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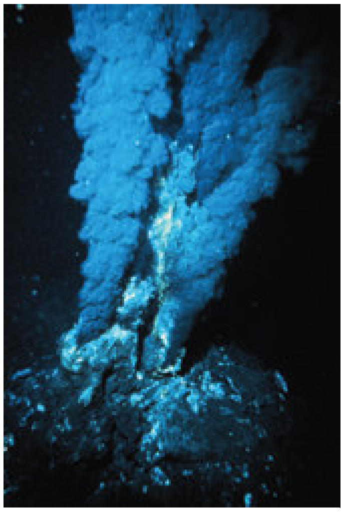
A Rocky Start - Fresh take on life's oldest story

Kendall Morgan April 26, 2003

In the dark ocean depths, kilometers beneath the waves, scalding water spews from hydrothermal vents as it has for billions of years. Bubbling up at the breaks between Earth's plates, that water is a searing brew of minerals dominated by black iron sulfide. As it billows upward in vast quantities, the minerals roil like smoke from a raging fire. It looks like a place that ought to be dead as stone. Yet on the ancient Earth, that abundant black mineral might have been the crucial ingredient that first sparked all life, some scientists say. As they see it, the simplest life forms got their start within tiny cell-like chambers in iron sulfide rock that settled out from the hydrothermal vents' exhalations.

What's more, these origin-of-life researchers suspect that the two major groups of bacteria, known as archaebacteria and eubacteria, originated on two separate occasions about 3.8 billion years ago. Only much later, the scientists propose, did these original microbes join forces to create the first eukaryotes, the group that includes plants and animals.



SMOKIN'. Iron sulfide spewing from hydrothermal vents like this one may have sparked the first life on Earth nearly 4 billion years ago, according to a new theory on life's origins. NOAA

The first complete synthesis of what might be called the iron sulfide theory for the origin of life appeared in the January Philosophical Transactions of the Royal Society of London B. Nearly 15 years in the making, this portrait of life's start, by microbiologist William Martin of the Heinrich-Heine-Universität Düsseldorf in Germany and Michael J. Russell of the Scottish Universities Environmental Research Centre in Glasgow, is stirring up fellow origin-of-life researchers. Some of them describe the theory as speculative, while others call it ingenious.

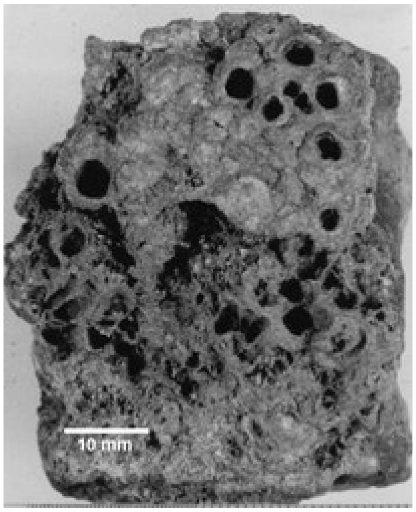
But at the most basic level, says Martin, it's simple. "All you need is rocks and water, and everything else happens by itself," he says. "There's no magic here."

Where most versions of life's origins are "fuzzy around the edges," the new theory is explicit, Martin says. It traces life's opening chapters from the beginnings of biochemistry to the emergence of cells that look much like modern-day bacteria.

The theory also presents a notably wide target for anyone looking to criticize it, says chemist David W. Deamer of the University of California, Santa Cruz. So far, however, it's drawing more praise than flak as scientists agree that Martin and Russell's bold outlook and interdisciplinary approach promise to launch a new prong of research aimed at one of the biggest questions there is: How did life begin?

Ironclad beginning

Russell began imagining that rocks might have been the spawning ground of life itself while studying iron sulfide mineral deposits collected from old hydrothermal vents.

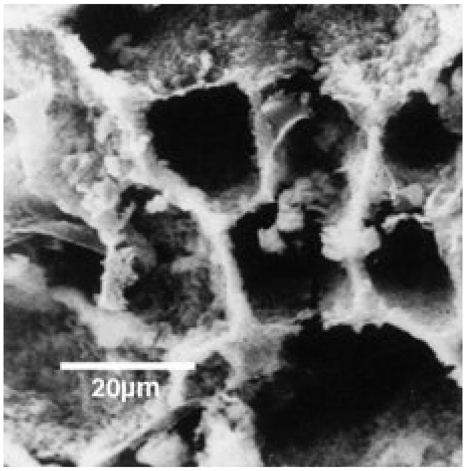


ROCKY CRADLE. Hunks of iron sulfide rock from undersea chimneys that surround hydrothermal vents are made up of cell-like compartments that may have housed the first life, scientists say.
Russell and A. Hall

When hot iron sulfide–containing water meets the cooler ocean, some of the mineral forms into chimneys, which now can be found in many places underneath the Pacific and Atlantic Oceans and elsewhere. Some of the rock spires have reportedly grown at rates up to 1 meter every 2 months. One off the coast of Oregon reached the towering height of a 15-story building before toppling over. Researchers often find thriving communities of creatures around these vents, some of the animals specially adapted to the intense chemical environment.

