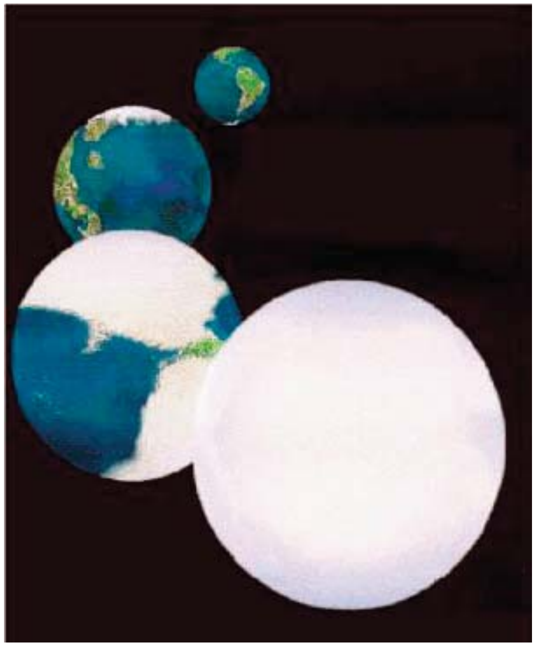
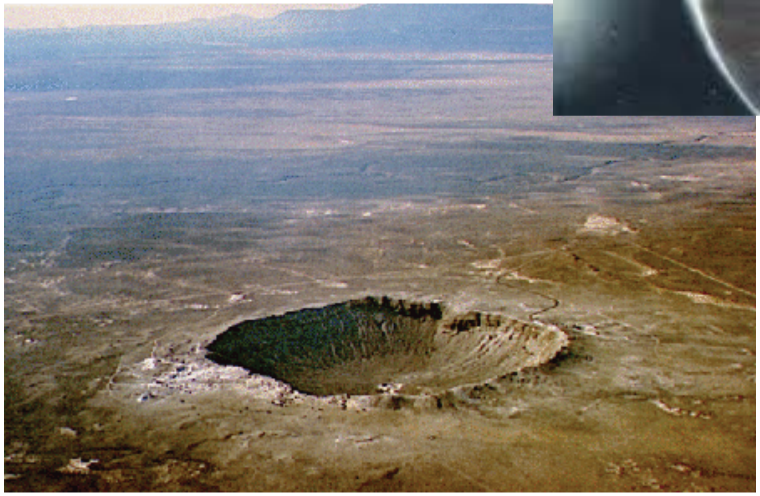
Geobiology 2013
Lecture 12

The Climate History of Earth

1. Proterozoic events- this lecture

Phanerozoic Climate
later-maybe





Images courtesy of NASA.

Need to know

Timing of 5 periods of ‘extreme’ climate in Earth’s history

Elements of Snowball Earth Theory

Evidence for widespread, low latitude glaciations at end of Precambrian

Scenarios to enter extreme climate states

Scenarios to escape

Possible role in evolution of multicellular complex life

Assigned Readings

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Hoffman & Schrag, Snowball Earth, Scientific American January 2000

Hoffman & Schrag, The snowball Earth hypothesis: testing the limits of global change, Terra Nova 2002

Stanley, pp. 84-101 & 288-289

See also: http://www.snowballearth.org

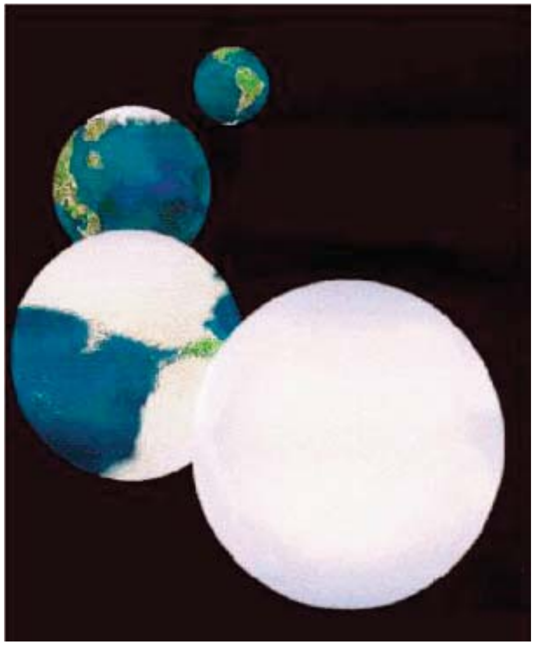
Extras:

Kump LR, Kasting JF and Crane RG (1999) *The Earth System*, Chap. 7.

Royer DL, Berner RA, Montanez IP, Tabor NJ and Beerling DJ, CO2 as a primary driver of Phanerozoic climate GSA Today March 2004, pp. 4-10

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

Hoffman, P.F., 2008. Snowball Earth: status and new developments. GEO (IGC Special Climate Issue) 11, 44-46.



Images courtesy of NASA.

Animals and the invention of the Phanerozoic Earth System

Nicholas J. Butterfield

Trends in Ecology and Evolution, February 2011, Vol. 26, No. 2

Recap on O_2-Paradigm

- The C-cycle has evolved radically through time
- Prior to 2.2 Ga anaerobic prokaryotes dominated; wide spread of δ_{org} (δo) values; oxygenic photosynthesis extant but oxygen remained low as sinks >> sources
- Mantle may have been an important sink for electrons ie oxidising power (Cloud/Holland)
- Extreme δ_{carb} (δa) values around 2.2 Ga probably signify the 'GOE' and rise to prominence of aerobes; Decreased spread of δorg (δa) values may reflect dominance of aerobic autotrophs and reductive pentose (Benson-Calvin; C3) cycle

Recap on O_2-Paradigm

- Although ample evidence for aerobes, the abundance of O_2 in atm and ocean remained low (sulfidic ocean) until another major oxidation event caused a second ‘reorganization’ In the Neoproterozoic. This was also signified by extreme δa fluctuations.

- The Neoproterozoic ‘reorganization’ culminated in pO_2 rising to near PAL allowing animals to flourish and stabilizing of the new regime.

- Environmental evolution reflected changes in the balance between thermal, crustal, atmospheric & biological processes

