Record: 1

Title: Ice magic.

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Source: New Scientist; 4/12/2003, Vol. 178 Issue 2390, p30, 5p, 3 Color Photographs, 1 Diagram

Document Type: Article

Subject Terms: *SNOWBALL Earth (Geology)
*EVOLUTION

Geographic Terms: EARTH

People: HOFFMAN, Paul
SCHRAG, Dan

Abstract: This article focuses on the evolution of life on Earth. Geologists Paul Hoffman and Dan Schrag from Harvard University suggested in 1998 that a momentous ice age had occurred just before the dawn of the Ediacarans. In their "Snowball Earth" scenario our planet was encased in ice up to a kilometer thick. This carapace stretched from the poles all the way to the equator and lasted for up to 10 million years before it finally melted in a climatic backlash of intense heat. Not a single alternative theory exists to explain one of the most dramatic evolutionary innovations, the leap from single to multicellular organisms. A palaeontologist at the South Australian Museum in Adelaide, South Australia, Gehling is trying to reconstruct the shape and behavior of a bizarre, jelly-like creatures called Ediacarans from the smudgy fossils from snowball earth. One popular alternative to Hoffman's Snowball theory is the Slushball Earth, in which most of the oceans are frozen, but an open band of water persists around the equator. INSET: LIVING WITH THE ICE.

Full Text Word Count: 3167

ISSN: 02624079

Accession Number: 9612876

Database: Academic Search Complete

Ice magic

For billions of years life consisted of microscopic blobs. Then along came a giant snowball and suddenly complex critters emerged. Coincidence? Gabrielle Walker doesn't think so

CRUNCH! Jim Gehling's foot lands on a Coke can and squashes it into the ground. He picks up the can, points to the misshapen circle its trace has left in the mud, and grins. “Go on,” he says. “Look at that, and tell me what shape the can was originally, or what it was used for.” This is Gehling's favourite metaphor for the work he does.

A palaeontologist at the South Australian Museum in Adelaide, South Australia, Gehling spends his days trying to reconstruct the shape and behaviour of bizarre, jelly-like creatures called Ediacarans from the smudgy fossils they have left behind. In the process, he is hoping to explain one of evolution's biggest mysteries.

By the time Ediacarans appeared on Earth, a little under 600 million years ago, simple, single-celled organisms had already ruled the world for more than 3 billion years. So successful was this early primordial sludge that palaeontologists have wondered for decades why it ever yielded its pre-eminence. What shook the planet out of its primitive complacency, and heralded the arrival of multicellular animals? And why did it happen at that particular time, so very long after life first appeared on Earth?

The answer may come from rocks just beneath the Ediacaran fossils, which speak of an extraordinary environmental catastrophe. Rocks of this age on every single continent bear the unmistakable signs of glaciation, leading geologists Paul Hoffman and Dan Schrag from Harvard University to suggest in 1998 that a momentous ice age had occurred just before the dawn of the Ediacarans (Science, vol 281, p 1342). In their “Snowball Earth” scenario our planet was encased in ice up to a kilometre thick. This carapace stretched from the poles all the way to the equator and lasted for up to 10 million years before it finally melted in a climatic backlash of intense heat. Although they are unsure what triggered the big freeze, Hoffman and Schrag believe that between 750 million and 590 million years ago, the climate swung back and forth between ice and heatwave up to four times.

The Snowball Earth theory has sparked controversy among geologists, many of whom balk at the notion of a world fully encased in ice. But while they are still wrangling about exactly how far the ice went, almost everyone now accepts that this was a time of extraordinary, unprecedented cold. During the more recent ice ages of mammoth and mastodon fame, ice barely reached as far south as New York. By contrast, even Hoffman and Schrag's most vociferous opponents agree that Snowball ice must have travelled at least to the tropics, if not all the way to the equator.

