoic marine reptiles.*

mosasaur • *an extinct, carnivorous, marine vertebrate reptile characterized by a streamlined body for swimming, a powerful fluked tail, and reduced, paddle-like limbs.*

Fossils of the Pacific Border

Region 5

The Pacific Border includes terranes and former island arcs that **accreted** onto the West Coast, along with sediments deposited after this merger. Nearly every newly-exposed hillside or roadcut in this region exposes fossiliferous sediment, even in developed areas.

Fossil-bearing rocks of both Jurassic and Cretaceous age can be found in this region in northwestern California and southwestern Oregon. Jurassic marine fossils include abundant clams such as *Buchia* (*see Figure 3.8B*) and ammonoids (*see Figure 3.8A*). During the Cretaceous, sea levels were higher, and the Pacific shoreline was much further inland. The shore was lined with palms, and the waters were filled with bivalves such as *Inoceramus* (*see Figure 3.13B*) and *Trigonia* (*see Figure 3.14C*). Recognizable relatives of many extant bivalves, such as oysters, also became common during the Cretaceous. Ammonoid cephalopods, including the straight-shelled *Baculites* (*Figure 3.25*), were extremely diverse and can be found in many Cretaceous rocks. Marine reptiles such as ichthyosaurs, **plesiosaurs**, and **mosasaurs** are also found through much of coastal California.

Although there were presumably many dinosaur species on land, only a few dinosaur fossils have been found in this region. These include the bones of hadrosaurs and the armor-plated ankylosaur *Aletopelta* (*Figure 3.26*). One specimen of *Aletopelta* found in California evidently floated out to sea, where its armor plates and spines were encrusted by bivalves!

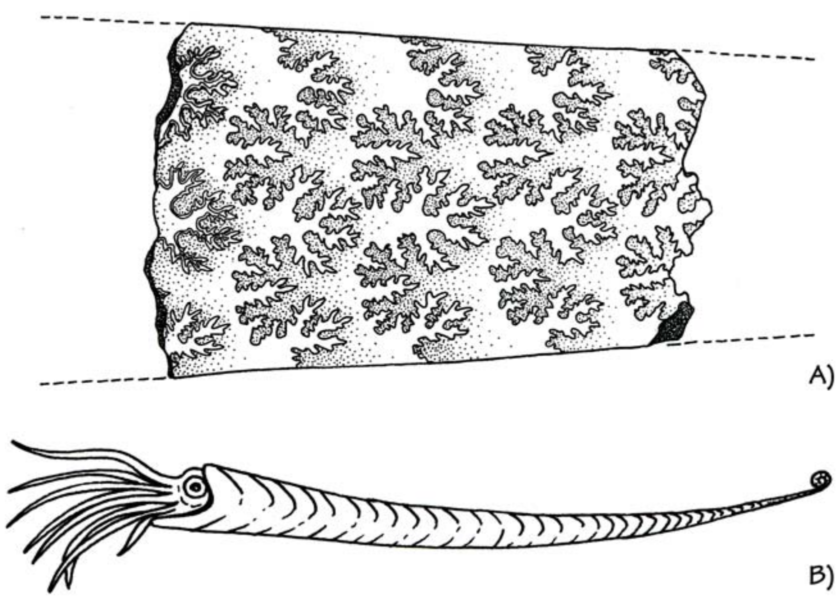


Figure 3.25: A) Broken specimen of Baculites*, a straight-shelled ammonite from the Cretaceous, showing internal suture lines. Usually around 3-4 centimeters (2 inches) in diameter. B) Reconstruction.*

Region 5

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

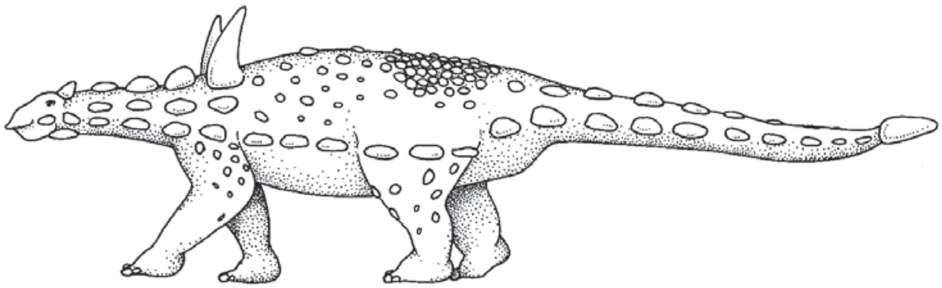


Figure 3.26: Reconstruction of the Cretaceous ankylosaur Aletopelta *from California, about 6 meters (20 feet) long.*

The **Paleogene** marine fossils of the Pacific Border strongly resemble the hard-shelled organisms living in the Pacific today, although some may seem geographically out of place (an important piece of evidence for environmental change through geological time). Gastropods and bivalves are the most

Bivalves

Clams and their relatives, such as mussels, scallops, and oysters, are mollusks possessing a pair of typically symmetrical shells. Most are filter feeders, collecting food with their gills. Paleozoic bivalves typically lived on the surface of the sediment ("epifaunally"), but in the Mesozoic they evolved the ability to burrow more deeply into the sediment and live "infaunally." This innovation led to the rapid evolution of a large number of groups present in the modern oceans.

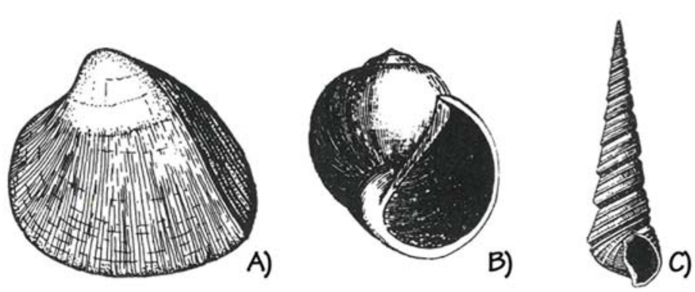


Figure 3.27: Eocene marine mollusks from Washington, Oregon, and California. A) Bivalve, Nemocardium, *about 3 centimeters (1.3 inches). B) Gastropod,* Natica, *about 2 centimeters (1 inch). C) Gastropod,* Turritella, *about 3 centimeters (1.3 inches).*

3 Fossils

Region 5

concretion *• a hard, compact mass, usually of spherical or oval shape, found in sedimentary rock or soil.*

nodule *• a small, irregular or rounded mineral deposit that has a different composition from the sedimentary rock that encloses it.*

Gastropods

Commonly known as snails, gastropods are among the most diverse marine organisms in the ocean today. Modern gastropod mollusks encompass terrestrial, freshwater, and marine species, and include varieties with and without shells (e.g., slugs). Only insects have more named species. The soft parts of gastropods are similar to those of bivalves, but typically have coiled shells. Gastropods are present in Paleozoic and Mesozoic rocks but are more common in Cenozoic rocks.

common marine fossils of the Paleogene and include clams, oysters, whelks (Buccinidae), moon snails (Naticidae), and tower snails (Turritellidae) (*Figure 3.27*). Crabs are sometimes common, although it is rare to find fossils of whole individuals, as these organisms typically break apart after death. However, some locations preserve crabs (and other fossils) within **concretions** (*Figure 3.28*). Concretions are hard, layered **nodules**, often with a different chemical makeup from the surrounding rock. They form when minerals precipitate (crystalize) around a nucleus within the sediment. While concretions are not fossils themselves, they may contain fossils—even trace fossils, as many organisms line their burrows with mucus, and the decay of that mucus may begin the formation of a concretion.

