Long-Term Climate Cycles & The Proterozoic Glaciations (‘Snowball Earth’)

Assigned Reading:
Skeletal of Veizer results; questions SST proxy record and paleo-CO$_2$ proxy record.


Suggests evolution of rooted vascular plants caused Devonian (~400 Ma) CO$_2$ drawdown by enhancing chemical weathering rates. Supports CO$_2$-climate link through Phanerozoic.

Exception is Late Ordovician glaciation, explained by "unique paleogeographic circumstances".


Excellent review of paleo-CO$_2$ proxies.


**Recommended Readings:**


Stomatal indices on fossil leaves during last 300 Myr indicate that the only two periods of low CO$_2$ were associated with known ice ages, in support of the CO$_2$-climate link.


Leaf stomatal indices through "known" warm intervals (Miocene 15-17 Ma, and Paleocene/Eocene boundary (53-59 Ma) indicate low CO$_2$, refuting CO$_2$ climate link.


Paleosol $8^\circ$C data across Triassic/Jurassic boundary (208 Ma) suggests only small CO$_2$ increase associated with that mass extinction. Argue therefore that deposition of large flood basalt at that time (volcanic events) did not cause high CO$_2$ and runaway greenhouse, as previously hypothesized.


Phytoplankton $8^\circ$C indicates low CO$_2$ through Miocene warm interval (~14-18 Ma) and no sharp drop associated with the expansion of the East Antarctic Ice Sheet, refuting strong CO$_2$-climate link.


**Tectonics and Cenozoic Climate**

**Recommended Readings:**


Climate Controls - Long & Short Timescales

• Solar output (luminosity): $10^9$ yr
• Continental drift (tectonics): $10^8$ yr
• Orogeny (tectonics): $10^7$ yr
• Orbital geometry (Earth -Sun distance): $10^4$-$10^5$ yr
• Ocean circulation (geography, climate): $10^1$-$10^3$ yr
• Atmospheric composition (biology, tectonics, volcanoes): $10^0$-$10^5$ yr
Earth’s Climate History: Mostly sunny with a 10% chance of snow

• What caused these climate perturbations?
What caused these massive perturbations to the carbon cycle during the late Proterozoic?

Hayes et al, Chem Geol. 161, 37, 1999
Late Proterozoic Glaciations: Evidence

~4 global glaciations followed by extreme greenhouses 750-580 Ma

- Harland (1964); Kirschvink (1992)

Snowball Events:
- Breakup of equatorial supercontinent 770 Ma
- Enhanced weathering from increased rainfall (more land close to sea)
- Drawdown atmospheric CO$_2$ $\rightarrow$ Global cooling
- Runaway albedo effect when sea ice < 30° latitude
- Global glaciation for ~10 Myr (avg T ~ -50°C)
- Sea ice ~1000 m thick, geothermal heat flux (0.07 W/m$^2$) keeps ocean liquid
Evidence for Glaciers on All Continents

Fig. 12.3. Global distribution of major late Precambrian glacial centers on a map showing the present dispersal of continents. I, II, III refer to glaciations identified by Williams (1975) as centered on ~610 Ma, 750 Ma, and 950 Ma, respectively. A subsequent summary of late Precambrian glaciations (Hambrey and Harland, 1981a) suggests that these glaciations may not be as episodic as inferred by Williams. The letter A signifies that all three time intervals may be represented. [Modified from Frakes, 1979] Reprinted by permission from L. Frakes. "Climates Throughout Geologic Time," copyright, 1979. Elsevier Scientific Publishers.

Frakes (1979), in Crowley & North (1991)
Late Proterozoic (\( \sim 0.9 - 0.6 \text{ Ga} \)) Glaciations

![Continental Reconstruction Diagram]

FIGURE 8-12
Possible continental reconstruction for the Late Proterozoic Period. All the continents appear to have been glaciated at that time. (After J.L. Kirschvink in the Proterozoic Biosphere: A Multidisciplinary Study, J.W. Schopf and C. Klein, eds., Ch. 12.1, Cambridge University Press, Cambridge, 1992.)
Geologic Evidence for Glaciers

- **Tillites**: Packed pebbles, sand & clay. Remnants of moraines
- **Glacial Striations**: Scratches from rocks dragged by moving ice
- **Dropstones**: Rocks transported by icebergs and dropped into finely laminated sediment (IRD).

