

= Paleontology =

Paleontology or palaeontology (/ ˈpeɪləntɒlədʒi / , / ˈpeɪləntɒlədʒi / or / ˈpæləntɒlədʒi / , / ˈpæləntɒlədʒi /) is the scientific study of life that existed prior to , and sometimes including , the start of the Holocene Epoch (roughly 11 @, @ 700 years before present) . It includes the study of fossils to determine organisms ' evolution and interactions with each other and their environments (their paleoecology) . Paleontological observations have been documented as far back as the 5th century BC . The science became established in the 18th century as a result of Georges Cuvier 's work on comparative anatomy , and developed rapidly in the 19th century . The term itself originates from Greek ??????? , palaios , i.e. " old , ancient " , ?? , on (gen. ontos) , i.e. " being , creature " and ????? , logos , i.e. " speech , thought , study " .

Paleontology lies on the border between biology and geology , but differs from archaeology in that it excludes the study of anatomically modern humans . It now uses techniques drawn from a wide range of sciences , including biochemistry , mathematics , and engineering . Use of all these techniques has enabled paleontologists to discover much of the evolutionary history of life , almost all the way back to when Earth became capable of supporting life , about 3 @, @ 800 million years ago . As knowledge has increased , paleontology has developed specialised sub @-@ divisions , some of which focus on different types of fossil organisms while others study ecology and environmental history , such as ancient climates .

Body fossils and trace fossils are the principal types of evidence about ancient life , and geochemical evidence has helped to decipher the evolution of life before there were organisms large enough to leave body fossils . Estimating the dates of these remains is essential but difficult : sometimes adjacent rock layers allow radiometric dating , which provides absolute dates that are accurate to within 0 @. @ 5 % , but more often paleontologists have to rely on relative dating by solving the " jigsaw puzzles " of biostratigraphy . Classifying ancient organisms is also difficult , as many do not fit well into the Linnean taxonomy that is commonly used for classifying living organisms , and paleontologists more often use cladistics to draw up evolutionary " family trees " . The final quarter of the 20th century saw the development of molecular phylogenetics , which investigates how closely organisms are related by measuring how similar the DNA is in their genomes . Molecular phylogenetics has also been used to estimate the dates when species diverged , but there is controversy about the reliability of the molecular clock on which such estimates depend .

= = Overview = =

The simplest definition is " the study of ancient life " . Paleontology seeks information about several aspects of past organisms : " their identity and origin , their environment and evolution , and what they can tell us about the Earth 's organic and inorganic past " .

= = = A historical science = = =

Paleontology is one of the historical sciences , along with archaeology , geology , astronomy , cosmology , philology and history itself . This means that it aims to describe phenomena of the past and reconstruct their causes . Hence it has three main elements : description of the phenomena ; developing a general theory about the causes of various types of change ; and applying those theories to specific facts .

When trying to explain past phenomena , paleontologists and other historical scientists often construct a set of hypotheses about the causes and then look for a smoking gun , a piece of evidence that indicates that one hypothesis is a better explanation than others . Sometimes the smoking gun is discovered by a fortunate accident during other research . For example , the discovery by Luis Alvarez and Walter Alvarez of an iridium @-@ rich layer at the Cretaceous ? Tertiary boundary made asteroid impact and volcanism the most favored explanations for the Cretaceous ? Paleogene extinction event .

The other main type of science is experimental science , which is often said to work by conducting experiments to disprove hypotheses about the workings and causes of natural phenomena ? note that this approach cannot confirm a hypothesis is correct , since some later experiment may disprove it . However , when confronted with totally unexpected phenomena , such as the first evidence for invisible radiation , experimental scientists often use the same approach as historical scientists : construct a set of hypotheses about the causes and then look for a " smoking gun " .

= = = Related sciences = = =

Paleontology lies on the boundary between biology and geology since paleontology focuses on the record of past life but its main source of evidence is fossils , which are found in rocks . For historical reasons paleontology is part of the geology departments of many universities , because in the 19th century and early 20th century geology departments found paleontological evidence important for estimating the ages of rocks while biology departments showed little interest .

