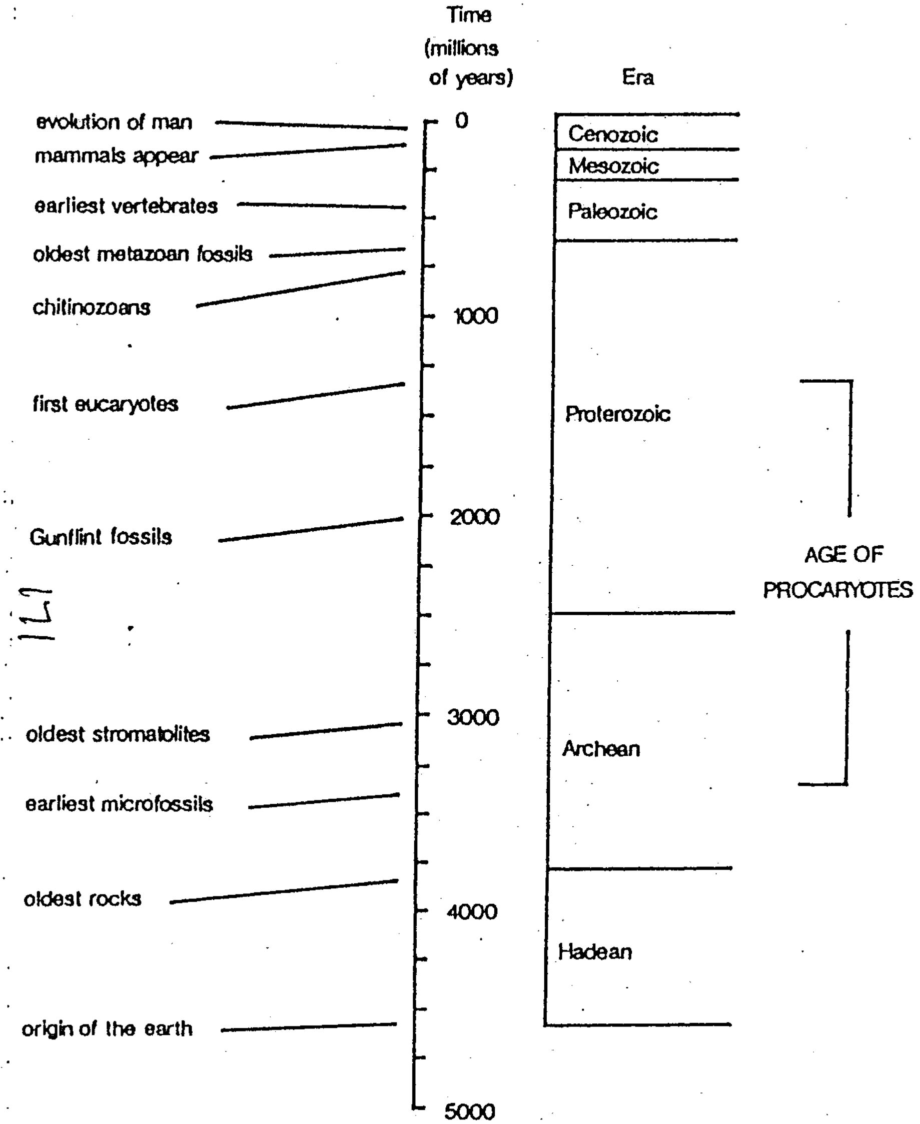

Geologic time and formations.

from W. Day, Genesis on Planet Earth 2nd ed
Yale, 1984

1

Building Blocks

#10

From Genesis on Planet Earth by William Day. (c) 1984 by Yale University Press. Permission to reprint granted by the publisher.

The time was an autumn afternoon in 1951. Harold Urey, physical chemist and discoverer of deuterium, a heavy form of hydrogen, began his lecture at the University of Chicago on a subject that was one of his life's studies, the origin of the solar system. In his latest book,[1] then just recently completed, he had postulated that, because of the reduced conditions of the solar nebula that gave rise to the planets, the primordial atmosphere of the earth did not contain oxygen, as it does today, but consisted of methane, ammonia, and hydrogen.

The gathering of students and faculty sat listening with interest. Theories regarding the origin of the sun, the earth, and the planets had changed throughout the centuries. No longer was it believed that the planets were formed from molten globs of matter ejected from the sun during a close encounter with another star. In 1943, only eight years earlier, a German scientist had postulated that the planets were formed by the accretion of solid material in swirling eddies of an immense cloud of dust and gases. And only since 1929 had it been realized that the universe is mostly hydrogen and that the presence of free oxygen in the earth's atmosphere is a strange cosmic occurrence.

The professor went on into another favorite subject of his, the origin of life. Scientists generally believed that life must have begun on early earth billions of years ago in a manner that could be explained scientifically. But to demonstrate how it could have happened has been extremely difficult. As a result, studies on the origin of life were in a state of paralysis. The life sciences have shown that all forms of life consist of certain chemical substances that are the building blocks: amino acids, sugars, lipids, and two kinds of heterocyclic bases called purines and pyrimidines. These components are linked together into large polymeric molecules: the amino acids form proteins; the sugars, polysaccharides; and the bases, nucleic acids. The assembly of these complex polymers into units bound by a lipid membrane creates living cells. The difficulty that thwarted scientists for over one hundred and fifty years, however, is that the building blocks of life appear to be produced in nature only by living organisms. There, then, lies the paradox. If only living plants and animals can synthesize the amino acids and other building blocks necessary for their own creation, how, Urey asked, could life ever have begun on earth?

Some students jotted down notes, most allowed their thoughts to sweep over the problem, searching for ready answers to the question. The seminar was becoming more engrossing. Theories on matter, energy, and the universe were fascinating and stimulating, but to speculate on the formation of life from inanimate substances excited the imagination and sensed of the momentous.

Urey went on: There must have existed circumstances on primordial earth that no longer exist that permitted life to begin. The absence of free oxygen and the reduced atmosphere would have produced a different chemical environment. In order for a living cell to develop, some organic compounds must have preceded the origin of life. But this was only a hypothesis. There was no experimental proof that organic substances necessary for the assembly of life could ever have formed on prebiological earth. Nonetheless, logic dictated that organic compounds must have been created on earth in some way before life could form.

As Urey continued to lecture on the paradox of life's beginning, one of the first-year graduate students, a young Californian by the name of Stanley Miller, listened intently. Miller, twenty-one at the time, had come to Chicago in September from Berkeley and was still searching for a suitable research problem to work on for his dissertation. The point that Professor Urey made seemed valid, but to prove how organic matter formed under primordial conditions probably would take a considerable amount of time. Miller brushed the thought aside and resigned himself to his original intention of finding a more theoretical problem.

The seminar ended with the customary question period. Did not the Russian biochemist Alexandre Oparin also discuss the possibility that organic compounds had been produced in a reduced atmosphere before there was oxygen? Urey answered in the affirmative, pointing out that no one had yet put the hypothesis to the test of experimental verification.

That winter the young graduate student from California discussed with the various chemistry professors their particular research interests in the hope of finding a rewarding project to work on for his thesis. Eventually, he decided to study under Professor Edward Teller, an authority on atomic physics, the manner in which elements are synthesized in extremely hot stars.

Six months later Teller announced that he was leaving the University of Chicago to set up a laboratory in Livermore, California. Faced with the problem of finding a new mentor and a new topic for his dissertation, Miller's thoughts turned to Urey's seminar and the questions it had posed. Perhaps the experimental work would not be as messy as he had originally imagined. The more he thought about it, the more the problem appealed to him and his enthusiasm mounted.

When he approached Urey with the proposition that he study how organic compounds could have formed on prebiotic earth, his enthusiasm was met with caution. The professor explained that the research could become a long and fruitless task. Perhaps Miller should consider studying the occurrence of thalium in meteorites. Only after realizing the student's determination did Urey consent to his attacking the problem of the synthesis of organic compounds. If, however, nothing came of the study within six months, he insisted that Miller switch to a more conventional research problem to assure success for his thesis.

During the following weeks Miller studied Urey's paper on the subject[2] and read the book by Oparin.[3] With Urey he then attempted to design a laboratory apparatus that would simulate the postulated atmospheric conditions of primordial earth. Something resembling a natural source of energy was needed to act on a mixture of gases to generate a chemical reaction. Since the atmosphere receives moisture evaporated from the oceans, which condenses again to return to the surface as rain, a supply of water would have to be included. A design was sketched and taken to the glassblower for construction.

A week later the drawing had been converted into a full-scale model of connecting glass tubes and flasks. The complete apparatus consisted of a 5-liter glass chamber atop a glass tube into which two tungsten electrodes protruded with their tips close enough to each other to permit a spark to leap across the gap. Joined below this was a condenser connected to a U-tube that ran over to a reflux flask for water; a return tube extended from the flask back to the chamber. It was a closed system in which water boiled in the flask would be carried as vapor past the electric spark, condensed, and returned to the flask. The apparatus was to be a model of the atmospheric conditions of primitive earth simulating the occurrence of thunderstorms in the primordial atmosphere.

Miller set up the apparatus and pondered its construction. He read the instructions for the Tesla coil that was to generate the electric spark and was astounded that it produced 60,000 volts. He hesitated, and doubts began to cloud his thoughts on the feasibility of the experiment. Hydrogen and methane both form explosive mixtures with air. Any leak could be disastrous. Even the thought of sparking 60,000 volts in water vapor seemed hazardous. And since it was an airtight system, heating the water to a reflux temperature would expand the gases and could create dangerous pressures. He took the apparatus back to the glassblower and had him interchange the positions of the condenser and the tube containing the spark gap.

