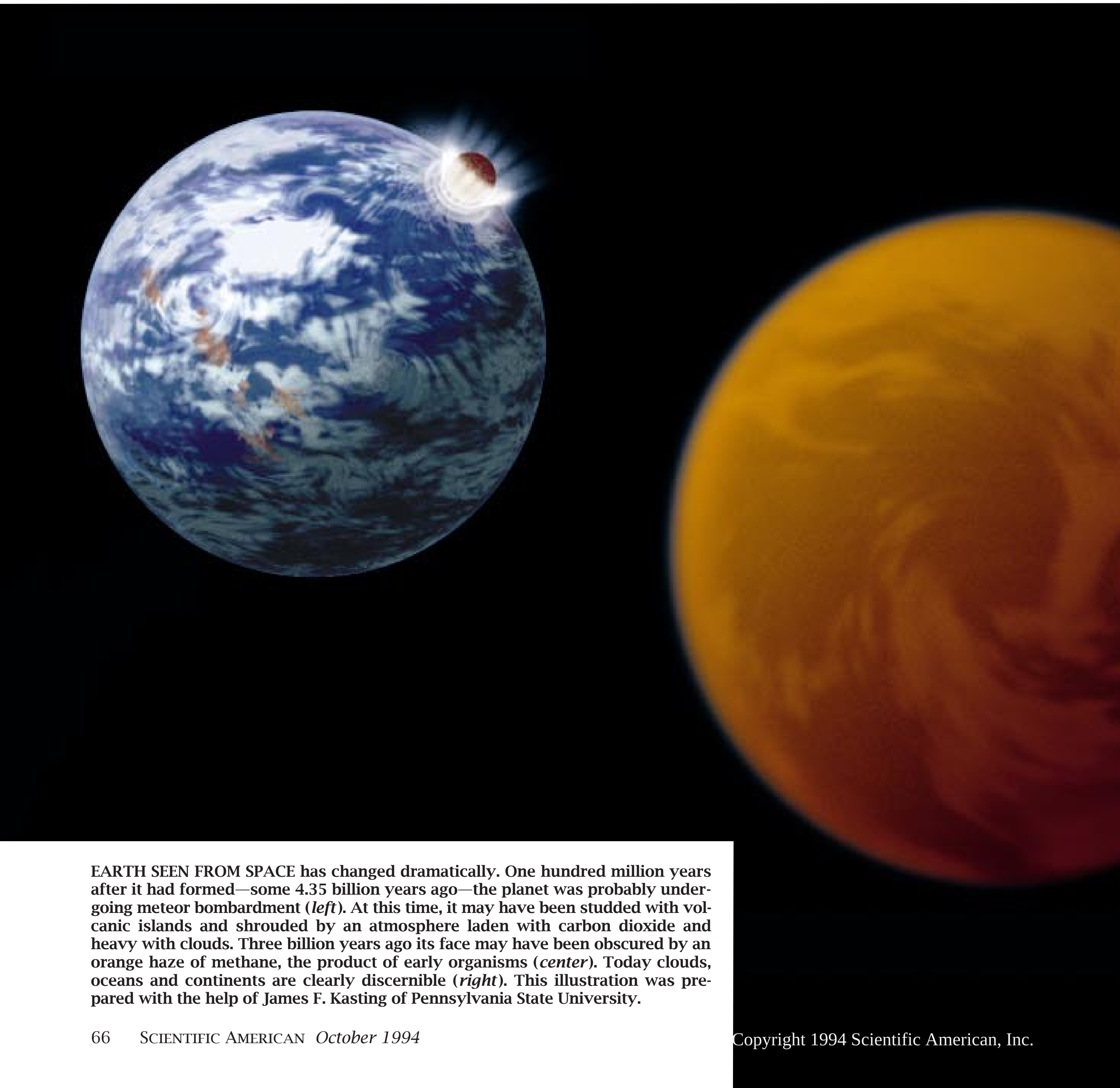
The Evolution of the Earth

The formation of this planet and its atmosphere gave rise to life, which shaped the earth's subsequent development. Our future lies in interpreting this geologic past

by Claude J. Allègre and Stephen H. Schneider



EARTH SEEN FROM SPACE has changed dramatically. One hundred million years after it had formed—some 4.35 billion years ago—the planet was probably undergoing meteor bombardment (*left*). At this time, it may have been studded with volcanic islands and shrouded by an atmosphere laden with carbon dioxide and heavy with clouds. Three billion years ago its face may have been obscured by an orange haze of methane, the product of early organisms (*center*). Today clouds, oceans and continents are clearly discernible (*right*). This illustration was prepared with the help of James F. Kasting of Pennsylvania State University.

Like the lapis lazuli gem it resembles, the blue, cloud-enveloped planet that we recognize immediately from satellite pictures seems remarkably stable. Continents and oceans, encircled by an oxygen-rich atmosphere, support familiar life-forms. Yet this constancy is an illusion produced by the human experience of time. The earth and its atmosphere are continuously altered. Plate tectonics shift the continents, raise mountains and move the ocean floor while processes that no one fully comprehends alter the climate.

Such constant change has characterized the earth since its beginning some 4.5 billion years ago. From the outset, heat and gravity shaped the evolution of the planet. These forces were gradually joined by the global effects of the emergence of life. Exploring this past offers us the only possibility of understanding the origin of life and, perhaps, its future.

Scientists used to believe the rocky planets, including the earth, Mercury, Venus and Mars, were created by the rapid gravitational collapse of a dust cloud, a deflation giving rise to a dense orb. In the 1960s the Apollo space program changed this view. Studies of moon craters revealed that these gouges were caused by the impact of objects that were in great abundance about 4.5 billion years ago. Thereafter, the number of impacts appeared to have quickly decreased. This observation rejuvenated the theory of accretion postulated by Otto Schmidt. The Russian geophysicist had suggested in 1944 that planets grew in size gradually, step by step.

