Precambrian Time—
The Story of the Early Earth

The Precambrian is the least understood part of Earth history, yet it is arguably the most important. Precambrian time spans almost nine-tenths of Earth history, from the formation of the Earth to the dawn of the Cambrian Period. It represents time so vast and long ago that it challenges all comprehension.

The Precambrian is the time of big questions. How old is the Earth? How old are the oldest rocks and continents? What was the early Earth like? What was the early atmosphere like? When did life appear, and what did it look like? And, how do we know this?

In recent years, remarkable progress has been made in understanding the early evolution of the Earth and life itself. Yet, the scientific story of the early Earth is still a work in progress, humankind's latest attempt to understand the planet. Like previous attempts, it too will change as we learn more about the Earth. Read on to discover what we know now, in the early 21st century.

Measuring the Age of the Earth

The Earth and other planets formed by collapse of a cloud of gas and dust about 4.5–4.6 billion years ago. Much of this collapse is estimated to have taken place in a relatively short time, perhaps a few tens of million years. Planets like Earth grew as they gathered small objects from their orbital paths. The age of the solid Earth has been estimated fairly precisely at 4.54 billion years, even though no rock this old has been found on Earth. The estimate comes from the evolution of lead isotope ratios since the Earth formed. This estimate falls between the measured ages of the oldest lunar rocks, brought back to Earth by the Apollo missions, and the ages of meteorites left over from the formation of the solar system. Measurements of tungsten and hafnium isotopes in lunar rocks reveal that the Moon cooled from a molten state 4.53 billion years ago; thus the Moon is only slightly younger than Earth. In contrast, the age of the solar system has been estimated from meteorites at 4.57 billion years, only slightly older than Earth.

The oldest rocks on Earth are not as old as the planet itself. The earliest history of the Earth was so violent that little remains from the first half-billion years. Scientists know from studying the age of craters on the Moon that the early Earth was bombarded by millions of large objects. One of these objects, a giant perhaps the size of Mars, struck the Earth near the end of its formation and burst into a huge cloud of hot particles that coalesced into the Moon—scientists call this scenario the "Giant Impact Theory." This theory has come to be widely accepted as the probable explanation for the origin of the Moon. "The Great Bombardment" did not end gradually, but instead with a final, intense pummeling about 3.9 billion years ago. The late heavy bombardment may have come from objects thrown into the inner solar system by the large outer planets when they assumed their final orbits.

The oldest rock dated so far is about 4 billion years old; it was found in the Northwest Territories of Canada. In Western Australia, tiny crystals of zircon (zirconium silicate, a widespread and durable mineral) deposited in a younger sedimentary rock are an amazing 4.4 billion years old. Geochemical analyses of these zircons also suggest that water and continental rocks already may have been present on the Earth's surface.

The age of rocks can be determined by using the principle of radioactive decay, in which an element spontaneously changes into a more stable form. Imagine a basket of white marbles that have the peculiar property that during a year exactly half of the marbles turn black; the next year, half of the remaining white marbles turn black, and so on. A graph of the ratio of white-to-black marbles for each year declines steeply at first, then gradually in later years; this graph is a decay curve. The rate of decay is called the "half-life." For the white marbles, the half-life is one year. If at some later time you counted the marbles in the basket and found the ratio of white ones to black ones, you could determine from the graph the length of time since all the marbles in the basket were white. The white marbles represent the parent element, and the black marbles represent the daughter element produced by radioactive decay. These parent-daughter elements are called "isotopes." Isotopes of the same element have the same atomic number but different atomic weights. Unstable isotopes of uranium decay to distinct lead isotopes, each having its own atomic weight. If the rate of decay (half-life) is known, minerals that contain uranium can be dated by comparing the amount of the remaining parent isotope to the amount of the daughter lead isotope, just like the white and black marbles. There are several different isotopes of uranium that decay at different rates, each to a distinctive lead isotope. This means that the ratios among different lead isotopes also change as decay proceeds. Isotope ratios in lead ore record the progress of radioactive decay up to the time when the ore formed. By comparing ratios in lead ores of different ages with the initial lead-isotope ratios of iron meteorites, the time of the Earth's formation can be estimated. The marble analogy was suggested by J.C. Reed, Jr. For an in-depth discussion of the use of lead isotopes in dating the Earth, see The age of the Earth, *by G.B. Dalrymple, listed under "For More Information."*