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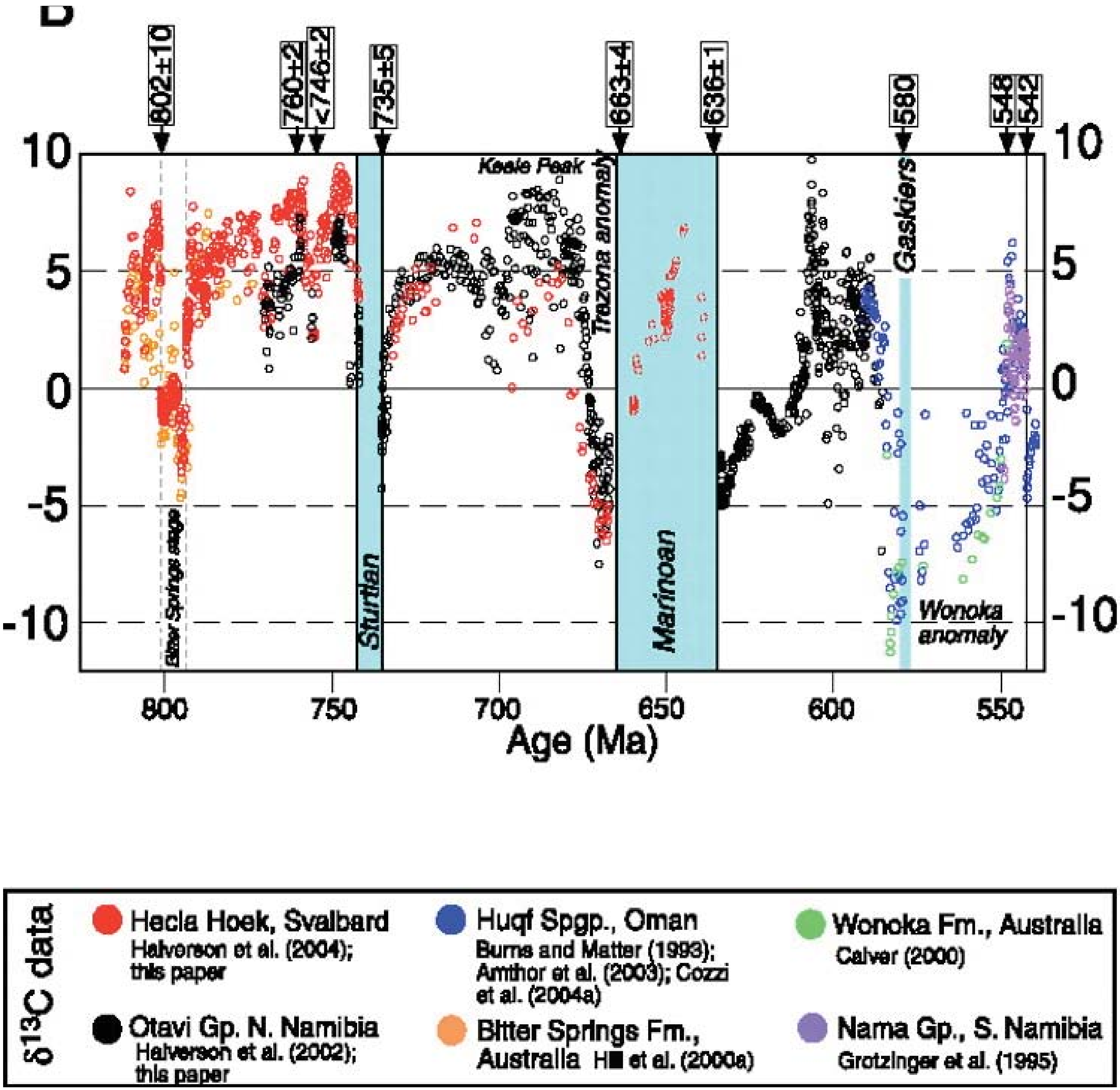
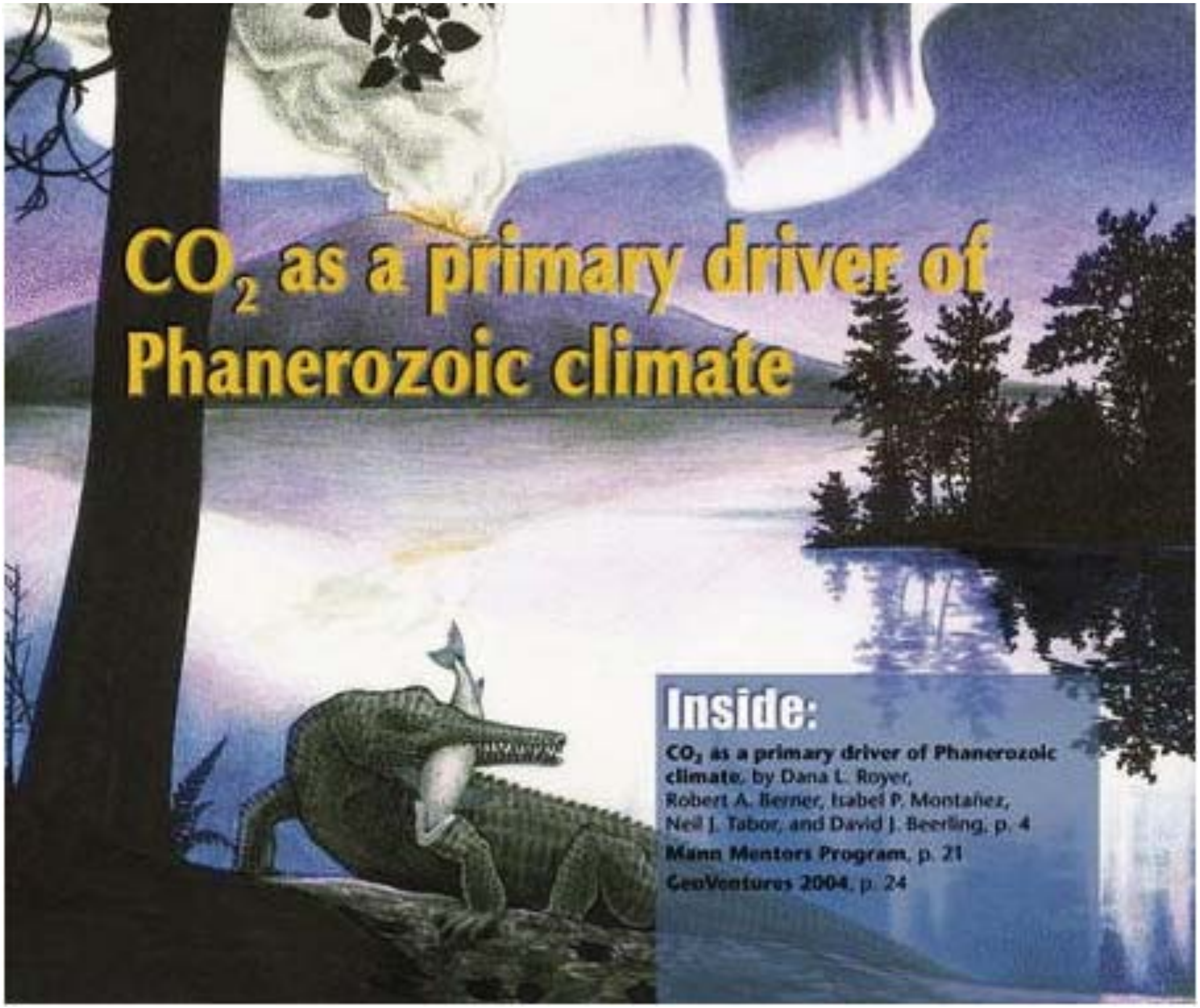
Please see:
Figure 1. in A. D. Anbar and A. H. Knoll, Proterozoic Ocean Chemistry and Evolution: A Bioinorganic Bridge? *Science* 2002, 297, 1132.



GSA Bulletin; September 2005; v. 117; no. 9-10; p. 1181-1207;
Toward a Neoproterozoic composite carbon-isotope record
Galen P. Halverson, Paul F. Hoffman, Daniel P. Schrag, Adam C. Maloof and A. Hugh N. Rice

Image courtesy of the Geological Society of America. Used with permission.

GSA Today
Volume 14, Number 3, March 2004



CO_2 as a primary driver of Phanerozoic climate

Inside:

CO_2 as a primary driver of Phanerozoic climate, by Dana L. Royer, Robert A. Berner, Isabel P. Montañez, Neil J. Tabor, and David J. Beerling, p. 4

Mann Mentors Program, p. 21

GeoVentures 2004, p. 24

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Outline

- Overview of Earth's climate history

- Climate feedbacks: what keeps climate away from extremes?
  - Planetary Energy Balance
  - Greenhouse Effect
  - Geochemical Carbon Cycle, CO_2
  - Temperature, Precipitation-Weathering Feedback

- Case studies: Neoproterozoic glaciations (750-580 Ma)
  - http://www.snowballearth.org/
  - Permo-carboniferous Glaciations (300-275 Ma)
  - Mesozoic Warmth (245-65 Ma)
  - Cenozoic Cooling (100-0 Ma)
  - Pleistocene Glaciations (0.5-0 Ma)

Earth's Climate History:

Mostly sunny with a 10% chance of snow

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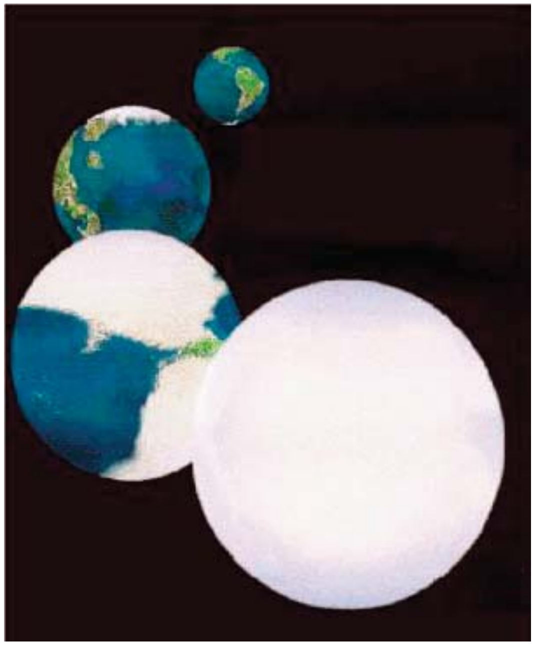
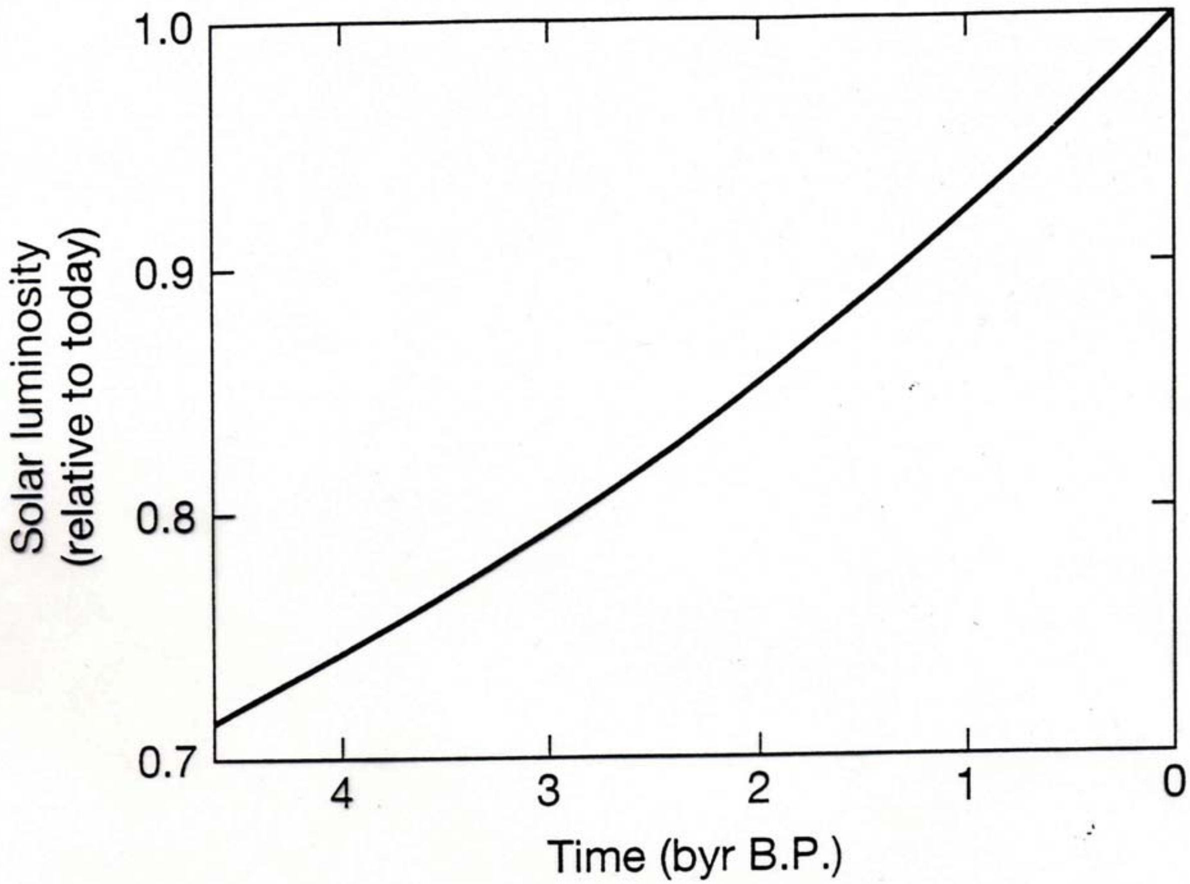


Images courtesy of NASA.