According to Schmidt, cosmic dust lumped together to form particulates, particulates became gravel, gravel became small balls, then big balls, then tiny planets, or planetesimals, and, finally, dust became the size of the moon. As the planetesimals became larger, their numbers decreased. Consequently, the number of collisions between planetesimals, or meteorites, decreased. Fewer items available for accretion meant that it took a long time to build up a large planet. A calculation made by George W. Wetherill of the Carnegie Institution of Washington suggests that about 100 million years could pass between the formation of an object measuring 10 kilometers in diameter and an object the size of the earth.

The process of accretion had significant thermal consequences for the earth, consequences that have forcefully directed its evolution. Large bodies slamming into the planet produced im-

CLAUDE J. ALLÈGRE and STEPHEN H. SCHNEIDER study various aspects of the earth's geologic history and its climate. Allègre is a professor at the University of Paris and directs the department of geochemistry at the Institut de Physique du Globe de Paris. He is a foreign member of the National Academy of Sciences. Schneider is a professor in the department of biological sciences at Stanford University and is a senior fellow at the university's Institute of International Studies. He is also a senior scientist at the National Center for Atmospheric Research in Boulder, Colo.

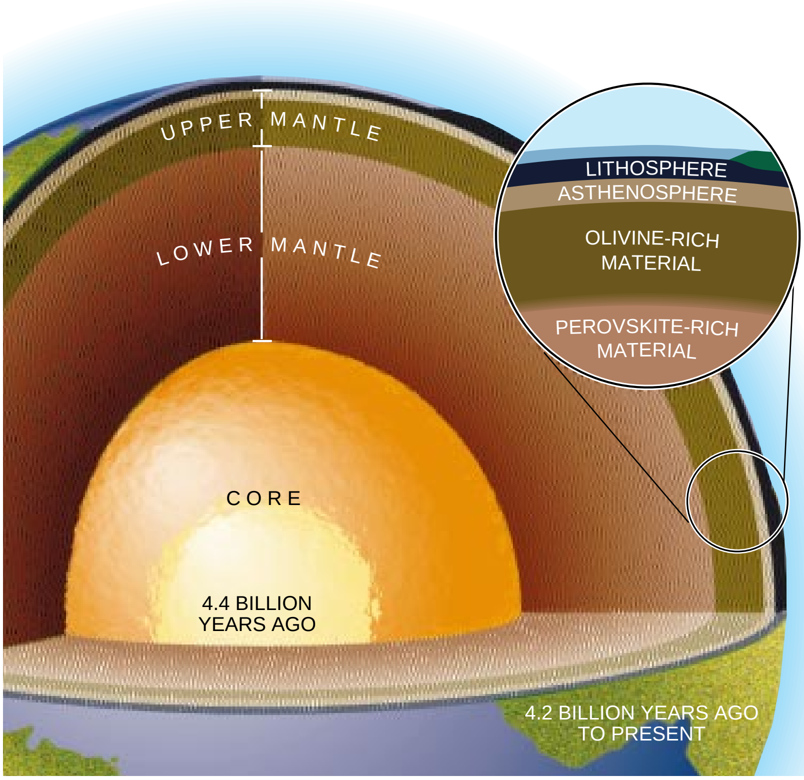
mense heat in the interior, melting the cosmic dust found there. The resulting furnace—situated some 200 to 400 kilometers underground and called a magma ocean—was active for millions of years, giving rise to volcanic eruptions. When the earth was young, heat at the surface caused by volcanism and lava flows from the interior was supplemented by the constant bombardment of huge planetesimals, some of them perhaps the size of the moon or even Mars. No life was possible during this period.

Beyond clarifying that the earth had formed through accretion, the Apollo program compelled scientists to try to reconstruct the subsequent temporal and physical development of the early earth. This undertaking had been considered impossible by founders of geology, including Charles Lyell, to whom the following phrase is attributed: No vestige of a beginning, no prospect for an end. This statement conveys the idea that the young earth could not be recreated, because its remnants were destroyed by its very activity. But the development of isotope geology in the 1960s had rendered this view obsolete. Their imaginations fired by Apollo and the moon findings, geochemists began to apply this technique to understand the evolution of the earth.

Dating rocks using so-called radioactive clocks allows geologists to work on old terrains that do not contain fossils. The hands of a radioactive clock are isotopes—atoms of the same element that have different atomic weights—and geologic time is measured by the rate of decay of one isotope into another [see "The Earliest History of the Earth," by Derek York; SCIENTIFIC AMERICAN, January 1993]. Among the many clocks, those based on the decay of uranium 238 into lead 206 and of uranium 235 into lead 207 are special. Geochronologists can determine the age of samples by analyzing only the daughter product—in this case, lead—of the radioactive parent, uranium.

How the Earth Got Its Core

The differentiation of the planet took place quite quickly after the earth was formed by the accretion of cosmic dust and meteorites. About 4.4 billion years ago the core—which, with the mantle, drives the geothermal cycle, including volcanism—appeared; gases emerging from the interior of the planet also gave rise to a nascent atmosphere. Somewhat later, although the issue has not been entirely resolved, it seems that continental crust formed as the various elements segregated into different depths.

