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ONE

Introduction and the Evolution of Life on Earth

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Summary

This chapter serves as an introduction to the book. It discusses the origin of Planet Earth and its Moon, their dependence on the Sun for energy, and the evolution of life on Earth. The evolution of the first living cell seems to have been a single event and all life on Earth is directly derived from this individual primary organism. The first life forms were anaerobic bacteria, but these later gave rise to photosynthesising cyanobacteria, which produced oxygen. The presence of oxygen eventually led to the emergence of aerobic animals and plants. The chapter then details the emergence of the oceans and supercontinents Pangea and Gondwanaland, the eventual break-up of the supercontinents and the development of the varied ecosystems which characterise Planet Earth at the present time.

1.1 Introduction

We are currently in the middle of a so-called great extinction of the world's wildlife, one to add to many past extinctions. These include the extinction of the dinosaurs some 65 million years ago (sometimes called the K–T or K–Pg extinction), apparently caused by a huge meteorite striking Earth in the vicinity of the Gulf of Mexico and the Yucatan peninsula, the catastrophic Triassic–Jurassic extinction of 2000 million years ago (2000 Mya), resulting from a mix of climate change and volcanism, and causing the extinction of 75% of all the species living at that time, and the even more disastrous Permian–Triassic extinction with 96% of all marine species dying out, including the trilobites.

The present extinction, sometimes called the Holocene extinction event, began about 10,000 years ago and is ongoing, and is uniquely attributed to human activity. The agents by which humans have brought about this devastation are the use of fire and hunting by early hominids (think of the demise of the mammoths) followed by more recent habitat destruction and deforestation, together with overexploitation of other biological

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resources, agricultural intensification often preceded by slash and burn, overextraction of water and land drainage, pollution of land, water and air by oil, pesticides and herbicides (consider Rachel Carson and her predictions of DDT damage), spread of urban and industrial areas with construction of road and rail networks, and destruction of corridors between surviving islands of suitable wildlife habitat. Also the accidental or intentional release of many destructive exotic species such as mice, rats, cats, pigs, mongoose, cane toads, brown snakes and many others, such as possum in New Zealand and lion fish in the Caribbean. So this book sets out to detail which species have recently become extinct and which ones remain, and of these, which are prospering and which declining, together with some success stories of recent conservation efforts.

The present scenario is not without hope, in fact there are many recent success stories, such as the redesign of fishing methods (involving hooks that are only effectively exposed on reaching a certain depth) to avoid accidental death of albatrosses, the global moratorium on whaling and recovery of stocks of many whale species, and the successful exploitation of human habitats by species as diverse as polar and brown bears, nighthawks, peregrine falcons and the successful reintroduction programmes with condors, red kites, white-tailed sea eagles, wolves and others.

The section that follows will consider the history of Planet Earth, how early life evolved, and how the break-up of Pangea has led to the subdivision and distribution of species on the remaining continents.

1.2 The Origin of Planet Earth and its Moon

Recent evidence has led to a revision of our understanding of the relationship between Earth and Moon. Initially it was believed that a small planet called Theia grazed the Earth at a 45 degree angle and broke up after this impact, one of the resulting chunks being caught by the gravitational pull of Earth and forming the orbiting Moon. But in more recent years it has become apparent that Earth and Moon have identical chemical compositions. So the revised view is that the violent collision between Earth and Theia led to the formation of a single larger planet from which a chunk of the mantle layer became detached to form the Moon. The crash between the original Earth and Theia happened about 100 million years after the Earth originally formed, which was about 4.5 billion years ago. Rocks brought back to Earth from the Moon by Apollo missions 12, 15 and 17 reveal that the Moon has an identical oxygen isotope signature to Earth, having 99.9% of its oxygen atoms as ^{16}O, the remainder being a mix of ^{17}O and ^{18}O (the numbers indicate the sum of the protons and neutrons in the oxygen atom).

