Popsicle Planet

The king of all ice ages may have spurred animal evolution

By RICHARD MONASTERSKY

On the eastern flank of the Blue Ridge range lies a misnamed nub of mountain called Sharp Top. From a distance, the rounded peak near Batesville, Va., could easily be mistaken for hundreds of other green Appalachian hills covered with chestnut oaks and Virginia pines. Beneath the canopy of leaves, however, Sharp Top reveals something unusual. House-size lumps of bedrock protrude from the hillside like icebergs piercing the surface of the ocean. These outcrops contain hints of the greatest set of ice ages ever to engulf the planet.

On a sweltering July day, Christopher M. Bailey fights his way through the underbrush to study Sharp Top's legacy of frozen times. Bailey, a geologist at the College of William and Mary in Williamsburg, Va., reaches a spot where a tree toppled during a recent hurricane, exposing a fresh slice of bedrock. The stone originally formed more than 700 million years ago, when this region bordered a seaway cutting through Rhodinia, a giant continent that included most of the world's land. At this site, baseball-size cobbles got mixed with a slurry of fine silt and sand to form a rock called diamictite. To geologists, diamictites often spell ice.

"You're looking at the base of the glacier," says Bailey, reconstructing the area as it was when the rocks formed. "You can imagine a piedmont [foothill] glacier like the kind in Alaska today, with its toes just sticking into the water." When the ice melted back, it left behind the jumbled mixture that eventually formed diamictite, he and a colleague propose in the July GEOLOGY.

Rocks on the other side of Sharp Top contain signs of tides, indicating that the glacier stretched down to the sea. At that time, Virginia was sitting within 15° to 30° of the equator, says Bailey. In today's world, ice couldn't survive at sea level at such a latitude. Think of a glacier covering the beaches of Miami.

For more than 35 years, geologists have been accumulating evidence that during the time when the Sharp Top rocks formed, glaciers thrived in regions that are now tropical. Scientists have puzzled without success to explain how ice could have reached so close to the equator in this period, known as the Neoproterozoic era.

Now, a team of geologists has culled clues from Namibia and fashioned a coherent hypothesis that could solve the enduring mystery. The key, they propose, is carbon dioxide. The atmospheric concentration of this heat-trapping greenhouse gas dropped so low in the Neoproterozoic that the planet froze over completely for 10 million years, killing off most life, which at the time consisted primarily of microbes and algae.

In a dramatic reversal of fortunes, carbon dioxide then grew so abundant in the atmosphere that the ice thawed and Earth roasted, according to the hypothesis. The planet swung between icehouse and greenhouse at least four times, severely stressing the established organisms. Ultimately, this crisis may have triggered the evolution of the first recognizable animals, the scientists argue in the Aug. 28 SCIENCE.

"Climate and biology and everything else was going on a see-saw through this interval. It's as if the Earth was going through growing pains," says Alan J. Kaufman of the University of Maryland in College Park, who collaborated in the new study. "This ended up being the cradle of animal life."

P.F. Hoffman

In Namibia, a student stands in front of boulder-studded rock called glacial diamictite—evidence of an ice age more than 700 million years ago. Carbonate layers, a sign of warm water, appear above his hand.

Seen from space during the Neoproterozoic glacial periods, Earth would have looked like a well-packed snowball, according to the new hypothesis. No patches of blue ocean. No clouds in the sky. Just ice, with perhaps some bare rock.

In contrast, a satellite picture of the planet during the most recent Pleistocene ice ages would have looked far more familiar. Even at the peak of the Pleistocene cold spells, around 20,000 years ago, ice sheets covered the Northern Hemisphere only as far south as the Ohio River Valley in North America and Kiev in Europe. Much of the globe remained free of ice.

Adding to the mystery of the Neoproterozoic era, geologists have found that the glacial deposits from this time almost always lie directly below carbonate rocks—normally a signal of warm waters.