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
- Composition of the atmosphere (biology, tectonics, volcanoes): 10^0-10^5 yr

Faint Young Sun Paradox



4 $^1H \rightarrow {}^4He$
Incr. density=
incr. luminosity

Solar Luminosty ~30% less 4.6 Byr BP

→ Earth should have been frozen
until ~2 Byr BP

Liquid H_2O existed
>4 Ga (sed. rocks,
life, zircon $\delta^{18}O$)

Contemporary Solar Variability

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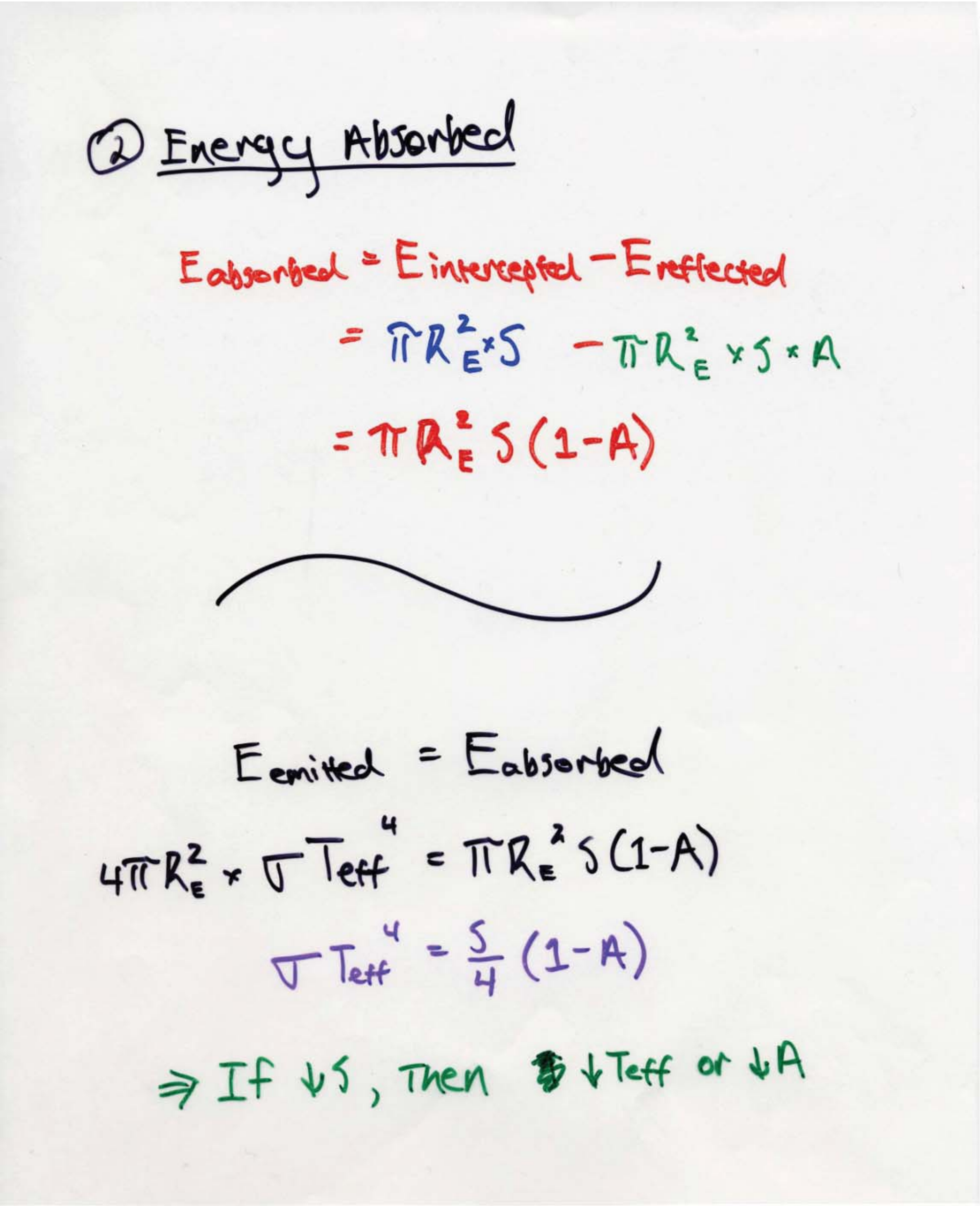
Please see Fig. 9 in Fröhlich, C. "Solar Irradiance Variability Since 1978." *Space Science Reviews* 125 (August 2006): 53-65.

- Contemporary Solar Variability ~0.1%
- Associated with 11-year sunspot cycle



② Energy Absorbed

$$E_{absorbed} = E_{intercepted} - E_{reflected}$$

$$= \pi R_E^2 * S \quad - \pi R_E^2 \times S \times A$$

$$= \pi R_E^2 S(1-A)$$

$$E_{emitted} = E_{absorbed}$$

$$4\pi R_E^2 \times \sigma T_{eff}^4 = \pi R_E^2 S(1-A)$$

$$\sigma T_{eff}^4 = \frac{S}{4}(1-A)$$

⇒ If ↓S, Then ↓Teff or ↓A

Energy Balance

S= solar flux

T = effective radiating temperature

A= albedo or reflectivity as a fraction of incident radiation

R_E = earth radius

Stefan_Boltzmann law

Energy Flux = const* T^4

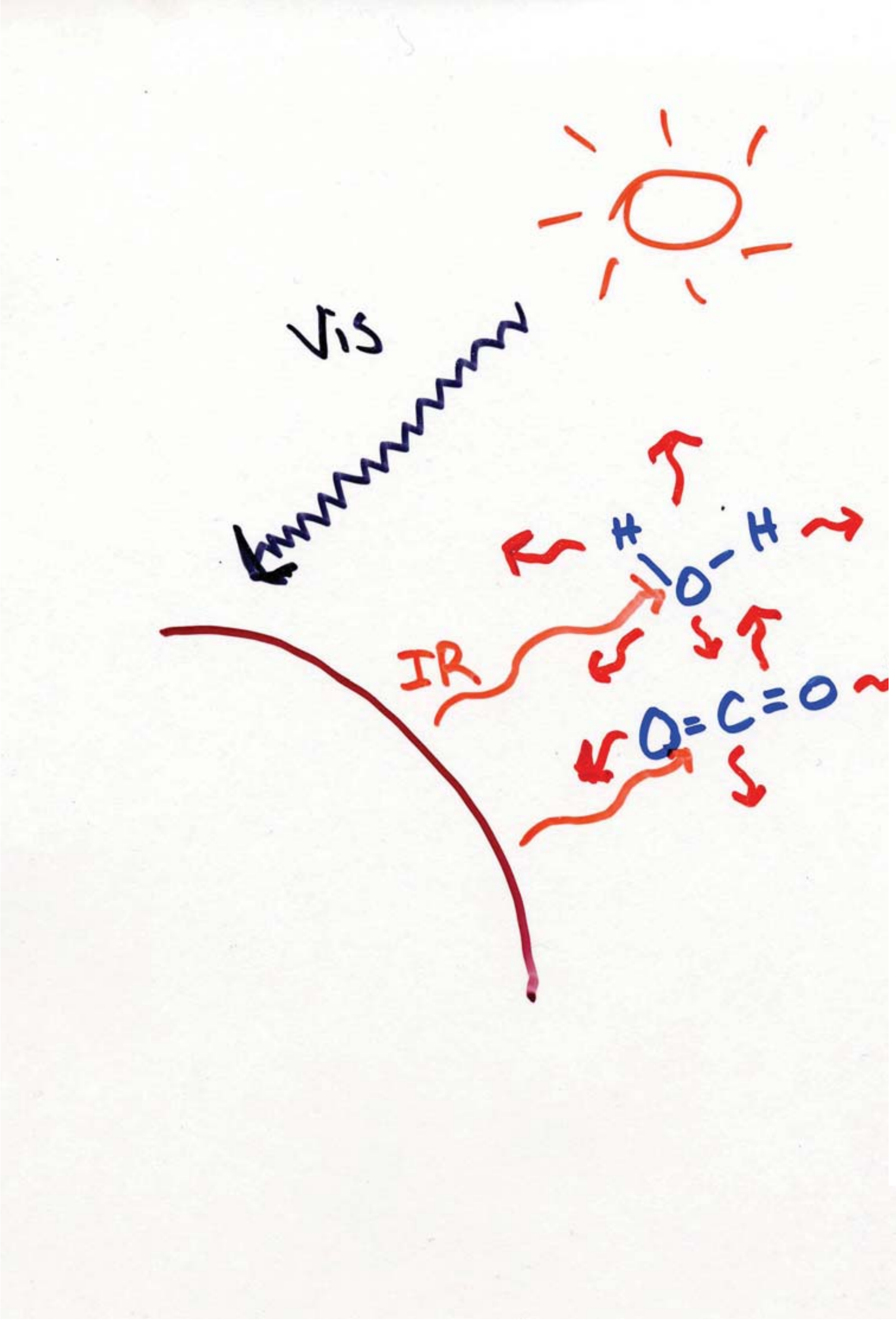
Const $\sigma = 5.67 * 10^{-8}$ w/m^2/K^4

The **Stefan–Boltzmann law** states that the total energy radiated per unit surface area of a black body in unit time (known variously as the black-body **irradiance**, **energy flux density** or **radiant flux,** $j^{\star}$, is directly proportional to the fourth power of the black body's **absolute temperature**):

Adapted from Kump et al. (1999)

Therefore:

Lower S must have been compensated by larger greenhouse effect



Greenhouse Gases:

Those that absorb IR radiation efficiently

N_2O, CO_2, CH_4, H_2O

Image removed due to copyright restrictions.

