The startling claim that Earth has frozen over from pole to pole for millions of years at a time has intrigued many earth scientists but as yet convinced few

An Appealing Snowball Earth That's Still Hard to Swallow

The farther back in Earth's history you go, the weirder things seem to get. Back in the Neoproterozoic era 600 million or 700 million years ago, before life was much more than a green scum, the world was particularly bizarre. Glaciers often flowed to the sea seemingly everywhere, including the tropics. Yet, as soon as rocky debris churned out by those glaciers settled on the floor of iceberg-clogged seas, the climate seems to have flipped: Warm seawater supercharged with carbon dioxide began depositing carbonate rock right on top of the glacial detritus. At the same time, life appears to have suffered a near-death experience after eons of stability. Even iron deposits supposedly banished by Earth's now-abundant oxygen reappeared in the late Neoproterozoic for one final bow. And shortly thereafter, geologically speaking, a profusion of animal life—all the basic body plans seen today—burst on the scene full blown after evolution had stagnated for a billion years or more.

For the past 18 months, geoscientists have themselves been thrown into turmoil by a bold explanation for all this weirdness: During the late Neoproterozoic, this theory goes, Earth suffered through at least two globe-engulfing ice ages that reinvigorated life by nearly snuffing it out. These deep freezes, according to this model, abruptly gave way to global warming that turned the entire planet into a sauna. Bizarre though it may seem, this hypothesis, widely known as the "Snowball Earth" scenario, is gaining ground.

Researchers from geologists and geochemists to paleontologists and climate modelers are suddenly taking snowball Earth seriously enough to trek to Namibia's Skeleton Coast and California's Death Valley for rocks and to crank up computer models for climatic insights. And last year, most researchers agreed that one part of the sweeping hypothesis—the claim that glaciers once flowed into ice-covered tropical seas—is correct, even though this idea had been rebuffed for more than 30 years. A few scientists are even persuaded that the entire theory most likely is true. Snowball Earth "is a very plausible explanation for some very puzzling observations," says geochemist James Walker of the University of Michigan, Ann Arbor. "It probably happened."

Most researchers, however, aren't yet ready to embrace the whole sequence of

events. Big, in-your-face ideas can be a bit hard to take, even when they solve all your problems. After all, the idea that a 10-kilometer chunk of rock blew away the dinosaurs 65 million years ago took 10 years of often-bitter debate before gaining widespread acceptance; microbes from Mars look like they may never gain acceptance. Snowball Earth is gaining ground faster than the dinosaur killer did, but it has a long way to go. It is "interesting, intriguing, provocative," says paleontologist Guy Narbonne of Queen's University in Kingston, Ontario. "It has focused us on a pivotal event in Earth's history, and it provides a testable hypothesis that links a number of observations, but I wouldn't say it's accepted." For Narbonne and many others, there are still too many details that don't fit yet. "I just don't know whether it will stand up," says paleontologist and molecular biologist Charles Marshall of Harvard University. But then, "I would have said the same thing about the K-T [Cretaceous-Tertiary] impact" in its first year.

A "freeze-fry" world

Although elements of the snowball Earth hypothesis have been around for several decades—geobiologist Joseph Kirschvink of the California Institute of Technology coined the term in 1992—it was a 1998 paper in *Science* (28 August, p. 1342) that made it a going concern among researchers. In that paper, geologist Paul Hoffman and geochemists Daniel Schrag and Galen Halverson of Harvard and geochemist Alan Kaufman of the University of Maryland, College Park, a former Harvard colleague, sketched a scenario that would resolve four paradoxes found 750 million to 580 million years ago late in the Neoproterozoic era and a few tens of millions of years before the explosion of animal diversity in the Cambrian period.

First up in the Harvard scenario is global glaciation. Climate modelers have long believed that if the natural greenhouse warming of early Earth were to weaken, say because unusually severe weathering of continental rocks sucked carbon dioxide out of the atmosphere, Earth would freeze over. The sun was fainter in those days, so if the greenhouse waned, bright white ice and snow would creep from polar regions toward the equator, reflecting more and more of the sun's heat back into space and further cooling the planet.

At some point, this albedo feedback effect would take over, the ice would push across all oceans to the equator, and Earth would be a snowball. This was the "White Earth solution" or "ice catastrophe" of a simple climate model run by Mikhail Budyko of the Leningrad Geophysical Observatory in the 1960s. At the time, however, climate modelers didn't think the real world ever iced over. How could life have survived, they asked, in a world in which the average surface temperature would have hovered around –50°C, not to mention the all-encompassing sea ice that would average a kilometer thick compared to the Arctic Ocean's few meters?