Paleontology also has some overlap with archaeology , which primarily works with objects made by humans and with human remains , while paleontologists are interested in the characteristics and evolution of humans as organisms . When dealing with evidence about humans , archaeologists and paleontologists may work together ? for example paleontologists might identify animal or plant fossils around an archaeological site , to discover what the people who lived there ate ; or they might analyze the climate at the time when the site was inhabited by humans .

In addition paleontology often uses techniques derived from other sciences , including biology , osteology , ecology , chemistry , physics and mathematics . For example , geochemical signatures from rocks may help to discover when life first arose on Earth , and analyses of carbon isotope ratios may help to identify climate changes and even to explain major transitions such as the Permian ? Triassic extinction event . A relatively recent discipline , molecular phylogenetics , often helps by using comparisons of different modern organisms ' DNA and RNA to re @-@ construct evolutionary " family trees " ; it has also been used to estimate the dates of important evolutionary developments , although this approach is controversial because of doubts about the reliability of the " molecular clock " . Techniques developed in engineering have been used to analyse how ancient organisms might have worked , for example how fast Tyrannosaurus could move and how powerful its bite was . It is relatively commonplace to study fossils using X @-@ ray microtomography A combination of paleontology , biology , and archaeology , paleoneurology is the study of endocranial casts (or endocasts) of species related to humans to learn about the evolution of human brains .

Paleontology even contributes to astrobiology , the investigation of possible life on other planets , by developing models of how life may have arisen and by providing techniques for detecting evidence of life .

= = = Subdivisions = = =

As knowledge has increased , paleontology has developed specialised subdivisions . Vertebrate paleontology concentrates on fossils of vertebrates , from the earliest fish to the immediate ancestors of modern mammals . Invertebrate paleontology deals with fossils of invertebrates such as molluscs , arthropods , annelid worms and echinoderms . Paleobotany focuses on the study of fossil plants , but traditionally includes the study of fossil algae and fungi . Palynology , the study of pollen and spores produced by land plants and protists , straddles the border between paleontology and botany , as it deals with both living and fossil organisms . Micropaleontology deals with all microscopic fossil organisms , regardless of the group to which they belong .

Instead of focusing on individual organisms , paleoecology examines the interactions between different organisms , such as their places in food chains , and the two @-@ way interaction between organisms and their environment . One example is the development of oxygenic photosynthesis by bacteria , which hugely increased the productivity and diversity of ecosystems . This also caused the oxygenation of the atmosphere . Together , these were a prerequisite for the evolution of the most complex eukaryotic cells , from which all multicellular organisms are built .

Paleoclimatology , although sometimes treated as part of paleoecology , focuses more on the history of Earth 's climate and the mechanisms that have changed it ? which have sometimes included evolutionary developments , for example the rapid expansion of land plants in the Devonian period removed more carbon dioxide from the atmosphere , reducing the greenhouse effect and thus helping to cause an ice age in the Carboniferous period .

Biostratigraphy , the use of fossils to work out the chronological order in which rocks were formed , is useful to both paleontologists and geologists . Biogeography studies the spatial distribution of organisms , and is also linked to geology , which explains how Earth 's geography has changed over time .

=== Body fossils ===

Fossils of organisms ' bodies are usually the most informative type of evidence . The most common types are wood , bones , and shells . Fossilisation is a rare event , and most fossils are destroyed by erosion or metamorphism before they can be observed . Hence the fossil record is very incomplete , increasingly so further back in time . Despite this , it is often adequate to illustrate the broader patterns of life 's history . There are also biases in the fossil record : different environments are more favorable to the preservation of different types of organism or parts of organisms . Further , only the parts of organisms that were already mineralised are usually preserved , such as the shells of molluscs . Since most animal species are soft @-@ bodied , they decay before they can become fossilised . As a result , although there are 30 @-@ plus phyla of living animals , two @-@ thirds have never been found as fossils .