Please see Fig. 1 in Hofmann, D. J., et al. “Tracking Climate Forcing: The Annual Greenhouse Gas Index.” *Eos* 87 (November 14, 2006): 509-511.

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Please see Fig. 2 in Hofmann, D. J., et al. “Tracking Climate Forcing: The Annual Greenhouse Gas Index.” *Eos* 87 (November 14, 2006): 509-511.

How much CO_2 Required for $T_S > 0°C$?

Image removed due to copyright restrictions.

Please see Fig. 2 in Kasting, James F. “Earth’s Early Atmosphere.” *Science* 259 (February 12, 1993): 920-926.

http://www.geosc.psu.edu/~kasting/PersonalPage/Pdf/Science_93.pdf

*Venus: Same qty. of C as Earth;
All in atmos. -> $T_S \leq 450°C$

Earth's Climate History:

Mostly sunny with a 10% chance of snow

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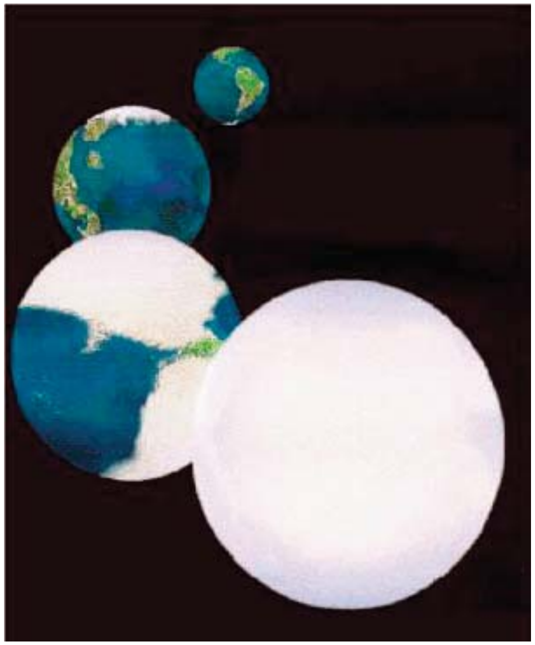


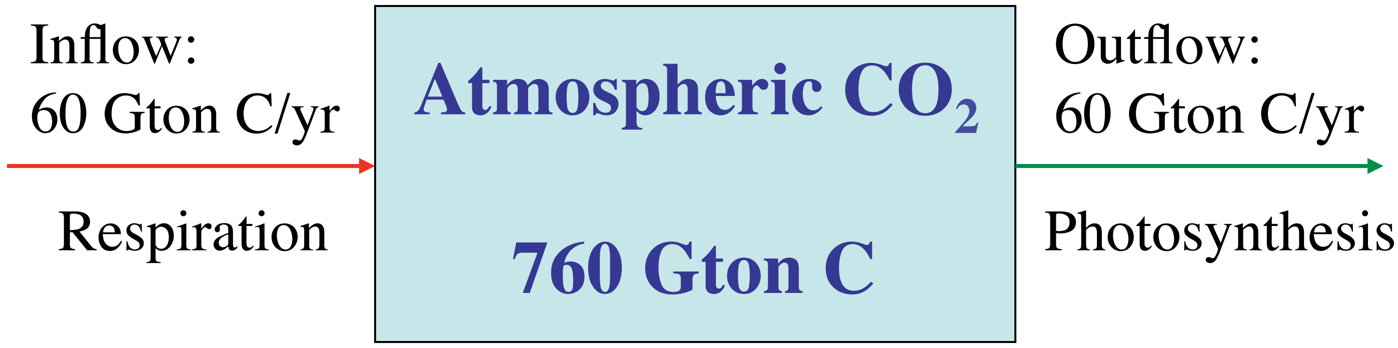
Images courtesy of NASA.

What caused these climate perturbations?

Steady State & Residence Time

Steady State: Inflows = Outflows

Any imbalance in I or O leads to changes in *reservoir* size



Inflow:
60 Gton C/yr

Respiration

Atmospheric CO_2

760 Gton C

Outflow:
60 Gton C/yr

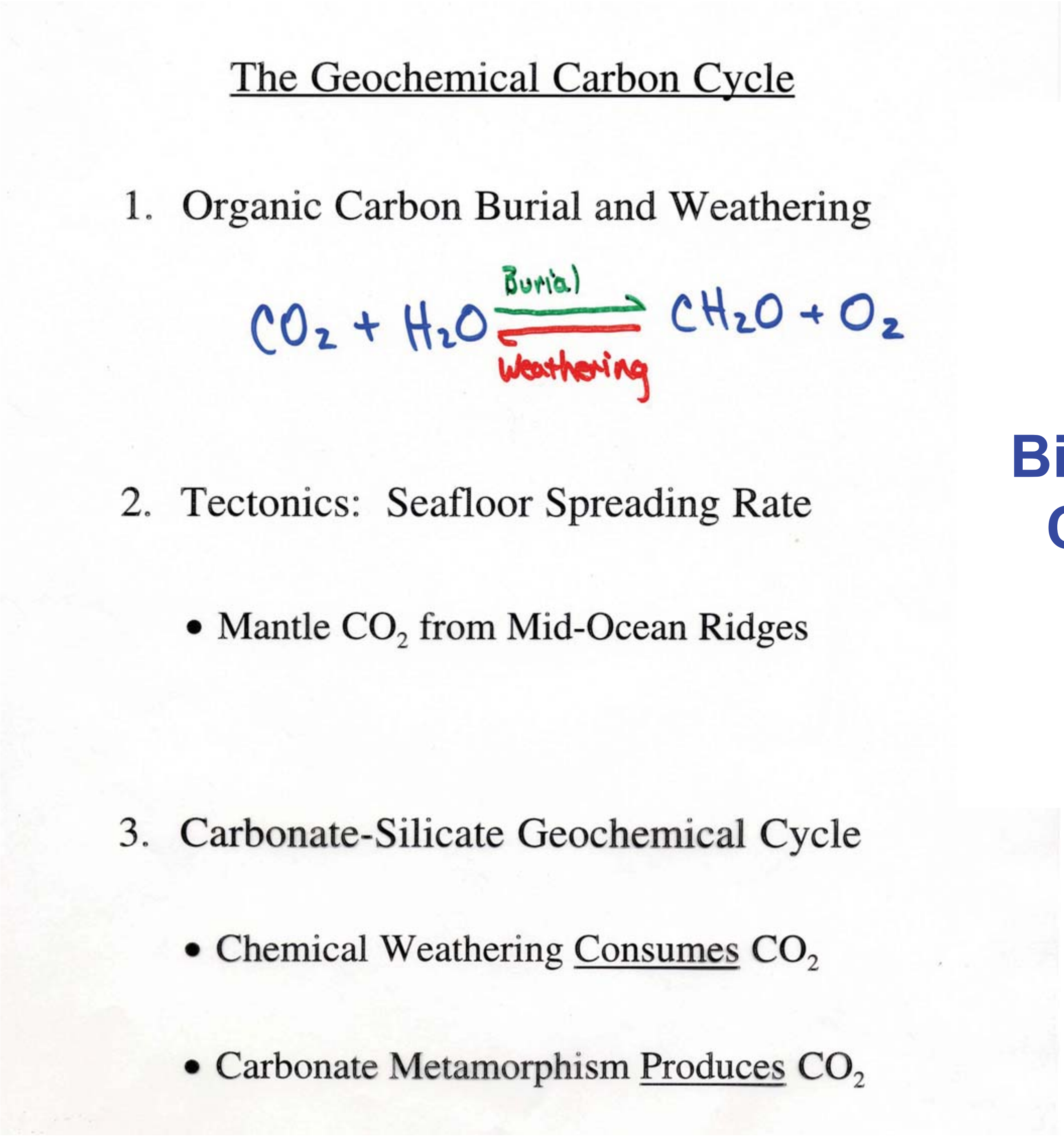
Photosynthesis

1 Gton = 10^9 * 1000 kg = 10^{15} g

The *Residence time* of a molecule is the average amount of time it is expected to remain in a given reservoir.

Example: t_R of atmospheric CO_2 = 760/60 = 13 yr

The Biogeochemical Carbon Cycle



The Geochemical Carbon Cycle

1. Organic Carbon Burial and Weathering

$$CO_2 + H_2O \xrightleftharpoons[\text{Weathering}]{\text{Burial}} CH_2O + O_2$$

2. Tectonics: Seafloor Spreading Rate

   - Mantle CO_2 from Mid-Ocean Ridges

3. Carbonate-Silicate Geochemical Cycle

   - Chemical Weathering <u>Consumes</u> CO_2
   - Carbonate Metamorphism <u>Produces</u> CO_2

The Biogeochemical Carbon Cycle

Chemical Weathering = chemical attack of rocks by dilute acid

$$\boxed{CO_2} + H_2O <---> \boxed{H_2CO_3}$$

1. Carbonate Weathering:

$$CaCO_3 + \boxed{H_2CO_3} --> Ca^{2+} + 2\ HCO_3^-$$

2. Silicate Weathering:

$$CaSiO_3 + \boxed{2\ H_2CO_3} --> Ca^{2+} + 2HCO_3^- + SiO_2$$

- 2x CO_2 consumption for silicates
- Carbonates weather faster than silicates

Image removed due to copyright restrictions.

