Introducing Palaeontology

A Guide to Ancient Life

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DUNEDIN

1.1 Preface: the fascination of fossils

Fossils are the remains of plants and animals that lived in the past, and which are now frequently, but not necessarily always, preserved in stone. They may be found either as body fossils (Figure 1) which represent all or parts of the organism, or as trace fossils (Figure 2) which indicate the activities of the past organisms. Many years ago the term 'fossil' referred to anything that had been dug up, but now it is restricted to the remains of ancient organisms. Roman coins, old leather boots, and deposits of lead and zinc are not fossils, but trilobites and dinosaur eggs are. The study of fossils is called palaeontology and scientists who study fossils are called palaeontologists. The subject is generally studied as part of geology, the science that investigates the structure and history of the Earth and now adjacent planets.

This book has been written with two groups of readers in mind. Many members of the

Figure 1 The ammonites *Promicroceras planicosta* and *Asteroceras obtusum* from the Lower Jurassic of Marston Magna, Somerset, England. These are preserved in their original mother-of-pearl shell, and the rock is known as Marston Marble. [×1.7]

Figure 2 *Gigandipus*, a dinosaur footprint in the Lower Jurassic Moenave Formation at the St George Dinosaur Discovery Site at Johnson Farm, southwestern Utah, USA. [×0.5]

general public will be aware of fossils; those of Missouri in the USA are proud that crinoids are their State Fossil, but I suspect few residents of that State have a real grasp of the significance and nature of fossils. It is hoped that this book will develop and enhance the fascination of fossils amongst the general public. The book is also intended for first and second-year university students taking courses in geology, biology and palaeontology.

This book provides a broad introduction to palaeontology by means of two distinct sections. The first part discusses aspects and uses of the subject through a discussion of how to collect fossils responsibly, how to care for collections, and how to name and classify them. Fossil collections remain the staple diet for researchers. They act as the database that can be searched when new questions of old specimens need to be answered. Therefore collections should be cared for. Without taxonomy and associated rules of nomenclature it would be an impossible task to sift through the palaeontological literature and understand what fossils were being described. Many thousands of fossils have been named to date, and researchers from across the globe that meet can converse with each other by

Figure 3 An Eocene buccinid gastropod showing traces of the original shell coloration. [×2]

means of the taxonomic monikers applied to each fossil even though they may not understand each other enough to order a cup of coffee in each other's native language. Many answers about the nature of the past history of the Earth have been provided through the study of fossils, and this section outlines our current understanding of the Earth's past environments and climates as revealed by ancient organisms, and documents how geologists have used fossils to develop an ever more precise geological timescale. Graptolites have been used to subdivide parts of the Lower Palaeozoic into short time slices of not much more than 4 million years' duration. How fossils are formed and the ways in which they are preserved is discussed, and a number of case studies of exceptional preservation in the fossil record are provided. Where are jellyfish or soft-bodied worms preserved? How often is original colour preserved? (Figure 3) Fossils have been the subject of study for several hundred years and over time their significance and the understanding of what they represented has changed from being objects of local curiosity to objects of huge scientific value. The second part of this book provides an outline of the major fossil groups, their form and function, and their links to living floras and faunas, and this will enable the reader to broadly identify and understand a broad range of invertebrate and vertebrate fossils. From plants, to microfossils such as foraminifera and radiolarians, through the myriad of invertebrate animals such as bryozoans, corals, molluscs and graptolites, to the vertebrates, this part also contains a synopsis of our own human origins, as well as a section on trace fossils. Readers will gain an overall appreciation of the evolutionary record of life on Earth.

A glossary of terms that are highlighted in **bold** throughout the text is given at the end of the book, which is illustrated throughout by photographs, line drawings and diagrams.

1.2 A chancy business: the preservation of fossils

Fossils are rare objects: for every one fossil that is preserved, many thousands of once living organisms have disappeared. Why should this be? The potential for preservation is controlled by various factors. If the organism consists of only soft tissue then the chances of its preservation in the fossil record are very slim indeed. In some exceptional circumstances soft tissues are preserved (*see* Section 1.8). When an organism dies, almost immediately the soft tissues begin to decay under microbial action, and if this is not arrested soon only the hard parts will remain. These hard parts such as shells and bone are therefore most commonly preserved. Depending on the circumstances, delicate skeletal parts may get damaged, disintegrate and be lost, whereas in general, more robust portions survive. Equally the mineralogy of the skeleton or shelly material may determine whether preservation happens. Commonly shells are composed of the minerals **calcite** or **aragonite** ($CaCO_3$), **silica** (SiO_2) as in radiolarians and many sponges, **apatite** (calcium phosphate) as in the case of many teeth or conodonts. Aragonite is more unstable than calcite and is prone to dissolving away faster.

A great deal of information about the living organism can be lost following its death and before it is fossilised, and the longer this takes, the greater amount of information loss will occur. Palaeontologists attempt to determine the nature of the living organisms by gaining an understanding of the geological and biological processes that have affected the organism after death and before it finally became fossilised. This is called **taphonomy** and can be divided into two stages: **biostratinomy** which covers death to burial, and **diagenesis** which is the period from burial to fossilisation. If one takes a living organism or assemblage of organisms, then on death information is lost due to soft tissue decay that leaves the skeletal hard parts. These can then get disarticulated, fragmented by scavenging organisms, attacked by microorganisms that **bioerode** the hard parts, abraded by knocking against other hard surfaces, dissolved or dispersed by water currents or occasionally wind. Once buried, the hard parts that remain can dissolve away, may be replaced chemically, or can get flattened and distorted, and finally the fossils may form.

Therefore even though a great number of fossils have been found and described it is not surprising that palaeontologists consider that the fossil record is incomplete. As we have seen, the chances of survival in the fossil record depend on many variables. Preservation may occur in one geological setting at a certain place on the planet at a particular time in the past, but may for a variety of reasons not occur in the same or similar setting at a different place and time. Shells and skeletons may be selectively removed from one environmental or geological setting due to the nature of their mineralogy or their morphological form but may survive in pristine condition in another setting. The comparison of living assemblages and those of the past can sometimes indicate those organisms that may have disappeared from the former (should they have been there in the first place). If this can be determined then important information can be gathered on the taphonomic processes that affected the **fossil assemblage** that is now seen. Palaeontology is all about data gathering, however thin and slight, and interpretation of that data, and it is worthwhile remembering that fossilisation is a chancy business.

There are a number of states in which a plant or animals may be fossilised:

Moulds and Casts. When a shell has been buried in sediment (or a pair of conjoined shells buried and infilled with sediment) that subsequently hardens and becomes **lithified** the shell may dissolve away leaving a **mould** (or a hollow where the shell had been). The mould of the external surface of the shell is called an external mould (Figure 4A) and of the internal surface an internal mould (Figure 4B). Should the mould become infilled a **cast** of the original shell shape is produced, which could be either an external cast of the external surface of the shell (Figure 4C) or an internal cast of the internal surface of the shell. When only moulds are available for study palaeontologists will often produce a cast in latex rubber or plasticine for examination and photographing.

Original material. Sometimes the original material remains intact and chemically unaltered (Figure 5A). Many Cenozoic shells are preserved in this way, as are Woolly Mammoth carcasses frozen in ice, or Shark's Teeth from the Miocene (Figure 82). When preserved in limestone many graptolites retain their original **collagen periderm** and three-dimensional shape.