Occasionally , unusual environments may preserve soft tissues . These lagerstätten allow paleontologists to examine the internal anatomy of animals that in other sediments are represented only by shells , spines , claws , etc . ? if they are preserved at all . However , even lagerstätten present an incomplete picture of life at the time . The majority of organisms living at the time are probably not represented because lagerstätten are restricted to a narrow range of environments , e.g. where soft @-@ bodied organisms can be preserved very quickly by events such as mudslides ; and the exceptional events that cause quick burial make it difficult to study the normal environments of the animals . The sparseness of the fossil record means that organisms are expected to exist long before and after they are found in the fossil record ? this is known as the Signor @-@ Lipps effect .

=== Trace fossils ===

Trace fossils consist mainly of tracks and burrows , but also include coprolites (fossil feces) and marks left by feeding . Trace fossils are particularly significant because they represent a data source that is not limited to animals with easily fossilised hard parts , and they reflect organisms ' behaviours . Also many traces date from significantly earlier than the body fossils of animals that are thought to have been capable of making them . Whilst exact assignment of trace fossils to their makers is generally impossible , traces may for example provide the earliest physical evidence of the appearance of moderately complex animals (comparable to earthworms) .

=== Geochemical observations ===

Geochemical observations may help to deduce the global level of biological activity , or the affinity of certain fossils . For example , geochemical features of rocks may reveal when life first arose on Earth , and may provide evidence of the presence of eukaryotic cells , the type from which all multicellular organisms are built . Analyses of carbon isotope ratios may help to explain major transitions such as the Permian ? Triassic extinction event .

=== Classifying ancient organisms ===

Naming groups of organisms in a way that is clear and widely agreed is important, as some disputes in paleontology have been based just on misunderstandings over names. Linnean taxonomy is commonly used for classifying living organisms, but runs into difficulties when dealing with newly discovered organisms that are significantly different from known ones. For example: it is hard to decide at what level to place a new higher taxonomic level grouping, e.g. genus or family or order; this is important since the Linnean rules for naming groups are tied to their levels, and hence if a group is moved to a different level it must be renamed.

Paleontologists generally use approaches based on cladistics, a technique for working out the evolutionary "family tree" of a set of organisms. It works by the logic that, if groups B and C have more similarities to each other than either has to group A, then B and C are more closely related to each other than either is to A. Characters that are compared may be anatomical, such as the presence of a notochord, or molecular, by comparing sequences of DNA or proteins. The result of a successful analysis is a hierarchy of clades: groups that share a common ancestor. Ideally the "family tree" has only two branches leading from each node ("junction"), but sometimes there is too little information to achieve this and paleontologists have to make do with junctions that have several branches. The cladistic technique is sometimes fallible, as some features, such as wings or camera eyes, evolved more than once, convergently; this must be taken into account in analyses.

Evolutionary developmental biology, commonly abbreviated to "Evo Devo", also helps paleontologists to produce "family trees", and understand fossils. For example, the embryological development of some modern brachiopods suggests that brachiopods may be descendants of the halkieriids, which became extinct in the Cambrian period.

= = Estimating the dates of organisms = =

Paleontology seeks to map out how living things have changed through time. A substantial hurdle to this aim is the difficulty of working out how old fossils are. Beds that preserve fossils typically lack the radioactive elements needed for radiometric dating. This technique is our only means of giving rocks greater than about 50 million years old an absolute age, and can be accurate to within 0.5% or better. Although radiometric dating requires very careful laboratory work, its basic principle is simple: the rates at which various radioactive elements decay are known, and so the ratio of the radioactive element to the element into which it decays shows how long ago the radioactive element was incorporated into the rock. Radioactive elements are common only in rocks with a volcanic origin, and so the only fossil-bearing rocks that can be dated radiometrically are a few volcanic ash layers.

