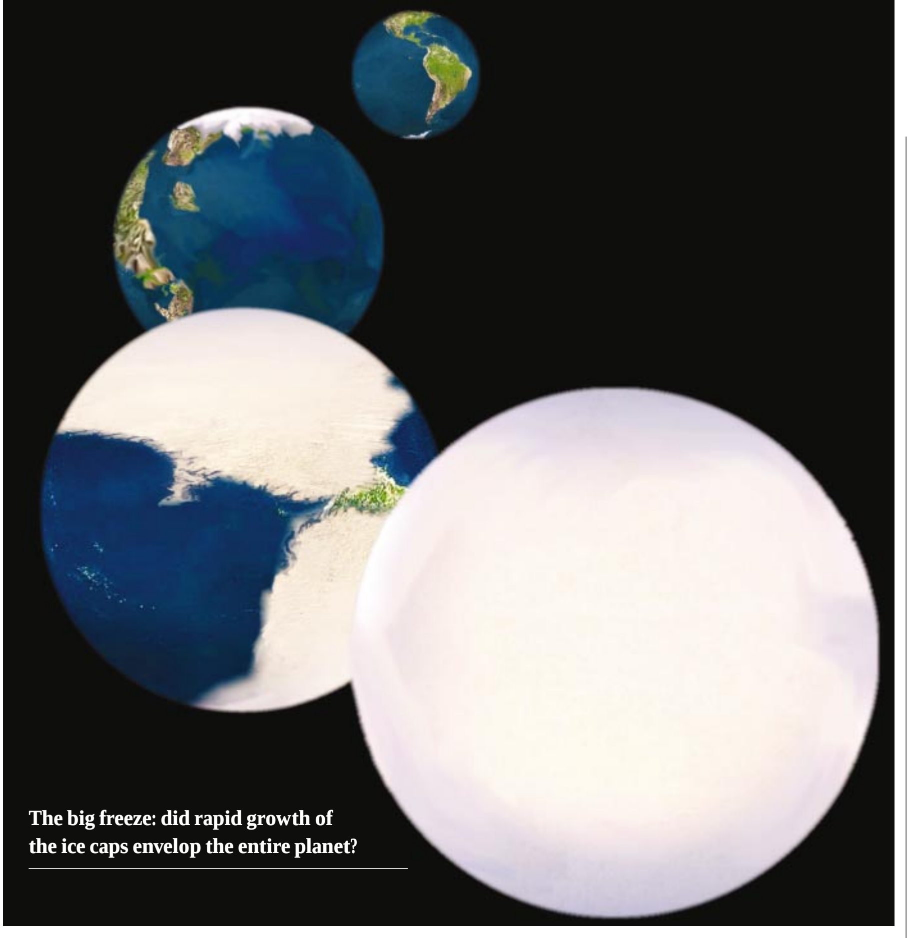
news feature

Snowball fights

Did the world freeze over some half a billion years ago? Two Harvard scientists think so, but convincing other climatologists is proving difficult. Naomi Lubick tracks the latest twists and turns in the snowball Earth debate.



The big freeze: did rapid growth of the ice caps envelop the entire planet?

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Paul Hoffman and Daniel Schrag have had a busy few years. In 1998, the two Harvard University geologists rekindled a radical idea: that on at least one occasion between 580 million and 750 million years ago, the Earth lay entirely encrusted in ice for tens of millions of years. This 'snowball Earth' hypothesis seemed to explain some puzzling geological data. But it was controversial then, and the debate shows no sign of letting up.

Sceptics first asked how the Earth could freeze and thaw in such a short geological time. Climate modellers have since questioned whether ice sheets could have reached the Equator. And last year came an assault on Hoffman and Schrag's central line of geological evidence. The proponents of snowball Earth, it seems, are on the defensive once more.

The idea of a global glaciation was first proposed in the 1960s by Mikhail Budyko of the Main Geophysical Observatory in St Petersburg, Russia. Budyko looked at what would happen if the Earth's climate were to cool slightly, prompting an increase in the size of the polar ice-caps. Ice reflects heat from the Sun, so this growth would cause further cooling. Runaway growth of the ice-caps could result, Budyko argued, eventually leaving the Earth entirely sheathed in ice[1].

