Lesson 9: Stratigraphy and Geologic Time

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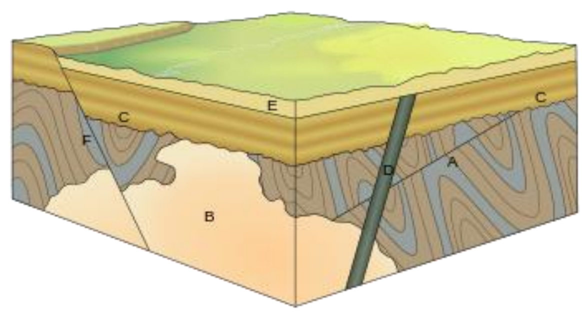
Learning objective for lesson 9: Students will understand basic stratigraphic concepts and the scale of earth history. Students will understand the evolution of dinosaurs through time, including which groups evolved when and where.

Learning objective 9.1: Describe the geological Principle of Superposition

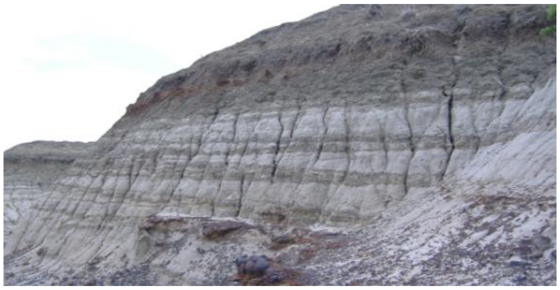
Learning objective 9.2: Arrange geological formations in order by interpreting a simple geological cross-section

As has been previously discussed, sedimentary rocks form from small organic or inorganic particles (called sediments) that accumulate and are cemented or compacted together. As sediments are deposited, they gradually build up on top of each other in layers. Over time, deep sequences of layered sedimentary rocks result. In such a sequence, the oldest rocks (which are formed from the oldest deposited sediments) are at the bottom, and the layers become increasingly younger towards the top. The tendency for rock layers to be chronologically stacked is called the **Principle of Superposition**.

The Principle of Superposition is only an expression of how things normally work, and there can be exceptions. Igneous rocks that form from volcanic activity may vertically cut through horizontally arranged layers of rocks, and mountain building events may tilt, fold, and even flip rock layers.



This diagram shows the complex stratigraphy that can happen when rocks are folded, broken, and eroded. A are ancient folded sedimentary layers that have been folded and broken (faulted). B is a large igneous intrusion that partially melted A. These rocks were then uplifted and eroded, creating a flat surface called an unconformity. New sedimentary layers were deposited on top of the old rocks. D is a new igneous intrusion that cut through A, B, and C, and then E is yet another horizontal layer of sedimentary rocks deposited over top of A-D. Image by Woudloper via Wikimedia Commons, used under the CC-BY-SA license.



Alternating light and dark sedimentary layers at Dinosaur Provincial Park. Photo by V. Arbour.

Stratigraphy is the science of using the arrangement and composition of rock layers to interpret geological history. A large uninterrupted sequence of rock that is made of multiple layers that all share similar properties (such as mineral composition and average sediment grain size) and that all formed under similar conditions is termed a **formation**. When a sequence of rock changes from one formation to another, it indicates that a large scale change occurred in the environment where the rocks were being deposited.

The Principle of Superposition allows a stratigrapher to infer the relative age of rock layers (that is, how old one layer is relative to another), but it does not determine the absolute age (that is, how old in years the layers are). To age rocks in absolute terms, a technique called **radiometric dating** is used. All matter (including rocks) is composed of chemical elements, which are atoms composed of a particular number of protons and electrons (positive and negatively charged particles). Some chemical elements are also composed of neutrons (neutrally charged particles), and some of these chemical elements may exist as isotopes. An **isotope** is a variant of a chemical element that has an unusual number of neutrons. Some isotopes are unstable and will undergo radioactive decay, whereby energy is released and a new atom (or atoms) with a different composition of particles results. These resulting atoms with different particle compositions are called the decay products. At what time a single isotopic atom will undergo radioactive decay is unpredictable, but a large collection of isotopes will radioactively decay at a mathematically predictable rate.