Kump et al. (1999)
• Glacial sediments – poorly sorted, angular clasts including dropstones – Namibia c. 750 Ma
Neo-proterozoic Glacial Deposits

From Norway, Mauritania, NW Canada, Namibia.

- Glacial striations
- Dropstones

Hoffman & Schrag (2002)
Harland & Rudwick (1964) identified glacial sediments at what looked like equatorial latitudes by paleomagnetism.

George Williams (1975) identified low a latitude glacial sequence in S. Australia & attributed to episode of extreme obliquity (tilt).

Equatorial Continents?

**EARTH'S LANDMASSES** were most likely clustered near the equator during the global glaciations that took place around 600 million years ago. Although the continents have since shifted position, relics of the debris left behind when the ice melted are exposed at dozens of points on the present land surface, including what is now Namibia (*red dot*).
Determining Paleolatitude from Remnant Magnetism

- Paleomagnetism: latitude of formation of rock
- Natural Remnant Magnetism (NRM): inclination varies with “magnetic” latitude
  - vertical @ magn poles
  - horz. @ magn equator (many Neoprot glac deposits)
- Magnetic polar drift averages out on T~10 ky

Image from P. Hoffman
Paleolatitude from Paleomagnetism

Fig. 1 Global distribution (a) of Neoproterozoic glaciogenic deposits with estimated palaeolatitudes based on palaeomagnetic data (modified from Evans, 2000). ‘Reliability’ takes into account not only palaeomagnetic reliability but also the confidence that the deposits represent regionally significant, low-elevation ice sheets (Evans, 2000). Histogram (b) of the same glaciogenic deposits according to palaeolatitude. The discontinuous steps show the expected density function of a uniform distribution over the sphere. Note the preponderance of low-latitude deposits and absence of high-latitude deposits. This finding would not be invalidated by plausible non-dipole components of the field, which would effectively raise the palaeolatitudes of only the mid-latitude results (Evans, 2000). The minimum in the distribution in the subtropics may reflect the meridional variation in precipitation minus evaporation due to the Hadley cells.

How to explain glaciers on all continents when those continents appear to have been close to the equator?
High Obliquity Hypothesis
Williams (1975)

- Earth’s tilt (obliquity) controls seasonality
- At high tilt angles (> 54°) the poles receive more mean annual solar radiation than the tropics (sun constantly overhead in summer)!
- Glaciers may be able to form at low latitudes

Problems:
- Even the tropics get quite warm at the equinoxes
- Moon stabilizes obliquity
- Would need very large impact to destabilize; moon orbit doesn’t support this

For obliquities >54 degrees, mean annual temperatures in the tropics are lower than at the poles, but low-latitude glaciation is unlikely because of very high seasonality.

Image from P. Hoffman
Snowball Earth Hypothesis

~4 global glaciations followed by extreme greenhouses 750-580 Ma

- Harland (1964); Kirschvink (1992)

**Snowball Events:**
- Breakup of equatorial supercontinent 770 Ma
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Lubick (2002)
Prologue to Snowball

- Breakup of equatorial supercontinent
- Enhanced weathering from increased rainfall (more land close to sea)
- Drawdown atmospheric CO$_2$ → Global cooling

Hoffman & Schrag (2000)
• Global cooling causes sea ice margin to move equatorward

• Runaway albedo effect when sea ice <30° latitude

• Entire ocean possibly covered with ice

Hoffman & Schrag (2000)
1. Eq. continents, incr. weathering, lowers CO$_2$, slow cooling, equatorward movement of ice.
2. Runaway albedo
3. Weathering shuts down
4. Slow buildup of CO$_2$ from volcanoes
5. Rapid decay of ice in 10$^2$ yr. High T$_s$ from enhanced H$_2$O-T feedback.
6. Slow CO$_2$ drawdown from weathering

Steady-state ice lines as a function of atmospheric pCO$_2$, see Caldeira and Kasting (Nature 359: 226, 1992), andIkeda and Tajika (Geophys. Res. Lett. 26: 349, 1999).
Carbonate-Silicate Geochemical Cycle

Kump et al. (1999)
Snowball?