With the construction now changed so that the spark came after the water vapor had condensed, it seemed safer, and Miller decided to put the experiment to the test. He added water to the flask, then pumped the air from the system and replaced it with a mixture of methane and hydrogen, making certain it was cleared

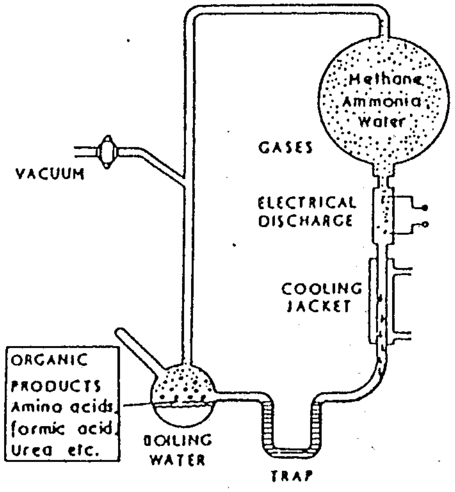

Figure 1.1. Apparatus used by Miller to simulate the prebiotic synthesis of amino acids and other organic compounds.

completely of any traces of oxygen. He checked for leaks and found the apparatus to be tight. Cautiously, he plugged in the Tesla coil and slowly ran the discharge up to 60,000 volts. Flashing streaks of blue darted across the gap between the tungsten electrodes with a crackling cadence.

Nothing else seemed to happen. Miller went to his desk and tried to study, but walked over to check the apparatus periodically that afternoon to see if he could detect any change. When it came time to go home, he decided to let it run overnight. The next morning when he entered the lab he saw a faint film of hydrocarbon floating on the surface of the water in the flask. There was nothing new in that. Earlier researchers had observed the same result when they exposed methane to an electric discharge. He allowed the experiment to continue for several days. The hydrocarbon film thickened, but an analysis of the water failed to show anything resembling organic substances of a biological nature.

Perhaps the 60,000 volts was less dangerous than had appeared. Miller returned the apparatus to the glassblower and asked him to restore the condenser and the tube with the electrodes to their original arrangement. After a week he was ready for another attempt.

The experiment was repeated. This time the water in the flask was warmed to a low heat with a heating coil. Again the experiment was allowed to run continuously. After two days Miller saw that the hydrocarbon film was no longer present and the solution had become a pale yellow. Something was happening. The water was analyzed, and the results were suggestive but not conclusive.

Again the experiment was repeated. This time Miller turned up the heat so that the water boiled vigorously. As he saw the water dripping from the condenser, he knew the apparatus had held the pressure until a steady state was reached and the water was circulating through the cycle. The discharge sparked and crackled across the gap as the boiling water drove its vapors with the gases past the electric discharge. Miller looked on with satisfaction as the experiment performed the way it was designed to in simulating the primordial atmosphere.

He could do nothing now but wait. Hour after hour the sparking continued as the water vapors and gases circulated around and around, imitating the cycle of water evaporating from the oceans into the atmosphere where it mixes with the atmospheric gases and is exposed to thunderstorms, only to return to the oceans as rain. For a long while there was no perceptible change. The experiment was left to run overnight.

The next morning when Miller entered the lab he immediately noticed that the water in the flask had turned pink. Excitement seized him and he rushed over to look more closely. Then as he saw that the heating mantle had an exposed coil that glowed red through the water, his exuberance was dampened. Slowly he lowered the mantle and looked at the solution in the flask. It was still pink. A definite chemical reaction had been taking place after all. His thoughts raced. Porphyrins? They give red color to blood. Were porphyrins being produced in this simulation of the conditions of prebiotic earth?

He let the experiment run. Day followed day. The color deepened. After one week the water in the flask had become decidedly red.

The time had finally arrived to test the results. Miller stopped the experiment and allowed the apparatus to cool. Extracting a sample from the flask, he analyzed it by paper chromatography, a standard procedure for separating and detecting small amounts of material. After running the chromatogram, he sprayed the strip of paper with a mist of ninhydrin solution and warmed it in an oven. Within minutes purple spots appeared, indicating the components. The compounds were amino acids!

Miller analyzed his one-gram sample by anion and cation exchange chromatography. He fractionated the components, made chemical derivatives of the ones in greatest yield, and compared the melting points to those of known amino acids. He sterilized the entire apparatus and repeated the experiment to be certain the results could not be due to bacterial contamination. There was no question of the results. They were amino acids, the very compounds that are used by plants and animals to construct their proteins.[4] No longer was there a dilemma of how organisms could have produced organic compounds before they themselves existed—the building blocks had already been there on primordial earth.

It was the experiment that broke the logjam. Its simplicity, the high yield of the products, and the specific biological compounds in limited number produced by the reaction were enough to show that the first step in the origin of life was not a chance event but one that had been inevitable. In effect, the experiment revealed that the basic components from which biological systems are constructed are energetically favored compounds. With the appropriate mixture of gases, any energy source that can cleave the chemical bonds will initiate a reaction resulting in the formation of life's building blocks.[5]

2

Early Earth

It was a stark, barren earth over which the sun rose quickly each morning, searing in a black sky in a blaze of intense ultraviolet radiation. The accretion of the unmelted mass of dust, aggregates, and stones which formed the planet had left it looking much like the dry, barren face of the moon. And as the sun followed its diurnal course, it rushed across the sky in a few hours to descend below the horizon just as quickly. For on this airless, waterless, hadean world, the day was only five hours long.[1]

Nightfall brought the rise of the moon, an awesome globe so close as to appear to touch the earth's surface as it loomed over the horizon, brightening the austere landscape with its huge glowing face. Each time as it ascended rapidly, its pull played in tidal oscillations on the viscous molten lava pouring onto the earth's surface from the many eruptions. The moon revolved just beyond Roche's limit of 2.86 radii (11,000 miles) and escaped the destruction into a ring system like the outer ring circling Saturn at 2.3 times the planet's radius. In quick succession the months passed, as the moon spun around the earth in 6.5 hours in an orbit approximately 46 degrees to the ecliptic.

As bleak as the rocky interior may have appeared, within its creation the inner earth contained the essence of a new existence. The planet was still essentially an unsorted conglomerate accreted at a temperature low enough to have retained the volatile constituents within its rocky structure. But also trapped in its interior were the radioisotopes of the elements potassium, uranium, and thorium. As time passed, the heat generated from the radioactive disintegration of potassium-40, uranium-235 and 238, and thorium-232, unable to escape, was absorbed by the rocks, and their temperature

began to rise. After millions of years the accumulating heat drove the temperatures above the melting point of the silicates. As the rocks melted, they expanded and, becoming less dense, migrated upward while the denser material moved downward. A differentiation of the interior of the earth based on density, begun during the accretion stage, was now accelerated by a new dynamic mechanism.

Volatile components held in chemical bonds were liberated by the heat and created immense pressures beneath the weak, rocky surface. After a while the crust, no longer able to detain the cauldron within, opened in fissures, and the volatiles and molten material spewed out in volcanic eruptions, fumaroles, and hot springs. Oxygen, hydrogen, nitrogen, and carbon, long frozen in nonvolatile combinations with metals as oxides, hydrates, nitrides, and carbides, were freed from the nongaseous elements and blown and sweated to the surface, where they began forming an atmosphere. Any free oxygen quickly reacted with the reduced gases to form water, and the gaseous envelope that began to form over the globe consisted of hydrogen, nitrogen, water vapor, carbon monoxide, carbon dioxide, and the acids of sulfur and chlorine. Phosphorus, bound in rock as the mineral apatite, was freed by the intense heat and belched to the surface with volcanic ash to react quickly with water.

Beneath the hot surface, the cauldron began churning in great convection currents, moving the heat and lighter substances outward and the dense iron-nickel melt toward the center of the earth. The radioactive elements, bound selectively in the crystal lattice of minerals of less density, were carried toward the surface. There was no distinct crust at this time but only the outer surface of the yet unsorted conglomerate. The inner core, heated by the radioactive decay from above and the intense pressure of gravity, began to grow with the inward migration of the molten iron.

The surface was not stabilized as it is today by being of lighter material, and it continued to subside to displace magma that flowed to the top and poured out in great floods of lava. The molten rock that reached the surface solidified and took on the fine-grained texture of basalt, a volcanic rock coal black to dark gray in color, with the principal minerals being the ferromagnesium silicate pyroxene and calcium-bearing plagioclase.

The earth was an aggregation of rocky materials in which most of the rock-forming minerals were silicates of iron, aluminum, magnesium, calcium, sodium, and potassium. The oxides of iron were present, as were apatite, the calcium phosphate mineral. Only four elements—iron, oxygen, silicon, and magnesium—comprised 93 percent of the total weight. Most of the iron migrated toward the center of the earth to build the core, whereas silicates became the principal minerals of the outer layers.

Igneous rocks—those crystallized from the silicate melt called magma—are the closest approximation to the primordial earth material. Rocks may be a single mineral such as quartz (SiO_2), but generally they are a combination of minerals, the composition and physical properties characterizing the rocks. When magma

Table 2.1. Principal minerals in the earth's crust.

Mineral	Percent weight
SiO_2	60.18
Al_2O_3	15.61
CaO	5.17
Na_2O	3.91
FeO	3.88
MgO	3.56
K_2O	3.19
Fe_2O_3	3.14
TiO_2	1.06
P_2O_5	0.30

Source: F. W. Clarke and H. S. Washington, U.S. Geol. Survey, Profes. Paper 127 (1974).

