HISTORY OF THE EARTH

J. Dostal
Department of Geology, Saint Mary's University, Canada

J. B. Murphy
Department of Earth Sciences, St. Francis Xavier University, Canada

R. D. Nance
Department of Geological Sciences, Ohio University, USA

Keywords: Solar System, Solar Nebula, Solar Radiation, Atmosphere, Hydrosphere, Precambrian, Archean, Proterozoic, Paleozoic, Mesozoic, Cenozoic, Quaternary, Plate Tectonics, Pangea, Gondwana, Origin of Life, Oxygen, Photosynthesis, Mass Extinction, Ice Age, Fossils, Hominid

Contents

Summary

The Earth has evolved from its tumultuous beginnings during the formation of the Solar System to a relatively benign, life-sustaining planet. As the inner portion of the Solar System cooled, small objects called planetesimals formed. These objects collided with one another, and grew into protoplanets. One of these protoplanets evolved to become the Earth. Calculations indicate that the Earth's principal layers, the core, mantle and crust, formed within 20 million years of the planet's formation. The earliest atmosphere, consisting of hydrogen and helium, was lost and was replaced by an atmosphere

generated by volcanoes that was dominated by water vapour, with subordinate amounts of carbon dioxide, carbon monoxide, sulfur dioxide, sulfur, chlorine, nitrogen, argon, hydrogen and no oxygen. Water vapour accumulated in the atmosphere and turned to rain as temperatures cooled. This stripped water vapour and soluble gases, such as carbon dioxide, from the atmosphere. The solid Earth evolved from the primitive crust of the Hadean and early Archean Eons to one that had many of the attributes of modern crust by the end of the Archean. The contrast in densities between continental and oceanic crust allowed water to accumulate in regions we now call ocean basins. The oldest marine sedimentary records indicate that oceans (and therefore the hydrologic cycle) had originated by about 4 billion years ago.

The origin of life is controversial and hypotheses include the effects of lightning storms in the atmosphere, the utilization of energy adjacent to deep-sea vents, the seeding from extra-terrestrial impacts, and the formation of organisms in inter-tidal pools. Life originated early in the Archean in the form of organisms known as prokaryotes. Prokaryotes were single-celled organisms that lived in anaerobic (oxygen-poor) environments and were only capable of asexual reproduction. As a result, evolution was slow. The oldest, widely accepted examples of these organisms occur in rocks that are 3.5 billion years old. As life began to proliferate, oxygen produced by photosynthesis was initially consumed by iron-rich ocean waters, which absorbed the oxygen to produce iron-rich minerals, preserved in the record as banded iron formations.

Late Archean crust consisted of granite-gneiss complexes and greenstone belts. During the Proterozoic, continents and continental shelves grew from smaller, Archean nuclei to the large-scale continents of the modern era. Much of the geologic history of the Late Proterozoic and Phanerozoic is influenced by the formation and dispersal of super-continents. This includes the formation and destruction of oceans, and the distribution of mountain belts, earthquakes and volcanoes.

By about 2 billion years ago, the rate of oxygen production by photosynthesis exceeded the ability of ocean waters to absorb it, and free oxygen entered the atmosphere. The presence of free oxygen in the atmosphere is supported by the sudden abundance of red, continental, sedimentary deposits. The resulting environmental crisis initiated a mass extinction. By 1.8 billion years ago, eukaryotes had evolved that could exist in aerobic (oxygen-rich) environments.

The geologic record suggests that a super-continent called Rodinia formed about 1.0 billion years ago. Between 850 and 750 million years ago, Rodinia fragmented and the Pacific Ocean formed when Australia, Antarctica, and India separated from ancestral North America, which is known as Laurentia.

Towards the end of the Proterozoic Eon, the oxygen content in the atmosphere reached 2%, and an ozone layer formed, providing organisms with some protection from ultraviolet radiation. As ecological niches expanded, organisms became more numerous and diverse. A controversial hypothesis, called the Snowball Earth hypothesis, proposes that at various times between 750 and 580 million years ago, there were rapid oscillations in climate with average surface temperatures varying from $-50^{o}C$ to $+50^{o}C$.

By the end of the Proterozoic Eon, life was relatively prolific in marine environments, and at the dawn of the Paleozoic Era, the first shelly fossils appeared. The fossil record of subsequent eras is far superior to that of the Proterozoic Eon. The Paleozoic Era spans the fragmentation of a Late Proterozoic super-continent, and ends 245 million years ago with the amalgamation of Pangea.