Consequently, paleontologists must usually rely on stratigraphy to date fossils. Stratigraphy is the science of deciphering the "layer cake" that is the sedimentary record, and has been compared to a jigsaw puzzle. Rocks normally form relatively horizontal layers, with each layer younger than the one underneath it. If a fossil is found between two layers whose ages are known, the fossil's age must lie between the two known ages. Because rock sequences are not continuous, but may be broken up by faults or periods of erosion, it is very difficult to match up rock beds that are not directly next to one another. However, fossils of species that survived for a relatively short time can be used to link up isolated rocks: this technique is called biostratigraphy. For instance, the conodont *Eoplacognathus pseudoplanus* has a short range in the Middle Ordovician period. If rocks of unknown age are found to have traces of *E. pseudoplanus*, they must have a mid-Ordovician age. Such index fossils must be distinctive, be globally distributed and have a short time range to be useful. However, misleading results are produced if the index fossils turn out to have longer fossil ranges than first thought. Stratigraphy and biostratigraphy can in general provide only relative dating (A was before B), which is often sufficient for studying evolution. However, this is difficult for some time periods, because of the problems involved in matching up rocks of the same age across different continents.

Family tree relationships may also help to narrow down the date when lineages first appeared. For instance, if fossils of B or C date to X million years ago and the calculated "family tree" says

A was an ancestor of B and C , then A must have evolved more than X million years ago .

It is also possible to estimate how long ago two living clades diverged ? i.e. approximately how long ago their last common ancestor must have lived ? by assuming that DNA mutations accumulate at a constant rate . These " molecular clocks " , however , are fallible , and provide only a very 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 techniques may vary by a factor of two .

= = Overview of the history of life = =

The evolutionary history of life stretches back to over 3.8 billion years ago , possibly as far as 4.1 billion years ago . Earth formed about 4.5 billion years ago and , after a collision that formed the Moon about 40 million years later , may have cooled quickly enough to have oceans and an atmosphere about 4.4 billion years ago . However , there is evidence on the Moon of a Late Heavy Bombardment from 4.0 billion to 3.8 billion years ago . If , as seems likely , such a bombardment struck Earth at the same time , the first atmosphere and oceans may have been stripped away . The oldest clear evidence of life on Earth dates to 3.8 billion years ago , although there have been reports , often disputed , of fossil bacteria from 3.4 billion years ago and of geochemical evidence for the presence of life 3.8 billion years ago . Some scientists have proposed that life on Earth was " seeded " from elsewhere , but most research concentrates on various explanations of how life could have arisen independently on Earth .

For about 2.8 billion years microbial mats , multi-layered colonies of different types of bacteria , were the dominant life on Earth . The evolution of oxygenic photosynthesis enabled them to play the major role in the oxygenation of the atmosphere from about 2.4 billion years ago . This change in the atmosphere increased their effectiveness as nurseries of evolution . While eukaryotes , cells with complex internal structures , may have been present earlier , their evolution speeded up when they acquired the ability to transform oxygen from a poison to a powerful source of energy in their metabolism . This innovation may have come from primitive eukaryotes capturing oxygen-powered bacteria as endosymbionts and transforming them into organelles called mitochondria . The earliest evidence of complex eukaryotes with organelles such as mitochondria , dates from 1.8 billion years ago .

Multicellular life is composed only of eukaryotic cells , and the earliest evidence for it is the Francevillian Group Fossils from 2.1 billion years ago , although specialisation of cells for different functions first appears between 1.4 billion years ago (a possible fungus) and 1.2 billion years ago (a probable red alga) . Sexual reproduction may be a prerequisite for specialisation of cells , as an asexual multicellular organism might be at risk of being taken over by rogue cells that retain the ability to reproduce .

