Early Life Thrived Despite Earthly Travails

Life learned resilience in a school of hard knocks, where rocks rained down from the sky, the climate control was precarious, and oxygen was either too scarce or too abundant—and that was just the first 2 billion years

Earth's youth is its most mysterious epoch, only dimly registered in a geologic record largely erased by billions of years of plate tectonics and erosion. Yet the first 2 billion years of our planet's history saw the first stirrings of life, when systems of molecules began reproducing themselves and deriving energy from chemicals and from sunlight. Because fossils from those early eons are rare and frustratingly cryptic, many researchers trying to understand the origins of life are turning to geology, hoping to learn the state of the planet's surface and atmosphere when it first hosted living things.

This approach to understanding life's early days joins clever techniques to wrest more direct information about life from long-dead rocks (see sidebar on p. 2111) and laboratory efforts to explore the likely chemistry of early life or infer its genetic nature from the genes of living creatures. But the geologic approach is adding unique plot elements to the story of early life: a series of hair-raising escapes.

For its first half-billion years, Earth endured a punishing rain of impacts, which vaporized the oceans and scorched the globe so fiercely that some researchers now propose that life could have first evolved on a more hospitable world, then later hitchhiked to Earth on a meteorite. After the heavy bombardment stopped came a new trial: The young sun was faint and relatively cold, leaving Earth perennially teetering on the edge of a planet-enveloping ice age. And as that threat began to lift, oxygen—for eons little more than a nuisance waste product—suddenly flooded the atmosphere, threatening the anoxic life of the time but also perhaps sending the planet into the threatened deep freeze.

Obviously, life survived all these trials—and emerged with resilience as its prime characteristic, says paleontologist J. William Schopf of the University of California, Los Angeles. "Environment and life go hand in hand," he says. The imprint of those cataclysms remains in the hardy survivors from early times, such as blue-green algae, and indeed in the genes of all life, as the ancestor of every organism on Earth passed through these trials. "Life is persistent," concludes paleontologist Andrew Knoll of Harvard University. "It can absorb a range of shocks from the environment."

Heavy bombardment

In the beginning, from 4.5 billion to 3.8 billion years ago, rock bodies left over from solar system formation, called planetesimals, were still battering Earth and the other planets. At least one of these impactors was gigantic; the size of Mars or larger, it struck Earth within about a hundred million years after the planet began forming and dislodged a mass of material that became the moon. Soon thereafter, water from Earth's own rock and impacting comets collected to form a planetwide ocean, providing a cradle for life.

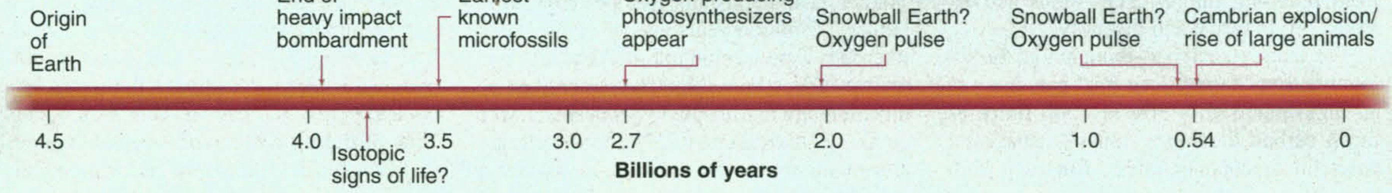
But the pummeling wasn't over, as the 1000-kilometer-wide impact basins still visible on the moon as its dark "seas" testify. Earth, being a bigger target with a stronger gravitational pull, would have suffered blows from hundreds of objects of that size between 4.0 billion and 3.8 billion years ago, geophysicist Norman Sleep of Stanford University and planetary physicist Kevin Zahnle of NASA's Ames Research Center in Mountain View, California, noted in the *Journal of Geophysical Research* last year. A few of these impactors were probably 500 kilometers in diameter—big enough to create a superheated atmosphere of vaporized rock that would in turn have vaporized the oceans for 2700 years and sterilized even the subsurface, say Sleep and Zahnle.

Yet despite this brutal environment, the very first, simple organisms emerged at most only a few hundred million years after the bombardment stopped. The first recognizable fossils appear at 3.5 billion years ago, and there are controversial isotopic traces of life as far back as 3.7 billion or 3.8 billion years ago (see timeline). Indeed, life might have arisen even earlier, during the millions of years between sterilizing impacts—only to be wiped out by the next big one, say planetary physicists Kevin Maher and David Stevenson of the California Institute of Technology in Pasadena, who call this the "impact frustration" of life.

Even after the large, sterilizing impacts ended, smaller impacts continued until about 3.8 billion years ago, say Sleep and Zahnle, so any survivors were probably adapted to living deep in the crust where temperatures are high. That may explain why the genes of living microbes suggest that the ancestor of all life had much in common with today's hyperthermophiles, microbes that thrive in hot springs at temperatures of 113°C or more.

