The Fossil Record as Evidence for Evolution
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Fossils tell us when organisms lived, as well as provide evidence for the progression and evolution of life on earth over millions of years.

What Fossils Tell Us

Fossils are the preserved remains or traces of animals, plants, and other organisms from the past. Fossils range in age from 10,000 to 3.48 billion years old. The observation that certain fossils were associated with certain rock strata led 19th century geologists to recognize a geological timescale. Like extant organisms, fossils vary in size from microscopic, like single-celled bacteria, to gigantic, like dinosaurs and trees.

"Sue" T-rex skeleton: The bones of this Tyrannosaurus rex were preserved through the process of permineralization, which suggests that this organism was covered by sediment soon after death.

Permineralization

Permineralization is a process of fossilization that occurs when an organism is buried. The empty spaces within an organism (spaces filled with liquid or gas during life) become filled with mineral-rich groundwater. Minerals precipitate from the groundwater, occupying the empty spaces. This process can occur in very small spaces, such as within the cell wall of a plant cell. Small-scale permineralization can produce very detailed fossils. For permineralization to occur, the organism must be covered by sediment soon after death, or soon after the initial decay process.

The degree to which the remains are decayed when covered determines the later details of the fossil. Fossils usually consist of the portion of the organisms that was partially mineralized during life, such as the bones and teeth of vertebrates or the chitinous or calcareous exoskeletons of invertebrates. However, other fossils contain traces of skin, feathers or even soft tissues.

Trace Fossils

Fossils may also consist of the marks left behind by the organism while it was alive, such as footprints or feces. These types of fossils are called trace fossils, or ichnofossils, as opposed to body fossils. Past life may also leave some markers that cannot be seen but can be detected in the form of biochemical signals; these are known as chemofossils or biomarkers.

Dinosaur footprints: Footprints are examples of trace fossils, which contribute to the fossil record.

The Fossil Record

The totality of fossils, both discovered and undiscovered, and their placement in fossiliferous (fossil-containing) rock formations and sedimentary layers (strata) is known as the fossil record. The fossil record was one of the early sources of data underlying the study of evolution and continues to be relevant to the history of life on Earth. The development of radiometric dating techniques in the early 20th century allowed geologists to determine the numerical or “absolute” age of various strata and their included fossils.

Evidence for Evolution

Fossils provide solid evidence that organisms from the past are not the same as those found today; fossils show a progression of evolution. Fossils, along with the comparative anatomy of present-day organisms, constitute the morphological, or anatomical, record. By comparing the anatomies of both modern and extinct species, paleontologists can infer the lineages of those species. This approach is most successful for organisms that had hard body parts, such as shells, bones or teeth. The resulting fossil record tells the story of the past and shows the evolution of form over millions of years.

Fossil Formation

Fossils can form under ideal conditions by preservation, permineralization, molding (casting), replacement, or compression.

Fossil Formation

The process of a once living organism becoming a fossil is called fossilization. Fossilization is a very rare process, and of all the organisms that have lived on Earth, only a tiny percentage of them ever become fossils. To see why, imagine an antelope that dies on the African plain. Most of its body is quickly eaten by scavengers, and the remaining flesh is soon eaten by insects and bacteria, leaving behind only scattered bones. As the years go by, the bones are scattered and fragmented into small pieces, eventually turning into dust and returning their nutrients to the soil. As a result, it would be rare for any of the antelope’s remains to actually be preserved as a fossil.

Fossilization can occur in many ways. Most fossils are preserved in one of five processes:

- preserved remains
- permineralization
- molds and casts
- replacement
- compression

Preserved Remains

The rarest form of fossilization is the preservation of original skeletal material and even soft tissue. For example, some insects have been preserved perfectly in amber, which is ancient tree sap. In addition, several mammoths and even a Neanderthal hunter have been discovered frozen in glaciers. These preserved remains allow scientists the rare opportunity to examine the skin, hair, and organs of ancient creatures. Scientists have collected DNA from these remains and compared the DNA sequences to those of modern creatures.