What fascinates Martin and Russell most, however, is the internal structure of the chimneys themselves. Far from being solid lumps of stone, they have a "highly compartmentalized internal fabric," the scientists say.

In 1997, while working with another colleague, Russell simulated formation of these rock structures by injecting a warm, alkaline solution of sodium sulfide into a cooler, iron-rich solution in the lab. Immediately after the injection, iron sulfide bubbles spontaneously began to form, Russell recalls. Just a minute later, an iron sulfide structure several centimeters high had formed. The resulting mineral construction contained a honeycomb of tiny compartments.



A micrograph of structures similar to those above, recreated in the lab, reveals some compartments the size of cells.
Russell and A. Hall

Russell proposes that at undersea hydrothermal vents around 4 billion years ago, such compartments acted as an incubator in which life's basic ingredients concentrated and the first cells were born. In this model, the walls of the compartments serve as the first cellular membranes.

Like the age-old chicken-and-egg question, the source of the first cell membrane has been a major hurdle for the theories about the origin of life. Today's cell membranes are made of long, oily, lipid molecules that form into pliant fluidlike films surrounding a cell's biomolecular machinery. Such walls concentrate the molecules of life into a small space in which they can work together. "Without a membrane, a cell bleeds to death," Russell says.

Decades ago, Deamer proposed a solution to the problem. He suggested that lipid membranes, similar to those that envelop cells today, might have preceded other complex molecules of life. After all, he says, chemists have shown that under the right conditions, cell-like membranes will form spontaneously from simple chemical ingredients (SN: 2/3/01, p. 68: http://www.sciencenews.org/articles/20010203/fob1.asp).

Lipid membranes may have self-assembled on the early Earth, acknowledge Martin and Russell. However, they question how those first lipid droplets could have contained precisely the right mix of ingredients for life. Perhaps more importantly, they ask, how would such protocells capture the energy required to create more of themselves? "It's a huge stumbling block," Deamer agrees.

Jump-started

The rock compartments nestled within the hydrothermal chimneys provide a possible answer. When rock membranes form in the laboratory, they create a voltage of 600 millivolts as their thin walls separate the simulated hydrothermal and ocean solutions, which have different ion concentrations. The voltage lasts for several hours, says Russell, and is comparable to that across the membranes of today's living cells. "That energy would be sufficient to drive a putative metabolism," Russell notes.

Deamer remains skeptical, but he's intrigued enough that he's planning to conduct laboratory tests of his own to see whether iron sulfide structures can sustain voltages sufficient for catalyzing reactions that help form, for example, ATP—the cell's biochemical fuel.

Martin and Russell point to previous evidence, such as that amassed by organic chemist Günter Wächtershäuser. He was one of the first scientists to suggest that iron sulfides and nickel sulfides might have held an important role in early life. He suspects that the flat surfaces of such minerals could have served catalytic roles similar to those of a modern cell's enzymes.

Wächtershäuser and his colleagues showed that metal sulfides can catalyze the formation of a so-called activated thioester from simple ingredients (SN: 1/9/99, p. 24: http://www.sciencenews.org/pages/sn_arc99/1_9_99/bob1.htm). Some scientists suspect that thioesters may have preceded ATP as carriers of biochemical energy.

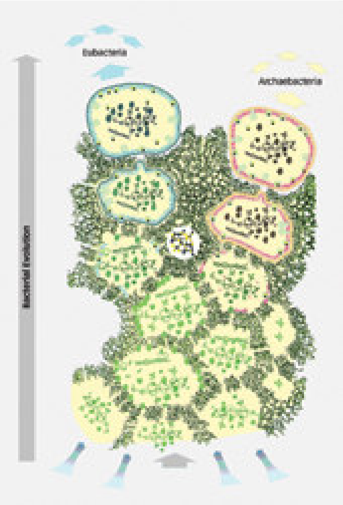
Later, Wächtershäuser's team showed that when catalyzed by iron sulfide, amino acids link into short peptide chains, the beginnings of proteins. Two years ago, geophysicist George D. Cody of the Carnegie Institution of Washington, D.C., and his colleagues added another piece of the puzzle: Iron sulfide leads to the synthesis of pyruvate, a molecule involved in many metabolic reactions. In a series of lab experiments that simulate the hot, highly pressurized conditions found in deep hydrothermal vents, Cody's team found that fundamental chemical ingredients, including carbon dioxide and hydrogen, in the presence of iron sulfide, "enter into cycles that look a lot like metabolism." Says Cody: "It's hard to imagine a better catalyst [than iron sulfide], which we know was there in abundance" in the early ocean. "It's guaranteed that on the early Earth, all sorts of organic chemistry was happening," he adds.