To Sleep and Zahnle, the severity of the bombardment coupled with the early appearance of microbes suggests another possibility: that Earth was seeded with life from elsewhere, namely Mars. Calculations have shown that rocks blasted off Mars by large impacts might have fallen to Earth quickly enough to deliver martian microbes, perhaps as rock-encased spores, before they succumbed to the rigors of space.

And Sleep and Zahnle say that in those days, Mars had the more benign environment. It is a smaller target than Earth, and its weaker gravity would pull in fewer planetesimals, so big, potentially sterilizing impacts were less frequent there. Mars probably had no oceans, or only small and shallow ones, so the

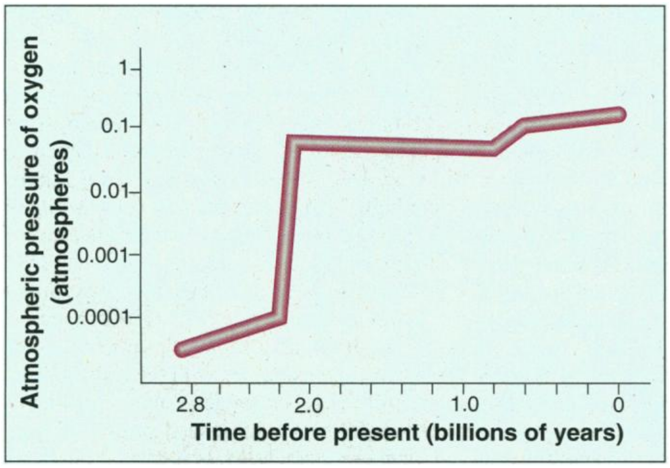


Troubled youth. Life evolved during the early Earth's extremes.

CREDITS: (LEFT TO RIGHT) VISUALS UNLIMITED; SCHOPF, *SCIENCE* 260, 640 (1993); T. E. ADAMS/VISUALS UNLIMITED; JEANNETTE THOMAS/VISUALS UNLIMITED; MARK SCHNEIDER steam from a 500-kilometer impactor would have condensed out within a mere decade, giving subsurface life a fighting chance of survival. And Mars's interior was cooler, say geophysicists, allowing microbes to penetrate further into the planet, away from the searing surface. "It's possible Mars would have been more suitable for life," agrees Stevenson.

The snowball threat

Even as blasts of heat were weeding out cold-adapted microbes, early life faced another threat: a long-term deep freeze. When Earth formed 4.5 billion years ago, astrophysicists believe, the young sun provided 30% less warmth than it does today. All else being equal, Earth and all its oceans should have been frozen over from pole to pole until the sun had brightened significantly, about 2 billion years ago, says planetary climatologist James Kasting of Pennsylvania State University (PSU) in University Park.



Gassing up. The first leap in oxygen levels was a toxic challenge to life and may have shattered a life-sustaining greenhouse.

Yet the record shows that this chilly fate didn't befall Earth—or at least not for very long. Not only are there clear signs of life at 3.5 billion years ago, there are signs of running water and erosion, too. And traces of photosynthesis—a telltale pattern of isotopes—found in marine rocks from about 2.7 billion years ago make it seem unlikely that the oceans were constantly frozen over, says Knoll. The first fossil of a eukaryote—the term for organisms, from yeast to humans, that have a cell nucleus—appears in the form of the alga *Grypania* at about 2.2 billion years ago, when the ice would have been breaking up. So what kept the world from plunging into a deep freeze and allowed life to thrive and diversify?

For years, researchers thought that the solution to this "faint young sun" paradox was an atmosphere with 300 to 1000 times as much carbon dioxide as today's, creating a powerful greenhouse effect. But such high levels of the gas would have combined with iron in the soil to leave iron carbonate in ancient rock, which has not been found. The late Carl Sagan and cosmochemist Christopher Chyba of the SETI Institute in Mountain View suggested that high levels of atmospheric ammonia could have shored up the early greenhouse (*Science*, 23 May 1997, p. 1217). But that idea has problems too, because the sunlight-sensitive ammonia would have required a methane haze for protection. Yet that haze would ultimately have reflected light back to space and cooled Earth as much as the ammonia greenhouse could warm it, as cosmochemist Christopher McKay of Ames reported in *Icarus* early this year.

Now Kasting is offering another solution: a methane greenhouse spawned by life itself. Methane is a powerful greenhouse gas, and at July's International Conference on the Origin of Life in San Diego, Kasting will argue that methane produced by ancient methanogenic bacteria—the ancestors of organisms now responsible for the methane oozing from swamps, river bottoms, and landfills—could have reached levels 1000 times higher than today's.