In the Ordovician, marine life included corals, bryozoans, and jawless fishes called ostracoderms. The increased protection afforded by the ozone layer allowed the colonization of land by plants and animals, such as amphibians. Reptiles evolved from, and then out-competed the amphibians. By the end of the Paleozoic Era, the decomposition of prolific plant life in oxygen-deficient environments led to the formation of widespread coal deposits. The end of the Paleozoic Era was accompanied by a mass extinction event that is most commonly attributed to the loss of habitat as Pangea amalgamated. Marine life was more profoundly affected, with 90% of all marine species becoming extinct.

At the beginning of the Mesozoic Era, Pangea began to break up and the resulting generation of continental shelves allowed surviving species to occupy the new ecological niches. Reptiles, including dinosaurs, ruled the land and sky, and flourished in the relatively warm climates. As land plants progressively diversified, herbivores and carnivores became more established. The mass extinction at the end of the Mesozoic Era is most popularly attributed to the fall-out of an extra-terrestrial impact. Mammals were the chief beneficiaries of the demise of the dinosaurs, and one family of mammals, the hominids, ultimately evolved to produce *Homo sapiens*, modern humans. The long-term fate of planet Earth depends on its ability to sustain plate tectonics, and the energy supply from the Sun. Plate tectonics depend on mantle convection, which is driven by radioactive decay. The heat production provided by radioactive decay should be sufficient to sustain plate tectonics for another five billion years. The Sun has a five billion year supply of nuclear fuel. When this supply is exhausted, the Sun will expand and engulf the Earth.

1. Introduction

According to the solar nebula theory, the Earth and other planets in the Solar System formed about 4.57 billion years ago by condensation of interplanetary dust. The Sun is a star that formed at the centre of our Solar System about 4.6 billion years ago. Compared to other stars in the heavens, the Sun is a rather mediocre star, and is referred to as a "Yellow Dwarf."

The primordial Earth was a hostile environment with its thin primitive crust, abundant volcanic activity, and extra-terrestrial impacts. Since that time, however, the planet has evolved from its tumultuous origins to a relatively benign, modern world capable of supporting diverse ecosystems. The evolutionary process has been dominated by slow, progressive change involving ongoing interaction between solid earth, air, water, and life. However, there is increasing evidence of rapid global change in narrow time intervals, and the punctuation of progressive evolution by catastrophic events that are best represented in the geologic record as mass extinctions. This section describes the fundamental processes responsible for the Earth's evolution through geologic time, and on that basis makes some predictions for the future.

The Earth formed at about the same time as the other terrestrial planets in the inner part of the Solar System as it cooled. The first 4 billion years of Earth's history, from its formation to the first appearance of shelly fossils 545 million years ago, is known as the Precambrian (see Figure 1). During that time, simple, marine-dwelling, soft-bodied organisms dominated life. The Precambrian is divided into three eons: the Hadean (4.57 to 4.0 billion years ago), for which there is no rock record; the Archean (meaning "ancient"), which extends from 4.0 to 2.5 billion years ago, and the Proterozoic (meaning "earlier life"), which stretches from 2.5 billion to 545 million years ago. The last 545 million years is known as the Phanerozoic Eon (meaning "visible life"). As a result of the presence of shelly fossils, the fossil record of the Phanerozoic is far superior to older eons, allowing it to be subdivided into eras: the Paleozoic Era or "ancient life", the Mesozoic Era or "middle life", and the Cenozoic Era or "recent life", and each era is further subdivided into periods.