Life's industrial revolution

All of which has sent palaeontologists like Gehling racing back to their fossils, eager to find out whether these extraordinary events could have changed the course of evolution. The stakes are high. Not a single alternative theory exists to explain one of the most dramatic evolutionary innovations — the leap from single to multicellular organisms. Previously, each individual cell had to be master of all trades: it had to eat, digest, excrete, reproduce and perform all the other essentials of life within one small sac. But afterwards collaborations of cells shared the load. Thanks to structural cells, bodies could grow large and adopt inventive new architectures. Muscle cells, for example, could move these bodies to new grazing grounds; sensory cells could warn of danger; and appendage cells could rake in supplies. This specialisation turned the creep of evolution into a sprint as complex creatures competed to find ever more imaginative ways of exploiting the world's resources. If ice was the trigger of this remarkable event, it was ultimately responsible for the existence of all complex life on Earth today — humans included.

The first question facing palaeontologists eager to test the Snowball idea is exactly when did multicellular life arise? Until recently, it seemed that this momentous event occurred during the Cambrian explosion — a period of rapid development of new evolutionary shapes and strategies, during which the foundations were set for every modern phylum of animals. The problem for the Snowball idea is that this explosion happened around 545 million years ago, a good 45 million years after the Snowballs ended. That's far too long to sit around with a lighted fuse, waiting for the bang.

The Cambrian creatures are famous partly because they were easy to preserve. This was the time when life invented skeletons: scales, shells, spines, all the sorts of bodily supports that stick around long enough after death to turn into clear, unambiguous fossils. But they needn't have been the first multicellular animals, any more than language began with the printing press or papyrus. That accolade may well fall to the older and more mysterious Ediacarans, which many researchers had considered to be something of a curiosity, an evolutionary sideline that took place before the serious business of creating multicellular life started.

Ediacarans obtained their collective name in 1947, when geologist Reg Sprigg spotted what looked like squashed, petrified jellyfish near Ediacara Hills, in the Flinders ranges of South Australia. Most of the fossils have been removed from the site of Sprigg's original discovery, so Gehling does his research at a secret location elsewhere in the Flinders ranges, where a gentle hillside is covered with slabs of pale stone like broken, prophetic tablets. The stippled undersides of many of these rocks bear smudgy imprints of organisms that inhabited what was a shallow, sandy seafloor nearly 600 million years ago. There is Dickinsonia, for instance, an oval creature like a giant thumbprint, which grew up to a metre in size. A squashed, sponge-like creature, called Palaeophragmodictya, looks like a small disc set slightly off-centre within a larger one. And there's Aspidella, a disc with a set of grooves inside it, like the outline of a cartoon arrowhead.

All these creatures died, and were preserved, when a storm brought sand cascading down to smother them where they lay. The same sand also crushed their fragile bodies — which is why interpreting their original structure is such an art (and why Gehling uses his Coke can metaphor). Although some of the creatures look like nothing on Earth, others bear an uncanny resemblance to modern starfish, jellyfish, sponges and sea pens. This has persuaded many researchers, including Gehling, that at least some Ediacarans are direct ancestors of the complex animals we see today. Other experts, however, have continued to speculate that each Ediacaran was one giant single cell, quilted into many fluid-filled compartments like an air mattress; or perhaps even highly coordinated colonies of bacteria, banding together into deceptively complex shapes.

Now evidence from Russia leaves little doubt that some Ediacarans were indeed complex, multicellular animals. A few years ago, Misha Fedonkin from the Palaeontological Institute in Moscow found some puzzling fossils in cliffs along the White Sea coast near Arkhangelsk in northern Russia. On the underside of a sandstone slab he discovered four Dickinsonia. All were exactly the same size, but three were raised up proud from the rock in positive relief, and only the fourth was the usual indented mould. He also found an example of Kimberella — a creature shaped like a teardrop, with a flouncy frill around its edges — that had a mysterious long, dark trace at its rounded end.

At first Fedonkin was baffled. Then he realised that the four Dickinsonia fossils must all have come from one individual. Three times, this creature had rested on the slimy microbial mat that coated the seafloor, and left an imprint of its belly there. Only the fourth was indented — a true mould of an Ediacaran's body. And the Kimberella had left a trail in its wake, just like a slug or a snail. To make trails like these, an organism needs specialised tissues that behave like muscles. Quilted air mattresses can't do it, nor can groups of bacteria. The ability to move proves that these creatures were complex multicellular animals.