In the Harvard snowball scenario, microbes, simple seaweeds, and probably animals of near-microscopic size eked out an existence around sea-floor hot springs or the occasional rift in the ice, even as those same hot springs were loading the oceans with minerals and sucking oxygen from the water. This went on for perhaps 10 million years until volcanoes came to the rescue, in a brutal sort of way. Over millions of years, carbon dioxide seeped from the interior through continental volcanoes to rebuild the greenhouse, and then some. Eventually, an atmosphere with 350 times today's carbon dioxide countered the snowball's albedo effect, melting back the ice in a century or so and bringing on a steamy climate with an average global temperature of +50°C and replete with corrosive acid rain. And the Harvard group believes there were more than one of these "freeze-fry events," as Hoffman and Schrag dub them in a January *Scientific American* article. Geologists agree that there were at least two widespread, although not necessarily global, glaciations in the late Neoproterozoic; some researchers opt for three or four, including Kaufman, who sees all of them as global.

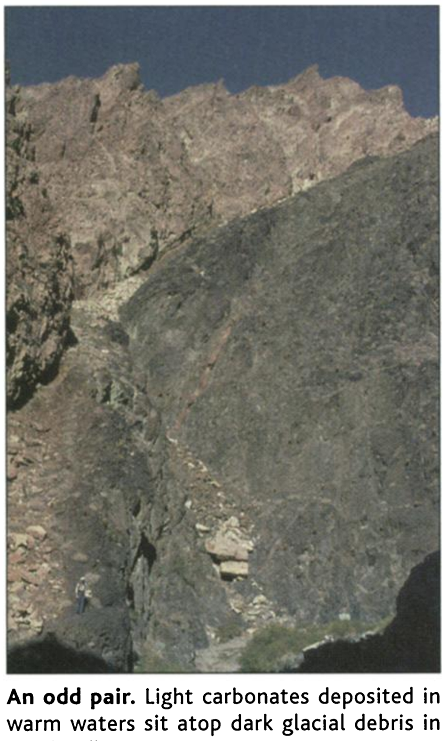
Melting opposition

Snowballs from hell didn't set well at first with most earth scientists: too extreme, too bizarre, too deadly, too speculative. But several developments, some from the Harvard group, have softened resistance. One supportive piece of evidence, oddly enough, comes from one of snowball Earth's more vociferous critics—as paradoxical as it seems, glaciers really did flow into icy tropical seas. In the 1960s, geologist Brian Harland of the University of Cambridge noted how many Neoproterozoic glacial deposits—rock ground up by glacial ice movement and "dropstones" carried out to sea by icebergs—seemed to have formed in tropical latitudes. Although the glacial deposits appeared authentic enough to most geologists, few were convinced that they had formed near the equator.

The problem was one of reliability. In order to tell at what latitude a deposit formed before 700 million years of peripatetic plate tectonics reshuffled it around the planet, paleomagneticians trace the alignment of magnetic minerals in the deposit. These minerals tend to line up at the time the deposit was formed in the direction of Earth's magnetic field: If horizontal, the deposit formed at the equator, where magnetic field lines running pole to pole parallel the surface; if vertical, at one of the poles, where field lines plunge toward the core. But rocks that have been around for a few hundred million years have a good chance of having their magnetic signatures later rewritten when the rock is reheated or chemically altered, so researchers remained skeptical.

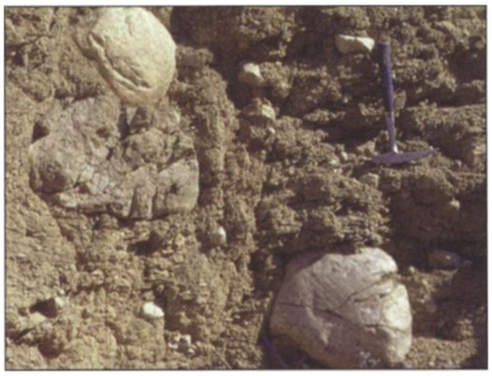
Now comes paleomagnetic evidence of low-latitude glaciation that everyone can believe. In last August's *Geological Society of America Bulletin*, geologists Linda Sohl and Nicholas Christie-Blick (a snowball critic) of the Lamont-Doherty Earth Observatory in Palisades, New York, and paleomagnetician Dennis Kent of Rutgers University in New Brunswick, New Jersey, published a paper on the Neoproterozoic Elatina Formation glacial deposit in Australia. They had finally collected enough samples from the deposit, they reported, to recognize not just a low latitude of deposition, but also at least three flip-flops of Earth's magnetic field recorded as glaciers laid down sediment. That meant that the low latitude could not be a later remagnetization, which would have wiped out the reversals and imposed a single magnetization.