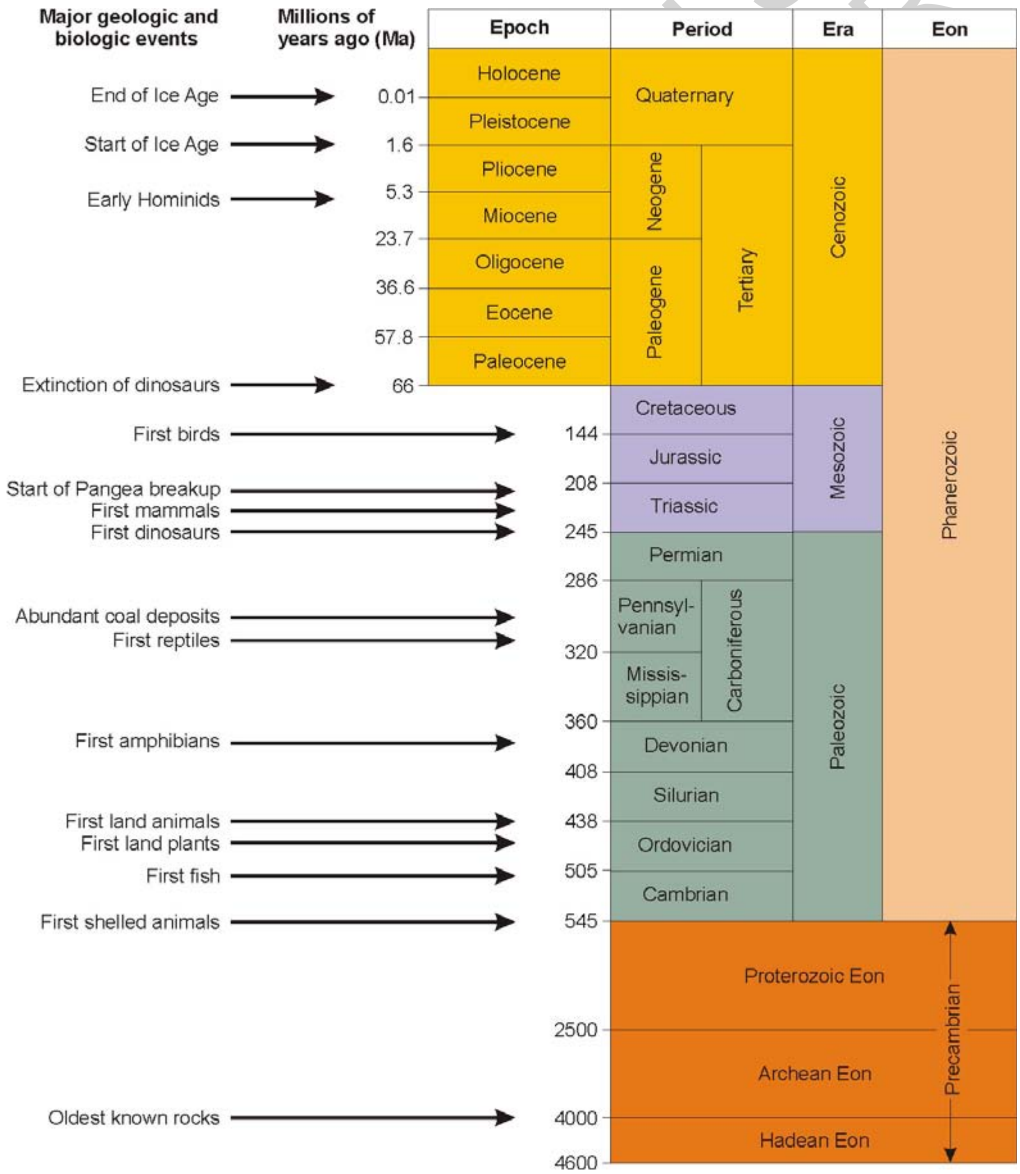

Figure 1. The geologic time scale subdivided into eons, eras, periods and epochs. Geologic dates are in millions of years (Ma) and indicate the beginning of each time division. The table is not drawn to scale. Relatively little is known about the events that occurred during the early part of the Earth's history and thus the first four billion years are given less space on this chart.

Changes in oceanic and atmospheric composition ultimately allowed life to spread onto land some 460 million years ago. By 300 million years ago, plant life was luxuriant and animal life prospered. However, mass extinction events passed on the evolutionary torch to opportunistic species, so that the dinosaurs came to dominate the lands during the Mesozoic Era, which is also known as the "age of the dinosaurs." There is strong evidence that the extinction of the dinosaurs and many other species at the end of the Mesozoic Era was related to an extra-terrestrial impact event. In the absence of the dinosaurs, mammals began to flourish, and the Cenozoic Era is often called "the age of the mammals." Only over the last 6 million years did *hominids* (the primate family to which *Homo sapiens* belongs) evolve; *Homo sapiens* themselves originated a mere 100 000 to 200 000 years ago.

2. Hadean and Archean Eons (4.57 to 2.5 billion years ago)

2.1 Formation of the Sun

Building on the ideas of Descartes, the eighteenth-century German philosopher Immanuel Kant and French mathematician Pierre-Simon Laplace proposed the nebular hypothesis for the origin of the Solar System. Although this hypothesis was subsequently modified into the solar nebula hypothesis, its essential elements remain unchanged. A nebula is a cloudy mixture of solid and gaseous particles. Nebulae are observed today between stars, and may represent the early stages of star formation.

According to the solar nebula hypothesis, a swirling cloud of dust and gas flattened into a disk as it contracted under the influence of gravity. 90% of the solar nebula condensed to form the Sun, and produced high enough temperatures to ignite and become a thermonuclear furnace. When the Sun formed near the centre of the cloud, it began to rotate. What caused the initial contraction is uncertain, but a hypothesis suggests that a shock wave associated with a nearby supernova may have initiated the collapse. Irrespective of the origin, once the collapse began, it initiated a chain of events that induced further, irreversible collapse. As the cloud contracted, its particles came closer together and the gravitational attraction between the particles increased, causing still further contraction.