Russell and Martin offer yet another piece of circumstantial evidence that life may have emerged from iron sulfide–catalyzed chemistry: Many of the large proteins that drive basic biochemical reactions today—such as ferredoxin, a protein that mediates metabolic reactions—rely on smaller iron sulfur cofactors. "It's a little bit of rock [in cells] that reminds us where we came from," Russell says. With these iron sulfide–based cofactors, proteins spur chemical reactions similar to the ones that the mineral itself can drive, Martin adds.

Breaking out

If Russell and Martin's theory has any chance of being right, naked, rock-cradled life-forms must at some point have invented the biochemistry required to produce their own membranes.

Once the ingredients for making lipids found their way inside the catalytically active iron sulfide compartments, the soft membranes emblematic of living cells could have formed. The microbes, now equipped with their own working membranes, could have begun emerging from their iron microwombs to colonize the early biosphere.
Actually, Russell and Martin say, this crucial evolutionary leap may have happened in two different ways that correspond to what subsequently became archaebacteria and eubacteria.



TWIN BIRTH. In this model, chemicals concentrate and react inside hydrothermal rock, forming essential life ingredients. Eventually, the two bacterial groups—archaebacteria and eubacteria—separately devise cell membranes and emerge. Martin/Royal Soc. London

The lipid molecules that build into the membranes of archaebacteria and eubacteria bear a subtle difference: One is the mirror image of the other. Although the difference between the forms carries no known consequence in terms of survival, it has major implications for the membranes' origins, says Yosuke Koga of the University of Occupational and Environmental Health in Kitakyushu, Japan.

Koga and his colleagues examined the genetic makeup of the key enzyme—(G-1-P) dehydrogenase—responsible for the formation of archaebacterial lipids. In 1998, the group reported that the genetic sequence encoding this membrane-building enzyme bore no resemblance to the corresponding enzyme in Escherichia coli, a representative eubacterium.

This genetic difference is too gaping for one type of membrane biochemistry to have evolved from the other, Koga argues. Therefore, he says, the two membrane types must have arisen independently, back when the first living cells emerged.

Martin and Russell conjecture that the bacterial ancestors living within their rock shelters cooked up two separate biochemical recipes for membranes. Then, with their distinctive membranes, the two types of cells presumably left their rocky starting places to begin paving their own evolutionary ways (see below).

For people hoping to find life on other planets, the iron sulfide theory's version of earthly events should come as good news. The environment that Russell and Martin propose as the birthplace of life requires only rocks, water, and the most basic of chemical ingredients. Given that there likely are billions of venues like that throughout the universe, says Russell, "life can't help but happen."

First Couple? Bacterial partners might have spawned a new life-form

Although archaebacteria and eubacteria, Earth's two main bacterial groups, diverged almost from their inception nearly 4 billion years ago, they came back together about 1.5 billion years later to form the third branch of life, the eukaryotes, according to William Martin of the Heinrich-Heine-Universität Düsseldorf in Germany and Michael J. Russell of the Scottish Universities Environmental Research Centre in Glasgow. They conjecture that an evolutionary quantum leap happened after an archaebacterium swallowed a eubacterium.

Other scientists are now discovering that the deep ocean is a hotbed of unconventional symbiotic relationships that they say may yield clues about eukaryotes' oldest ancestor. Microbiologist Joan M. Bernhard of the University of South Carolina in Columbia has found a diversity of single-celled eukaryotes, called protists, bearing bacterial partners. She describes the deep-sea environment as a "symbiotic oasis." Some of the critters, including members of two major protist groups—the whip-tailed flagellates and hairy ciliates—harbor bacteria internally. Still others are coated in bacterial partners.

The inner workings of these pairings haven't yet been defined, but their abundance suggests that teamwork is a useful solution to the stark ocean environment, Bernhard says. It's possible that the first eukaryotes originated in similar communities, she adds.

The first examples of bacterium-bacterium collaborations have begun to surface. Two years ago, Antje Boetius of the Alfred Wegener Institute for Polar and Marine Research in Bremen, Germany, and her colleagues found clumps of archaebacteria surrounded by a rind of sulfate-reducing eubacteria—the first example of a pairing between the two bacterial groups (SN: 10/7/00, p. 231). The duo apparently feeds on methane in the oxygen-depleted ocean. These and more recently discovered bacterial assemblages account for the "massive biomass" at the seafloor, forming mats up to 4 feet deep, Boetius' team reports in the August 9, 2002 Science. These organisms might represent the kinds of associations that led to the first eukaryote, Boetius says.

The only known instance of a bacterium within a bacterium—the structure proposed as the origin of eukaryotes—has turned up inside abdominal cells of a mealybug insect (SN: 7/28/01, p. 53: http://www.sciencenews.org/articles/20010728/fob4.asp).

So, why haven't such species collaborations more often led to new life-forms? Martin suspects that the shift from symbiosis to wholesale melding of the partners' genomes only rarely proves possible, let alone viable.

However, he admits, any theory of eukaryotic origins faces a grand challenge. "It has to be plausible enough to have happened once, but not so easy that it happens a thousand times," he says.

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