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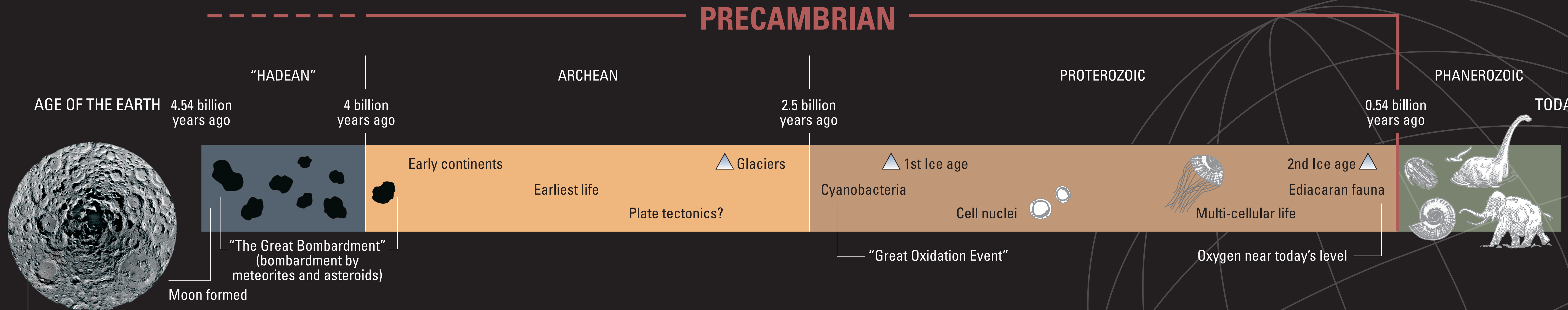
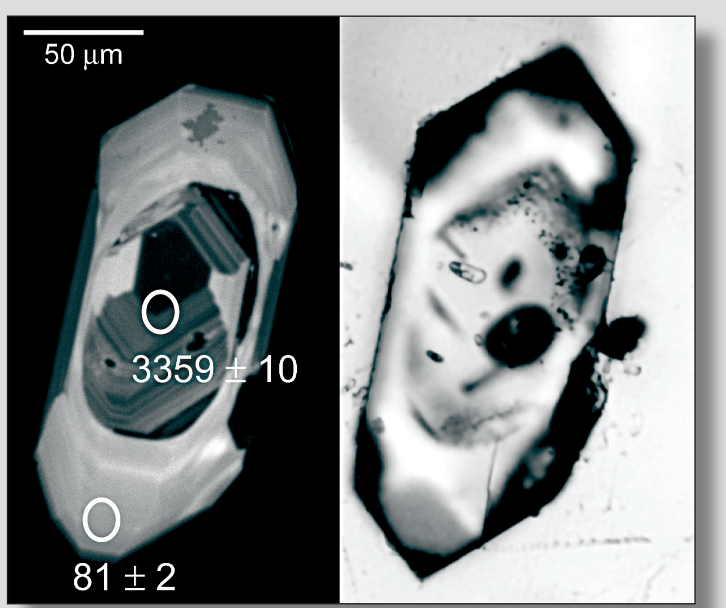
TIME'S RULER



Mosaic image of the south polar region of the Moon, showing densely cratered surface formed by asteroid and comet impacts dating from "The Great Bombardment" to present. Large, subdued craters are the oldest. The image gives an idea of what the Earth must have experienced during its first half-billion years. *Mosaic produced by the USGS from 1,500 images taken by the NASA Clementine spacecraft.*

The oldest rocks were dated in Australia using the SHRIMP, which stands for Sensitive High Resolution Ion MicroProbe. The SHRIMP focuses a tiny beam of ions on a zircon crystal to measure isotopes of uranium and lead. Some zoned crystals reveal more than one period of growth. Only the cores of such crystals reveal the oldest ages because the outer zones grew later. Another method, ID—TIMS (Isotope Dilution—Thermal Ionization Mass Spectrometer), uses an entire zircon crystal or a small number of crystals dissolved in solution and analyzed by mass spectrometer to give a composite uranium-lead age. ID—TIMS is a very precise method; it is best used to date crystals that formed during a short time, such as those in volcanic ash that has cooled quickly.