Budyko's ideas explained puzzling evidence, including signs of scouring of rocks by ice, that seemed to imply that glaciers reached the Equator on at least two occasions between 580 million and 750 million years ago, towards the end of the Neoproterozoic period. This was baffling, because ice sheets reached only as far as northern Europe during more recent ice ages. But Budyko's theory had some holes in it. What, for example, eventually caused the ice to thaw?

Iron out

In 1992, Joseph Kirschvink, a geologist at the California Institute of Technology in Pasadena, provided an explanation of how the ice could have receded[2]. Kirschvink, who coined the term 'snowball Earth', realized that normal cycles of rain and erosion, which play an important role in removing carbon dioxide from the atmosphere, would have shut down if ice had covered the oceans. Carbon dioxide released by volcanoes would then build up in the atmosphere, eventually creating enough greenhouse warming to melt the ice sheets.

MORGUNBLADET/AP

Volcanic CO_2 may have caused a greenhouse effect that freed snowball Earth from its ice age.

Kirschvink also pointed out that a snowball Earth could explain another strange geological deposit — iron-rich rocks that formed near the end of the Neoproterozoic. Iron is added to the ocean at geothermal vents in the sea floor and precipitates out of sea water when it comes into contact with oxygen. But if the oceans had been capped with ice, oxygen levels in water would have fallen and dissolved iron would have built up. Oxygen levels would have increased when the ice melted, causing large amounts of iron to precipitate out and fall to the sea floor.

Six years later, Hoffman and Schrag, together with colleagues at Harvard, published the paper that thrust the hypothesis back into the limelight[3]. They had studied ratios of carbon isotopes in rocks formed when carbon-containing compounds precipitated out of sea water. Photosynthetic marine microorganisms take up carbon, preferring the lighter carbon-12 isotope to the heavier carbon-13 — so photosynthesis causes carbon-12 levels in water to fall, leaving less of that isotope to precipitate out.

But when Hoffman and Schrag looked at 'cap carbonates' — sediments that were deposited towards the end of the Neoproterozoic glaciations — they found surprisingly high levels of carbon-12. In fact, the ratio of carbon isotopes suggested that almost no photosynthesis had occurred in the waters from which the rocks precipitated. This, they reasoned, was exactly what would occur if ice had covered the ocean and starved it of light.

Journals' correspondence columns were

soon buzzing with debate over the paper. Some critics pointed out that there was no evidence for a lowering of sea level that would be expected to accompany the freezing[4]. Hoffman countered by disputing the reasoning behind claims that sea level should fall[5]. The pattern was set: critics have continued to assail the snowball Earth theory, while Hoffman and, to a lesser extent, Schrag have defended the idea. With some of the most serious criticisms of their idea arising in the past year, the pair are as busy as ever.

Scouring the evidence

Most researchers now accept that ice reached equatorial regions — but only on land. Evidence for this comes from the deposits that once puzzled geologists. The alignment of magnetic particles in some rocks can be used to determine the latitude at which they formed, as the Earth's magnetic field — which pulls the particles into line as the rock forms — is inclined at different angles at different latitudes. Some Neoproterozoic rocks with equatorial magnetic signatures appear to show signs of scouring from moving ice.

But Michael Arthur, a geochemist at Pennsylvania State University in University Park, who is sympathetic to the snowball Earth theory, says that there still is not enough evidence to demonstrate that the tropical oceans froze over. "The nature of the glaciation is not well known," he says. "Is it a big ice sheet? Or are they just mountain glaciers coming down?"

Others share his doubts. In January this year, geologist Daniel Condon and colleagues at the University of St Andrews, UK, published an analysis of rocks formed on the sea floor during the period when Hoffman and Schrag claim the oceans were iced over. These rocks contained layers of stony debris of the kind carried by glaciers[6]. If the debris reached the sea floor, then the ice must have melted. And the layers are so close together, claims Condon, that the oceans must have been unfrozen for at least some time each year.