"There's no reason to doubt it," says Kent. "All the tests we've been able to do haven't been able to get around the low latitude." Paleomagnetician Joseph Meert of Indiana State University in Terre Haute had been highly critical of earlier claims by paleomagnetists of low-latitude glaciation, but the latest Elatina data have changed his mind. "The data look pretty strong now," he says. The Sohl results "make it pretty tough to argue against a low latitude [glaciation], at least for the Elatina."



An odd pair. Light carbonates deposited in warm waters sit atop dark glacial debris in Death Valley.

Another out-of-place deposit is also lending credibility to the snowball Earth scenario, this one out of place in time rather than geography. When Kirschvink first coined the term snowball Earth, he pointed out how an ice-covered planet could resolve the paradox of iron formations associated with Neoproterozoic glaciations. Massive amounts of iron that originally spewed from sea-floor hot springs precipitated from the sea in the Archean eon, more than 2.5 billion years ago. But about 2 billion years ago, enough oxygen rose in the deep sea to cut off formation of such iron deposits by precipitating the iron before it spread through the oceans—except, it turns out, around the time of glaciations in the Neoproterozoic. "These iron formations have always been a thorn in the flesh," says geologist Grant Young of the University of Western Ontario in London, Ontario. Kirschvink's scenario, adopted by the Harvard group, would have iron build up in the ice-covered, oxygen-free oceans, only to be precipitated when the ice melts away and oxygen reenters the ocean.



A long haul. A Neoproterozoic glacier dragged the lower boulder, as evidenced in its striations.

In addition to tropical glaciation and strange iron deposits, the snowball Earth scenario solves the paradox of the juxtaposition of the low-latitude glacial deposits and hundreds of meters of carbonate rock. Around the world, Neoproterozoic glacial deposits are capped by tens or even hundreds of meters of carbonate rock whose sometimes bizarre textures indicate rapid precipitation from warm seas saturated with carbonate. (Unlike most minerals, carbonates are more soluble in cold water than in warm.) Read literally, the rock record says that tropical seas iced up and then abruptly thawed to a carbon dioxide–rich warmth.

"I'm not a full supporter of snowball Earth yet," says geologist Frank Corsetti of the University of California, Santa Barbara, but "its strong point is that it explains why we get glacial sediments right under carbonate rocks that are more indicative of warm water." The juxtaposition implies "a weird flip" of climate, says Corsetti. That it flipped in a geologic instant in low latitudes "is doubly weird." But to Hoffman, it fits nicely into the snowball scenario. "This is no paradox," he says, "but a predictable consequence."

The Harvard group believes it has also found evidence for another predictable consequence of a snowball Earth: hard times for

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life. Plants alter the proportions of carbon-12 and carbon-13 in the environment by preferentially using the lighter isotope in photosynthesis. As plant organic matter gets stored in sediments, the relative abundance of the heavier isotope in the ocean and atmosphere increases. But volcanoes and seafloor hot springs have the opposite effect: They spew carbon dioxide that is relatively rich in the lighter isotope, pushing the isotopic composition of ocean and atmosphere toward the lighter side. Given a more or less steady volcanic flux, the carbon isotopic composition of the environment as recorded in carbonates can be taken as a gauge of how well plant life is doing: The greater the relative abundance of the lighter isotope, the worse off the plants were. And that's exactly what Kaufman and his Harvard colleagues found in the "cap" carbonate overlying the glacial deposit in Namibia.

Leading up to the glaciation, the group reported, plant productivity, as measured by carbon isotopes in various carbonates laid down below the glacial deposits, dropped precipitously to near zero. When the record picks up again after the big thaw, it continues to drop until plant life seems extinguished, recovering only slowly. So the biggest carbon-isotopic shift in recorded history was another predictable result of snowball Earth.