When a new rock forms, it has a ratio of isotopes and decay products that matches that of the environment. As the rock ages, the isotopes decay and the ratio of isotopes to decay products decreases. Using a special machine called a mass spectrometer, it is possible to measure the isotope ratio of a rock, and this ratio can tell you how long ago the rock formed.

Unfortunately, sedimentary rocks are never really “new” -- that is, they are made of sediments that had already formed and that were already potentially undergoing radioactive decay. Thus, sedimentary rock cannot usually be radiometrically dated. On the other hand, igneous rocks *are* formed anew and can usually be radiometrically dated. But, if fossils are usually found in sedimentary rocks and not in igneous rocks, how can we ever tell how old a fossil and its rock layer is? By combining radiometric dating and the principle of superposition. If sedimentary rocks that contain fossils are found between two horizontally deposited layers of igneous rocks, then dating the igneous rocks above the sedimentary layer will tell us what age the fossils must be older than, and dating the igneous rocks below the sedimentary layer will tell us what age the fossils must be younger than. So, we can confidently bracket the age of the fossils.

In some instances, it is even easier to date fossils, because we can be certain that particular particles of igneous rocks that compose the sedimentary rocks that the fossils are buried in were incorporated into the sediment at nearly the same time that they were formed. For instance, fossils may be buried by, or be buried near, deposits of volcanic ash. Volcanic ash forms at the moment of an eruption, and the time between when an eruption occurs and when its ash falls to the surface is inconsequently short. Volcanic ash deposits are a key tool in fossil dating.

Learning objective 9.3 – Describe important events in the geological history of Earth

Stratigraphy and radiometric dating are combined to piece together the history of the earth and to create the geologic time scale. **The geologic time scale** is a standardized series of chronological divisions that parses the Earth's history into discrete named units. The largest units in the time scale are Eons, followed by Eras, Periods, and Epochs. We'll post a PDF of the most recent version of the official geologic time scale on eClass, or you can download it from the International Commission on Stratigraphy: http://www.stratigraphy.org/index.php/ics-chart-timescale.

Here is a brief overview of the geologic time scale and of some of the important events that occurred during its different divisions.

THE HADEAN EON – 4.6 TO 4 BILLION YEARS AGO

The Hadean Eon is named for Hades (the Greek god of the underworld), and by the beginning of this eon, the rest of the universe was already over nine billion years old. The formation and early years of the earth were a tumultuous time, with the surface of the earth partially molten and with volcanic activity widespread. At roughly 4.5 billion years ago, the young earth collided with a smaller planetoid. This collision ejected a large mass of debris, which was held in orbit by the earth's gravity and eventually formed the moon. By the end of the Hadean, the earth had cooled and large oceans covered much of its surface. Complex organic molecules are thought to have formed in these early oceans and possibly the earliest true life forms. The oldest rocks on earth have been dated at only about 4.4 billion years old, though rocks discovered on the moon are older.

THE ARCHEAN EON – 4 TO 2.5 BILLION YEARS AGO

The oldest known fossils come from the Archean Eon. These fossils are of simple single-celled organisms. More advanced forms later evolved in the Archean, including cyanobacteria. The cyanobacteria were photosynthetic and eventually produced large amounts of oxygen gas, which became concentrated in the earth's atmosphere. Some cyanobacteria formed structures called stromatolites, which are some of the best records of early life. Stromatolites look like lumpy stones, but when you cut them in half you can see the layers that were created as the cyanobacteria secreted sticky films that trapped particles of sediment.

A stromatolite on display in the Paleontology Museum at the University of Alberta. Photo by V. Arbour.

THE PROTEROZOIC EON – 2.5 BILLION TO 541 MILLION YEARS AGO

At approximately 1.7 billion years ago, the first multicellular organisms evolved. Because single-celled and early multicellular life had no bones or other hard parts and was usually microscopic, the fossil record of this early life is poor. Within the Proterozoic, the time span from 630 to 542 million years ago is known as the Ediacaran Period. During the Ediacaran, large forms of life with some harder parts evolved, including the first animal life.