Permineralisation. Although appearing to be solid many shells are porous and also contain organic matter. Decay of the organic matter increases the porosity of the shells or bones, and these cavities may become infilled with calcite or silica or other additional minerals. This process is called **permineralisation** (Figure 5B). Delicate anatomical structures of plants such as **xylem** and **phloem** vessels and external **stomata** are preserved in this way.

Replacement. The skeletal material is replaced by another mineral such as iron pyrites or silica. Many fossils, such as the trilobites from Beecher's Trilobite Bed in New York, in

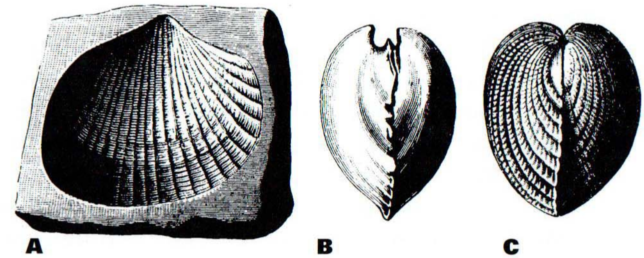


Figure 4 **A.** External mould of a single bivalve cockle shell; **B.** Internal mould of a conjoined pair of cockle shells; **C.** Exterior cast of a conjoined pair of cockle shells.

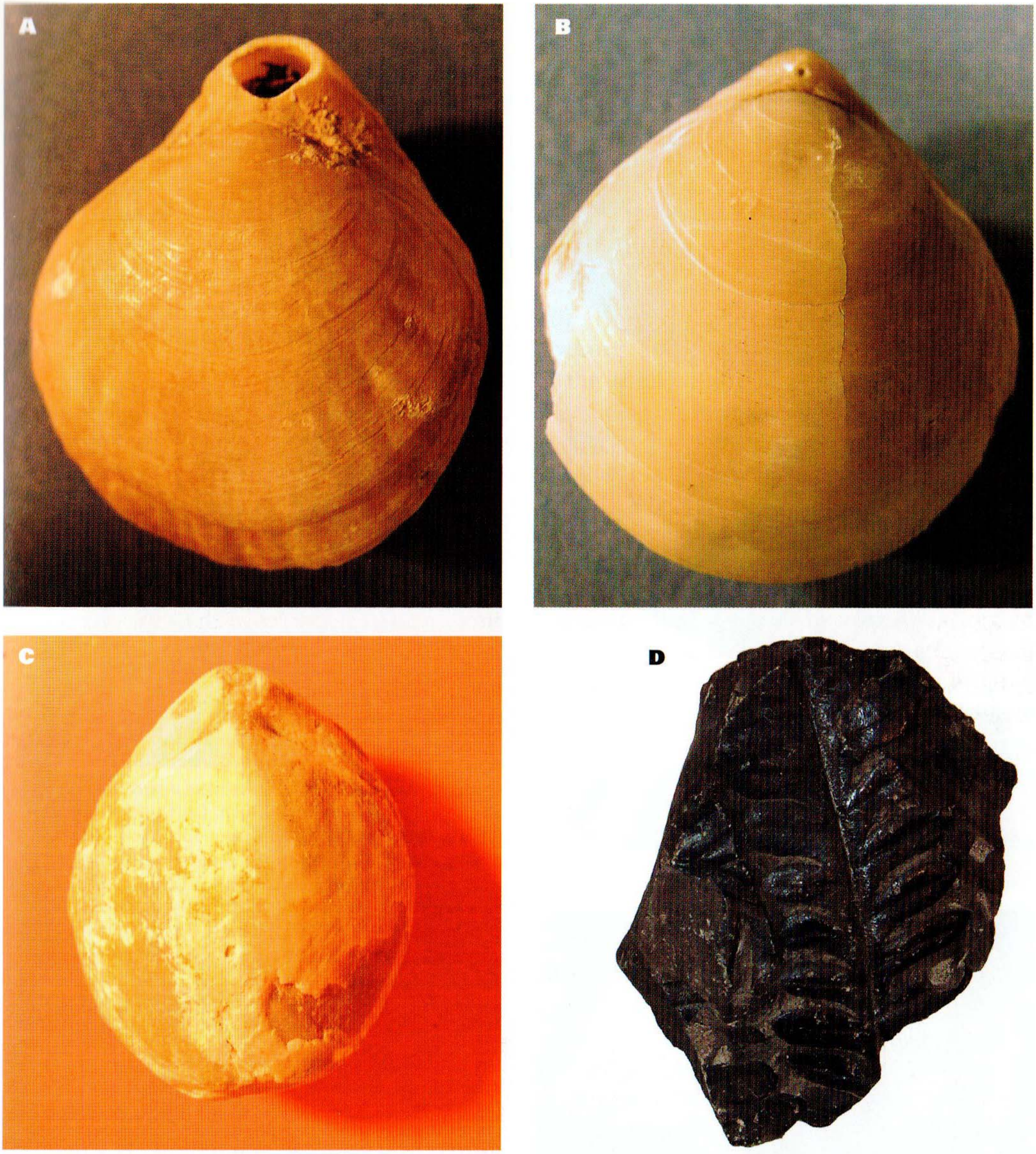
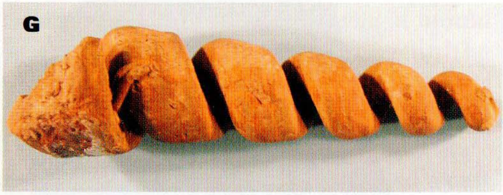


Figure 5 A–J Modes of preservation in fossils. **A.** Unaltered shell in the extant brachiopod *Magellania flavescens* from New South Wales, Australia [×2.25]; **B.** Permineralised shell of the brachiopod *Carneithyris carnea* from the Cretaceous of Norwich, England [×2.25]; **C.** Recrystallised shell of the brachiopod *Dielasma hastatum* from the Mississippian of Castleisland, Co. Kerry, Ireland [×1.7]; **D.** *Neuropteris*, a Pennsylvanian fern preserved in carbon as a compaction [×1]; ➲



➲ **Figure 5 (cont)** **E.** *Merocanites*, a pyritised goniatite from the Pennsylvanian of Rush, Co. Dublin, Ireland [×1.7]; **F.** *Gryphaea* from the Lower Jurassic of England preserved in silica forming a concentric circular pattern indicative of the variety beekite [×0.75]; **G.** Internal mould of a turritellid gastropod [×1]; **H.** Flattened ammonite preserved in clay [×0.5]; **I.** A flattened graptolite *Monograptus* preserved in clay from the Silurian of Co. Dublin, Ireland [×5]; ➲

which appendages are preserved, or some late Mississippian goniatites (Figure 5E), which are replicated in iron pyrites (FeS_2), suggest that they were deposited either in deep water or in **anoxic** iron sulphide rich sediments. Chemical replacement of the original shell subsequently took place. Replacement by silica, which in some instances can be **opaline** (Figure 5F),

➲ **Figure 5 (cont) J.** Deformed Cambrian trilobite preserved in shale [×0.7].

can often faithfully replicate the surface details of the fossil, but internal skeletal features are often obliterated. The useful feature of **siliceous** fossils is that they can be easily extracted from the surrounding matrix using weak acids such as acetic acid or hydrochloric acid. Such extraction should only be attempted in a dedicated laboratory fitted with a fume cupboard.

Carbonisation. Plant tissues that were rich in **cellulose** may become altered under the effects of pressure from overlying sediments to a film of carbon. These are called **compressions** and appear as black shiny fossils (Figure 5D). This mode of preservation is most often seen in the Pennsylvanian Coal Measures plants.