Amber: The image depicts a gnat preserved in amber. A lot of insects have been found to be perfectly maintained in this ancient tree sap.

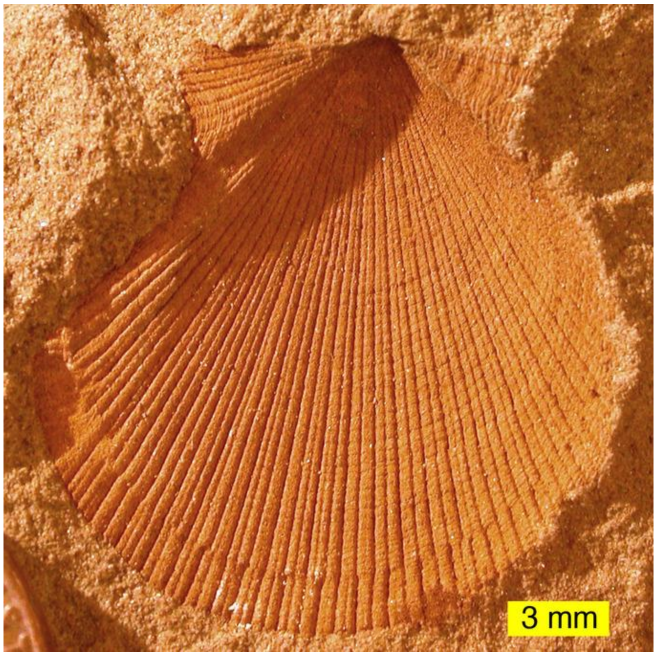
Permineralization

The most common method of fossilization is permineralization. After a bone, wood fragment, or shell is buried in sediment, it may be exposed to mineral-rich water that moves through the sediment. This water will deposit minerals, typically silica, into empty spaces, producing a fossil. Fossilized dinosaur bones, petrified wood, and many marine fossils were formed by permineralization.

Permineralization: These fossils from the Road Canyon Formation (Middle Permian of Texas) have been silicified (replaced with silica), which is a form of permineralization.

Molds and Casts

In some cases, the original bone or shell dissolves away, leaving behind an empty space in the shape of the shell or bone. This depression is called a mold. Later, the space may be filled with other sediments to form a matching cast in the shape of the original organism. Many mollusks (bivalves, snails, and squid) are commonly found as molds and casts because their shells dissolve easily.



Molds: The depression in the image is an external mold of a bivalve from the Logan Formation, Lower Carboniferous, Ohio

Replacement

In some cases, the original shell or bone dissolves away and is replaced by a different mineral. For example, shells that were originally calcite may be replaced by dolomite, quartz, or pyrite. If quartz fossils are surrounded by a calcite matrix, the calcite can be dissolved away by acid, leaving behind an exquisitely preserved quartz fossil. When permineralization and replacement occur together, the organism is said to have undergone petrification, the process of turning organic material into stone. However, replacement can occur without permineralization and vice versa.

Compression

Some fossils form when their remains are compressed by high pressure. This can leave behind a dark imprint of the fossil. Compression is most common for fossils of leaves and ferns but also can occur with other organisms.

Conditions for Fossilization

Following the death of an organism, several forces contribute to the dissolution of its remains. Decay, predators, or scavengers will typically rapidly remove the flesh. The hard parts, if they are separable at all, can be dispersed by predators, scavengers, or currents. The individual hard parts are subject to chemical weathering and erosion, as well as to splintering by predators or scavengers, which will crunch up bones for marrow and shells to extract the flesh inside. Also, an animal swallowed whole by a predator, such as a mouse swallowed by a snake, will have not just its flesh but some, and perhaps all, its bones destroyed by the gastric juices of the predator.

It would not be an exaggeration to say that the typical vertebrate fossil consists of a single bone, or tooth, or fish scale. The preservation of an intact skeleton with the bones in the relative positions they had in life requires a remarkable circumstances, such as burial in volcanic ash, burial in aeolian sand due to the sudden slumping of a sand dune, burial in a mudslide, burial by a turbidity current, and so forth. The mineralization of soft parts is even less common and is seen only in exceptionally rare chemical and biological conditions.