The Sun's core temperature was on the order of 15 000 000^{o} C, causing thermonuclear reactions primarily involving high-speed collisions between hydrogen ions (at about 1000 km s^{-1}). A succession of these collisions had sufficient energy to fuse four hydrogen ions together to become a helium atom. However, the helium atom produced is 0.7 % lighter than the mass of the four hydrogen ions. The loss of mass is converted into energy according to Einstein's famous equation:

$$E=mc^2$$

where E is the energy, m is the mass, and c is the speed of light (300 000 km s^{-1}). Since c is a very large number, the production of helium in the Sun releases vast amounts of energy that permeate the Solar System. It is the portion of this energy that reaches the Earth that has played a prime role in the Earth's evolution. According to the evolutionary models of stars, their brightness, or luminosity, increases from their youthful to their mature stage. Therefore, the amount of radiation output from the Sun to the Earth has increased by 25 to 30% over geologic time (see *History of The Sun*).

2.2 Formation of the Solar System

Although there is no direct evidence preserved on the Earth, important constraints are derived from theoretical studies and models for the early evolution of the Solar System, during which time the Earth, the other planets, and their satellites formed. Experimental evidence indicates that, as the nebula cools, an orderly sequence of compounds condense to become solid particles. Compounds that become solid at the highest temperatures form first and consist of silicates, oxides, and metals. These compounds were concentrated in the inner part of the Solar System and began to stick together, or accrete, to form small bodies known as planetesimals. In addition to silicon and oxygen, the composition of these planetesimals was rich in elements such as iron, nickel, and sulfur. The planetesimals ranged from a few cm to tens of km across and were incorporated into the swirling cloud of gas and dust orbiting the Sun.

Due to turbulence in the swirling cloud, however, collisions between planetesimals occurred, forming protoplanets, objects destined to become the terrestrial planets. Since this material was rotating in the same direction, their relative velocities were low, and collisions between planetesimals were probably quite gentle. Extra-terrestrial objects, such as some meteorites, are considered to be the leftover raw materials of the primitive Solar System that did not accrete to form planets (see *Early Earth*).

Because the oldest rocks on Earth are close to 4 billion years old, there is no direct evidence of the age of the Solar System preserved on Earth. Radioactive dating of meteorites that subsequently collided with the Earth reveals an age of 4.57 billion years, which is generally interpreted to be the age of formation of the planets. This age of the Solar System is supported by samples from the lunar highlands, which yield ages of up to 4.5 billion years. Because the Moon is widely believed to have been ejected from the Earth following a collision with a Mars-sized protoplanet, the 4.5 billion age obtained from lunar rocks is thought to provide a minimum age for the formation of the Earth.

2.3 Formation of the Atmosphere, Hydrosphere, and Solid Earth

Several sources of heat combined to produce large-scale melting of the primordial Earth. The formation of the Earth by gravitational collapse (contraction of the Solar nebula) converted potential energy into kinetic energy, releasing enormous quantities of heat. This release of heat was sufficient to cause large-scale melting within the Earth which, in turn, allowed the heavy elements, such as iron and nickel, to sink to the core and lighter elements to rise towards the surface to form the Earth's crust and atmosphere. Theoretical models and calculations suggest this event happened within the first 20 million years of the Earth's formation. The density segregation of heavy elements into the core, an event known as the iron catastrophe, generated yet another source of heat.

Heat production from radioactive decay, a third important heat source, occurs when unstable radioactive elements spontaneously convert to more stable elements. The decay releases the excess energy stored within the elements. Modeling of the evolution of stars shows that naturally occurring chemical elements are synthesized in thermonuclear reactions during the life cycle of stars. When large stars die in cataclysmic events, known as supernova explosions, the elements are dispersed throughout the Universe and form the raw materials for other stars and planets. Some of the elements formed are unstable and are, therefore, radioactive. Rapidly decaying isotopes, such as aluminium-26, were abundant in the primordial Earth and their decay to more stable products provided significant quantities of heat in the primitive Earth.

Numerous meteorite impacts on the Earth's surface would also have released vast amounts of heat. Since the Earth's surface is dynamic, direct evidence of these ancient impacts is missing. However, there is abundant evidence of meteorite impacts on bodies such as the Moon and Mercury, which preserve their primitive surfaces, indicating that all bodies in the Solar System were affected.

Heat from these sources triggered large-scale melting in the Earth's interior, leading to the formation of a delicate, thin, primitive crust and atmosphere on the surface. The buoyant crust probably floated on a pliable upper mantle. Since hydrogen and helium are the most abundant elements in the Universe, our primary atmosphere was probably dominated by these elements. However, the Earth has insufficient gravity to retain hydrogen and helium and a secondary atmosphere developed that was dominated by gases released by igneous activity (mainly volcanic out-gassing). As ancient and modern volcanoes are both predominantly formed by melting of the mantle, it is assumed that gases emitted from the primitive volcanoes are similar to modern ones (see Figure 2). These gases contained water vapour and subordinate amounts of carbon dioxide, carbon monoxide, sulfur dioxide, sulfur, chlorine, nitrogen, argon and hydrogen.