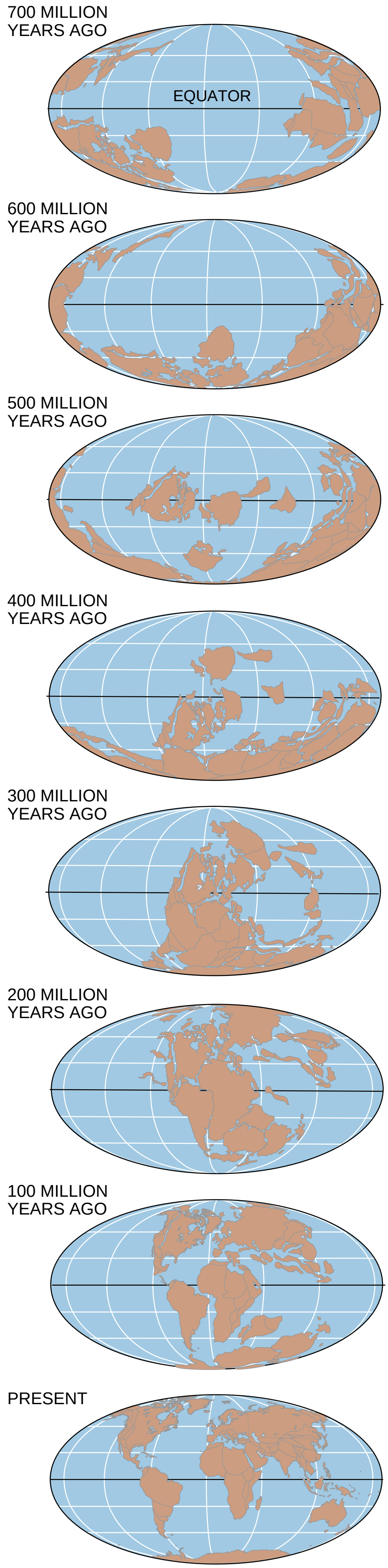


Isotope geology has permitted geologists to determine that the accretion of the earth culminated in the differentiation of the planet: the creation of the core—the source of the earth's magnetic field—and the beginning of the atmosphere. In 1953 the classic work of Claire C. Patterson of the California Institute of Technology used the uranium-lead clock to establish an age of 4.55 billion years for the earth and many of the meteorites that formed it. Recent work by one of us (Allègre) on lead isotopes, however, led to a somewhat new interpretation. As Patterson argued, some meteorites were indeed formed about 4.56 billion years ago, and their debris constituted the earth. But the earth continued to grow through the bombardment of planetesimals until some 120 to 150 million years later. At that time—4.44 to 4.41 billion years ago—the earth began to retain its atmosphere and create its core. This possibility had already been suggested by Bruce R. Doe and Robert E. Zartman of the U.S. Geological Survey in Denver a decade ago and is in agreement with Wetherill's estimates.

The emergence of the continents came somewhat later. According to the theory of plate tectonics, these landmasses are the only part of the earth's crust that is not recycled and, consequently, destroyed during the geothermal cycle driven by the convection in the mantle. Continents thus provide a form of memory because the record of early life can be read in their rocks. The testimony, however, is not extensive. Geologic activity, including plate tectonics, erosion and metamorphism, has destroyed almost all the ancient rocks. Very few fragments have survived this geologic machine.

Nevertheless, in recent years, several important finds have been made, again using isotope geochemistry. One group, led by Stephen Moorbath of the University of Oxford, discovered terrain in West Greenland that is between 3.7 and 3.8 billion years old. In addition, Samuel A. Bowring of the Massachusetts Institute of Technology explored a small area in North America—the Acasta gneiss—that is 3.96 billion years old.

Ultimately, a quest for the mineral zircon led other researchers to even more ancient terrain. Typically found in continental rocks, zircon is not dissolved during the process of erosion but is deposited as particles in sediment. A few pieces of zircon can therefore survive for billions of years and can serve as a witness to the earth's more ancient crust. The search for old zircons started in Paris with the work of Annie Vitrac and Joël R. Lancelot, now



CONTINENTAL SHIFT has altered the face of the planet for nearly a billion years, as can be seen in the differences between the positions of the continents that we know today and those of 700 million years ago. Pangaea, the superaggregate of early continents, came together about 200 million years ago and then promptly, in geologic terms, broke apart. This series was compiled with the advice of Christopher R. Scotese of the University of Texas at Arlington.

at the University of Marseilles and the University of Montpellier, respectively, as well as with the efforts of Moorbath and Allègre. It was a group at the Australian National University in Canberra, directed by William Compston, that was finally successful. The team discovered zircons in western Australia that were between 4.1 and 4.3 billion years old.

Zircons have been crucial not only for understanding the age of the continents but for determining when life first appeared. The earliest fossils of undisputed age were found in Australia and South Africa. These relics of blue-green algae are about 3.5 billion years old. Manfred Schidlowski of the Max Planck Institute for Chemistry in Mainz has studied the Isua formation in West Greenland and argues that organic matter existed as many as 3.8 billion years ago. Because most of the record of early life has been destroyed by geologic activity, we cannot say exactly when it first appeared—perhaps it arose very quickly, maybe even 4.2 billion years ago.

