CHAPTER ONE

The Origin of Life on Earth

HOW GEOLOGY WORKS

Geology is the study of Earth we live on. It draws on methods and principles from many sciences: physics, chemistry, biology, mathematics, and statistics are just a few. Geologists have to know at least a little of several sciences: they cannot be narrow specialists. Geology is a broad science that works best for people who think broadly. So most geologists cannot be successful if they are geeks (though a few seem to manage it). Above all, geology deals with the reality of Earth: its rocks, minerals, its rivers, lakes and oceans, its surface, and its deep structure. Always, the reality of evidence from fieldwork controls what can and what cannot be said about Earth. Geological hypotheses are tested against evidence from rocks, and many beautiful theories have failed those demanding tests.

Some geologists deal with Earth as it is now: they don't need to look at the past. Earth history doesn't matter much to a geologist trying to deal with ecological repair to an abandoned gold mine. But many geologists have to deal with the history of Earth, and they find that they are studying a planet that changes, at all scales of space and time, sometimes in the most surprising ways. We have known for 200 years that life on Earth has changed: we can collect fossils as direct and solid proof of that. But gradually, geologists have come to realize that life has evolved on a planet that is changing too.

Ideas about changing geography, changing climate, and changing chemistry have become much more important recently in discussing Earth history. And our best sources of insight into those changes come from the fossil evidence of the creatures that survived them (or not). So paleontology is not just a fascinating side branch of geology, but a vital component of it.

As they run their life processes, organisms take in, alter, and release chemicals. Given enough organisms and enough time, biological processes can change the chemical and physical world. Photosynthesis, which provides the oxygen in our atmosphere, is only one of these processes. In turn, physical processes of Earth such as continental movement, volcanism, and climate change affect organisms, influencing their evolution, and, in turn, affecting the way they affect the physical earth. This is a gigantic interaction, or feedback mechanism, that has been going on since life evolved on Earth. Paleontologists and geologists who ignore this interaction are likely to get the wrong answers as they try to reconstruct the past.

HOW PALEONTOLOGY WORKS

Some of Earth's ancient life has been preserved in rocks as fossils, and the study of these fossils is the science of paleontology. Paleontology deals with the interpretation of fossils as organisms, living, breeding, and dying in a real environment on a real, but past, Earth that we can no longer touch, smell, or see directly: we perceive a virtual Earth through our study of fossils and the rocks they are preserved in.

Most paleontologists don't study fossils for their intrinsic interest, although some of us do. Their greater value lies in what they tell us about ourselves and our background. We care about our future, which is a continuation of our past. One good reason for trying to reconstruct ancient life is to manage better the biology of our planet today, so we need to set up some kind of reasonable logic for interpreting life of the past.

Some basic problems of paleontology are like those of archaeology and history: how do we know we have found the right explanation for some past event? How do we know we are not just making up a story?

Anything we suggest about the biology of extinct organisms should make sense in terms of what we know about the biology of living organisms, unless there is very good evidence to the contrary. This rule applies throughout biology, from cell biochemistry to genetics, physiology, ecology, behavior, and evolution.

But suggestions are only suggestions until they are tested against evidence from fossils and rocks. Because fossils are found in rocks, we have access to environmental information about the habitat of the extinct organism: for example, the rock might show clear evidence that it was deposited under desert conditions or on a shallow-water reef. Fossils are therefore not isolated objects but parts of a larger puzzle. For example, it is difficult to interpret the biology of the first bird, *Archaeopteryx*, unless we consider environmental evidence from the Solnhofen Limestone in which it is preserved (Chapter 13).

An alert reader should be able to identify four levels of paleontological interpretation. First, there are *inevitable conclusions* for which there are no possible alternatives. For example, there's no doubt that extinct ichthyosaurs were swimming marine reptiles. At the next level, there are *likely interpretations*. There may be alternatives, but a large body of evidence supports one leading idea. For example, there is good evidence to suggest that ichthyosaurs gave birth to live young rather than laying eggs. Almost all paleontologists view this as the best hypothesis available and would be surprised if contrary evidence turned up.

Then there are *speculations*. They may be right, but there is not much real evidence one way or another. Paleontologists are allowed to accept speculations as tentative ideas to work with and to test carefully, but they should not be surprised or upset to find them wrong. For example, it seems reasonable to me that ichthyosaurs were warm-blooded, but it's a speculative idea because it's difficult to test. If new evidence showed that the idea was unlikely, I might be personally disappointed but I would not be distressed scientifically.

Finally, there are *guesses*. They may be biologically more plausible than others one might suggest, but for one reason or another they are completely untestable and must therefore be classified as nonscientific. For example, if I asked an artist to draw an ichthyosaur, I might suggest bold black-and-white color patterns, like those of living orcas, but another paleontologist might opt for more muted tones like those of living dolphins. Both ideas are reasonable, and are surely better than the green-with-pink-spots that one might find in a TV cartoon. But they are guesses, because there is no evidence at all.

You will find examples of all four kinds of interpretation in this book. Often it's a matter of opinion in which category to place different suggestions, and this problem has caused many controversies in paleobiology. Were dinosaurs warm-blooded? Some paleobiologists think this is an inevitable conclusion from the evidence, some think it's likely, some think it's only speculative, some think it's unlikely, and some think it is plain wrong. New evidence almost always helps to solve old questions but also poses new ones. Without bright ideas and constant attempts to test them against evidence, paleontology would not be as exciting as it is.

The fossil record gradually gets poorer as we go back in time, for two reasons. Biologically, there were fewer types of organisms in the past. Geologically, relatively few rocks (and fossils) have survived from older times, and those that have survived have often suffered heating, deformation, and other changes, all of which tend to destroy fossils. Earth's early life was certainly microscopic and soft-bodied, a very unpromising combination for fossilization. So direct evidence about the origin of life on Earth is very scanty.