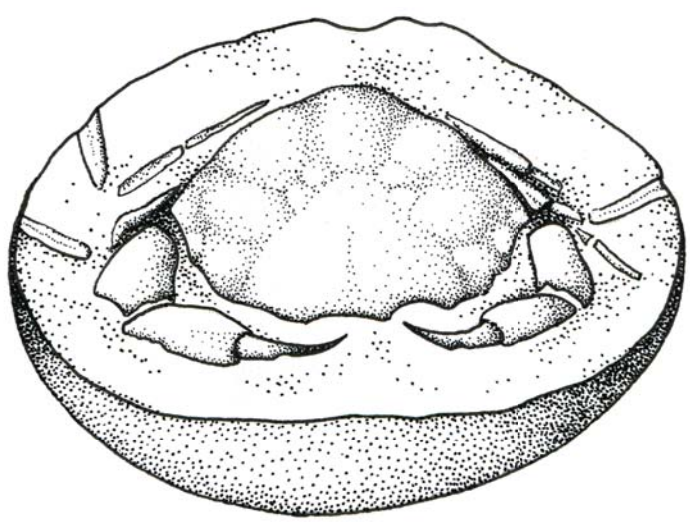


Figure 3.28: The crab Zanthopsis vulgaris*, preserved in a concretion from Oligocene strata in Vernonia, Oregon. Specimen is about 10 centimeters (4 inches) wide.*

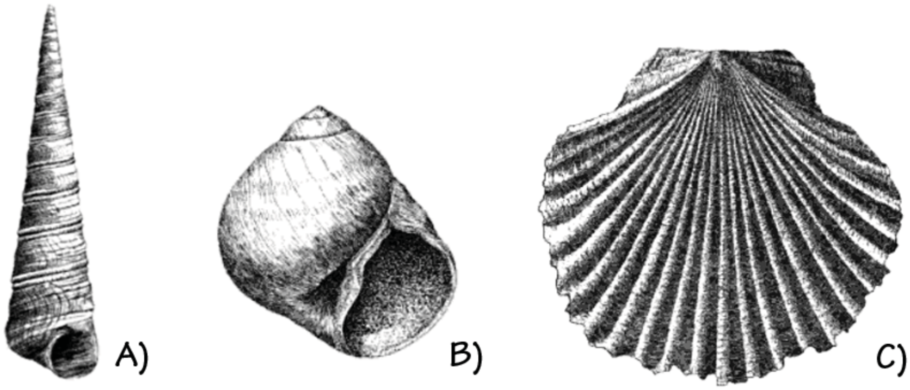


Figure 3.29: Neogene (Miocene–Pliocene) fossil mollusks of the coast of Oregon and California. A) Turritella*, about 3 centimeters (1.3 inches). B)* Polinices*, about 2 centimeters (1 inch). C)* Flabellipecten*, about 4 centimeters (1.5 inches).*

The general character of fossils from the Neogene is similar to that of the Paleogene, with gastropods such as moon snails, whelks, and tower snails remaining important components of the marine fauna (*Figure 3.29*). Mussels, clams, scallops, and oysters are all common, and can often be found in the rocks exposed at beach cliffs along much of the Oregon and California coasts.

Prior to 100,000 years ago, much more of the coast was submerged, and the region was ultimately exposed when the expansion of **glaciers** caused a **regression** in sea level. The coasts of California, Oregon, and Washington and the central valley of California contain numerous Pleistocene-age fossil deposits. Bivalves and gastropods are the most common marine invertebrate fossils from this time, particularly scallops (*Pecten*) and oysters (*Ostrea*), but also clams such as *Saxidomus*, *Mya,* and *Clinocardium* and snails such as *Polinices, Neptunea, Turricula,* and *Cancellaria*.

During the Pleistocene, large terrestrial mammals were common, including mammoths, woolly rhinos, horses, camels, bison, saber-toothed cats, and dire wolves. The famous La Brea Tar Pits in downtown Los Angeles provide a spectacular window into the region's Pleistocene mammal communities. The tar pits formed around 40,000 years ago, when natural **asphalt** deposits began to seep up from cracks in the ground to form pools. As this asphalt seeped from the ground, it became covered with leaves and dust. Animals that wandered in became trapped, as did predators that arrived to eat the mired animals (*Figures 3.30, 3.31*). The oldest remains from La Brea have been dated to 38,000 years old, and the tar pits still continue to trap unsuspecting animals today.

As bones sink into the asphalt, it stains them dark brown or black, leading to the unique appearance of the fossils found here (*Figure 3.32*). Fossils of more than 600 species of animals and plants have been excavated from the asphalt here (*Figure 3.33*)—in addition to large mammals and birds, the tar pits have preserved a remarkable array of microfossils ranging from insects and leaves to pollen grains, seeds, and ancient dust.