The age of the Earth is approximately one-third the age of the Universe, 4.5 billion years rather than the 13.8 billion years since the Big Bang. The Moon has, together with the Sun, led to the tidal flows and ebbs, the combined effect of their gravitational pull, when in line, providing the regular dramatic spring tides. The Moon also stabilises the axial tilt of the Earth and this results in climatic changes being reduced to moderate levels.

Evolution of the first life forms on Earth seems to have occurred soon after conditions became permissible by the availability of water and the stabilisation of temperatures, and

Figure 1.1 Image of Planet Earth from space.

this occurred probably about 4000 Mya, only 500 million years after Earth's formation. There is now agreement that the ocean was present very early, so the date for the origin of life lies somewhere between 4000 and 4400 Mya.

One of the necessary prerequisites for the development of life was the presence of water and recent thinking about the arrival of water on Earth has changed. A large proportion of the Earth's surface is water and so from space Earth looks to be a largely blue planet (see Figure 1.1). This water is 96% oceanic and 1.2% freshwater, with the remainder locked up in polar ice, glaciers and permafrost.

It used to be argued that most of the Earth's water arrived in comets, but it is now accepted that water was already integral to the interstellar dust grains which accreted to form our planet. Calculations about the possible adhesion of water to the dust grains in the harsh conditions of interstellar dust clouds support this new interpretation of events.

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Initially much of the Earth was molten because of volcanism and frequent collisions with other bodies, but quite rapidly a cooler crust formed, interspersed by the oceans. The initial atmosphere contained almost no oxygen, but was made up of 60% hydrogen, 20% water vapour, 10% carbon dioxide and 6% hydrogen sulfide, with lesser amounts of nitrogen, methane, carbon monoxide and inert gases. The Earth's atmosphere also helped to shield the surface from too much solar radiation. Early oceans probably had temperatures of about 250 °C, at least for brief periods, with the dense atmosphere preventing complete vaporisation. Ocean cooling then followed. In years gone by it was assumed that life could not survive at temperatures much above 60 °C, since most proteins are denatured at higher temperatures, but more recently we have learned about the so-called extremophile microorganisms, including organisms called Archaea, which will thrive at temperatures above 120 °C. Such organisms can still be found in hot springs, such as those in Yellowstone Park in the United States, as well as occurring in the hydrothermal vents in the deep oceans. Enzymes from bacteria such as *Thermus aquaticus* (Taq polymerase) have revolutionised molecular biology and underlie the important polymerase chain reaction (PCR) now used to replicate DNA sequences worldwide. Other extremophile bacteria include species such as *Thermus brockianus*, *Halobacterium volcanii* and *Deinococcus radiodurans*.

Although cells similar to the Archaea certainly evolved early in the Earth's history, it is likely that originally living systems were acellular, employing membranous surfaces and enzymatic forms of RNA (ribonucleic acid) rather than DNA (deoxyribonucleic acid), together with amino acids, which are the building blocks of protein.

Soon after cellular life evolved, involving DNA as well as RNA as genetic material, it is likely that photosynthetic cells evolved. Notice that the earliest life grew independently of oxygen, and indeed oxygen would have been highly toxic to this early life, but then oxygen was released by photosynthetic bacteria (cyanobacteria) using solar energy with carbon dioxide and water.

One of the hardest steps to envisage in cellular evolution is to conceive how early cells became self-replicating, and the improbable nature of this evolutionary step is underscored by the fact that all modern life seems to have evolved from a single evolutionary event in the production of the first replicating cell (see the publication by Douglas L. Theobald (2010), 'A formal test of the theory of universal common ancestry').

So the earliest cellular life was not aerobic (oxygen requiring) but some 2.3 Bya, photosynthetic cells (cyanobacteria) evolved, which produced oxygen as a by-product, and this paved the way for the evolution of oxygen-dependent life, which accounts for most of the species that we know of as living organisms on Planet Earth.