175

solidifies at or near the surface, the slow growth of constituent minerals creates plutonic rocks, of which granite is a common type. Granite is one of the lightest rocks, having 66 percent or more silica; basalt has less than 50 percent; and andesitic rocks make up the intermediate range.

For hundreds of millions of years the earth was a hot, inhospitable place as volcanism poured out noxious fumes and vapors at an enormous rate. There were no oceans, a scant atmosphere, and a surface barren, pitted, and scarred by fissures and fiery eruptions from within. The earth would have seemed to have little destiny. But vast amounts of water bound in the rocks as hydrates were being liberated into the atmosphere and remained there as the surface was hot. After a very long time, with the air saturated and the surface of the earth cooling, a new phenomenon took place..

It rained.

It rained, and the rain evaporated, and it rained some more. It poured down on the bare rocky surface and ate the rock and collected in great flat basins. It was not the sweet rain of the earth's spring; it was the bitter, corrosive acid rain from the bowels of the earth, heavy-laden with hydrogen sulfide, carbon, and hydrogen chloride. The principal volatiles from the volcanoes were water, carbon dioxide, and hydrogen chloride in a ratio of 20:3:1; the rain was approximately 1 molar hydrochloric acid.

But as the rains were acid, bringing with them the chloride, bromide, sulfide, and carbon dioxide, the rocks were basic with sodium, potassium, and calcium. The acid rain dissolved the rock until it was neutralized, and where the water evaporated the salts formed broad, flat salt plains.

As the volcanoes continued the outgassing of the earth's interior, they were restoring the atmosphere and creating oceans. It was a reducing atmosphere devoid of oxygen, and the oceans were merely shallow catchbasins for gathering the rains. Nearly two billion years would pass before oxygen would be present in significant quantities, and the oceans came into being only by growing throughout the ages from the water expelled from the earth's rocky interior.

Table 2.2. Volatile materials now on or near the earth's surface unaccounted for by rock weathering.

Volatile	Wt. (10^{20} grams)
Water	16,600
C as CO_2	910
Sulfur	22
Nitrogen	42
Chlorine	300
Hydrogen	10
B, Br, Ar, F etc.	4

Source: Modified from W. W. Rubey, Bull. Geol. Soc. Am. *62* 1111–1147 (1951).

Two billion years in the future the oceans would achieve their modern characteristics (see chart, p. xx). But the oceans of Hadean Earth were solutions resulting from an acid leach of basaltic rock. The atmosphere was devoid of oxygen, so that anaerobic deposition environments with carbon dioxide pressures of about $10^{-2.5}$ atmospheres, or ten times today's level, were prevalent. Under these conditions, the pH* of early ocean water was lower than today's. The calcium concentration was higher, and the ocean was probably saturated with respect to amorphous silica. In addition to the other ions from the basaltic rocks, reduced iron and sulfur would have been in their proportions found in the rocks. Only when the pH approached neutrality would aluminum ions begin to precipitate as the hydroxide and combine with silica to form cation-deficient alumino-silicates. As long as the hydrogen chloride exceeded carbon dioxide, the oceans would have had a high content of calcium chloride, and the carbonate would not have been precipitated, as it was at later times.

As the atmosphere was being formed, important changes began to take place. In the upper level, radiation from the sun dissociated water molecules to hydrogen and oxygen. The hydrogen escaped to outer space and the oxygen reacted quickly with the reduced atmospheric gases, reverting to water. The photodissociation continued to consume some of the atmospheric water, but as the principal volatile brought to the surface by volcanic activity, it accumulated much faster than it was consumed. As carbon dioxide poured into the atmosphere from the volcanoes, the amount built up was restricted by absorption of the carbon dioxide into the oceans. In this way the level of atmospheric carbon dioxide was kept at a relatively low level.

---

* pH is a logarithmic scale of hydrogen ion concentration. Neutral solutions have pH 7; 0–7 is acidic; 7–14 is basic.

It has generally been believed that the earth heated to a hot stage at this time, forcing out the water and other volatiles into a dense atmosphere, from which they would condense out at a later time after the earth cooled sufficiently. William Rubey,[2] who studied the matter, has found convincing evidence that this could never have happened. Instead, it appears that at no time in the earth's history has there ever been more than a fraction of the excess volatiles of the earth's interior in the atmosphere.

The amount of carbon dioxide buried as carbonates and organic carbon in sedimentary rocks is 600 times greater than all the carbon in the atmosphere, hydrosphere, and biosphere. If even as much as 1 percent of the carbon dioxide now locked in these rocks had been in the atmosphere, the oceans of today's volume would have gone from their pH of 8.2 down to 5.9.

The equilibrium of atmospheric carbon dioxide and that absorbed by the oceans proved to have profound significance. Carbon dioxide in the atmosphere creates what is called the greenhouse effect. Like the glass of a greenhouse, carbon dioxide in the atmosphere is transparent to visible light but absorbs heat-generating infrared rays. When sunlight is absorbed by the surface of the earth, the warmed solid substances reemit much of the energy as invisible infrared radiation. If the level of carbon dioxide in the earth's atmosphere were too high, this energy would be reabsorbed by the air instead of being radiated into space, and the earth would heat up. By absorbing carbon dioxide and keeping the atmospheric concentration level low (about 0.024 percent today), the oceans have controlled the greenhouse effect on the earth.

On Hadean Earth there were no continents, and the crust was the outer surface of the mantle. The radioactive elements were not yet concentrated in the crust or upper mantle as they are today, but were still distributed throughout the undifferentiated mantle. Nonetheless, the accumulating heat from the nucleoclides over hundreds of millions of years was fractionating the earth into concentric layers. And as the radioactive elements migrated upward toward the outer crust, they brought with them their heat-producing capacity nearer the surface. The magma would have concentrated in a transitional layer below the surface as it is today between the crust and the upper mantle.

Toward the end of Hadean times the buildup of radiogenic heat, the partial melting of the mantle, and the upward convection of heat in the magma must have reached climactic proportions, causing the original crust to undergo modifications in areas around the globe. The intrusion of igneous rocks and the extrusion of lavas deformed the surface and accelerated erosion, and the earliest sedimentary rocks formed.

It was probably still too early for the formation of true crystalline rocks. Nor did the sea-floor spreading process—in which crustal plates separate by the welling up of magma—occur during this time. There was not yet the irreversible differentiation of the initially homogeneous mantle. But the passing of the Hadean time was marked by the release of the heat buildup in great floods of lava spewing out from volcanoes onto the earth's surface and beneath the waters of the growing oceans. It was the end of the first long age of the earth's history, an era that had seen the birth of the earth's atmosphere and the oceans; it had lasted 800 million years.

Still 3.8 billion years in the future the rocks crystallized from the magma in that primordial scene were to play a significant role in science. In 1966, Vic McGregor, a young geologist from New Zealand working with the Geological Survey of Greenland, began mapping in detail the mountain area around a fjord named Amerlik on the western coast near Godthaab, the capital. It was not an easy task. The great assortment of rocks and their complex arrangements made interpreting the geologic history difficult. But after several years McGregor began to piece together a distinctive sequence of events that had occurred down through the ages. The rocks recognized to be the oldest from that region were the Amitsôq gneisses, igneous rocks that had undergone metamorphosis and deformation by mighty forces acting on the earth's crust. By McGregor's interpretation, there should be rocks that were formed even earlier than the Amitsôq gneisses.

Stephan Moorbath of Oxford joined McGregor in the summer of 1971, and the two geologists began to collect rock samples to be sent back to England for age measurements by radioactive isotopes. At Isua, a mountainous area 60 miles northwest of Godthaab at the very edge of the great inland ice sheet, a mining company was exploring a large iron ore deposit. The ore was a part of a great arc of highly metamorphosed volcanic and sedimentary rock 7 to 15 miles in diameter and 1.8 miles thick. When McGregor and Moorbath reached the site, they saw that the arc of rock was supercrustal, that is, laid down on a surface and flanked by granite gneisses with edges of contact sheared and deformed.

Samples were collected and sent back to Oxford for rubidium-strontium and uranium-lead measurements to determine their ages. When the results were finally received, the age of the rocks was found to be 3.76 billion years. McGregor and Moorbath learned that on that bleak Arctic upland near the great ice sheet where the rock is totally exposed, they had been walking on a section of what may have been the original continental crust of the earth.[3]

Throughout the Hadean era the internal heat distilled to the surface the volatile materials bound to the rocks, and a primitive atmosphere and hydrosphere were born. By the time of the Isua Iron Formation 3.76 billion years ago, there was enough water on the surface for rain, erosion, and sediments. Following the Hadean, the earth entered the Archean era.

The early Archean would have been a consolidation interval following the great eruptions that ushered out the Hadean. Over the hundreds of millions of years erosion wore down the old volcanic mountains and deposited thick layers of sediments on their margins. While the surface was being weathered, within the earth's interior the heat of radioactive decay continued to accumulate on a worldwide scale for the next episode.

Then around 3 billion years ago, when shallow primitive oceans skimmed the earth's surface, the earth underwent another period of crustal formation. The cauldron no longer detained, the crust split into huge rifts, and the molten magma caused the adjoining sections of crust to decouple from the upper mantle and slide over the layer of molten rock at the interface. The movement wasn't much—only a centimeter or so a year—but over the millions of years it was enough to force the surface of the earth to lose this increase in its crust in some manner elsewhere. In order to relieve the pressure the crust split at other places and the section under pressure began to slide over the neighboring section, driving down the edge of cleavage into the mantle beneath it.