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

regression • *a drop in sea level.*

asphalt • *a black, sticky, semi-solid and viscous form of petroleum.*

Figure 3.30: A life-size model of a Columbian mammoth (Mammuthus columbi) *shown stuck in the tar outside the Page Museum at the La Brea Tar Pits in downtown Los Angeles. Columbian mammoths were close relatives of woolly mammoths, and became extinct about 11,000 years ago. They ranged from the southern US to Nicaragua and Honduras, but not as far north as the woolly mammoth.*

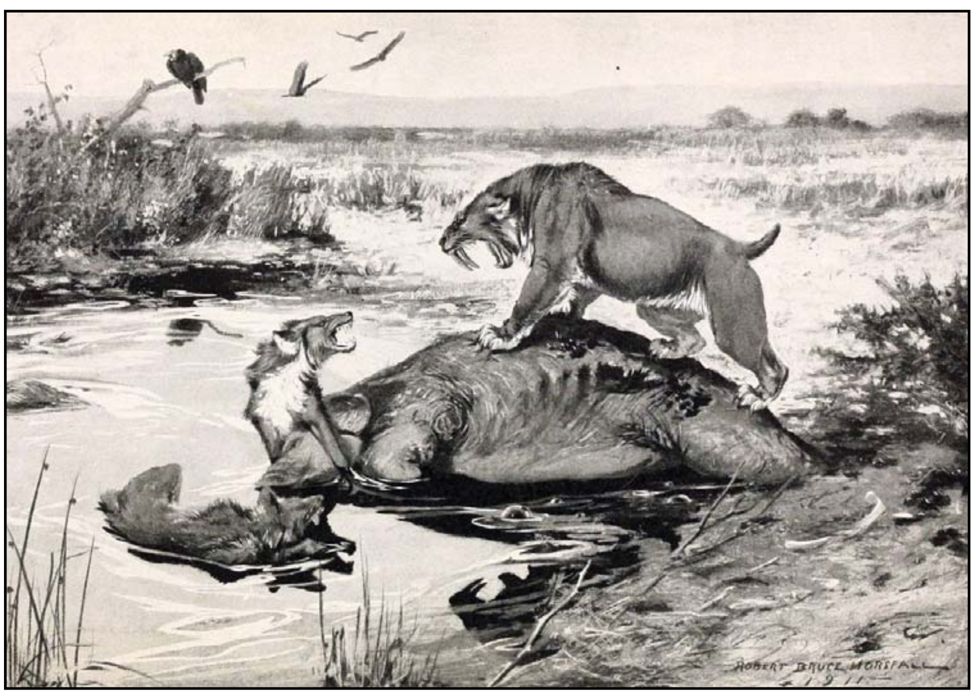


Figure 3.31: A 1911 illustration of several mammal species becoming mired in the tar pit—Smilodon fatalis *and* Canis dirus *fight over a* Mammuthus *corpse.*

Figure 3.32: Skeleton of the most common large mammal at the site, the dire wolf, Canis dirus.

Figure 3.33: Ongoing excavation of the asphalt deposit continues to uncover new fossils.

Smilodon fatalis, the saber-toothed cat, is among the most famous species represented in the La Brea Tar Pits, and is well known for its prominently elongated canine teeth (*Figure 3.34*). While these animals are sometimes referred to as "saber-toothed tigers," they are not actually close relatives of tigers or any other living feline group. Elongated canines actually evolved separately in a number of cat-like lineages, including some groups more closely related to living marsupials than living cats. *Smilodon* belongs to the group known as "dirk-toothed" cats, which possess teeth with fine serrations. The elongated canines of *Smilodon* were also fairly thin and would have broken if they bit into bone, so these teeth would likely have been used to kill prey that was already subdued. The cats' most common prey were likely bison and camels, and dire wolves were probably their direct competitors. *Smilodon* became extinct during the Quaternary extinction around 10,000 years ago, along with many of the large mammals it utilized for food. These extinctions have been related to both **climate change** and hunting by humans, although the relative importance of each of these factors is still debated.

Figure 3.34: The skull of Smilodon fatalis.

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

Mesozoic • *a geologic time period that spans from 252 to 66 million years ago.*

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).*

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

Fossils of Alaska
Region 6

Although most of Alaska had not been assembled before the **Mesozoic**, the state does contain fossil-bearing rocks from the **Precambrian** through the Quaternary. The weakly metamorphosed Precambrian rocks in eastern Alaska contain **stromatolites** (*Figure 3.35*)—layered, mound-shaped fossils built by **cyanobacteria**.

See Chapter 2: Rocks for more information about stromatolites.

Figure 3.35: Stromatolite of the Baicalia *type showing curved laminations, found in late Proterozoic (800–1000-million-year-old) rocks in east-central Alaska. About 15 centimeters (6 inches) long.*

Carboniferous rocks found in parts of northern Alaska, including the Brooks Range, Point Hope, and Gates of the Arctic National Park, contain corals, brachiopods, gastropods, and **crinoids** (*Figure 3.36*).

Jurassic marine rocks in Alaska—found around Iliamna Lake in southern Alaska, and across the Brooks Range on the North Slope—contain abundant ammonites and bivalves (*Figure 3.37*).

Shallow marine rocks from the Cretaceous are well represented on Alaska's Northern Coastal Plain, around Norton Sound, the Kuskokwim Mountains, the Kenai Peninsula, and Kodiak Island. The Brooks Range and other mountains arose during the Cretaceous, which led to extensive erosion and deposition of sediment in shallow marine environments and coastal swamps. Alaska's Cretaceous marine fossils are dominated by modern groups such as bivalves and gastropods; bivalves, such as *Inoceramus* (*see Figure 3.13B*) are well represented in these rocks.

Although Alaska reached its present latitude during the Cretaceous, the world as a whole was much warmer, and fossils of dinosaurs, crocodilians, palms, and other temperate to tropical species are common in Alaskan rocks. Some Cretaceous dinosaurs found near the Colville River on the North Slope are spectacularly well preserved, containing more than half of their original bone material. Alaskan dinosaurs included herbivorous ceratopsians similar to *Triceratops*, such as *Pachyrhinosaurus* (*Figure 3.38*); *Alaskacephale,* a

Region 6

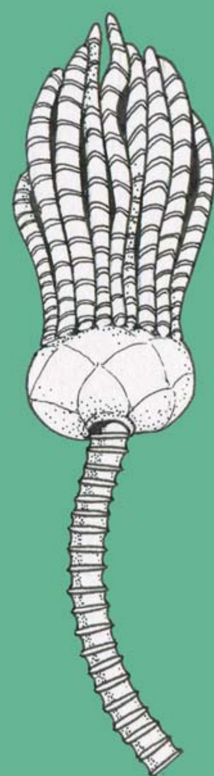
cyanobacteria *• a group of bacteria, also called "blue-green algae," that obtain their energy through photosynthesis.*

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

crinoid *• a marine invertebrate animal characterized by a head (calyx) with a mouth surrounded by feeding arms.*

Crinoids

Crinoids are echinoderms, related to sea urchins and sea stars. These invertebrate animals feed by using their arms to filter food out of the water. Most are attached to the sediment by a stalk that ends in a root-like structure called the holdfast—however, some forms are free-floating. Crinoid fossils are most commonly found as "columnals," pieces of the stalk that hold the head (*calyx*) above the surface. The calyx and the holdfast are only occasionally preserved as fossils.



Crown and stem, about 15 centimeters (6 inches) long.

Stem fragments.

