Goldschmidt 2000
September 3rd–8th, 2000
Oxford, UK.

Journal of Conference Abstracts
Volume 5(2), 897

On the Initiation of a Snowball Earth

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The Snowball Earth hypothesis proposes that Neoproterozoic glacial deposits and associated "cap" carbonates represent a series of global glaciations followed by extreme greenhouse conditions. In the context of the hypothesis, a runaway ice-albedo feedback causes a global glaciation, with near-complete sea-ice cover, and a greatly reduced hydrologic cycle dominated by sublimation. Escape from this frozen state requires several to several 10's of millions of years for carbon dioxide, released by magmatic outgassing, to build up in the ocean/atmosphere system, providing adequate radiative forcing to overcome the high planetary albedo. Meltback would be extremely rapid (i.e., hundreds of years), transforming the earth from frozen to ultra-greenhouse conditions.

The hypothesis predicts that the cap carbonates were rapidly deposited, with alkalinity supplied by intense carbonate and silicate weathering. Banded iron formations, associated with the glacial deposits, represent chemical precipitates that formed as the ocean, anoxic from millions of years of ice cover, mixed with the atmosphere as the ice melted away. The carbon isotopic compositions of the cap carbonates are consistent with this hypothesis. Values immediately on top of the glacial deposit are approximately -2 per mil, consistent with dissolved inorganic carbon in isotopic equilibrium with a CO_2-rich atmosphere. This value implies approximately equal partitioning of carbon between the atmosphere and the ocean. With this constraint, assuming a range of alkalinities, the pCO_2 can then be calculated for the glacial termination. Values within the cap carbonate rapidly decrease to -5 per mil, consistent with Rayleigh distillation of the atmosphere as carbonate is deposited, and mass balance considerations. The basal unit of the cap exhibits a "tube" texture, with evidence for shallow water deposition, followed by a transgressive sequence of carbonate all within the cap sequence. This suggests that the basal unit of the cap precipitated over a very short time interval before continental glaciers had melted causing the eustatic sea level rise. The basal unit, predominantly dolomite, may represent the unusual conditions in the aftermath of the snowball earth, with dolomite saturation enhanced by addition of fresh water to the surface ocean from melting of sea ice.

The reasons why the Earth was susceptible to such glaciations in the Neoproterozoic remain a mystery. The convergence of continents at low-latitudes may have been a contributing factor. When all the continents move to tropical latitudes, there are at least two interesting perturbations of the carbon cycle that result. Firstly, most of the ocean area would exist in the polar regions, with no land mass available to supply dust (the atmosphere is inefficient at transporting dust from the tropics to higher latitudes). This condition would make biological productivity in the high latitude oceans extremely iron-limited, focusing most of the productivity into low latitudes ocean basins which would be smaller and more removed from global circulation. In essence, this would yield a world with multiple basins like the Black Sea, more prone to suboxic or anoxic conditions. In these oceans, organic matter burial would dramatically increase due to more efficient recycling of phosphate. This can explain the high carbon isotope values observed in the millions of years of sediment preceding each of the snowball glaciations. Secondly, the low latitude continents would allow for lower carbon dioxide levels by removing the glacial barrier to chemical weathering. In the current continental configuration, as carbon dioxide emissions from volcanic sources decrease, ice caps on high latitude continents would decrease the rate of chemical weathering, stabilizing the amount of carbon dioxide in the atmosphere. If all the continents were at low latitudes, no such "safety switch" would exist, and carbon dioxide could reach lower levels for the same rate of volcanic emissions. This may explain why the snowball glaciations occurred at this time, and not in the Phanerozoic, and not in the 1.5 billion years preceding. The release of methane from the anoxic basins immediately preceding the onset of glaciation may play a role in lowering the carbon dioxide in the atmosphere. The effects of methane on climate in a Proterozoic atmosphere will be discussed.