In contrast to the age of the Earth, the end of Precambrian time can be dated directly from rocks. Beds of volcanic ash just below and above the Precambrian-Cambrian boundary at several places in the world contain tiny crystals of zircon. These zircons have been carefully studied and dated using the ID—TIMS method. In Siberia, southwest Africa, and the Arabian Peninsula, the boundary is very close to 542 million years old.



Photomicrographs of a zircon crystal, illuminated by electron beam (left side) and plain light (right side), illustrating the use of uranium-lead dating by the Sensitive High Resolution Ion MicroProbe (SHRIMP) to unravel a complex history. The inner zoned core (3,359 million years; 3.359 billion years) is surrounded by a thin, dark, rounded zone that grew over the original grain. The new, composite grain was eroded from the parent rock, rounded by running water, and deposited in sediment. At 81 million years ago, the grain was engulfed by molten rock of the Boulder batholith, Montana, which is when the outer zone formed. Scale bar is 50 µm (micrometers) long. A micrometer is one-millionth of a meter. *Photographs and explanation by J.N. Aleinikoff, USGS.*

Dividing Precambrian Time

The Precambrian is usually divided at 2.5 billion years ago into two eons, the Archean and the Proterozoic. Both are well represented in the geologic record, but further subdivision has been difficult. Commonly these eons are divided arbitrarily on the basis of age. Geologic time before the Archean, from the Earth's formation to about 4 billion years ago, is sometimes informally called the "Hadean." Following the Proterozoic Eon, all time of abundant life (after 542 million years ago) is assigned to the Phanerozoic Eon and further subdivided into eras and periods. Phanerozoic time began with the Cambrian Period of the Paleozoic Era. In 2004, the Ediacaran Period was defined and adopted for latest Precambrian time by the International Union of Geological Sciences. The Ediacaran is the first period defined by rocks of a known span of time to be formally added to the geologic time scale since 1891.

The First Continents and Ocean Basins

Continental rocks, which are rich in aluminum and silicon, and oceanic rocks, which are rich in iron and magnesium, form the outer layer, or crust, of the Earth. Both continental and oceanic crust overlies the Earth's mantle and core. Continental crust is lightest, followed by oceanic crust, the mantle, and the core. Crustal rocks probably formed soon after the molten Earth solidified more than 4.4 billion years ago, but the only evidence for their existence comes from the oldest zircons.

The earliest identified remnants of continental and oceanic crust, found in Greenland and a few other places, are 3.9–3.6 billion years old. Still younger but larger areas of early Archean crustal rocks have been found in Western Australia and South Africa. Although features in early crustal rocks have been cited as evidence for plate tectonic processes, the actual time when plate tectonics first started remains controversial among scientists. By late Archean time, however, colliding plates were forming continents by accretion and partial melting as oceanic plates were forced beneath continental plates. Also, large volumes of intrusive and volcanic rock were formed, then eroded and deposited as sediments on the ocean floor. A 2.7-billion-year-old plate boundary beneath parts of Ontario and Quebec was found by scientists who used seismic waves to peer deep into the Earth's crust, much like a doctor uses sound waves to see inside the human body.

Belts of granite and greenstone, shown on geologic maps, reveal the accreted margins of late Archean and early Proterozoic continents. Greenstone is altered basalt. Basalt is a dark volcanic rock that makes up lava flows like those on Hawaii. Mineral-filled vesicles, which were originally gas bubbles in lava, and pillow-like structures that form when lava is erupted into water, are common in greenstone, confirming its underwater volcanic origin. Turbidites (sand and gravel deposited by underwater slurries), banded iron-formation, and chert (a hard silica-rich rock) accompany greenstones. These deposits of ancient oceans were swept against and underneath continental plates during plate collision. Granite is a coarse, light-colored rock formed by slow crystallization of molten magma. Such magma typically forms by partial melting of the descending plate, which yields giant globules (diapirs) of molten rock that rise through the overlying plate and solidify before reaching the surface. Volcanic island arcs bordering eastern Asia and Alaska provide the closest modern examples of how granite-greenstone belts formed.