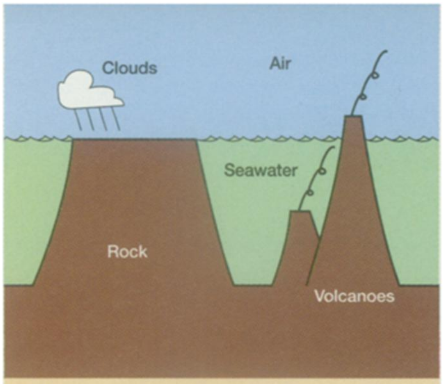
"This has been a paradox. We assume diamictites represent cold temperatures, and we assume the carbonates represent temperatures like in the Bahamas or the Yucatán," says Kaufman.

Like any enigma in science, the Neoproterozoic glaciations have attracted their share of inventive, even oddball, theories. One scientist proposed that Earth's axis of rotation tilted so far over that the poles received more sunlight than the tropics, causing the planet's midsection to freeze but leaving the poles clear. Another researcher suggested that Earth had Saturnlike rings, which blocked sunlight reaching the tropics. But such ideas did not match the available evidence.

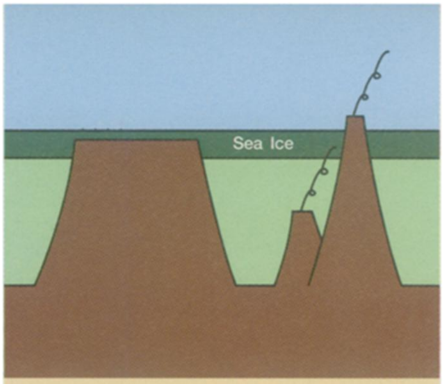
Even without rings, Earth would have looked otherworldly in the interval leading up to the Neoproterozoic glaciations. Almost all land areas were plastered together to form the supercontinent of Rhodinia. It was centered in the tropics, leaving a single vast ocean sweeping across the other side of the globe, from one pole to the other. The only rocks from that time whose original locations are well known come from the tropics and midlatitudes, so geologists know little about what happened at the poles during this era.

In 1992, Joseph L. Kirschvink of the California Institute of Technology in Pasadena reached the conclusion that the tropical land areas had frozen and that the poles must have been even colder. The globe, he said, would have been a "Snowball Earth," with pack ice covering much of the ocean.

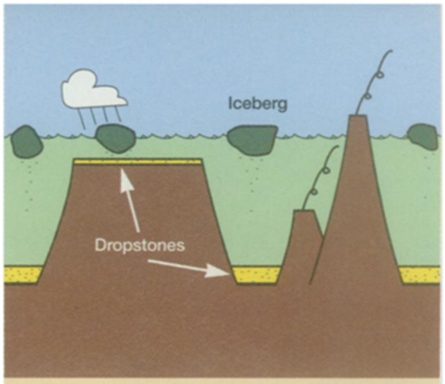
Although it drew on suggestions made by earlier researchers, Kirschvink's model languished, in part because it failed to explain the curious carbonates. Now, Kaufman and his colleagues offer an all-



A new theory for an ancient ice age: As a giant continent splits, ocean life flourishes, pulling carbon dioxide out of the air. The ratio of carbon-13 to carbon-12 in seawater rises high.



Without much carbon dioxide in the air, the oceans freeze. The ratio of carbon-13 to carbon-12 drops, reflecting an almost total absence of photosynthesis. During the ice age, the seafloor sinks.



Carbon dioxide from volcanoes warms the climate. Rocks falling from icebergs form a layer of glacial diamictite.

encompassing theory to tie together both diamictites and carbonates.

The force behind the new hypothesis is Harvard University's Paul F. Hoffman, who has spent decades studying the much-overlooked rocks of the Precambrian time, which ran from the birth of Earth 4.5 billion years ago to the start of the Cambrian period 543 million years ago. The last part of the Precambrian is the Neoproterozoic.

In 1992, Hoffman launched a series of investigations in northern Namibia, which during the Neoproterozoic was a continental shelf bordering the Congo land mass. Like similarly aged deposits in Australia, northwestern Canada, and the arctic islands of Svalbard, the rocks of Namibia have layers of glacial diamictites covered by a cap of carbonates. The Namibian carbonate layers, however, are unique because they each measure 200 to 300 meters thick—10 to 100 times the size of layers elsewhere. This extensive stack of rocks provides a close-up look at what happened during the time they formed, say the researchers.