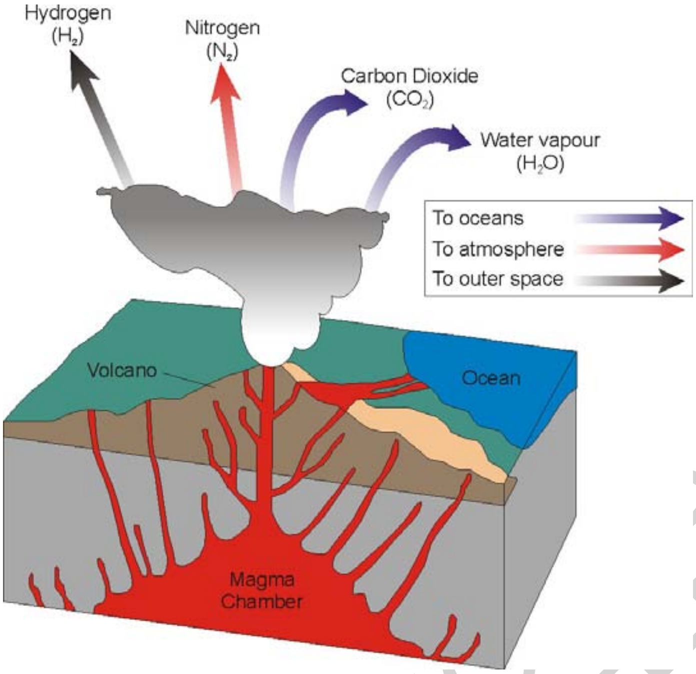

Figure 2. Release of gases from an erupting volcano.
Water and carbon dioxide are accumulated in the hydrosphere; nitrogen concentrates in the atmosphere, while hydrogen escapes into space.

It is unclear how fast this secondary atmosphere grew, and at present there are two rival hypotheses. One theory proposes a steady state model in which the atmosphere grows with time due to de-gassing of the Earth, most dramatically represented by volcanic activity. Another theory, known as the big burp model, proposes that this secondary atmosphere was in place very early in the Earth's history and that subsequent growth was minor. If the big burp hypothesis is correct, the gases released from modern volcanoes approximately balance the gases extracted from the atmosphere by other processes such as the hydrologic cycle.

The formation of the hydrosphere also occurred early in the Earth's history. There are probably several sources of water, including volcanic out-gassing and the burning of icy comets as they enter the atmosphere. Irrespective of its origin, water vapour formed a shroud of thick clouds, and as temperatures cooled it began to rain, which then drained to lower elevations. The formation of the hydrosphere stripped the atmosphere of water vapour and soluble gases, such as carbon dioxide and sulfur dioxide. Since nitrogen was not extracted, its abundance steadily grew so that over time, nitrogen became the dominant atmospheric gas.

In the modern world, rainwater drains into ocean basins. For ocean basins to form in the primitive world, it was necessary for the crust to have variable compositions so that the more buoyant crust stood at a higher elevation than the relatively dense crust. Continental crust is rich in lightweight elements, such as silicon and aluminium, making it buoyant and elevated, whereas oceanic crust is rich in dense (heavier) elements, such as iron and magnesium, and so is dense and depressed. Thus, when continental and oceanic crust first formed, water drained from elevated continents toward the lowerlying ocean basins, and a hydrologic cycle similar to the modern world commenced.

The oldest dated continental rocks occur in the Northwest Territories of Canada and in western Australia and are approximately 4.0 billion years old. The oldest dated crystals are 4.4 billion years old and occur in a sedimentary sequence in Western Australia. Since the sedimentary rocks were presumably derived from the erosion of a continent, this indicates that continental crust had formed by that time and that the hydrologic cycle also existed.

2.4 Origin and Early History of Life

In the nineteenth century, the prevailing view was that life on Earth started at the beginning of the Cambrian Period, and that no life existed throughout the Precambrian. Charles Darwin was particularly perplexed by this problem. Upon his return to England following the voyages of the HMS Beagle, his ideas on evolution began to develop. Darwin acknowledged that the apparent sudden explosion of life at the start of the Cambrian Period was a weak point in his theories on evolution. He wrote: "As to the question why we do not find rich fossiliferous deposits belonging to these assumed earliest periods prior to the Cambrian system, I can give no satisfactory answer." Darwin would be relieved to know that life is now known to have originated relatively early in the Earth's history, and while the start of the Cambrian does represent an important step in the evolution of life, it is not the dramatic beginning as envisaged by the paleontologists of his time.

