12.842 / 12.301 Past and Present Climate
Fall 2008

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

Assigned Reading:

•Hoffman & Schrag (2002) *Terra Nova*, Vol. 14(3):129-155.

•Lubick (2002) *Nature*, Vol. 417: 12-13.

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

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What caused these climate perturbations?

Carbon Isotopic Excursions 800-500Ma

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Citation: Hayes et al, *Chem Geol*. 161, 37, 1999.

- **What caused these massive perturbations to the carbon cycle during the late Proterozoic?**

Late Proterozoic Glaciations: Evidence

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

•Harland (1964); Kirschvink (1992)
•Hoffman et al. (1998) *Science*, v. 281: 1342-6; Hoffman & Schrag (2000) *Sci. Am.*, Jan: 68-75.

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Snowball Events:

- Breakup of equatorial supercontinent 770 Ma
- Enhanced weathering from increased rainfall (more land close to sea)
- Drawdown atmospheric CO_2 → 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

Geologic Evidence for Glaciers

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Citation: Kump et al. (1999).

- *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).

- Glacial sediments – poorly sorted, angular clasts including dropstones – Namibia c. 750 Ma

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Image removed due to copyright restrictions.
Citation: See Figure 2. Paul F Hoffman, Daniel P Schrag (2002). The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14 (3), 129-155. doi:10.1046/j.1365-3121.2002.00408.x

Neo-proterozoic Glacial Deposits

From Norway, Mauritania, NW Canada, Namibia.

- Glacial striations
- Dropstones

Hoffman & Schrag (2002) *Terra Nova*, Vol. 14(3):129-155.

Equatorial Continents?

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Citation: Hoffman & Schrag (2000).

•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).

Determining Paleolatitude from Remnant Magnetism

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•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

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Citation: See Figure 1. Paul F Hoffman, Daniel P Schrag (2002). The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14 (3), 129-155. doi:10.1046/j.1365-3121.2002.00408.x

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-diplole 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.

Hoffman & Schrag (2002)
Terra Nova, Vol. 14(3):129-155.

How to explain glaciers on all continents when those continents appear to have been close to the equator?

High Obliquity Hypothesis

Williams (1975)

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•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

<u>Problems</u>:
•Even the tropics get quite warm at the equinoxes
•Moon stabilizes obliquity
•Would need v. large impact to destabilize; moon orbit doesn't support this

Image from P. Hoffman

Snowball Earth Hypothesis

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

•Harland (1964); Kirschvink (1992)
•Hoffman et al. (1998) *Science*, v. 281: 1342-6; Hoffman & Schrag (2000) *Sci. Am.*, Jan: 68-75.

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Lubick (2002)

Snowball Events:

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Prologue to Snowball

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Hoffman & Schrag (2000)

- Breakup of equatorial supercontinent
- Enhanced weathering from increased rainfall (more land close to sea)
- Drawdown atmospheric CO_2 → Global cooling

Deep Freeze

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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

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•Runaway Albedo Feedback

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_2O-T feedback.**
6. **Slow CO_2 drawdown from weathering**

Image from P. Hoffman

Snowball?

•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

Images removed due to copyright restrictions.

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 ~ -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

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Image from P. Hoffman

Carbon Isotope Fractionation

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- As fraction of carbon buried approaches zero, $\delta^{13}C$ of $CaCO_3$ approaches mantle (input) value

Image from P. Hoffman

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Extreme Carbon Isotopic Excursions 800-500Ma Require Massive Perturbation of Global carbon Cycle

Hayes et al., Chem Geol. 161, 37, 1999

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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?

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McKenzie Mtns., Western Canada

Image from P. Hoffman

Metazoan Explosion: Response to genetic bottlenecks & flushes?

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Image from P. Hoffman

Breaking out of the Snowball

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Citation: Lubick (2002) *Nature*, Vol. 417: 12-13.

- Volcanic outgassing of CO_2 over ~10^6 yr may have increased greenhouse effect sufficiently to melt back the ice.

Bring on the Heat: Hothouse follows Snowball?

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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

Image removed due to copyright restrictions.

