Snowball Earth

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Roy Jenne  
April 20, 2004
SNOWBALL EARTH
THE STORY OF THE GREAT GLOBAL CATASTROPHE THAT SPAWNED LIFE AS WE KNOW IT
GABRIELLE WALKER

CROWN PUBLISHERS / NEW YORK
Did the Earth once undergo a super ice age, one that froze the entire planet from the poles to the equator? In *Snowball Earth*, gifted writer Gabrielle Walker has crafted an intriguing global adventure story, following maverick scientist Paul Hoffman's quest to prove a theory so audacious and profound that it is shaking the world of earth sciences to its core.

In lyrical prose that brings each remote and alluring locale vividly to life, Walker takes us on a thrilling natural history expedition to witness firsthand the supporting evidence Hoffman has pieced together. That evidence, he argues, shows that 700 million years ago the Earth did indeed freeze over completely, becoming a giant "snowball," in the worst climatic catastrophe in history. Even more startling is his assertion that, instead of ending life on Earth, this global deep freeze was the trigger for the Cambrian Explosion, the hitherto unexplained moment in geological time when a glorious profusion of complex life forms first emerged from the primordial ooze.

In a story full of intellectual intrigue, we follow the irascible but brilliant Hoffman and a supporting cast of intrepid geologists as they scour the planet, uncovering clue after surprising clue. We travel to a primeval lagoon at Shark Bay in western Australia, where dolphins cavort with swimmers every morning at seven and "living rocks" sprout out of the water like broccoli heads; to the desolate and forbidding ice fields of a tiny Arctic archipelago seven hundred miles north of Norway; to the surprising fossil beds that decorate Newfoundland's foggy and windswept coastline; and on to the superheated salt pans of California's Death Valley.

Through the contours of these rich and varied landscapes Walker teaches us to read the traces of geological time with expert eyes, and we marvel at the stunning feats of resilience and renewal our remarkable planet is capable of. *Snowball Earth* is science writing at its most gripping and enlightening.

**GABRIELLE WALKER** earned a Ph.D. in natural sciences from Cambridge University. She served as the features editor at *New Scientist* magazine for seven years and is currently a contributing editor there. She has also taught in the science writing program at Princeton University. Her travels in search of stories have taken her to all seven continents—including a stint at the South Pole.
ADVANCE PRAISE FOR SNOWBALL EARTH

"Snowball Earth is riveting in its vivid portrayal of the great, icy catastrophes which may have gripped our planet nearly a billion years ago, and in its depiction of the very human scientists involved—their mutual influences and conflicts, their fascinatingly different styles. Both the geological and the human story are brilliantly told."
—Oliver Sacks, M.D., author of Uncle Tungsten

"Paul Hoffman is a charismatic genius who has devoted himself to proving what will be one of the most important scientific theories of the twenty-first century. He is fortunate to have a writer as gifted as Gabrielle Walker to document his extraordinary intellectual adventures. This is a fascinating story, brilliantly told."
—Simon Singh, author of The Code Book

"Snowball Earth is more than a great geological detective story—it's a great illustration of how science works. Scientists don't simply have the truth handed to them. They dream up wild ideas and then fight for them tooth and nail, while other scientists try to show that they're wrong. Gabrielle Walker gives us a front row seat for one of the most fascinating of these battles being found anywhere in science today."
—Carl Zimmer, author of Evolution: The Triumph of an Idea

"We have been waiting for a book that explains in an accessible way what may be the most important events in the history of our planet—times when the Earth froze from pole to pole. Gabrielle Walker has provided a colorful and lively account of both the science and the scientists. It fulfills the task admirably."
—Richard Fortey, author of Trilobite

"Gabrielle Walker tells the compelling story of one of the most dramatic discoveries of modern science. Along the way she paints a lively picture of the all-too-human strengths and foibles of the characters involved: their suspicions and dreams, their passions and churlishness. I have never seen the scientist's life captured so vividly as in the pages of Snowball Earth."
—Niles Eldredge, author of Life in the Balance
ABOUT THE AUTHOR

Gabrielle Walker earned a Ph.D. in chemistry from Cambridge University. She spent seven years at New Scientist magazine, where she was features editor and is currently a consultant, and has taught at the science writing program at Princeton University. She has written on science and technology for a host of newspapers and magazines, including Nature and The Economist, and she is a frequent pundit for BBC radio and television. Her travels in search of stories have taken her to all seven continents—including a stint at the South Pole.

COMMENTS ABOUT THE AUTHOR

Gabrielle Walker has done an excellent job in telling the story of The Snowball Earth. The reader gets a front seat in viewing the discovery process of trying to figure out what the slow accumulation of data is trying to tell us. I really like to see the stories about the geology, biology, climate, and oceanography—all woven together. There are critters from flies to snakes to elephants that may add to the problems of field work. Lots of adventure! And to top it off, this book is also a great people story.