- Global glaciation for ~10 Myr (avg T ~ -50°C)
- Sea ice ~1000 m thick, geothermal heat flux (0.07 W/m²) keeps ocean liquid

Hoffman & Schrag (2000)
Evidence cited for Snowball

• *Stratigraphy*: globally-dispersed glacial deposits.

• *Carbon isotopes*: negative $\delta^{13}C$ excursions through glacial sections (inorganic $\delta^{13}C$ reaches $\sim$ -5 to -7‰). Little or no biological productivity (no light).

• *Banded iron formations* w/ice-rafted debris (IRD): only BIFs after 1.7 Ga. Anoxic seawater covered by ice.

• *Cambrian explosion*: Rapid diversification of multicellular life 575-525 Ma expected to result from long periods of isolation and extreme environments (genetic "bottleneck and flush").
Carbon Isotopic Evidence for Snowball

$\delta^{13}C$ values of -5‰ (mantle value) consistent with “dead” ice-covered ocean

Secular variation in carbon isotopic composition of shallow marine carbonates over the last 1600 million years (adapted from Kaufman, 1997; Kah et al., 1999).
Carbon Isotope Fractionation

- As fraction of carbon buried approaches zero, $\delta^{13}C$ of CaCO$_3$ approaches mantle (input) value

$^{13}C_{\text{PDB}}(\text{sample}) = [(R_{\text{sample}} - R_{\text{PDB}}) / R_{\text{PDB}}] \times 10^3$

(where $R = ^{13}C / ^{12}C$)

Image from P. Hoffman
Extreme Carbon Isotopic Excursions 800-500Ma Require Massive Perturbation of Global carbon Cycle

Hayes et al., Chem Geol. 161, 37, 1999
The Return of Banded Iron Formations

After a ~1 Gyr absence, BIFs return to the geologic record

Implies anoxic ocean

Consistent with ice-covered ocean

Image from P. Hoffman
BIF + Dropstone = Ice-covered, anoxic ocean?

McKenzie Mtns., Western Canada

Image from P. Hoffman
Metazoan Explosion: Response to genetic bottlenecks & flushes?

Image from P. Hoffman
Breaking out of the Snowball

• Volcanic outgassing of CO\textsubscript{2} over $\sim$10\textsuperscript{6} yr may have increased greenhouse effect sufficiently to melt back the ice.

Bring on the Heat: Hothouse follows Snowball?

**Hothouse Events**
- Slow CO$_2$ buildup to ~350 PAL from volcanoes
- Tropical ice melts: albedo feedback decreases, water vapor feedback increases
- Global T reaches ~ +50°C in 10$^2$ yr
- High T & rainfall enhance weathering
- Weathering products + CO$_2$ = carbonate precipitation in warm water
SNOWBALL FREEZE-FRY SCENARIO

1. albedo ~ 0.3
   ![Map 1]

2. albedo ~ 0.6
   ![Map 2]

3. albedo ~ 0.7
   ![Map 3]

4. albedo ~ 0.4 (with clouds)
   ![Map 4]

Cartoon of one complete 'snowball' episode, showing variations in planetary albedo, atmospheric carbon dioxide, surface temperature, tropospheric depth, precipitation, glacial extent, and sea ice thickness. Stage 1. incipient glaciation; 2. runaway ice-albedo (onset of 'snowball'); 3. end of 'snowball'; 4. transient 'hothouse' aftermath.