Recrystallisation. Under pressure of burial under sediment the original skeletal material of shells may become **recrystallised** (Figure 5C). If this happens, the original internal layering and orientation of the crystallites of the shell will be lost. Many Mississippian brachiopods are preserved in this way and the shell is preserved in coarse calcite.

Flattening and distortion. Fossils may become flattened under the pressure of overlying layers of sediment. Ammonites which are hollow often become compressed in clays (Figure 5H). Flattened graptolites are preserved in shale where the original periderm is frequently replaced with **chlorite** or other **clay minerals** (Figure 5I). Although flattened, many of the **crustaceans** found in the Solnhofen Limestone have retained their original **chitin** skeletons. In the Middle Cambrian Burgess Shale, a diverse assemblage of weird and wonderful animals have been preserved in a flattened state as a thin film of clay. When fossils are subjected to **tectonic activity** they can become distorted. Many Cambrian trilobites exhibit such features (Figure 5J), and by using computer restorations the degree of strain and the direction of stress can be evaluated and can provide structural geologists with essential data for tectonic reconstructions.

1.3 From the field to the laboratory: how to collect, curate and study fossils

It is probably true to say that the best collectors of fossils are firstly those with infinite patience, and secondly those who have seen a large number of fossils in the field. The first major collections were assembled in the late 1700s by various learned societies in European capitals, and in the 1800s by members of the landed gentry and by the more locally-based institutions of science and literature that developed in the growing urban centres across Europe. Today collecting is not the sole preserve of learned societies, nor indeed of academic palaeontologists, but the assembly of a good fossil collection is within the capability of almost anyone with a keen interest in the subject. However, if you are intending to collect fossils please give heed to a number of important rules that are outlined in the next section (1.4 Code of Conduct for Collectors).

Think before you collect – why are you collecting material? Is there a scientific question that needs investigation, and if so, what size of collection is required? If conducting a taxonomic revision of a particular **taxon** then a scientist may only need a dozen specimens, whereas a **palaeoecological** study that examines the interaction of organisms on a particular **bedding plane** or through a **succession** of bedding planes may need more material. Collect only the actual number of specimens that are needed. Sometimes the study can be conducted in the field without resorting to collecting specimens – perhaps it might be possible to produce replicas of bedding planes for further study in the laboratory. In some cases it is necessary to collect specimens before they are lost to natural erosion, or lost due to construction of roads or buildings. In other cases a fossil has been located that represents a new taxon and the palaeontologists require further information about the geological context in which it lived. This would require them to visit the site from which the specimen had been collected so that they could gather data about the fossiliferous rocks and the nature and preservation of the fossils themselves.

Preparations for collecting

Many people enjoy building up collections of fossils – they are beautiful objects that tell a fascinating story both about the animals and plants that they represent but also about the history of our planet when these organisms were alive. In order to ensure that your collection survives and that it is scientifically useful there are a number of steps that a collector should take.

Assemble the correct equipment for collecting (Figure 6). You will need a geological hammer – that with a chisel-end is preferable to that with a pick-end; a set of cold chisels; a pair of goggles with wrap-around sides; a hard hat; a compass clinometer for measuring

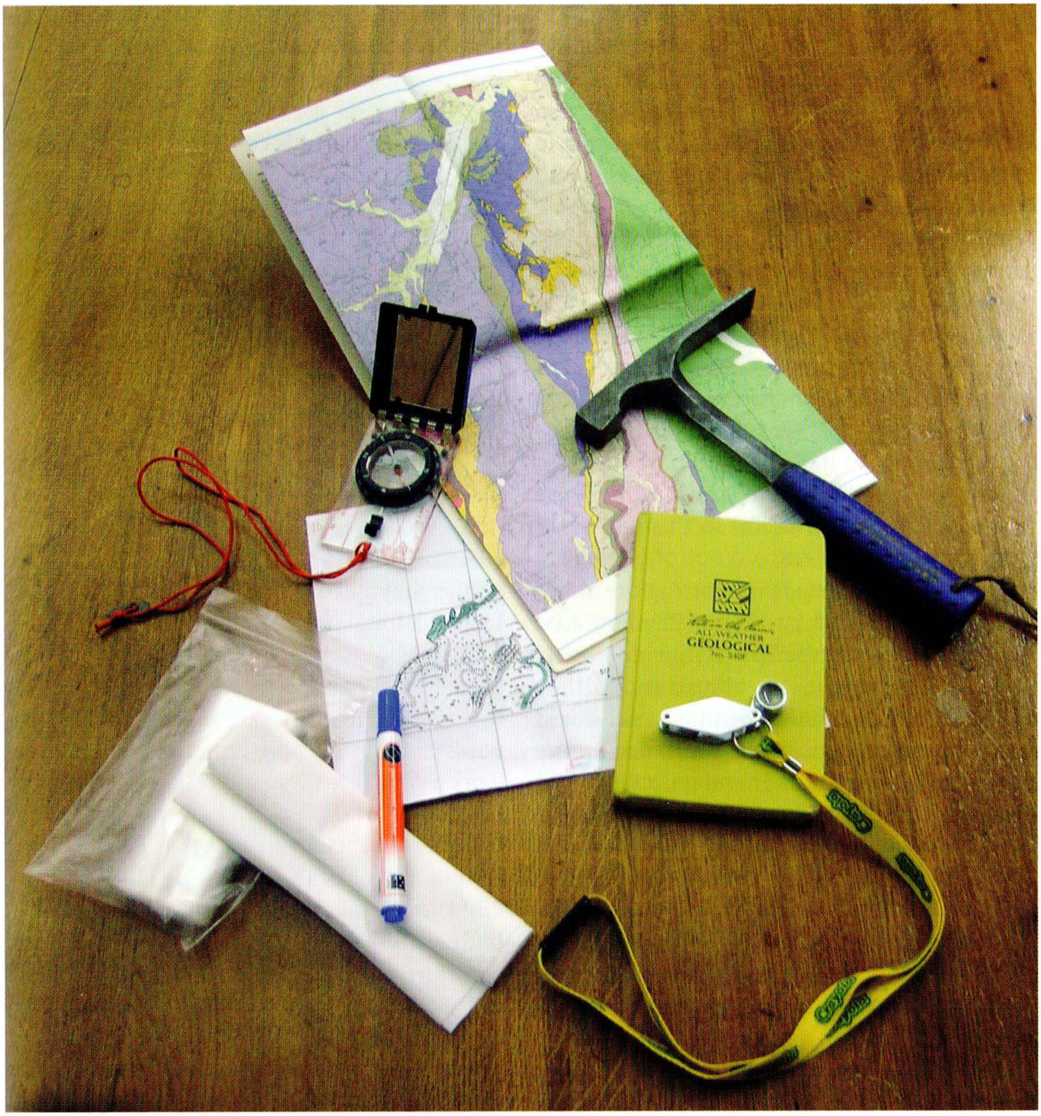


Figure 6 Equipment needed for collecting and transporting fossils in the field.

strike and dip of the fossiliferous rocks; plastic self-seal or zip-lock bags of different dimensions for packing your specimens into; small clear plastic tubes for storing small specimens; newspaper and kitchen paper for wrapping specimens; pencils for note taking; indelible markers for labelling the specimen or bag in which it has been placed; a strong canvas bag or rucksack to carry your specimens from the collecting locality to your transport. It is also essential that you carry a hand-lens with a magnification of at least × 10, as this is useful for examining fossils in the field.