I first saw this book for sale in March 2004, and almost passed it by. I'm certainly glad that I got it!

Roy Jenne
NCAR
April 2004
An ice age in the tropics

Alan J. Kaufman

One of the enduring enigmas of Proterozoic Earth history (up until almost half a billion years ago) is the intimate association of glacial deposits with carbonates that appear to have formed in warm tropical seas. This palaeoclimatic paradox implies that, billions of years ago, Earth's surface thermostat was occasionally turned down low enough to allow glaciers to spread from the poles to very near the Equator, blanketing most of the planet in ice and snow. In contrast, the glaciers that scoured the Northern Hemisphere over the past few million years only reached as far south as the Ohio River valley in North America, and a line from near London to Kiev in Europe. The paradox might instead be explained by the formation of ancient carbonates in cold water at high latitudes, but support for at least one "Snowball Earth" comes from a new palaeomagnetic study by Evans et al. on page 262 of this issue—it suggests that glaciers covered most of southern Africa over two billion years ago, when that region sat roughly 11 degrees from the Equator.

Surface temperatures must have dropped considerably for glaciers to have existed in the tropics. The cause of the temperature drop was probably a decline in the atmospheric level of carbon dioxide, the greenhouse gas believed to be the main regulator of Earth's climate. The transfer of water from the oceans to a global network of Proterozoic glaciers would have lowered sea level, making the ocean more dense and salty; and the presence of thick, extensive sea ice might have caused the oceans to stagnate, by slowing down wind-driven circulation and blocking the sunlight that fuels biological photosynthesis and oxygen production. Covered with ice, the Earth would have reflected most of the Sun's warming rays back into space. Only a catastrophic event, like a huge volcanic eruption, a comet or asteroid impact, the sudden release of methane hydrates, or the overturn of a deep, stagnant ocean, could have pumped enough carbon dioxide back into the atmosphere to melt the planet's icy shell.

Some time after the Palaeoproterozoic ice age in Africa, molten rock erupted onto the surface to form the widespread Onguluk Formation. Evans and colleagues make a strong case that this thick pile of volcanic rocks has remained largely unaltered, so that after two billion years certain iron-rich minerals still record the direction of Earth's magnetic field, like tiny compasses frozen in time. The angle of the preserved magnetic field is used to determine the latitude at which the rocks formed. The authors further suggest that there is no significant hiatus between these tropical lavas and the underlying glacial rocks. That is critical, because the age of this glaciation is not well known. A 20- to 40-million-year break between the ice age and the volcanic episode would have allowed the southern African continent enough time to travel from high to low latitudes. If, on the other hand, there is no time missing between the two units, the thick lavas may mean that the ice age was ended by the volcanic release of massive amounts of carbon dioxide to the atmosphere.

There are several other Palaeoproterozoic glacial deposits recognized worldwide, although the exact correlation of the ice ages that they mark is not well established. In Ontario and Wyoming, for example, there is evidence of three discrete Palaeoproterozoic glaciations (Fig. 1), but which, if any, of these matches the South African example is difficult to say. Immediately overlying the second of the North American glacial deposits is a layer of the enigmatic carbonates noted above, which are distinctive in both their fine-grained texture and chemistry, specifically in their carbon-isotope compositions. Relative to most carbonates deposited in the oceans over the past 2,500 million years, these 'cap' carbonates atop both Palaeoproterozoic and Neoproterozoic glacial rocks have consistently low δ13C (a measure of the ratio of 13C to 12C; see Fig. 2), suggesting that they were formed under very strange circumstances, by modern standards.

In the Neoproterozoic, where palaeomagnetic data also point to two low-latitude glaciations, strong positive-to-negative δ13C excursions in carbonates bracket at least four discrete ice ages, and the highly positive δ13C values beneath Neoproterozoic glaciations match those in some Palaeoproterozoic carbonates. At present, however, poor age constraints and stratigraphic uncertainties make it unclear whether these older biogeochemical event markers precede or post-date glaciation.

The remarkable positive-to-negative trends in δ13C encompassing Proterozoic glaciations suggest that carbon cycling is at the heart of the palaeoclimatic paradox. These variations are consistent with the
The Snowball Earth, Complex Life, and the Time Period

- Life on earth was single cell slime for about 3 billion years.

- Two to five snowball earth periods rocked the earth starting around 750 million years ago and the last one ended 590 million years ago.

- They say that the snowball periods happened because almost all of the continents were located at the equator.
  - But it is not clear to me how that would give a snowball.

- How would a snowball period end? Volcanoes would gradually build up the amount of CO₂ in the atmosphere and that would warm the earth and melt the ice.

- Complex life first appeared someplace between 590 and 550 million years ago.
  - Some people think that the difficult snowball periods helped to set the stage for complex life.