Appealing to a point

All this paradox resolution has a strong appeal. "When you have a series of paradoxes, all of which are plausibly explained by one hypothesis," says Hoffman, "that makes the hypothesis very, very attractive." Adds Schrag:

Ice and iron. A stone dropped by a Neoproterozoic iceberg sank into an iron formation in Canada's Mackenzie Mountains.

"It's one hypothesis that can explain all these incredible observations, each of which was mysterious." And the appeal extends beyond Harvard. "The proposal is very attractive," says geochemist Lee Kump of Pennsylvania State University, University Park. "I have a strong suspicion they've got the story right, although the details may evolve."

But those details trouble most researchers. Take the problem of life: It's still here. "Quite a few major clades [of organisms] made it through" the Neoproterozoic glaciations, notes paleontologist Narbonne, including such relatively complex organisms as multicellular green, red, and brown algae living on the sea floor and probably some simple animals. "It's difficult to imagine how these could have survived if the ocean were totally ice covered," says Narbonne. "Things like cyanobacteria could have survived; they'll survive anything. But [the algae] need sunlight." Paleontologist Bruce Runnegar of the University of California, Los Angeles, adds that the ocean's presumed lack of oxygen would present another seemingly insurmountable obstacle; oceanic anoxia would even be a serious problem for life around deep-sea vents, he says.

Then there's the details of timing. Some events in the real world didn't happen when the snowball scenario would seem to call for them. In Scotland, notes Young, carbonates aren't just perched on top of glacial deposits but interlayered with them as well. And iron formations or iron-rich sediments around the world, while associated with Neoproterozoic glaciations, occur not only at the top of the glacial deposit, as predicted, but also down in the glacial deposits. In fact, notes Christie-Blick, the older of the two certain glaciations left smidgens of iron here and there and one huge deposit in northwest Canada, while the younger glaciation left virtually no iron behind. "Why isn't there more iron? The absence of iron formations everywhere is a big problem," he says.

Another problem lies in the glacial deposits themselves, Christie-Blick has noted. Even the Elatina Formation took on the order of a million years to be laid down, implying that much of it must have formed while Earth was ice covered. Yet with the oceans frozen over, there would have been no source of moisture for snow and therefore no glaciers moving to create those glacial deposits. "Paul [Hoffman] has always looked at the big picture," says Christie-Blick. "I'd rather look at the details to see if they fit. When you look at them, they don't fit quite as well."

The Harvard group has responses to these and most other complaints about mismatches between the snowball scenario and the real Earth. In general, Hoffman and Schrag explain the apparent discrepancies in terms of a real snowball world that is far more complex and heterogeneous than most people are imagining. As to the survival of life, for example, they envision—though there is no geologic record—numerous refuges for plant and animal life through millions of years of global freeze. Long-lived volcanism near the sea surface, as now occurs in places like Iceland and the Galápagos Islands, would have provided warm

A survivor. Green algae, like this 700-million-year-old example from Spitsbergen, made it through any snowball Earth.

spots, says Schrag. And the ice would have varied in thickness, especially in the tropics, where ice as thin as 50 or 100 meters might have allowed frequent cracking and open leads. Thus, life could have hung on, they argue, while suffering the kind of stresses that might have snapped evolution out of its eon-long lethargy. After all, they note, the oddball Ediacara fossils, life's first attempt at large-scale animal life, appeared shortly after the last Neoproterozoic glaciation, followed shortly by the appearance of all the basic animal body plans seen today.

The geological inconsistencies might be similarly resolved, Hoffman and Schrag say. Those cracks and leads in the ice might let enough air in to oxygenate at least the upper layer of the ocean, giving life a respite and providing a means of precipitating iron formations during the glacials. And the long-running deposition of glacial debris might have been driven by slow but steady sublimation of ice from tropical sea ice, instead of evaporation from open ocean waters, and deposition at higher elevations as snow.

No one has accused Hoffman and Schrag of failing to think big, but big ideas—even if they're right—take time to sink in. In the meantime, this one is stimulating thinking. "This hypothesis has really generated a lot of interest in rocks that haven't been worked on in years," says Corsetti. And that's what will be needed to test the snowball Earth, says Christie-Blick. "None of the models work that well," he says, "but something happened." By broadening field studies beyond Namibia to places like China and Canada's Mackenzie Mountains, as is happening now, "maybe we'll figure it out."

–RICHARD A. KERR

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