THE ORIGIN OF LIFE

There is no good evidence of life, let alone intelligence or civilization, anywhere in the universe except on our planet, Earth. This fact of observation comes in the face of strenuous efforts by tabloid magazines, movie directors, and NASA publicists to persuade us otherwise. However, it is a fact as I write this in 2003, and we have to face up to its implications. This simple observation implies (but does not prove) that life evolved here on Earth. How difficult would that have been?

We can test the idea that life evolved here on Earth, from nonliving chemicals, by observation and experiment. Geologists and astronomers look for evidence from Earth, Moon, and other planets to reconstruct conditions in the early solar system. Chemists and biochemists determine how complex organic molecules could have formed in such environments. Geologists try to find out when life became established on Earth, and biologists design experiments to test whether these facts fit with the idea of the evolution of life from nonliving chemicals.

Complex organic molecules form in interstellar space, on comets and asteroids and interplanetary dust, and on the meteorites that hit Earth from time to time. These compounds probably form naturally in space, because gas clouds, dust particles, and cometary and meteorite surfaces are bathed in cosmic and stellar radiation. But life as we know it consists of cells, composed mostly of liquid water that is vital to life. It is impossible to imagine the formation of any kind of water-laden cell in outer space: that could only have happened on a planet that had oceans and therefore an atmosphere.

Planets have organic compounds delivered to them from space, from comets or meteorites, but it is unlikely that this process by itself leads to the evolution of life. Organic molecules must have been delivered to Mercury, Mars, Venus, and the Moon as well as to Earth, only to be destroyed by inhospitable conditions on those lifeless planets.

Experiments show that it is fairly simple to form large quantities of organic compounds in planetary atmospheres and on planetary surfaces, given the right conditions. Space-borne molecules may have added to the supply on a planetary surface, but they would never be the only source of organic molecules that led to the origin of life.

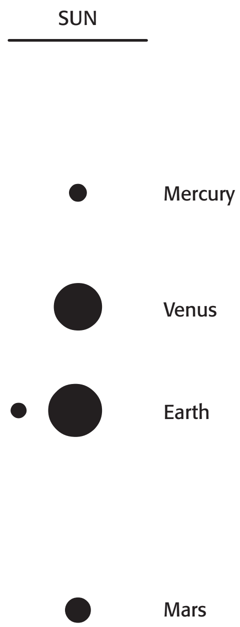

Figure 1.1 The Sun and the terrestrial or inner planets. Their relative sizes and their relative distances are correct, but their sizes are exaggerated by about five billion times compared with their distances.

The Inner Planets of the Solar System

Earth is one of the four terrestrial (rocky) planets in the inner part of our solar system (Figure 1.1). Venus and Earth are about the same size, and Mars and Mercury are significantly smaller. They all formed in the same way about 4570 million years ago (Ma), from dust and gas, and most likely, they were all largely complete as planets by 4500 Ma, though they were bombarded heavily for hundreds of millions of years as stray asteroids struck their surfaces. All of them were hot, and the heat energy released as the planets formed would have made them partly or totally molten. Earth in particular was struck by a huge Mars-sized body late in its formation, and that impact probably melted the entire Earth. We know from crater impacts and lunar samples that Earth and the Moon suffered a heavy late bombardment around 3900 Ma, and the same event probably affected all the other inner planets.

All the inner planets melted deeply enough to have hot surfaces that gave off gases to form atmospheres. But there the similarity ended, and each inner planet had its own later history. Even so, it is clear that an early planet is not a place where life could evolve.

Once a planet cools, conditions on its surface are largely controlled by its distance from the Sun and by any volcanic gases that erupt into its atmosphere. The geology of a planet therefore greatly affects the chances that life might evolve on it.

Liquid water is vital for life as we know it, so surface temperature is perhaps the single most important feature of a young planet. Surface temperature is mainly determined by distance from the Sun: too far, and water freezes to ice; too close, and water evaporates to form water vapor.

But distance from the Sun is not the only factor that affects surface temperature. A planet with an early atmosphere that contained gases such as methane, carbon dioxide, and water vapor would trap more of the Sun's radiation in the "greenhouse" effect, and would be warmer than an astronomer might predict just from distance.

In addition, distance from the Sun alone does not determine whether a planet has water, otherwise the Moon would have oceans like Earth's. The size of the planet is important, because gases escape into space from the weak gravitational field of a small planet. Gas molecules such as water vapor are lost faster from a small planet, and heavier gases are lost as well as light ones.

Gases may also be absorbed out of an atmosphere if they react chemically with surface rocks. They can be released again only by volcanic activity that melts those rocks. But a small planet cools faster than a large one, so any volcanic activity quickly stops as its interior freezes. After that, eruptions no longer return or add gases to the atmosphere. Therefore, a small planet quickly evolves to have a very thin atmosphere or no atmosphere at all, and no chance of gaining one.

Volcanic gases typically include large amounts of water vapor and CO_2 (Figure 1.2), and they are powerful greenhouse gases. Earth would have been frozen for most of its history without CO_2 and water vapor in its atmosphere. Together they add perhaps 33°C to Earth's average temperature.

With all these principles in mind, let's look at the prospects for life on the planets of our solar system. Both Mercury and the Moon had active volcanic eruptions early in their history, but they are small. They cooled quickly and are now solid throughout. Their atmospheric gases either escaped quickly to space from their weak gravitational fields or were blown off by major impacts. Today Mercury and the Moon are airless and lifeless.

Venus is larger than the Moon or Mercury, almost the same size as Earth. Volcanic rocks cover most of its surface. Like Earth, Venus has had a long and active geological history, with a continuing supply of volcanic gases for its atmosphere, and it has a strong gravitational field that can hold in most gases.