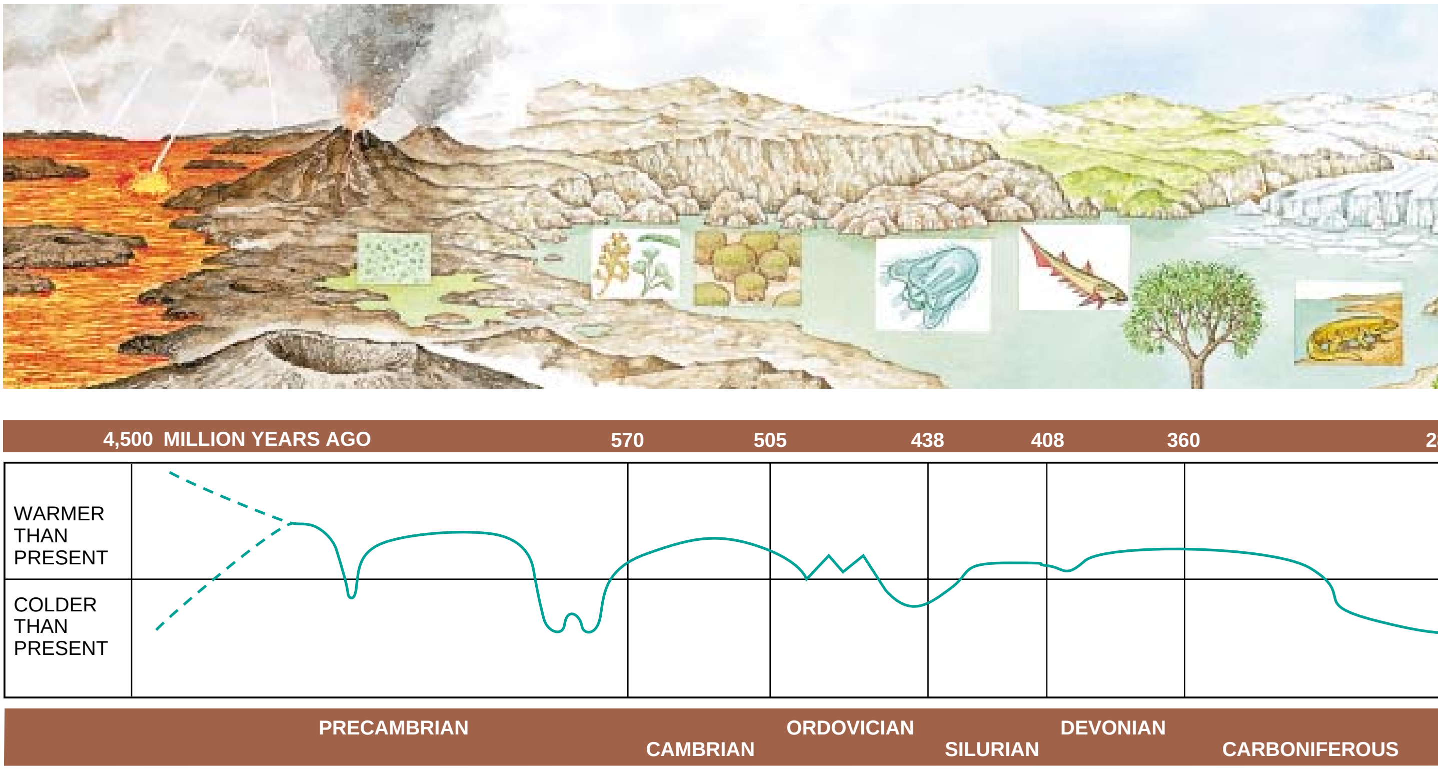
One of the most important aspects of the earth's evolution is the formation of the atmosphere, because it is this assemblage of gases that allowed life to crawl out of the oceans and to be sustained. Researchers have hypothesized since the 1950s that the terrestrial atmosphere was created by gases emerging from the interior of the planet. When a volcano spews gases, it is an example of the continuous outgassing, as it is called, of the earth. But scientists have questioned whether this process occurred suddenly about 4.4 billion years ago when the core differentiated or whether it took place gradually over time.

To answer this question, Allègre and his colleagues studied the isotopes of rare gases. These gases—including helium, argon and xenon—have the peculiarity of being chemically inert, that is, they do not react in nature with other elements. Two of them are particularly important for atmospheric studies: argon and xenon. Argon has three isotopes, of which argon 40 is created by the decay of potassium 40. Xenon has nine, of which 129 has two different origins. Xenon 129 arose as the result of nucleosynthesis before the earth and solar system were formed. It was also created from the decay of radioactive iodine 129, which does not exist on the earth anymore. This form of iodine was present very early on but has died since, and xenon 129 has grown at its expense.

Like most couples, both argon 40 and potassium 40 and xenon 129 and iodine 129 have stories to tell. They are excellent chronometers. Although the atmosphere was formed by the outgassing of the mantle, it does not contain any potassium 40 or iodine 129. All argon 40 and xenon 129, formed in the earth and released, are found in the atmosphere today. Xenon was expelled from the mantle and retained in the atmosphere; therefore, the atmosphere-mantle ratio of this element allows us to evaluate the age of differentiation. Argon and xenon trapped in the mantle evolved by the radioactive decay of potassium 40 and iodine 129. Thus, if the total outgassing of the mantle occurred at the beginning of the earth's formation, the atmosphere would not contain any argon 40 but would contain xenon 129.

The major challenge facing an investigator who wants to measure such ratios of decay is to obtain high concentrations of rare gases in mantle rocks because they are extremely limited. Fortunately, a natural phenomenon occurs at mid-oceanic ridges during which volcanic lava transfers some silicates from the mantle to the surface. The small amounts of gases trapped in mantle minerals rise with the melt to the surface and are concentrated in small vesicles in the outer glassy margin of lava flows. This process serves to concentrate the amounts of mantle gases by a factor of 10^4 or 10^5. Collecting these rocks by dredging the seafloor and then crushing them under vacuum in a sensitive mass spectrometer allow geochemists to determine the ratios of the isotopes in the mantle. The results are quite surprising. Calculations of the ratios indicate that between 80 and 85 percent of the atmosphere was outgassed in the first one million years; the rest was released slowly but constantly during the next 4.4 billion years.