The earliest known animals are cnidarians from about 580 million years ago , but these are so modern-looking that the earliest animals must have appeared before then . Early fossils of animals are rare because they did not develop mineralised hard parts that fossilise easily until about 548 million years ago . The earliest modern-looking bilaterian animals appear in the Early Cambrian , along with several " weird wonders " that bear little obvious resemblance to any modern animals . There is a long-running debate about whether this Cambrian explosion was truly a very rapid period of evolutionary experimentation ; alternative views are that modern-looking animals began evolving earlier but fossils of their precursors have not yet been found , or that the " weird wonders " are evolutionary " aunts " and " cousins " of modern groups . Vertebrates remained an obscure group until the first fish with jaws appeared in the Late Ordovician .

The spread of life from water to land required organisms to solve several problems , including protection against drying out and supporting themselves against gravity . The earliest evidence of land plants and land invertebrates date back to about 476 million years ago and 490 million years ago respectively . The lineage that produced land vertebrates evolved later but very rapidly between 370 million years ago and 360 million years ago ; recent discoveries have overturned earlier ideas

about the history and driving forces behind their evolution . Land plants were so successful that they caused an ecological crisis in the Late Devonian , until the evolution and spread of fungi that could digest dead wood .

During the Permian period synapsids , including the ancestors of mammals , may have dominated land environments , but the Permian ? Triassic extinction event 251 million years ago came very close to wiping out complex life . The extinctions were apparently fairly sudden , at least among vertebrates . During the slow recovery from this catastrophe a previously obscure group , archosaurs , became the most abundant and diverse terrestrial vertebrates . One archosaur group , the dinosaurs , were the dominant land vertebrates for the rest of the Mesozoic , and birds evolved from one group of dinosaurs . During this time mammals ' ancestors survived only as small , mainly nocturnal insectivores , but this apparent setback may have accelerated the development of mammalian traits such as endothermy and hair . After the Cretaceous ? Paleogene extinction event 65 million years ago killed off the non avian dinosaurs ? birds are the only surviving dinosaurs ? mammals increased rapidly in size and diversity , and some took to the air and the sea .

Fossil evidence indicates that flowering plants appeared and rapidly diversified in the Early Cretaceous , between 130 million years ago and 90 million years ago . Their rapid rise to dominance of terrestrial ecosystems is thought to have been propelled by coevolution with pollinating insects . Social insects appeared around the same time and , although they account for only small parts of the insect " family tree " , now form over 50 % of the total mass of all insects .

Humans evolved from a lineage of upright walking apes whose earliest fossils date from over 6 million years ago . Although early members of this lineage had chimp sized brains , about 25 % as big as modern humans ' , there are signs of a steady increase in brain size after about 3 million years ago . There is a long running debate about whether modern humans are descendants of a single small population in Africa , which then migrated all over the world less than 200 000 years ago and replaced previous hominine species , or arose worldwide at the same time as a result of interbreeding .

== = Mass extinctions == =

Life on earth has suffered occasional mass extinctions at least since 542 million years ago . Although they are disasters at the time , mass extinctions have sometimes accelerated the evolution of life on earth . When dominance of particular ecological niches passes from one group of organisms to another , it is rarely because the new dominant group is " superior " to the old and usually because an extinction event eliminates the old dominant group and makes way for the new one .

The fossil record appears to show that the rate of extinction is slowing down , with both the gaps between mass extinctions becoming longer and the average and background rates of extinction decreasing . However , it is not certain whether the actual rate of extinction has altered , since both of these observations could be explained in several ways :

The oceans may have become more hospitable to life over the last 500 million years and less vulnerable to mass extinctions : dissolved oxygen became more widespread and penetrated to greater depths ; the development of life on land reduced the runoff of nutrients and hence the risk of eutrophication and anoxic events ; marine ecosystems became more diversified so that food chains were less likely to be disrupted .

Reasonably complete fossils are very rare , most extinct organisms are represented only by partial fossils , and complete fossils are rarest in the oldest rocks . So paleontologists have mistakenly assigned parts of the same organism to different genera , which were often defined solely to accommodate these finds ? the story of *Anomalocaris* is an example of this . The risk of this mistake is higher for older fossils because these are often unlike parts of any living organism . Many " superfluous " genera are represented by fragments that are not found again , and these " superfluous " genera appear to become extinct very quickly .