Rocky formations known as stromatolites, which are layered biochemical accretionary structures, can still be found today in shallow seas such as exist in Shark Bay in Western Australia. These structures include microbial biofilms (mats) of bacteria, especially cyanobacteria, which are photosynthetic, and fossilised stromatolites dating to 3.5 Mya. Some geologists now think that the earliest stromatolites may have been inert, and that the release of oxygen by cyanobacteria did not occur until 2.3 Bya.

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It thus appears that life evolved on Earth soon after the presence of water and moderate surface temperatures provided appropriate conditions. It has been estimated that more than 99% of the five billion or so species that have evolved on Earth are now extinct. Estimates about the number of present species on Earth range from 10 to 14 million, although some naturalists put the figure at more than 20 million. An entomologist called Terry Erwin has tried to tackle the question by addressing the question of how many species remain undescribed. The majority of these are small insects, especially ants, in rainforest canopy. What Erwin has done is to visit various rainforest areas, put down extensive plastic sheets under the trees and, on climbing up into the canopy, he has released a fog cloud of dense insecticidal vapour and allowed this to descend through the canopy. The casualties are collected from the plastic sheets and identification attempted. By estimating the number of species caught and the number of secured species which are currently not recorded in taxonomy, Erwin has estimated the number that represent new species. The estimates are highly variable but the total is usually over 30 million species. This number breaks down into 300,000 to 400,000 plant species, 1.4 million non-insect animals (85,000 molluscs, 1.1 million mites and spiders, 47,000 crustaceans, 31,000 fish, 7,000 amphibians, 10,000 reptiles, 10,000 birds and 5,500 mammals). The insects make up the rest, between 10 to 15 million of them, and fungi at 1.5 million. The total numbers of species of bacteria and Archaea is hard to know but will certainly be in millions. Some of these figures, such as the number of bird species, is certainly accurate, but others, such as the figures for the number of insect and bacterial species, are less certain.

1.3 What is a Species?

Having thought of these millions of different life forms on Earth which are separated by taxonomy (the science of classification) into different species, it is high time to try to define what exactly is meant by a species.

Biologists define a species as a group of freely interbreeding individuals which do not breed with other neighbouring individuals of different species; the individuals within a species are morphologically the same, except for the separate sexes. Sometimes even within a species there is some morphological variation, and this is referred to as polymorphism. For example the little land snail *Cepaea nemoralis* appears with different amounts of banding, and some individuals have no banding. When the ratios between these variant individuals remain the same, it is referred to as a balanced polymorphism, sometimes explained by the success of the variant individuals in differing environmental situations.

Occasionally, neighbouring species will interbreed, and this is referred to as hybridisation. This may occur if one individual cannot find a mate within the same species. Duck species quite often hybridise, especially if an individual duck of the American wigeon (*Anas americana*) flies the Atlantic Ocean and finds itself in a population of European wigeon (*Anas penelope*). Hybridisation between the two ‘sister-species’ will then readily occur. There are examples of so-called ‘clines’, where individuals show increasing variation in one parameter so that the individuals at each end of the cline do not recognise one another as being con-specific. This can result in so-called 'ring speciation' as has occurred with the greenish warblers (*Phylloscopus trochiloides*) which forms a ring species around the Himalayas, and the subspecies at the ends of the ring, *P. trochiloides plumbeitarsus* and *P. trochiloides viridanus*, overlap but do not interbreed. The plane tree so widely planted in London is also a plant hybrid between the oriental plane (*Platanus orientalis*), and the American plane (*Platanus occidentalis*); it is now referred to as *Platanus hispanica*.