But Venus is closer to the Sun than Earth is, and the higher solar radiation hitting the planet was trapped so effectively by water vapor and CO_2 that water molecules may never have been able to condense out as liquid water. Instead, water remained as vapor in the atmosphere until it was dissociated, broken up into hydrogen (H_2), which was lost to space, and oxygen (O_2), which was taken up chemically by reacting with the hot surface rocks of the planet.

Today Venus has a dense, massive atmosphere made largely of CO_2. Volcanic gases react in the atmosphere to make tiny droplets of sulfuric acid (H_2SO_4), forming the clouds that hide the planetary surface. Water vapor has vanished completely. Although the sulfuric acid clouds reflect 80% of solar radiation, CO_2 traps the rest, so the surface temperature is about 450°C (850°F). We can be sure there is no life on Venus.

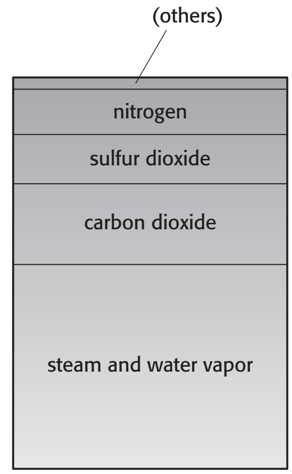

Figure 1.2 A planetary interior may be hot enough to melt rock. If molten rocks reach the planetary surface in volcanic eruptions, the gases they give off may help to form an atmosphere. The mixture of gases shown in this diagram was measured at Kilauea Volcano, in Hawaii; other volcanoes erupt different mixtures, but the basic ingredients are the same. Sulfur dioxide is caught up in raindrops, leaving water vapor, carbon dioxide, and nitrogen as the main constituents of the atmosphere.

Mars is much more interesting than Venus from a biological point of view. It is smaller than Earth, and farther from the Sun. But it is large enough to have held on to a thin atmosphere, mainly of CO_2. Mars today is cold, dry and windswept: dust storms sometimes cover half the planet.

No organic material can survive now on the surface of Mars. There is no liquid water, and the soil is highly oxidizing. But while Mars was still young, and was actively erupting volcanic gases from a hot interior, the planet may have had a thicker atmosphere with substantial amounts of water vapor. Cracks and crevices in the crust may still contain ice that could be set free as water, if large impacts heated the surface rocks deeply enough to melt it, or if climatic changes were to melt it briefly.

Mars had surface water in the distant past. Canyons, channels, and plains were shaped by huge floods, and other features look like ancient sandbars, islands, and shorelines. Ancient craters on Mars, especially in the lowland plains, have been eroded by gullies, and sheets of sediment lap around and inside them, sometimes reducing them to ghostly rims sticking out of the flat surface. However, the most recent summary of evidence indicates that Mars has always been cold and dry, with an occasional hot flash flood generated by impacts. The floods probably drained and dried very quickly, and there may never have been oceans.

Mars was too small to sustain geological activity for long. As the little planet cooled, its volcanic activity stopped (Figure 1.3). Its atmosphere and its water were blasted off by impacts, or lost by slow leakage to space, and by chemical reactions with the rocks and soil. The surface is now a dry frozen waste, and likely has been for three billion years. Even if floods were generated by a large meteorite impact, they could not last long enough to sustain life.

Did Mars once have life? In 1996, researchers reported they had found fossil bacteria in a meteorite that originated on Mars. (It was splashed into space by an asteroid impact, falling on Earth's Antarctic ice cap after spending thousands of years in space.) The researchers suggested that the bacteria were Martian. By now the evidence has been discounted: the objects are not bacteria and they are not evidence for life.

The asteroid belt lies outside the orbit of Mars. Some asteroids have had a complex geological history, but there is no question of life in the asteroid belt now. No planet or moon outside the orbit of Mars could trap enough solar radiation to form liquid water on its surface to provide the basis for life. Complex hydrocarbon compounds can accumulate and survive on asteroids, or in the atmospheres of the outer planets or on some of their satellites, but those bodies are frigid and lifeless .

Looking further afield, there is absolutely no evidence of life anywhere else in the Universe. The science-fiction writer Brian Aldiss thinks that the persistent search

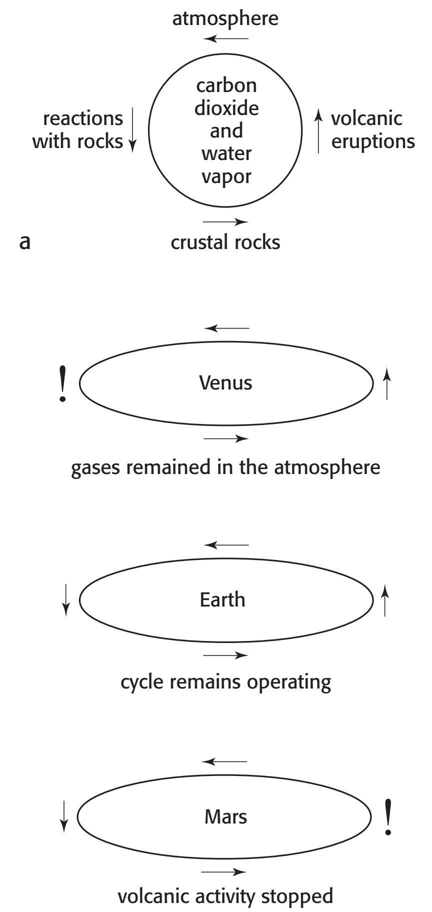

Figure 1.3 Atmospheric evolution took completely different courses on Venus, Earth, and Mars. On a model planet (a), water and carbon dioxide cycle around the rocks, the atmosphere, and the ocean. This still happens on Earth. Mars cooled so quickly that volcanic activity soon ceased, stopping the cycle with the gases frozen in the crust. Venus heated so much that carbon dioxide remained permanently in the atmosphere, stopping the cycle with a hot, dense atmosphere.

for such alien life reflects a deep-seated yearning for bogeymen deep in the human psyche.