As the subducted surface slid deeper into the mantle, it melted at the subterranean temperatures. The lighter silica-rich rock moved upward, while the ferromagnesian rocks sank. Where one edge of the surface slid beneath the other, a deep trench resulted, and parallel to the trench the subducted crustal material extruded as magma onto the surface, creating an arc of volcanic islands. These island arcs must have appeared in a number of locations on the face of the earth.

The magma that erupted along rifts in the earth's crust, pouring out vast quantities of lava, became the basement rocks of the continental shields. These foundation rocks, although 3 billion years old and folded and metamorphosed, can be seen as long successions of pillow lava as much as several miles thick, formed by the rapid chilling of being erupted under water. There is evidence that these belts, known as greenstone belts because of their greenish tinge from chlorite, hornblendes, and epidote, may have been crustal regions that subsided 6 to 9 miles as volcanic rocks and sediments accumulated layer upon layer over a long passing of time.

The rocks in greenstone belts have no exact equivalent among contemporary active volcanic regions, although they show some resemblances to present volcanic island arcs, such as the Kuriles north of Japan and the southwestern Aleutian islands. The rocks around the greenstone belts are often predominantly granite, and many Archean provinces consist of strongly folded, steeply dipping volcanic successions compressed between granitic bodies. The distribution of land and water during the Archean is not well known, but the sediments and volcanic rocks were accumulating under water.

The island arcs then were probably what they appear to be today—a significant evolutionary intermediate stage between oceanic and continental crusts. Oceanic crust is basaltic and represents the surface of the mantle, whereas continental crust, thicker and of lower density, is principally granite. Island arcs are of crustal material thicker than oceanic crust, but not as thick as continental, and composed of rocks common to both.

Toward the end of the Archean another stage of crustal development occurred. As oceanic crusts slid beneath the overriding plates, the molten rock from the subducted crusts rose by its buoyancy and moved into placements on the margins of the island arcs. Sometimes the magma extruded onto the crust, pouring out thick series of volcanic rock. More often, it remained intruded until the final

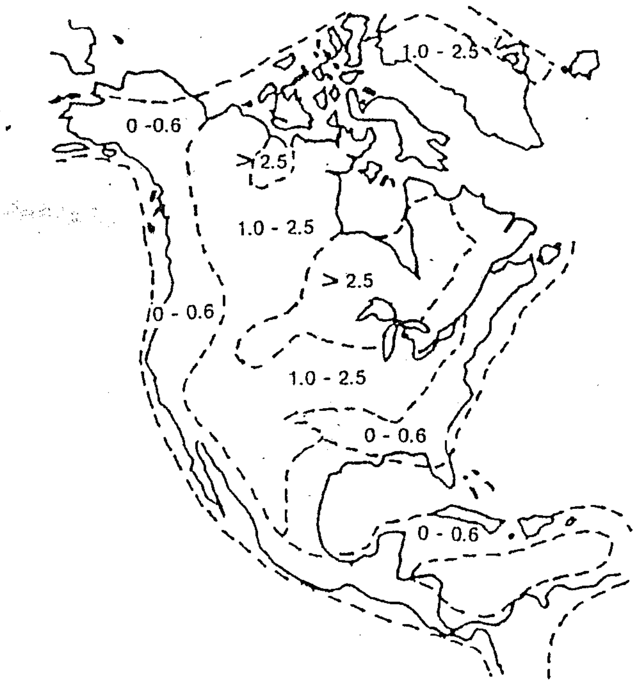

Figure 2.1. The growth of North America. The numbers indicate the ages of rocks of the continental platform in billions of years.

stage of mountain building, or orogeny, as it is called by geologists. Orogeny went on over hundreds of millions of years. Then, at a time when the confining pressure over the intrusive body weakened, its buoyancy drove it upward like a cork through the crust in the last, spectacular stage of mountain building.

In this way the continents have grown step by step from their nucleus of granite by addition to their margins of the lighter material fractionated from the mantle. The entire procedure of mountain building apparently has occurred in six or seven episodes throughout the earth's history, each episode lasting approximately 800 million years.

The thrust of the mountains on the margins of the greenstone belts severely metamorphosed and deformed the rocks. The subsidence of the belts created the flat, low-lying terrain known as the continental shields. These are the cratons, or nuclei, from which the continents grew by subsequent mountain building episodes. The Canadian Shield, the largest of these features, lies like a gigantic saucer with the center holding the Hudson Bay. The mountains are gone now, long ago worn down to their root stocks, but the area remains a vast hoard of mineral deposits.

The greenstone belts, dating from 3.4 to 2.5 billion years ago, are the oldest belts of metamorphosed and deformed rocks. From about 2.7 billion years onward, individual sedimentary basins formed from the erosion of the ancient mountains. The cratons upon which the continents were growing may have been 5 to 10 percent of the present continental area 3.8 billion years ago, but between 2.9 and 2.5 billion years ago they grew in area until they were 50 to 60 percent of the present area. The earth's crust was becoming stable enough by 2.7 billion years ago to allow sediments to accumulate in large basins without being altered by subsequent stresses.

During the Archean the atmosphere was still without oxygen, but it contained nitrogen, and the carbon dioxide content was probably 4 to 10 times today's value, keeping the lower atmosphere extremely hot. According to geologists L. Paul Knauth and Samuel Epstein,[4] in studies at the California Institute of Technology using isotopic analysis of 66 samples of chert from central and western United States, 3 billion years ago the average temperature may have been as high as 70°C (160°F). The findings are based on measurements of the relative abundances of isotopes of oxygen and hydrogen in water of hydration of chert from different past geologic ages. The data indicate that climatic temperatures with some fluctuations have been generally declining from that time.

The Archean era lasted until 2.5 billion years ago. When it ended the crust was stable enough to hold heavy platforms of sediment and sufficiently rigid to withstand intrusions of magma. From then on the geologic column is characteristically cratonal sediments deposited on submerged continental margins.

The Archean era was followed by the Proterozoic—an era that extended for nearly 2 billion years. It came to an end 570 million years ago with the beginning of the Cambrian period—and fossils.

3

Life before the Precambrian

The work of constructing a standard stratigraphic and geologic chronology was vigorously pursued by geologists from the early part of the last century. As their science expanded, they learned that unique fauna were associated with particular intervals in geologic time. By integrating the sedimentary rock throughout the world into an orderly sequence based on faunal succession, they were able to construct from fossils a geological column for the history of the earth.

Adam Sedgwick, an English geologist, was the first to use the name Paleozoic, in a lecture in 1838, to designate the era of geologic history from the earliest fossils to and including the land plants, amphibians, and the earliest reptiles. Soon Mesozoic was used for the era of dinosaurs and marine and flying reptiles, and Cenozoic for the most recent era. The Paleozoic, Mesozoic, and Cenozoic eras were subdivided into periods. And the Cambrian period, set at the first appearance of fossils 570 million years ago, was followed in succession by geologic periods characterized by their fossils.

The fossil record, though fragmentary in some instances, gives clear testimony to the principle of evolution. In many lines of descent, the sequence can be worked out in considerable detail. The most ancient fossils from the Cambrian include only invertebrates. Later, somewhat fishlike vertebrates appear and gradually blend in succession to true fish. Fossils of amphibians and reptiles follow, and finally birds and mammals. The geologic column is clearly correlated with the simplest form of animals appearing in the oldest strata and evolving to greater complexity late in geologic history.

As we study the fossil record, we find that the Cambrian fauna contain representatives of every important invertebrate phylum, but the only groups that are abundant and widespread are the trilobites and the brachiopods. Almost 75 percent of all fossils found in the Cambrian are trilobites. These arthropods, which were distantly related to the modern horseshoe crab, ranged in size from one-fourth of an inch to almost two feet and fed on microscopic organisms in the sea and on the bottom detritus. For the next 70 million years of the Cambrian period, from 570 to 500 million years ago, there is no record of any vertebrate fossils or any plants and animals on land or in fresh water.

The abrupt appearance of the Cambrian fauna constituted a major biological problem. The various organisms found in the Cambrian are life forms with organs and characteristics as complex and developed as those of some found today. Furthermore, to compound the mystery, all phyla (divisions based on fundamental anatomical features) known today are present in the Cambrian fossils. All, that is, except one: the Chordata, the phylum of the vertebrates. The vertebrates were not to appear until about 450 million years ago. The phyla that were present appeared quickly with no apparent origin. Moreover, the earliest Cambrian beds with skeletal remains contained several distantly related trilobite, brachiopod, mollusk, and echinoderm groups and representatives of the other phyla that totaled about twenty distinct kinds of invertebrates, but there was no indication of convergence back toward a common ancestor. Where the Cambrian plants and animals came from remained a mystery.

Then in 1947, Reginald Sprigg, an Australian geologist, was exploring the Ediacara Hills, an abandoned mining area 380 miles north of Adelaide, when he discovered abundant fossil remains of jellyfish in upper strata of quartzites. At first he believed them to be of the lower Cambrian, but further investigation established the rocks to be late Proterozoic. About 1,500 fossil specimens were collected from the beds. Two-thirds of these fossils were outlines of the characteristic swimming bell of the coelenterate medusa, around one-quarter were annelid worms, and the remainder, extinct invertebrate organisms.[1]

The composition of the fauna was that of a marine environment, and studies of the encasing sediment indicated their deposition in shallow water. The wormlike creatures probably lived in shallow water, where they tunneled in the mud or fed on the surface, whereas the *Medusa* may have drifted in from the open seas. There were no signs of predation, such as the tearing of large bodies.

