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.

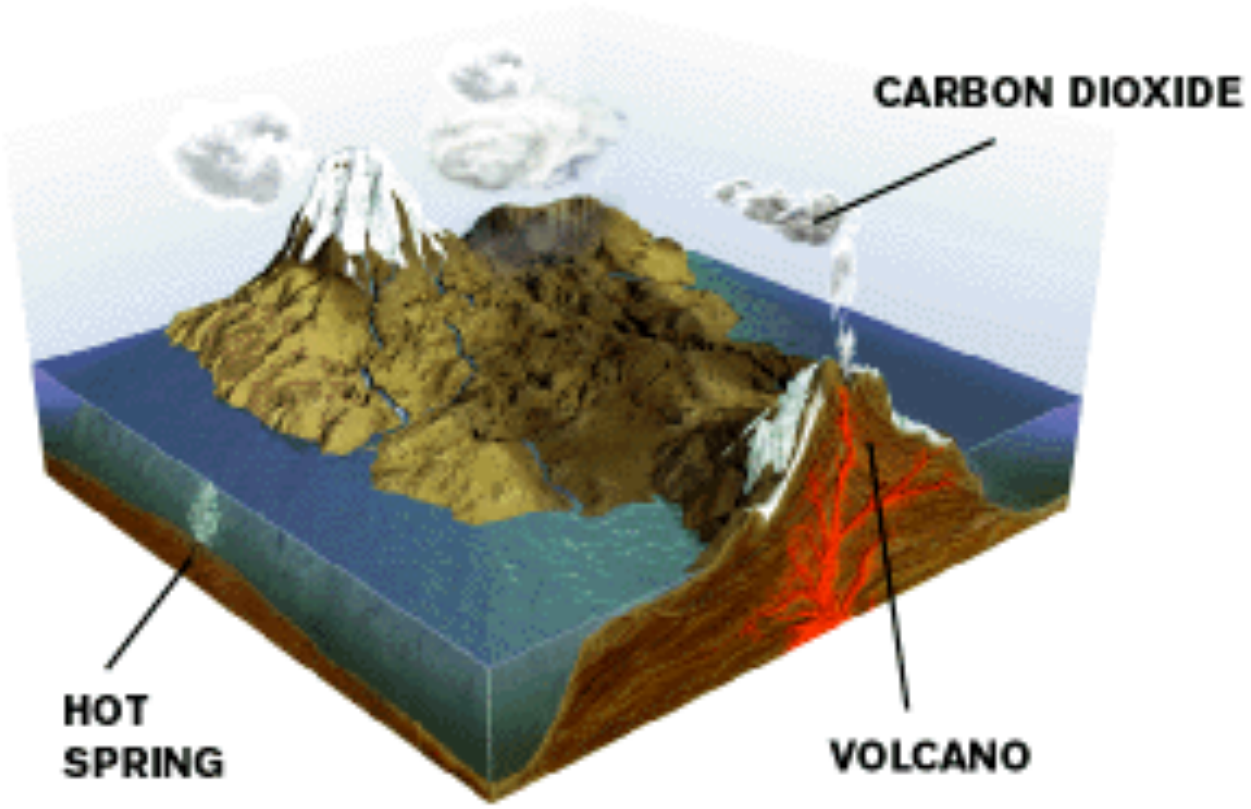
•Glacial sediments – poorly sorted, angular clasts including dropstones – Namibia c. 750 Ma