- Where were the continents in the past? There is good evidence to figure out where the moving continents were located in the past.
  - I think that we know these positions back to at least 300 million years ago.
  - I do not know whether I should trust these estimated locations back to 800 million years ago or not.

Roy Jenne
April 20, 2004
Evaporation on a Full Snowball Earth

- There is not much evaporation from a full ice sheet.
- Yet there were big sheets of ice on the land (near the equator, they say).
- The ice sheets made icebergs that carried dirt, etc., and dumped it in the ocean. They see these deposits on the old sea floor.
- There must have been plenty of open water to give enough evaporation to generate the big ice sheets on the land.
- Was the ice really at the equator? It does seem that the magnetic evidence in the rocks indicate this.

Roy Jenne
April 2004
Anti-freeze for snowball Earth

Does complex life stop the planet freezing over? Andy Ridgwell investigates.

There is a Gary Larson Far Side cartoon showing penguins and a polar bear together on an ice floe. Spot anything wrong? Of course – polar bears live in the Arctic while penguins live in the Antarctic, with warm climates in between. Ice stretching from the Arctic to Antarctic is impossible. Or is it?

The geological record of the late Precambrian, around 600 million years ago, tells us huge glaciers gouged the landscape and deposited layers of crushed rock debris thousands of meters thick. So far so ordinary – the Earth has had many cold periods since then. Each time glaciers have left tell-tale marks on the landscape. But in the Precambrian, glaciers seem to have deposited sedimentary rocks in the tropics. We know this because even though the continents have since moved, we can read a rock's original latitude from tiny magnetic fields imprinted when it formed.

If the coast near the equator had glaciers, most of the planet must have been frozen. From space, the Earth would have looked like a giant snowball. There is evidence that this wasn't a one-off and something similar had happened several times before. However, the last 'snowball' catastrophe occurred at about the time complex multi-cellular animal life first appeared on Earth. So might there be a link between evolution and extreme climate changes?

At the University of East Anglia I studied how carbon cycles through living systems, and how carbon dioxide in the atmosphere is regulated (Planet Earth summer 2002 p6-7). More recently, working with experts on Precambrian geology at the University of California in Riverside, I began to see a fundamental difference in the carbon cycle in modern and ancient times.

The difference involves life. In the modern ocean, some microscopic marine plants (phytoplankton) and animals (zooplankton) use chemicals dissolved in sea water to make protective shells out of the mineral calcium carbonate. These tiny organisms can have a big effect, sometimes turning the ocean surface milky-white when vast blooms form. When the plankton die, their bodies settle on the ocean floor. In shallow seas, this is how chalk rocks are formed.

In the deep sea, calcium carbonate can dissolve, and over thousands of years the rate these shells dissolve helps regulate ocean chemistry and the amount of atmospheric carbon dioxide. But back in the Precambrian, life had not yet thought about building shells, and there would have been no carbonate shell 'regulator'.

Earth would have looked like a giant snowball.

There would be the greatest ice age the Earth ever experienced.

Once organisms that use calcium carbonate became widespread in the ocean, carbon dioxide in the atmosphere would have been better regulated and the Earth could no longer 'snowball'. Perhaps we are only here because the recent ice ages that our caveman ancestors had to live though were not too cold.

Carbon dioxide from burning fossil fuels is now making the ocean more acidic and environmental conditions more difficult for organisms that lock up calcium carbonate in shells and skeletons. Recent reports of declining coral reefs might be showing there is already a problem. So what are the implications for future climate? This type of complex issue, involving interactions between climate, carbon cycling, and living organisms responding to global change is just what NERC's new programme Quantifying the Earth System (QUEST) aims to tackle.

I am now testing my theories using the GENIE Earth System model (part of NERC's e-Science programme), which represents carbon cycling as well as ocean and atmosphere circulations, and will soon be able to show how ice sheets grow and decay. This will give a much better idea of how important calcium carbonate-forming plankton are in regulating climate and maintaining conditions suitable for complex life like you and me.
To answer this, Paul Hoffman has seized on an idea that was first proposed sixty years ago, and was then dropped, halfheartediy resurrected, and dropped again several times over the intervening years. There's nothing halfhearted, however, about the resurrection Paul has now effected. He's marshaled new evidence, restored and amalgamated old ideas, and employed fierce argument to persuade the people around him. According to Paul, life's richness, diversity and sheer overwhelming complexity arose from a mighty catastrophe. It's called the "Snowball Earth."

Compare that to Paul's picture of the Snowball. A global freeze. A planet that looked more like Mars than home. Ice everywhere. And then a sudden lurch from the coldest to the hottest that the Earth has ever been. Every way you look at it, his Snowball stretches the bounds of decency. It's as extreme and catastrophic as they come.