Carbonate rocks weather faster than silicate rocks!

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copyright restrictions.

Please see Kump, L. R., et al. *The Earth System*. Upper Saddle River, NJ: Pearson Prentice Hall, 1999.

Products of weathering precipitaed as $CaCO_3$ & SiO_2 in ocean

Net reaction of geochemical carbon cycle (Urey Reaction)

Net Reaction of Rock Weathering
+
Carbonate and Silica Precipitation in Ocean

$$CaSiO_3 + \boxed{CO_2} \dashrightarrow CaCO_3 + SiO_2$$

- CO_2 consumed (~ 0.03 Gt C/yr)
- Would deplete atmospheric CO_2 in 20 kyr
- Plate tectonics returns CO_2 via Volcanism and Metamorphism

---

Carbonate Metamorphism

$$CaCO_3 + SiO_2 \dashrightarrow CaSiO_3 + \boxed{CO_2}$$

- CO_2 produced from subducted marine sediments

Carbonate-Silicate Geochemical Cycle

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Please see Fig. 10-11 in Stanley (course text).

- CO_2 released from volcanism dissolves in H_2O, forming carbonic acid H_2CO_3
- H_2CO_3 dissolves rocks
- Weathering products transported to ocean by rivers
- $CaCO_3$ precipitation in shallow & deep water
- Cycle closed when $CaCO_3$ metamorphosed in subduction zone or during orogeny.

How are CO_2 levels kept in balance?

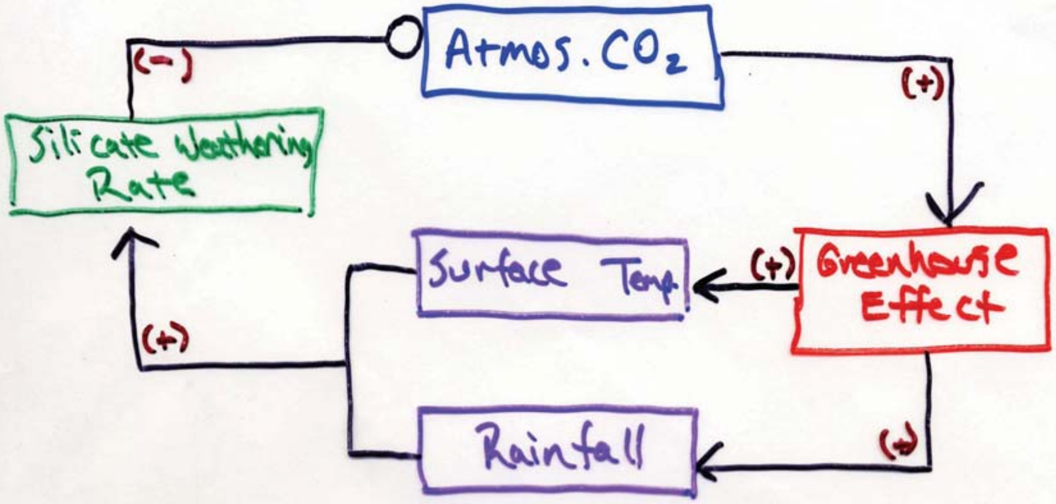
- Geologic record indicates climate has rarely reached or maintained extreme Greenhouse or Icehouse conditions....
- Negative feedbacks between climate and Geochemical Carbon Cycle must exist
- Thus far, only identified for Carbonate-Silicate Geochemical Cycle:

<u>Temp., rainfall enhance weathering rates</u>

(Walker et al, 1981)

(I.e., no obvious climate dependence of tectonics or organic carbon geochemical cycle.)

Feedbacks

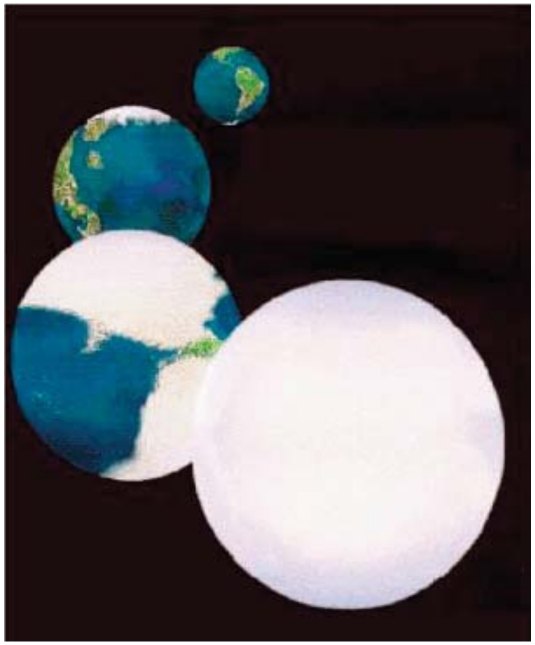


Adapted from Kump et al. (1999)

The Proterozoic Glaciations

(‘Snowball Earth’)

http://www.snowballearth.org



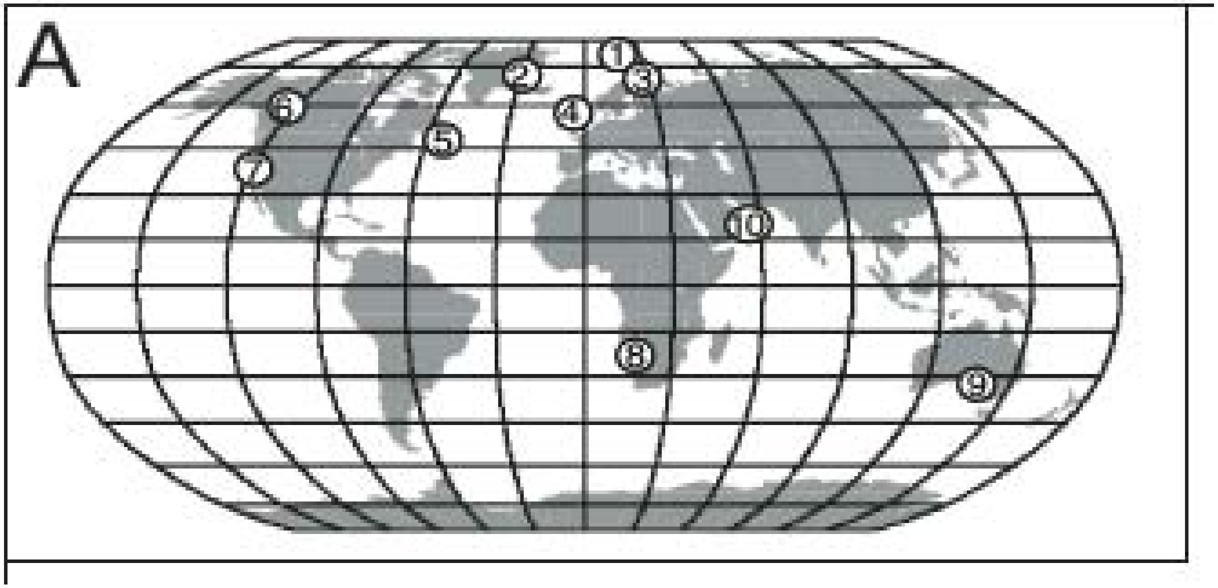
Images courtesy of NASA.

<u>Reading</u>:

- •Hoffman & Schrag (2002) *Terra Nova*, Vol. 14(3):129-155.
- •Lubick (2002) *Nature*, Vol. 417: 12-13.

Figure 1. (A) Present-day locations of the Neoproterozoic successions

HALVERSON et al.



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GSA Bulletin; September 2005; v. 117; no. 9-10; p. 1181-1207;
Toward a Neoproterozoic composite carbon-isotope record
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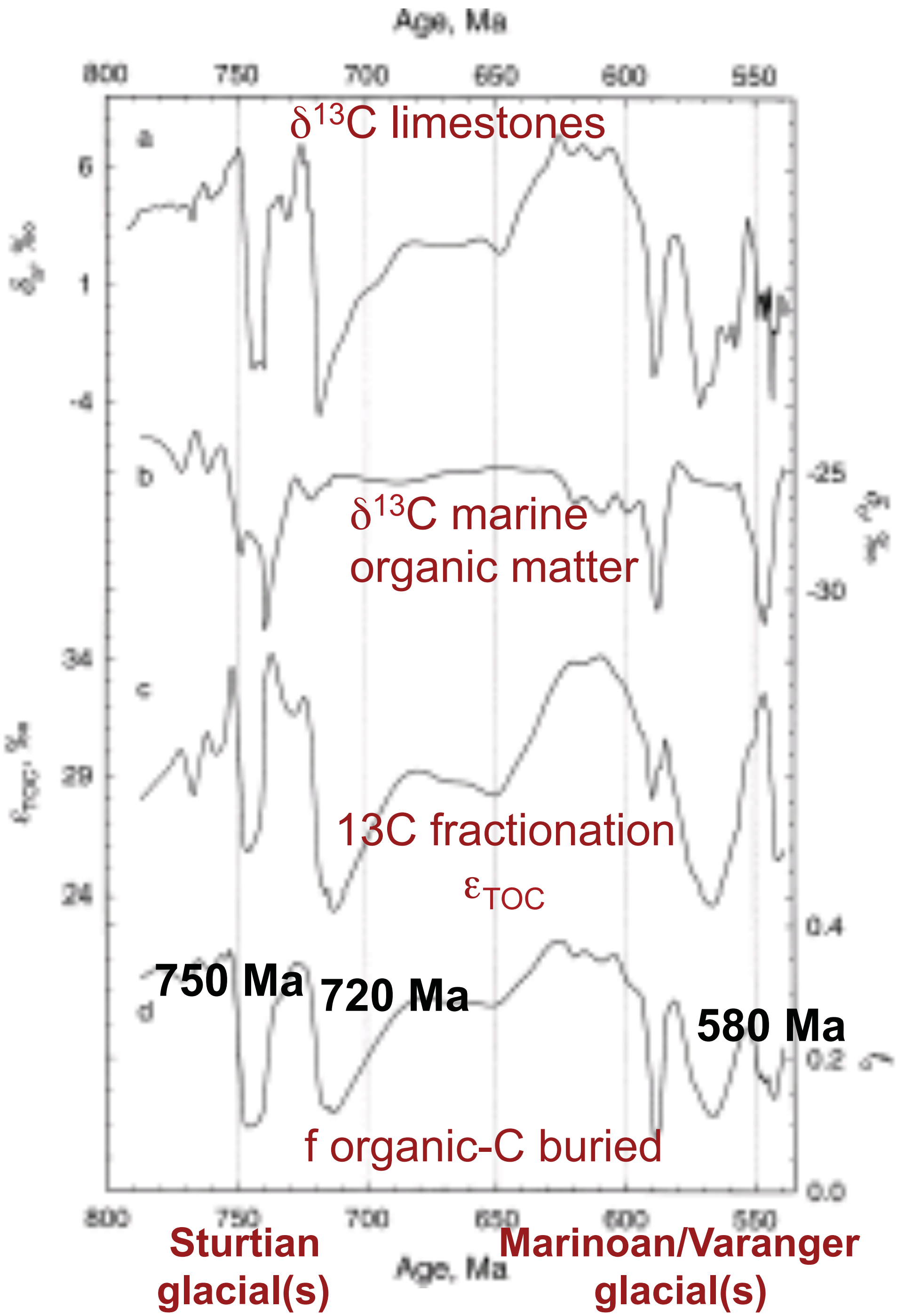