So we return to Earth, the only known site of life. We can guess that impacts and eruptions released gases that formed a thick atmosphere around early Earth, consisting mainly of CO_2, with small amounts of nitrogen, water vapor, and sulfur gases (Figure 1.2). By about 4 billion years ago (4000 Ma or 4 Ga), but maybe as early as 4.4 Ga, Earth's surface was cool enough to have a solid crust, and liquid water that accumulated on it, forming oceans. Ocean water in turn helped to dissolve CO_2 out of the atmosphere and deposit it into carbonate rocks on the seafloor. This absorbed so much CO_2 that Earth did not develop runaway greenhouse heating as Venus did (Figure 1.4). Large shallow oceans probably covered most of Earth, with a few crater rims and volcanoes sticking out as islands.

Almost all geological evidence of these early times has been destroyed, especially by the catastrophic impacts around 3.9 Ga: the scenario of a cool watery Earth very early in its history is based on evidence from a few zircon crystals that survived as recycled grains in later rocks. But if there was early life on Earth, it would have been wiped out by the catastrophes at 3.9 Ga. The life forms that were our ancestors could not have evolved and survived until after the last sterilizing impact.

However, small late impacts may have encouraged the evolution of life. All comets and a few meteorites carry organic molecules, and comets in particular may have delivered some to Earth. But processes here on Earth also formed organic chemicals. Intense ultraviolet (UV) radiation from the young Sun acted on the atmosphere to form small amounts of very many gases. Most of these dissolved easily in water, and fell out as rain, making Earth's surface water rich in carbon compounds. The gases included ammonia (NH_3), methane (CH_4), carbon monoxide (CO), and ethane (CH_3), and formaldehyde (CH_2O) could have formed, at a rate of millions of tons a year. Nitrates built up in water as photochemical smog and nitric acid (HNO_3) from lightning strikes also rained out. But perhaps the most important chemical of all was cyanide (HCN). It would have formed easily in the upper atmosphere from solar radiation and meteorite impact, then dissolved in raindrops. Today it is broken down almost at once by oxygen, but early in Earth's history it built up at low concentrations in lakes and oceans. Cyanide is a basic building block for more complex organic molecules such as amino acids and nucleic acid bases. Life probably evolved in chemical conditions that would kill us instantly!

Life Exists in Cells

The simplest cell alive today is very complex: after all, its ancestors evolved through many billions of generations. We must try to strip away these complexities as we wonder what the first living cell might have looked like and how it worked.

A **living thing** has several properties: it has organized structure; the capacity to reproduce (replicate itself); stored information; behavior; and metabolism. Mineral crystals have the first two but not the last two.

First, a living thing **has a boundary** that separates it from the environment. As we shall see, a living thing operates its own chemical reactions, and if it did not have a boundary those reactions would be unable to work: they would be diluted by outside water or compromised by outside contaminants. So we refer to a living "**cell**" that has some sort of **cell membrane** or **cell wall** around it.

Second, there must be instructions that define the structure, the timing, and the ingredients for the chemical reactions needed to produce (and maintain) the organization of the cell. In all living cells today, that **information** is coded in nucleic acids (**RNA** or **DNA**), the instructions are carried round the cell by RNA, and proteins are involved in most of the reactions.

Third, a living thing can grow, and it can **replicate**: that is, it can make another structure just like itself. Both processes require complex chemistry which in turn requires a cell membrane. Growth and replication use materials that must be brought in from outside, through the cell wall.

Fourth, a living thing interacts with its environment in an active way: it has **behavior**. The simplest behavior is the activity involved with growth and reproduction: the chemical flow of substances in and out of the cell is an interaction with the outside world that can be turned on and off. The chemical flow will change the immediate environment, and, of course, the presence or absence of the desired chemicals will decide whether the cell turns on the flow. Temperature and other outside conditions will also affect the behavior of even the simplest cell.

Fifth, the chemical activity of the cell represents an energy flow: the energy flow is called **metabolism** in living things. The cell must operate reactions that synthesize molecules from simpler precursors, or break down complex molecules into simpler ones. If a cell grows or reproduces, it is building complex organic molecules, and those reactions need energy. The cell must obtain that energy from outside, in the form of radiation or "food" molecules that it can break down.

It's important to remember that these five attributes of a living cell are not five different things: they are all intertwined. They are all connected with the processes of gathering and processing energy and material into new chemical compounds (tissues), and continuing those processes into new cells. Any theory of the evolution of life, as opposed to its creation by a Divine Being, must include a period of time during which lifeless molecules developed the characters listed above and thereby became living. The phrase for this is **chemical evolution**. We have to be able to argue that every step in the process could reasonably have happened on early Earth (or somewhere else) in a natural, spontaneous way. It's easy to see that with the right starting compounds, a protocell could grow effectively. The critical turning point that defines life comes when "accurate" replication evolves.

Even with a time machine, we would find it very difficult to pick out the first living thing from the mass of growing organic blobs that must have surrounded it. But that cell survived and reproduced, however "accurately," and as time went by, cells that were more efficient remained alive and replicated, while those that were less efficient died or replicated more slowly. So at the same time that living things emerged, so did the processes of natural selection and extinction. Some lines of cells flourished, others became extinct. Of course, we do not see any descendants of those first cells living today with the same genetic and biochemical machinery their ancestors had: they have long had major upgrades of their original software.

