# Goodbye to the Warm Little Pond?

*Early Earth was a violent, nasty place when life was getting under way; it was subjected to an asteroid bombardment far worse than anything the dinosaurs ever saw*

EVER SINCE 1871, WHEN CHARLES DARWIN made his oft-quoted allusion to life's beginnings in a "warm little pond," scientists have tended to imagine the origin of life as being a rather tranquil affair—something like a quiet afternoon in a country kitchen, with a rich organic soup of complex carbon compounds simmering slowly in the sunlight until somehow they became living protoplasm.

Sorry, Charles. Your Warm Little Pond was a beautiful image. It's been enshrined in innumerable textbooks as *the* scientific theory of the origin of life. But to hear the planetary scientists talking these days, you were dead wrong. The Warm Little Pond never existed.

Earth's first billion years did indeed see the rise of bacteria, they say, including some that were advanced enough to leave recognizable microfossils. Yet during those years our world was anything but tranquil. The planet endured rampant volcanism, scorching heat, and a murderous bombardment from comets and asteroids.

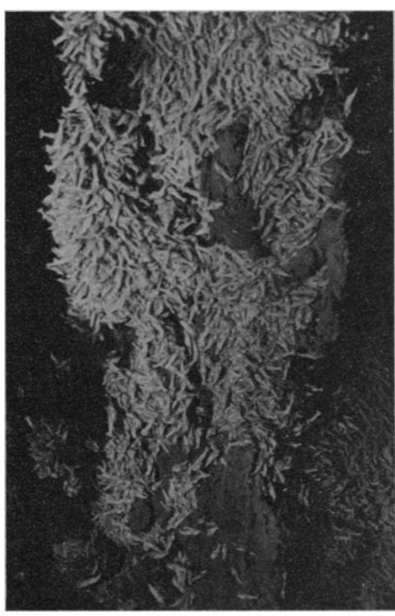
So ghastly is the emerging portrait of early Earth that many origin-of-life researchers now think it warrants a complete revision of the conventional wisdom. "The field is in ferment," says Pennsylvania State University geologist James Kasting, who chaired a Gordon Conference on the origin of life this past summer, and who was coauthor last year of one of the key papers dealing with the early bombardment.

The new view, admittedly controversial, is that our ancestors' birthplace had a harsh environment—like that in the sulfurous, deep-sea hot springs along the mid-ocean ridge, where magma wells up to form the spreading tectonic plates. This idea has been greatly reinforced by the realization that even the lesser asteroid and comet impacts could have vaporized the upper levels of oceans. But at the depths of the hot springs, any emerging life forms would be protected.

The bombardment pummeling early Earth was actually a kind of cosmic cleanup operation, explains Kasting. In the aftermath of our solar system's formation some 4.6 billion years ago, interplanetary space was still littered with megatons of construction debris in the form of rocky asteroids and icy comets roaming around at tens of kilometers per second. The resulting collisions were both inevitable and devastating, says Kasting: The newborn planets took a billion-year pounding that was several hundred thousand times more energetic than anything they've experienced since.

The scars of those early impacts have long since been obliterated on Earth by erosion and tectonic activity. But a record of that time can be seen on the battered face of the moon, whose most heavily cratered terrains are some 4 billion years old. During this period the moon was hit by at least two projectiles roughly 100 kilometers in diameter, with results that are visible today as the great lava-filled basins known as Mare Imbrium and Mare Orientale. And Earth, because of its larger size and greater gravity, had a statistical chance of getting hit by objects of a similar size (or larger) about 16 times more often.

All this had been known in a general way since the mid-1970s. But few researchers really thought very much about impacts until 1980, when the late Luis Alvarez and his collaborators suggested that a 10-kilometer asteroid or comet may have destroyed the dinosaurs some 65 million years ago. Since then, geologists and planetary scientists have been thinking about impacts very hard indeed. The first paper to seriously consider what the primordial bombardment might have done to Earth was published in 1988 by California Institute of Technology geophysicists Kevin Maher and David Stevenson, who coined the term "impact frustration" to denote the repeated destruction of life forms that the impacts might have caused. Kasting, Stanford University geophysicist Norman Sleep, and their colleagues published an independent assessment reaching similar conclusions in 1989.