1.4 Latin Names and Genera

All species have a Latin binomial (ever since the scheme drawn up by the father of taxonomy, Linnaeus). The first name indicates the genus (which is a group of related species) and the second name the species. So we, *Homo sapiens*, belong to the genus *Homo*, which includes *erectus*, *neandertalensis* and many others, while *sapiens* denotes our species, the 'wise' hominid. There are further levels of hierarchy which need not concern us much. They are, going up from Genus, Family, Order, Class, Phylum and Kingdom. There are also some fine subdivisions such as subclasses and suborders. A group of organisms classified together is normally assumed to be monophyletic (having one common ancestor) but some groupings are seen as paraphyletic, that is 'not quite monophyletic'. Taxonomy must always beware of evolutionary convergence, where two organisms look alike but are not related. For example, in Madagascar there is an animal called a hedgehog tenrec. The animal closely resembles a European hedgehog, but is actually a tenrec. Selective evolution has led to convergence in appearance since both have adapted to similar ecological conditions. The birds called barbets in the New World of Latin America closely resemble the barbets of Asia, but the two groups of birds are not at all related. It is another example of convergent evolution.

A group of related organisms in one or more populations is referred to as a 'taxon' of which the plural word is 'taxa'. In taxonomy, the Archaea and true Bacteria are referred to as Prokaryotes (before nuclei) while all the higher groupings of organisms are referred to as Eukaryotes (with nuclei). There has been a vexed question over the years about how many kingdoms exist in life forms. There is little doubt that the mitochondria of eukaryotic cells are derived from bacteria and that chloroplasts and other plastids are derived from cyanobacteria, but the precise derivation of the original eukaryotic cell, with its bacterial and cyanobacterial inclusions, remains a little uncertain in terms of the derivation from Archaea and true Bacteria. It is worth emphasising that viruses are not in the lineage of organisms, they are in fact escaped parts of organisms and can only replicate by re-entering a living cell and using its cellular machinery to make more virus particles. Bacteria have their own viruses, called 'bacteriophage'. Just where the chromosome-possessing nucleus of the eukaryotic cell came from remains somewhat mysterious, but the eukaryotes with their elaborate membranes, mitochondria, nuclei and, if a plant, their chloroplasts, has proved to be a winning formula.

There used to be only five Kingdoms, the Prokaryotes (bacteria etc.), Protista (Protozoa etc.), Fungi, Plants and Animals. However it is now clear that neither of the first two Kingdoms is a single taxonomic grouping, the Archaea and Eubacteria being quite distinct

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and not closely related, while the Protista (the Protozoa) are now known to be a taxonomic rag-bag of unicellular forms of life.

Early in the history of life on Earth the original Kingdom diverged, leading to primitive Protozoa and primitive Fungi, Plants and Animals. There are still living fossils around which represent some of the early forms of life. These include the curious sago palms (*Cycads*), the horsetails (*Equisetum*), red seaweeds and the curious welwitschia plants of the Namibian desert. Potato blight (*Phytophthora infestans*) seems to be a very primitive Fungus and the two groups of slime moulds Plasmodium and Acrasiomycota are somewhere between Fungi and Protozoa.

1.5 Pangea and the Break-up of the Continents

It is time for us to return from our preoccupation with taxonomy to what happened to Planet Earth itself after the origin of life. The Earth's crust and oceans were themselves subject to major changes, and here we must now follow up on these.

The crust of the Earth was (and still is) highly dynamic, especially in the early life of the planet, and the tectonic plates that lay beneath it were frequently moving. Tectonic plates are large solid slabs which lie under the surface of the Earth's crust. The lithosphere, which is the rigid outermost shell of the planet, is divided into separate plates, of which there are seven or eight major plates and many minor ones. Where the plates meet, the boundaries are areas of earthquake and volcanic activity, together with mountain building and oceanic trench formation. Plate movement may be up to 10 cm annually. Along plate boundaries, plates may crunch together or slide under one another. The lithosphere is about 100 km thick and becomes thicker with time as the surface cools. Most of the world's active volcanoes lie along plate boundaries, as in the 'Ring of Fire' of the Pacific plate, Africa's Rift Valley and the San Andreas fault.