Life probably began some time during the Archean. The oldest, widely accepted example of life is found in northwestern Australia in sediments that contain primitive, single-celled organisms known as prokaryotes. These organisms lack complex internal structures, such as a cell nucleus. The age of these sediments is derived from isotopic dating of the basalts with which they are interbedded; dating of the basalts gave an age of 3450 million years. However, there is controversial evidence for the existence of life preserved in metamorphosed sedimentary rocks in southwestern Greenland that are 3.86 billion years old. Although the strata are too altered to preserve the morphological structures of organisms, the isotopic analysis of the heavy to light carbon (carbon-13 to carbon-12) ratio is consistent with an organic origin.

Although the formation of primitive continents and oceans provided the physical environment in which life could form, the origin of life remains controversial. In 1953, Stanley Miller, then a graduate student at the University of Chicago, subjected a gas mixture of hydrogen, water vapour, methane and ammonia (thought to represent the early atmosphere) to an electrical discharge (which was used to simulate lightning). These experiments produced amino acids, which if bound together into long chains, are one of the basic constituents of life. However, most researchers now believe the primitive atmosphere also contained important amounts of carbon dioxide and nitrogen. When an electrical discharge strikes this mixture, amino acids are not produced, and other hypotheses are being actively evaluated (see, *Origin and Establishment of Life on Earth*).

In the primitive atmosphere, oxygen was essentially absent. As a result, there was no ozone layer providing protection from ultraviolet radiation. Since amino acids are broken down by ultraviolet radiation, the environment where life began must have provided protection from radiation poisoning. One hypothesis associates the origin of life on Earth with submarine volcanic activity, which is thought to have been abundant in the Archean. The deep ocean water would have provided protection from radiation poisoning. The process, known as chemosynthesis, involves superheated fluids that provide the energy for bacteria to convert inorganic molecules to organic compounds. In similar modern environments, seawater seeps down into ocean crust and becomes heated by the underlying magma. The hot water rises and produces jets of superheated water called black smokers. With temperatures as high as 350^{o}C, these black smokers are erupted through fractures in the oceanic crust on the sea floor. This water is rich in hydrogen sulfide, chlorine and a variety of metals. Bacteria use the energy released when hydrogen sulfide reacts with oxygen in the seawater to synthesize organic compounds from inorganic carbon dioxide in seawater.

Another hypothesis involves an extra-terrestrial origin, claiming that life was seeded by impacts from meteorites or comets. These bodies contain carbon and hydrocarbons, and their burning in the atmosphere may have generated amino acids in a manner similar to those described in Miller's experiments. One particular class of meteorites found in the Antarctic contains trapped gases that are identical in composition to the Martian atmosphere. This suggests that these meteorites were blasted off the Martian surface, perhaps by impact events, and were subsequently captured by the Earth's gravity. Some of these meteorites contain tiny rods that resemble fossilized bacteria. Although highly controversial, if this interpretation is correct, it would provide evidence that life on Earth may have been seeded by life on Mars.

An additional hypothesis proposes that life originated in pools of water in inter-tidal environments. The geologic record provides evidence that supports this origin. It is thought that clay minerals, abundant in primitive oceans, may have provided the template upon which life developed. Clay minerals have thin, sheet-like, crystal structures, like a wafer, where layers separate into individual sheets when they interact with water. Since they bond easily with amino acids, the clay minerals may have afforded the amino acids protection from ultraviolet radiation.