Carbon Isotopic Excursions 800-500Ma

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

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

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Neoproterozoic Glaciations: Evidence

3-4 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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Please see Fig. 3 in Hoffman, Paul F., and Schrag, Daniel P. "Snowball Earth." *Scientific American* 282 (January 2000): 68.

Snowball-related 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

Tillites

Packed pebbles, sand & mud. Remnants of moraines

Copyright Marli Miller, University of Oregon.
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http://www.earthscienceworld.org/images
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Glacial Striations

Scratches from rocks dragged by moving ice

Courtesy Walter Siegmund. Image from Wikimedia Commons, http://commons.wikimedia.org

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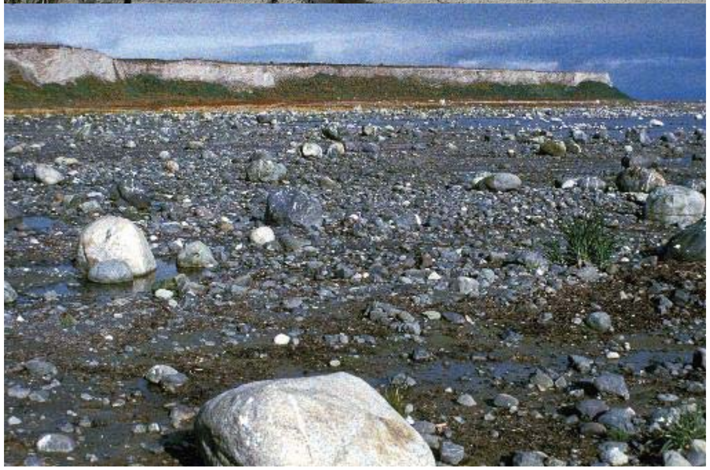

Dropstones:

Rocks transported by icebergs which melt, releasing load into finely laminated sediment (IRD)

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Image from Earth Science World Image Bank,
http://www.earthscienceworld.org/images

Used with permission.

Kump et al. (1999)

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

Image: Daniel P. Schrag

Courtesy Daniel Schrag. Used with permission.

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Please see Fig. 2 in Hoffman, Paul F., and Schrag, Daniel P. “The Snowball Earth Hypothesis: Testing the Limits of Global Change.” *Terra Nova* 14 (2002): 129-155.

Neoproterozoic Glacial Deposits

From Norway, Mauritania, NW Canada, Namibia, Australia Oman

- Glacial striations
- Dropstones
- Diamictites
- Anomalous Iron Formations

Equatorial Continents?

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Please see Fig. 1 in Hoffman, Paul F., and Schrag, Daniel P. “Snowball Earth.” *Scientific American* 282 (January 2000): 68.

- 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)
- •Magn polar drift avgs out on T~10 ky

Image from P. Hoffman

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Please see Fig. 1 in Hoffman, Paul F., and Schrag, Daniel P. “The Snowball Earth Hypothesis: Testing the Limits of Global Change.” *Terra Nova* 14 (2002): 129-155.

Paleolatitude from Paleomagnetism

What can explain glaciers on all continents when they appear to have been close to the equator?

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High Obliquity Hypothesis

George 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 v. large impact to destabilize; moon orbit doesn't support this**

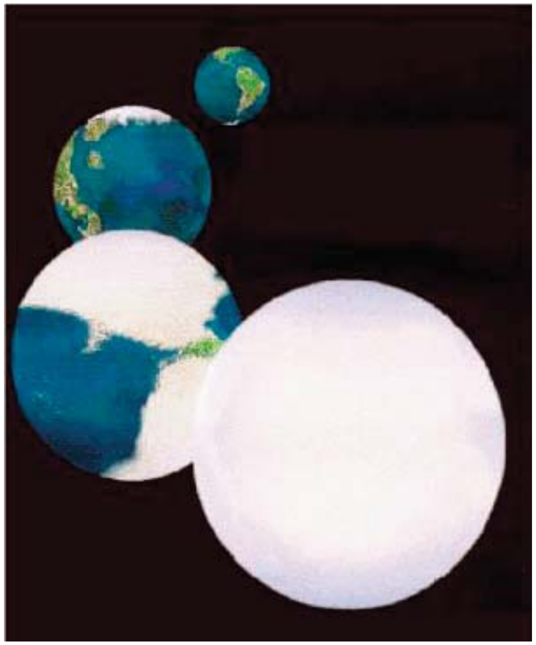
Image from P. Hoffman

Snowball Earth Hypothesis

~3-4 global glaciations followed by extreme greenhouses 750-580 Ma

•Harland (1964); Williams 1976-86; Kirschvink (1992)

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



Images courtesy of NASA.

Snowball Events:

- Breakup of equatorial supercontinent 770 Ma
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- Drawdown atmCO_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

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Please see Fig. 2 in Hoffman, Paul F., and Schrag, Daniel P. “Snowball Earth.” *Scientific American* 282 (January 2000): 68.

‘Prologue’ to Snowball

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

- Is this enough???

Deep Freeze

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Please see Fig. 2 in Hoffman, Paul F., and Schrag, Daniel P. “Snowball Earth.” *Scientific American* 282 (January 2000): 68.

- 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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Budyko-Sellers Runaway Albedo Feedback

1. **Eq continents, incr weathering, lowers CO_2, slow cooling, equatorward movement of ice.**
2. **Runaway albedo**
3. **Slow buildup of CO_2 from volcanoes**
4. **Rapid decay of ice in 10^2 yr. High T_s from enhanced H_20-T feedback.**
5. **Slow CO_2 drawdown from weathering**

Image from P. Hoffman

Profiles of the 1998 Blue Planet Prize Recipients

Dr. Mikhail I. Budyko（Д—р. М.И. Будыко）
(Born in January 1920 in Gomel in the former Soviet Union (now Belarus)
Head of the Division for Climate Change Research, State Hydrological Institute, St. Petersburg

As shown by the unusual weather patterns caused by the El Nino effect, a wide spectrum of climate changes on Earth is having a profound effect on human lives and the environment. Since the 1970s, great advances have been made in climatology, the scientific study of the close relationship between climate and the environment. Playing a pivotal role in the development of climatology has been Dr. Mikhail I. Budyko, one of this year's winners of the Blue Planet Prize. In the 1950s, Dr. Budyko conducted quantitative studies of the global climate by calculating the heat balance of the Earth's surface. This balance involves energy from the sun, which is the most important determining factor for the Earth's climate. First, Dr. Budyko calculated the energy balance of certain regions of the Earth, and then he verified his calculations by making comparisons with observational data. Next, using weather data collected from all over the world, Dr. Budyko carried out heat balance calculations for all regions of the world and confirmed that they checked out with observational data. He announced his findings in 1956 with the publication of his book Heat Balance of the Earth's Surface.

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Please see Fig. 3 in Hoffman, Paul F., and Schrag, Daniel P. “Snowball Earth.” *Scientific American* 282 (January 2000): 68.

Snowball Peak

- •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

Breaking out of the Snowball

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Please see Fig. 2 in Lubick, Naomi. “Palaeoclimatology: Snowball Fights.” *Nature* 417 (May 2, 2002): 12-13.

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

Bring on the Heat: Hothouse follows Snowball?

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Please see Fig. 3 in Hoffman, Paul F., and Schrag, Daniel P. “Snowball Earth.” *Scientific American* 282 (January 2000): 68.

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

Evidence for Snowball Earth Hypothesis

•*Stratigraphy*: globally-dispersed glacial deposits.

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

•*Anomalous 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").