National Oceanic and Atmospheric Administration

**Font of life?** *The mid-ocean ridge hot springs support abundant life forms, such as these shrimp.*

On a global scale, Kasting says, such "local" phenomena as the 1500-kilometer-wide crater and the miles-high tidal wave created by an impact would not have been terribly important. According to computer simulations, the real problem would have been the plume of vaporized rock and other debris from the impact, which would have exploded outward into space. Quickly spreading around the world, the plume would have enveloped the planet in a blanket of rock vapor having a temperature of 2000K, and a pressure about 100 times that of our modern atmosphere. Exposed to that, the oceans would have soon begun to flash into steam. In fact, says Kasting, an incoming comet or asteroid with a diameter of 400 to 500 kilometers, about the size of the modern asteroids Vesta and Pallas, would "dump in enough energy to evaporate the entire ocean."

The rock vapor would have settled back to the ground within a few months of the impact. But by then, says Kasting, the environment down below would have long since gone from bad to worse. The vaporized ocean would have raised the surface pressure to some 270 atmospheres, and the water vapor would have acted as a greenhouse gas, trapping heat inside the atmosphere and making it very difficult for Earth to cool off. "The temperature could have easily reached 1500K," says Kasting. "So it's likely you would have sterilized the whole planetary surface." Calculations suggest that it would have taken some 2000 to 3000 years before Earth cooled enough for the first raindrops to reach the ground again, and for the ocean basins to begin to refill.

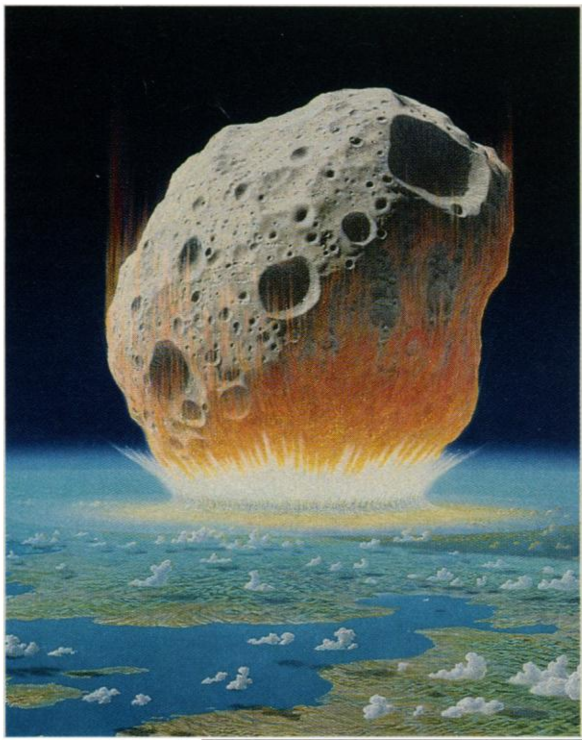
So how often did this total sterilization happen in Earth's history? It's hard to say, notes Cornell University graduate student Christopher Chyba, who has recently published some of the most careful and conservative calculations of the impact rates. The data on cratering rates is just too uncertain, especially for the earliest epochs. "Maybe Earth sustained ocean-evaporating impacts," says Chyba, "but the statistics only allow you to say it sustained zero to several of them." And each time it happened life would have to arise anew.

But even if Earth was not struck by any of the full-scale ocean blasters, he says, there were still plenty of smaller objects whirling around the solar system—say on the 100-kilometer scale. Any one of these projectiles would have stripped off the top 100 meters or so of the ocean, which is the only level where sunlight can penetrate and which is where most of the organisms in the ocean live today. As Kasting notes dryly, "That's still a sizable catastrophe." Calculations suggest that such "partial vaporizers" could have regularly sterilized the surface waters and the continents until the bombardment tapered off some 3.8 billion years ago.

For many researchers, such calculations make the idea of an origin of life at the deep-sea hot springs look very attractive. Most obviously, as Kasting and many others have pointed out, the deep-sea floor would have been relatively safe: After the last big ocean blaster, protoorganisms could have originated and flourished in the depths for hundreds of millions of years while the partial evaporators were still at work high above them.

Having that extra time, in turn, makes it easier to understand how paleontologists can find fossils of organisms that look remarkably like modern cyanobacteria (blue-green algae) in rocks that formed 3.4 to 3.5 billion years ago—only 300 to 400 million years after the bombardment. Granted, 300 million years is a long time even by geologists' standards. But bacteria, with all their machinery for cell division and metabolism, are very complicated beasts already; it's not at all clear that they could have evolved that fast in a Warm Little Pond.