That introduces one other concept into our discussion: **progress** or **improvement**. There is no question that the simplest living cells are more efficient than their distant ancestors. Arguments rage about the politically correct word to use to describe this. I used "improvement" in previous editions because many biologists have a phobia about the word "progress" (there are too many connotations associated with military and industrial technology, I suspect). But the reality of the fossil record is that here are many examples of improved performance that can be assessed mechanically. Thus modern horses run far more efficiently, living whales swim more efficiently, and living birds fly more efficiently than their ancestors did. I don't

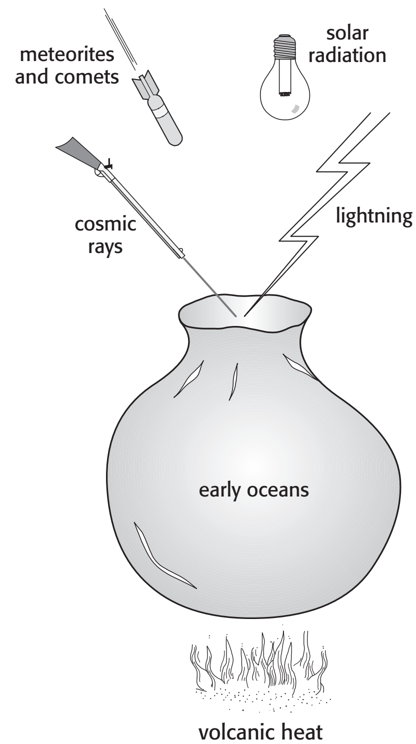

Figure 1.4 Some of the energy sources that would have been available to power chemical reactions on early Earth. (After Cowen, *History of Life*. © 1976 McGraw-Hill Book Company.)

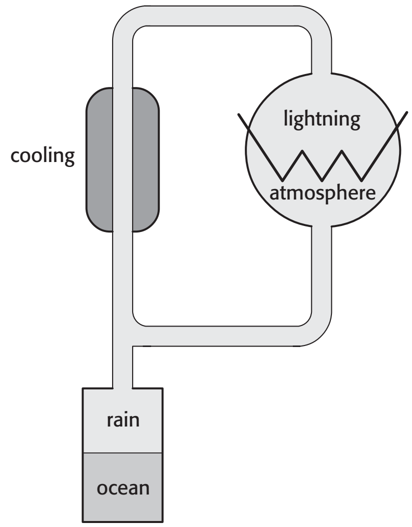

Figure 1.5 Stanley Miller's experiment was designed to simulate conditions on early Earth. An atmosphere of methane, ammonia, and hydrogen was subjected to lightning discharges, and the reaction products cooled, condensed, and rained out to collect in the ocean. The reaction products included amino acids.

see that one could doubt that similar trends have occurred in physiology, biochemistry, reproduction, and so on, though it would be more difficult to prove it. I can't think of a better word to describe this than "progress."

Now we turn to experiments that help us to see the steps by which life evolved from nonliving chemicals. In Chapter 2, we look at the rock record to try to find evidence of the earliest life on Earth: in particular, we look for evidence of structured fossils, and for any trace of their behavior, or chemical traces of the metabolic reactions they performed.

Making Organic Molecules

Certain conditions are necessary if life is to evolve from nonlife (Box 1.1). The first experiment to include some of them was published in 1953 by Stanley Miller, who was then a graduate student at the University of Chicago. He passed energy (electric sparks) through a mixture of hydrogen, ammonia, and methane in an attempt to simulate likely conditions on early Earth (Figure 1.5). Any products fell out into a protected flask. Among these products, which included cyanide and formaldehyde, were amino acids. This result was surprising at the time because amino acids are not simple compounds. Miller's experiment used a rather unlikely mixture of starting gases, but it encouraged many other experiments on the origin of life, and showed that such experiments were not only good science but were very exciting and rewarding.

Many experiments have shown that most of the amino acids found in living cells today could have formed naturally on early Earth, from a wide range of ingredients, over a wide range of conditions. They form readily from mixtures that include the gases of Earth's early atmosphere. The same amino acids that form most easily in laboratory experiments are also the most common in living things today. The only major condition is that amino acids do not form if oxygen is present.

Amino acids form easily on the surfaces of clay particles (Figure 1.6). Clay minerals are abundant in nature, have long linear crystal structure, and are very good at attracting and adsorbing organic substances: cat litter is clay and works on this principle.

Organic molecules occur in comets and meteorites. Again, the most common ones are also the most abundant in laboratory experiments. Sugars and nucleic acid bases are also found in meteorites, so all these compounds would have been supplied in quantity to early Earth. We do not know how much organic matter was supplied by natural synthesis on Earth and how much by comets and meteorites. Either way, the right materials were present on early Earth to encourage further reactions.

Linking sequences of amino acid molecules into chains to form protein-like molecules involves the loss of water, so scientists have tried evaporation experiments to

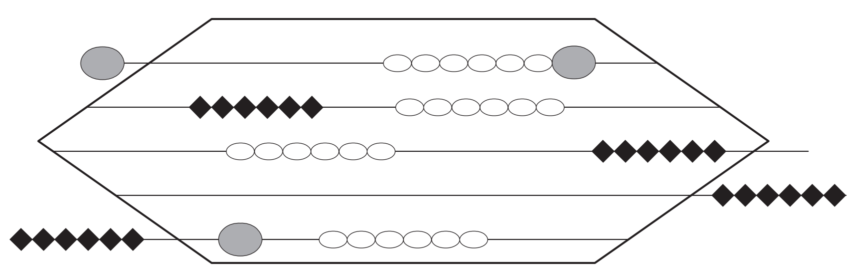

Figure 1.6 Clay minerals have long, straight cleavage planes. Linear organic molecules may line up along the cleavages, encouraging reactions that form long-chain organic molecules such as amino acids and nucleic acids.

BOX 1.1 Necessary Conditions for Chemical Evolution Toward Life

Energy. Energy is needed to form complex organic molecules in the absence of life, given the presence of simple precursors. Some laboratories have used electrical discharges to simulate lightning on early Earth; others use high-energy particles from a cyclotron in place of radioactivity from rocks and cosmic rays, heat for volcanic activity, shock waves or laser beams for meteorite impacts, or lamps for solar UV radiation (Figure 1.4). All these energy sources were present on the early Earth.

