

What exactly happened on earth that led to the beginning of life? Dr. Stephen Mojzsis analyses the chemical and biological environment of the early earth.

Life in the First Billion Years

by

Stephen J. Mojzsis



Dr. Stephen Mojzsis is a professor in the Department of Geological Sciences, Center for Astrobiology, at the University of Colorado in Boulder Colorado. Dr. Mojzsis' research interests include stable and radiogenic isotope geology, Archean biology and studies of Martian meteorites. He may be contacted at mojzsis@colorado.edu.

Imagine standing on the surface of the Moon looking up at the Earth hanging in the lunar sky. Now imagine that the time is about four billion years ago during the Archean Eon of Earth history. What would you see? The globe of the brightly shining Earth fills your field of vision, but it is a different world from the one we know so well. The seas washing over its shores are a deep green color and the sky has a reddish cast with nary a whiff of free oxygen. No large continents cover the surface as they do today, but hundreds of large island chains dot the planet interspersed with the crumbling remains of eroded craters. The young Earth was the stage whereupon the emergence of life was played ...

The search for evidence of early life on Earth is complicated by the fact that our planet is constantly undergoing geological upheaval. Through plate tectonics, surface rocks become subterranean rocks and vice versa. In general, the older the rock unit, the more time it has spent in the Earth's crust. Although the most ancient rocks have survived this slow churning, they tend to be severely altered from their original state because of geological transformations. Figuring out the age and origin of the oldest rocks is difficult and trying to find evidence of early life in a complicated and ancient rock record is even more of a challenge. Yet, despite this, progress is being made by geologists to unravel the mysteries of the early Earth. For instance, studies of some of the oldest known rocks known demonstrate they were deposited in ancient seas several billion years ago. Some rocks from southern West Greenland seem to preserve a record of early life in the form of "chemical fossils" as opposed to preserved shapes like a bone or footprint. When these ancient Greenland rocks formed, the life that was around became trapped inside the accumulating sedimentary layers. Judging from just how old these rocks are and the signs of life they contain, a surprising conclusion can now be drawn: The first life appeared on Earth at around the same time as the events in space that shaped the mottled face of the Moon almost four billion years ago.

These new discoveries are beginning to help us paint a self-consistent picture of early life emerging in "extreme" environments of heat and pressure on the early Earth. Geolo-

gists are now beginning to use the tools of molecular biology to peer into the ancestry of bacteria and their ilk. We are now in hot pursuit of the "last common ancestor of all life". What was it? When did it arise? Today many of the most "primitive" microbes currently live at the very edge of what we consider "habitable." New ways of knowing how the emergence of life on Earth came to be will eventually become applicable to other planets when samples are returned for study early in the 21st century. The challenge we will have to face in the search for extraterrestrial life will be: What shall we look for in those precious samples collected from far off planets? The oldest rocks on Earth hold the key.

The Chemical Criteria for Life

It is pretty obvious that life appeared on Earth at some time in the past, but when, how and where? Life that we know of is primarily made up of the common elements sulfur, phosphorus, oxygen, nitrogen, carbon and hydrogen, collectively known as "SPONCH." These elements are combined together into complex biomolecules that make up a cell. All known life requires liquid water. We think that a covering of liquid water such as seas or oceans, stable over the billion-year timescale, is critical for the origin, evolution and propagation of life on any planet. With that, it makes sense that the best sources of information to understand the habitats for early biological organisms are sediments deposited in watery environments like the ocean. Marine sedimentary rocks are readily recognizable in the ancient geologic record. Extremely ancient water-sculpted terranes, more than

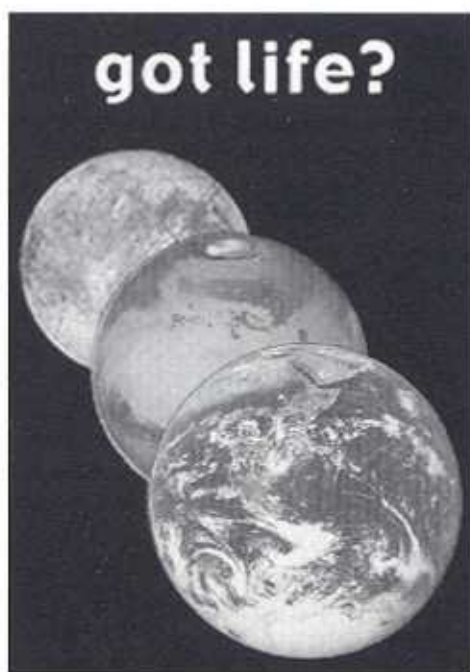


Photo courtesy of Centre for Astrobiology, University of Colorado. See argyre.colorado.edu/life.