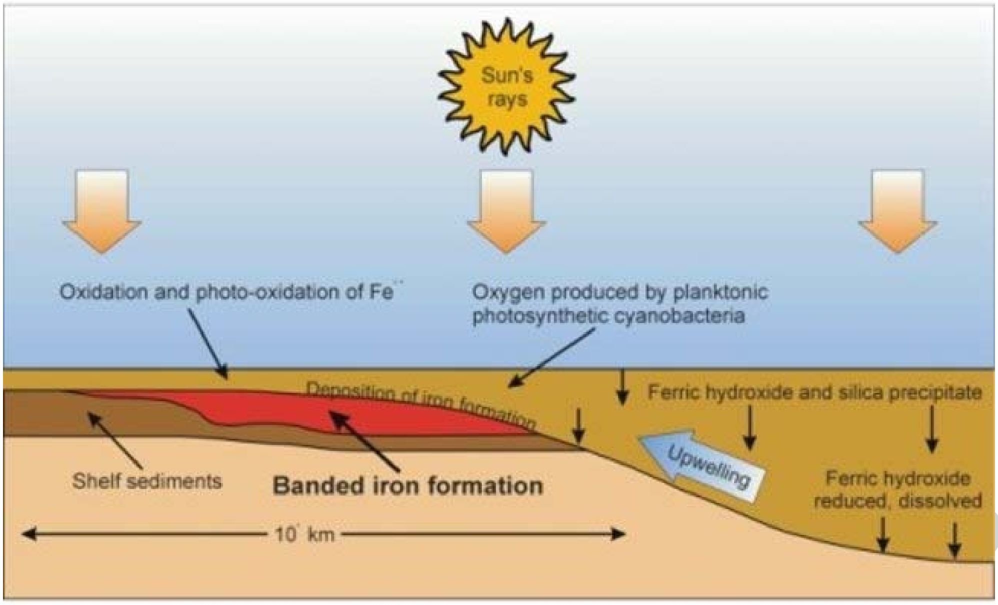

Figure 3. Origin of Precambrian banded iron formations. Marine photosynthetic organisms (blue–green algae) produce oxygen, which oxidizes iron in ocean water from Fe^{2+} (ferrous) to Fe^{3+} (ferric). Unlike soluble ferrous iron, Fe^{3+} is insoluble and forms compounds that precipitate (iron hydroxide minerals) and sink to the ocean floor, generating a banded iron formation.

The earliest examples of life, prokaryotes, which are found in 3.5 billion year old sedimentary rocks in Australia, were deposited in a shallow marine inter-tidal environment. These organisms were bound with clay minerals by cyan bacteria (blue-green algae), which are gelatinous and sticky, to form stromatolites; representatives of stromatolites still exist today. Prokaryotes were asexual and, therefore, their pace of evolution was slow. In asexual reproduction, an organism that possesses a favourable mutation reproduces countless replicas of itself. This form of reproduction is suggested by the geologic record, which shows limited evolution of life until about 2.0 billion years ago. Prokaryotes were also capable of photosynthesis. The oxygen produced by prokaryotes, which would have been toxic to these simple oxygen-intolerant organisms, was absorbed by iron in the primitive ocean water to form insoluble iron hydroxide minerals that sank to the bottom of the water. Evidence of this process is preserved in the geologic record by rock layers known as banded iron formations (see Figure 3). Banded iron formations are thinly bedded, sedimentary rocks whose layers can be correlated for hundreds of kilometers. These layers consist of alternating bands of pale quartz and dark, iron-rich minerals, such as hematite and magnetite. As a result of the absorption of oxygen by iron, the atmosphere and oceans were essentially devoid of free oxygen, and prokaryotes lived in an anaerobic (oxygen-poor) environment.