Image: Daniel P. Schrag

Prologue to Snowball

Stage 1

Snowball Earth Prologue

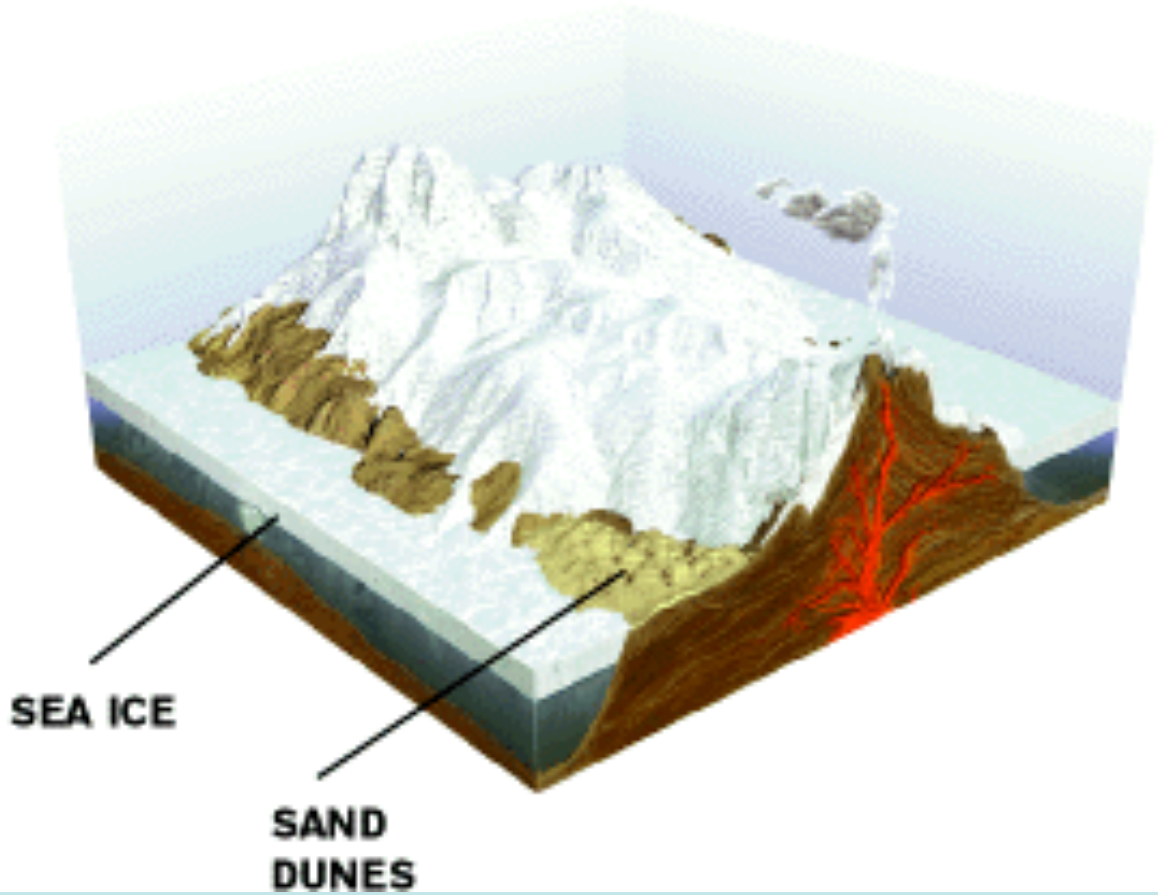


- Breakup of equatorial supercontinent
- Enhanced weathering from increased rainfall (more land close to sea)
- Drawdown atmospheric CO_2 → Global cooling

Hoffman & Schrag (2000)