Figure 3.36: Polished slab of limestone made up almost completely of crinoid bits and pieces, seen under a microscope.

pachycephalosaur (dome-headed dinosaurs similar to *Pachycephalosaurus*); and ankylosaurs, such as *Edmontonia*, the first dinosaur discovered in Alaska. Alaska even has its own native tyrannosaur, *Nanuqsaurus* (*Figure 3.39*), which was about half the length of *Tyrannosaurus rex.* Other carnivores included *Albertosaurus* and possibly *Gorgosaurus*. Plant fossils include *Parataxodium*, a relative of the bald cypress, as well as cycads, pines, and palms (*Figure 3.40*).

In Alaska's Neogene rocks, which occur mostly along the southern coast and onto the peninsula, gastropods and bivalves are the most common marine fossils. Land plants preserved in these rocks include *Metasequoia*, willows, poplars, alders, oaks, and elms.

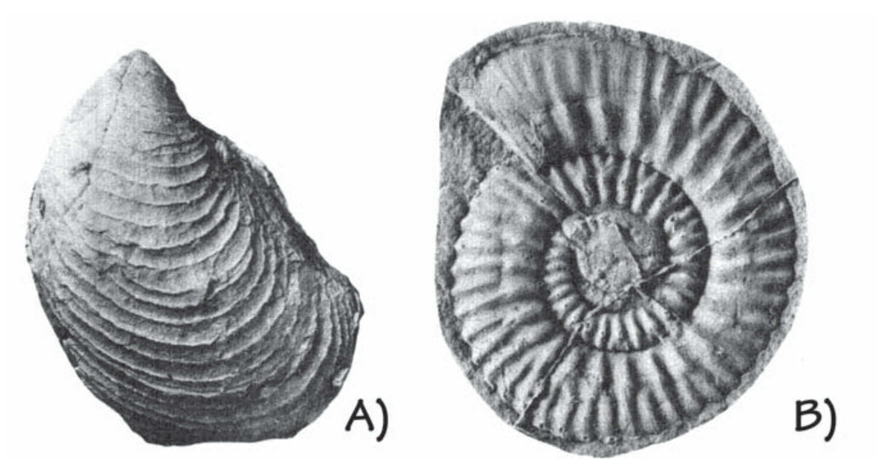


Figure 3.37: Jurassic mollusks from northern Alaska. A) Bivalve, Aucella rugosa*, about 3 centimeters (1 inch). B) Ammonite,* Reineckeia *sp., around 3 centimeters (1 inch).*

Figure 3.38: Pachyrhinosaurus perotorum*; about 8 meters (26 feet) long from head to tail.*

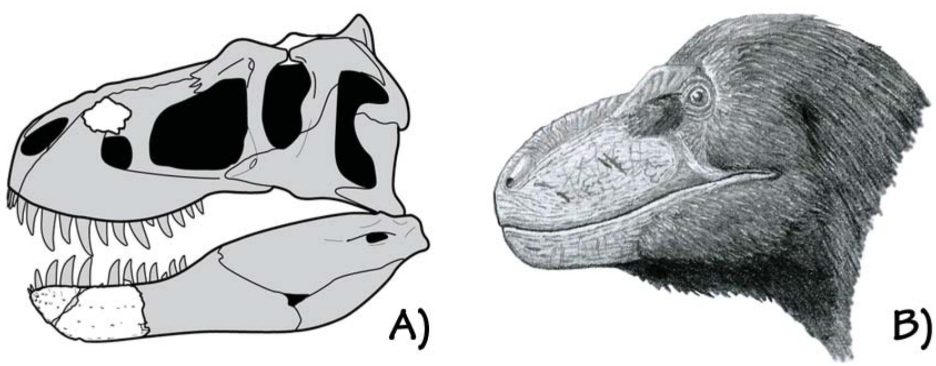


Figure 3.39: Nanuqsaurus *is a small species of Cretaceous carnivorous dinosaur from Alaska, known only from an incomplete skull. A) Drawing of the skull, with white shading showing the known fossils. B) Reconstruction of the head.*

Region 6

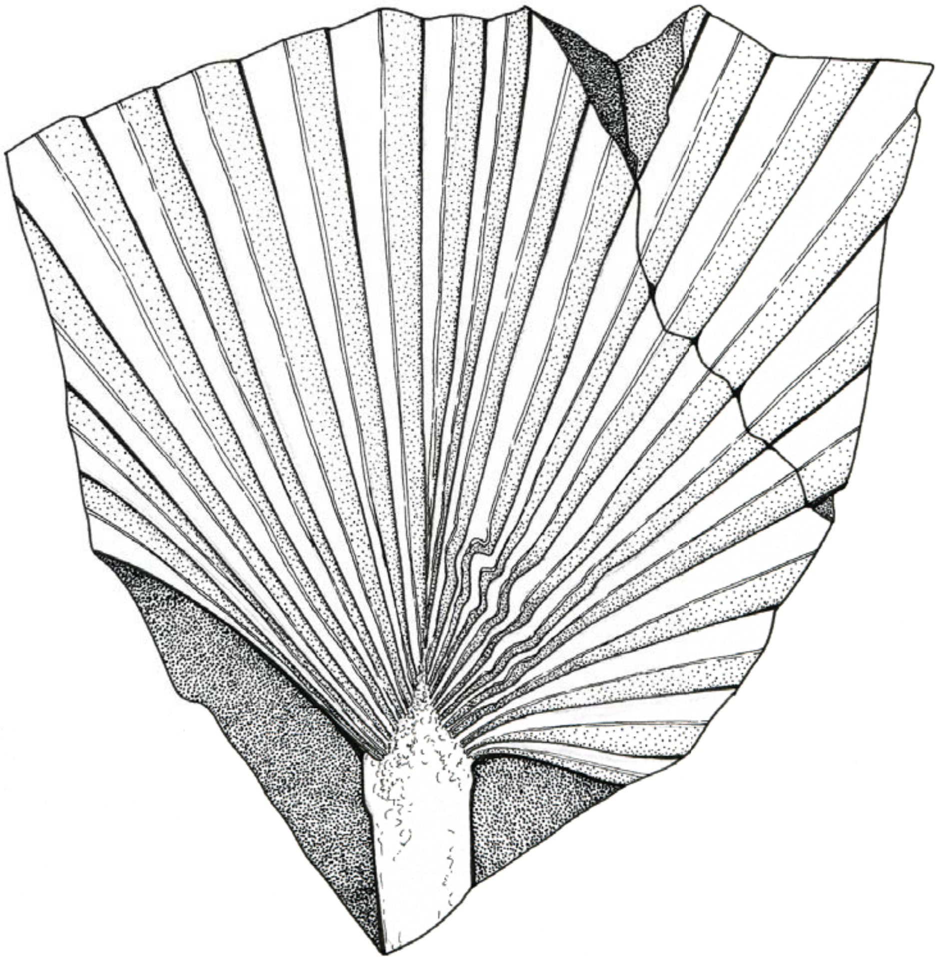


Figure 3.40: A palm fossil, common in the Mesozoic and today known primarily in warm climates. About 0.7 meters (2 feet) wide.