Protection. Continued energy input (especially heat) will destroy any complex organic molecules that form in reactions, so after they form they must quickly be protected from strong radiation. Laboratory experiments are often designed to allow organic molecules to drop into cold water away from the energy source. On early Earth, molecules may have been protected under shallow water, in sheltered tide pools or rock crevices, under rocks, ice, or particles of sediment.

Concentration. All chemical reactions run better at high concentration, but almost all reactions leading toward life give low yields in the laboratory. Life is water-based, yet too much water dilutes chemicals so that they react slowly. Some process must have concentrated chemicals on early Earth. Evaporation is the simplest one, but there are others such as absorption on to clay surfaces.

Catalysis. Catalytic converters in the exhaust systems of cars contain platinum as a catalyst that encourages the breakdown of pollutants. An organic substance that works as a catalyst is called an enzyme. All the reactions inside our cells and our bodies are aided by enzymes, which are necessary even in the simplest possible living cell. Suitable catalysts may have encouraged difficult reactions on early Earth, even at low energy levels and low concentrations. Later, the last stages leading toward life may have been aided by catalysts trapped on, or inside, membranes.

simulate the process under early Earth conditions. High temperatures help evaporation, but they also pose a problem, because organic molecules tend to break down if they are heated: the longer the molecule, the more vulnerable it is to damage. Here again, natural minerals provide an attractive alternative.

Nucleic acids (RNA and DNA) have structures made up of nucleic-acid bases, sugars, and phosphates. All four nucleic-acid bases can be made in reasonable laboratory experiments. Sugars form in experiments that simulate water flow from hot springs over clay beds. Naturally occurring phosphate minerals are associated with volcanic activity. Thus all the ingredients for nucleic acids were present on early Earth, and the cell fuel ATP (adenosine triphosphate) could also have formed easily.

Linking sugars, phosphates, and nucleic-acid bases to form fragments of nucleic acid called **nucleotides** is also a dehydration process, and the phosphates themselves can act as catalysts here. Long nucleotides form much more easily on phosphate or clay surfaces than they do in suspension in water (Figure 1.6).

Toward the First Living Cell

The basic organic molecules that make up cell membranes and cell contents may have been present in reasonable amounts in the oceans of early Earth. We must still explain how they evolved into a cell that could reproduce itself.

A membrane separates a cell from the environment. Many organic membranes are made of sheets of molecules called **lipids**. A lipid molecule has one end that attracts water and one end that repels water (Figure 1.7a). Lipids line up naturally with heads and tails always facing in opposite directions; a sheet of lipid molecules therefore repels water (Figure 1.7b). If the sheet of lipids happens to fold around to meet itself, it forms a waterproof membrane around whatever contents it has trapped. Such packets, called liposomes, form spontaneously in lipid mixtures.

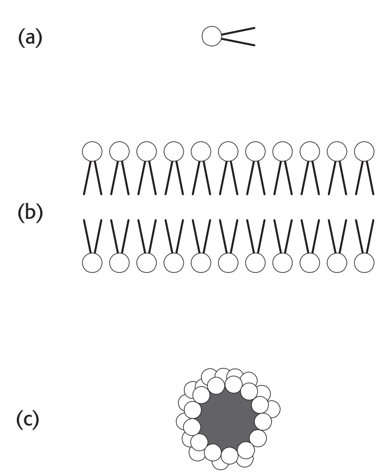

Figure 1.7 (a) The polar structure of a lipid molecule repels water at one end (○) and attracts it at the other. This allows lipids to form either (b) water-repellent sheets and scums or (c) water-repellent spherical containers (liposomes).

They are simple spheres with an outer membrane of lipids (Figure 1.7c). Whipping up an egg in the kitchen produces liposomes as the yolk is frothed around.

David Deamer (see Zimmer, 1995) discovered that liposomes can form from molecules that would have been present on early Earth: fatty acids, glycerol, and phosphates. Later, he found fatty acid molecules in meteorites, and made globules from them by drying them out and then rewetting them. When he added DNA to the original solution, it was sometimes trapped inside the liposomes as they formed, sometimes concentrated 100 times. Jack Szostak's research group (see Szostak et al., 2001) found that fatty acid globules form 100 times as fast as usual if clay is added to the mixtures.

This suggests that the formation of liposomes that had cell-like contents may not have been difficult on early Earth. They could have formed in great numbers as waves thrashed around lipid layers on water surfaces, or as lipid scums washed up on a muddy shore with clays in the water. These processes could have formed liposomes with greatly variable contents (some with amino acids, primitive forms of nucleic acid, and so on). The "best" ones would have operated chemical reactions much more efficiently than the "worst."

Chemicals react faster and more efficiently if they are concentrated. Four concentration mechanisms could have occurred naturally: evaporation; freezing; concentration in scums, droplets, or bubbles; and concentration on the surfaces of mineral grains.

"Naked Genes" in an RNA World

In living cells today, each protein is coded on long sequences of nucleic acid. The long sequences of DNA that specify these protein structures are themselves difficult to replicate, and replication requires many proteins to act as enzymes to catalyze the reactions. Protein synthesis and DNA replication are interwoven in cells today: they depend on one another, even though they use very different chemical pathways and probably evolved independently. How could these two processes have begun independently, then evolved to depend on each other?

The answer lies with the simpler nucleic acid, RNA. Some RNA sequences called **ribozymes** can act as enzymes and make more RNA even when no proteins are present. Other RNA sequences speed up the assembly of proteins. Perhaps the first living things were pieces of RNA, ribozymes caught up inside liposomes, which happened to have the right structure to act as enzymes that helped the RNA to replicate itself. In theory, RNA ribozymes on early Earth could have replicated themselves without proteins, slowly and inaccurately, and therefore could have been considered alive. The ribozymes are sometimes called "naked genes," but in reality they would have been inside liposomes, as described above.