Stage 2

Snowball Earth at Its Coldest



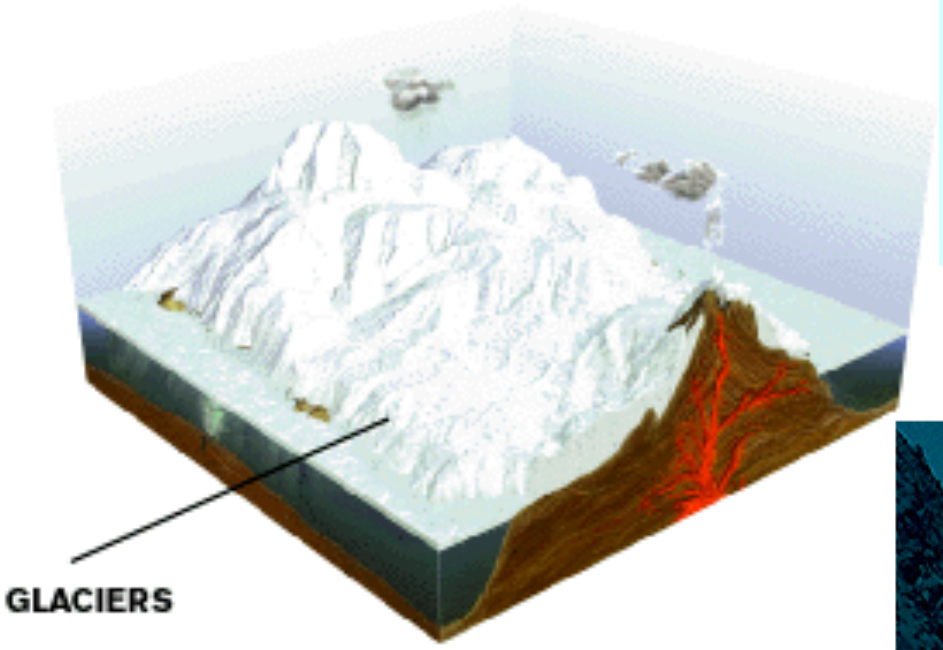
Deep Freeze

- 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)

Stage 3

Snowball Earth as It Thaws



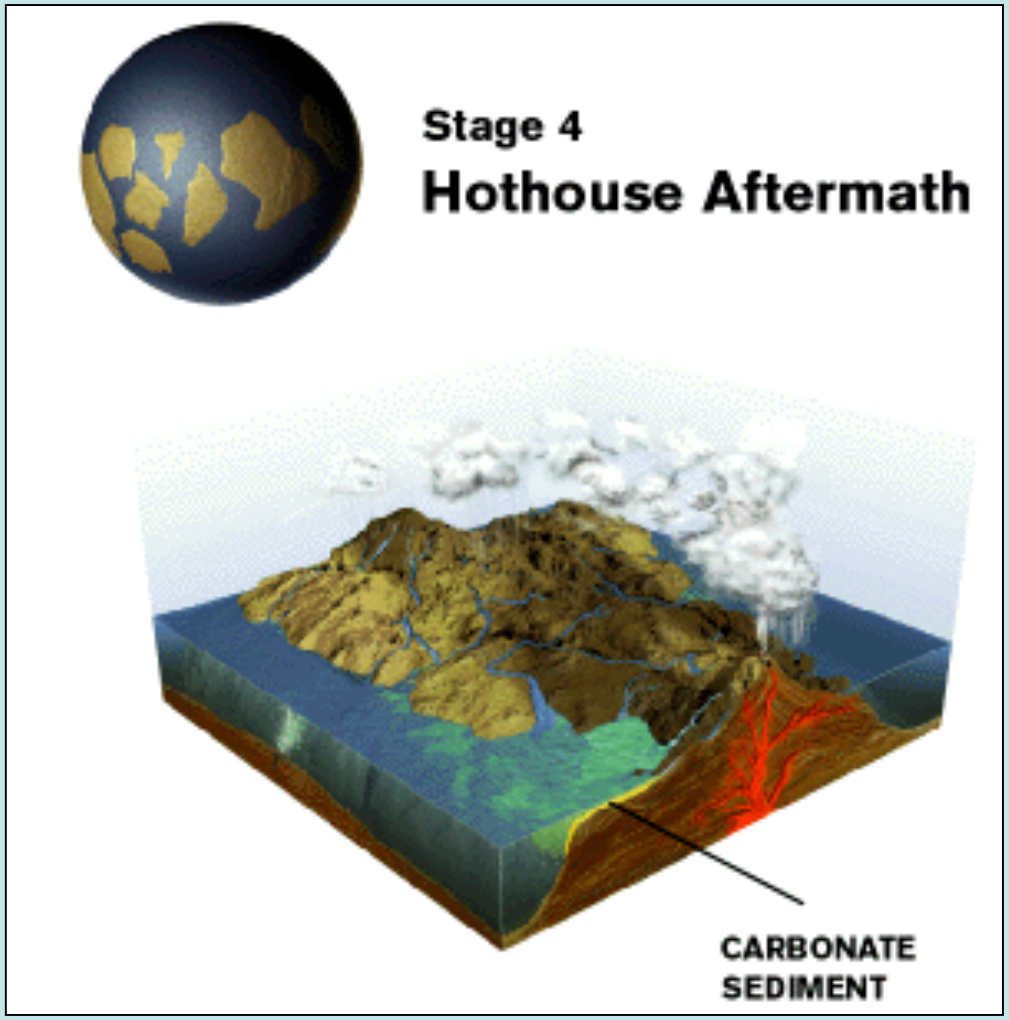
Snowball?