It is useful to learn something about the geology of the area you intend visiting. The Geologists' Association has published many guides on the geology of the UK, which are good sources of information. In order to record information in the field, you should also obtain a set of Ordnance Survey Maps for the locality so that you can mark on them the precise location where you obtained your fossils. A GPS is also useful in this regard. In tandem with these maps a set of geological maps can be beneficial. Information about the fossils and geology of the site should be recorded in a weather-proof file notebook. Spiral-bound notebooks are useless, as they fall apart in bad weather – you should invest in a purpose geological notebook such as one from the 'Rite-in-the-Rain' range. You should ultimately be able to cross-reference the data in the notebook with the specimens, so it is very useful to develop an easily remembered code for particular collections. For example, 2010/1/001 would refer to the first location visited and collected on the first collecting trip of 2010.

Collecting

You are now ready to start collecting. Ideally any trip should be undertaken with a friend or friends. If venturing out alone, notify someone of where you plan to visit and when you plan to return. If you don't return, then a search party can be sent out. When you reach the fossiliferous locality spend some time just examining it (Figure 7A). Work out where the fossils occur: are they scattered throughout the rock or are they concentrated in one place; do all the **beds** contain the same fossils? This will enable you to decide where is best to collect from. If the location is pristine it would be a serious mistake to hammer extensively at it. Look around the site and you may locate an equally fossiliferous but scruffy **horizon** from which it would be preferable to collect.

At many sites the fossils have been eroded out of **limestones** and **clays** and can simply be picked up. It is also a good idea to collect some of the **muds** or clays, as these can be sieved in the laboratory or at home later in the hope of finding smaller microfossils. At other places such as beaches, fossils can be found in loose stones that make up the shingle. If you have to extract a fossil using your hammer and chisel, first assess whether it is going to be difficult to obtain the fossil in this way without breaking or smashing it. If so, leave it where it is. Otherwise, carefully use the hammer and chisel to work around the fossil from some distance and eventually it should loosen. In well-bedded fossiliferous rocks use your chisel and hammer to split the rocks along bedding planes (Figure 7B). Often fossils will be revealed in this way on both slabs – these are known as the **part and counterpart** and should both be saved, as part of the fossil may be present on one slab and the rest remaining on the other slab.

Once a fossil has been collected it should be carefully wrapped in kitchen paper or newspaper, which should then be labelled with the location code and placed in a self-seal or zip-lock plastic bag. Record the find in the notebook and place the bag beside your rucksack. At the end of the collecting session

Figure 7 **A.** Collecting fossils in the Ordovician of Ohio, USA; **B.** Splitting fine-grained Jurassic limestone along bedding planes, Solnhofen, Germany.

carefully pack the specimens, now in their individual bags, into the rucksack, making sure that the large heavy samples are at the bottom and the more delicate specimens are at the top. If necessary, pack newspaper between the bags to stop them bumping against each other, which might cause damage during transport home. If you have collected material abroad it is tempting to mail it home rather than pay any excess baggage charges levied by an airline. Pay the excess charges, because that way you know your specimens will get home, and you will not have to worry about the vagaries of the postal system.

Curation

Once in the laboratory or at home unpack the specimens carefully, retaining the collection codes that go with each specimen. Fossils may need to be cleaned, and for most this can be done either by dry brushing off excess dirt, or when wet, under a tap. In some instances placing a specimen in an **ultrasonic tank** of **deionised water** for 30 seconds or less can remove adherents that won't be removed by brushing. Adding a **surfactant agent** can remove even more dirt. If you are unsure of what effect cleaning methods might have on your specimens, then clean one and note the effect before proceeding to another method. Some specimens may need to be trimmed or excess rock removed. This can often be done with a small chisel and small hammer, or engraving tool, but patience is required. Very delicate preparation is best done on a specimen viewed under a microscope using dental tools.

Large **macrofossils** should be labelled, and the best and permanent method is to paint a small rectangle in white gloss paint on the reverse of the specimen, let it dry, number the specimen in Indian ink, let it dry, and seal the number with a smear of clear varnish. The number that you use does not necessarily have to be the collection code but could simply be an **accession number** that will be recorded in the collection catalogue. The fossil should then be placed into an acid-free card box with a clear lid into which should be placed a tray label (Figure 8A). This should always carry the taxonomic name of the fossil, the name of the collector and date when collected, and the geological horizon and geographical location from where the specimen was obtained. If necessary place acid-free tissue around the specimen to stop it rolling around, without which it may be liable to get damaged. **Microfossils** should be placed in small sealed receptacles such as cavity slides (Figure 8B) which are available from many scientific suppliers, and the accession number and taxonomic and geological information should be inked onto the card sleeve.

Having curated the specimen the collector should list it in a Collection Catalogue that should replicate the information provided on the tray label. It is also useful to record in your catalogue where you have stored the specimen. Many collectors will use purpose-built specimen cabinets made of steel, or cabinets designed to hold 24 trays of microfossil cavity slides. Cabinets should be kept in a dry environment, as should any pyritised fossils. If stored in humid, damp surroundings the **iron pyrites** may become altered during a process called '**pyrite disease**', expand and produce sulphuric acid (Figure 8C). This destroys the specimens, labels and the trays in which they are kept. Storing your collection is a damp basement will lead to its rapid deterioration.

Figure 8 **A.** Specimen of *Euomphalus pugilis*, a Mississippian gastropod from Co. Kildare, Ireland, that has been well curated with information given on the accompanying tray label [×1]; **B.** Recent foraminiferan in a cavity slide [×1]; **C.** An ammonite that is suffering from pyrite disease which has caused the pyrite to expand and sulphur to exude from the surface [×1.2].

Expert advice on the **curation** of geological collections can be obtained from the Geological Curators' Group which is an organisation affiliated with the Geological Society of London (www.geocurator.org).

Studying your fossils

The way that you study your fossil collection all depends on what information you require and where your interests lie. Some collectors only study particular taxonomic groups such as sharks' teeth or ammonites, and to aid them they have obtained relevant books, monographs and scientific papers (These are described in more detail in the following section 1.6). Others are interested in the interactions between groups, while other collectors are interested in fossils from particular geological horizons such as the Chalk or the Gault Clay. If you are interested in studying certain taxonomic groups only, then contact similar-minded palaeontologists who may have formed a formal society for just that purpose. Most professional palaeontologists, whether they be university or museum-based, will be delighted to discuss the significance of your collections and may suggest and help with publication of significant finds. Some collectors are teachers and use their specimens in the classroom, while others are members of local natural history or geological societies where they can display and talk about their collections and thus educate like-minded people.

For general information on fossils it would be worthwhile joining one or all of the palaeontological organisations. In the UK and wider afield the Palaeontological Association has been active since the 1960s and it publishes the journal *Palaeontology* six times a year, while the Paleontological Society is based in the USA and also publishes a journal.

Nowadays palaeontologists utilise a range of high-powered equipment to aid the study of fossils, and examination under **Scanning Electron Microscopes**, or analysis of skeletons and shells in a **Mass Spectrometer** is commonplace. For the general collector a standard **binocular microscope** is useful and not beyond most budgets, and on some of these a camera can be mounted for those interested in photographing their collections. Some fossils are best seen in **thin-section**, which most university departments routinely prepare, and for examination of these a **petrological microscope** is needed.