Even so, these particular Ediacarans aren't quite old enough to help with the Snowball theory. They lived 555 million years ago, which is an improvement on the Cambrian explosion, but it's still some 35 million years too late. However, more recent finds from Newfoundland, Canada, show that some Ediacarans were around much earlier. In January, Gehling and Guy Narbonne from Queen's University in Ontario described the oldest complex Ediacaran fossils in the world (Geology, vol 31, p 27). They identified faint traces of thin fronds around a metre in length as the well-known Charnia masoni. Another specimen turns out to be a new species, which the researchers have named Charnia wardi. Narbonne believes both species lived within a few million years of the end of the Snowballs.

For many researchers, this is beginning to look like more than a coincidence. “I think the odds are the Snowball kick-started something,” says Gehling. “I don't know too many people who think they're unconnected.” However, not all the fossil finds are quite so encouraging. A few researchers have turned up signs of multicellular life from before the Snowball, which would scotch the whole theory. For instance, there are the pencil-thin branching tubes etched on billion-year-old rocks from India. Their discoverer, Dolf Seilacher, who divides his time between the University of Tübingen in Germany and Yale University, believes these were made by some kind of early worm. And last year Birger Rasmussen from the University of Western Australia in Perth and colleagues reported a discovery of blobby grooves, like worm casts, in 1.2-billion-year-old sandstones from south-western Australia (Science, vol 296, p 1112). But neither find has any sign of an animal associated with the “trails”.

More troubling for the Snowball Earth theory, perhaps, are multicelled algae found in the Canadian Arctic by Nick Butterfield from the University of Cambridge. These tiny creatures are 1.2 billion years old, and under a microscope they clearly show different kinds of cells: some making a “holdfast” to bind the algae to the seafloor, others forming the filaments. If algae did become multicelled 1.2 billion years ago, this begs the important question: why do the first fossilised multicellular animals date from 600 million years later? There are two possibilities. Either algae invented complexity separately, and kept the secret to themselves, which would pose no particular problem for the Snowball hypothesis, or there were plenty of complex animals around before the Snowballs, but they left no trace in the rocks.

Though this second idea is hard to test, one way is to forget about fossils and use a more oblique approach, known as a molecular clock. By measuring the differences in DNA between species that are alive today, and estimating the rate at which the DNA changes — how fast the molecular clock ticks — it is possible to calculate the amount of time that has passed since the species diverged. Choose species that diverged when complex animals first emerged and you can work out exactly when this event took place. Many different research groups have tried this approach to discover when complexity began, but the problem is that they require so many assumptions that the answers they give are often radically different. Some say the ancestor of all multicellular animals lived around 900 million years ago, others that it was more than 1.2 billion years ago.

Last year, Kevin Peterson from Dartmouth College in New Hampshire decided to try to refute the Snowball theory by making the best possible molecular clock. He used the sequence from three different proteins found in five modern echinoderms — the family that contains urchins and sea stars — because there is a complete, well-dated set of fossils for the echinoderm ancestors to help calibrate the clock. These creatures also had similar body size, metabolic rate and time spans between one generation and the next, which Peterson felt would help with accuracy. He then compared the sequences with the same proteins in a polychaete worm and a type of sponge. To Peterson's astonishment, his clock threw out a date for the common ancestor of all complex animals of somewhere around 700 million years ago. Admittedly, it's not the magic date of 590 million years — which marks both the ending of the ice and the beginning of the first complex fossils — but it does lie in the middle of the series of Snowballs.

Spurred on by these findings, biologists are now designing newer and better molecular clocks and scouring the world's rocks for trails blazed by ancient life. Though the world of ancient fossils is pretty well explored, it's still possible that someone, somewhere, will find a vast stash of complex animals that existed long before the Snowball. But enough evidence has accumulated aligning the end of the big freeze with the origin of biological complexity that biologists are now starting to wonder how the former could have triggered the latter.

One idea is that the ice might have opened up new niches, by wiping out many of the single-celled creatures that were previously hogging all the resources. Palaeontologist Andy Knoll from Harvard University suggests that such a “permissive ecology” — where competition for resources is relatively weak — instigates biological revolution. “[That's because] you don't have to be good to win the game of evolution,” he argues. “You only have to be better than the other players.” Another possibility, advanced by Gehling, is that multicellular life could be a response to the sheer changeability of climate during the Snowballs and their sweltering aftermaths. When the Earth is alternately frozen and then scorched there could be some advantage in having differentiated cells that can help an organism control its internal environment.