This is Paul Hoffman's vision, and he is enchanted by it. Most other geologists are horrified. Accept his story, they say, and you have to reconsider everything you thought you knew about the workings of the world. Geologists are taught from an early age that the Earth is a slow and steady place.

So, in his sophomore year at McMaster, he began to ask around. The Arctic, he was saying. How can I get to the Arctic? For that, it turned out, he needed to approach the Geological Survey of Canada, an august, government-funded institution that sends geologists prying and poking at rocks in the remotest, most inaccessible locations.
The mosquitoes appear first. They are big and noisy and desperately annoying. They insert hypodermic needles into your skin, and the moment they bite, you can feel it. A few weeks after the mosquitoes come the black flies, smaller but more devious. They are master miners. They carve out a cavity in your skin, injecting you first with anesthetic to prevent you noticing. The anesthetic they use is a nerve poison. If you get a few hundred black fly bites quickly enough—within an hour, say—you begin to feel the effects of the toxin. You feel nauseated, can’t concentrate, and lose your bearings.

The Cambrian, roughly 550 million years ago, is the time when serious fossils first appear in the rocks. If you look at a section of rock from the beginnings of the Cambrian, you start to see real creatures with legs and teeth and armor plating, and you see changes in the fossils over time.

But where should he go? Harvard University offered him a haven for his academic base, and he moved there gladly. But he needed a new field site, one with exposed rocks from the right time, the Precambrian.

Farther north still, the Precambrian outcrops emerged from beneath the volcanic floods. When these rocks formed, more than 600 million years ago, Namibia was covered with a broad, shallow sea that left behind sandstones and mudstones, pink carbonates and dark gray shales. Peering closely at these rocks, Paul found the thumbprint whorls of the ancient stromatolites that had inhabited the Precambrian shores; he found sand dunes, beaches and lagoons, all now petrified and awaiting his notebook and hammer.

Then something began to nag at him. Everywhere Paul went in Namibia, he spotted signs of ancient ice. He would be hiking up a gully and suddenly he would see a huge white boulder embedded in the gray siltstone. Siltstone is formed from an ancient seabed. Over time in the ocean, a fine rain of sediment lands gently on the seafloor and is gradually converted to rock. But a boulder had to be brought in separately.
from the shore. Something must have carried it out into the ocean and then flung it overboard. There were no ships in the Precambrian, and certainly no creatures capable of flinging anything. The culprit had to be icebergs. The boulder, a "dropstone," must have fallen from a melting berg up on the sea surface.

The five geologists attached their harnesses to the heavily loaded Nansen and began to plod their way up the glacier. Step, heave. Step, heave. They had almost reached the top of the slope. Then the ground vanished from under them.

The sled and the nearest two people plummeted immediately into a vast cavern of ice. One, two, three, the others followed, whipped backward on their harnesses through a huge hole in the snow. The foremost man came last, his ski catching on the surface and tearing away from his foot as he fell.

And as Brian returned to the islands time and again, one particular feature of the rocks began to bother him. In many of the outcrops that poked through Ny Friesland's sheath of ice, a strange red stripe stood out against the pale yellows and browns and grays around it. Up close, the stripe was a chaotic mix of reddish boulders and rocks, all shapes and sizes, bound together in a background of fine silt.

And then suddenly he had it. He conjured up a way out of the ice catastrophe. The melters of the Snowball, the evaders of the ice catastrophe, were volcanoes.

The tusks were the first thing I saw—short, white and wicked. Then the rest of the elephant's head took shape against a backdrop of dusty acacia leaves. Tiny eyes set in a creased, anxious forehead. Ears thrust outward, making the great head seem monstrous. This, I dimly recalled, was the elephants' universal warning signal. "Ears back: good. Ears forward: very bad." I froze.

African elephants are immense creatures—they weigh up to six tons and stand some eleven feet tall. They're fabulous, viewed from the window of a safari truck. But between me and this
He was more baffled still by the “cap” carbonates that came after the ice. These are the same rocks that show up all around the world. Brian Harland had seen them in Svalbard. They stretch for miles in Australia, Canada, almost everywhere that the glacial rocks appear. And that’s peculiar.

So where did these cap carbonates come from? Everywhere the ice rocks appeared, the caps seemed to be. And the ice rocks showed up on every single continent. Why? Why?

Crystal fans, tubes, ice rocks, strange isotopes. Paul was increasingly convinced that all this evidence added up in some way, and would somehow yield crucial clues about the Snowball. He tried continually to make sense of all these features. He visited and revisited the strange carbonate formations to collect samples, to note and map and muse.

By the end of 1997, Paul was feeling frustrated. He had now

How to make sense of the evidence??