The composition of this primitive atmosphere was most certainly dominated by carbon dioxide, with nitrogen as the second most abundant gas. Trace amounts of methane, ammonia, sulfur dioxide and hydrochloric acid were also present, but there was no oxygen. Except for the presence of abundant water, the atmosphere was similar to that



CLIMATE FLUCTUATIONS are apparent over time. Although the earth's early temperature record is quite uncertain, good estimates can be made starting 400 million years ago, when fossils were more abundantly preserved. As climate shifted, so did life—suggesting feedback between the two. The dates of these evolutions remain unclear as well, but their order is

of Venus or Mars. The details of the evolution of the original atmosphere are debated, particularly because we do not know how strong the sun was at that time. Some facts, however, are not disputed. It is evident that carbon dioxide played a crucial role. In addition, many scientists believe the evolving atmosphere contained sufficient quantities of gases like ammonia and methane to give rise to organic matter.

Still, the problem of the sun remains unresolved. One hypothesis holds that during the Archean era, which lasted from about 4.5 to 2.5 billion years ago, the sun's power was only 75 percent of what it is today. This possibility raises a dilemma: How could life have survived in the relatively cold climate that should accompany a weaker sun? A solution to the faint early sun paradox, as it is called, was offered by Carl Sagan and George Mullen of Cornell University in 1970. The two scientists suggested that methane and ammonia, which are very effective at trapping infrared radiation, were quite abundant. These gases could have created a super-greenhouse effect. The idea was criticized on the basis that such gases were highly reactive and have short lifetimes in the atmosphere.

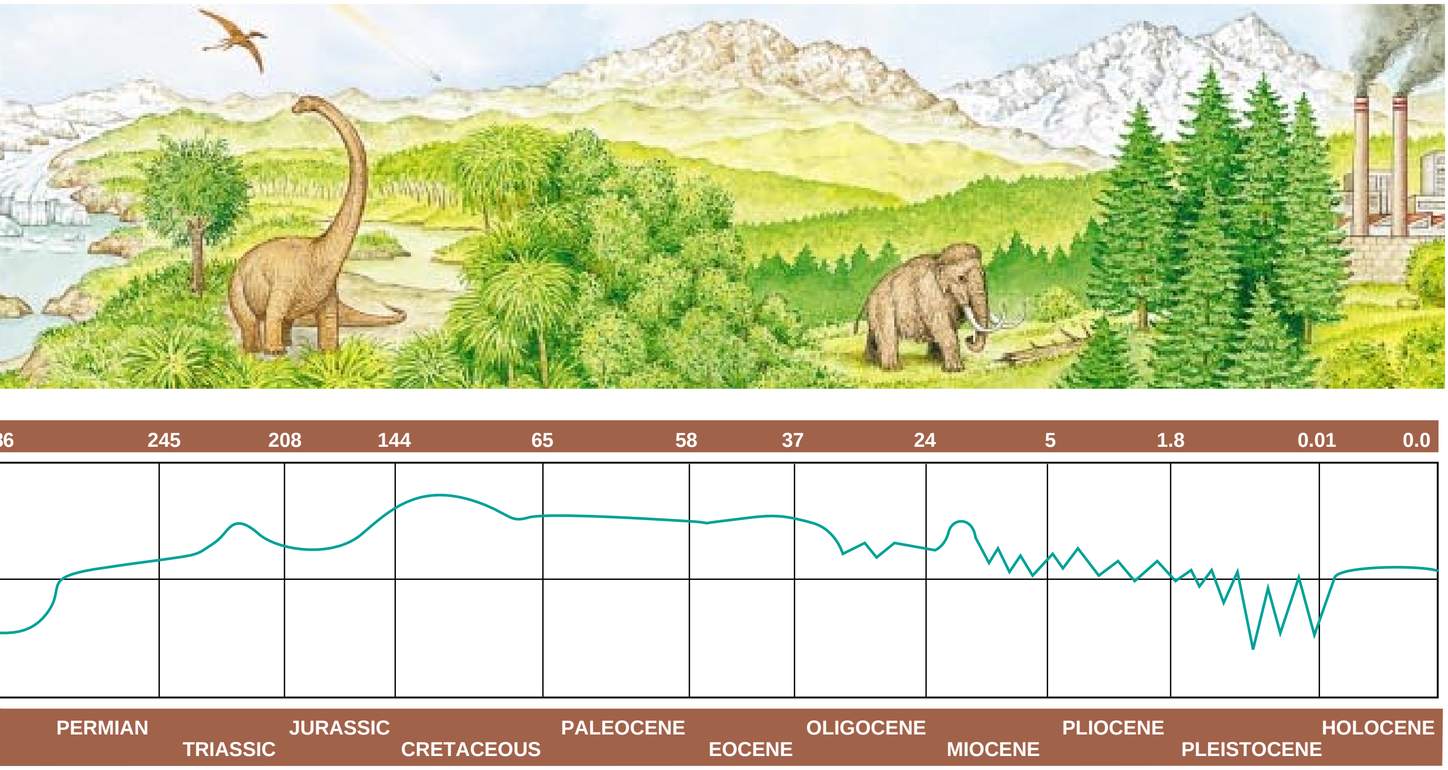
In the late 1970s Veerabhadran Ramanathan, now at the Scripps Institution of Oceanography, and Robert D. Cess and Tobias Owen of the State University of New York at Stony Brook proposed another solution. They postulated that there was no need for methane in the early atmosphere because carbon dioxide was abundant enough to bring about the super-greenhouse effect. Again this argument raised a different question: How much carbon dioxide was there in the early atmosphere? Terrestrial carbon dioxide is now buried in carbonate rocks, such as limestone, although it is not clear when it became trapped there. Today calcium carbonate is created primarily during biological activity; in the Archean period, carbon may have been primarily removed during inorganic reactions.