THE PHANEROZOIC EON – 541 TO 0 MILLION YEARS AGO

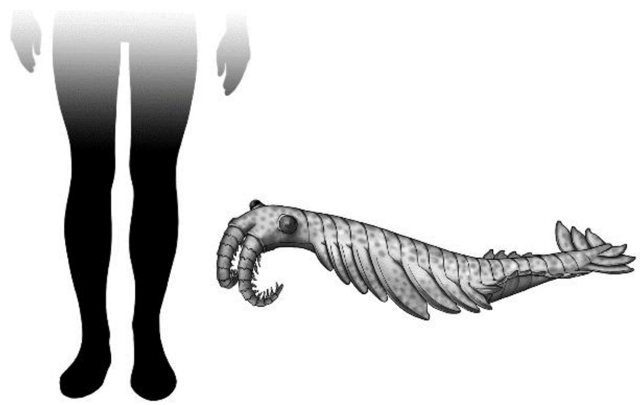
The Phanerozoic Eon is subdivided into three eras, which are themselves subdivided into numerous periods. It is during the Phanerozoic that animal life rapidly evolved into a multitude of diverse forms, including dinosaurs. We will consider the events of the each Phanerozoic era and period.

The Paleozoic Era – 541 to 252 million years ago

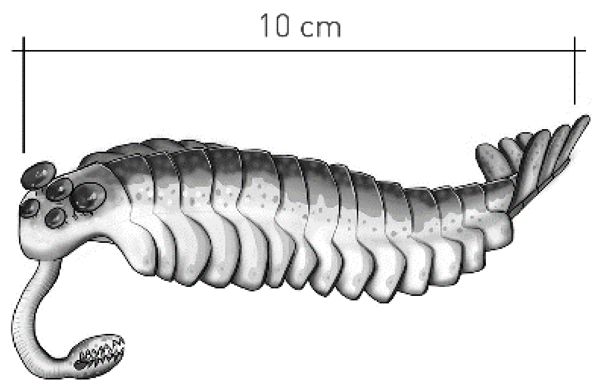
At the start of the Paleozoic, animal life was restricted to primitive invertebrates living in the oceans, but, by its close, great forests covered the land and teamed with reptiles, amphibians, and insects.

The Cambrian Period – 541 to 485 million years ago

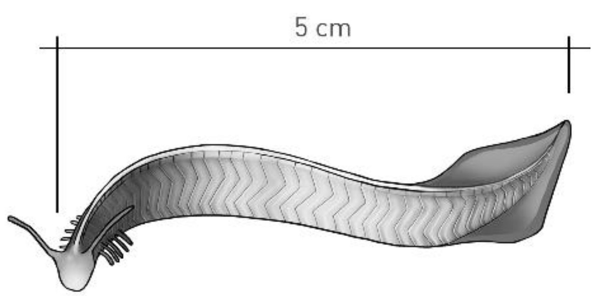
The beginning of the Cambrian marks such a dramatic diversification of aquatic animal life that it is often referred to as **The Cambrian Explosion**. Sponges, molluscs, worms, and many kinds of arthropods (including trilobites) evolved. A close early relative of the vertebrates, called *Pikaia*, didn't have vertebrae, but had several other features found in vertebrates.



The invertebrate *Anomalocaris* was once the top predator in the Cambrian oceans. Illustration by Rachelle Bugeaud.



With a bizarreness characteristic of Cambrian life, *Opabinia* remains a mystery in teams of both its life habits and its evolutionary relationships to modern animals. Illustration by Rachelle Bugeaud.



Though it lacked a hard skeleton, *Pikaia* was one of the earliest ancestors of the vertebrate animals. Illustration by Rachelle Bugeaud.

<u>The Ordovician Period – 485 to 443 million years ago</u>

Global sea levels were high. Life in the oceans continued to diversify, with fish increasingly becoming the dominant large aquatic animals.

<u>The Silurian Period – 443 to 419 million years ago</u>

Until this point, fish had not yet evolved jaws. With the evolution of jaws came the evolution of large predatory fish. Primitive plant life began to flourish on land.

Osteostracans, a group of early jawless vertebrates, in the Paleontology Museum at the University of Alberta. Photo by V. Arbour.

<u>The Devonian Period – 419 to 359 million years ago</u>

The first forests appeared on land. Huge jawed fishes, like *Dunkleosteus*, evolved in the seas, and the first true sharks appeared. Lobe-finned 'fishapods', like *Tiktaalik*, ventured onto land, and give rise to the tetrapods.