Gaps in the Fossil Record

Because not all animals have bodies which fossilize easily, the fossil record is considered incomplete.

Incompleteness of the Fossil Record

Each fossil discovery represents a snapshot of the process of evolution. Because of the specialized and rare conditions required for a biological structure to fossilize, many important species or groups may never leave fossils at all. Even if they do leave fossils, humans may never find them—for example, if they are buried under hundreds of feet of ice in Antarctica. The number of species known about through the fossil record is less than 5% of the number of species alive today. Fossilized species may represent less than 1% of all the species that have ever lived.

Types of Fossils in the Fossil Record

The fossil record is very uneven and is mostly comprised of fossils of organisms with hard body parts, leaving most groups of soft-bodied organisms with little to no fossil record. Groups considered to have a good fossil record, including transitional fossils between these groups, are the vertebrates, the echinoderms, the brachiopods, and some groups of arthropods. Their hard bones and shells fossilize easily, unlike the bodies of organisms like cephalopods or jellyfish.

Romer’s Gap

Romer’s gap is an example of an apparent gap in the tetrapod fossil record used in the study of evolutionary biology. These gaps represent periods from which no relevant fossils have been found. Romer’s gap is named after paleontologist Alfred Romer, who first recognized it. Romer’s gap spanned from approximately 360 to 345 million years ago, corresponding to the first 15 million years of the Carboniferous Period.

Romer's Gap: The bank of the Whiteadder Water in Scotland is one of the few known localities bearing fossils of tetrapods from Romer's gap.

There has been much debate over why there are so few fossils from this time period. Some scientists have suggested that the geochemistry of the time period caused bad conditions for fossil formation, so few organisms were fossilized. Another theory suggests that scientists have simply not yet discovered an excavation site for these fossils, due to inaccessibility or random chance.

Carbon Dating and Estimating Fossil Age

The age of fossils can be determined using stratigraphy, biostratigraphy, and radiocarbon dating.

Determining Fossil Ages

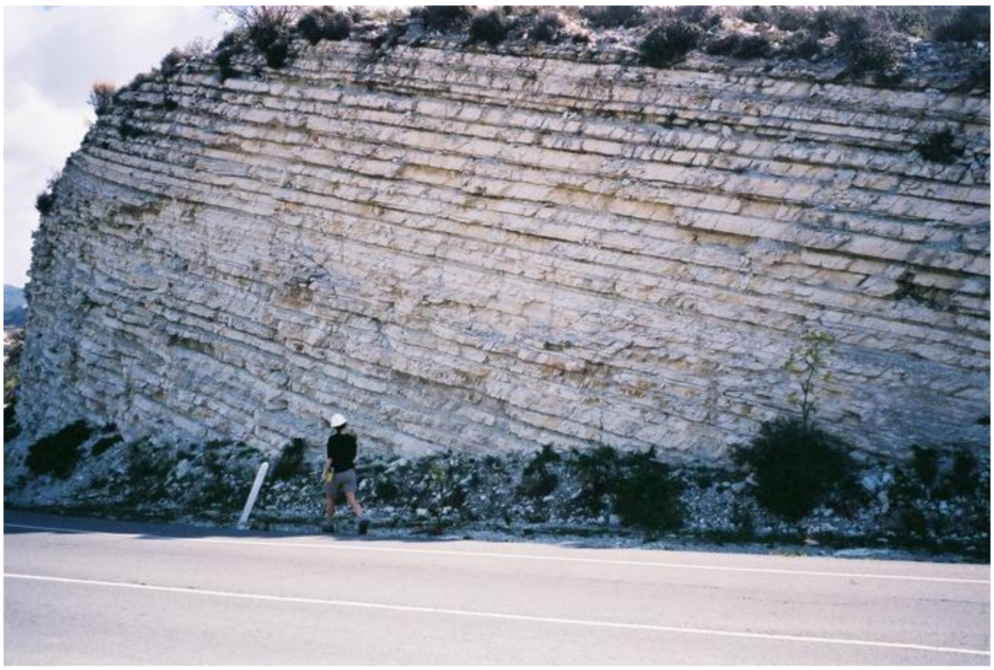
Paleontology seeks to map out how life evolved across geologic time. A substantial hurdle is the difficulty of working out fossil ages. There are several different methods for estimating the ages of fossils, including:

1. stratigraphy
2. biostratigraphy
3. carbon dating

Stratigraphy

Paleontologists rely on stratigraphy to date fossils. Stratigraphy is the science of understanding the strata, or layers, that form the sedimentary record. Strata are differentiated from each other by their different colors or compositions and are exposed in cliffs, quarries, and river banks. These rocks normally form relatively horizontal, parallel layers, with younger layers forming on top.

If a fossil is found between two layers of rock whose ages are known, the fossil's age is thought to be between those two known ages. Because rock sequences are not continuous, but may be broken up by faults or periods of erosion, it is difficult to match up rock beds that are not directly adjacent.



Sedimentary layers: The layers of sedimentary rock, or strata, can be seen as horizontal bands of differently colored or differently structured materials exposed in this cliff. The deeper layers are older than the layers found at the top, which aids in determining the relative age of fossils found within the strata.

Biostratigraphy

Fossils of species that survived for a relatively short time can be used to match isolated rocks: this technique is called biostratigraphy. For instance, the extinct chordate *Eoplacognathus pseudoplanus* is thought to have existed during a short range in the Middle Ordovician period. If rocks of unknown age have traces of *E. pseudoplanus*, they have a mid-Ordovician age. Such index fossils must be distinctive, globally distributed, and occupy a short time range to be useful. Misleading results can occur if the index fossils are incorrectly dated.

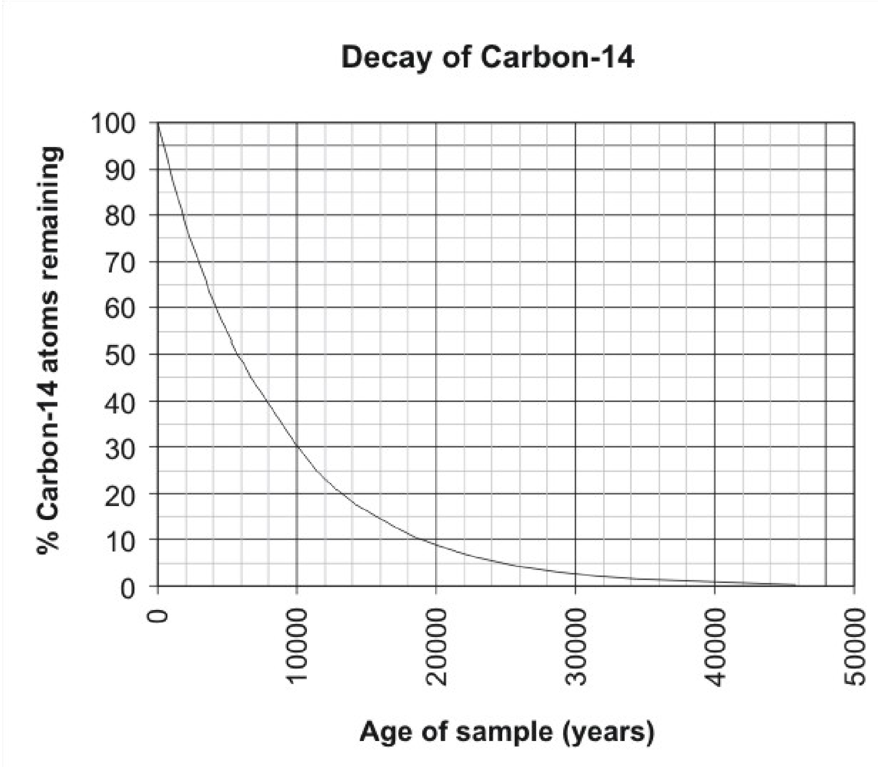
Relative Dating

Stratigraphy and biostratigraphy can in general provide only relative dating (A was before B), which is often sufficient for studying evolution. This is difficult for some time periods, however, because of the barriers involved in matching rocks of the same age across continents. Family-tree relationships can help to narrow down the date when lineages first appeared. For example, if fossils of B date to X million years ago and the calculated “family tree” says A was an ancestor of B, then A must have evolved earlier.