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.*

permafrost • *a layer of soil below the surface that remains frozen all year round. Its thickness can range from tens of centimeters to a few meters.*

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

Much of Alaska was covered in ice during the Pleistocene **ice age**, but some refuges did exist where terrestrial animals were able to persist. Beringia, the land bridge that allowed humans and other animals to pass into North America from Asia, was likely one of these refugia. Numerous mammal fossils can be found throughout the state—the area around Fairbanks has many Quaternary deposits that yield mammoth, mastodon, bison, and elk bones.

Alaska is famously home to a number of Quaternary fossils, such as woolly mammoths, that are preserved in **permafrost**. The woolly mammoth was a Pleistocene and early **Holocene** elephant that coexisted with humans (*Figure 3.41*). Frozen carcasses preserving hair, skin, and even stomach contents have been found in Alaska, as well as in Siberia. The woolly mammoth was similar to extant elephants in size but had a heavy coat of fur, small ears, and a short tail to minimize heat loss. Mammoths primarily ate grasses and sedges and had flat

Regions 6–7

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

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

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

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

teeth similar to those of modern elephants (in contrast to the pointed teeth of mastodons, which browsed trees as well; see box p. 100). Woolly mammoths survived on Wrangel Island (Russia) until 4000 years ago but became extinct in North America, along with many other megafauna, during the Quaternary extinction event as a result of climate change and exploitation by human hunters (the relative contribution of each of these factors is still disputed).

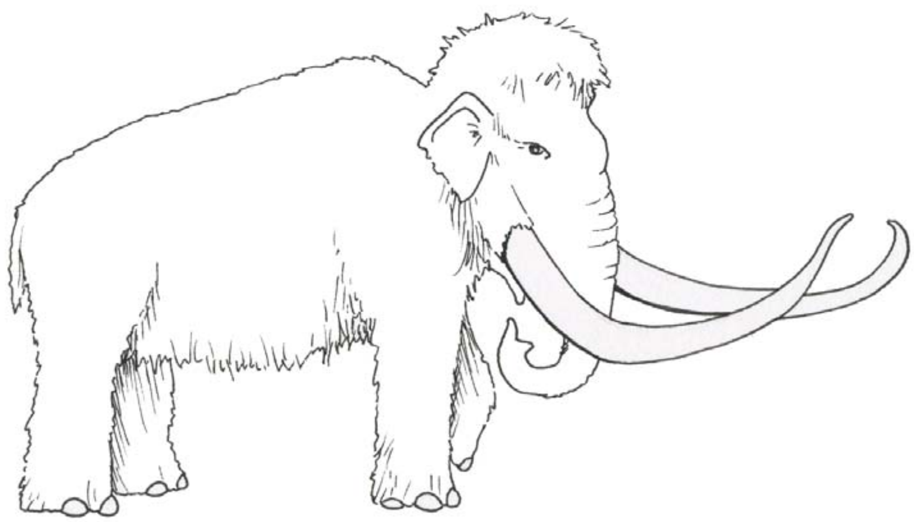


Figure 3.41: The woolly mammoth, Mammuthus primigenius, *was present in North America, Europe, and Asia during the Pleistocene.*

Fossils of Hawai‘i
Region 7

Most fossils occur in sedimentary rocks, but almost all of Hawai‘i consists of igneous rock. Nevertheless, Hawai‘i does have a fossil record, and most of these fossils are found in three unusual geological settings:

- Inside **lava tubes** or caves.
- In **limestones** formed by the coral reefs surrounding the islands, which, when exposed to the air (when sea level falls or the island is **uplifted**) can become **karst.**
- As charcoalized imprints of trees in or between lava flows.

Many of the organic remains described from Hawai‘i can be called “subfossils,” meaning that they are less than 10,000 years old (the standard—though arbitrary—age definition for fossils). In practice, such materials are treated like “true” fossils and provide the same kind of information.

The fossil record of the Hawaiian Islands preserves a 400,000-year history of island biodiversity. Fossils of plants, birds, fish, terrestrial and marine invertebrates, and a lone native terrestrial mammal paint a picture of surprisingly diverse Hawaiian ecosystems prior to the arrival of the first humans. As the most isolated archipelago in the world, the Hawaiian Islands were colonized by a relatively small number of species that could successfully disperse across the ocean by flying, floating, or being blown by **wind**. Most seed arrivals came with migratory birds, either in their stomachs, or stuck to their feathers or skin. A smaller number of organisms drifted on air or on floating plant matter in ocean currents. Those that survived the voyage and were able to reproduce in their new environment were also able to move into new ecological niches because competitors for those resources were few. This gave rise to an **adaptive radiation** of species: the creation of multiple new species from a colonizing ancestor.

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

adaptive radiation • *process in which many new species evolve, adapting to vacant ecological niches in a relatively short interval of geological time.*

The long distance and duration of the trip to Hawai‘i favored certain types of organisms and selected strongly against others. Thus there are no native Hawaiian terrestrial reptiles and amphibians, and only one terrestrial mammal, the Hawaiian hoary bat. In contrast, there are many native species of terrestrial birds, invertebrates, and plants. Even in the marine realm, the abundance

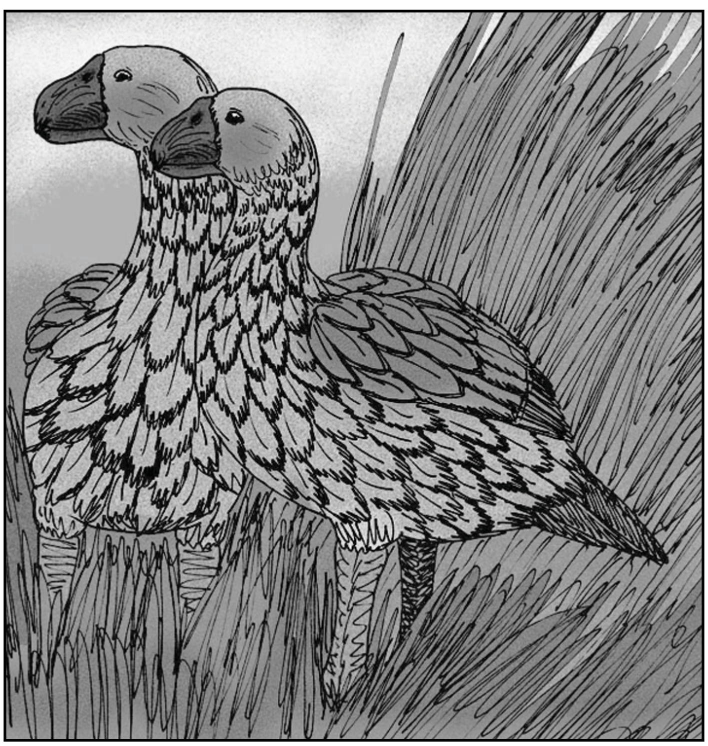


Figure 3.42: An extinct Hawaiian duck known as the turtle-jawed moa-nalo (Chelychelychen quassus). *This flightless bird became extinct prior to European contact with Hawai‘i. DNA analysis places its arrival on the islands at 3.6 million years ago.*

of species is skewed toward those that could travel across the open ocean, and a similar adaptive radiation occurred following the arrival of early near-shore reef species. These factors—long distance travel and subsequent species radiation—give Hawai‘i a very unusual and highly **endemic** group of organisms.