The skull of *Dunkleosteus* in the Paleontology Museum at the University of Alberta. Photo by V. Arbour.

The Carboniferous Period – 359 to 299 million years ago

Amphibians were widespread in the abundant swamps, and reptiles, the first amniotes, evolved. Much of the coal that is mined today formed from the rotting plants of Carboniferous swamps.

The Permian Period – 299 to 252

The continents collided together and formed a single super continent called **Pangaea**. Reptiles evolved into three main lineages: the anapsids (which would go on to evolve into turtles), the synapsids (which go on to evolve into mammals), and the diapsids (which would go on to evolve into lizards, snakes, crocodilians, and dinosaurs). Many of the terrestrial rocks from this period of time represent dry, desert environments. The single greatest mass extinction in our planet's history occurred at end of the Permian, with one of the most notable losses being the trilobites.

The Mesozoic Era – 252 to 66 million years ago

The Mesozoic is often referred to as the Age of Dinosaurs. It is during this time that dinosaurs evolved and became the dominant form of large terrestrial animal life. Many kinds of marine reptiles evolve, including the ichthyosaurs, plesiosaurs, and mosasaurs. The first true turtles, crocodilians, lizards, snakes, mammals, and birds evolved at this time as well. The first flowering plants evolved towards the end of the Mesozoic. The Mesozoic Era has been, and will continue to be, examined and discussed throughout this course. We'll go into more detail on the Mesozoic Era in the next section!

The Cenozoic Era – 66 to 0 million years ago

The Cenozoic is often referred to as the Age of Mammals. Although mammals had been around since the Triassic, the extinction of the dinosaurs (except for birds) allowed mammals to evolve larger forms and to fill many new ecological roles. Grasses only become abundant at this time!

The Paleogene Period – 66 to 23 million years ago

Global temperatures began to cool. Mammals diversified into a variety of new forms, including primates, bats, and whales. Birds also diversified.

The Neogene Period – 23 to 2.6 million years ago

Global temperatures continued to cool. The first hominids evolved in Africa.

The Quaternary Period – 2.6 to 0 million years ago

The earth experienced several large glaciation events, or "ice ages". The first anatomically modern humans evolved. Human civilization spread.

Learning objective 9.4 – Classify types of dinosaurs based on the geological age in which they were most common.

Many dinosaur books and movies depict dinosaur species from vastly different periods existing at the same time and place. This can be a big mistake! The non-avian dinosaurs existed for 135 million years. There is less time separating the first humans from the last dinosaurs than there is separating the last dinosaurs from the first dinosaurs, and not all clades of dinosaurs were present throughout the entire Mesozoic.

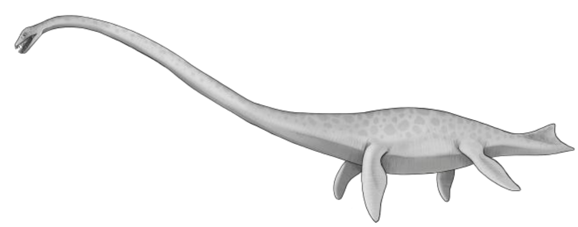
The Triassic Period – 252 to 201 million years ago

During the first ten million years of the Triassic, life gradually recovered from the mass extinction that occurred at the end of the Permian. The first mammals and dinosaurs evolved during the later portion of the Triassic, and so did the first pterosaurs - the first vertebrates to fly. The supercontinent Pangaea began to break apart. Many of the dinosaurs from this period of time look fairly similar to each other. The first representatives of the ornithischians (like *Pisanosaurus*), theropods (like *Eoraptor* and *Herrerasaurus*), and sauropodomorphs (like *Panphagia*) were all mostly small and bipedal. "Prosauropods" like *Plateosaurus* were some of the first large herbivorous dinosaurs. We'll discuss life on land in the Triassic in more detail in lesson 11.

As dinosaurs were evolving to fill large-bodied ecological roles on land, other amniote groups were evolving to fill them in the sea and air. It was in the Triassic that the first **ichthyosaurs** evolved. The name ‘ichthyosaur’ literally means “fish lizard,” but ichthyosaurs are not lizards, and they certainly aren’t fish. Even so, the name ‘ichthyosaur’ still seems fitting, because they are a group of reptiles that took on a fish-like lifestyle and evolved a very fishy body form.