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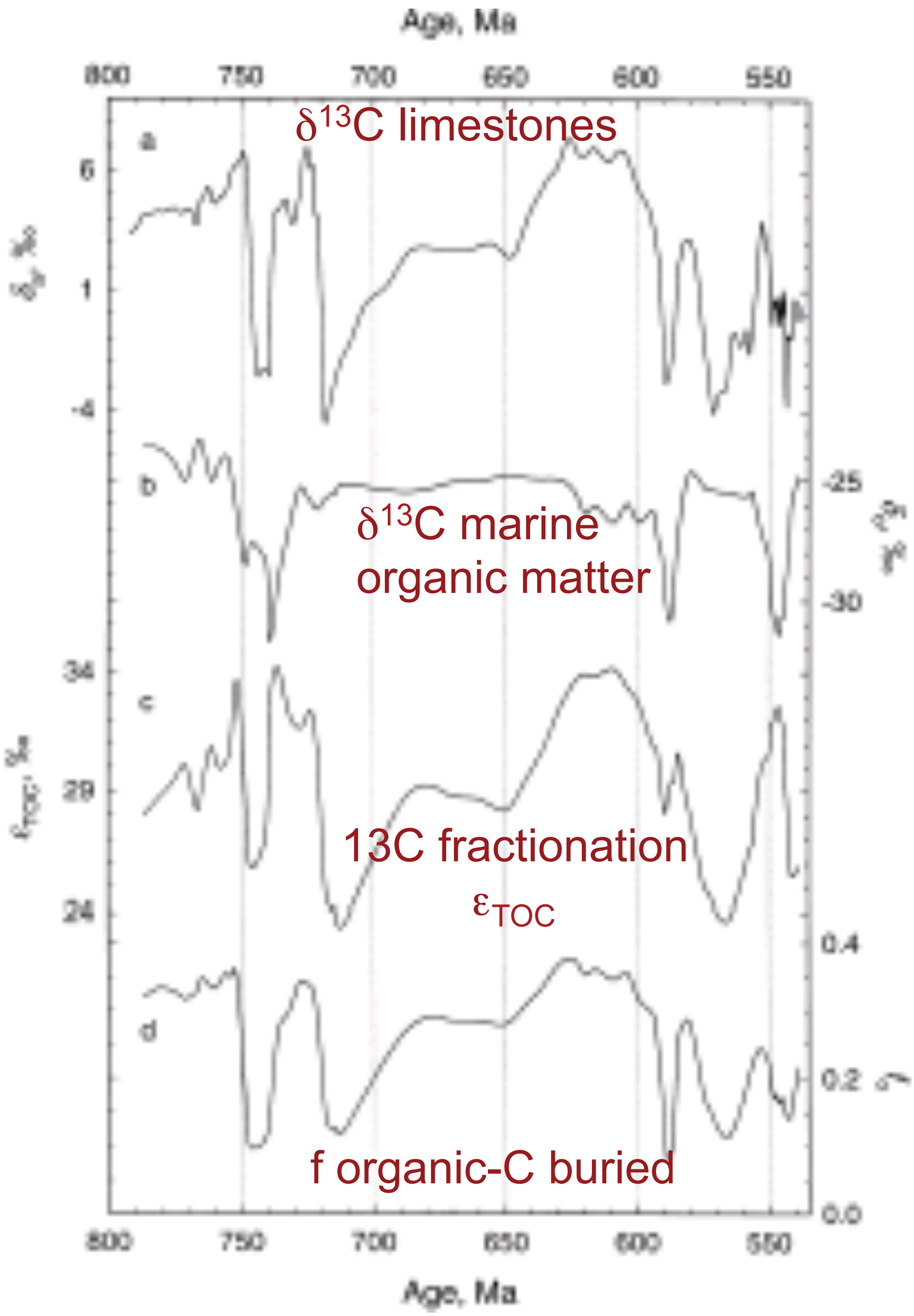
- As fraction of organic carbon buried approaches zero, $\delta^{13}C$ of $CaCO_3$ approaches mantle (input) value

Image from P. Hoffman



Carbon Isotopic Excursions 800-500Ma

More complete sediment record

+

Improved chronology

=

More detailed picture showing abrupt and extreme C-isotopic shifts

A global composite of 13C data shows 4 excursions

Plus one at the pC-C boundary

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

Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

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Please see Figure 2. Details ->

Calibrating the Cryogenian

Francis A. Macdonald, Mark D. Schmitz, James L. Crowley, Charles F. Roots, David S. Jones, Adam C. Maloof, Justin V. Strauss,Phoebe A. Cohen, David T. Johnston, Daniel P. Schrag

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Fig. 2. Neoproterozoic composite carbonate d13C chemostratigraphy with U-Pb ID-TIMS ages that are directly linked to isotopic profiles (11). Bars indicate the time spans of fossil assemblages representing eukaryotic crown groups. Asterisks indicate fossil groups of uncertain taxonomic affinity. Bars faded upward reflect uncertainty in the minimum age constraint; bars faded downward reflect uncertainty in the maximum age constraint. Dashes represent the time span where a fossil record has not been identified but for which the eukaryotic group's presence is inferred from its occurrence in Ediacaran or Phanerozoic strata. Dashes with question marks indicate that earlier records have been proposed but the relationships between these fossils and the crown groups are uncertain.

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Anomalous Banded Iron Formations

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

Animal Radiation: Response to genetic bottlenecks & flushes?

Image from P. Hoffman

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One Complete Snowball-Hothouse Episode

Image from P. Hoffman

The Geochemical Carbon Cycle

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Geologic Evidence for Hothouse Aftermath: “Cap Carbonates”

Thick sequences of inorganically precipitated $CaCO_3$ overly all Neoproterozoic glacial deposits

Neoproterozoic Cap Carbonates-1

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Please see Fig. 3 in Hoffman, Paul F., and Schrag, Daniel P. “The Snowball Earth Hypothesis: Testing the Limits of Global Change.” *Terra Nova* 14 (2002): 129-155.

- Thick sequences of inorganically precipitated carbonate minerals overly Late Proterozoic glacial deposits.
- Consistent with massive flux of weathering products to ocean in snowball aftermath.

Cap Carbonates 3

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Please see Fig. 5c in Hoffman, Paul F., and Schrag, Daniel P. “The Snowball Earth Hypothesis: Testing the Limits of Global Change.” *Terra Nova* 14 (2002): 129-155.

- Namibia

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Please see Prof. Hoffman's site on the Snowball Earth hypothesis, http://www.snowballearth.org/

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

Hoffman & Schrag (2000)

Geologic & Isotopic Change Associated with Snowball Event (Namibia)

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Please see Fig. 9 in Hoffman, Paul F., and Schrag, Daniel P. “The Snowball Earth Hypothesis: Testing the Limits of Global Change.” *Terra Nova* 14 (2002): 129-155.

How Long Did it Last?

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

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Please see Prof. Hoffman's site on the Snowball Earth hypothesis,
http://www.snowballearth.org/

- Canadian glacial episode, with good age controls, probably lasted < 1 Myr
- Cap carbonates likely deposited within 10^3-10^4 yr

Image from P. Hoffman

How Long Did it Last?

Gaskiers Fm.
Newfoundland

Images removed due to copyright restrictions.

Images from S Bowring

How Long Did it Last?

Ediacaran-burying ash (Drook Formation)

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Image from S Bowring

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 offsets lower weathering rates.

- lower iron and phosphorous concentrations in better-oxygenated Phanerozoic ocean [Fe(II) is soluble; Fe(III) is less so]: Decreased 1° production = Decreased CO_2 drawdown.

→ <u>What we would like to know:</u>

CO_2 concentrations through snowball/hothouse cycle.

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Please see Lubick, Naomi. “Palaeoclimatology: Snowball Fights.” *Nature* 417 (May 2, 2002): 12-13.

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.

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.

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Please see Fig. 1 in Kennedy, Martin J., et al. “Are Proterozoic Cap Carbonates and Isotopic Excursion a Record of Gas Hydrate Destabilization Following Earth’s Coldest Intervals?” *Geology* 29 (May 2001): 443-446.

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

A Biogeochemical Model of the Proterozoic Ocean

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Please see Fig. 3a in Logan, Graham A., et al. “Terminal Proterozoic Reorganization of Biogeochemical Cycles.” *Nature* 376 (July 6, 1995): 53-56.