The key to such high methane levels is a lack of free atmospheric oxygen, says Kasting. A molecule of methane wafting into today's atmosphere of 20% oxygen lasts about 12 years, on average, before being oxidized to carbon dioxide. But Kasting believes oxygen was nearly absent 2.8 billion years ago, so that a methane molecule could have survived 20,000 years, according to calculations he did with Lisa Brown of PSU. Combine that with a bit of carbon dioxide, which would prevent a cooling methane haze from forming, and the paradox could be resolved: By exuding a methane blanket, life itself could have warmed the potentially frigid world to within a few degrees of its current temperature.

McKay thinks the idea is plausible, although he says more lab work on the atmospheric chemistry of methane is needed. Studies of minerals and isotope ratios from before 2.2 billion years ago do suggest that microbes were turning out methane and free oxygen was scarce. Most researchers agree that although marine photosynthesizers were cranking out oxygen by 2.7 billion years ago, almost all of it was used up in oxidizing things like the copious iron dissolved in the ocean and emissions from volcanoes, and little made it to the atmosphere.

Still, the existing geologic data put the upper limit on atmospheric oxygen at around 0.1%—and Kasting's scenario requires virtually no oxygen in the atmosphere, notes geologist Roger Buick of the University of Sydney in Australia. Kasting recognizes the problem. "The story I'm telling is self-consistent," he says. "It's just hard to prove."

If methanogens did warm the world, other microbes may have inadvertently cooled it, by pumping out oxygen. At about 2.2 billion years ago, just as the sun was strengthening and eukaryotes appeared, oxygen levels apparently jumped in what Buick calls "one of the biggest environmental changes of Earth history." Isotopic and mineralogi-

SOURCE: AFTER RYE AND HOLLAND, AM. J. OF SCIENCE

Going Beyond Appearances to Find Life's History

You wouldn't think of watching a 3D movie without the proper goggles, but that's the situation of paleontologists trying to view the early history of life on Earth from the small, flattened blobs of rock that are all that's left of the earliest organisms. Researchers have been missing an entire dimension of information hidden in these fossils: the chemical traces of life, left behind billions of years ago as organisms took in nutrients and built cellular structures. Now, with an array of high-tech instruments and an influx of funding from NASA—which seeks new ways to track possible life-forms on other worlds—researchers are starting to read these faint chemical signatures.

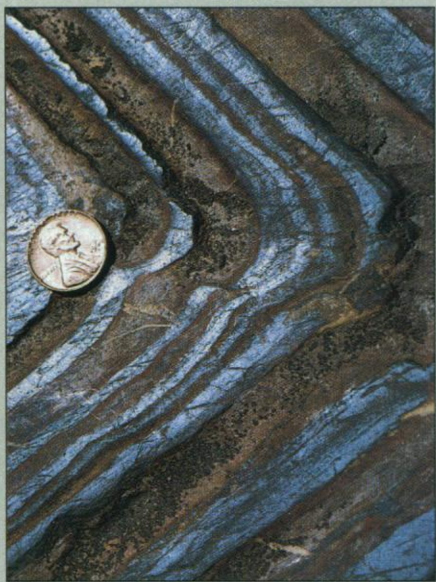
Isotopic and chemical methods are uncovering billion-year-old traces of cellular and even molecular structure, even in rocks where no visible fossils remain. "This is a fundamentally different way of looking at the evolution of life," says paleobiologist J. William Schopf of the University of California, Los Angeles. "There are a number of us who have been looking for tools for 20 years to sort out the biochemistry and physiology and metabolism of ancient life. Now the technology has finally come along that allows us to get at these questions."

The earliest fossils themselves are few and far between. The most ancient are 3.5 billion years old, but the cells are arrayed in long filaments, mats, and other complex clusters—implying a long history of even earlier evolution that is missing from the record. And determining what kind of organism is preserved in a microfossil by looks alone is difficult at best. Inorganic activities can leave little round blebs behind too—hence many researchers' skepticism about putative martian fossils (*Science*, 20 November 1998, p. 1398). "All [researchers] have is the morphology to look at," says geochemist Clark Johnson of the University of Wisconsin, Madison. "Everyone thinks [microfossils] are prokaryotes [when] they're little. When they get bigger they think, 'Well, they must be eukaryotes.' "

So researchers are striving to put the science of tracking life on a more sophisticated footing. Whereas some scientists try to infer life's history by reconstructing the environment on early Earth (see main text), others are trying to glean more detail from the fossils themselves. NASA's $24 million astrobiology program, which funds this and other work, began only last year, but it is building on some promising results from earlier studies.