- 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

The Vallee Blanche, Mont Blanc, French Alps

Hoffman & Schrag (2000)

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

BIF + Dropstone = Ice-covered, anoxic ocean?

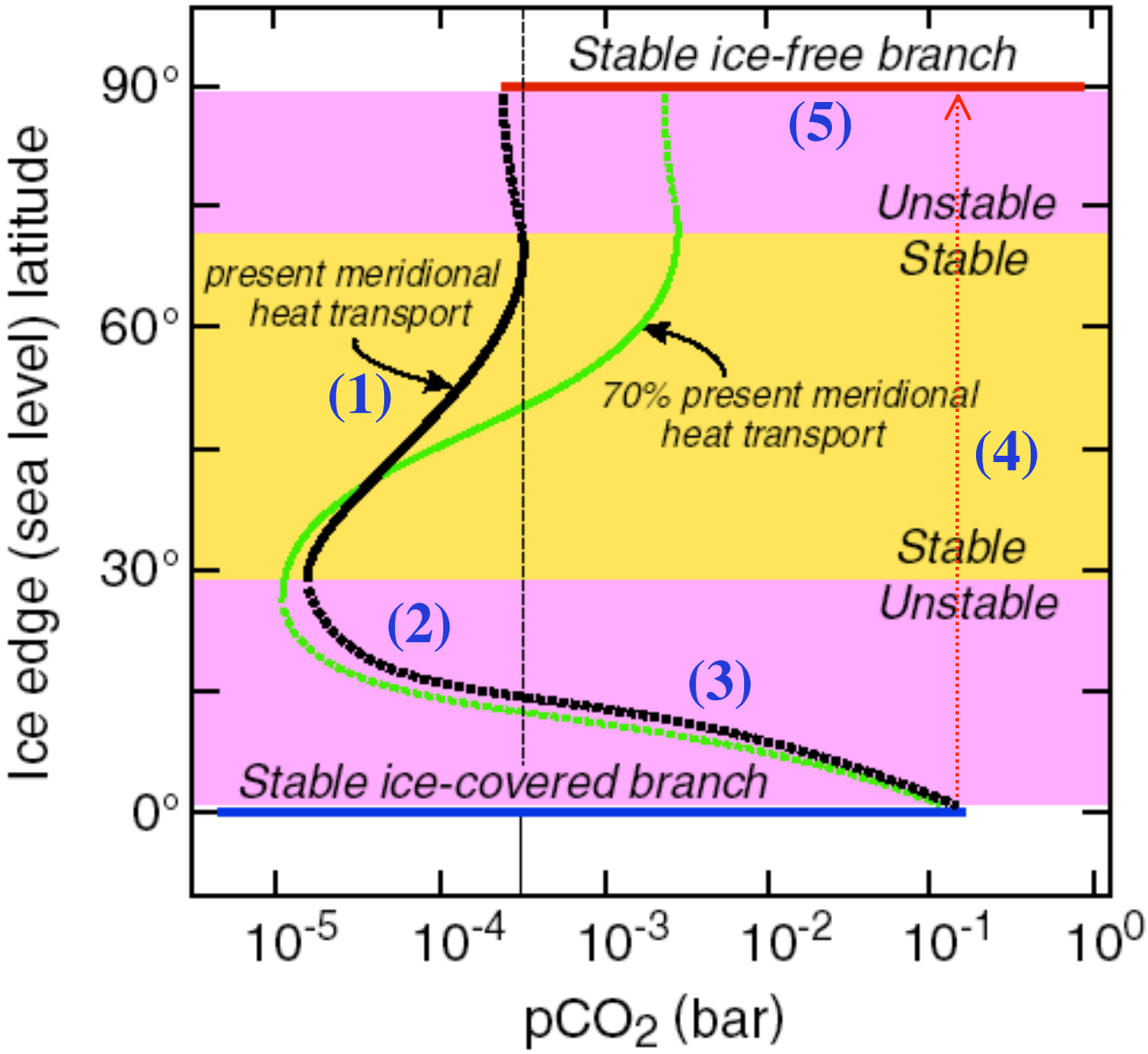
McKenzie Mtns., Western Canada

Image from P. Hoffman

Breaking out of the Snowball

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

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



Steady-state ice lines as a function of atmospheric pCO_2, *see* Caldeira and Kasting (*Nature* **359**: 226, 1992), and Ikeda and Tajika (*Geophys. Res. Lett.* **26**: 349, 1999).