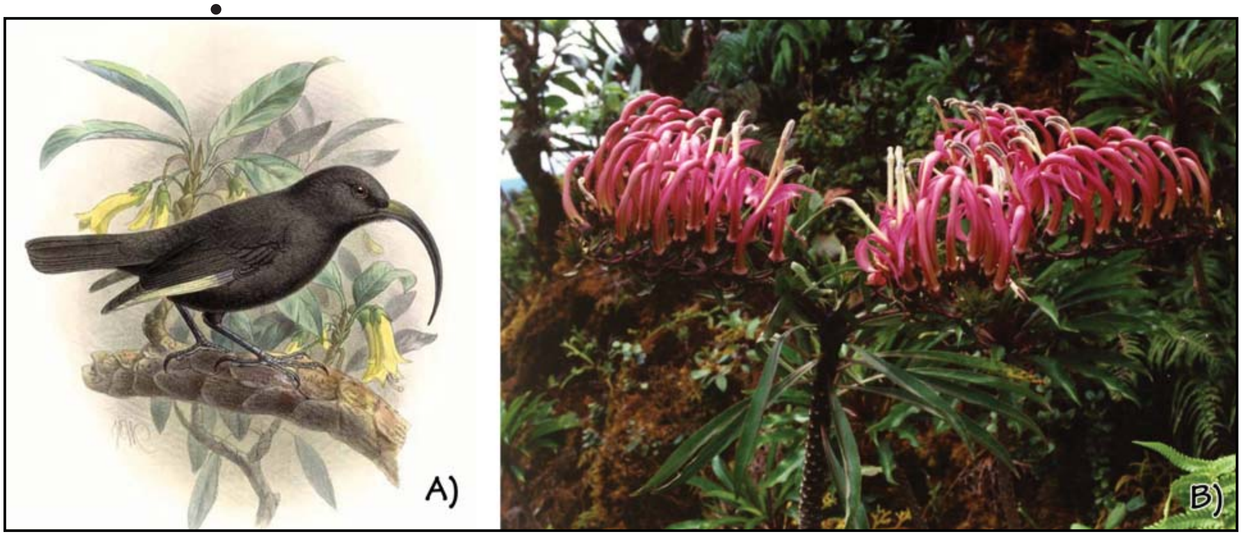


Figure 3.43: The Hawaiian Islands exhibit numerous examples of coevolution between bird and plant species. A) Extinct black mamo (Drepanis funerea)*, and B) modern* Trematolobelia *plant on O'ahu.*

Before the introduction of continental species by humans, Hawaiian terrestrial ecosystems lacked grazing mammals and were characterized by large—often flightless—grazing ducks and geese (*Figure 3.42*). The top predators were raptors, and plants lost the chemical defenses needed to guard against large herds of grazing mammals. Carnivorous caterpillars and plants can still be found in Hawaiian forests. Without diverse insect pollinators, nectar-sipping birds co-evolved curved bills to match long curved flowers like that of the *Trematolobelia* plant (*Figure 3.43*).

The oldest terrestrial fossils in Hawai‘i are found in lake sediments at the bottom of Ulupau crater on O‘ahu. This fossil occurrence is an unusual one for Hawai‘i, and does not fall into one of the three more common modes of preservation described above. The island does not have many lakes, as its base is made up of porous lava. Eleven species of extinct birds have been identified there, dating to 400,000 years ago.

The richest fossil site in the islands is Makauwahi Cave on Kaua‘i. Makauwahi is a karstic cave system in limestone containing a sinkhole lake, in which sediments accumulated over the last 10,000 years, providing excellent preservation. The hundreds of fossil organisms identified at Makauwahi include more than 40 species of birds (half of which are now extinct), 15 or more species of native land snails (*Figure 3.44*), all now extinct, and scores of endemic plants. In

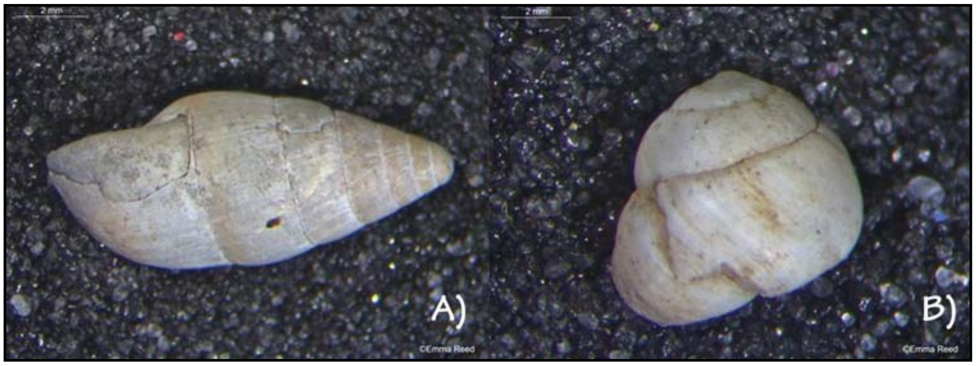


Figure 3.44: Extinct Hawaiian land snails. A) Leptachatina *sp., roughly 12 millimeters (0.5 inches) long. B)* Orobophana juddii, *roughly 6 millimeters across (0.2 inches).*

addition to extinct species, many species of living plants and animals found in the fossil record no longer grow at low elevation, rather, they are found only in high-elevation refuges in remote parts of the islands.

Radiocarbon dating of specimens at Makauwahi Cave documents the arrival of humans—and the continental species they introduced—and the relationship between these new arrivals and the native organisms. Prehistoric native species began to disappear as the first human colonists arrived; lowland birds, along with large flightless geese and ducks, were among the earliest extinctions. These species disappear from sedimentary layers shortly after the appearance of human-introduced rat fossils and other evidence of human habitation. More than half of Kaua‘i’s 140 historically described native bird species are now extinct. One of the most curious is the Kaua‘i mole duck, a bird with unusually small eyes but very large nerve passages to its bill, leading paleontologists to believe that it was nearly blind and may have inhabited caves, or was perhaps a nocturnal feeder.