Some of the members of the Ediacara fauna have been found elsewhere. *Charnia* were discovered by Trevor Ford in England in Proterozoic rocks with an age of 680 million years. And a fossil closely resembling *Charnia* was found in the Olenck Highlands of northern Siberia in rocks dated at 675 million years.

The fossils of many of the animals of the Cambrian period were invertebrates with mineralized skeletons. These organisms were absent in the Ediacara fossils, which yielded impressions of soft-bodied animals or tracks and trails of invertebrates without hard parts. There appears to have been a period of possibly 100 million years when soft-bodied animals flourished in the sea, as many do today, before the evolutionary development of mineralized shells and skeletons.

The significance of the Ediacara fauna is that the animals belong to a phylum that is on a simpler level of development than those phyla found in the Cambrian. These animals are coelenterates, represented today by jellyfish, sea anemones, and corals. The coelenterates are multicellular animals at the tissue level of construction, which means in general that they lack organs.

The only multicellular animals simpler in form than the coelenterates are sponges. These primitive animals lack a well-defined organization of tissue and indicate similar ties with certain types of protozoan colonies, both lacking integrated parts, mouth, and digestive systems, both having a type of skeletal formation in which single elements are produced by a single cell or by a group of cells. Sponges are not well preserved as fossils, but specimens from the Cambrian have been found.

The measurement of fossil-bearing strata carried the age of life back 570 million years to the base of the Cambrian, and the Ediacara fossils extended this to 680 million years. In no place on earth, however, are the strata all laid in one continuous succession. If the maximum strata for all the ages from the time of the earliest fossils were stacked vertically, the column would be nearly 400,000 feet (76 miles) thick.

Yet, it was apparent that the fossil record seriously underestimated the age of the earth. Beneath the Cambrian lie the pre-Cambrian formations—strata of volcanic and sedimentary rocks of immense thickness and covering a time span of over 3 billion years: five times the length of time since the earliest fossils. What happened in that incredibly long span of time representing nearly 85 percent of the earth's history before the Cambrian phyla inhabited the earth?

The enormous thicknesses of Cambrian strata attest to the millions upon millions of years that life existed only on the level of sponges, jellyfish, and trilobites. In the Inyo Mountains of California the strata containing trilobites and archaeocyathids, an extinct type of calcareous sponge, descend for 14,000 feet, or nearly 3 miles. Yet, this is not down to the point when life first appeared. There is tangible evidence that living organisms existed on earth for a very long time before the Cambrian period.

The discovery of the Ediacara fossils and others found below the Cambrian strata that began 570 million years ago caused a restriction in the definition of Cambrian rocks to those strata that contain fossils recognized to be characteristically Cambrian. As more geological surveys were conducted, it became apparent that the Cambrian fossils emerged from a trail that led back deep into earlier periods. In Morocco it was found that 3,000 feet of archaeocyathid-bearing strata conformably underlie the lowest Cambrian, and in turn, rest upon 10,000-foot-thick limestone containing the ancient remains of "water biscuits," the calcareous masses of fossiliferous mats and tufts with concentric laminations that grew in shallow water.

These cabbage-shaped or branched laminated structures called stromatolites are the most widespread and abundant fossils before the Cambrian. They are generally composed of limestone or dolomite, but in some cases they are siliceous. Stromatolites were probably formed in an intertidal environment in the same manner that they are still being formed today, by cyanobacteria, or blue-green algae. Many of these hemispherical fossils are as small as buttons, but others can be thousands of feet in area. The giant stromatolite domes in the Belt Series near Helena, Montana, are up to 15 feet thick and extend for thousands of feet.[2]

Although stromatolites were formed in greatest abundance during the long Proterozoic era, their occurrence extends back into the Archean era, where they have been found in the African Pongola Formation dated at around 3 billion years. Like most fossil stromatolites, those of the Pongola show no cellular detail. Nevertheless, they resemble structures of the type being formed today in the Bahamas and at Shark Bay, Western Australia,[3] and well-preserved stromatolites of various ages have yielded microscopic cellular detail. No inorganic processes are known which form such structures.

Stromatolites are not the only evidence that the cyanobacteria must have an extremely old ancestry. Additional testimony is the oxygen. The earth's atmosphere with 21 percent free oxygen is an oddity in a universe that is 75 percent hydrogen. The oxygen-liberating photosynthesis has created an oxidizing atmosphere that has elevated all life to a thermodynamically unstable situation.

Oxidation of organic compounds is a spontaneous reaction, which means that without a continuous input of energy, all biological matter would ultimately revert to the oxidized state of carbon dioxide and water. This unstable condition is maintained by the absorption of energy from sunlight for the reduction of carbon dioxide and the liberation of oxygen, 90 percent of which is generated by the planktonic algae of the oceans. It has been estimated that if photosynthesis were to cease today, all the oxygen in the atmosphere would disappear within 2,000 years through absorption by rocks unsaturated with respect to oxygen.[4]

Despite the earth's losing its protoplanetary atmospheric hydrogen, the atmosphere formed by outgassing was also reduced and devoid of free oxygen. For photosynthetic organisms to oxidize the constituents of the atmosphere and hydrosphere before the buildup of free atmospheric oxygen was possible must have taken an extremely long time. But there is geological evidence that free oxygen began to accumulate in the atmosphere as long ago as 2 billion years. Between 2.3 and 2.0 billion years ago there was the last apparent occurrence of abundant and easily oxidized detrital pyrite and uranite.[5] These minerals, which were eroded from rocks and transported considerable distance before being laid down in sediments, would have been oxidized if the atmosphere at the time had contained significant levels of oxygen. The fact that they do not occur in later sediments as detrital deposits in abundance suggests that atmospheric oxygen was beginning to build up at this time.

And between 2.2 and 1.8 billion years ago, virtually the last and volumetrically the greatest phase of deposition of banded iron formation took place.[6] The

the greatest phase of deposition of banded iron formation took place.[6] The
reducing conditions of the Archean and Early Proterozoic favored the formation of minerals containing ferrous iron from the alteration of basaltic rocks. The characteristic minerals that occur in iron formations are siderite (iron carbonate), greenalite (iron silicate), and pyrite (iron sulfide) in association with chert, originally an amorphous silica. But much if not most of iron formation was biogenic. Ferrous salts are relatively soluble, whereas oxidized iron is not. The liberation of oxygen by photosynthetic organisms oxidized the ferrous iron, creating deposits of precipitated iron. These became banded iron formations, unique rocks consisting of alternating layers of iron-rich and iron-poor silica representing rhythmically banded precipitated sediment.

It is uncertain whether the cherty iron zones of the 3.76-billion-year-old Isua Formation of west Greenland[7] or the 3.4-billion-year-old Onverwacht Group of Africa resulted from biological activity. The last major episode of banded iron formation was 1.8 to 2.0 billion years ago. Thereafter, with much or most of the iron oxidized, the oxygen was added to the atmosphere. Iron deposits that have formed in more recent geological time are red beds where the individual grains are coated with ferric oxide.

The paleochemistry of oxygen can thus be traced back to the pre-Cambrian red beds and limestones. From that time too "coals" containing beds of almost pure carbon have been found in Michigan and Finland. It is difficult to explain these except that they apparently were formed by well-organized photosynthetic life. As impressive as is some of the evidence of early life forms, it is circumstantial in that these are products of life before the Cambrian—not fossils of the actual organisms.

In the early 1950s, however, Stanley Tyler of the department of geology at the University of Wisconsin was prospecting for iron along the Michigan shores of Lake Superior when he came upon ancient coal deposits. The coal contained what he thought to be microscopic plants. Tyler showed the coal to William Shrock, the chairman of the geology department at the Massachusetts Institute of Technology. Shrock thought the plants looked like the fungus that grows on a jar of jelly that has been left open too long and suggested to Tyler that he show them to Harvard botanist Elso Barghoorn.

The result of this consultation was that Tyler and Barghoorn teamed up and made a field trip to the site for a closer study. A search for whatever had wrinkled the seam of coal led the two to the Canadian side, where they found black shales and chert known as the Gunflint Formation, a layer of Precambrian rock on the northern shore of Lake Superior near Shreiber, Ontario, just east of Thunder Bay. The Gunflint chert is overlaid by shale and is generally regarded as Middle Hurian of the Canadian Shield.

Samples of the chert were collected and cut with a diamond saw into slices so thin that light could pass through them. When Barghoorn viewed the thin

Tyler and Barghoorn cut more than 800 thin sections of the flintlike black chert for study. Hydrofluoric acid was used to dissolve the silica of the bedded chert to free fragments of the primitive plants and the organic residue of spores and filaments. Five morphologically distinct forms of biota were recognized: two were algal, two fungal, and one appeared to be calcareous flagellate. These tiny, very simple plants seemed to be representative of cyanobacteria and simple forms of fungi. The Gunflint Formation was dated at 1.9 to 2.0 billion years ago, making these fossils at that time the oldest structurally preserved organisms.[8]

In a subsequent paper in 1965, Barghoorn and Tyler[9] reported finding an array of microscopic fossils in other samples of the Gunflint Formation. In this paper they show 12 assemblages of unicellular spheroidal and filamentous microfossils. From their morphology the spheroids appeared to be related to the coccoid blue-green algae, and the filamentous fossils to the modern iron bacteria *Sphaerotilus* and *Siderococcus*. These were all excellent specimens, preserved by the mineralization of the cellular structure in a siliceous matrix. Here, entombed in 2-billion-year-old chert, were the remains of the microorganisms that had precipitated the ironstone formations and generated the free oxygen that made future life possible.