The ancestors of ichthyosaurs were fully terrestrial reptiles, but, just like the ancestors of modern whales, dolphins, seals, and sea turtles, the group found success by making an evolutionary return to the water. To adapt to an aquatic life, ichthyosaurs evolved paddle-like front and hind limbs, a finned tail, and even a shark-like dorsal fin. The long snouts of most ichthyosaurs resemble those of dolphins, and are filled with conical teeth – good equipment for a piscivorous diet. Despite their many fish-like adaptations, ichthyosaurs never evolved gills and needed to come to the surface in order to breathe air.

Late into the Triassic, ichthyosaurs were joined in the seas by another group of reptiles that also evolved a secondarily aquatic lifestyle: the **plesiosaurs**. Most plesiosaurs had large chests and torsos, broad paddle-shaped limbs, and relatively short tails. In front of their shoulders, plesiosaurs varied tremendously. Some had short necks and huge jaws, other had elongated serpentine necks with small heads.



Elasmosaurus is an example of a plesiosaur, although it lived during the Cretaceous Period. Art by Rachelle Bugeaud.

The airways of the Dinosaur Age were also busy places. Insects had already evolved flight at least as far back as the Carboniferous, and dinosaurs would take to the air and give rise to birds in the Jurassic. In addition, there was a third group fluttering over the heads of dinosaurs: the pterosaurs. **Pterosaurs**, or as they are commonly called, “pterodactyls”, are close relatives of dinosaurs who branched off from the reptilian family tree at roughly the same time in the Triassic that dinosaurs did. Pterosaurs were the first vertebrates to fly.

Unlike birds, which have arms that support wings made of feathers, and bats, which have wings made from skin stretched between multiple fingers, pterosaurs have membranous wings supported by a single extremely elongated finger.

Early pterosaurs belong to a group called **rhamphorhynchoids**, which were common in the Late Triassic and throughout the Jurassic.

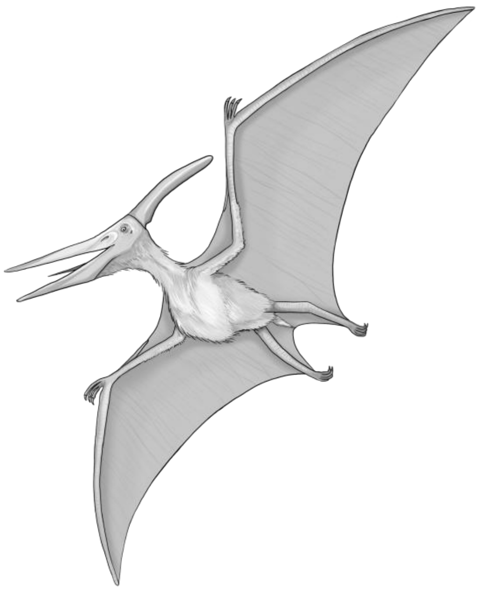
The Triassic of New Mexico: the small, early theropod *Coelophysis* chases an early mammal, while the synapsid *Placerias* looks on. Art by Jan Sovak.

<u>The Jurassic Period – 201 to 145 million years ago</u>

Dinosaurs diversified. This was the peak of sauropod diversity, and they were the dominant terrestrial herbivores. Small and medium sized ornithopods were common. Non-coelurosaurian theropods, like *Allosaurus*, were the dominant terrestrial carnivores. The stegosaurs are almost completely restricted to the Jurassic, and the first ankylosaurs, ornithopods, and ceratopsians appear at this time, although they are not particularly abundant or diverse. The first birds, including *Archaeopteryx*, evolved during the Jurassic. The Morrison Formation of the western USA, and the Solnhofen limestone of Germany, are some of the best and most famous records of dinosaurs from this time.

In the Jurassic, rhamphorhynchoid pterosaurs gave rise to a new pterosaur group: the pterodactyloids. **Pterodactyloids** differed from rhamphorhynchoids in the morphology of their tails, which were short, and the carpels in their wrists, which were elongated and made a greater contribution to the length of the wing.