What makes Hawai‘i’s extinct fossil species so surprising and important is the recency of many of the extinctions. Hawaiian fossil assemblages describe the unusual suite of organisms that once inhabited Hawai‘i, and help us better understand precisely when and how these species became extinct. Hawai‘i’s highly diverse prehuman landscape has been completely transformed, with the decline or extirpation of most native species and their replacement with a small number of introduced species. These human-caused extinctions began about 1000 years ago, accelerated 200 years ago, and the extinction rate continues to increase even today.

Trace fossils in Hawai‘i are most often represented by the trunks and branches of trees that have been consumed by molten lava. When lava flows through a forested area, the molten liquid chills and solidifies almost instantly when it comes in contact with large vegetation. The lava is still quite hot—enough to ignite and burn the trees, leaving behind a mold of the former tree trunk. Lava flows commonly deflate and subside after solidification, and tree molds can protrude above the frozen surface of the flow, leaving behind “lava trees” (*Figure 3.45*).

endemic *• native to a particular geographic area or range.*

radiocarbon dating *• a method of determining the age of a biological object by measuring the ratio of carbon isotopes ^{14}C and ^{12}C.*

Fossils

Figure 3.45: Lava molds of tree trunks at Lava Tree State Monument, Hawai'i.

Marine fossils in Hawai'i are not widespread, but can be very abundant where they do occur, along the coasts of Kaua'i, Oahu, Molokai, Lanai, and Maui. All are found in limestones formed by uplifted Pleistocene or Holocene coral reefs, and can be studied either from coastal outcrops or from cores taken by ship. More than 150 species of mollusks (bivalves and gastropods) have been reported in these reef limestones, together with numerous fossil corals.

State Fossils

Alaska
Mammuthus primigenius (woolly mammoth) (*Figure 3.20*)

California
Smilodon fatalis (saber-toothed cat) (*Figure 3.34*)

Hawai‘i
Hawai‘i has no state fossil.

Nevada
Shonisaurus popularis (Triassic ichthyosaur) *(Figure 3.7)*

Oregon
Metasequoia glyptostroboides (dawn redwood) (*Figure 3.17*)

Washington
Mammuthus columbi (Columian mammoth) (*Figure 3.30*)

Resources

General Books on the Fossil Record & Evolution

Allmon, W. D., 2009, *Evolution & Creationism: A Very Short Guide, 2nd edition,* Paleontological Research Institution, Ithaca, NY, 128 pp.

Benton, M. J., 2008, *The History of Life: A Very Short Introduction,* Oxford University Press, Oxford, UK, 170 pp.

Fenton, C. L., M. A. & Fenton, 1958, *The Fossil Book: A Record of Prehistoric Life*, Doubleday, Garden City, NY, 482 pp. (A well-illustrated classic.)

Fortey, R. A., 1998, *Life: A Natural History of the First Four Billion Years of Life on Earth,* Alfred A. Knopf, New York, 346 pp.

Knoll, A. H., 2003, *Life On a Young Planet: The First Three Billion Years of Evolution on Earth,* Princeton University Press, Princeton, NJ, 277 pp.

Switek, B., 2010, *Written In Stone: Evolution, the Fossil Record, and Our Place In Nature,* Bellevue Literary Press, New York, 320 pp.

Thomson, K. S., 2005, *Fossils: A Very Short Introduction,* Oxford University Press, Oxford, UK, 147 pp.

Books and Articles on Fossils of Specific Areas

Allison, R. C., 1978, Late Oligocene through Pleistocene molluscan faunas in the Gulf of Alaska region, *The Veliger*, 21(2): 171–188.

Bishop, E. M., 2003, *In Search of Ancient Oregon: A Geological and Natural History,* Timber Press, Portland, OR, 288 pp.

Blodgett, R. B., & G. D. Stanley, eds., 2008, The Terrane Puzzle: new perspectives on paleontology and stratigraphy from the North American Cordillera, *Geological Society of America Special Paper* 442, 326 pp.

Burney, D. A., H. F. James, L. P. Burney, S. L. Olson, W. Kikuchi, W. L. Wagner, M. Burney, D. McCloskey, D. Kikuchi, F. V. Grady, R. Gage, & R. Nishek, 2001, Fossil evidence for a diverse biota from Kaua`i and its transformation since human arrival, *Ecological Monographs*, 71(4): 615–641.

Chappell, W. M., J. W. Durham, & D. E. Savage, 1951, Mold of a rhinoceros in basalt, Lower Grand Coulee, Washington, *Geological Society of America Bulletin*, 62(8): 907–918.

English, A. M., & L. E. Babcock, 2010, Census of the Indian Springs Lagerstätte, Poleta Formation (Cambrian), western Nevada, USA, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 295(1–2): 236–244.

Fletcher, C. H., C. Bochicchio, C. L. Conger, M. Engels, E. Feirstein, E. Grossman, R. Grigg, J. N. Harney, J. B. Rooney, C. E. Sherman, S. Vitousek, K. Rubin, & C. V. Murray-Wallace, 2008, Geology of Hawaii reefs, pp. 435–488, in: B. M. Riegl & R. E. Dodge, *Coral Reefs of the USA*, Springer, London, 803 pp.

Gangloff, R. A., 2012, *Dinosaurs Under the Aurora,* Indiana University Press, Bloomington, IN, 176 pp.

Hilton, R. P., 2003, *Dinosaurs and Other Mesozoic Reptiles of California,* University of California Press, Berkeley, CA, 356 pp.

Kohn, A. J., 1980, *Conus kahiko*, a new Pleistocene gastropod from Oahu, Hawaii, *Journal of Paleontology*, 54(3): 534–541.

Manchester, S. R., 1987, Oligocene fossil plants of the John Day Formation, Fossil, Oregon, *Oregon Geology,* 49(10): 115–127.

Manchester, S. R., 1994, Fruits and seeds of the Middle Eocene Nut Beds flora, Clarno Formation, Oregon, *Palaeontographica Americana* 58, 205 pp.

Orr, E. L., & W. N. Orr, 1999, *Oregon Fossils*. Kendall/Hunt Publishing Company, Dubuque, IA, 381 pp.

Raynolds, B., 1999, Rhino revelation, http://fossilnews.com/1999/rhino.html.