Dan listened carefully. He retreated into a corner to think, while Paul and the friend politely chatted. When Dan is concentrating on a problem, he goes silent. His eyes dart around, focusing on something out of view. He often bites his bottom lip. Then, when he comes upon an answer, his eyes fire up. He immediately, eagerly, blurts it out. Wait! I’ve got it! I can explain the carbonates!

Then why did it take so long? Though the history of life is ambiguous, traced through an imperfect record of fossils and rocks, most researchers believe that complexity was invented somewhere between 550 and 590 million years ago. That’s after more than 3 billion years of simple, single-celled slime.

Biologists have been trying for decades to understand why complex life appeared on Earth at that particular moment. And then, along came Paul Hoffman, talking of global catastrophe. Paul’s evidence suggested that at least two, and possibly as many as five, successive Snowballs had rocked the Earth starting around 750 million years ago. Most significantly, this series of Snowballs ended 590 million years ago, just around the time complex life was beginning to emerge.
So now we know what Ediacarans were. But when were they? The fossils at Ediacara and in the White Sea lived around 555 million years ago. That’s an improvement on the Cambrian explosion, but it’s still some 40 million years after the Snowball. The next step would be to find Ediacarans from nearer the end of the ice. (at 590 mil years ago)

Biologists aren’t so very different from geologists, under the skin. Some of them have jumped eagerly onto Paul’s Snowball bandwagon, and some have declared furiously that it must be stopped. And some are still waiting to see what will happen.

Other snowballs

So now we know that Snowballs have happened twice. At least one occurred a little over 2 billion years ago, and then a series of perhaps four engulfed the Earth between 750 and 590 million years ago. There have apparently been no others. Why?

Continents all at the equator

But on a few rare occasions, they can find themselves in a band around the Earth’s equator. And this might be exactly what happened during the Snowball periods.

India hits Asia (50 mil years ago)

So India crashed into Asia, and the land began to rise. First the crust of Asia squeezed around the sides of the thrusting arri-viste. Then, as India wedged itself like a chisel farther beneath Asia, the surface crust crumpled and folded into a range of moun-

Meanwhile, partway around the world, Africa was aggressively reacquainting itself with its old Pangaean neighbor, Europe. The first part to hit was a peninsula, sticking out from the northern part of the African plate and bearing what is now Italy and Greece and the countries of former Yugoslavia. This collision threw up the beginning of the Alps. Spain crammed into France, and henceforth there were Pyrenees.
SIX: ON THE ROAD


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**Low Oxygen in Old Oceans**

Earth's early atmosphere was reducing, and atmospheric $\text{O}_2$ appeared in appreciable amounts only about 2.3 billion years ago. When did the deep ocean become oxygenated? Banded iron formations, which are indicative of low $\text{O}_2$ concentrations, were produced until 1.8 billion years ago, but that does not necessarily mean that $\text{O}_2$ appeared in the deep ocean at that point. It has been suggested that the deep oceans remained anoxic or euxinic (low in $\text{O}_2$ and high in $\text{H}_2\text{S}$) until 1 billion years ago, only then reaching $\text{O}_2$ concentrations near today's values. Arnold et al. (p. 87) test that hypothesis by measuring the isotopic composition of molybdenum, which is sensitive to redox conditions, in modern and ancient marine sediments. Their results from samples 1.7 and 1.4 billion years old indicate that the deep ocean at those times was largely euxinic, an important finding for understanding Proterozoic ecosystems and biogeochemical cycles.
A Neoproterozoic Snowball Earth

Paul F. Hoffman,* Alan J. Kaufman, Galen P. Halverson, Daniel P. Schrag

Negative carbon isotope anomalies in carbonate rocks bracketing Neoproterozoic glacial deposits in Namibia, combined with estimates of thermal subsidence history, suggest that biological productivity in the surface ocean collapsed for millions of years. This collapse can be explained by a global glaciation (that is, a snowball Earth), which ended abruptly when subaerial volcanic outgassing raised atmospheric carbon dioxide to about 350 times the modern level. The rapid termination would have resulted in a warming of the snowball Earth to extreme greenhouse conditions. The transfer of atmospheric carbon dioxide to the ocean would result in the rapid precipitation of calcium carbonate in warm surface waters, producing the cap carbonate rocks observed globally.

During the 200 million years (My) preceding the appearance of macroscopic metazoans, ~750 to 550 million years ago (Ma) (1), the fragmentation of a long-lived supercontinent (2) was accompanied by intermittent, but widespread, glaciation (3–5). Many of the glacial deposits contain carbonate debris or are directly overlain by carbonate rocks (6, 7), including inorganic sea-floor precipitates, which are normally limited to warm-water settings (8). Post-glacial carbonate rocks (cap carbonates) occur even in terrigenous-dominated sections (6, 7). Certain glacial units contain large sedimentary iron formations (9), which reappear after a 1-billion-year hiatus in the stratigraphic record. The glacial intervals are spanned by decreases of as much as 14 per mil in the δ13C value of the surface ocean (10, 11). These isotopic excursions are enormous in comparison with any excursions in the preceding 1.2 billion years (12) or in the Phanerozoic con (13).