Many early continental rocks have been transformed into gneiss, obscuring their original appearance. Gneiss is a hard, crystalline rock of quartz, feldspar, and dark minerals; it is produced by intense heat and pressure. This process of rock transformation, called metamorphism, is a major obstacle to understanding what happened in Precambrian time. Only chemical tests and rare preservation of original features give us clues to the original nature of gneiss. At some places, where heat and pressure did not prevail, original features are preserved intact. For example, hard, resistant beds of quartzite still contain rounded pebbles and features formed by flowing water.

In plate tectonics, the outermost part of the Earth acts as rigid "plates," which move around the surface of the globe. Some plates move away from one another, allowing molten rock to rise to the surface. This molten rock solidifies and attaches itself to the "trailing margin" of separating plates. Elsewhere, at "leading margins," plates move toward each other and collide. Where they collide one plate is forced beneath the other. The down-going plate melts and the lightest part liquefies and rises to the surface to form volcanoes. Molten rock that does not reach the surface solidifies within the upper plate. Traditionally, convection cells (picture a pot of vigorously boiling water) driven by hotspots in the Earth are thought to produce rising magma and to move plates. However, variations in temperature, pressure, and composition among plates and between plates and underlying mantle may cause plates to thicken, collapse, or move. Much remains to be learned about what drives plate motion. For an online discussion of plate tectonics and the interior of the Earth, see This dynamic Earth: The story of plate tectonics, *by W.J. Kious and R.I. Tilling, listed under "For More Information."*

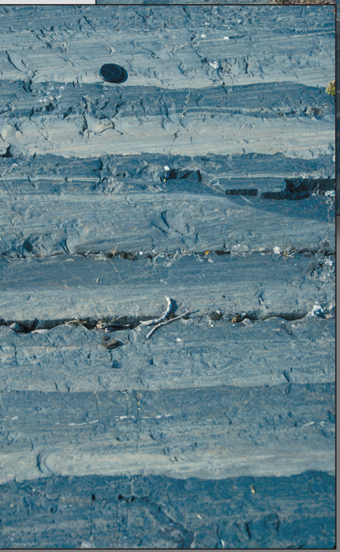
Fortunately, there are many places in the world where heat and pressure have not destroyed the original structures in Precambrian rocks. In Montana, a section of sedimentary rocks (the Belt Supergroup) as much as 9 miles thick was deposited in the Belt basin almost 1.5 billion years ago. Mudcracks and ripple marks abound in Belt rocks, showing that Belt sediments in which they formed were exposed to sun and flowing water at the earth's surface. In Ontario, Canada, a section of sedimentary rock as much as 7 miles thick, known as the Huronian Supergroup, was deposited on a continental margin 2.4–2.2 billion years ago. Other thick successions of Precambrian rocks with well-preserved original features are found in the Northwest Territories of Canada, in the State of Minas Gerais in Brazil, in Siberia, and in South Africa, among other places.

Precambrian Ice Ages

Evidence for the Earth's oldest glaciers has been found in 2.9 billion-year-old rocks in South Africa, but we do not know whether these glaciers were confined to mountains or were more widespread. The oldest evidence of widespread glaciers is recorded in early Proterozoic rocks, notably in the 2.4–2.2 billion-year-old Huronian rocks of Ontario. Like the most recent ice age, early Proterozoic glaciers may have covered parts of several continents. The evidence for this ice age is recorded in distinctive glacial sediments called tills, dropstones, and varves. Glacial tills are unsorted mixtures of boulders and clay. Tills deposited in water by floating glaciers and icebergs contain distinctive isolated stones (dropstones) that fell to the bottom of a lake or ocean and became embedded in sediment. Varves are thin clay layers deposited yearly on the bottoms of glacial lakes. The tills, dropstones, and varves in Huronian rocks are identical to those deposited during the most recent ice age, only a few thousand years ago.

