

Climate Change Science
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Lecture 42
Snowball Earth Cycle

During a Snowball Earth episode, when the oceans potentially froze all the way to the equator, the survival of surface life, particularly photosynthetic organisms, poses an important question. Several mechanisms are proposed for how life could have persisted under such extreme conditions. One possibility involves geothermal hotspots, where internal heat from Earth's radioactive decay could melt overlying ice, forming subglacial meltwater pools. Additionally, if the sea ice was thin in some tropical regions, sunlight could penetrate the ice, supporting photosynthesis in the waters below. Another potential refuge is water-filled crevasses at the edges of ice sheets, where cracks in the ice allow light penetration and create habitable environments. Observations from modern polar glaciers support this idea, showing that microbial life thrives in such niches. Life is known to be resilient and capable of surviving in harsh, cold, and low-light environments, suggesting that even under a global glaciation scenario, photosynthetic life could endure in isolated refugia near the tropics.

As for how Earth escapes a Snowball state, the key driver is the gradual accumulation of atmospheric CO₂ due to volcanic outgassing. With silicate weathering nearly shut down under a frozen surface, CO₂ levels can rise unchecked over millions of years. Eventually, the greenhouse effect intensifies sufficiently to initiate melting. Once the melting point of ice is reached in any region, ice-albedo feedback becomes positive, melting exposes darker ocean water, which absorbs more sunlight, accelerating warming. Model simulations suggest that this runaway deglaciation could melt a global sea ice layer 300–400 meters thick within 100 to 1000 years. This rapid transition is referred to as the transient ultra-greenhouse phase, characterized by extremely high CO₂ levels and very high global temperatures. Tropical surface temperatures may spike to 40–50 °C, shifting the climate abruptly from Snowball Earth to a Hothouse Earth state. The warm, moist atmosphere then triggers intense rainfall, enhancing silicate weathering and drawing down CO₂, eventually stabilizing the climate. This deglaciation mechanism is believed to have occurred at the termination of the last Snowball Earth event.

During the aftermath of Snowball Earth, the silicate weathering cycle operates at an accelerated pace due to the extremely high levels of atmospheric CO₂ and intense rainfall. Carbon dioxide dissolves in rainwater to form carbonic acid, which reacts with calcium silicate rocks in a chemical weathering process that produces calcium carbonate. This

calcium carbonate is eventually transported to the oceans, where it precipitates and settles on the seafloor as sediment.

One of the most striking geological signatures of this post-Snowball weathering is the presence of cap carbonates, distinctive layers of calcium carbonate that lie directly above glacial deposits. These cap carbonates serve as compelling evidence for the Snowball Earth hypothesis. Their consistent appearance immediately above rocks bearing glacial striations and other cold-climate features strongly suggests a rapid climatic transition from a globally glaciated state to a warm, greenhouse Earth. This stratigraphic pattern was instrumental in convincing the scientific community that a Snowball Earth event had indeed occurred.

The long-term carbon cycle operates over geological timescales of hundreds of thousands to millions of years and plays a central role in regulating Earth's climate. In this cycle:

- Volcanoes act as the primary source of atmospheric CO₂, injecting it through eruptions driven by plate tectonic processes. These processes are independent of surface conditions and are governed by internal planetary heat.
- Once in the atmosphere, CO₂ dissolves in rainwater, forming carbonic acid, which weathers silicate rocks on land. This chemical weathering reaction consumes CO₂ and produces dissolved ions that are transported by rivers into the ocean.
- In the ocean, these ions precipitate to form carbonate sediments, such as limestone, which sequester carbon in the form of calcium carbonate.
- Over time, plate tectonics subducts these carbonate-rich sediments into the mantle. Heating during subduction causes thermal decomposition, releasing CO₂, which is eventually outgassed back into the atmosphere by volcanoes.

This cycle forms a planetary thermostat, where:

- Higher atmospheric CO₂ leads to warming, which increases rainfall and runoff, enhancing silicate weathering and drawing down CO₂.
- Lower CO₂ causes cooling, reducing weathering and allowing CO₂ to accumulate via volcanic emissions.

Thus, Earth's surface temperature is self-regulated through a feedback loop between CO₂ concentration, temperature, and silicate weathering.

During Snowball Earth, this thermostat still operated, albeit slowly. Despite a frozen surface, volcanic outgassing continued, gradually increasing CO₂ levels. Once the greenhouse effect overcame the albedo of global ice, rapid melting ensued, transitioning the planet from a Snowball to a hot, ice-free Earth.