One Complete Snowball-Hothouse Episode

Image from P. Hoffman

The Geochemical Carbon Cycle

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Image from P. Hoffman

CARBONATE WEATHERING

weathering:

$$CaCO_3 + CO_2 + H_2O \rightarrow$$

transport:

$$Ca^{2+} + 2HCO_3^- \rightarrow$$

sedimentation:

$$\boxed{CaCO_3} + CO_2 + H_2O$$

SILICATE WEATHERING

weathering:

$$CaSiO_3 + 2H_2O + 2CO_2 \rightarrow$$

transport:

$$Ca^{2+} + 2HCO_3^- + 2H^+ + SiO_3^{2+} \rightarrow$$

deposition:

$$\boxed{CaCO_3 + SiO_2.H_2O} + H_2O + CO_2$$

Enhanced Weathering of Rocks Results in Precipitation of Minerals in Ocean

- High T & CO_2 cause increase in weathering rate of continents
- Products of weathering carried to ocean by rivers
- Precipitated as $CaCO_3$ and SiO_2 minerals in ocean

Geologic Evidence for Hothouse Aftermath: “Cap Carbonates”

Thick sequences of inorganically precipitated $CaCO_3$ overly Neoproterozoic glacial deposits globally.

Neo-proterozoic Cap Carbonates-1

Image removed due to copyright restrictions.
Citation: See Figure 3. Paul F Hoffman, Daniel P Schrag (2002). The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14 (3), 129-155. doi:10.1046/j.1365-3121.2002.00408.x

- 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.

Hoffman & Schrag (2002) *Terra Nova*, Vol. 14(3):129-155.

Neoprot. Cap Carbonates: 2

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Citation: See Figure 4. Paul F Hoffman, Daniel P Schrag (2002). The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14 (3), 129-155. doi:10.1046/j.1365-3121.2002.00408.x

- Ripples, storm waves
- Aragonite crystal fans

Hoffman & Schrag (2002) *Terra Nova*, Vol. 14(3):129-155.

Aragonite Fan in Namibia

Image removed due to copyright restrictions.

- Carbonate fans form when $CaCO_3$ is rapidly precipitated from water.

Image from P. Hoffman

Image removed due to copyright restrictions.
Citation: See Figure 9. Paul F Hoffman, Daniel P Schrag (2002). The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14 (3), 129-155. doi:10.1046/j.1365-3121.2002.00408.x

Geologic & Isotopic Change Associated with Snowball Event:

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

Hoffman & Schrag (2002) *Terra Nova*, Vol. 14(3):129-155.

Summary of Snowball-Hothouse Sequence

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Citation: See Figure 7. Paul F Hoffman, Daniel P Schrag (2002). The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14 (3), 129-155. doi:10.1046/j.1365-3121.2002.00408.x

Note: T estimated from
E balance model

Hoffman & Schrag (2002) *Terra Nova*, Vol. 14(3):129-155.

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

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• Glacial episodes probably lasted < 1 Myr

• Cap carbonates likely deposited within 10^3-10^4 yr

Image from P. Hoffman

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'

Image removed due to copyright restrictions.

Citation: Lubick (2002) *Nature*, Vol. 417: 12-13.

- 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.

Citation: Pierrehumbert, R. T. (2005), Climate dynamics of a hard snowball Earth, *J. Geophys. Res.*, *110*, D01111, doi:10.1029/2004JD005162.

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

Kennedy et al. (2001) *Geology* Vol. 29(5): 443-446.

•$CaCO_3$ 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.

$$CH_4 + SO_4^{=} \rightarrow HCO_3^{-} + HS^{-} + H_2O$$

Image removed due to copyright restrictions.

Structures in Cap Carbonates May Result from Gas Release

- Gas Hydrate = [H_2O + hydrocarbon (CH_4)] ice
- CH_4 from biogenic + thermogenic decomposition of deeply buried C_{org}
- Biogenic CH_4 has very low $\delta^{13}C$ (-60 to-90‰)
- Sequestered as hydrate in *permafrost* (> 150 m) & along continental margins (> 300 m)
- Destabilized by increased temperature
- CH_4 released from flooded permafrost during deglaciation

Kennedy et al. (2001) *Geology* Vol. 29(5): 443-446.

Gas Hydrate Stability

Image removed due to copyright restrictions.

Smith et al. (2001) *Geophys. Res. Lett.*, Vol.28(11): 2217-2220.

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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_2CO_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 $\delta^{13}C$

Image removed due to copyright restrictions.

Citation: Orphan, et al. *Science* 293 (2001): 484-487.

CH_4 consumption by sulphate reducers is observed at methane seeps in modern ocean, & $CaCO_3$ precipitates there as a result

- SO_4^{2-} reducers produce highly ^{13}C depleted HCO_3^- which goes into ocean/atmosphere

Image removed due to copyright restrictions.

Citation: Orphan, et al. *Science* 293 (2001): 484-487.

Consortia of sulphate reducers & methane-oxidizing microbes from modern CH_4 seep

Santa Barbara Basin: Recent methane hydrate releases?

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- 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)

Kennett et al. (2000) *Science*, Vol. 288: 128-133.