Gneiss formed by metamorphic heat and pressure 1.7 billion years ago, near Idaho Springs, Colorado. Pink minerals were formed by partial melting and recrystallization of the original rock. No features from the original rock remain. The layering seen was formed by shearing and crystallization in open spaces. Hammer is about 30 centimeters long. *Photograph by D.A. Lindsey, USGS.*

Dropstone lodged in seafloor sediment beneath a floating glacier 2.2 billion years ago, in Huronian rocks, Whitefish Falls, Ontario. Knife is about 8 centimeters long. *Photograph by D.A. Lindsey, USGS.*



(Lower Left and Left) Turbidites deposited in the deep ocean 2.7 billion years ago, Yellowknife Bay, Northwest Territories, Canada. Light-colored sandy layers have sharp bases and grade upward from coarse to fine sand; they were deposited suddenly by underwater slurries. Intervening dark layers were deposited by slow settling of suspended clay. Black lens cap is about 6 cm across. *Photographs by D.G. Hadley, USGS.*

(Left and Above) Pillow structure in greenstone formed 2.7 billion years ago, near Yellowknife, Northwest Territories, Canada. Tops of pillows are toward lower left. Pillows like these have been observed forming today in lava erupted underwater. Hammer is about 30 centimeters long. *Photographs by D.G. Hadley, USGS.*

From about 750 to 580 million years ago, near the end of Precambrian time, a second series of ice ages gripped much of the Earth. Glacial deposits from this time have been found all over the world and may have extended even to the equator. From this evidence, some scientists envision a "Snowball Earth," when glaciers covered Earth's continents and its oceans were frozen at the surface. Rapid warming and deposition of carbonate rocks followed such extreme periods of cold, perhaps triggering the rapid evolution of late Precambrian life.

The Early Atmosphere

The early atmosphere probably consisted of water vapor, carbon dioxide, nitrogen, and methane. The relative proportions of atmospheric gases may have changed rapidly in early Hadean time and are a matter of great speculation. Later, in Proterozoic time, oxygen became abundant. Early life, especially oxygen-generating bacteria, may have played an important role in the evolution of Earth's atmosphere from reducing (oxygen-poor) to oxidizing (oxygen-rich). One place this important atmospheric event is recorded is in the Precambrian Huronian rocks of Canada.

Today's atmosphere has enough oxygen to rust (oxidize) iron. In contrast, iron did not rust in the early atmosphere. For example, fresh pyrite (iron sulfide, commonly known as "fools gold") was eroded from very old Precambrian rocks, worn into rounded grains by running water, and buried in the first Huronian sediments. Preservation of rounded pyrite grains shows that the early Huronian atmosphere did not have enough oxygen to cause iron minerals to rust. In contrast, iron oxide minerals ("rust") are abundant (and pyrite is absent) in the youngest Huronian sedimentary rocks. Some of the Earth's oldest redbeds are found near the top of the Huronian sedimentary succession. Like much younger redbed sedimentary rocks, the iron in these rocks turned rusty red from contact with oxygen-bearing water. The Precambrian atmosphere did not have as much oxygen as today, but by 2.2 billion years ago, it had just enough to rust iron. Other evidence dates the rise of atmospheric oxygen during a time called "The Great Oxidation Event," about 2.4–2.2 billion years ago.

For many years the origin of pyrite—and the evidence for an early reducing atmosphere—in rocks older than 2.4 billion years was controversial. Because this pyrite occurs with gold and uranium minerals in the rich goldfields of South Africa, its microscopic and chemical features attracted much research. Some scientists pointed to the rounded outlines of these mineral grains in ancient sedimentary rocks as evidence that they were deposited as tiny nuggets and sand grains, but others noticed that the same minerals also formed veins and other features that indicated deposition long after the original sediment was laid down. Eventually, scientists realized that both theories were correct; some mineral grains were deposited as sediment, but others formed later. Recent isotopic studies confirm that the pyrite, gold, and uranium originally came from older rocks, consistent with an early reducing atmosphere, and that some of these original minerals were remobilized later to form veins.

Evidence for dating "The Great Oxidation Event" comes from the way in which sulfur dioxide gas is broken down (reduced) in the Earth's atmosphere. In an oxygen-free atmosphere, breakdown by sunlight produces a distinctive mixture of sulfur isotopes that is independent of their weight. If oxygen is present, a different, weight-dependent mixture is produced. Each of these isotope mixtures is preserved in sulfur-bearing minerals in sedimentary rocks. Extensive sampling of sedimentary rocks first revealed that the mixture of sulfur isotopes produced by an oxygen-free atmosphere disappeared after 2.4 billion years ago. However, more recent studies of Archean rocks from Western Australia reveal the possibility of oxygen in the atmosphere before that date. Whatever the final outcome of this controversy, the amount of oxygen in the early atmosphere was still perhaps 5–10 times less than today. Oxygen, a product of photosynthesis, probably did not approach modern levels until 600–700 million years ago.