Image from P. Hoffman
The Geochemical Carbon Cycle

[Processes lettered in blue are absent in a snowball Earth]

Image from P. Hoffman
Enhanced Weathering of Rocks Results in Precipitation of Minerals in Ocean

- High T & CO₂ cause increase in weathering rate of continents
- Products of weathering carried to ocean by rivers
- Precipitated as CaCO₃ and SiO₂ minerals in ocean

**CARBONATE WEATHERING**

Weighthing:
\[ CaCO_3 + CO_2 + H_2O \rightarrow \]

Transport:
\[ Ca^{2+} + 2HCO_3^- \rightarrow \]

Sedimentation:
\[ CaCO_3 + CO_2 + H_2O \]

**SILICATE WEATHERING**

Weighthing:
\[ CaSiO_3 + 2H_2O + 2CO_2 \rightarrow \]

Transport:
\[ Ca^{2+} + 2HCO_3^- + 2H^+ + SiO_3^{2+} \rightarrow \]

Deposition:
\[ CaCO_3 + SiO_2.H_2O + H_2O + CO_2 \]
Geologic Evidence for Hothouse Aftermath: “Cap Carbonates”

Thick sequences of inorganically precipitated CaCO$_3$ overly Neoproterozoic glacial deposits globally.
• Thick sequences of inorganically precipitated carbonate minerals are found over Late Proterozoic glacial deposits.
• Consistent with massive flux of weathering products to ocean in snowball aftermath.

• Ripples, storm waves
• Aragonite crystal fans

Aragonite Fan in Namibia

• Carbonate fans form when CaCO₃ is rapidly precipitated from water.

Image from P. Hoffman
Geologic & Isotopic Change Associated with Snowball Event:

Glacial Deposit Overlain by Cap Carbonate in Namibia (~700 Ma)

Summary of Snowball-Hothouse Sequence

Note: T estimated from E balance model

Evidence for Snowball / Hothouse

- **Stratigraphy**: globally-dispersed glacial deposits overlain by thick sequences of inorganic (cap) carbonates.

- **Carbon isotopes**: negative $\delta^{13}C$ excursions through glacial sections ($\delta^{13}C$ reaches ~ -5 to -7‰). Little or no biological productivity (no light). Remain low through most of cap carbonate deposition.

- **Banded iron formations w/IRD**: only BIFs after 1.7 Ga. Anoxic seawater covered by ice.

- **Cambrian explosion**: Rapid diversification of multicellular life 575-525 Ma expected to result from long periods of isolation and extreme environments (genetic "bottleneck and flush").
How Long Did it Last?

• Big open question! Recent work by Sam Bowring (MIT) suggests glacial episode lasted < 1 Myr

• Glacial episodes probably lasted < 1 Myr
• Cap carbonates likely deposited within $10^3$-$10^4$ yr
What kept this from happening after ~580 Ma?

• Higher solar luminosity (~5% increase)

• Less landmass near equator = lower weathering rates (?)
  → John Edmond: weathering rates limited by abundance of fresh rock, not temperature.

• Increased bioturbation (eukaryote diversity following re-oxygenation of ocean): Less C accumulation in sediments sequesters less atmospheric CO$_2$, offsetting lower weathering rates (from higher-latitude continents).

• lower iron and phosphorus concentrations in better-oxygenated Phanerozoic ocean [Fe(II) is soluble; Fe(III) is less so]: Decreased 1° production = Decreased CO$_2$ drawdown.

→ What we would like to know:
  CO$_2$ concentrations through snowball/hothouse cycle.
Potential Problems with the ‘Snowball Earth hypothesis’

- Ocean/atmosphere climate models cannot seem to keep entire ocean covered with ice.
- No evidence for lower sea level.
- Weathering reactions are slow….. Maybe too slow to be the source of cap carbonates.