3.8 billion-years-old, have been identified from space missions to Mars, and the water there seems to be locked up in permafrost. Liquid water appears to exist beneath the icy crusts of moons Europa and Callisto in the cold regions of the outer solar system, heated by the tidal interaction with Jupiter. The hypothesis is (1) that once liquid water becomes stabilized on (or within) a planet, and (2) energy resources in the form of light, heat and chemical energy are available along with (3) abundant organic building blocks, life has the potential to appear on a world. It has long been understood, however, that variations in the chemistry of the bio-essential "SPONCH" elements cited above that can be created by different kinds of metabolism. These chemical variations are potentially preserved in ancient sediments even into the oldest rocks of all and can be measured by sensitive laboratory instruments such as mass spectrometers. This tactic permits new insights into the development of early life inferred from chemical studies rather than solely on interpretation of microfossil shapes that can deceive the eye.

Marine sedimentary rocks nearly 4 billion years old have now been identified on the Earth. These rocks offer us a remarkable opportunity to investigate possible environments from which life arose here on our planet as a test case in the search for life in the cosmos. Nothing comes easy, however. What complicates this opportunity is that the oldest rocks all have a long history of transformation by temperature and pressure. They have been recrystallized under high-grade geological processes termed "metamorphism." Because of this metamorphic process, the most ancient sediments (unlike their much younger equivalents) could not have preserved recognizable and interpretable fossil shapes.

The Early Earth-surface State

Based on various lines of evidence, it appears certain that the Early Earth was governed by different oceanic and atmospheric conditions than what exist today. The internal heat of the young planet was greater in the past; Earth has been slowly cooling through time. Volcanism releases hot, acidic gases into the environment and this would have been pronounced on the hot early Earth. Nowadays, seawater is very low in metallic elements (Iron, Copper, Zinc, etc.) and has a pH that is slightly alkaline (pH = 8.2). Seawater on the early Earth was likely more acidic (lower pH) and richer in metallic elements, such as dissolved iron (as $[\text{Fe}^{2+}]_{aq}$). The oceans would have had a deep olive green color rather than the blue of today. The atmosphere would have been a thick unbreathable mixture of water vapor, carbon dioxide, nitrogen, carbon monoxide and sulfur gases. Such a dense, oxygen-poor sky would have appeared more reddish than the



In the early earth the sea was green and the sky was red.

pale blue we are familiar with.

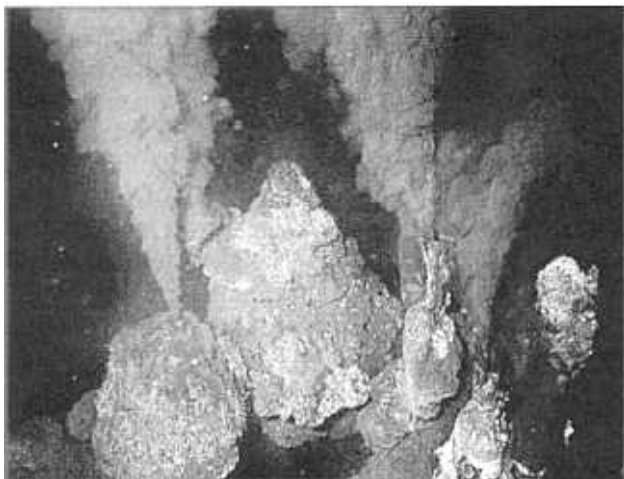
Several key environmental factors were unique to the early Archean Earth. Among the most important of these is a higher deep ultraviolet radiation flux from the Sun that was about 30% dimmer than today. Also, based on the ages of giant craters on the Moon, we think that rates of impact from asteroids and comets were many times greater. Some of the largest impacts were frequent enough to have caused significant disruptions to the global biosphere and may have brought all life to the brink of extinction. These impact conditions would in all probability have restricted the number of continuously habitable environments to a few refuges deep in the oceans. Age estimates of some of the oldest Greenland rocks ap-



The cratered face of the moon that we see today was shaped by ancient impacts. The early earth likely underwent bombardment.

pear to overlap in time with the bombardment epoch as recorded on the Moon. The catastrophic thermal and shock effects associated with the Late Heavy Bombardment epoch were long presumed to have rendered Earth unsuitable for the emergence of life

until after the massive bombardments ceased. This of course was before we learned just how tenacious the microbial biosphere can be. There are certain strains of microbial life that survive (and even thrive) in extremes of temperature, pressure and acidity/alkalinity in watery environments at the bottom of the ocean or in hot springs. Indeed, it may be that global environment conditions during the bombardment epoch favored the survival of primitive ancestors to bacteria. The bacterial castaways of the Late Heavy Bombardment lived through the tumult to later diversify into wider ecological niches throughout the planet.



Deep-sea hydrothermal vents may have been the abode for the first life forms. Even today anaerobic bacteria derive their energy from the highly acidic environment of these vents on the ocean floor.