It is also possible to estimate how long ago two living branches of a family tree diverged by assuming that DNA mutations accumulate at a constant rate. However, these “molecular clocks” are sometimes inaccurate and provide only approximate timing. For example, they are not sufficiently precise and reliable for estimating when the groups that feature in the Cambrian explosion first evolved, and estimates produced by different approaches to this method may vary as well.

Carbon Dating

Together with stratigraphic principles, radiometric dating methods are used in geochronology to establish the geological time scale. Beds that preserve fossils typically lack the radioactive elements needed for radiometric dating (” radiocarbon dating ” or simply “carbon dating”). The principle of radiocarbon dating is simple: the rates at which various radioactive elements decay are known, and the ratio of the radioactive element to its decay products shows how long the radioactive element has existed in the rock. This rate is represented by the half-life, which is the time it takes for half of a sample to decay.



Half-life of Carbon-14: Radiometric dating is a technique used to date materials such as rocks or carbon, usually based on a comparison between the observed abundance of a naturally occurring radioactive isotope and its decay products, using known decay rates.

The half-life of carbon-14 is 5,730 years, so carbon dating is only relevant for dating fossils less than 60,000 years old. Radioactive elements are common only in rocks with a volcanic origin, so the only fossil-bearing rocks that can be dated radiometrically are volcanic ash layers. Carbon dating uses the decay of carbon-14 to estimate the age of organic materials, such as wood and leather.

The Fossil Record and the Evolution of the Modern Horse

The detailed fossil record of horses has provided insight into their evolutionary progress.

The Fossil Record

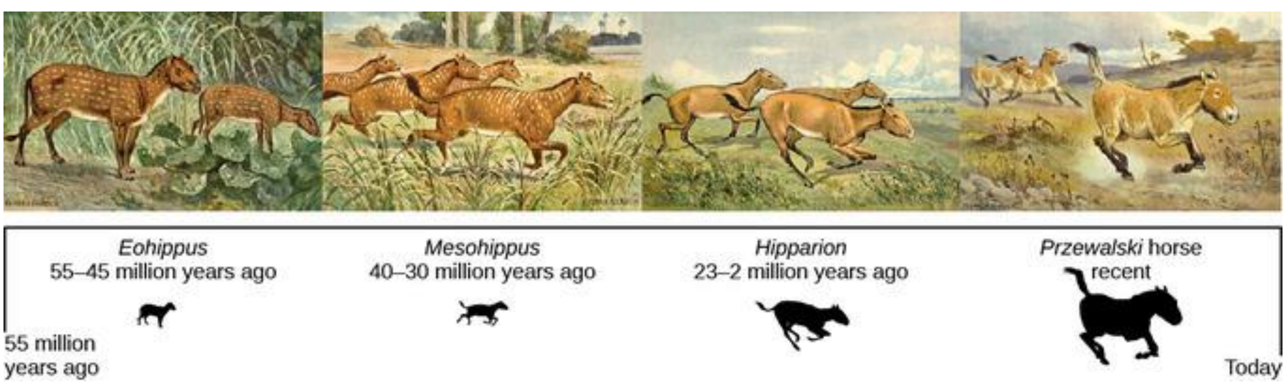
Fossils provide evidence that organisms from the past are not the same as those found today, and demonstrate a progression of evolution. Scientists date and categorize fossils to determine when the organisms lived relative to each other. The resulting fossil record tells the story of the past and shows the evolution of forms over millions of years.