Two supercontinents were evident some 200 million years ago, a southerly one called Gondwana and a northerly one called Laurasia. The former included Antarctica, South America, Africa, Madagascar, India and Australasia, while the latter included North America, Europe and Asia. About 300 million years ago a larger supercontinental mass called Pangea (see Figure 1.2) existed, and its first break-up yielded the two separate masses which characterised the Triassic some 200 million years ago.

Many plants are believed to have a Gondwana distribution, as, for example, the Proteaceae family now found in southern South America, South Africa and Australasia. The eucryphia trees are today found in the southern areas of South America and Australia once joined in Gondwana. Similarly the existence of marsupial mammals in Australia and South America is also explained in this way, although in the latter they have now been largely superseded by the more successful Eutherian placental mammals that spread from North America.

The existence of Pangea is also strongly supported by fossil evidence, as, for example, fossil remains of *Cynognathus*, a 3 m long Triassic land reptile, in both South America and West Africa, fossil evidence of the Triassic land reptile *Lystrosaurus* in Africa, India and Antarctica, fossil remains of the freshwater reptile *Mesosaurus* in southern parts of South

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Figure 1.2 Pangea chart.

America and South Africa, and fossil remains of the plant *Glossopteris* in Australia, South Africa, South America and parts of Antarctica. The supercontinent Pangea eventually broke up under the influence of the moving tectonic plates, to yield the continents as we know them today, separated as they are by the large tracts of ocean, Atlantic, Pacific, Indian and Southern, and many smaller seas. Some distribution anomalies remain which are hard to reconcile with Pangea and its break-up. One such is the existence of boa snakes in Madagascar, with their nearest relatives being in South America.

1.6 Early Evolution of Multicellular Life

We should now return to consider how the early eukaryotic cells evolved into the huge array of multicellular life which followed. One recent technique which has greatly helped in understanding early evolution and the relationships between the resulting organisms is the use of DNA sequencing. The DNA of both mitochondria and chloroplasts is itself quite simple, carrying only a few genes, and analysis of these sequences in different organisms allows one to trace early relationships. Some of the simpler conserved sequences in the nuclear DNA have also proved useful in this regard. The recent development of PCR, referred to earlier in the context of the DNA polymerase enzymes recovered from extremophile Archaea bacteria, has greatly assisted in this analysis.

There is an excellent reference book to consult on the diversity of life forms. It is *The Variety of Life* by Colin Tudge (2000). As mentioned before, the Protozoa, the single-celled organisms, have proved to be very diverse and are hard to classify accurately. The bacteria themselves have become diverse, developing cell walls, flagellae and spiral morphology, as in the Spirochaetes. Some also became obligate intracellular parasites like *Chlamydia*. Many higher vertebrates are entirely dependent on intestinal bacteria to help digest their food.

Amongst Protozoa, few have become more complex than the multiflagellated *Trichonympha*, which lives in the guts of termites and helps them to digest the wood on which they feed. Some of the algal Protozoa with chloroplasts have become partially multicellular for part of their life cycle, as displayed by *Pandorina* with 16 cells and *Volvox* with many hundreds.

Early multicellularity prepared the way for the great leap forward in Eukaryotic life, namely the development of different kinds of cells within the same organism. This development, first evident in the most primitive plants and animals, allowed the development of differentiated cell types to take on different roles within the same organism. In turn, this allowed the specialisation of sex cells in different sexes of the same species, a major advance in the Eukaryotes.

Soon after the development of multicellularity (which actually evolved independently in several groups of organisms), the Plants, Fungi and Animals diverged from one another, all retaining the mitochondria derived from intracellular bacteria, but only the plants retaining chloroplasts derived from cyanobacteria. This scenario of evolution has also been shown by looking at the nucleus, mitochondrial and chloroplast genomes, and comparing them with those of the presumed prokaryotic originals.