Biological studies aimed at linking the genetic history of different organisms take advantage of the highly conserved genetic (ribosomal RNA) sequences contained in every cell. Such genetic markers as RNA evolve only very slowly over many millions of years and reveal that the deepest branches of life derive from “heat-loving,” or thermophilic, bacteria that live in hot spring environments and other extreme ecological niches. Extreme microbial organisms such as these could have survived the worst thermal assaults from giant impacts. This is especially true if the oldest life was sequestered deep in the oceans or in rocks away from a destructive surface zone bathed both in the intense ultraviolet radiation of the early Sun and a rain of extraterrestrial debris in the early Archean Eon. The only way to better understand this time period is to investigate the heavily modified rock record that stretches back to the beginning.

Early Archean History of West Greenland

“Itsaq” is a Greenlandic term meaning “from olden times” and indeed the diverse rock types, including sediments, present in Itsaq Complex of West Greenland are ancient, some stretching back to ~3.9 billion



The oldest rocks on Earth are locked up in the highly altered terrane of West Greenland.

years. The oldest rocks are all locked within extensive early Archean granites that have been severely modified by metamorphism. Careful work over the years on the “Itsaq” has identified rocks that originally formed in water providing proof for a marine system soon after the end of the bombardment epoch. Although the exact depositional setting is poorly understood, the lack of sandstones and other rocks typically derived from eroding continents would seem to indicate that there was little in the way of dry land. These rocks formed in marine basins between island chains, much like what we see happening in the Western Pacific today.

The oldest known rock with evidence of biological processes active during time of deposition is a continuous ~3 meter thick layer of highly altered sedimentary rocks interleaved with volcanic rocks



Akilia Island, southern West Greenland is a repository for ancient life.

on the southern tip of Akilia island, West Greenland. Rock associations such as these are actually found throughout the Itsaq Gneiss Complex and this is but one of the best studied ones.

Late Bombardment of the Moon and Earth

The pock-marked surface of the Moon displays its own clear evidence of an intense bombardment by asteroids and comets that took place at some time between original crust formation and the outpourings of lava that form the dark plains termed "Mare." The oldest of the components of the dark lunar mare are dated at about 3.8 billion years or similar to the ages found for the West Greenland rocks. Broken rock fragments collected by the Apollo astronauts yield ages that are somewhat older than this; these are interpreted as reflecting erasure of the original dates by impacts. Since there exists a relatively narrow distribution of ages and rapid transition from older, impact-dominated landscapes on the Moon to landscapes of volcanic plains, it is generally believed that a cataclysmic spike in impacts



Carbon residues found in some West Greenland rocks provide evidence for life nearly 3.9 billion years ago.

in the time interval 3.8 to 3.9 billion-years-ago took place. The intense bombardments coincide with near simultaneous creation of the large Imbrium, Orientale and Schrödinger basins at about 3.85 billion-years-ago, and abruptly ended.

Details of impact timing are important in two ways: An age of 3.85 billion years closely corresponds to that of the oldest sediments on Akilia in West Greenland cited above, and that age has been taken as a temporal marker horizon for estimating the age of heavily cratered crust on other planets that pre-

serve a cratered terrane from the bombardment such as Mercury, Mars and the icy satellites of the outer planets.

Giant impacts by comets and asteroids to the Earth at the same time as life was arising would have apparently been lethal for near-surface life emerging from "warm little ponds" as envisioned by Charles Darwin more than 100 years ago. Some of the effects from the largest of the giant impacts include wholesale destruction of the oceans and crust. These effects would have rendered the surface truly hellish in character some 4 billion years ago. The "genetic genealogy" studies mentioned previously could indicate that life itself originated in deep marine or crustal nurseries. Wherever the origin of life occurred, it had occasion to reside in the depths until bombardment ceased so that events at the surface might have had little immediate consequence to survivability of the living world.

To search for evidence of impacts in the geologic record, workers have taken advantage of the geochemistry of a rare metallic element named iridium (Ir). The crust of the Earth is very poor in Ir and other so-called "Platinum Group" metals relative to the deep mantle, which is itself very low in concentration relative to the undifferentiated primitive meteorites that went into forming the planets. Most of Earth's iridium became trapped in the formation of the core. Thus, the iridium content of sediments is used as a sensitive indicator of the presence of extraterrestrial debris arriving to the Earth. If iridium were found in high concentration in ancient sediments, this might represent some important contribution from interplanetary dusts, meteorites, world-spanning impact ejecta, explosions and other products of comet or asteroid showers in the early solar system. If estimates can be made of the rate of deposition of sediments, values of Ir can provide information about the significance of extraterrestrial material to the surface zone. There appears to be an overlap between the time the Moon was bombarded by meteors and comets, and the formation of the oldest known sediments. If that is correct, then we might expect the old Greenland rocks to record the bombardment. Sounds simple, right?

We have found that unless rates of sedimentation rates were unusually high (much greater than 1 mm/yr, which would dilute a signal of extraterrestrial input), the contents of iridium for all West Greenland samples in our studies are lower than that expected from simple models for the Late Heavy Bombardment. This observation may be explained by the fact that the bombardment itself cannot be simply described as an era of continuous massive impacts. Instead of being a "chicken little world", the early surface was most likely dominated by long

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