Climate modellers are also reluctant to embrace snowball Earth. "It's very, very difficult to simulate," says Chris Poulsen, a modeller at the University of Southern California in Los Angeles. Last year, he published a simulation showing that the ice sheets would have stopped at northern Europe during the late Neoproterozoic[7]. One problem, say the modellers, is that oceans contain too much heat for them to freeze over completely.

Even the evidence from cap carbonates, which is considered by Hoffman and Schrag to be the 'smoking gun' for snowball Earth, has recently come under attack. Last May, Martin Kennedy, a palaeoclimatologist at the University of California, Riverside, proposed that the unusual carbon isotope ratios in the cap carbonates were caused by a sudden release of methane gas[8].

Methane matter

Kennedy, together with Nicholas Christie-Blick and Linda Sohl of the Lamont-Doherty Earth Observatory in Palisades, New York, noted that large amounts of organic matter would have been trapped under ice sheets on land during the Neoproterozoic. Methane released when this matter decomposed would have remained trapped in this ice. When the ice started to melt, ice sheets close to the oceans would have been flooded by rising sea levels, and the methane slowly released. But this methane, like the organic matter that produced it, would have contained high levels of carbon-12 and could have caused the skewed isotope ratios seen in the cap carbonates.

Last December, Kennedy and Christie-Blick teamed up with Anthony Prave of the University of St Andrews to publish a paper that cast doubt on another piece of evidence central to the snowball Earth hypothesis. In an analysis of samples of carbonate rocks from Namibia that formed before the melting of the land ice[9], they found little evidence of the odd isotope ratios that Hoffman and Schrag found in their cap carbonates. "The results indicate a very normal ocean," says Kennedy. "There was clearly no ice sheet."

Chris Poulsen's simulation of temperatures on Neoproterozoic Earth suggest that polar ice sheets (white lines) did not reach low latitudes.

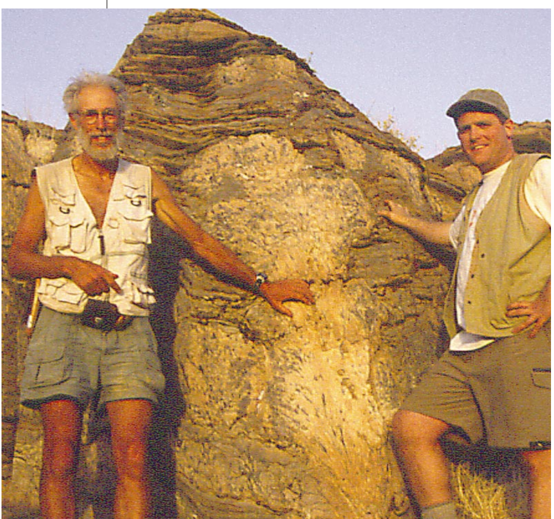
Hoffman and Schrag have not taken such criticisms lying down, and their rebuttals are scattered throughout the geological literature of the past few years. In March this year, for example, Hoffman took on what he described as Kennedy's "creative" methane hypothesis[10].

Kennedy had pointed to several unusual features of cap carbonates, such as tube-shaped cavities, as evidence that methane gas was released into the rocks as they were formed. But Hoffmann counters that these features are absent from other cap carbonates in the same area, and also disputes whether there would have been sufficient organic matter to generate the methane. To the modellers, he points out that the oceans have reached freezing point during the coldest periods of the past 10,000 years. Hoffman, sometimes with Schrag, has managed to publish a reply to almost every article on snowball Earth.

Although the debate remains polarized, most geologists and climate researchers believe that elements of many of the competing ideas are likely to be correct. But few palaeoclimatologists back the 'hard' version of snowball Earth, with its ice-covered oceans. A 'slushball Earth', with oceanic ice sheets extending to middle latitudes, seems to be gaining broader support.

But Hoffman remains unperturbed, arguing that radical ideas always face a barrage of scepticism. Both plate tectonics and evolution by natural selection faced similar battles for acceptance, for example. "I like to say I'm Kirschvink's bulldog," he laughs. ■

D. SCHRAG



Paul Hoffman (left) and Daniel Schrag claim that snowball Earth left its hallmark on rocks...

...but Martin Kennedy argues that the sediments' carbon signature was left by a methane release.

M. J. KENNEDY

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