Paleomagnetic evidence suggests that the ice line reached sea level close to the equator during at least two Neoproterozoic glacial episodes (14). The origin of these extreme glacializations has been controversial (1, 15, 16). Kirschvink (17) proposed a snowball Earth hypothesis by a runaway albedo feedback, in which the world ocean was virtually covered by sea ice but continental ice cover was thin and patchy because of the virtual elimination of the hydrologic cycle. Kirschvink applied this hypothesis to explain the low-paleolatitude glacial deposits as well as the occurrence of banded iron formations, suggesting that an ocean sealed by sea ice would quickly become anoxic and rich in dissolved ferrous iron (17). Here, we present new data on the amplitude, timing, and duration of inorganic δ13C variations in Neoproterozoic rocks of northern Namibia and the relation between these variations and glaciation. We show that the snowball Earth hypothesis best explains the geological and geochemical observations, including the δ13C excursions and the existence of carbonates immediately following glaciations.

We studied the Otavi Group (Fig. 1), a carbonate platform covering the southern promontory of the Congo Craton in northern Namibia (15, 18, 19). In the late Neoproterozoic, the Congo Craton was a Bahama-type sea-level platform that was about the size of the continental United States. Paleomagnetic data from the eastern part of the craton (20) imply that the Otavi Group was at ~12°S paleolatitude at 743 ± 30 Ma and at ~39°S at 547 ± 4 Ma. The Otavi Group contains two discrete glacial units (Chaus and Ghaub formations) of Sturtian (~760 to 700 Ma age (15, 19). Both units are underlain by thick carbonate successions with high δ13C values, and both units are overlain by distinctive cap carbonates, recording negative δ13C excursions (10, 11).

The younger of the two glacial units (the Ghaub Formation) is represented by unstratified diamictics, debris flows, and, at the top, varved detrital couplets crowded with ice-rafter drostones (15). Both the onset and the termination of glaciogenic sedimentation were abrupt. The glacial deposits are composed predominantly of dolomite and limestone debris derived from the underlying Ombaatjie platform (Fig. 1). Clast and matrix lithologic compositions coarsen; thus, we interpreted the matrix of debris detrital in origin and not as a seawater proxy. Glacial deposits on the platform are thin and highly discontinuous (not due to subsequent erosion). Alternately grounded and floating sea ice caused large horizontal plates to be detached from the directly underlying bedrock. The subglacial erosion surface has remarkably little relief on the platform (~50 m relative to underlying strata over a distance of 150 km), suggesting that any fall in relative sea level was limited or short-lived. Comparatively thick sections (~180 m) of diamictics and debris flows occur on the continental slope, suggesting that the ice grounding line remained close to the platform edge (Fig. 1). These observations are consistent with an abrupt development and a subsequent dissipation of grounded sea ice on a tropical or sub...
tropical platform, consistent with a snowball glaciation.

We measured inorganic $\delta^{13}C$ values of carbonate rocks that spanned the glacial interval from several sections (Fig. 2) (10, 11). In general, $\delta^{13}C$ values in carbonates are rather insensitive to diageneosis because aqueous fluids contain little carbon in comparison with carbonate rocks (21). This inference is supported by the overall agreement of the pattern of isotopic variations from multiple sections. The $\delta^{13}C$ data on the platform (summarized in a composite section in Fig. 3) show that (i) preglacial values are 5 to 9 per mil through ~200 m of section just below the subglacial surface; (ii) values fall abruptly to as low as ~5 per mil in the final regressive platformal parasequences and slope apron directly beneath the subglacial unconformity; and (iii) immediate postglacial values are about ~3 per mil (~2 per mil higher than minimum preglacial values), decline through ~40 m of section to a nadir of ~6 per mil, and then rise to 0 per mil at about 480 m above the base of the cap carbonate. Lower subglacial $\delta^{13}C$ downturns are known elsewhere on the Otavi platform (22) and on other continents (10, 11). The overall negative $\delta^{13}C$ excursion occupies ~500 m of the platformal carbonate section. Much of the lateral variance in $\delta^{13}C$ curves between sections (Fig. 2) can be accounted for in terms of subglacial erosional truncation and slope progradation.

Constraints on the duration of the isotopic excursion from a model of thermally driven subsidence of the platform (13) allow a maximum subsidence rate of 14 m/Ma (equivalent to a maximum carbonate accumulation rate, with sediment loading, of ~50 m/Ma). The $\delta^{13}C$ excursion begins and ends in sediments deposited near nonglacial sea level and occupies a total thickness on the platform of ~500 m (~50 m of which can be accounted for isostatically as a consequence of subglacial erosion). The remainder of the thickness (~450 m) required time-dependent thermal subsidence for its accommodation. Thus, the minimum time required to accommodate the $\delta^{13}C$ excursion (below 0 per mil) was 9 My (~450 m/50 m/Ma).