The rapid outgassing of the planet liberated voluminous quantities of water from the mantle, creating the oceans and the hydrologic cycle. The acids that were probably present in the atmosphere eroded rocks, forming carbonate-rich rocks. The relative importance of such a mechanism is, however, debated. Heinrich D. Holland of Harvard University believes the amount of carbon dioxide in the atmosphere rapidly decreased during the Archean and stayed at a low level.

Understanding the carbon dioxide content of the early atmosphere is pivotal to understanding the mechanisms of climatic control. Two sometimes conflicting camps have put forth ideas on how this process works. The first group holds that global temperatures and carbon dioxide were controlled by inorganic geochemical feedbacks; the second asserts that they were controlled by biological removal.

James C. G. Walker, James F. Kasting and Paul B. Hays, then at the University of Michigan, proposed the inorganic model in 1981. They postulated that levels of the gas were high at the outset of the Archean and did not fall precipitously. The trio suggested that as the climate warmed, more water evaporated, and the hydrologic cycle became more vigorous, increasing precipitation and runoff. The carbon dioxide in the atmosphere mixed with rainwater to create carbonic acid runoff, exposing minerals at the surface to weathering. Silicate minerals combined with carbon that had been in the atmosphere, sequestering it in sedimentary rocks. Less carbon dioxide in the atmosphere meant, in turn, less of a greenhouse effect. The inorganic negative feedback process offset the increase in solar energy.

This solution contrasts with a second paradigm: biological removal. One theory advanced by James E. Lovelock, an



more apparent. First a primordial soup formed, then primitive organisms, such as algae, stromatolites and jellyfish, arose; spiny fish were followed by the ichthyostega, perhaps the first creature to crawl from ocean onto land. The rest of the story is well known: dinosaurs appeared and died out, their place taken by mammals.

originator of the Gaia hypothesis, assumed that photosynthesizing microorganisms, such as phytoplankton, would be very productive in a high–carbon dioxide environment. These creatures slowly removed carbon dioxide from the air and oceans, converting it into calcium carbonate sediments. Critics retorted that phytoplankton had not even evolved for most of the time that the earth has had life. (The Gaia hypothesis holds that life on the earth has the capacity to regulate temperature and the composition of the earth's surface and to keep it comfortable for living organisms.)

More recently, Tyler Volk of New York University and David W. Schwartzman of Howard University proposed another Gaian solution. They noted that bacteria increase carbon dioxide content in soils by breaking down organic matter and by generating humic acids. Both activities accelerate weathering, removing carbon dioxide from the atmosphere. On this point, however, the controversy becomes acute. Some geochemists, including Kasting, now at Pennsylvania State University, and Holland, postulate that while life may account for some carbon dioxide removal after the Archean, inorganic geochemical processes can explain most of the sequestering. These researchers view life as a rather weak climatic stabilizing mechanism for the bulk of geologic time.

The issue of carbon remains critical to the story of how life influenced the atmosphere. Carbon burial is a key to the vital process of building up atmospheric oxygen concentrations—a prerequisite for the development of certain life-forms. In addition, global warming may be taking place now as a result of humans releasing this carbon. For one or two billion years, algae in the oceans produced oxygen. But because this gas is highly reactive and because there were many reduced minerals in the ancient oceans—iron, for example, is easily oxidized— much of the oxygen produced by living creatures simply got used up before it could reach the atmosphere, where it would have encountered gases that would react with it.

Even if evolutionary processes had given rise to more complicated life-forms during this anaerobic era, they would have had no oxygen. Furthermore, unfiltered ultraviolet sunlight would have likely killed them if they left the ocean. Researchers such as Walker and Preston Cloud, then at the University of California at Santa Barbara, have suggested that only about two billion years ago, after most of the reduced minerals in the sea were oxidized, did atmospheric oxygen accumulate. Between one and two billion years ago oxygen reached current levels, creating a niche for evolving life.

By examining the stability of certain minerals, such as iron oxide or uranium oxide, Holland has shown that the oxygen content of the Archean atmosphere was low, before two billion years ago. It is largely agreed that the present-day oxygen content of 20 percent is the result of photosynthetic activity. Still, the question is whether the oxygen content in the atmosphere increased gradually over time or suddenly. Recent studies indicate that the increase of oxygen started abruptly between 2.1 and 2.03 billion years ago, and the present situation was reached 1.5 billion years ago.

The presence of oxygen in the atmosphere had another major benefit for an organism trying to live at or above the surface: it filtered ultraviolet radiation. Ultraviolet radiation breaks down many molecules—from DNA and oxygen to the chlorofluorocarbons that are implicated in stratospheric ozone depletion. Such energy splits oxygen into the highly unstable atomic form O, which can combine back into O_2 and into the very special molecule O_3, or ozone. Ozone, in turn, absorbs ultraviolet radiation. It was not until oxygen was abundant enough in the atmosphere to allow the formation of ozone that life even had a chance to get a root-hold or a foothold on land. It is not a coincidence that the rapid evolution of life from prokaryotes (single-celled organisms with no nucleus) to eukaryotes (single-celled organisms with a nucleus) to metazoa (multicelled organisms) took place in the billion-year-long era of oxygen and ozone.

Although the atmosphere was reaching a fairly stable level of oxygen during this period, the climate was hardly uniform. There were long stages of relative warmth or coolness during the transition to modern geologic time. The composition of fossil plankton shells that lived near the ocean floor provides a measure of bottom water temperatures. The record suggests that over the past 100 million years bottom waters cooled by nearly 15 degrees Celsius. Sea levels dropped by hundreds of meters, and continents drifted apart. Inland seas mostly disappeared, and the climate cooled an average of 10 to 15 degrees C. Roughly 20 million years ago permanent ice appears to have built up on Antarctica.