Early Life

The earliest life appeared on Earth more than 3.5 billion years ago. Life may have originated on Earth itself, or meteorites from outside Earth may have seeded it. Perhaps life first formed around warm springs in the protected environment of the ocean floor. The earliest fossils are microscopic. Abundant microscopic fossils, including fossil bacteria that have living counterparts, are preserved in exquisite detail in Precambrian chert. Some lived by converting sunlight and carbon dioxide or water into energy (photosynthesis); others produced energy from chemical reactions (chemosynthesis). More obvious are fossil structures called "stromatolites," often shaped like cabbages and composed of delicate layers. These layers formed by entrapment of mud in sticky microbial mats of blue-green bacteria (cyanobacteria, formerly called algae). Stromatolites are common in shallow-water limestone of all ages and can be observed in tidal zones to this day. The most spectacular modern-day stromatolites are large columnar forms in Shark Bay, Western Australia.

Stromatolites formed by blue-green bacteria 1.4 billion years ago, in the Belt Supergroup, Glacier National Park, Montana. Individual layered columns are about 10–15 centimeters wide. *Photograph by R.K. Hunt, Augustana College and National Park Service.*

(Left) Geologists look for evidence of storm waves in 1.4 billion-year-old rocks. Salmon River Mountains, Idaho. *Photograph by R.G. Tysdal, USGS.*

Although the first life consisted of simple cells, more complex organisms with cell nuclei (and probably requiring oxygen) may have appeared by 2.5 billion years ago. Blue-green bacteria could have begun to add oxygen to surface water of the oceans even before "The Great Oxidation Event," thus allowing complex organisms to evolve there first. The oldest fossils with cell nuclei are 2 billion years old, but an even earlier ancestry is suggested by chemical signatures in rocks older than 2.5 billion years. By 1.2 billion years ago, multicellular red algae had appeared. Microscopic vase-shaped shells of fossil protozoans (single-celled animals, such as amoebae) are in 740 million-year-old rocks of the Grand Canyon, and a diverse group of microscopic animals is beautifully preserved in 600 million-year-old rocks of China. The stage was set for the rise of large, complex animals. Abundant well-preserved fossils of large animals had to await the development of hard skeletons at the dawn of Phanerozoic time.

Large animals with only soft parts first appeared in latest Precambrian time, perhaps about 570 million years ago. Not life as we know it, or even life as it appeared so abundantly later in Cambrian time, but mysterious forms that challenge our understanding. Called the "Ediacaran fauna" from hills by that name in South Australia, these strange fossils have been found in rocks of latest Precambrian age in other parts of the world, most notably in Newfoundland, southwest Africa, and northern Russia. Ranging in size from a few centimeters to more than 30 centimeters, they look like disks, mats of quilted tubes, and leaves. Some evidently lay on the seafloor while others may have lived upright and attached to the sea bottom. Ediacarans had no visible mouth or digestive tract. A few appear to be related to jellyfish and sea anemones, but many Ediacarans are so different from familiar organisms that experts disagree about their relation to other life forms.

Beds with fossils that are clear ancestors to animals that live today directly overlie beds with Ediacaran fossils. The boundary between the two groups of organisms marks the end of Precambrian time.

The Evidence Is in the Rocks

The Earth was formed in the early solar system more than 4.5 billion years ago. During the next 4 billion years, all major earth systems appeared. The Precambrian Earth saw bombardment by large objects, separation of the crust into the first continents and ocean basins, mobilization of crustal plates, transition of the atmosphere from reducing to oxidizing, and the origin and evolution of early life. Life formed, survived, and even thrived as the Earth experienced large meteorite and asteroid impacts from space, great ice ages, fundamental atmospheric change, and extensive resurfacing by plate tectonics. The evidence for this story is in the rocks.

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