Over time some collections can be very extensive, running into hundreds if not thousands of specimens. Remember that the life of your collection will undoubtedly be longer than your own, and that you should make provision for its well-being after you have died. In many instances relatives don't show the same enthusiasm for your passion, and where this is clearly the case you should arrange that your collection will be deposited in a museum or institution where it will continue to be enhanced and cared for.

Collecting fossils can bring enormous pleasure and is most rewarding. It enhances our understanding of our planet's history. Collecting and curation takes time and effort, but this is adequately paid back both in the enjoyment and the scientific value that your collection can bring.

1.4 Code of conduct for fossil collectors

When you are collecting fossils please remember to adhere to a few rules. Many fossil sites worldwide are now protected by local laws and it is *illegal* to remove any geological specimens from them. In the UK many fossil localities are within National Nature Reserves, or have been designated **Sites of Special Scientific Interest** (SSSI) (Figure 9) or **Regionally Important Geological and Geomorphological Sites** (RIGS). In the Republic of Ireland a number of geological sites fall within Special Areas of Conservation (SAC) that are protected under European legislation, or are National Heritage Areas (NHA) under Irish law. The networks of Geoparks in Europe are protected, while in the USA it is illegal to collect on Federal-owned land. Find out which sites are protected and avoid using your geological hammer at them. Elsewhere use restraint when hammering and collecting.

It may also be illegal to remove material from one jurisdiction to another even if you legitimately purchased the material, and other material may fall under the **CITES legislation**. For many countries a Code of Conduct for fossil collectors exists – that for Scotland is very informative (Figure 10) and can be applied to most collecting situations. This can be downloaded from the Scottish Natural Heritage website (www.snh.org.uk) and should be read by all collectors.

In particular the following should be adhered to when collecting:

- Always ask written permission of land-owners to visit and collect on their land. If given permission to collect, respect the land, close gates and do not damage fences and property.
- Do not enter working quarries. Quarries of any type whether they are active or disused can be very dangerous.
- Wear protective goggles and a hard hat when collecting.
- Do not climb cliffs, or hammer at the base of them, as this may cause rockfalls or landslides and lead to death or injury.
- Think before you collect. Do you require the fossils in the first place, and what will you do with them once collected?
- Do not over collect even if you think that there is an unlimited supply of fossils available to you. There certainly won't be, and such irresponsible collecting will lead to complete stripping of a fossil locality. There is no point in eventually assembling a large collection of miscellaneous fossils that end up filling a garage or attic.
- Record geological and stratigraphical information for your specimens.
- If you find anything unusual please contact your nearest geological museum for help identifying your specimen. If your material turns out to be of scientific importance, donate it to an accredited museum.

Figure 9 **A.** The Wren's Nest, Dudley, West Midlands, England – this is both an SSSI and a National Nature Reserve rich in Silurian fossil assemblages (© Natural England); **B.** Charmouth Beach, Dorset, England – this is part of the West Dorset Coast SSSI. The rocks in the cliffs are largely Lower Jurassic in age (© Natural England).

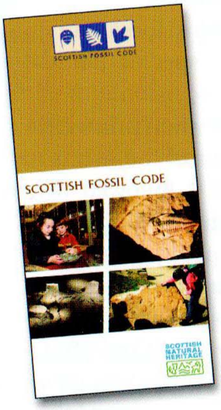


Figure 10 Leaflet on the Scottish Fossil Code.

1.5 Taxonomy: how to name and classify fossils

Taxonomy is the science of naming organisms and arranging them in a series of groups. The largest grouping is that of **Kingdom**, which is followed in descending order by **Phylum**, **Class**, **Order**, **Family**, **Genus**, **Species**, and **Subspecies**. Taxonomy is said to have begun on 1 January 1758, which is the date of publication of the 10th edition of Carl Linnaeus's *Systema Naturae*. He was a Swedish naturalist who realised that a consistent method of naming organisms was required because otherwise a plant given a name in Britain might be identical to a plant given a different name in Sweden, which would be terribly confusing.

Most fossils are simply known by their genus and species names (a **binomial** name), i.e. *Homo neanderthalensis* or *Tyrannosaurus rex*, and when printed these are italicised. The first letter of the genus name is always capitalised and is followed where known by the species name; if used frequently in a document it may be abbreviated to *T. rex* after first appearing. The name of the author who first named the fossil will also be given: i.e. *Vincularia megastoma* M'Coy, 1844. If a subsequent author placed the fossil into a different genus because they considered the original designation to be incorrect, the species name stays the same but the name would now be cited as *Baculopora megastoma* (M'Coy, 1844). The rules for plants are slightly different and both the author of the original name and the authors of the subsequent change would be cited.

Usually fossils are not given common names, unlike most living plants and animals, but occasionally such names exist as a hangover from local folklore, as in the Devil's Toenail (*Gryphaea arcuata*).

The names used for animals in palaeontology are governed by rules laid down by the International Commission on Zoological Nomenclature (www.iczn.org) which was established in 1895. Fossil plant names are governed by the International Commission on Botanical Nomenclature. If there are problems with nomenclature, then the relevant commission will decide on the correct solution.

When naming a new species or animal – and over 15,000 new species are named every year – a scientist has to publish a description in a valid journal or book. They also should cite and illustrate (if possible) the actual specimen on which the species name was based. This specimen is the **holotype**, and any other specimens in the collection are known as **paratypes**. These should be placed in a museum so that they are available to future researchers. The author of a name has the honour of deciding on the name, which utilises Latin or Greek roots. Often a fossil is named after an important person (*Caryophyllia smithii*, named after Sidney Smith, an expert on fossil corals, or *Arietites bucklandi*, named after the Rev. William Buckland (Figure 11)), a place (these names often end in *–ensis*), or after some characteristic feature that the fossil exhibits (*Cnemidopyge bisecta*, an Ordovician trilobite with a central ridge on its **glabella** (Figure 23)).

In palaeontology, of course, it can be difficult to prove if a species is a true biological species, although recent advances using DNA studies on fossils are beginning to yield some results and may be useful for species recognition in young fossils. Most species are still differentiated on the basis of morphological differences between fossils, which can be recognised through detailed measurements taken on them. These are **morphospecies**. In some cases binomial names were applied to different disarticulated parts of organisms, such as the Pennsylvanian plant *Lepidodendron*, to which names have been applied to its leaves, trunk, cones and roots; or to the different elements of conodonts. These are known as **Form taxa**. In trace fossil studies binomial names, too, have been applied to traces even though the maker may be unknown. *Oldhamia* from the Cambrian is an example of one such **ichnogenus** and *O. radiata* is an **ichnospecies** contained within that ichnogenus (Figure 12).

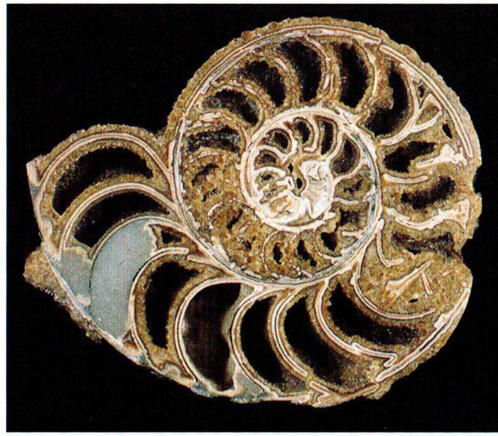


Figure 11 The ammonite *Arietites bucklandi* from the Lower Jurassic of Lyme Regis, Dorset, England. [×0.2]

Figure 12 *Oldhamia radiata* from the Cambrian of Bray Head, Ireland. [×0.75]

Resources for taxonomists

If you wish to identify fossils there are a number of useful resources available to you. The serious collector should build up a resource library of identification guides (Figure 13). The least expensive are the various identification guides that can be purchased in any good bookstore. The Natural History Museum in London produced the wonderful three volume guide to fossils of Britain that may be available through secondhand dealers.