Ribozymes that by chance had RNA that coded for protein enzymes would have replicated faster than other ribozymes. Increasingly successful ribozymes would very quickly have outcompeted all others to become the ancestors of all later life on Earth: I shall call them **protocells** from now on. The scenario that begins with ribosomes in an RNA world is currently the best hypothesis for the origin of life on Earth.

RNA is simpler than DNA, and likely evolved before DNA. But even simpler types of nucleic acid than RNA have been made in the laboratory, though they are not used now by living cells. They provide hints that the first living things may have evolved even before the RNA world. Molecules named PNA and TNA are now being used in experiments to see if they could have formed the basis for a living thing. PNA forms more easily in early Earth experiments than RNA does. In 2002, DNA was made in the laboratory from TNA.

Even the first genetic code might have been simpler than today's: experiments in 2002 showed that ribozymes can reproduce themselves even if they have only two nucleic acid bases, rather than the four found in RNA today.

WHERE DID LIFE EVOLVE?

Many different habitats have been seriously suggested as the environment in which life began (Box 1.2). However, some are less likely than others. **Soil surfaces** would not attract the quantity of organic material that would be available in water. **Interstellar space** and the **atmosphere** are too dry.

BOX 1.2 Possible Habitats for the Origin of Life

- Soils;
- the upper atmosphere;
- space;
- lakes or lagoons;
- glacial volcanic islands;
- deep sea rifts.

Most theories of the origin of life suggest surface or shoreline habitats in lakes, lagoons, or oceans. But it's unlikely that life evolved in the sea. Complex organic molecules are vulnerable to damage from the sodium and chlorine in seawater. Most likely, then life evolved in **lakes**, or in **seashore lagoons** that were well supplied with river water. We have come to think of lagoons as tropical: the very name conjures up blue water and palm trees. Warm temperatures promote chemical reactions, and an early tropical island would most likely have been volcanic and therefore liable to have interesting minerals. But RNA bases are increasingly unstable as temperatures rise above 0°C: normal tropical water (25°C) may be about as warm as it could be for the origin of life.

So perhaps **cold volcanic islands** were the best environments favoring organic reactions on early Earth. In the laboratory, cyanide and formaldehyde reactions occur readily in half-frozen mixtures. Volcanic eruptions often generate lightning storms, so eruptions, lightning, fresh clays, and near-freezing temperatures (ice, snow, hailstones) could all have been present on the shore of a cold volcanic island.

Note that if this environment is the correct one, there had to have been land *and* sea when life evolved: fresh water can only occur on Earth if it is physically separated from the ocean.

Solar radiation or atmospheric phenomena are likely energy sources for the reactions leading toward life. But deep in the oceans lie the mid-ocean ridges, long underwater **volcanic rifts** where the seafloor is tearing apart and forming new oceanic crust. Enormous quantities of heat are released in the process, much of it through hot water vents on the floors of the rifts, and myriads of bacteria flourish in the hot water. Perhaps life began nowhere near the ocean surface, but deep below it, at volcanic vents.

Laboratory experiments have implied that amino acids and other important molecules can form in such conditions, even linking into short protein-like molecules, and currently the deep-sea hypothesis is popular. But if life evolved by way of naked genes, then it did not do so in hot springs. RNA and DNA are unstable at such high temperatures. Naked genes could not have existed (for long) in hot springs.

The deep-sea hypothesis, even though it looks unlikely (to me), has led to speculation that life might have evolved deep under the surface layers of other planets or satellites. (For example, Jupiter's moon Europa probably has liquid water under its icy crust.) The speculation helps to generate money for NASA's planetary probes. But the internal energy of such planets and moons is very low, and water-borne organic reactions are much less likely to work deep under the icy crust of Europa than in Earth's oceans. In any case, the under-ice oceans of icy moons are salty (that's how they were detected), so an origin of life is very unlikely in such environments.

New experiments are producing organic chemicals in conditions that simulate ices forming on dust grains in the freezing near-vacuum of space; in other words, on comets. Even so, the ices have to be thawed out to a water-based chemistry to react further. Processes in space may generate chemicals and deliver them to planets; but if a planet is hospitable, the right conditions for generating organic molecules and life already existed on that planet.

ENERGY SOURCES FOR THE FIRST LIFE

We have seen that living things use energy. Much of biology consists of studying metabolism and ecology: the ways in which living things acquire and use the energy they need to grow and reproduce.

The earliest cells likely evolved in a watery environment that contained large quantities of naturally formed organic molecules. So the first protocells had energy available to them in the form of ATP, amino acids, and other organic compounds that they could absorb from water. Those compounds had been accumulating for a long time, and they all have chemical energy stored in them, especially in the bonds between hydrogen and carbon atoms. If early protocells had the enzymes to break those bonds, the molecules would have provided plenty of fuel for cell growth and replication. But as protocells became more numerous and more effective in attracting and using organic molecules, there must have come a time when demand exceeded supply. As simple organic molecules became scarcer and scarcer, protocells encountered the world's first energy crisis. Paradoxically, this would have happened first in environments where protocells were most successful and abundant. Two very different reactions to a shortage of "food" can still be seen among living organisms nearly 4 billion years later.

Living organisms gain energy in two ways: **heterotrophy** and **autotrophy**. Heterotrophs obtain their metabolic energy by breaking down organic molecules they absorb from the environment: hummingbirds sip nectar and humans eat doughnuts. Heterotrophs do not pay the cost of building the organic molecules, they just have to operate the reactions that break them down: but they must live in an environment in which there are "food" molecules. Autotrophs do not need food molecules from outside: they make them inside the cell, typically paying the cost of building the molecules by absorbing *energy* from outside. Since they then break down the molecules again for growth and replication, they must operate in an environment that gives them outside energy.

Were the first cells heterotrophic or autotrophic? One can argue either case. Whichever is true, autotrophy and heterotrophy must have been exceedingly early developments. I argue that heterotrophy evolved first. Autotrophic cells must be able to break down the molecules they build, and they do so using the same universal biochemical reactions that heterotrophic cells use. It is easier to argue that existing heterotrophs added photosynthesis than to argue that the first cells evolved photosynthesis *and* heterotrophic breakdown reactions at the same time.