Biodiversity in the fossil record , which is

" the number of distinct genera alive at any given time ; that is , those whose first occurrence

predates and whose last occurrence postdates that time "

shows a different trend : a fairly swift rise from 542 to 400 million years ago , a slight decline from 400 to 200 million years ago , in which the devastating Permian ? Triassic extinction event is an important factor , and a swift rise from 200 million years ago to the present .

= = History of paleontology = =

Although paleontology became established around 1800 , earlier thinkers had noticed aspects of the fossil record . The ancient Greek philosopher Xenophanes (570 ? 480 BC) concluded from fossil sea shells that some areas of land were once under water . During the Middle Ages the Persian naturalist Ibn Sina , known as Avicenna in Europe , discussed fossils and proposed a theory of petrifying fluids on which Albert of Saxony elaborated in the 14th century . The Chinese naturalist Shen Kuo (1031 ? 1095) proposed a theory of climate change based on the presence of petrified bamboo in regions that in his time were too dry for bamboo .

In early modern Europe , the systematic study of fossils emerged as an integral part of the changes in natural philosophy that occurred during the Age of Reason . In the Italian Renaissance , Leonardo Da Vinci made various significant contributions to the field as well designed numerous fossils . At the end of the 18th century Georges Cuvier 's work established comparative anatomy as a scientific discipline and , by proving that some fossil animals resembled no living ones , demonstrated that animals could become extinct , leading to the emergence of paleontology . The expanding knowledge of the fossil record also played an increasing role in the development of geology , particularly stratigraphy .

The first half of the 19th century saw geological and paleontological activity become increasingly well organised with the growth of geologic societies and museums and an increasing number of professional geologists and fossil specialists . Interest increased for reasons that were not purely scientific , as geology and paleontology helped industrialists to find and exploit natural resources such as coal .

This contributed to a rapid increase in knowledge about the history of life on Earth and to progress in the definition of the geologic time scale , largely based on fossil evidence . In 1822 Henri Marie Ducrotay de Blanville , editor of *Journal de Physique* , coined the word " palaeontology " to refer to the study of ancient living organisms through fossils . As knowledge of life 's history continued to improve , it became increasingly obvious that there had been some kind of successive order to the development of life . This encouraged early evolutionary theories on the transmutation of species . After Charles Darwin published *Origin of Species* in 1859 , much of the focus of paleontology shifted to understanding evolutionary paths , including human evolution , and evolutionary theory .

The last half of the 19th century saw a tremendous expansion in paleontological activity , especially in North America . The trend continued in the 20th century with additional regions of the Earth being opened to systematic fossil collection . Fossils found in China near the end of the 20th century have been particularly important as they have provided new information about the earliest evolution of animals , early fish , dinosaurs and the evolution of birds . The last few decades of the 20th century saw a renewed interest in mass extinctions and their role in the evolution of life on Earth . There was also a renewed interest in the Cambrian explosion that apparently saw the development of the body plans of most animal phyla . The discovery of fossils of the Ediacaran biota and developments in paleobiology extended knowledge about the history of life back far before the Cambrian .

Increasing awareness of Gregor Mendel 's pioneering work in genetics led first to the development of population genetics and then in the mid @-@ 20th century to the modern evolutionary synthesis , which explains evolution as the outcome of events such as mutations and horizontal gene transfer , which provide genetic variation , with genetic drift and natural selection driving changes in this variation over time . Within the next few years the role and operation of DNA in genetic inheritance were discovered , leading to what is now known as the " Central Dogma " of molecular biology . In the 1960s molecular phylogenetics , the investigation of evolutionary " family trees " by techniques derived from biochemistry , began to make an impact , particularly when it was proposed that the human lineage had diverged from apes much more recently than was generally thought at the time .

Although this early study compared proteins from apes and humans , most molecular phylogenetics research is now based on comparisons of RNA and DNA .