To find the signature of life itself, some methods exploit the fact that living organisms tend to preferentially take up lighter isotopes of various elements. So, for example, former cells leave traces of carbon that have unusually high amounts of carbon-12 compared to the heavier isotope carbon-13. Researchers have found such isotopic anomalies in some of the earliest known sedimentary rocks—so-called banded iron formations from Greenland, which are older than 3.7 billion years (*Science*, 29 January, p. 674). But this kind of evidence doesn't convince everyone. "We would like to believe that those low [carbon isotope] ratios are indicative of life," says Johnson. "But there are no fossils to prove it," and heating, high pressure, and weathering can produce similar isotope signatures.

Isotopes of other elements might be more persuasive. Organisms also preferentially take up light isotopes of iron, for example, and this element is heavy enough that its isotope ratio is not thought to be affected by most geologic processes. Johnson and his colleagues Brian Beard and Kenneth Nealson of NASA's Jet Propulsion Laboratory in Pasadena, California, have found that iron in the purported bacterial layers of banded iron formations has relatively less of the heavy isotope iron-56 than other rocks (*Science*, 4 December 1998, p. 1807).



Layer cake of life? Light layers in banded iron formations like this one have the isotopic signatures of life.

Other techniques promise to reveal what kind of life-form created a particular microfossil. For example, geochemist Roger Summons of the Australian Geological Survey Organization in Canberra noted that bacteria and eukaryotes—complex cells with nuclei, like those in our bodies—differ in much more than size. Bacterial cell membranes include hopanoids, large organic molecules with a five-ring carbon backbone, whereas eukaryotes produce sterols—similar molecules with a four-ring backbone. Billions of years of heat and pressure transform the cell's remains into insoluble organic matter—but, amazingly, the telltale backbones of the rings can remain intact and can be detected.

Summons and colleagues analyzed the hydrocarbon content of 2.5-billion-year-old black shale from Western Australia. At a recent meeting on ancient fossils,* he reported finding molecules characteristic of both bacteria and eukaryotes—300 million years before the first suspected eukaryotic fossils. "It's very, very nice work, and very difficult work," says Schopf. "Now we've got to find [biomarkers] of intermediate age to show that this is part of an evolutionary continuum."

Studies using a variety of other clever methods are in the pipeline. Schopf is using ion probes to measure the isotope ratios in individual microfossils and learn about their metabolism; other researchers are tracking the evolution of biological polymers with nuclear magnetic resonance spectroscopy, which can identify telltale carbon-nitrogen and carbon-carbon bonds. And Nealson and colleagues are blasting synchrotron radiation at rocks between 2.5 billion and 3.2 billion years old. The brilliant x-rays could reveal the remains of bacteria inside iron or manganese oxide deposits; and because they cause different molecules to fluoresce in predictable ways, they could also reveal chemical composition.

The new techniques will have their pitfalls and may take some years to perfect, cautions Schopf. "We're crawling along now," he says. "But at least we're moving forward."

–GRETCHEN VOGEL

* Bridging Two Worlds: From the Archean to the Proterozoic, University of California, Los Angeles, 18 to 20 February.

cal data have suggested that atmospheric oxygen rose to perhaps 10% to 15% of the present-day level, and the most recent data suggest that the change was abrupt, from 1.8 billion to 2.2 billion years ago (*Science*, 5 March, p. 1519). Somehow, the oxygen being turned out by photosynthesizers finally gained the upper hand, perhaps because volcanoes had slowed their emission of compounds that react with oxygen. "It's looking suspiciously like [the oxygen spike] might be real," says Buick.

Such an oxygen jump would have driven some major changes, forcing anoxic organisms to adapt, perish, or hide out in the oxygen-poor mud on the sea floor and lake beds, where they remain today. Even worse, if Kasting's scenario is right, oxygen would have destroyed the methane and collapsed the greenhouse. "You can imagine that would trigger [Earth becoming] a big snowball," says Kasting.

A snowball Earth is a startling idea, but that's just what paleomagnetist David Evans of the University of Western Australia in Perth and his colleagues suggested in 1997. They found 2.2-billion-year-old glacial sediments in South Africa that apparently formed when the site lay near the equator and close to sea level, and they concluded that glaciers penetrated deep into the tropics just when oxygen appears to have shot up. If ice were in the tropics, they reasoned, it probably covered the rest of the planet, including a thick layer on all the oceans.

Most researchers aren't quite ready to accept this scenario. But evidence reported last year strengthened the case for another global deep-freeze, 600 million years ago, when oxygen was rising again and multicellular animals may have been appearing (*Science*, 28 August 1998, p. 1259). The more recent cold snap, perhaps triggered by waning atmospheric carbon dioxide levels, lends a touch more credibility to the older one.

Such a global freeze would mean hard times for Earth's microbes—but not extermination. Photosynthesizers, for example, could have gotten by with the low levels of light trickling down through thin spots or cracks in the ice. However it managed, life not only survived but thrived after the snowballs, just as it had dodged impacts, suffocation, and oxygen poisoning. From its beginnings, it seems, life has been honed by crisis.

–RICHARD A. KERR

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