In contrast, modern fossil fuel emissions inject CO₂ into the atmosphere far more rapidly than the silicate weathering process can remove it, bypassing this natural thermostat and disrupting the long-term climate balance.

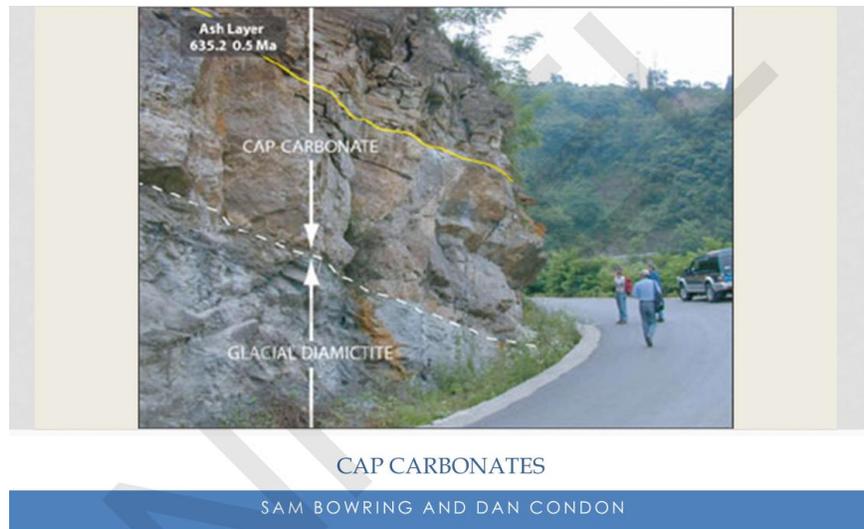
If the earth froze over, an ultrahigh carbon dioxide atmosphere would be needed to raise temperatures to the melting point at the equator. Once melting of ice begins, low-albedo seawater replaces high-albedo ice and the runaway freeze is reversed .

The greenhouse atmosphere helps to drive surface temperatures upward to almost 50 degrees C, would scrub some of the carbon dioxide out of the air in the form of carbonic acid, which would rapidly erode the rock debris left bare as the glaciers subsided.

Chemical erosion products would quickly build up in the ocean water.

From Snowball earth by Hoffman and Schrag, Scientific American,2000

The above figure shows a summary of what Hoffman and Schrag wrote more than 24 years ago in Scientific American. It is a well written popular article for people to understand about Snowball Earth.



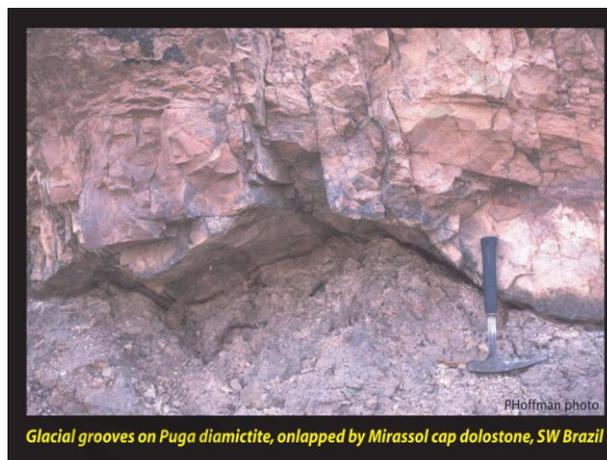
Compelling evidence for the Snowball Earth hypothesis is visible in certain geological formations, notably in places like roadside outcrops in Canada like the one shown above. Here, geologists have identified glacial diamictites, rocks consisting of a chaotic mixture of particles of various sizes, ground and deposited by glacial action. The presence of such rocks strongly indicates past glacial activity, likely extending to equatorial regions during a Snowball Earth episode. What makes these sites particularly remarkable is that

immediately above these glacial deposits lies a distinct layer of cap carbonate, composed primarily of calcium carbonate. This layer signifies a dramatic climatic shift: following the Snowball period, rising atmospheric CO₂, primarily from sustained volcanic outgassing intensified the greenhouse effect, leading to warming, increased rainfall, and enhanced weathering. This process delivered calcium and bicarbonate ions into the ocean, where they precipitated as carbonate sediments. The juxtaposition of glacial diamictites and cap carbonates in the rock record serves as a strong geological signature confirming the occurrence of Snowball Earth and its aftermath.