Unlike rhamphorhynchoids, many pterodactyloids had large head crests, which were presumably display structures. There were many species of small pterodactyloids, some smaller than a robin, but some species had wingspans of over ten meters, making them the largest animals to ever fly.



Left: Pteranodon is an example of a Cretaceous pterodactyloid pterosaur. Illustration by Rachelle Bugeaud.

Below: The Morrison Formation of the western USA: sauropods dominate the landscape, like the slender-necked *Diplodocus* (to the right), tall *Brachiosaurus* (center), and stubby-faced *Camarasaurus* (to the left). Art by Jan Sovak.

The Early Cretaceous Period – 146 to 100 million years ago

Dinosaurs continue to diversify and the first flowering plants evolved. In the Early Cretaceous new theropods, like spinosaurids and carcharodontosaurids evolve, coelurosaurian theropods become more diverse, and iguanodonts become larger and more abundant. The Yixian Formation of China, the Wealden Supergroup of England, and the Cedar Mountain Formation of Utah are important Early Cretaceous fossil-rich rock units.

Sometime in the Cretaceous Period, a third major reptilian group began patrolling the Mesozoic waters. **Mosasaurs** were relatives of modern monitor lizards and snakes. Like ichthyosaurs and plesiosaurs, mosasaurs had tail fins and limbs modified into paddles, but the bodies and tails of mosasaurs were more elongate. Many mosasaurs are the right size to have preyed on small and medium sized fish, but some were true sea monsters with huge jaws and bodies over eighteen meters long. These aquatic giants seem adapted for deep-sea big-game hunting, and they likely ate large fish and other marine reptiles.

A Wealden scene: the theropod *Neovenator* attacks a pair of *Iguanodon*, while the small heterodontosaurid *Echinodon* flees; the early ankylosaur *Polacanthus* is well protected by its armour. Art by Jan Sovak.

Meanwhile in China, the coelurosaurian theropods show a wide variety of feathery integuments. A pair of the *Sinosauropteryx* (to the right; these are compsognathid theropods) chase a small mammal, a pair of *Caudipteryx* (center; these are oviraptorosaurian theropods) display their tail feathers, and a pair of *Microraptor* (to the left; these are dromaeosaurid theropods) glide using their four wings. Art by Jan Sovak

<u>The Late Cretaceous Period - 100 to 65 million years ago</u>

Often considered the apex of non-avian dinosaur diversity, many of the most famous dinosaurs come from this period of time. The coelurosaurian theropods are abundant and diverse in the northern hemisphere, and include the tyrannosaurs, ornithomimids, therizinosaurs, oviraptorosaurs, dromaeosaurids, troodontids, and many more interesting clades. The ankylosaurs have diverged into two groups, the tail-clubbed ankylosaurids and the clubless nodosaurids. Ceratopsians and hadrosaurs are the dominant large herbivores in the northern hemisphere. Only a single lineage of sauropods remains, but the titanosaurid sauropods are the dominant herbivores in the southern hemisphere. Pachycephalosaurs are only known from the Late Cretaceous. The first flowering plants evolved. At the end of the Cretaceous, a large meteor collided with the earth, and this event along with its catastrophic consequences is thought to have brought about a mass extinction, which killed all non-avian dinosaurs. We'll go into more detail about the end Cretaceous extinction in lesson 12.

The Horseshoe Canyon Formation of Alberta: the tyrannosaurid theropod *Albertosaurus* chase the ceratopsian *Arrhinosaurus*; to the right, the ankylosaurid ankylosaur *Anodontosaurus* battles another *Albertosaurus*.
Art by Jan Sovak

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Supplementary Materials.

The Evolution of Life in 60 Seconds [video]

Dinosaur Tracking – Dinosaur turnover. [blog post]

Everything Dinosaur – Palaeocommunities in the Upper Campanian strata of Alberta. [blog post]

Smithsonian.com – Where have all the sauropods gone? [blog post]

British Museum of Natural History – Dino Timeline. [interactive timeline of dinosaurs – explore!]

University of Alberta: UAlberta provides a copy of *Pteranodon* to American Museum of Natural History. [Video]

Optional: Royal Tyrrell Museum Speaker Series – Revisiting the Horseshoe Canyon Formation: Why Drumheller Rocks. [Lecture]