Since the 1850s the Palaeontographical Society has been publishing monographs on the palaeontology of Britain. Each of these monographs provides detailed descriptions and illustrations of a particular fossil group of a certain age. For example, Thomas Davidson published a multipart monograph on the brachiopods (Figure 63), while the Rev. George Whidborne published on the Devonian fossils of southwest England. The Palaeontological Association and Paleontological Society both publish journals that frequently contain taxonomic information, while the former also produces a Guide Series to fossils of certain geological periods.

The bible for taxonomic palaeontologists remains the multi-volume series *Treatise on Invertebrate Paleontology* which commenced publication in 1953 under the editorship of the energetic Raymond Moore. Updated volumes continue to be prepared and copies can now be purchased either as hard copy or online. Each individual volume covers a major taxonomic group such as the Goniatites or Rugose and Tabulate Corals, and every genus is illustrated and described.

Collectors may also find it useful to visit their local geology museum and simply compare their specimens with those on display.

Figure 13 Various taxonomic books and monographs of use to palaeontologists. From top: *Fossils of the Upper Ordovician* (Palaeontological Association); *British Fossils* [3 volumes] (Natural History Museum); *Treatise on Invertebrate Paleontology* (Geological Society of America & University of Kansas) and *Atlas of Invertebrate Macrofossils* (Longman).

1.6 Uses of fossils

Scientists have long found the study of fossils to be of huge benefit in unravelling Earth history. In the infancy of palaeontology most studies were confined to taxonomy, in which many fossils were formally named. In the 1830s they were discovered to be useful for correlation, and many field geologists until the 1950s spent a great deal of time collecting material and documenting their finds as 'faunal lists' in publications. This work, while now considered to be somewhat routine, has provided palaeontologists with a rich database, and since the 1960s scientists have drawn on it to tackle other questions.

We now know a great deal more about the ages of fossiliferous rocks, thanks to biostratigraphical studies, and the rocks of a number of **Periods** have been correlated globally on the basis of their fossil content. We also have a better understanding of the past **palaeogeography** of our planet. Plants and animals display provincialism today and did so also in the past, and so the positions of former continents and oceans have been determined. Needless to say, geophysical investigations of the oceans and onshore have also provided clues to the past tectonic and continental plate movements.

Palaeontologists are now often interested in the biological evidence for lifestyles and any ecological interactions of the fossils that they study. Can any inferences about biological affinities, relationships, phylogenies and perhaps feeding habits be drawn out of hardpart morphology? Modern methodologies and equipment have helped reveal skeletal morphologies and mineralogies even in 3D. How did particular organisms interact with other organisms that they lived adjacent to in the past?

Palaeontologists are rather like genealogists as they try to find out about the **phylogeny** and ancestry of fossil groups and their evolution through time. Rather than browsing through old dusty tomes they carefully browse through the layers of fossiliferous rocks in the search for answers.

No doubt as new fossils come to light, and new methods are applied to pre-existing collections, palaeontologists will discover new information that will help assemble the complex history of life on Earth.

The sections that follow discuss some uses of fossils in more detail.

1.6.1 Palaeobiological history of life on Earth

The complexities of life on Earth and the numerous variations of the theme preserved in the rock record allow palaeontologists to assemble a huge database, the study and manipulation of which provides an inordinate number of questions and many answers. The progression of life is neatly documented, and the episodes where plants and animals have disappeared, and the reasons, may be deciphered too. The biological realm on Earth is constantly changing – species are evolving at the present but unfortunately are becoming extinct at the same time. Such developments in producing diversity have gone on ever since life first evolved on earth.

It is convenient to divide this section into four portions that correspond to the four major subdivisions called **Eons** into which the Earth's history is divided. The first three sections discuss the earliest life forms until the advent of the major shelly organisms at the beginning of the **Cambrian Period**.

Hadean history of the Earth

The earliest Eon on Earth is the **Hadean**, which began with its formation 4567 million years ago (**Ma**) (Figure 14) and continued until 4000 Ma. This was a time when the hot molten planet began to cool down, segregated into **core** and **mantle**, and small **proto-continents** of **crust** developed. Considerable **degassing** and volcanic activity produced an **atmosphere** that was rich in nitrogen, methane, carbon dioxide, ammonia, hydrogen sulphide and water vapour but lacked oxygen. Over time the protocontinents collided into each other and larger continental masses began to be accreted on the crust. The water eventually condensed and produced the oceans.

Archean history of life on Earth

Life began on Earth approximately 3500 Ma ago, some 350 Ma after the commencement of the **Archaean**, when a combination of gases, water, and the addition of an electrical spark instantly generated **amino-acids**. For a long time the mechanism of the genesis of life puzzled scientists until two Americans, Stanley Miller and Harold Urey, in 1952 conducted some experiments in a laboratory in Chicago.

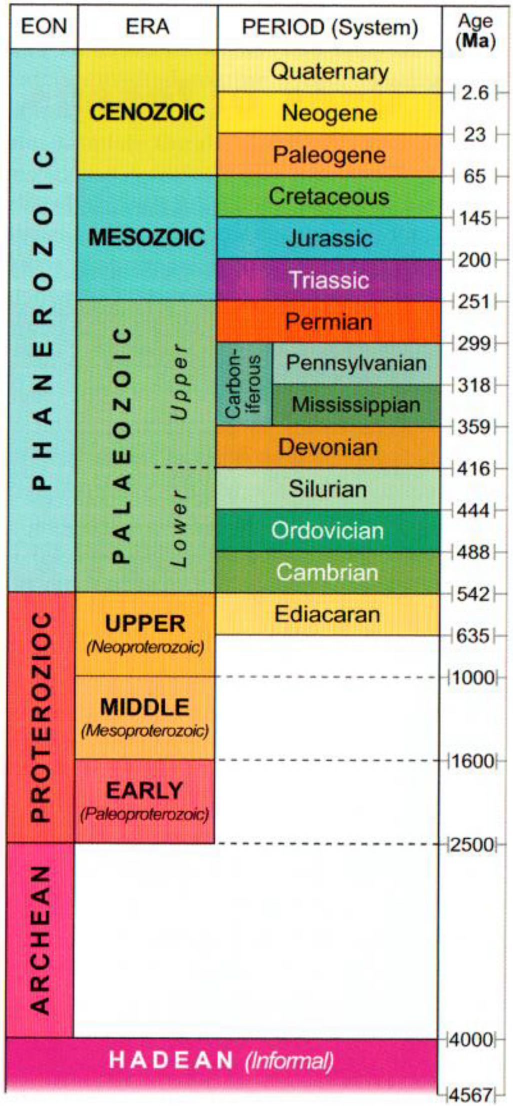


Figure 14 The geological timescale. The colour codings for the various units are those prescribed by the Commission for the Geological Map of the World, Paris, France.