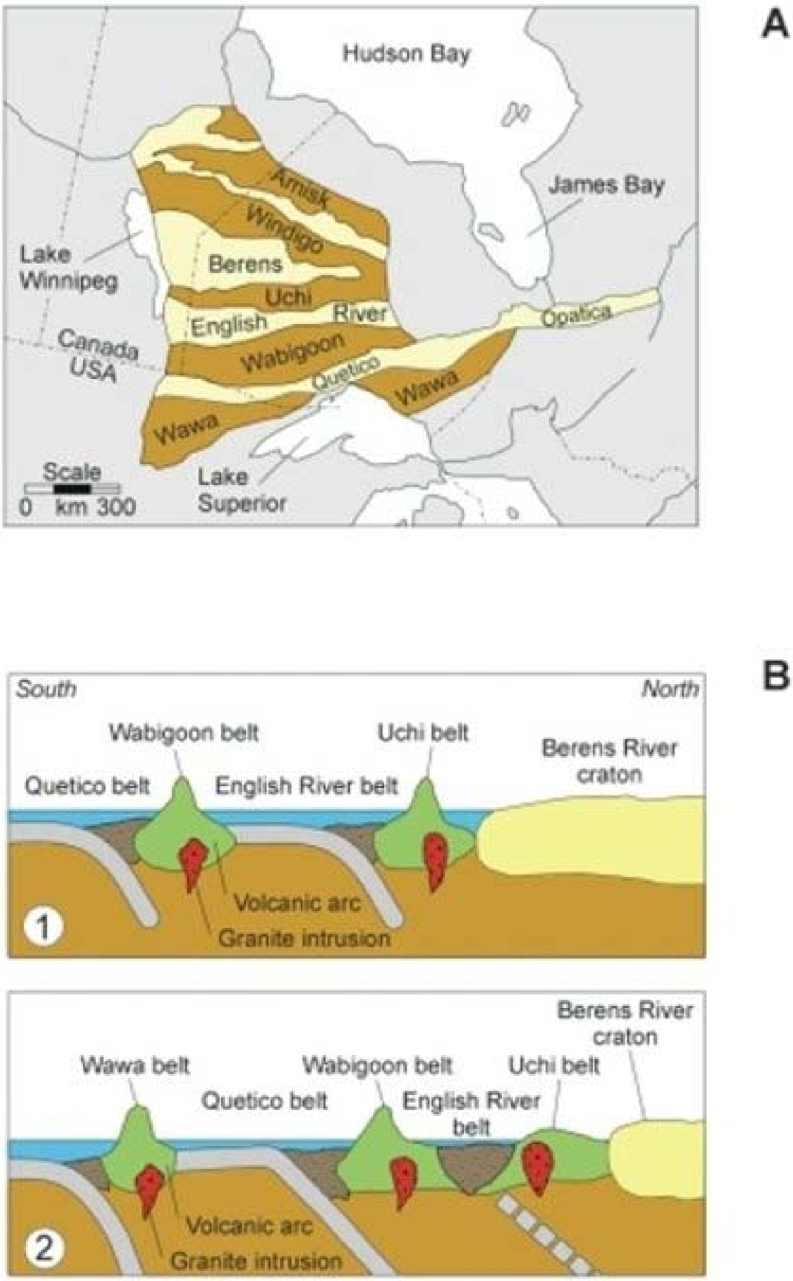

Figure 4. Formation of cratons. A) Geologic sketch of the Superior craton of the Precambrian Canadian Shield. The craton is composed of several granite–gneiss complexes (yellow,) and greenstone belts (brown). B) Diagrammatic (north–south) cross-sections illustrating a model for the origin of the Superior craton through the collision of smaller microplates. 1. Several volcanic arcs (green) are composed of greenstone belts and granite-gneiss complexes 2. The volcanic arcs eventually collided as a result of the subduction of the oceanic crust, leaving belts of deformed sedimentary rocks (dark brown) at the sites of the former subduction zones

Up until three billion years ago, the rock record is poorly represented. However, the abundance of igneous and metamorphic rocks between 3.0 and 2.5 billion years old suggests the rapid development of the continental crust during that period. This crust has two components: granite-gneiss complexes, which represent a mixture of typical continental plutonic and metamorphic rocks, and greenstone belts, which predominantly consist of volcanic rocks and interbedded marine sedimentary rocks. The origin of greenstone belts is controversial and hypotheses range from large-scale melting of the Earth's mantle causing rifting of continental crust, to volcanism associated with the opening of a small ocean basin as a result of a style of subduction similar to that found in the modern Sea of Japan. By 2.5 billion years ago, these granite-gneiss complexes and greenstone belts welded together to produce small continental blocks, or cratons, that have remained stable since that time, and form the core of modern, continental landmasses (See Figure 4).

-
-
-

Bibliography

Cooper J. D., Miller R. H., and Patterson J. (1986.) *A Trip Through Time: Principles of Historical Geology*, 469 pp. London: Merrill Publishing Company. [Standard textbook of historical geology].

Kummel B. (1970.) *History of the Earth*. Pp. 1–700. San Francisco: Freeman & Co. [Detailed descriptive monograph on the Earth' s rocks.]

The other most important monographs are listed under individual articles of the *History of the Earth*, chapter.

Biographical Sketches

Jaroslav Dostal received his initial education in geology at Charles University in Prague, Czechoslovakia. He was a lecturer at that university before immigrating to Canada where he received his doctoral degree from McMaster University in Hamilton, Ontario, in 1974. After a year of postdoctoral studies at Dalhousie University, Halifax, Nova Scotia, Saint Mary's University at Halifax, where he is now a professor of geology, hired him. Dr. Dostal has also worked as a researcher at the Universite de Montpellier, and the Universite d'Aix-Marseille, France, and the Universita di Modena, Italy. He has authored or co-authored over 150 papers in academic journals as well as more than 200 conference abstracts and other publications.

Brendan Murphy is an Irish citizen who completed high school and his B.Sc. degree in Ireland, before immigrating to Canada in 1975. He acquired an M.Sc. from Acadia University in Wolfville, Nova Scotia, in 1977 and a doctorate degree from McGill University (Montreal, Quebec) in 1982. In 1982, he joined St. Francis Xavier University, where he is now a professor of geology. He has published over 100 scientific articles in academic journals, book chapters, monographs, or geological field guidebooks, and has authored or co-authored more than 120 conference abstracts.

Damian Nance is a citizen of both the United Kingdom and the United States. He completed his education in England with a B.Sc. from the University of Leicester in 1972 and a Ph.D. from Cambridge University, before emmigrating to Canada in 1976 to teach at St. Francis Xavier University in Nova

Scotia. In 1980, he joined Ohio University where he is now a professor of geology. He has published over 150 scientific articles in academic journals, books and government documents, and has authored or co-authored more than 180 conference abstracts.