Retallack, G. J., E. A. Bestland, & T. J. Fremd, 1996, Reconstructions of Eocene and Oligocene plants and animals of central Oregon, *Oregon Geology*, 58(3): 51–69.

Websites on Fossils of Specific Areas

Alaska Paleontological Database, http://www.alaskafossil.org.
John Day Fossil Beds National Monument (Oregon), National Park Service, http://www.nps.gov/joda/index.htm.
Oregon Paleo Lands Institute (OPLI), http://www.oregonpaleolandscenter.com/.
Page Museum, La Brea Tar Pits, http://www.tarpits.org/.

Guides to Collecting and Identifying Fossils

Arduini, P., G. Teruzzi, & S. S. Horenstein, 1986, *Simon & Schuster's Guide to Fossils,* Simon and Schuster, New York, 317 pp.

Garcia, F. A., & D. S. Miller, 1998, *Discovering Fossils: How To Find and Identify Remains of the Prehistoric Past,* Stackpole Books, Mechanicsburg, PA, 212 pp.

Lichter, G., 1993, *Fossil Collector's Handbook: Finding, Identifying, Preparing, Displaying,* Sterling Publishing Company, New York, 160 pp.

Macdonald, J. R., 1983, *The Fossil Collector's Handbook: A Paleontology Field Guide,* Prentice-Hall, Englewood Cliffs, NJ, 193 pp.

Murray, M., 1967, *Hunting for Fossils: A Guide to Finding and Collecting Fossils in All Fifty States*, Macmillan Company, Toronto, Canada, 348 pp.

Nudds, J. R., & P. A. Selden, 2008, *Fossil Ecosystems of North America: A Guide to the Sites and their Extraordinary Biotas,* University of Chicago Press, Chicago, 288 pp.

Parker, S., 1990, *The Practical Paleontologist. A Step-By-Step Guide To Finding, Studying, and Interpreting Fossils,* Simon and Schuster, New York, 159 pp.

Parker, S., 2007, *Fossil Hunting: An Expert Guide to Finding and Identifying Fossils and Creating a Collection,* Southwater, London, 96 pp.

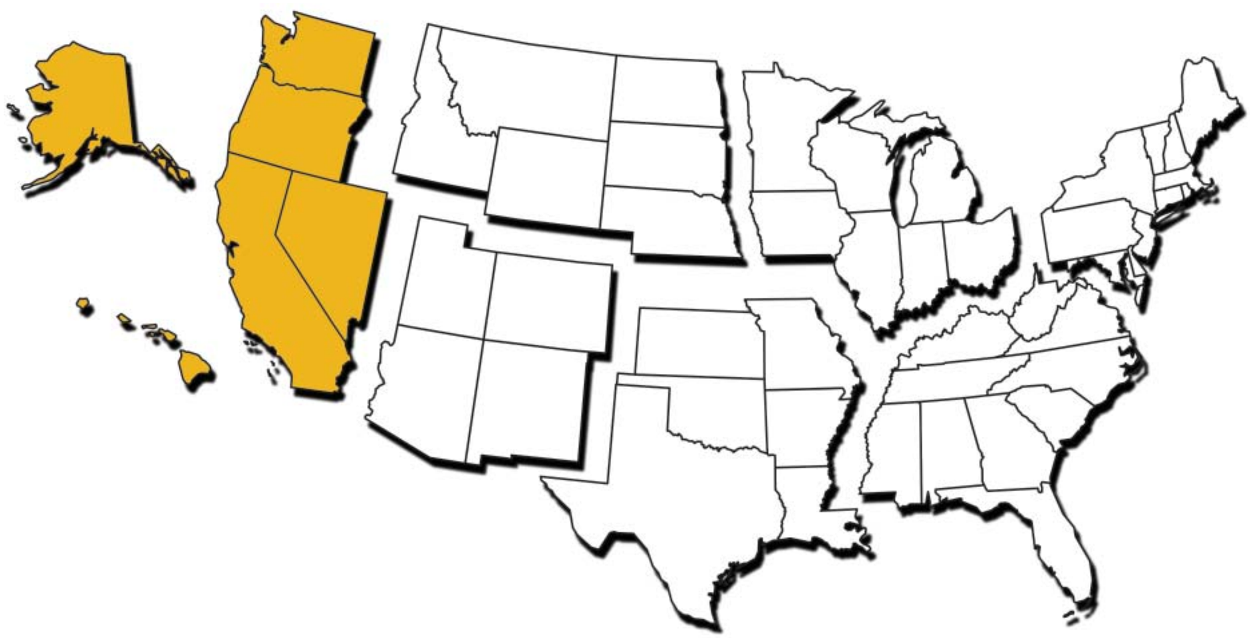
Ransom, J. E., 1964, *Fossils In America: Their Nature, Origin, Identification and Classification and a Range Guide To Collecting Sites*, Harper and Row, New York, 402 pp.

Thompson, I., 1982, *The Audubon Society Field Guide To North American Fossils,* Knopf, New York, 846 pp.

Walker, C., D. Ward, & C. Keates, 2009, *Fossils,* Dorling Kindersley (Smithsonian Handbooks), New York, 320 pp.

The Teacher-Friendly Guide™

to the Earth Science of the Western US



Edited by Mark D. Lucas, Robert M. Ross, & Andrielle N. Swaby

Paleontological Research Institution
2014

ISBN 978-0-87710-509-1
Library of Congress no. 2014959038
PRI Special Publication no. 47

1259 Trumansburg Road
Ithaca, New York 14850 USA
priweb.org

First printing December 2014

This material is based upon work supported by the National Science Foundation under grant DRL-0733303. Any opinions, findings, and conclusions or recommendations are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The publication also draws from work funded by the Arthur Vining Davis Foundations and The Atlantic Philanthropies.

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

The Teacher-Friendly Guide™ series was originally conceived by Robert M. Ross and Warren D. Allmon. Original illustrations in this volume are mostly by Jim Houghton (The Graphic Touch, Ithaca), Wade Greenberg-Brand, and Christi A. Sobel.

Layout and design by Paula M. Mikkelsen, Elizabeth Stricker, Wade Greenberg-Brand, and Katherine Peck.

Cite this book as:
Lucas, M. D., R. M. Ross, & A. N. Swaby (eds.), 2014, *The Teacher-Friendly Guide to the Earth Science of the Western US,* Paleontological Research Institution, Ithaca, New York, xii + 424 pp.

Cite one chapter as (example):
Anderson, B., A. Moore, G. Lewis, and W. D. Allmon, 2014, Fossils of the Western US. Pages 81–123, in: M. D. Lucas, R. M. Ross, & A. N. Swaby (eds.), *The Teacher-Friendly Guide to the Earth Science of the Western US.* Paleontological Research Institution, Ithaca, New York.

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.