Furthermore, notes University of Indiana microbiologist Norman Pace, a hot springs origin fits in well with geologists' current thinking about Earth's early volcanism. Presumably, the hot springs back then operated just as they do today, with cold water seeping down through cracks on the sea floor until it encountered a shallow magma chamber, and then roaring back upward to reemerge at temperatures as high as 400°C. The difference, says Pace, is that the primordial hot springs probably were much more widespread than today's. "The crust was so thin and so smashed up that rather than having a global network, you would have had local volcanism all over," he says. "The entire Earth's surface was like a hydrothermal vent."



Don Davis

**Ocean blaster.** *How many times was life wiped out on early Earth?*

Not only were the hot springs ubiquitous, adds Pace, but they would have been copious fountains of energy-rich "food stuffs": iron ions, sulfide ions, hydrogen sulfide, methane—anything that superheated water could extract from superheated rock. In the modern hot springs, these rather noxious-sounding nutrients support dense colonies of sulfur- and heat-loving bacteria, says Pace. And the bacteria, in turn, form the base of a food chain that culminates in a multitude of exotic crabs, fish, and tube worms.

Finally, as University of Washington microbiologist John Baross points out, everything we know about the hot springs suggests that they are capable of producing an immensely rich web of organic reactions—exactly what would be needed for the origin of life. As the hot water surges upward through cracks in the rock, it mixes with cold water seeping downward, thereby producing any temperature gradient and flow rate you could want. (Most of the hot springs actually emerge at no more than 45°C.) The water itself is full of highly reactive metal ions such as iron, manganese, and cobalt. The rock fractures are lined with catalytic crystal surfaces and clays. It's potentially a chemical wonderland, he says (also see page 1080).

In sum, then, the argument is that the primordial hot springs *could* have hosted the origin of life. But did they? One intriguing bit of circumstantial evidence comes from University of Illinois microbiologist Carl Woese, who has spent more than a decade using genetic sequencing techniques to work out the evolutionary family tree of microbial life. None of the microbes now in existence is likely to represent a common ancestor, says Woese. But of the branches that do exist, the oldest seem to be occupied by thermophiles—heat-loving bacteria. Moreover, the heat- and sulfur-loving bacteria now thriving in the hot springs belong to one of the oldest branches of all. "This suggests that the most recent common ancestor [to the modern microbial families] was thermophilic," says Woese—and that by extension, life itself began in an environment rich in heat and sulfur.

As it happens, however, not everyone is willing to accept that suggestion. Perhaps the strongest critic of the hot springs idea is biochemist Stanley Miller of the University of California, San Diego, whose voice carries considerable weight in the origin of life community. Back in 1953, while working as a graduate student under Nobel laureate chemist Harold Urey at the University of Chicago, Miller was the first to show experimentally that amino acids and other key ingredients for life could form spontaneously in a plausible early Earth environment.

To begin with, says Miller, he sees no problem in getting from amino acids to bacteria in 300 million years: "My position is that life had to arise very quickly, in less than 10 million years," he says. "All the prebiotic processes we know about are fast."

Furthermore, he says, the hot springs are too hot. Water at 400°C would destroy organic molecules as fast as they formed. At least in a mild, cool prebiotic soup they have had a chance of surviving until they produced a more complex biochemistry.

And as for the ancestral microbes being thermophilic, he says, "I won't dispute that." But all it means is that we are descended from organisms that colonized the hot springs and survived there. He thinks it more likely that the ancestors of those thermophiles arose elsewhere under much milder conditions before being wiped out by an impact.

Washington's Baross, meanwhile, concedes that Miller has some cogent points.

# The Golden Crystal of Life

The theory came out of the blue in 1987, the brainchild of a Münich patent attorney whom few professional scientists had ever heard of. And yet it has excited the tiny origin of life community like few ideas in recent memory: Life, says Günter Wächtershäuser, began with pyrite. $FeS_2$. Fool's gold.

"It's perhaps the most interesting theory ever in this field," declares University of Illinois microbiologist Carl Woese. Compared to the general run of origin-of-life hypotheses, moreover, it is refreshingly concrete: "The theory is specific in what it predicts," says Woese. "You can test it."

Neither Woese nor anyone else contacted by *Science* seems to worry about Wächtershäuser's being an amateur. He does have a Ph.D. in organic chemistry, after all—from the University of Marburg in 1965—and he publishes his work in peer-reviewed journals.