About two to three million years ago the paleoclimatic record starts to show significant expansions and contractions of warm and cold periods on 40,000-year or so cycles. This periodicity is interesting because it corresponds to the time it takes the earth to complete an oscillation of the tilt of its axis of rotation. It has long been speculated, and recently calculated, that known changes in orbital geometry could alter the amount of sunlight coming in between winter and summer by about 10 percent or so and could be responsible for initiating or ending ice ages.

Most interesting and perplexing is the discovery that between 600,000 and 800,000 years ago the dominant cycle switched from 40,000-year periods to 100,000-year intervals with very large fluctuations. The last major phase of glaciation ended about 10,000 years ago. At its height 20,000 years ago, ice sheets a mile thick covered much of northern Europe and North America. Glaciers expanded in high plateaus and mountains throughout the world. Enough ice was locked up on land to cause sea levels to drop more than 100 meters below where they are today. Massive ice sheets scoured the land and revamped the ecological face of the earth, which was five degrees C cooler on average than it is currently.

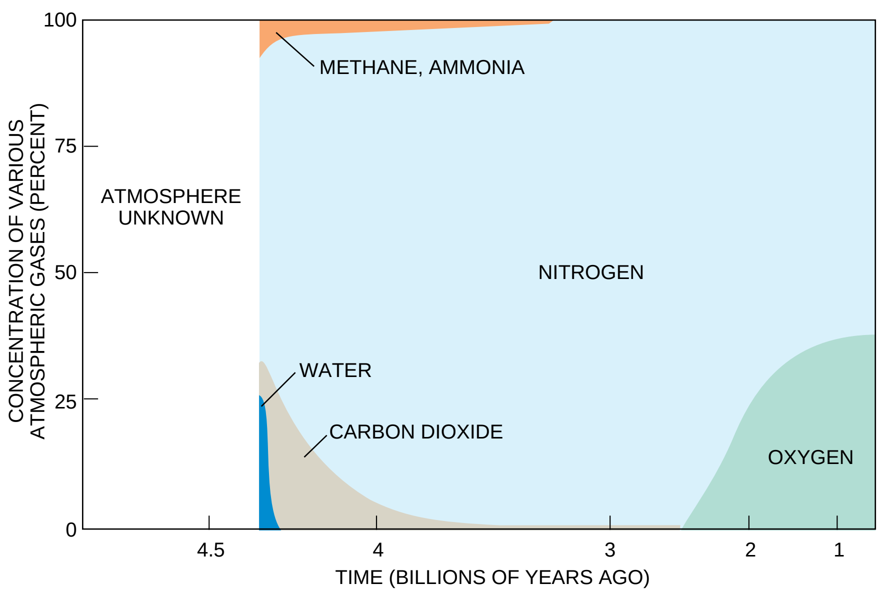
The precise causes of these changes are not yet sorted out. Volcanic eruptions may have played a significant role as shown by the effect of El Chichón in Mexico and Mount Pinatubo in the Philippines. Tectonic events, such as the development of the Himalayas, may influence world climate. Even the impact of comets can influence short-term climatic trends with catastrophic consequences for life [see "What Caused the Mass Extinction? An Extraterrestrial Impact," by Walter Alvarez and Frank Asaro; and "What Caused the Mass Extinction? A Volcanic Eruption," by Vincent E. Courtillot; SCIENTIFIC AMERICAN, October 1990]. It is remarkable that despite violent, episodic perturbations, the climate has been buffered enough to sustain life for 3.5 billion years.

One of the most pivotal climatic discoveries of the past 20 years has come from ice cores in Greenland and Antarctica. When snow falls on these frozen continents, the air between the snow grains is trapped as bubbles. The snow is gradually compressed into ice, along with its captured gases. Some of these records can go back as far as 200,000 years; scientists can analyze the chemical content of ice and bubbles from sections of ice that lie as deep as 2,000 meters below the surface.

The ice-core borers have determined that the air breathed by ancient Egyptians and Anasazi Indians was very similar to that which we inhale today—except for a host of air pollutants introduced over the past 100 or 200 years. Principal among these added gases, or pollutants, are extra carbon dioxide and methane. The former has increased 25 percent as a result of industrialization and deforestation; the latter has doubled because of agriculture, land use and energy production. The concern that increased amounts of these gases might trap enough heat to cause global warming is at the heart of the climate debate [see "The Changing Climate," by Stephen H. Schneider; SCIENTIFIC AMERICAN, September 1989].

The ice cores have shown that sustained natural rates of worldwide temperature change are typically about one degree C per millennium. These shifts are still significant enough to have radically altered where species live and to have potentially contributed to the extinction of such charismatic megafauna as mammoths and saber-toothed tigers. But a most extraordinary story from the ice cores is not the relative stability of the climate during the past 10,000 years. It appears that during the height of the last ice age 20,000 years ago there was between 30 and 40 percent less carbon dioxide and 50 percent less methane in the air than there has been during our period, the Holocene. This finding suggests a positive feedback between carbon dioxide, methane and climatic change.

The reasoning that supports the idea of this destabilizing feedback system goes as follows. When the world was colder, there was less concentration of greenhouse gases, and so less heat was trapped. As the earth warmed up, carbon dioxide and methane levels increased, accelerating the warming. If