•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

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").

Evidence for Glaciers on All Continents

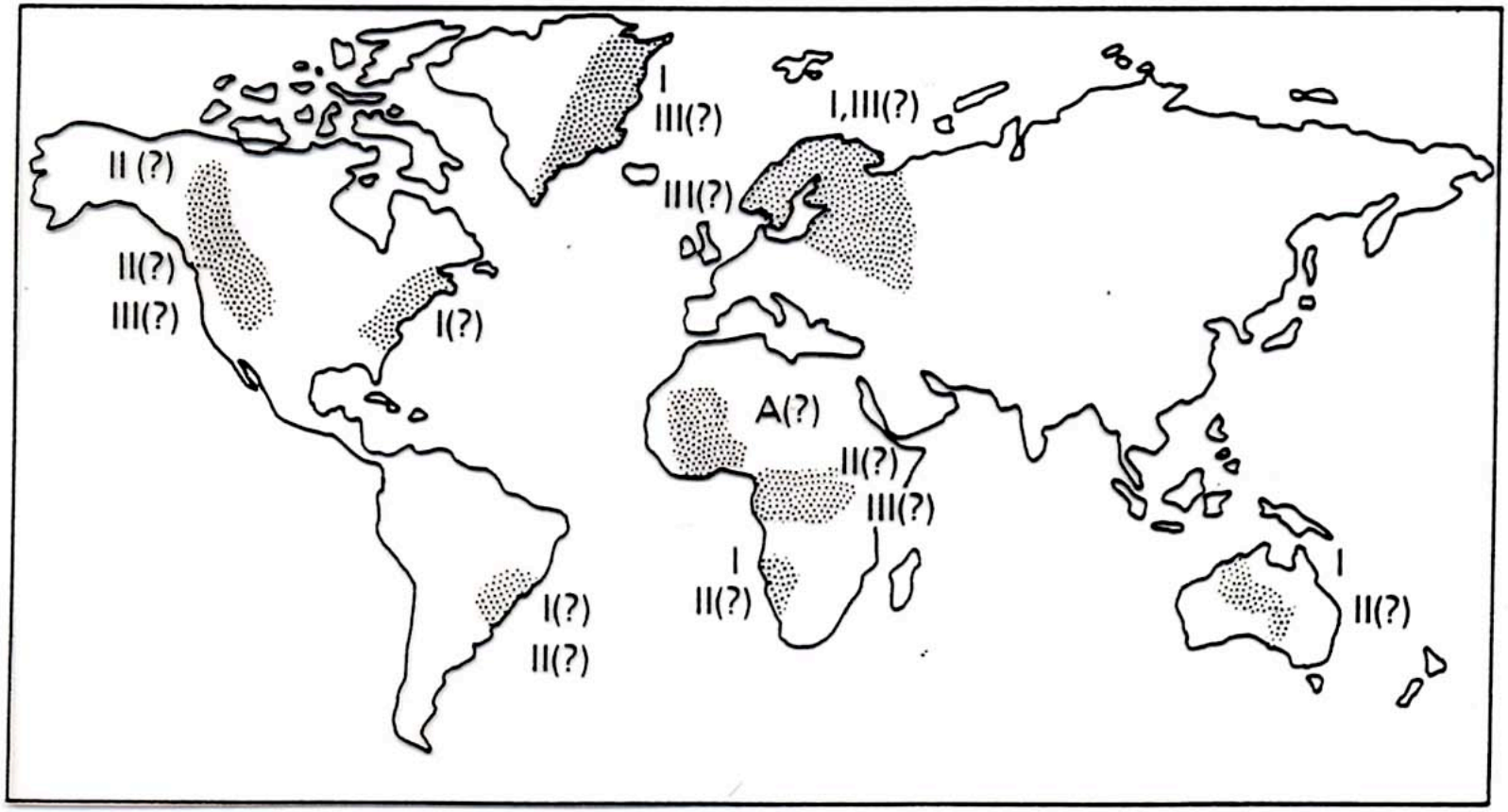
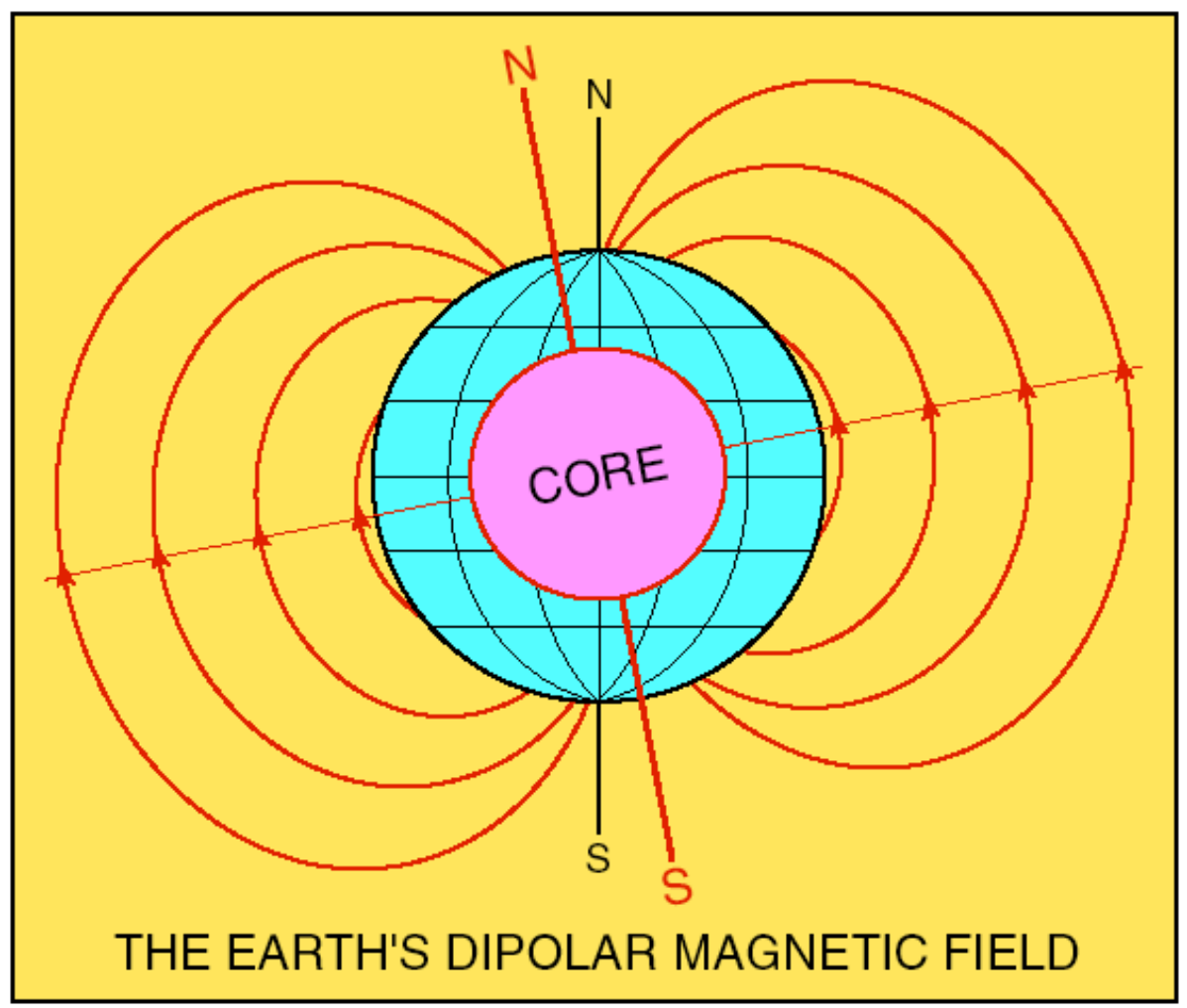


Fig. 12.3. Global distribution of major late Precambrian glacial centers on a map showing the present dispersal of continents. I, II, III refer to glaciations identified by Williams (1975) as centered on ~610 Ma, 750 Ma, and 950 Ma, respectively. A subsequent summary of late Precambrian glaciations (Hambrey 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)

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

Equatorial Continents?

Hoffman & Schrag (2000)

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*).

•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).