Climate dynamics of a hard snowball Earth

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[1] The problem of deglaciating a globally ice-covered (“hard snowball”) Earth is examined using a series of general circulation model simulations. The aim is to determine the amount of CO$_2$ that must be accumulated in the atmosphere in order to trigger deglaciation. Prior treatments of this problem have been limited to energy balance models, which are incapable of treating certain crucial physical processes that turn out to strongly affect the conditions under which deglaciation can occur. CO$_2$ concentrations up to .2 bars are considered in the general circulation model simulations, and even at such high CO$_2$ content the model radiation code is found to perform well in comparison with codes explicitly designed for high CO$_2$. In contrast to prevailing expectations, the hard snowball Earth is found to be nearly 30 K short of deglaciation, even at .2 bars. The very cold climates arise from a combination of the extreme seasonal and diurnal cycle, lapse rate effects, snow cover, and weak cloud effects. Several aspects of the atmospheric dynamics are examined in detail. The simulations indicate that the standard scenario, wherein snowball termination occurs after a few tenths of a bar of CO$_2$ has built up following cessation of weathering, is problematic. However, the climate was found to be sensitive to details of a number of parameterized physical processes, notably clouds and heat transfer through the stable boundary layer. It is not out of the question that other parameterization suites might permit deglaciation. The results should not be construed as meaning that the hard snowball state could not have occurred, but only that deglaciation requires the operation of as-yet undiscovered processes that would enhance the climate sensitivity. A brief survey of some of the possibilities is provided.

Alternate Cause for Cap Carbonate Deposition & $^{13}$C Depletions: Gas Hydrate Destabilization


- CaCO$_3$ precipitation does not require increased weathering flux of minerals.
- Can be caused by increased seawater alkalinity resulting from CH$_4$ consumption by sulphate-reducing bacteria.

$$\text{CH}_4 + \text{SO}_4^{=} \rightarrow \text{HCO}_3^- + \text{HS}^- + \text{H}_2\text{O}$$
Gas Hydrate = \([H_2O + \text{hydrocarbon (CH}_4\text{)] ice}

- \text{CH}_4\text{ from biogenic + thermogenic decomposition of deeply buried C}\text{}_\text{org}

- \text{Biogenic CH}_4\text{ has very low } \delta^{13}\text{C (-60 to-90‰)}

- \text{Sequestered as hydrate in permafrost (> 150 m) & along continental margins (> 300 m)}

- \text{Destabilized by increased temperature}

- \text{CH}_4\text{ released from flooded permafrost during deglaciation}

\text{Kennedy et al. (2001) Geology Vol. 29(5): 443-446.}

**Figure 1.** Cap carbonate lithofacies: A: Typical laminated dolomicrite. B: Facies with domal and tepee-shaped structures and abundant cement, overlain by laminated dolomite. C: Detail of B showing growth of tepee-shaped structure and sheet cracks lined by isopachous cement. D: Breciation in core of structure, related to repeated bedding disruption and cementation. E: Tubestone facies, attributed to outgassing of methane. F: Roll-up structure, interpreted to represent microbial binding by chemosynthetic and/or heterotrophic organisms in deep water. All examples are from northern Namibia, except D (Kimberley region, Australia).
Gas Hydrate Stability

Rather than increased weathering flux of cations & HCO$_3^-$ to ocean causing CaCO$_3$ precipitation, decreased seawater alkalinity could have caused CaCO$_3$ precipitation.

CH$_4$ consumption by SO$_4^{2-}$ reducers @ seafloor & in flooded permafrost.

Drives ΣCO$_2$ (H$_2$CO$_3$ + HCO$_3^-$ + CO$_3^{2-}$) toward CO$_3^{2-}$, causing CaCO$_3$ to precipitate out of seawater.

CH$_4$-derived CaCO$_3$ has low $\delta^{13}$C.
CH₄ consumption by sulphate reducers is observed at methane seeps in modern ocean, & CaCO₃ precipitates there as a result.

SO₄²⁻ reducers produce highly ¹³C depleted HCO₃⁻ which goes into ocean/atmosphere.

Orphan et al. (2001), Science, Vol. 293, pp. 484-487.
Consortia of sulphate reducers & methane-oxidizing microbes from modern CH$_4$ seep

Santa Barbara Basin: Recent methane hydrate releases?

- Large $^{13}$C-depletions in seawater & biogenic carbonates
- Suggested as due to massive releases of CH$_4$ when gas hydrates were destabilized by changing T & P (i.e., sea level)