Photosynthetic algae and Protozoa preceded the evolution of proper plants, but by the Cambrian period some 500 million years ago fossil plant spores become evident. The earliest plants probably resembled liverworts (Hepatophyta) which formed small tetrads of spores. They grow in wet terrestrial environments and today many of these early primitive plants, including mosses, clubmosses, hornworts and *Selaginella* (examples of which are still alive today) are lumped together as Bryophytes. Other early plants included horsetails (*Equisetum*) and ferns (Pterophyla). Some 370 million years ago in the Devonian, the seed-bearing plants evolved. Early examples included cycads and ginkos, both still with us today, but the really major advances were the evolution of gymnosperms (conifers) and the dramatic and hugely varied angiosperms (flowering plants). Angiosperms first appeared some 130 million years ago in the early Cretaceous and in that period we can find examples of some of the earliest angiosperms, magnolias, water lilies and arums. By the late Devonian there were forests of tree-like plants with internal conducting vessels.

The appearance of all these large plants, which coincided with the earliest tetrapods, the amphibians, has been called the 'Devonian Explosion'.

Fungi are first found about 1500 Mya and 'higher fungi' about 600 Mya. They probably first colonised the land in the Cambrian, but only became common in the Devonian, some 400 Mya. Since fungi do not mineralise to form good fossils, early fungi are shrouded in mystery. The first fungi were probably aquatic, but became terrestrial when they exploited growth on dead or dying Devonian trees.

The earliest animal evolution seems to have been jump-started by increases in marine oxygen levels associated with the so-called 'snowball Earth' glaciations (see Lyons and Planavsky (2012) 'Extreme climate change linked to early animal evolution'). The first fossil evidence for early animals comes from the remains of burrows made by worm-like organisms in rocks found in China. Animals really diversified during the 'Cambrian Explosion', and one of the most famous assemblages are those found in the 'Burgess Shale' (see 'Wonderful Life' by S. J. Gould (2000)).

The oldest fossil of undoubted animal character is that of *Charnia masoni*, found in pre-Cambrian rocks in Charnwood Forest in Leicestershire, England. It was first discovered by Roger Mason when a schoolboy. Originally thought to be a plant, it is now recognised to be a sessile sea pen or crinoid (a sister group to the soft corals). But it was in the later Cambrian explosion that animal life really diversified. Sponges, Ctenophores and worms were amongst the simplest but starfish and Mollusca soon followed. They also conquered land as the early arthropod insects and the marine sea squirts, tunicates placed in the subphylum Urochordata, which have tadpole-like larvae with the beginnings of a notochord (early backbone). Other arthropods, besides insects, the Crustaceans, radiated hugely in the sea to give crabs, shrimps and lobsters, and the once-abundant trilobites. The latter flourished in the Cambrian but all became extinct in the great Permian extinction 250 million years ago. Their success can be measured in part by their speciation, which reached almost 4000 separate species. The trilobites included predators and species which fed on both marine plants and animals, and even plankton. They were heavily armoured with numerous walking legs, although these were not evident in the initial fossils found. Some were as large as 45 cm long and weighed up to 4.5 kilos. For details of these animals see the book 'Trilobite!: Eyewitness to Evolution' by Richard Fortey (2000). They had excellent eyesight with multifaceted eyes and lenses of calcite. Fossil trilobites are abundant, especially in Morocco, where there is a special museum dedicated to Trilobites.

'Onychophora' are often called velvet worms or *Peripatus*. These animals occur mainly on the forest floor of tropical rainforest in Africa, Australia and South America. They resemble intermediates between worms and insect larvae, walking by means of paired oncopods or stub feet. Their main importance in animal evolution is that they were amongst the earliest life forms to move from an aquatic environment to a terrestrial one. To this end they have lost gills and breathe air through a tracheal network for aerobic respiration. They seem to be distant relatives of Arthropods and Tardigrades (water bears). Velvet worms are mainly predatory on other small animals such as worms and woodlice,