Stratigraphic mapping shows that no tectonic activity occurred at the time of the $\delta^{13}C$ excursion that would affect the subsidence calculation. We cannot estimate the time span of the deposition of the cap carbonate because we do not know the water depth or the potential glacioeustatic and ice-loading effects at the onset of deposition.

If we interpret the $\delta^{13}C$ excursion in terms of carbon burial fluxes, then the proportion of organic carbon to total carbon burial changed from almost 0.5 before the glacial deposits to virtually zero immediately after. Carbonates, precipitated from an ocean in which most biological productivity had ceased for a time period greatly exceeding the carbon residence time (>10^5 years), would approach a value of ~5 to ~7 per mil, which is the isotopic composition of carbon entering the ocean (23, 24). The isotopic pattern, therefore, is consistent with the hypothesis of a snowball Earth, in which oceanic photosynthesis would be severely reduced for millions of years because the ice cover would block out sunlight. Meltwater pools and bare ground, exposed through gravitational thinning and ablation of ice sheets without much rejuvenative snowfall, might provide refugia for a variety of bacteria and simple eukaryotes.

Caldeira and Kasting (25) estimated that, at
trations by 1,320 p.p.m. This indicates that tectonic changes could have triggered a progressive transition from a 'greenhouse' to an 'icehouse' climate during the Neoproterozoic era. When we combine these results with the concomitant weathering effect of the voluminous basaltic traps erupted throughout the break-up of Rodinia\(^1\), our simulation results in a snowball glaciation.

Long-term (\(10^8\text{--}\text{yr}\)) evolution of the partial pressure of atmospheric CO\(_2\) (P\(_{\text{CO}_2}\)) is controlled by the relative importance of degassing through volcanic and mid-ocean-ridge processes and the consumption of CO\(_2\) through continental silicate weathering\(^2\). Any long-term decrease in atmospheric CO\(_2\) can be induced either by a decrease in solid Earth degassing rate, or by an increase in the weathering of continental surfaces. Little is known about the evolution of the degassing rate over the Neoproterozoic era, so linking the global Neoproterozoic cold climate to low degassing rate would be extremely speculative. On the other hand, the sink of CO\(_2\) via continental silicate weathering depends on a variety of parameters, such as the air temperature, continental runoff\(^3\), vegetation\(^4\), and mechanical weathering\(^5\). The long-term evolution of some of these parameters can be evaluated within the particular context of the Neoproterozoic. The tectonic environment is indeed characterized by the dispersal of continental plates through the break-up of Rodinia supercontinent between 800 and 700 Myr ago. This break-up may have had two major effects on the sink of CO\(_2\) via continental silicate weathering. First, the break-up of Rodinia is heralded by, and accompanied by, the eruption of large basaltic provinces\(^6\), resulting in an increase in the weatherability of the continental surface and consumption of atmospheric CO\(_2\) on the \(10^8\text{--}\text{yr}\) timescale\(^7,8\). More importantly, the break-up of a supercontinent into several smaller plates will result in an increase of precipitation and runoff over the continental masses, owing to an increase in the sources of moisture along continental borders. This process can boost continental silicate weathering and consume atmospheric CO\(_2\). Hence, precise quantitative evaluation of changes in atmospheric P\(_{\text{CO}_2}\) due to palaeogeographic changes requires a sophisticated approach in which the weathering rates are spatially resolved.

We have interfaced a long-term global carbon cycle model to a coupled ocean--atmosphere model (GEOCLIM: 'geological timescales climate'). This approach allows us to account for the spatial variations (for example, longitude and latitude) of the climatic parameters used in the geochemical model to estimate continental weathering rates: runoff and temperature. We show here that the dispersal of the supercontinent results in an enhanced consumption of atmospheric CO\(_2\) of the order of 1,320 p.p.m., and in a significant cooling of global temperatures (\(-8\text{°C}\)). We further demonstrate that experiments accounting for the palaeogeographic effect on weathering rates together with the weathering of the large magmatic provinces produce conditions able to trigger a full snowball glaciation at 750 Myr ago.