Case Study: Evolution of the Modern Horse

Highly detailed fossil records have been recovered for sequences in the evolution of modern horses. The fossil record of horses in North America is especially rich and contains transition fossils: fossils that show intermediate stages between earlier and later forms. The fossil record extends back to a dog-like ancestor some 55 million years ago, which gave rise to the first horse-like species 55 to 42 million years ago in the genus *Eohippus*.

The first equid fossil was found in the gypsum quarries in Montmartre, Paris in the 1820s. The tooth was sent to the Paris Conservatory, where Georges Cuvier identified it as a browsing equine related to the tapir. His sketch of the entire animal matched later skeletons found at the site. During the H.M.S. Beagle survey expedition, Charles Darwin had remarkable success with fossil hunting in Patagonia. In 1833 in Santa Fe, Argentina, he was “filled with astonishment” when he found a horse’s tooth in the same stratum as fossils of giant armadillos and wondered if it might have been washed down from a later layer, but concluded this was “not very probable.” In 1836, the anatomist Richard Owen confirmed the tooth was from an extinct species, which he subsequently named *Equus curvidens*.

The original sequence of species believed to have evolved into the horse was based on fossils discovered in North America in the 1870s by paleontologist Othniel Charles Marsh. The sequence, from *Eohippus* to the modern horse (*Equus*), was popularized by Thomas Huxley and became one of the most widely known examples of a clear evolutionary progression. The sequence of transitional fossils was assembled by the American Museum of Natural History into an exhibit that emphasized the gradual, “straight-line”
evolution of the horse.



Horse evolution: This illustration shows an artist’s renderings of species derived from fossils of the evolutionary history of the horse and its ancestors. The species depicted are only four from a very diverse lineage that contains many branches, dead ends, and adaptive radiations. One of the trends, depicted here, is the evolutionary tracking of a drying climate and increase in prairie versus forest habitat reflected in forms that are more adapted to grazing and predator escape through running.

Since then, as the number of equid fossils has increased, the actual evolutionary progression from *Eohippus* to *Equus* has been discovered to be much more complex and multibranched than was initially supposed. Detailed fossil information on the rate and distribution of new equid species has also revealed that the progression between species was not as smooth and consistent as was once believed.

Although some transitions were indeed gradual progressions, a number of others were relatively abrupt in geologic time, taking place over only a few million years. Both anagenesis, a gradual change in an entire population 's gene frequency, and cladogenesis, a population "splitting" into two distinct evolutionary branches, occurred, and many species coexisted with "ancestor" species at various times.

Adaptation for Grazing

The series of fossils tracks the change in anatomy resulting from a gradual drying trend that changed the landscape from a forested habitat to a prairie habitat. Early horse ancestors were originally specialized for tropical forests, while modern horses are now adapted to life on drier land. Successive fossils show the evolution of teeth shapes and foot and leg anatomy to a grazing habit with adaptations for escaping predators.

The horse belongs to the order Perissodactyla (odd-toed ungulates), the members of which all share hoofed feet and an odd number of toes on each foot, as well as mobile upper lips and a similar tooth structure. This means that horses share a common ancestry with tapirs and rhinoceroses. Later species showed gains in size, such as those of *Hipparion*, which existed from about 23 to 2 million years ago. The fossil record shows several adaptive radiations in the horse lineage, which is now much reduced to only one genus, *Equus*, with several species. Paleozoologists have been able to piece together a more complete outline of the modern horse's evolutionary lineage than that of any other animal.

Biogeography and the Distribution of Species

The biological distribution of species is based on the movement of tectonic plates over a period of time.

Distribution of Species

Biogeography is the study of the geographic distribution of living things and the abiotic factors that affect their distribution. Abiotic factors, such as temperature and rainfall, vary based on latitude and elevation, primarily. As these abiotic factors change, the composition of plant and animal communities also changes.