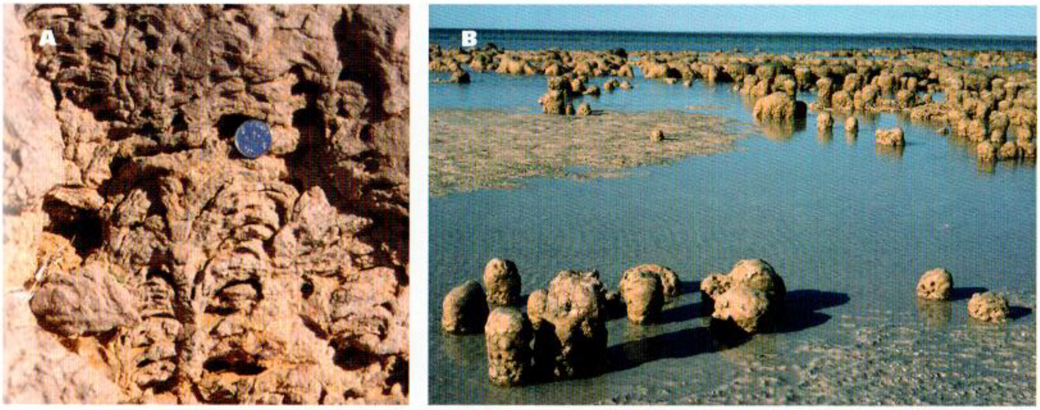


Figure 15 A. Fossil Stromatolites from the Cambrian Huqf Group, Huqf Desert, Sultanate of Oman. **B.** Modern Stromatolites from Shark Bay, Western Australia.

They simulated what they considered the conditions of the early Earth were like by filling a flask with methane and ammonia, caused a spark to cross a gap between some wires in the flask and later discovered proteins in a water reservoir at the bottom of the glass apparatus. The first life forms were tiny bacterial **prokaryotic** microbes that produced **stromatolites** found in the Oman and Namibia (Figure 15A), ancient forerunners of the modern examples in Western Australia (Figure 15B). These could photosynthesise and took carbon dioxide and water, and in the presence of sunlight produced sugars and oxygen. Slowly the levels of oxygen built up in the atmosphere.

Proterozoic history of life on Earth

The **Proterozoic** began 2.5 Ga ago when increased oxygen levels resulted in the precipitation of large volumes of iron dissolved in the oceans. This settled out and produced the **Banded Ironstone Formation** that is widespread in parts of Africa and Australia. By the middle of the Proterozoic (1.5 Ga) the atmosphere contained nearly 20% oxygen which is close to the proportion today, and **eukaryotic** cells first appeared. These have a **nucleus** surrounded by a membrane, and two types developed that gave rise to plants such as the algal **acritarchs**, and to animals (*see* Section 2.1). Continued photosynthesis caused the levels of carbon dioxide to plummet and the Earth was subjected to a number of glaciations around 700 to 650 Ma. Volcanic activity replenished the carbon dioxide to such an extent that limestone was precipitated extensively.

At 600 Ma a remarkable event took place in the evolution of life when **multicellular** forms began to be assembled. These **Ediacaran** floras and faunas were soft-bodied and most of this fossil biota is unrecognisable in terms of the modern biota. Frondose and disc-like organisms (Figure 16) abounded that may have had affinities with cnidarians, echinoderms and algae.

Phanerozoic history of life on Earth

By 540 Ma at the beginning of the **Phanerozoic** some animals discovered the secret of **mineralisation** and were able to extract dissolved

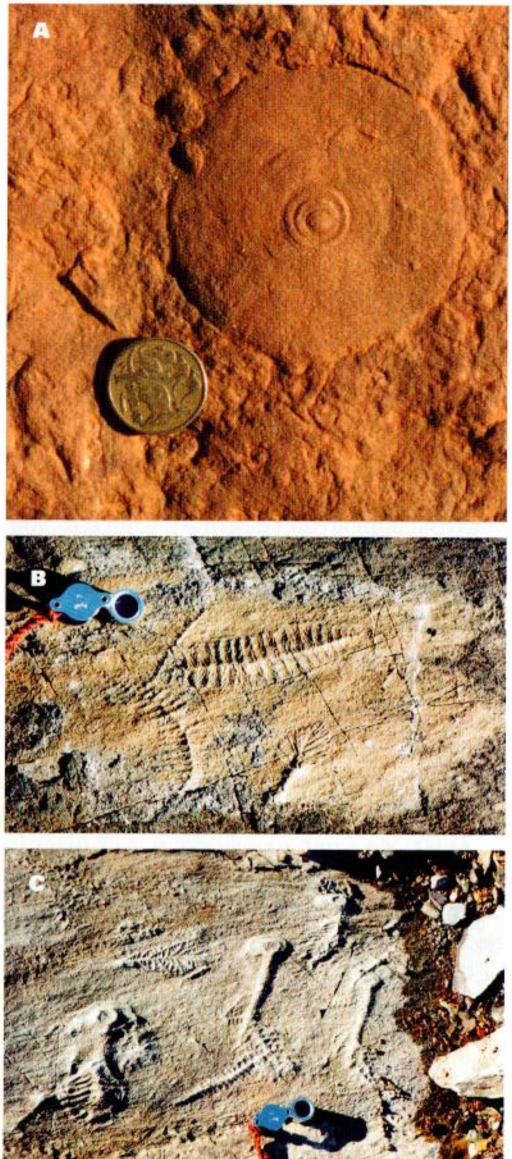


Figure 16 **A.** *Cyclomedusa plana*, an Ediacaran fossil from the Flinders Ranges, Australia [×0.5]; **B–C.** The oldest Ediacaran fossils dating from 603 Ma at Mistaken Point, Newfoundland, Canada [both ×0.25].

Figure 17 *Cloudina* from Blasskranz, Namibia [×0.3]. Dating from 542 Ma these are the oldest fossil shells.

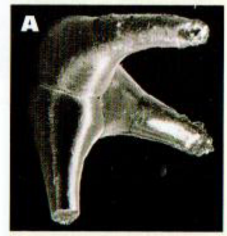
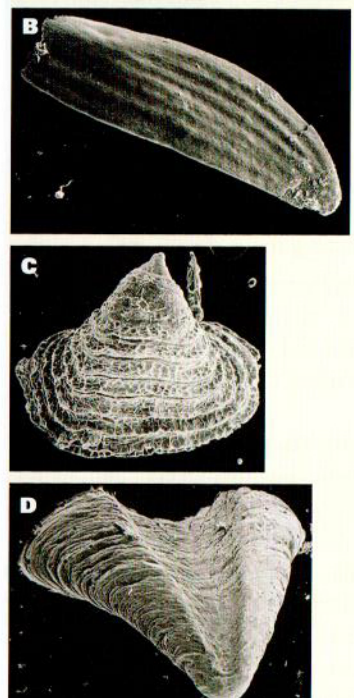


Figure 18 'Small Shelly Fossils': **A.** *Chancelloria* [×20]; **B.** *Halkieria* [×25]; **C.** *Lapworthella* [×75]; **D.** *Tannuolina* [×50]. From the Cambrian of Meishucun section, Maidiping, Sichuan, China dating from 542 Ma.



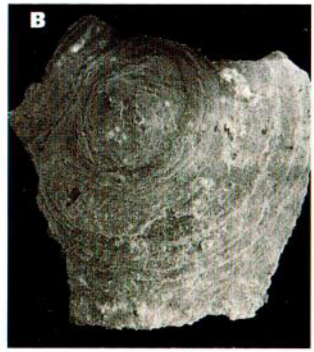


Figure 19 **A.** Precambrian–Cambrian boundary at Dvortsy Cliffs, Aldan River, eastern Siberia, Russia; **B.** Small Cambrian inarticulate brachiopod [×30].

minerals from seawater and use them for the construction of hard shells. In one stroke the nature of the fossil record changed, and the potential for preservation had increased enormously. Organisms such as *Cloudina* from Namibia (Figure 17) are amongst the first shelly fossils, and this period was also marked by a proliferation at the base of the **Cambrian** of what palaeontologists group together as '**Small Shelly Fossils'** or SSFs (Figure 18) whose affinities remain ambiguous. Use of the Scanning Electron Microscope has revolutionised the study of such material. The start of the Cambrian is marked by the appearance of these shells as well as others such as inarticulate brachiopods (Figure 19) which diversified rapidly and produced a significant fossil record.