The climate model of our coupled geochemical--climate model enabled us to address the following requirements. First, the model must explicitly simulate the hydrologic cycle, and second, the model must have a fast turnaround time. The coupled climate model CLIMBER-2 meets these requirements since, first, water fluxes are explicitly resolved, and second, the design of CLIMBER-2 results in a low computational cost, enabling very long simulations (a few thousand years). Briefly, the atmospheric module is a 2.5-dimensional statistical-dynamical model and has a resolution of 10° in latitude and approximately 51° in longitude. The ocean module describes the zonally averaged characteristics for the ocean realm with a latitudinal resolution of 2.5°. The CLIMBER-2 model is fully described in ref. 9, and successfully simulates the last glacial/interglacial cycle\(^9\); it has been used previously to investigate Neoproterozoic climates\(^7\). In order to determine the atmospheric CO\(_2\) evolution, we use the geochemical COMBINE model\(^7,8\), which is a box-model including the mathematical description of the global
biogeochemical cycles of carbon, phosphorus, alkalinity and oxygen (see Methods).

Figure 1a, b displays the two palaeogeographies used in this study; ~800 Myr ago (denoted SC, supercontinent configuration) and ~750 Myr ago (denoted DC, dispersed configuration), illustrating the dispersal of the supercontinent5,6. The numerical experiments are described in the Methods section. Changes in the continental distribution, from SC to DC, trigger a large decrease in atmospheric CO₂ levels from 1,830 p.p.m. to 510 p.p.m. for the standard runs with the present-day degassing rate (Fig. 2). The climate of the SC experiment at 1,830 p.p.m. is rather cold, given the reduction of 6% of the incoming solar radiation. Indeed, the mean global temperature is 10.8 °C (against 15 °C for the modern one). Nevertheless, regions of the Earth where temperatures are below the freezing point are mainly located over the polar oceans, and extend down to 60° latitude in both hemispheres (not shown). In contrast, in the DC climate simulation at 510 p.p.m., the freezing temperatures migrate towards mid-latitudes (40–45°; not shown) and the global mean temperature is reduced to only 2 °C. Figure 1a, b shows the spatially-resolved weathering rates at 1,830 p.p.m. for the SC and DC experiments.

The vast size of the supercontinent restricts the delivery of precipitation from oceanic moisture sources (Fig. 1c). Thus, the SC experiment yields the driest continental climates and the lowest weathering rates. In contrast, the DC experiment is characterized by high runoff and large weathering rates in the equatorial regions, because the continents are smaller and widely dispersed with numerous oceans and seaways available as moisture sources. Thus, the larger runoff of the DC simulation results in higher consumption of CO₂ through weathering, and forces the climate to cool until the silicate weathering rate reaches a value equal to the SC simulation (itself equal to the degassing rate). Thus, using a complex model and quantifying the effect of the break-up, we predict a marked reduction in the concentration of CO₂ in the atmosphere to a persistently low value in the range 400–630 p.p.m. on timescales of >10 Myr (Fig. 2). We also find that model-predicted DC CO₂ values are in the range of radiative forcings, resulting in the build-up of ice sheets at latitudes greater than 30° (refs 5, 6). These CO₂ concentrations are just above the threshold value required to trigger a snowball Earth with the GEOCLIM model, that is, 250 p.p.m. (Fig. 2). Although a dispersed continental configuration is a common feature for reconstructions at 750 Myr ago, the true palaeogeography evolves during the snowball intervals via normal continental motion. Additional experiments (not shown) were performed to determine the sensitivity of our results to alternative dispersed configuration (for instance, the position of Siberia in Fig. 10b of ref. 20). Those runs demonstrate that the break-up effect may be larger (the atmospheric CO₂ level could be as low as 420 p.p.m. instead of 510 p.p.m. for the standard runs).

Although these experiments show that continental break-up could prepare the Earth for full glaciation, all the events that occurred before and during the dislocation have not been accounted for. Indeed, the break-up of Rodinia was heralded by intense volcanism, including the emplacement of large basaltic provinces between 825 and 750 Myr ago11. Figure 3 illustrates the combined

**Figure 2** Effect of the Rodinia break-up on the greenhouse effect. Steady-state atmospheric CO₂ level achieved by the GEOCLIM model with the SC and DC reconstructions (Fig. 1). Vertical bars on the two data points denote the upper and the lower range of atmospheric CO₂ levels calculated using a 20% increase and a 20% decrease in degassing flux, respectively (see Methods). The horizontal dashed lines denote the exact CO₂ values reached by the model for the standard runs. The vertical arrow displays the change of the radiative forcing from direct CO₂ effects alone. The dark grey area shows the CO₂ levels required for a globally glaciated state in the 750–Myr-ago climate simulations we used here. The dotted lines denote the range of atmospheric CO₂ levels required for low-latitude glaciations as predicted by a diverse array of climate models14 and are here for comparison with the threshold obtained by the GEOCLIM model. This range of CO₂ values is the consequence of several mechanisms that cannot be accounted for in a unique climate model. Among those mechanisms, ocean dynamics and sea-ice meltwater effects18,20 (but also the inclusion of an ice-sheet model) can have a profound effect on the position of the critical collapse point. PAL, present atmospheric level.