Patterns of Species Distribution

Ecologists who study biogeography examine patterns of species distribution. No species exists everywhere; for example, the Venus flytrap is endemic to a small area in North and South Carolina. An endemic species is one which is naturally found only in a specific geographic area that is usually restricted in size. Other species are generalists: species which live in a wide variety of geographic areas; the raccoon, for example, is native to most of North and Central America.

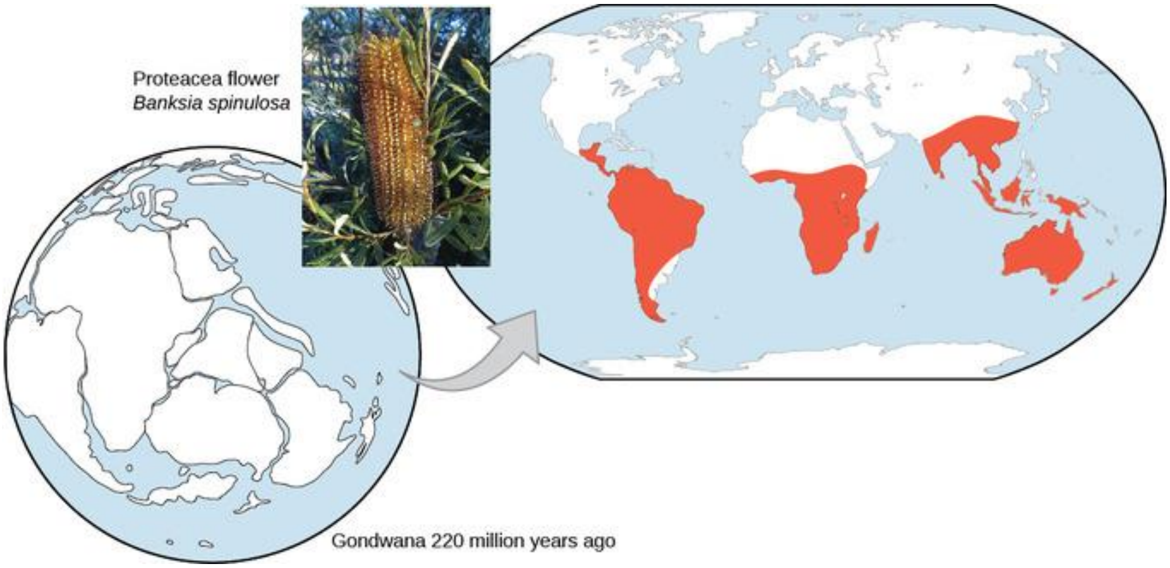
Since species distribution patterns are based on biotic and abiotic factors and their influences during the very long periods of time required for species evolution, early studies of biogeography were closely linked to the emergence of evolutionary thinking in the eighteenth century. Some of the most distinctive assemblages of plants and animals occur in regions that have been physically separated for millions of years by geographic barriers. Biologists estimate that Australia, for example, has between 600,000 and 700,000 species of plants and animals. Approximately 3/4 of living plant and mammal species are endemic species found solely in Australia.


(a) (b)

Australia: Australia is home to many endemic species. The (a) wallaby (*Wallabia bicolor*), a medium-sized member of the kangaroo family, is a pouched mammal, or marsupial. The (b) echidna (*Tachyglossus aculeatus*) is an egg-laying mammal.

The geographic distribution of organisms on the planet follows patterns that are best explained by evolution in conjunction with the movement of tectonic plates over geological time. Broad groups that evolved before the breakup of the supercontinent Pangaea (about 200 million years ago) are distributed worldwide. Groups that evolved since the breakup appear uniquely in regions of the planet, such as the unique flora and fauna of northern continents that formed from the supercontinent Laurasia and of the southern continents that formed from the supercontinent Gondwana. The presence of

Proteaceae in Australia, southern Africa, and South America is best explained by the plant family's presence there prior to the southern supercontinent Gondwana breaking up.



Biogeography: The Proteacea family of plants evolved before the supercontinent Gondwana broke up. Today, members of this plant family are found throughout the southern hemisphere (shown in red).