To determine the timing of these events, geologists rely on volcanic ash layers embedded within the rock sequences. In this case, a major volcanic eruption around 635 million years ago deposited a distinct ash layer that was preserved in the sedimentary record. These ash layers serve as important time markers because such large eruptions are relatively rare and leave unmistakable traces that can be dated precisely. Their presence helps establish the sequence and age of geological events with confidence.

This illustrates the power of geological fieldwork, where seemingly ordinary roadside rocks can offer profound insights into Earth's climatic and tectonic history. Observing and interpreting such formations allows scientists and curious travellers alike to reconstruct episodes from Earth's deep past and appreciate the planet's dynamic evolution.

The Snowball Earth hypothesis not only proposes a period of near-global glaciation but also predicts that such a glacial episode would be followed by a dramatic climatic reversal into a Hot House Earth phase. To melt the extensive ice coverage produced during the Snowball period, atmospheric carbon dioxide concentrations must have reached extraordinarily high levels, estimated between 20,000 and 90,000 ppm, far exceeding present-day values. This accumulation of CO₂ is attributed to continuous volcanic emissions during the glaciation, as weathering - the primary sink for CO₂, was severely diminished under ice-covered conditions.



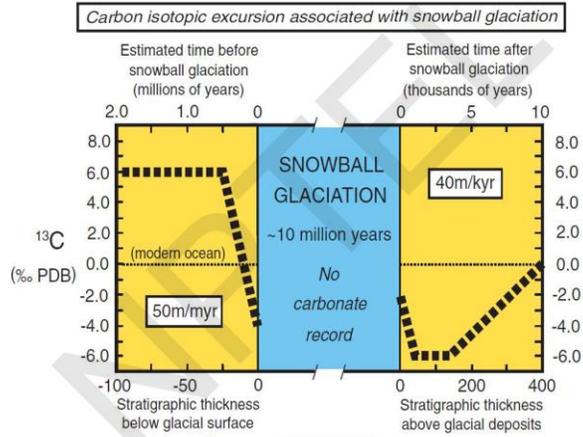
Glacial grooves on Puga diamictite, overlapped by Mirassol cap dolostone, SW Brazil

Compelling pieces of evidence supporting this transition comes from Brazil. Here, a clear boundary is observed between glacial deposits and a dolostone layer, signifying a sudden climatic shift from a frozen world to a much warmer Earth. While most geological processes occur gradually, a principle known as uniformitarianism, the transition from Snowball Earth to Hot House Earth represents an exception, marked by rapid and global environmental change. Similar rock sequences have been discovered across various continents, including South Africa, Canada, and Brazil, reinforcing the global nature of this event. This evidence by geologist Paul Hoffman was instrumental in convincing many scientists.

Based on volcanic outgassing rates, it is estimated that it would take approximately 4 million years for atmospheric CO₂ to rise to levels capable of terminating global glaciation, possibly as high as 120,000 ppm in some estimates. Once ice melt begins, particularly over tropical oceans, an ultra-greenhouse effect is triggered. This leads to further warming and initiates intense silicate weathering, a chemical process that draws CO₂ from the atmosphere and forms carbonate sediments. This rapid weathering is a crucial mechanism in restoring climate balance after such a perturbation.

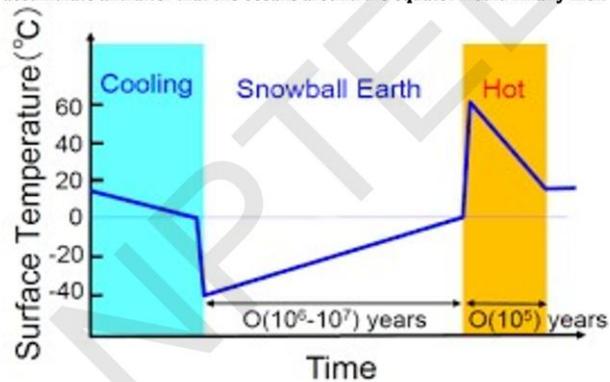
These climatic and geochemical transitions are traceable through carbon isotope analysis, particularly the ratio of carbon-13 (¹³C) to carbon-12 (¹²C) in carbonate deposits. Because photosynthetic organisms preferentially absorb the lighter ¹²C isotope, periods of active biological carbon fixation leave distinct isotopic signatures. Thus, changes in ¹³C concentrations serve as proxies for variations in biological productivity and atmospheric CO₂ levels, providing a window into the environmental conditions that prevailed during and after Snowball Earth episodes.