Soon thereafter, J. William Schopf,[10] a former graduate student of Barghoorn and presently at the University of California, Los Angeles, found varied assemblages of excellently well-preserved spheroidal and filamentous plant microfossils in the Bitter Spring Formation of Northern Territory, Australia. These fossils of microbiota occurred in carbonaceous cherts of the Late Precambrian strata in the Ross River area of Central Australia and were thought to be approximately 1 billion years in age. The fossils resulted from algae that apparently grew as laminar sheets or mats in a marine environment, forming widespread algal stromatolites. Of 19 species that Schopf found, 14 were of modern algal families. The filamentous and coccoid blue-green algae were predominant and must have been highly diversified at this time 1 billion years ago.

Apparently these cyanobacteria were flourishing as early as 2 billion years ago and may well have been responsible for the Bulawayan stromatolites of Zimbabwe, which formed 2.6 billion years ago, and the Pongola stromatolites of 3 billion years. However simple these plants were, they would have had predecessors that existed even earlier—microorganisms that were more ancient than the oldest blue-green algae. A goal of paleontology became a search to push back the fossil record as close as possible to the moment when life began on earth.

In 1965, Barghoorn was collecting cherts from several localities in the Barberton Mountain Land of the area of eastern Transvaal in South Africa near the Swaziland border where the waters of the Umbilizi River flow through the rolling hills on their way to Mozambique and the Indian Ocean. The Barberton Mountain Land is a few hundred square miles of hills formed of Archean greenstone belts whose ages date back as far as 3.4 billion years. The Swaziland Series of the formation consists of the Fig Tree Group underlain by the Onverwacht Series. Carbon is widespread in the formation, and in some places shales that were converted to graphic schists by metamorphism are found. Some black cherts contain as much as 0.20 percent organic matter.

Barghoorn and Schopf examined rocks of the Fig Tree Group by light microscope. The rock matrix contained many laminations of dark-colored, nearly opaque particles of organic substances. The laminations being aligned parallel to strata of chert suggested deposition in an aqueous environment. Nothing resembling fossils of microorganisms could be seen by the microscope. But then Schopf polished the surface of the rock sections and viewed them through an electron microscope. Under the greater magnification it was possible to see what had not been seen before. There were rodlike structures 0.5 to 0.7 millimicron long and 0.2 millimicron in diameter. They resembled rod-shaped bacteria! Later, spheroidal microfossils 17 to 20 millimicra in diameter resembling modern blue-green algae of the coccoid group were also found. In all, 29 well-defined specimens were detected in the fossils of the microbiota. These were fossils of what appeared to be bacteria that had been living on earth 3.0 to 3.3 billion years ago.[11]

At the same time, Hans Pflüg[12] of the Justus Liebig University of Giessen, West Germany, was examining cherts and shales of the Fig Tree sediments for structured organic remains. In samples collected in the vicinity of the Sheba Gold Mine near Barberton he found assemblages of remains of organisms. Chemical and optical studies of the organic material showed these structures to have cell walls. Pflüg suggested a similarity to ocalean cyanobacteria. The radiometric dating placed the age at 3.2 billion years.

These microfossils from the Fig Tree Group have to be regarded almost certainly of biological origin and are probably remnants of single-celled, algalike microorganisms. The organic composition, the constant morphology, the limited size range, and the similar appearance to the excellently preserved microfossils of the Gunflint cherts and the blue-green algae of the Bitter Spring Formation are strong indications of a unicellular, noncolonial, algalike form of life on earth over 3 billion years ago.

Approximately 35,000 feet below the Fig Tree Group lie the Onverwacht Series, covering 400 square miles of the southern part of the Mountain Land and 50,000 feet thick. In 1968, A. E. J. Engel and others[13] reported finding cup-shaped and spherical microstructures in this group of Archean rocks. The size of 590 structures ranges from 6 to 193 millimicra with no dominant size. This variance of 30-fold appeared, however, to be too much of a spread to be characteristic of organized biological systems.

Following this report, Jim Brooks and Marjorie Muir[14] investigated specimens of the Onverwacht strata by first treating slices of uncrushed rock with 20 percent hydrofluoric acid to digest the inorganic matrix. They recovered a concentrated dark residue of organic material representing 0.2 to 0.48 percent by weight of

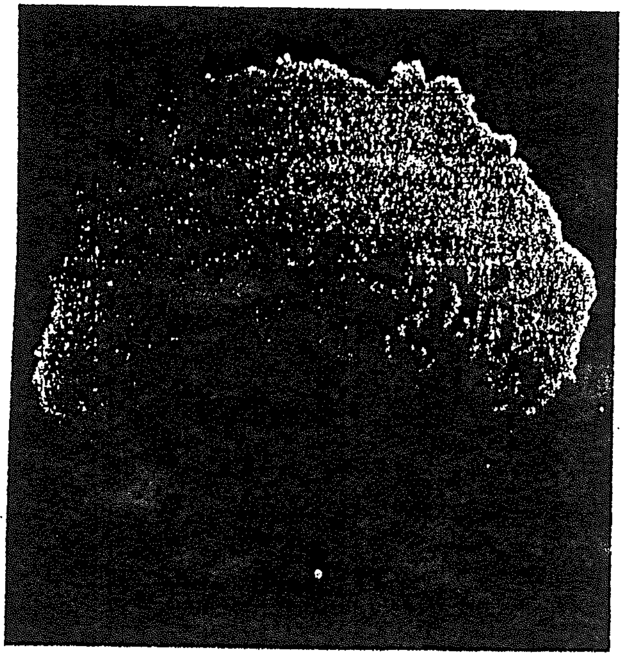

Figure 3.1. Microfossil from the Onverwacht Formation.

the samples. When viewed with an electron microscope the organic material was seen to be fossil remains of what appeared to be cell walls of microorganisms. There were two basic types: spheroids 7 to 10 millimicra in diameter and filamentous forms 15 to 20 millimicra in size. These fossils of microorganisms showed morphological similarities with those of the overlying and younger Fig Tree Group.

Chemical extraction and analysis of the organic matter from the Fig Tree Group have shown 0.003 to 0.015 parts per million of aliphatic hydrocarbons (C_{15}–C_{25}) and larger amounts of pristane ($C_{19}H_{40}$).[15] The Onverwacht chert had free aliphatic hydrocarbons, fatty acids, *n*-parafins C_{12}–C_{24}, pristane, and phytane.[16] Pristane and phytane, being isoprenoid hydrocarbons, are indicative of biogenic origin. But Nagy,[17] examining the porosity and permeability of the Onverwacht chert, showed that the hydrocarbons could have percolated into the rocks from above.

Nevertheless, most of the organic material in the rocks was kerogen, an intractable and insoluble residue that would have been formed in place. The kerogen was analyzed in a different manner by Dorothy Oehler[18] while she was working on her thesis with Schopf at UCLA. Photosynthetic organisms show a preference for $C^{12}O_2$ over $C^{13}O_2$ when they absorb carbon dioxide. By measuring the C^{13}/C^{12} ratio in kerogen, it was possible to establish whether or not it came from photosynthesis. Oehler's results suggested that it did and that autotrophs capable of fixing CO_2 had been on earth more than 3 billion years ago.[19]

Using the carbon isotope method, Schopf and his students[20] applied it to study the oldest stromatolites then known—those of the Bulawayan Formation. They confirmed that these structures were created by photosynthetic organisms, and Schopf suggested that their age of 2.6 billion years might be minimal for the time of origin of blue-green algae or photosynthetic bacteria as filamentous, integrated biological communities. The blue-green "algae," or at least the photobacterial ancestors of all algae today may go back as far as the earliest known fossils of living organisms on earth, those of the Onverwacht Series and the morphologically similar microfossils discovered in the Warrawoona Group at North Pole, Western Australia, and found to be 3.5 billion years old.[21]

Similar microfossils from the Archean and Proterozoic resembling bacteria and blue-green algae have also been found in Ontario, eastern California, southern Africa, central and southern Australia, and the USSR.[22] But there is a degree of uncertainty about organized structures over 2 billion years old. Organic material will commonly aggregate into spheroids, so this alone is not sufficient in establishing biogenic origin. Of the fossil-like microstructures more than 2 billion years old that have so far been described, many were probable not fossils of organisms.[23] Nevertheless, stromatolites of probably algal origin were flourishing as early as 3.0 to 3.1 billion years ago, and the algae responsible for them could be related to forms seen in Fig Tree and Onverwacht sedimentary rocks and those of the Warrawoona Group.

These possible microorganisms of the Archean are assumed to have been procaryotes, the simplest known form of living cell. At some time in the pre-Cambrian era the eucaryotic cell, the more sophisticated and complex type of biological cell that gave rise to all later forms of life, had to have appeared. If Preston Cloud, a geologist at the University of California, Santa Barbara, is correct, eucaryotes emerged between 2.0 and 1.3 billion years ago.