But the most popular idea to date involves oxygen. Larger, more complex creatures need efficient ways of mobilising their food into energy, and oxygen is one of the best. Oxygen is also necessary to make collagen — the connective tissue found in every complex animal. There are signs in the rocks that atmospheric oxygen was increasing around the end of the Snowballs. While nobody yet knows why, one possibility is that the rise was triggered by a burst of new life when the ice melted. For millions of years, life would have been restricted to a few small refuges so nutrients would have accumulated in the oceans, turning them into a tasty chemical soup. As soon as the ice receded, the oceans would have become green with massive colonies of bacteria and algae, which may have injected a pulse of oxygen into the post-Snowball oceans.

These are early days for the Snowball theory. It's still possible that ice had nothing to do with the complex life that followed. But if the theory turns out to be right, it bears a message for the future of our planet. Life, it seems, thrives on adversity. Whatever environmental catastrophes we succeed in inflicting on the Earth, it seems likely that living things will bounce back, stronger and more exotic than ever. Whether we are around to see this is another matter.

“To make trails an organism needs specialised tissues that behave like muscles. Quilted air mattresses can't do it, nor can groups of bacteria. These were complex animals”

“As soon as the ice receded, the oceans would have been green with colonies of bacteria and algae, which may have injected a pulse of oxygen into the post-Snowball oceans”

DIAGRAM: WHEN THINGS GET COMPLECATED

PHOTO (COLOR):

PHOTO (COLOR):

PHOTO (COLOR): Fossils found in these rocks in Newfoundland, Canada, date from just after the Snowball

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By Gabrielle Walker, Gabrielle Walker's book Snowball Earth is published in Britain by Bloomsbury and in the USby Crown. She will be giving a lecture on the topic at the Royal Institution in London on 7 May at 7.30 pm

LIVING WITH THE ICE

Many biologists are alarmed by Harvard University geologist Paul Hoffman's vision of a fully frozen world. Even if complex animals didn't evolve until after the ice melted, there were still plenty of simpler creatures — bacteria and algae — that needed to pull through. “I don't say it's impossible,”
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says Kevin Peterson of Dartmouth College in New Hampshire. “You never say ‘impossible’ when you're talking about life, because there are always some bacteria out there that will prove you wrong. But it's highly unlikely. You just can't freeze the whole world over and expect life to survive it.”

True, living things are extraordinarily resilient, especially simple ones. Bacteria can survive extremely hostile conditions; some have been found alive at the base of glaciers, and even inside solid rock. Unknown to the authorities, a small colony of Streptococcus mitis hitched a ride to the Moon in 1967 inside an Apollo TV camera, and the bacteria were still alive three years later when the camera was brought back to Earth. They had managed to survive without food, water or even air. However, biologists believe that most of the denizens of the pre-Snowball world would have depended heavily on the more normal requirements of life: liquid water, warmth and sunlight. And that means the Snowball oceans could not be completely frozen over.

One popular alternative to Hoffman's Snowball is a softer variety: a Slushball Earth, in which most of the oceans are frozen, but an open band of water persists around the equator (Nature, vol 405, p 425). However, Hoffman insists that this situation would be precarious, like a pencil balanced on its tip, and would quickly revert to one of two more stable options — a fully frozen ocean or a large-scale retreat of the ice. Instead, he proposes that the Snowball ocean had a few small refuges for life. Any hot spring or volcano on a shallow enough ocean floor would have created at least a small hole in the ice above it. Also, says Hoffman, although global temperatures would initially have plunged to around −40 °C, they would have gradually risen as carbon dioxide built up in the air, until the sea ice became thin enough to crack periodically.

Last year, Doug Erwin from the National Museum of Natural History in Washington DC decided to calculate just how many refuges Snowball life would have needed. In an isolated group, harmful genetic mutations can quickly spread. For the species as a whole to survive, any one group must contain enough individuals to dilute this danger, and there must be enough separate groups so that if a few of them fail the rest will still pull through. Using this reasoning, Erwin calculated that virtually all of the existing species at the time could have survived a Snowball with just 1000 different refuges, each housing around 1000 individuals. What's more, since the creatures were so tiny, each of these refuges need only have been about the size of a dinner plate.