The consequences of the Snowball Earth episode are vividly captured in the carbon isotope records, which provide a timeline of biological and geochemical activity through Earth's history. Specifically, the ratio of carbon-13 (¹³C) to a standard was notably high prior to the Snowball glaciation, reflecting robust photosynthetic activity. As Earth entered a globally glaciated state, photosynthesis effectively ceased due to widespread ice cover, leading to a sharp decline in ¹³C values. These values remained negative for about 10 million years, indicating the absence of substantial biological carbon fixation. When the climate warmed and photosynthesis resumed, the ¹³C signature began rising again, marking the recovery of biological productivity.



Models that incorporate weathering rates and surface albedo changes help simulate this timeline and match it with geological observations. A striking feature highlighted by these models is the contrast in sedimentation rates before and after the Snowball Earth event. During glaciation, the accumulation of glacial ice was slow, about 50 meters over 1 million years. In contrast, once deglaciation began, calcium carbonate sediments formed rapidly, with 40 meters deposited in just 1,000 years. This indicates a 1000-fold increase in deposition rate after deglaciation, driven by the onset of a super-greenhouse effect, intense weathering, and massive influxes of dissolved ions into the oceans. This phenomenon is well-documented in post-glacial rock records and serves as compelling evidence for the Snowball Earth hypothesis.

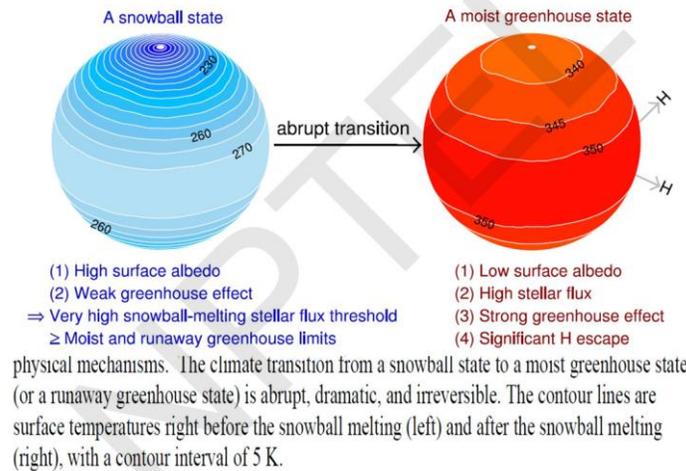
If the Earth was completely covered with ice, silicate rocks would not be exposed during erosion, and carbon dioxide would not then be removed from the atmosphere. Eventually enough CO₂ emitted by volcanoes would accumulate and after that the oceans around the equator would finally melt



A schematic reconstruction of surface temperature evolution further illustrates the dramatic climate transitions. Prior to Snowball onset, global mean temperatures hovered around 15–18°C. As ice advanced toward the equator, temperature dropped steeply, reaching lows that supported global ice coverage. The subsequent warming phase, powered by volcanically released CO₂, occurred slowly over 1–10 million years. However, once the ice melted completely, surface temperatures spiked rapidly to around

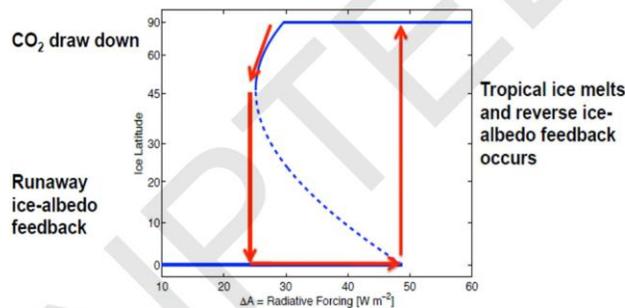
60°C, illustrating the extreme warmth of the Hot House Earth phase. This extreme post-glacial warming is consistent with the high atmospheric CO₂ concentrations required to melt a fully ice-covered Earth.

Though the hypothesis makes seemingly outrageous predictions, such as Earth reaching 60°C or experiencing 1000 times increases in sedimentation rates, geological evidence from rock strata including isotope anomalies, glacial diamictites capped by carbonates, and sediment thickness strongly supports these claims. It is this alignment of theory with observed stratigraphy that ultimately gave credibility to the Snowball Earth model.



The above illustration from Hoffman's article in the Scientific American, shows how the Earth went from Snowball Earth with high albedo and almost no greenhouse effect, to a moist hot greenhouse state with a very low surface albedo, high flux, strong greenhouse effect and significant water vapor escape. This is the theory of how Snowball ended.