In 1966, Cloud and his coworkers collected samples from black chert found 18.5 meters below the upper contact of the Beck Spring Dolomite in eastern California. Study of thin sections revealed preserved unicells and spiny sporelike bodies. These fossils were a line of microscopic spherical and filamentous shapes not unlike older fossilized microorganisms—except for two important differences: they were much larger than older forms; and some of the filamentous forms were branched.[24] Recent analysis of microfossils for size and distribution shows that eucaryotes are generally about ten times larger than the procaryotes.[25]

Fossiliferous outcrops occur 2,900 meters below the lowest metazoan trace fossils and are younger than 1.7 billion years. These have been correlated to another group dated at 1.2 to 1.4 billion years of age. The most numerous fossils from the various localities are filamentous cyanobacteria placed in the new genus, *Beckspringia*. By studying the microflora in formations of determined radiogenic ages, Licari and Cloud have attempted to bracket the origin of eucaryotes between about 1.3 and 1.6 billion years ago.[27]

A dispute exists as to when the eucaryotes appeared. Helen Tappan[28] of the University of California, Los Angeles, believes they existed at the time of the Gunflint Formation 2 billion years ago. Knoll and Barghoorn,[29] on the other hand, deny the existence of fossilized cell organelles and the appearance of eucaryotic cells before the *Metazoa*. If Preston Cloud, Gerald Licari, and others are correct about the Beck Spring Dolomite fossils, however, these fossils will then mark the greatest biological breakthrough in the history of life on earth—the eucaryotic cell.

The fossil record is still sketchy for the transitional period from the unicellular microorganisms of 1 billion years ago to the Ediacara fauna 680 million years ago, when the *Metazoa*, or multicellular animals, emerged with cells organized in layers of tissue. A discovery in the 1970s, however, may have helped to bridge the gap. Bonnie Bloeser and Schopf of UCLA, Robert Horodyski of Tulane University, and William Breed of the Museum of Northern Arizona[30] reported finding microfossils in the pre-Cambrian rocks of the Grand Canyon which appear to belong to a distinctive group of one-celled planktonic organisms called chitinozoans having an age of 750 ± 100 million years. The chitinozoans are thought to be unicellular heterotrophs, which means that they, like all animals, cannot produce their own food but depend upon the photosynthesis of plants. The chitinozoans are heterotrophs that exist between the multicellular animals and the autotrophic algae.

4

The Age of Procaryotes

The earth had traveled around the sun over one billion times before even the simplest form of living thing appeared that has left any trace of its existence. It was a world much different from today's. The barren, rocky surface that thrust above the primordial ocean was the dark gray and black face of volcanoes; the atmosphere had no oxygen and consisted of nitrogen, some hydrogen, carbon monoxide, and carbon dioxide. The carbon dioxide was less than 1 percent, but still as much as ten times the present concentration. And the oceans were shallow basins of hot wash of the basaltic surface.

The sediments were the detritus from the erosion of predominantly basaltic rocks of volcanic origin being deposited in an anaerobic marine environment. The reducing conditions of the atmosphere and oceans resulted in an appreciable amount of ferrous and sulfide ions in the seawater. The oceans were not to begin taking on modern characteristics until the recycling of sediments predominated over the erosion of basaltic rocks and the atmosphere contained free oxygen. This time was still far in the future.

It was a strange setting, quite alien to what we normally regard as conducive to life. But there it happened. Sometime before 3.4 billion years ago an aggregation of relatively small and simple organic compounds assembled in a lipid envelope and began to mediate elementary reactions. Those cells that were able to assimilate available substances and condense them into polynucleotides and polypeptides replicated and took on the nature of primitive bacteria. Metabolism developed from reactions the cells were able to use to degrade materials for their chemical energy and reactive products. In order to accomplish this, chemical energy had to be held in a carrier and transferred to other molecules to be converted into activated derivatives. Pyrophosphates, particularly adenosine triphosphate (ATP), were adopted early and probably initially. Once activated derivatives were formed, they were energetically favored to follow spontaneous degradation—reactions that proceed on their own, but often slowly unless promoted by a catalyst.

This level of development probably soon gave rise to another organism that was able to draw from the inexhaustible supply of carbon dioxide for its carbon. In order to do so it needed a source of energy and it needed hydrogen. Both were in plentiful supply. All that was needed were chemical procedures which could be used to extract and harness them. The earth's surface was bathed in boundless radiation from the sun each day, and the visible light was absorbed by colored substances and converted to heat. If, instead of being squandered as thermal energy, the light energy were trapped and held in a chemical structure long enough to be used to generate ATP and reduce carbon dioxide, the organism would have a supply of energy even when no food substances existed.

It apparently was at this stage when the first ferredoxin appeared. Formed from a complex of polypeptide and the abundant iron sulfide, this biochemical became incorporated in the biochemical system early and has remained as a universal constituent of living cells ever since. As a component of the photosynthetic apparatus, ferredoxin was able to accept the energy of light absorbed by pigments and retain it at an electron energy level until it could be used to reduce carbon dioxide.

The earliest photosynthetic organism would then have required a pigment, ferredoxin, and a source of hydrogen. The donor of hydrogen for the beginning organism would have been substances which required the least amount of energy to extract the hydrogen and were still readily available. This supply appears to have been accessible organic matter.

Presumably, the earliest organisms were heterotrophs that thrived by metabolizing a reservoir of organic matter, but developed a rudimentary form of photosynthesis when the food supply neared exhaustion. There survives today a pigmented bacterium called *Athiorhodacea* that seems to be of this early stage of life. The *Athiorhodacea* is able to grow anaerobically as a heterotroph in solutions containing butyric acid and other organic nutrients by using the chemical energy it derives from them. But this organism is also able to absorb light and carry out the photocatalytic transfer of hydrogen and reduce carbon dioxide. Its source of hydrogen in this case is the nonutilizable organic matter.

But when the organic matter was no longer available or was in short supply, another source of hydrogen was needed. Photosynthetic bacteria evolved that were capable of using hydrogen sulfide as their hydrogen donor. This type of anaerobe is still extant today as the purple sulfur bacterium (*Chromatium*) and the green sulfur bacterium (*Chlorobium*) that are found in shallow lagoons and sea inlets where hydrogen sulfide is in abundance. In each of these types of photosynthesis, oxygen is not a by-product.

These bacterial forms of photosynthetic life may have been the dominant organisms on earth for several hundred million years. Certainly the fixation of carbon dioxide was being carried out for a considerably long time before organisms evolved to the level of being capable of oxygen-liberating photosynthesis. Eventually, however, because of the failing supply of the other hydrogen donors, or perhaps simply because of the sheer abundance, an organism became biochemically sophisticated enough to extract hydrogen from the most plentiful supply on earth—water. It requires ten times as much energy to remove hydrogen from water as from hydrogen sulfide, but the supply of water was inexhaustible. The organism that developed the photocatalytic breakdown of water became the cyanobacteria and began the 3-billion-year history of oxygen production.

It has not been established exactly at what time the blue-green algae emerged on the scene. The carbon isotope studies of Oehler[1] indicate that fixation of carbon dioxide was coterminous with the oldest microfossils 3.4 billion years ago. This process could have taken millions of years to develop and would still have coincided with the earliest fossils. Bulawayan stromatolites of Zimbabwe apparently are the result of cyanobacterial activity. Since they are dated at 2.6 billion years, an interval of 800 million years—longer than it has taken man to evolve from the level of a single-celled protozoan—passed from the first appearance of life to the time when the blue-green algae were growing in abundance in the tepid waters of the Archean seas.

There is no question that the cyanobacteria were among the ancient forms of life to appear on earth—and one of the most successful. These simple microscopic organisms thrive even today and occur in abundance in small freshwater bodies—ponds, ditches, and shallow lakes—during and immediately after periods of high air temperature. To some extent they are found everywhere, from the polar regions throughout the temperate zones to the warm waters of the tropics. And except for some bacteria, they grow where no other organisms can—in the 80°C (176°F) waters of hot springs of New Zealand and the Yellowstone.[2]

The bacteria and cyanobacteria belong to a particular division of life called the *Monera*. All other living things are either eucaryotic unicellular microorganisms or eucaryotic multicellular forms of life. Unlike the traditional two-kingdom system of plants and animals, evolutionary relations are better represented by a five-kingdom classification. Members of the *Monera* are the procaryotes, distinguished by the simplicity of their cellular structure; whereas all other forms of life are either singular or multiple eucaryotic cells in which the nucleus, the mitochondria, and other subcellular components are sheathed in membranes. In the procaryotes, the only membrane-bound object is the cell itself.

The cells of the cyanobacteria are encased in an outer mucilaginous sheath, a middle pectin layer, and an inner wall of cellulose. In contrast to the cell walls of the other algae, those of the blue-green algae contain amino acids, as do bacterial walls. The blue-green algae developed early as a sturdy but efficient packet of photosynthesis. By extracting carbon dioxide and using water as the hydrogen

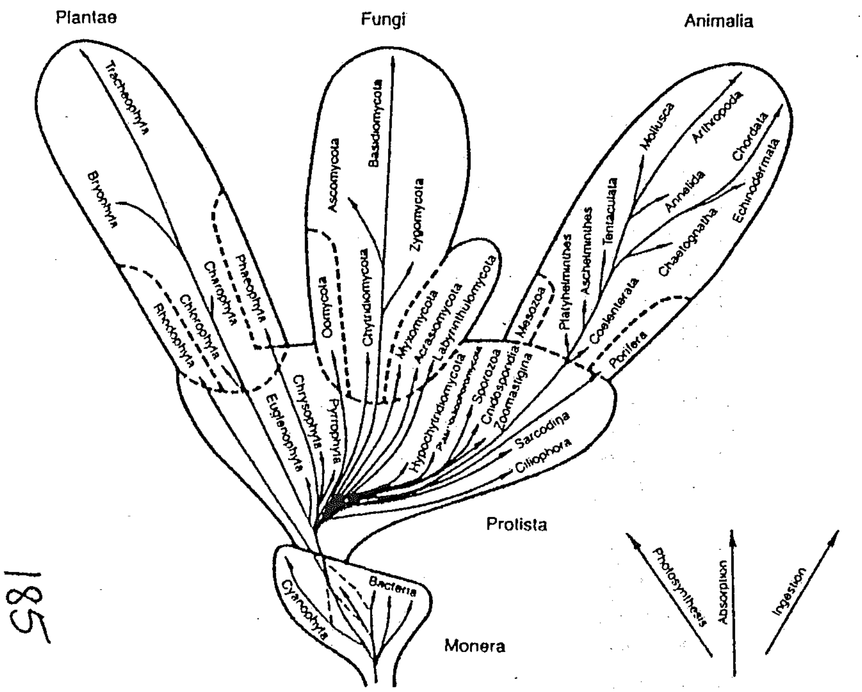

Figure 4.1. The five-kingdom-classification of life is based on three levels of development: the procaryotic (*Monera*), eucaryotic unicellular (Protista), and eucaryotic multicellular. Each level diverges in relation to modes of nutrition. *Monera* have photosynthetic and absorptive; the two higher levels are divided into photosynthetic, absorptive, and ingestive.

donor, they convert it to cyanophycean starch. These algae were and still remain the simplest food-producing plants.