To piece together the events, Hoffman and his colleagues focused on carbon atoms in the carbonate. Carbon in ancient rock comes in two flavors. The relatively rare isotope, carbon-13, has one neutron more than the abundant type, carbon-12. Living organisms, such as algae and microbes, tend to extract the lighter form from seawater when they turn carbon dioxide into sugars through photosynthesis. As these organisms die and fall to the ocean floor, the carbon-12 gets sealed away, leaving behind water rich in carbon-13.

In the Neoproterozoic, carbon precipitated out of this enriched ocean water to form carbonate rocks on continental shelves. Their isotopic fingerprint gives clues to ancient biology. By measuring the ratio of the two carbon isotopes, geologists can calculate how fertile the oceans were and how much of the ocean crop got buried beneath the seafloor.

Hoffman, Kaufman, and their colleagues collected 800 samples of carbonate rocks from below and above the glacial diamictites in Namibia. When Kaufman performed the isotope analysis, he found that the rock formed before the glacial deposits was chock-full of carbon-13.

Then, just before the time of the ice-age diamictites, the relative amount of carbon-13 dropped sharply. It declined slightly more after the glacial epoch. For isotope specialists, such swings signal profound events. "These isotopic excursions are enormous in comparison with any excursions in the preceding 1.2 billion years or in the Phanerozoic eon [the last 543 million years]," the researchers report in their SCIENCE paper.

The surplus of carbon-13 before the ice age reflects life in overdrive, says Kaufman. Photosynthesizing organisms were pulling carbon-12 out of the water, and their bodies were getting covered over by a vast supply of sediments washing into the oceans. Then, the ice age came and the good times ended. The depressed isotopic values indicate that photosynthesis in the shallow reaches of the ocean ground to a halt, says Kaufman.

In previous studies at other sites, Kaufman had pieced together part of the isotope story, but he had never known how long the glacial period lasted. In Namibia, Hoffman's team was able to make an indirect estimate using the thick carbonate layers.

The carbonates, the geologists knew, formed entirely underwater and quickly built up a layer 300 m thick—a sign that the Namibian site sat in deep water after the ice age. But before the glacial period, geological evidence indicates that the site was in shallow water. That means the continental shelf sank substantially during the ice age.

Since sea floor subsides at a predictable rate as it ages, Hoffman and his colleagues could calculate how long the ice age had lasted. They figured 10 million years—about a hundred times longer than each Pleistocene ice age.

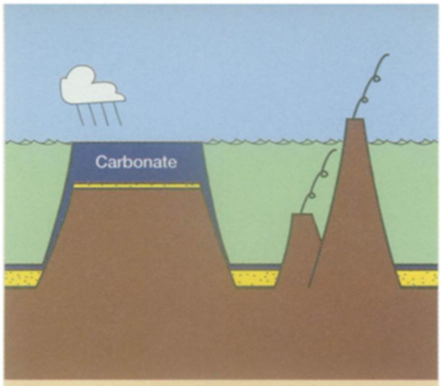
The most likely explanation for such a prolonged drop in isotopic ratios is a Snowball Earth even more extreme than Kirschvink imagined, according to Hoffman's team. If ice totally covered the oceans for 10 million years, it would have blocked out sunlight, shut down photosynthesis, and killed most ocean life.

The vagaries of plate tectonics may have set off this life crisis, according to the new hypothesis. Around 760 million years ago, Rhodinia started to split apart, forming a new ocean basin that was a forerunner to today's Pacific. As this rift tore open the ancient continent, it created new beachfront property as well as new coastal waters hospitable to plankton. Life bloomed in these regions. Rampant photosynthesis pulled billions of tons of carbon dioxide out of the air, and this carbon got quickly buried on the continental shelves.

Atmospheric concentrations of carbon dioxide eventually dropped so low that Earth's greenhouse effect weakened. The planet could no longer hold heat, and the ocean started to freeze. Because the sun was about 7 percent dimmer than it is today, Earth was particularly susceptible to such a fate.

The planet would have remained in its deep freeze had it not been for volcanoes. Over millions of years, carbon dioxide gas pouring out of volcanoes accumulated in the atmosphere until its concentration reached 350 times the present value. At that point, the supercharged greenhouse effect rapidly melted the ice and baked the Earth in temperatures far above those reached today, according to the researchers.