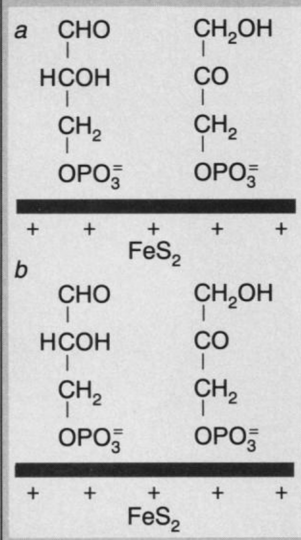
"Chemistry has been my great love since I was a high school student," says Wächtershäuser, explaining that he became a patent attorney because he didn't like the kind of overspecialization he saw waiting for him in an academic career. "It's been a blessing," he says. "This job of mine lets me think in much broader terms."

In imagining how life began, Wächtershäuser postulates an environment very much like that of the deep sea hot springs that some investigators now think were the font of life on Earth (also see p. 1078). The hot, iron- and sulfur-rich water bubbling up from these springs produces pyrite deposits in abundance. Also, the surface of the pyrite crystal happens to carry a slight positive charge. Thus, Wächtershäuser's origin-of-life scenario begins with pyrite crystals attracting and binding any molecule in the solution that contains a negatively charged ion such as carbonate, phosphate, or sulfide.

In short order, he says, every exposed pyrite surface would quickly be covered with a dense mat of these ionically bound molecules. However, he adds, since ionic bonds are much less restrictive than covalent ones, these molecules would actually be free to wander around the surface and mingle like guests at a submicroscopic cocktail party. And since they would be rubbing together cheek by jowl, instead of randomly tumbling around through the wider world, they would be much more likely to interact. As with human partygoers, their bonding rate would go up enormously.

Thus, says Wächtershäuser, the molecules would begin to form longer chains held to the pyrite surface by multiple ionic bonds. Indeed, he says, there would be a strong selection pressure for multiple bonds: The more points of attachment to the surface, the less chance of a molecule's drifting loose and being broken apart in the viciously hot surroundings. From the molecular point of view, says Wächtershäuser, the pyrite surface would be a refuge.

Next, he says, with dense fields of interacting molecules roaming around the pyrite surface, conditions would now be ripe for "autocatalysis"—a network of reactions in which molecule A would catalyze the creation of molecule B, B would catalyze C, and so on down the line until some molecule Z would catalyze A. Such a self-reinforcing network would take in simple "food" molecules and link them into more complex compounds, says Wächtershäuser, and would generally behave very much like a simple metabolism.




**Cheek by jowl.** *In the pyrite theory, ionic bonds allow organic molecules to move around the surface and interact.*

Following these ideas, Wächtershäuser has proposed a specific scenario for how the first metabolic cycle might have evolved; for the origin of cell membranes, which are made of long-chain molecules terminating in phosphate groups; for the origin of DNA and RNA, both of which feature a backbone containing phosphate; and for a multitude of other biochemical reactions, an astonishing number of which involve compounds containing phosphate groups or sulfide groups that might once have bound them to a pyrite surface.

At the University of California, Davis, microbiologist Mark Wheelis finds all this extremely appealing: "Wächtershäuser's chemistry rationalizes why certain biochemical pathways operate the way they do," he says. "As a piece of creative thought, this is an extremely important contribution."

Still, as Wächtershäuser himself admits, thought alone is a poor substitute for data. He has only recently begun a collaboration with researchers at the Universität Regensburg to test his theory in the laboratory. And until experimental evidence is forthcoming for his hypothesis, most other origin-of-life researchers find themselves in the same position as the Salk Institute's Leslie Orgel: "I'm highly skeptical," he says, "but happily awaiting having my skepticism dispelled." ■ **M.M.W.**

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But he also says that he finds such arguments endlessly frustrating. The fact is that it's all a debate on paper. No one has ever carried out the experiments to see what hot springs chemistry can really do.

"People have made noises about it," he says. But trying to do accurate chemistry several kilometers down at the hot springs themselves would be extraordinarily difficult. And setting things up on a laboratory bench wouldn't be much easier. "You'd need extremely high temperatures in a temperature gradient, flowing system," he observes. "You'd have to monitor the sample to know exactly what you're getting. And you'd need a large commitment from a granting agency."

Such commitments are hard to come by these days, especially for a speculative project like this one. Still, it would be a fascinating chemical challenge. And if the speculations of Baross and others were borne out, the results might have reverberations well beyond the theoretical realm. As Cornell's Chyba points out, many planetary scientists think there's a good chance that oceans and hot springs exist under the icy crust of Jupiter's moon Europa. And, of course, what happened here could also happen elsewhere... ■ **M. MITCHELL WALDROP**