Heterotrophy and Fermentation

The first heterotrophic cells would naturally have used the simplest possible reactions to break down organic molecules. These are **fermentation** reactions, in which cells break down sugars such as **glucose**. Glucose is often called the universal cellular fuel for living organisms, and it was probably the most abundant sugar available on early Earth. [Humans use fermenting microorganisms to produce beer, cheese, vinegar, wine, tea, and yogurt, and fermenting organisms break down much of our sewage.]

As heterotrophs used up the easiest molecules to break down, there would have been intense competition among them to break down more difficult ones. One can imagine a huge advantage for cells that could break down a molecule that was not available to other cells. A whole set of fermentation reactions would quickly have developed. In turn that would have worsened the energy crisis, because heterotrophs would at first have been limited to the molecules that formed naturally in the atmosphere and ocean.

Autotrophy: Lithotrophy and Photosynthesis

Autotrophs generate their own energy, but in two completely different ways. They may extract chemical energy from inorganic molecules (**lithotrophy**), or gain energy by trapping radiation (**photosynthesis**).

Lithotrophy can occur when a microorganism rips an oxygen molecule off one inorganic compound and transfers it to another, making an energy profit in the process. That energy is then used to build organic food molecules. For example, microorganisms called **methanogens** gain energy from lithotrophy by breaking up carbon dioxide and transferring the oxygen to hydrogen, forming water and methane as by-products:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O + \text{energy}$$

Methanogens are as different from true bacteria as bacteria are from us, and are part of a special group of microorganisms, the **Archaea**. Since carbon dioxide and hydrogen would have been available in the early ocean, it is reasonable to suggest that this reaction could have been operated by very early cells. Indeed, based on their molecular genetics, Archaea were among the first living things on Earth.

If this ability evolved very early, it may have been the first time (but not the last) that living things modified Earth's chemistry and climate. By replacing the greenhouse gas carbon dioxide with the even more powerful greenhouse gas methane, the activity of methanogens might have warmed early Earth (Chapter 2).

Photosynthesis is simple in concept, but biochemically more complex than lithotrophy. Some molecules can absorb light and store it as energy in their structure. An early microorganism that happened to have such molecules could have captured light energy and used it to build up food molecules such as sugars.

Living things use **porphyrins** as the most important light-trapping molecules, and they could have formed from simpler substances on early Earth. **Chlorophylls** of various kinds are the porphyrins most widely used by living organisms to trap light: complex biochemical reactions have evolved to release and use that energy.

LIMERICK 1.1
Their bacterial plight was pathetic
It's hard to be unsympathetic:
Volcanic heat diminished,
Organic soup finished,
Their solution was photosynthetic.

The evolution of photosynthesis produced major ecological changes on Earth. Immediately, the energy trapped by chlorophyll was used to build more **biomass** (biological substance). Photosynthetic cells now had an energy store, a buffer against times of low food supply, that could be used as needed. It's easy to see how such cells could come to depend almost entirely on photosynthesis for energy: they did not have to compete so directly with heterotrophs. In many habitats, sunlight is a richer and more reliable energy resource than organic matter that must be sought and captured. Then, as photosynthesizers died and their cell contents were released into the environment, they inadvertently provided a new source of nutrition for heterotrophs. Photosynthesis dramatically increased the energy flow through biological systems on Earth, and for the first time considerable amounts of energy were being transferred from organism to organism, in Earth's first true ecosystem.

The earliest photosynthetic cells probably used hydrogen from H_2 or H_2S. For example, the reaction:

$$H_2S + CO_2 + \text{light} \rightarrow (CH_2O) + 2S$$

released sulfur into the environment as a by-product of photosynthesis. Later, some bacteria began to break up the strong hydrogen bonds of the water molecule. The step might first have been an act of desperation in a sulfur-poor environment, but the bacteria that successfully broke down H_2O rather than H_2S, like this:

$$H_2S + CO_2 + \text{light} \rightarrow (CH_2O) + 2O$$

immediately gained access to a much more plentiful resource. There was a penalty, however. The waste product of H_2S photosynthesis is sulfur (S), which is easily disposed of. The waste product of H_2O photosynthesis is an oxygen radical, monatomic oxygen (O), which is a deadly poison to a cell because it can break down vital organic molecules by oxidizing them. Even for humans, it is dangerous to breathe pure oxygen or ozone-polluted air for long periods.

Cells needed a natural antidote to this oxygen poison before they could operate the new photosynthesis consistently. **Cyanobacteria** were the organisms that made the first breakthrough to oxygen photosynthesis using water. They used a powerful antioxidant enzyme called superoxide dismutase to prevent the O from damaging them: essentially, the enzyme packaged up the O into less dangerous O_2 that was ejected out of the cell wall into the environment.

From then on, we can imagine early communities of bacteria made up of autotrophs and heterotrophs, evolving improved ways of gathering or making food molecules.

Photosynthesizers need nutrients such as phosphorus and nitrogen to build up their cells, as well as light and CO_2. In most habitats, the nutrient supply varies with the seasons, as winds and currents change during the year. Light, too, varies with the seasons, especially in high latitudes. Since light is required for photosynthesis, great seasonal fluctuations in the primary productivity of the natural world began with photosynthesis. Seasonal cycles still dominate our modern world, among wild creatures and in agriculture and fisheries.

We can now envisage a world with a considerable biological energy budget and large populations of microorganisms: Archaea, photosynthetic bacteria, and heterotrophic bacteria. So there is at least a chance that a paleontologist might find evidence of very early life as fossils in the rock record. In Chapter 2 we shall look at geology, rocks, and fossils, instead of relying on reasonable but speculative arguments about Earth's early history and life.

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