With so much carbon dioxide in the atmosphere, rain would have turned highly acidic and eroded continental rocks. Calcium from these rocks would have washed into oceans and combined with abundant bicarbonate ions to form post-glacial carbonate layers around the globe. The isotopic ratio in these rocks reflects a deficit in carbon-13, because life had yet to recover and there was little photosynthesis to pull carbon-12 out of the water.



An overabundance of carbon dioxide in the air creates a hothouse climate. A thick carbonate layer forms on top of the diamictite in the shallow seas.

From the multiple glacial deposits recorded in the Neoproterozoic, Hoffman and his colleagues hypothesize that Earth lurched from icehouse to greenhouse and back again four or more times between 760 million and 550 million years ago. Each cycle would have winnowed the rolls of life, forcing new evolutionary developments, say the researchers.

"You have an alternation between times that are deadly—both the ice age and the meltback—and periods when productivity is just going crazy," says Hoffman.

Genetic experiments using fruit flies suggest that such extreme swings prompt new species to arise. "You have a severe restriction which only allows select organisms to survive, and you take that genetic material and you allow it to expand to fill all the niches, which doesn't take long," Hoffman points out.

The struggle may have jump-started evolution and promoted the development of animal life, according to the researchers. In Neoproterozoic sediments around the world, the first abundant large fossils on Earth appear just after the last glacial diamictites. Known as the Ediacaran biota, these fossils represent the earliest known animals as well as some unclassifiable creatures.

If Earth was so prone to freezing in Neoproterozoic times, why haven't total ice ages engulfed the planet anytime since then? Hoffman's team suggests that several key factors have prevented this frigid fate.

The sun deserves some credit, having grown steadily stronger since the Neoproterozoic. Worms have also provided some defense since their appearance in the late Precambrian. As they churn through seafloor sediments, worms liberate carbon that would otherwise remain buried, keeping atmospheric carbon dioxide at comfortable concentrations.

A totally ice-covered globe may appear extreme, but the hypothesis gives little trouble to researchers who study the Precambrian time. They are used to thinking of Earth as a foreign world.

"It wouldn't have been a very hospitable place, but it wouldn't have extinguished life," says paleobiologist J. William Schopf of the University of California, Los Angeles. Hot springs and volcanic features would have remained warm and provided a haven for many species, says Schopf.

Some microbes and algae may also have survived within the ice itself, he says.

"Snowfields are not pure white. They have dust particles and rocks spewed out of volcanoes. Those are dark and they absorb heat. As they absorb heat, they melt the surface of the ice and there are little puddles around them" where microorganisms can live, he says.

Guy M. Narbonne, a paleontologist at Queen's University in Kingston, Ontario, says the Snowball Earth hypothesis seems to explain the available evidence. "There seems little doubt that we're dealing with a glaciation the likes of which Earth has not seen in the last several hundred million years."

Narbonne and others suggest that some organisms may have survived below the thick ice through chemosynthesis, which draws energy from chemical reactions instead of from sunlight.

Hoffman has already started to test the Snowball Earth hypothesis by looking for geological evidence that the oceans were ice-covered—and cut off from the atmosphere—for millions of years. This month, he returned from another field season in Namibia and plans future trips to Newfoundland and Svalbard.

Paleobiologists will also look through the fossil record for signs of evolutionary stress at the time of the hypothesized glacial crises. Harvard's Andrew H. Knoll says that some changes in plankton communities appear to have coincided with the glacial epochs. On the other hand, some of the most complex life at the time—the red, green, and brown algae—survived just fine.

The Snowball Earth hypothesis comes at an opportune time, when many scientists are starting to focus attention on the Precambrian time, especially its turbulent ending. Researchers are hunting down new field localities, such as the Blue Ridge mountains, that may shed light on this neglected time.

Ken Caldeira, a climate modeler at Lawrence Livermore (Calif.) National Laboratory, says he remains unconvinced that ice could have covered so much of Earth. Nonetheless, he praises the new work: "Even if it's wrong, it will stimulate a lot of interesting research."

Hoffman admits that the hypothesis is initially hard to swallow. "Emotionally, it seems pretty fantastic," he says. "But the science drives me to it. How could I not believe it? It explains practically everything." □