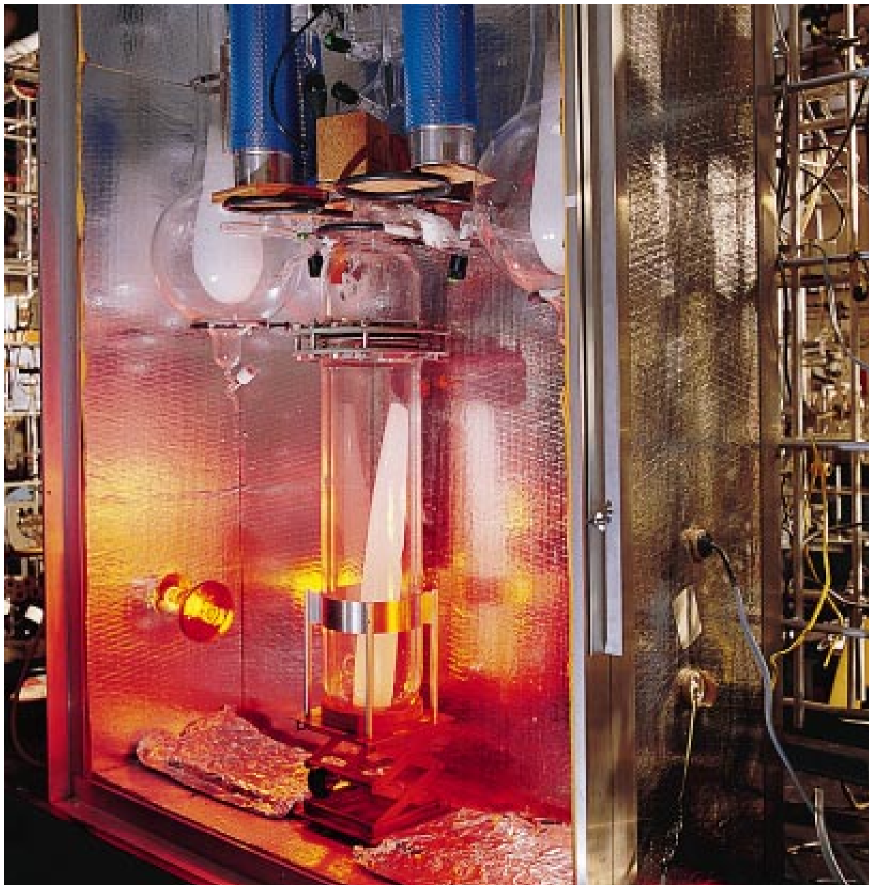


ATMOSPHERIC COMPOSITION, shown by the relative concentration of various gases, has been greatly influenced by life on the earth. The early atmosphere had fairly high concentrations of water and carbon dioxide and, some experts believe, methane, ammonia and nitrogen. After the emergence of living organisms, the oxygen that is so vital to our survival became more plentiful. Today carbon dioxide, methane and water exist only in trace amounts in the atmosphere.

life had a hand in this story, it would have been to drive, rather than to oppose, climatic change. Once again, though, this picture is incomplete.

Nevertheless, most scientists would agree that life could well be the principal factor in the positive feedback between climatic change and greenhouse gases. One hypothesis suggests that increased nutrient runoff from the continental shelves that were exposed as sea levels fell fertilized phytoplankton. This nutrient input could have created a larger biomass of such marine species. Because the calcium carbonate shell makes up most of the mass of many phytoplankton species, increased productivity would remove carbon dioxide from the oceans and eventually the atmosphere. At the same time, boreal forests that account for about 10 to 20 percent of the carbon in the atmosphere were decimated during the ice ages. Carbon from these high-latitude forests could have been released to the atmosphere, yet the atmosphere had less of this gas then. Thus, the positive feedback system of the ocean's biological pump may have offset the negative feedback caused by the destruction of the forests. Great amounts of carbon can be stored in soils, however, so the demise of forests may have led to the sequestering of carbon in the ground.

What is significant is the idea that the feedback was positive. By studying the transition from the high-carbon dioxide, low-oxygen atmosphere of the Archean to the era of great evolutionary progress about a half a billion years ago, it becomes clear that life may have been a factor in the stabilization of climate. In another example—during the ice ages and interglacial cycles—life seems to have the opposite function: accelerating the change rather than diminishing it. This observation has led one of us (Schneider) to contend that climate and life coevolved rather than life serving solely as a negative feedback on climate.



ICE CORES from Greenland or Antarctica have provided scientists with a swatch cut from the earth's atmospheric history. As snow is compressed into ice, air bubbles trapped between the flakes are preserved. By analyzing the gases in these tiny chambers, researchers can determine the composition of the atmosphere up to almost 200,000 years ago.

If we humans consider ourselves part of life—that is, part of the natural system—then it could be argued that our collective impact on the earth means we may have a significant coevolutionary role in the future of the planet. The current trends of population growth, the demands for increased standards of living and the use of technology and organizations to attain these growth-oriented goals all contribute to pollution. When the price of polluting is low and the atmosphere is used as a free sewer, carbon dioxide, methane, chlorofluorocarbons, nitrous oxides, sulfur oxides and other toxics can build up.

The theory of heat trapping—codified in mathematical models of the climate—suggests that if carbon dioxide levels double sometime in the middle of the next century, the world will warm between one and five degrees C. The mild end of that range entails warming at the rate of one degree per 100 years—a factor of 10 faster than the one degree per 1,000 years that has historically been the average rate of natural change on a global scale. Should the higher end of the range occur, then we could see rates of climatic change 50 times faster than natural average conditions. Change at this rate would almost certainly force many species to attempt to move their ranges, just as they did from the ice age–interglacial transition between 10,000 and 15,000 years ago. Not only would species have to respond to climatic change at rates 10 to 50 times faster, but few would have undisturbed, open migration routes as they did at the end of the ice age and the onset of the interglacial era. It is for these reasons that it is essential to understand whether doubling carbon dioxide will warm the earth by one degree or five.

To make the critical projections of future climatic change needed to understand the fate of ecosystems on this earth, we must dig through land, sea and ice to uncover as much of the geologic, paleoclimatic and paleoecological records as we can. These records provide the backdrop against which to calibrate the crude instruments we must use to peer into a shadowy environmental future, a future increasingly influenced by us.

FURTHER READING

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