The Archean ended 2.5 billion years ago with the climactic uplifting of mountains. For the Canadian Shield, this became the Kenoran province that added to the margins of the growing continent, extending from the Slave province in the northwest to Labrador eastward across Greenland to terminate in the continental shelves of the Atlantic between Greenland and Scotland. Comparable developments occurred in western Australia, in southern India, and in central and southern Africa. The sedimentary basins that were forming were of cratonal origin, in contrast to the volcanic sediments of earlier times.

When life began on earth, it was in an anoxygenic environment. The atmosphere contained a small amount of hydrogen, and the rocks and most minerals in solution in the oceans were in their reduced and lowest valence state. This is particularly notable for iron and sulfur. Ferrous salts are relatively soluble, but

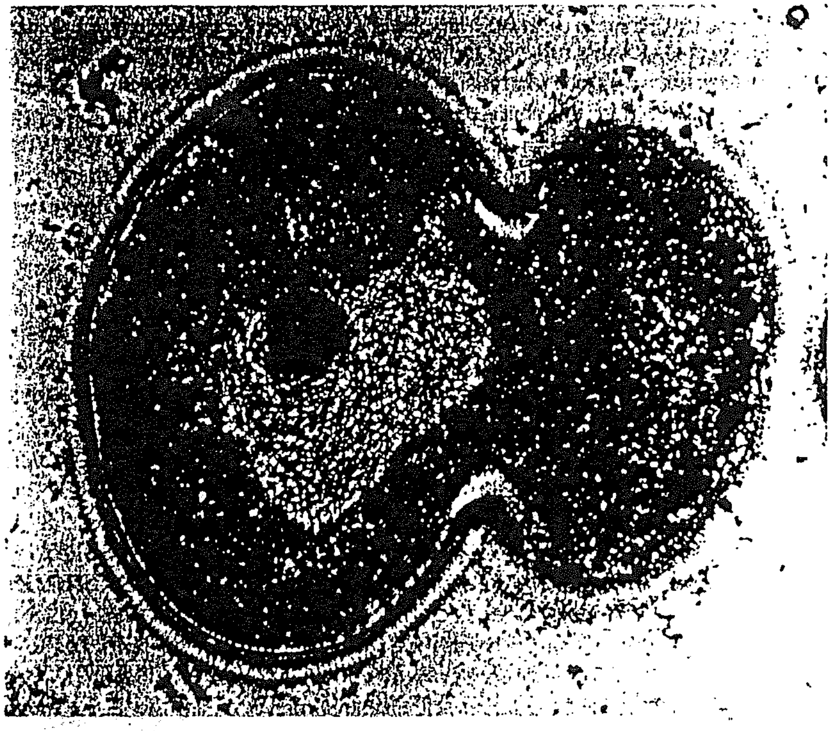

Figure 4.2. Cyanobacteria (*Gloeocapsa*) magnified 40.500 times in the electron microscope. This is a longitudinal section of a cell dividing. The light central area contains the DNA, the concentric striated lines are the lamellar where photosynthesis occurs.

oxidized iron is not. As a result, the concentration of dissolved iron in seawater today is extremely low (less than 10^{-7} molar), but this was not the case during the Archean. Sulfur, which is easily oxidized, exists principally as the sulfate ion in the present oceans. But in early times, it was as the sulfide from the dissolved hydrogen sulfide of volcanic origin.

The primordial life that evolved under these circumstances were the anaerobic microorganisms. They metabolized their carbohydrates by fermentative degradation, extracting the energy stored in the chemical bonds when carbon dioxide was reduced by photosynthesis to sugars, in the manner of yeasts today. It was a perfectly adequate biochemical method for a simple form of life under the environmental circumstances.

But the liberation of oxygen by the cyanobacteria in their photocatalysis of water introduced a perilous form of pollution to all life. Free oxygen is an extremely reactive agent that readily oxidizes reduced substances, mineral or biological. To avoid being destroyed by their own waste, the blue-green algae had to have the oxygen neutralized or removed from their immediate environment as it was generated. In the Archean oceans the most available and reactive chemical species for this role was the ferrous iron, and as the ferrous salts reacted with oxygen, the insoluble ferrous oxide precipitated. In time the evolution of oxygen was to change the character of the oceans. The blue-green algae were widespread and flourishing by the end of the Archean; after another 500 million years, they were generating so much oxygen that they were depleting the oceans of ferrous iron. Vast deposits of this precipitated iron banded chert from precipitated silica became the iron ore of North America around the Great Lakes and in Labrador, in the Hemersley region of western Australia, and in Mauritania of northwest Africa.

The climatic temperature was slowly declining from the 70°C (160°F) in the Middle Archean 3 billion years ago. Between 2.2 and 2.0 billion years ago the earth entered one of its cooling cycles and the first known ice age occurred. From that time on this was to be a recurring episode in the earth's history.

The last great deposition of banded iron formation was 2.0 to 1.8 billion years ago. Thereafter, with much or most of the iron oxidized, oxygen was leaked to the atmosphere. Some ironstone deposits from this time contain oölites and other structures indicative of shallow water deposition, showing that they were among the oldest shorelines in the earth's past. The remains of these can be seen today in Labrador and in Karelia, near the border of Finland and the USSR.

By this time the kinds of microscopic life forms had become much more diverse. This is the time of the Gunflint Formation, which left the multitude of bacterial and algalike microfossils. Nevertheless, all life was on the microbial level and confined to the oceans. The land stood sterile and barren of even the simplest form of vegetation.

Life in the oceans, on the other hand, was teeming. The efficient biological system of the blue-green algae for drawing on the unlimited reservoirs of carbon dioxide, water, and sunlight to construct their organic components allowed them to expand in an oceanwide ecological niche. By the Middle Proterozoic, they were so much the dominant life form that the time could be called the Cyanophycean period. And although the blue-green algae themselves are microscopic, they were leaving in shallow water monumental evidence of their presence.

Living at a time when there was no oxygen in the atmosphere, the early biological systems were without the benefit of an ozone layer to screen out the deadly ultraviolet rays. Any organism under these circumstances survived only in sheltered niches or at depths that afforded protection from the radiation. For this reason, cyanobacteria evolved from predecessors most suitably adapted for weak illumination. Eventually these phytoplankton evolved thick individual gelatinous sheaths, either colored or colorless, as protection against light too intense. Many lived in colonies or shapeless masses or layers of mucus, developed as the result of the dissolving and coalescing of individual sheaths. Being photoactic, they moved through any covering sediment that shut out the light completely, and as they did so their mucus cemented the particles in place. Many had sticky mucus sheaths that formed loose networks of filaments which sediments fell into, creating columnar shapes. So despite being perishable cellular matter, blue-green algae left enduring monuments in the widespread Precambrian stromatolites.

Around 1.5 billion years ago, the oldest deposits of calcium sulfate were being formed. This indicated that, although sulfate ions may have existed in solution for some time before this date, there was sufficient free oxygen at this time to oxidize the sulfur acids in the oceans. With the passing of nearly three-quarters of geologic time, the oceans must have been as large at this time as they are today, and they were taking on modern characteristics.

Having developed and evolved in an oxygen-free environment, all the microbiota that populated the oceans were anaerobic organisms, which is to say, they did not use oxidative respiration. They neither needed nor desired oxygen, which to them was a deadly poison. But with the last of the ferrous iron laid down in banded iron formations, from about 1.8 billion years ago onward free oxygen had been entering the atmosphere from the photosynthesis reaction of the blue-green algae. It was taking over a billion years for the oxygen from photosynthesis to oxidize all the substances of the earth's atmosphere and hydrosphere, but the pace went unabated. Eventually, this changing of the earth's environment from reducing to oxidizing conditions constituted an encroaching peril to the occupants who had been the undisputed masters of the earth for nearly 2 billion years.

Many that lived met the threat by developing oxygen-mediating enzymes, the oxidases, to protect their biochemical constituents from destruction by oxygen. Some presumably survived by retreating to oxygen-deficient niches and exist today as anaerobic bacteria. But the age of the procaryotes was coming to an end. Their dominance was foredoomed by the ever-increasing oxygenation of the air and water.

It was Louis Pasteur who discovered that obligate anaerobes cannot tolerate oxygen concentrations above 1 percent of the present atmospheric level. Following the oxidation of the salts and minerals of the oceans and the reduced gases of the atmosphere, the concentration of free oxygen in the air began moving toward the Pasteur point. The level of oxygen may have reached a critical level for the anaerobes by 1.4 billion years ago, when the changing environment brought about the emergence of the eucaryotes.