The climate model and silicate weathering feedback can be put together to explain geological observations.



Very low weathering allows CO₂ to build up to ~10% of atmosphere over 1-10 million years

This can be understood through our energy balance model. If CO₂ increases, the radiative forcing due to CO₂ will go up to 50 Wm⁻², which is very large compared to 2.5 Wm⁻² we know that occurred in the last 150 years. Then, it jumps to an ice-free state. It remains there for a long time. Then, it comes back to the snow-covered Earth. So, this is the cycle that operated during the time.

The Snowball Earth hypothesis, while widely accepted, has faced skepticism, particularly about how life could have survived during such prolonged global glaciation. However, recent studies of polar biota have shown that even during the Last Glacial Maximum (~20,000 years ago), life managed to persist in and around ice-covered environments like Antarctica. Explorations in the Arctic and Antarctic have revealed unique life forms in ice cores. These organisms adapted to extreme cold and low-light conditions, suggesting that similar ecological refuges could have existed during Snowball Earth.

Despite these doubts, the Snowball Earth hypothesis stands out because it uniquely explains multiple geological puzzles from Earth's deep past. These include the presence of cap carbonates directly above glacial deposits, which indicate rapid weathering and carbonate precipitation after deglaciation; the occurrence of banded iron formations, suggesting anoxic ocean conditions during glaciation; paleomagnetic evidence of glacial deposits near the equator, pointing to a globally frozen Earth; and the long duration of the Snowball events. While alternative hypotheses have been proposed, none of them simultaneously account for all these phenomena. Thus, the comprehensive explanatory power of the Snowball Earth theory, as developed by Hoffman and Schrag, remains unmatched.

The Snowball Earth hypothesis remains a scientific hypothesis, not an absolute truth. Since it deals with events that happened over 600 million years ago, the evidence, though compelling, is largely indirect, derived from proxies like isotopic ratios, sedimentary layers, and paleomagnetic signals. All such data come with uncertainties and error bars, reminding us that scientific conclusions are always provisional.

Science does not claim final truths; rather, it relies on hypotheses that are continually tested against observations. A theory can never be proven with certainty. It can only withstand falsification over time. The longer a theory resists challenges, the more confidence it gains, but it must always remain open to revision if new evidence demands it. This principle applies to even the most foundational theories, like Newtonian gravity or Einstein's relativity. The Snowball Earth hypothesis, though bold and unconventional, has so far been supported by multiple lines of evidence. However, it is still incomplete, and new discoveries may yet alter our understanding.

The significance of this ancient climatic event lies in what it reveals about climate system behaviour. The Earth's climate is not inherently stable. It has the capacity to flip between

extreme states due to ice-albedo feedbacks and greenhouse gas forcings. These feedbacks can amplify cooling or warming to such a degree that the planet can become either fully glaciated or entirely ice-free. The period of apparent stability from 10,000 years ago to 1850 was not the norm, but an exception.

Thus, Snowball Earth serves as a cautionary example. It shows that Earth's climate has undergone dramatic transformations in the past due to natural feedbacks. Understanding such ancient events is essential as we confront the anthropogenic rise in CO₂, a driver that could potentially trigger nonlinear, irreversible shifts in the modern climate system. The lessons from Snowball Earth extend far beyond geology. They underscore the importance of understanding the fragility and complexity of Earth's climate.

In the following lecture, the focus will shift to aerosols, a topic that has not been explored in depth so far. Aerosols are tiny atmospheric particles that are invisible to the naked eye but have a significant influence on the Earth's albedo and, consequently, on climate. Unlike the well-understood roles of greenhouse gases and ice sheets, the influence of aerosols is less certain and far more complex.

One major difference is that carbon dioxide is well-mixed in the atmosphere, regardless of where it is emitted, its concentration becomes fairly uniform globally, from the poles to the equator. Aerosols, however, are not uniformly distributed. Their concentrations are highest near emission sources, such as urban areas and deserts, and much lower in remote or polar regions. This leads to a high spatial variability, making it difficult to assess their overall impact on climate.

Additionally, aerosols exhibit strong seasonal variation. For instance, Saharan dust levels peak in summer when dry conditions and strong winds lift large quantities of dust into the atmosphere. Such temporal and spatial heterogeneity adds to the complexity of quantifying their climatic effects.

Given these challenges, the next lecture will delve into the multifaceted role of aerosols and the difficulties involved in estimating their impact on Earth's climate system.