The Phanerozoic contains three **Eras** which are characterised by a distinctive fossil content and rich in a variety of different biological groups. These groups are discussed in detail in later sections. The **Palaeozoic** Era (Cambrian to **Permian**) is dominated by invertebrates, animals without backbones (Figure 20). The first vertebrates were **Ordovician** fish, which were followed by amphibians in the **Devonian**. Reptiles first made an

Figure 20 Silurian shelly assemblage from Dudley, West Midlands, England. [×0.5]

appearance in the **Mississippian** but became more abundant in the **Mesozoic** Era (**Triassic** to **Cretaceous**), but at its end nearly 50% of all life on Earth was wiped out after it was hit by a large **bolide**. **Angiosperms** first appeared in the Cretaceous and many were aided in their success by evolving reproduction strategies that depended on insects that **coevolved** to reap the benefits of this activity. The **Cenozoic** Era comprises the **Paleogene** and **Neogene** (formerly called the **Tertiary**), when mammals became the dominant group on land, and they evolved into many different types.

Throughout the Phanerozoic the invertebrate biota both on land and in the oceans waxed and waned, and some groups such as brachiopods predominated in shallow marine environments early on before being displaced by the bivalves from the Mesozoic onwards. Other organisms have managed to remain almost unaltered over long periods of time and have been referred to by the moniker **'living fossils'**. *Lingula*, the inarticulate brachiopod, first appeared in the Cambrian 580 Ma ago and the plant *Ginkgo* (Figure 21) is a relative newcomer but has been around nearly 300 Ma since the Permian.

The history and story of life on Earth is highly complex and has been likened to a tree, 'the tree of life'. In the early stages there were few stem groups, but as time passed new forms evolved, these branched out, and became more diverse.

Figure 21 *Ginkgo*, an example of a long-ranged 'living fossil' [×0.8]. A Mesozoic fossil is on the right and a leaf from a living tree on the left.

1.6.2 Evolution and extinctions

Evolution

Without the process of evolution there would be a low diversity record of life on Earth. Even before Charles Darwin and Alfred Russell Wallace, who published a joint paper in 1858 on natural selection, the driving force of evolutionary change had been considered by some scientists. Natural selection depends on the passing on of advantageous inherited traits to the next generation that make them better placed to live to reproductive age and to continue the lineage. Other scientists such as Jean-Baptiste Lamarck had recognised that animals appeared to change over time. Lamarck suggested that they became increasingly complex and that they had the ability to cause change for themselves by adapting to their environment. This didn't satisfy many scientists, and the question of what precisely caused evolution stumped most theorists. Darwin and Wallace identified the mechanism of evolution, and while their paper did not reach a wide audience, Darwin's subsequent book *The Origin of Species* published in 1859 did. It caused a storm of debate amongst scientists, some of whom argued that the Earth was just not old enough for evolution to have taken place. Later the enormous longevity of the Earth was recognised, and there is no problem with providing adequate time for evolutionary processes to take place.

Natural selection is the process by which species are generated, and this has yielded a huge diversity of morphologies. Examination of the fossil record clearly shows that the Palaeozoic biota was dominated by invertebrates that were later joined by primitive vertebrates. The Mesozoic faunas were reptile-dominated and the Cenozoic is mammal rich. Palaeontologists have built up a large database of information on evolution and now recognise evolutionary lineages in almost all fossil groups including conodonts, brachiopods, corals and mankind. The level of confidence of the veracity of these lineages and the phylogeny of the groups depends on the quality and volume of material available. Recording fossils preserved bed by bed in a long sequence of sediments can reveal evolutionary changes.

Within the fossil record there are numerous examples of co-evolution, of which that of the angiosperms and the insects is perhaps the best documented (Figure 22).

Figure 22 Leaf of the angiosperm *Viburnum* showing considerable damage by insects [×0.1]. Dakota Sandstone, Cretaceous of Ellsworth County, Kansas, USA.

Change, it has been shown, takes place at different rates. Nils Eldredge and Stephen J. Gould in 1972 argued for the process of 'punctuated equilibrium' where stocks remained largely constant for long periods of time, but that evolutionary change took place episodically and rapidly in short bursts, before the systems settled down to intervening stasis. Others, including the English palaeontologist Peter Sheldon, showed that evolutionary change could take place gradually but rather slowly. In a ground-breaking piece of work he showed that the number of ribs in the pygidia of eight trilobite genera of the Ordovician of central Wales increased steadily over a period of three million years (Figure 23) and that there was no evidence of punctuated equilibrium in his study.

Extinctions

Plants and animals have continually disappeared throughout geological time, either as small numbers of taxa over time or in a series of cataclysmic events that saw the removal of a considerable proportion of the biota. In many cases whole groups were wiped out and no modern examples are extant – there are no graptolites, trilobites or dinosaurs. In other cases most representatives in a group were removed but a small number of taxa survived, and from these new lineages evolved. The modern scleractinian corals that are major reef-builders are thought to have been derived from a single or small number of Palaeozoic corals. The ammonites that were highly successful in the late Mesozoic radiated from a single genus *Phylloceras* (Figure 55C) after

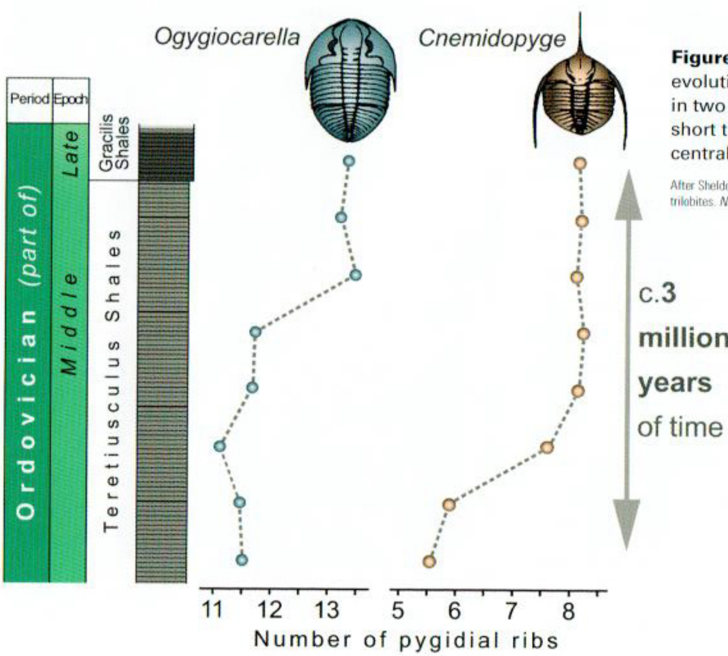


Figure 23 Graph showing the steady evolution of increased pygidium ribs in two trilobite genera over a relatively short timespan from the Ordovician of central Wales.

After Sheldon, P.R. 1987. Parallel gradualistic evolution of Ordovician trilobites. *Nature* **330**, 561–563.