After Ventilation

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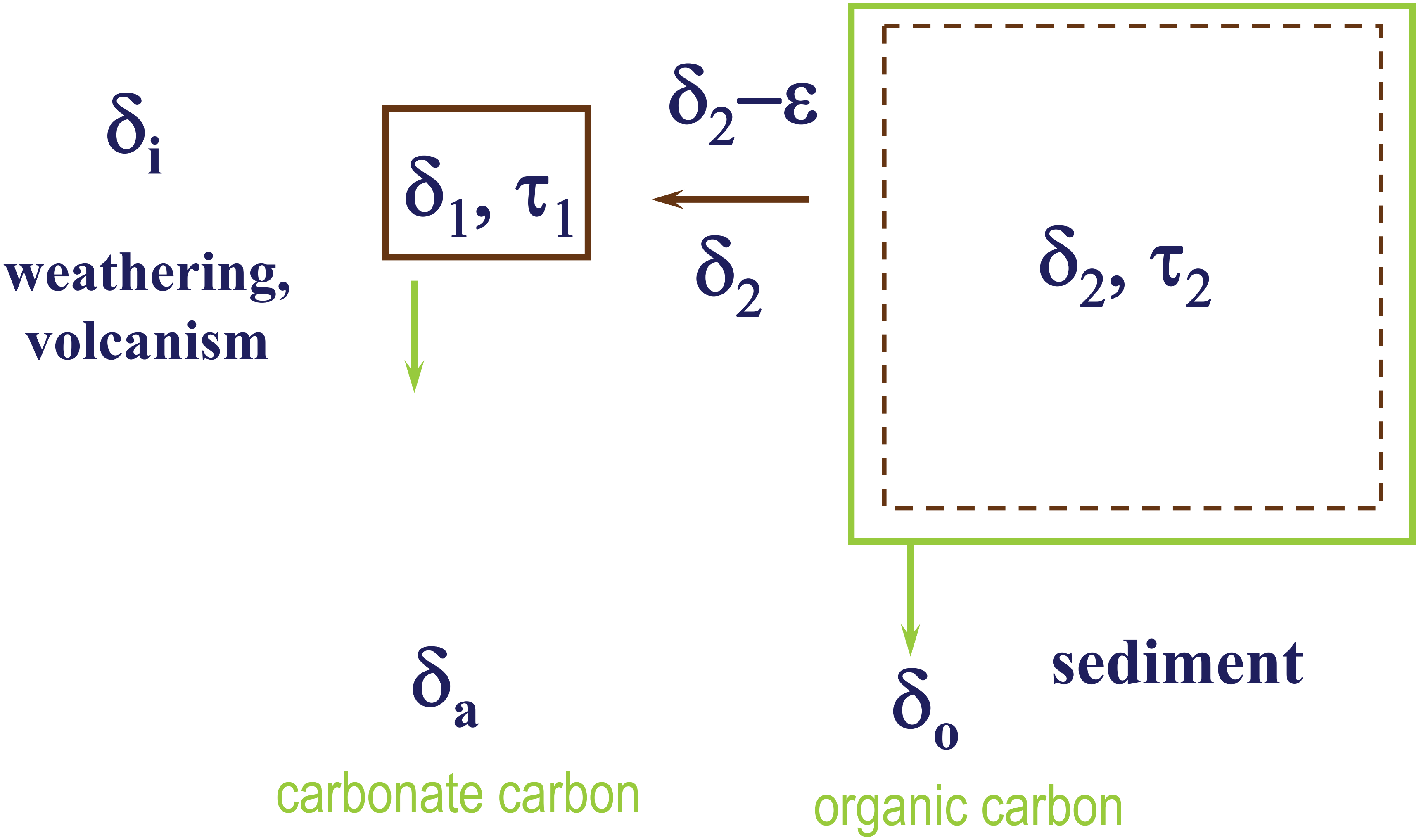
Please see Fig. 3b in Logan, Graham A., et al. "Terminal Proterozoic Reorganization of Biogeochemical Cycles." *Nature* 376 (July 6, 1995): 53-56.

A Carbon Cycle with Two Timescales



δ_i

weathering, volcanism

δ_1, τ_1

$\delta_2 - \varepsilon$

δ_2

δ_2, τ_2

δ_a

carbonate carbon

δ_o

sediment

organic carbon

Summary

- The C-cycle has evolved radically through time
- Prior to 2.2 Ga anaerobic prokaryotes dominated; wide spread of δ_{org} (δo) values; oxygenic photosynthesis extant but oxygen remained low as sinks >> sources
- Mantle may have been an important sink for oxidising power
- Extreme δ_{carb}(δa) values around 2.2 Ga probably signify the 'GOE' and rise to prominence of aerobes; Decreased spread of δorg (δa) values may reflect dominance of aerobic autotrophs and reductive pentose (Benson-Calvin; C3) cycle
- Although ample evidence for aerobes, the abundance of O_2 in atm and ocean remained low (sulfidic ocean) until another major oxidation event caused a second 'reorganization' In the Neoproterozoic. This was also signified by extreme δa fluctuations.
- The Neoproterozoic 'reorganization' led to pO_2 rising to near PAL allowing animals to flourish and stabilizing the new regime
- Environmental evolution reflected changes in the balance between thermal, crustal, atmospheric & biological processes

Permo-Carboniferrous Glaciations (~300-275 Ma)

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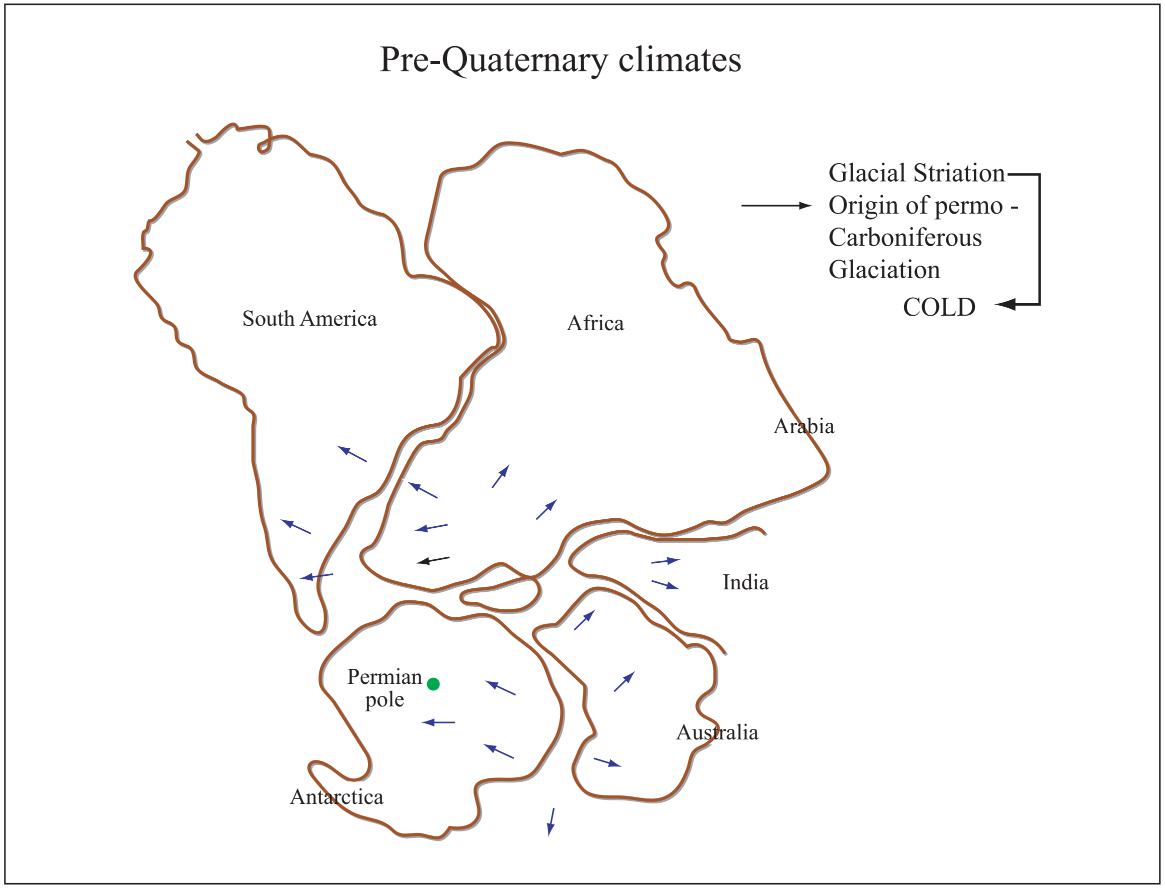

Figure by MIT OpenCourseWare.

Generalized diagram illustrating evidence for origination of Permo-Carboniferous glaciation on one large landmass. Arrows indicate direction of glacial flow. X = Permian pole position. [After Sullivan, 1974] *Reproduced by permission from W. Sullivan, "Continents in Motion: The New Earth Debate," copyright 1974, McGraw-Hill Publishing Co.*

C_{org} burial rate estimated from $\delta^{13}C$ in $CaCO_3$

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Please see Fig. 10-9 in Stanley (course text).

Atmospheric O_2 estimated from C_{org} burial rate

Mesozoic Warmth

-Ferns & alligators in Siberia

Image from http://simple.wikipedia.org/wiki/File:Alligator3.jpg, in public domain.

Jurassic
220-140 Ma

Image from http://commons.wikimedia.org/wiki/File:Coelurus_stegosaurus.jpg, in public domain.

High CO_2 Levels During Mesozoic

Decreasing CO_2

↑ ^{13}C = ↓ CO_2

Mesozoic

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Please see Fig. 2 in Popp, Brian N., et al. "The Post-Paleozoic Chronology and Mechanism of 13C Depletion in Primary Marine Organic Matter." *Am J of Science* 289 (April 1989): 436-454.

↑ Seafloor spreading rate:

1. ↑ CO_2 outgassing
2. ↑ subduction rate = ↑ carbonate metamorphism = ↑ CO_2 production
3. ↑ sea level (hotter oceanic crust/higher ridge volume = ↓ land area

↓ weathering

↓ CO_2 sink

Increasing CO_2

Cenozoic CO_2 Decrease

Decreasing CO_2

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Please see Fig. 2 in Popp, Brian N., et al. "The Post-Paleozoic Chronology and Mechanism of 13C Depletion in Primary Marine Organic Matter." *Am J of Science* 289 (April 1989): 436-454.

Increasing CO_2

What causes glacial-interglacial CO_2 variations?

(a still-unanswered question!)

Possible Scenario for lower glacial pCO_2

- Increased:
  Equator-Pole T gradient, Wind strength, Dust flux to ocean, Iron flux to ocean
- 50% of global 1° production occurs in ocean
- Ocean 1° production is limited by iron
- Higher 1° production draws CO_2 out of atmosphere & sequesters it in the deep ocean & sediments
- Colder seawater dissolves more CO_2

Text has been removed due to copyright restrictions.

Please see Veizer, Jan, et al. "Evidence for Decoupling of Atmospheric CO2 and Global Climate during the Phanerozoic Eon." *Nature* 408 (December 7, 2000): 698.

While a large and growing body of evidence indicates that CO_2 and climate co-vary, there is some indication that the two may not be closely linked at all times….

(& it is always important to remember that *correlation* does not always mean *causation*)

Text removed due to copyright restrictions.

Please see Hoffman, Paul F. “Comment on ‘Snowball Earth on Trial’.” *Eos* 88 (February 2007): 110.

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Please see Allen, Phillip A. “Reply to ‘Comment on Snowball Earth on Trial’.” *Eos* 88 (February 2007): 110.

Evidence for Glaciers on All Continents: 0.9-0.6 Ga

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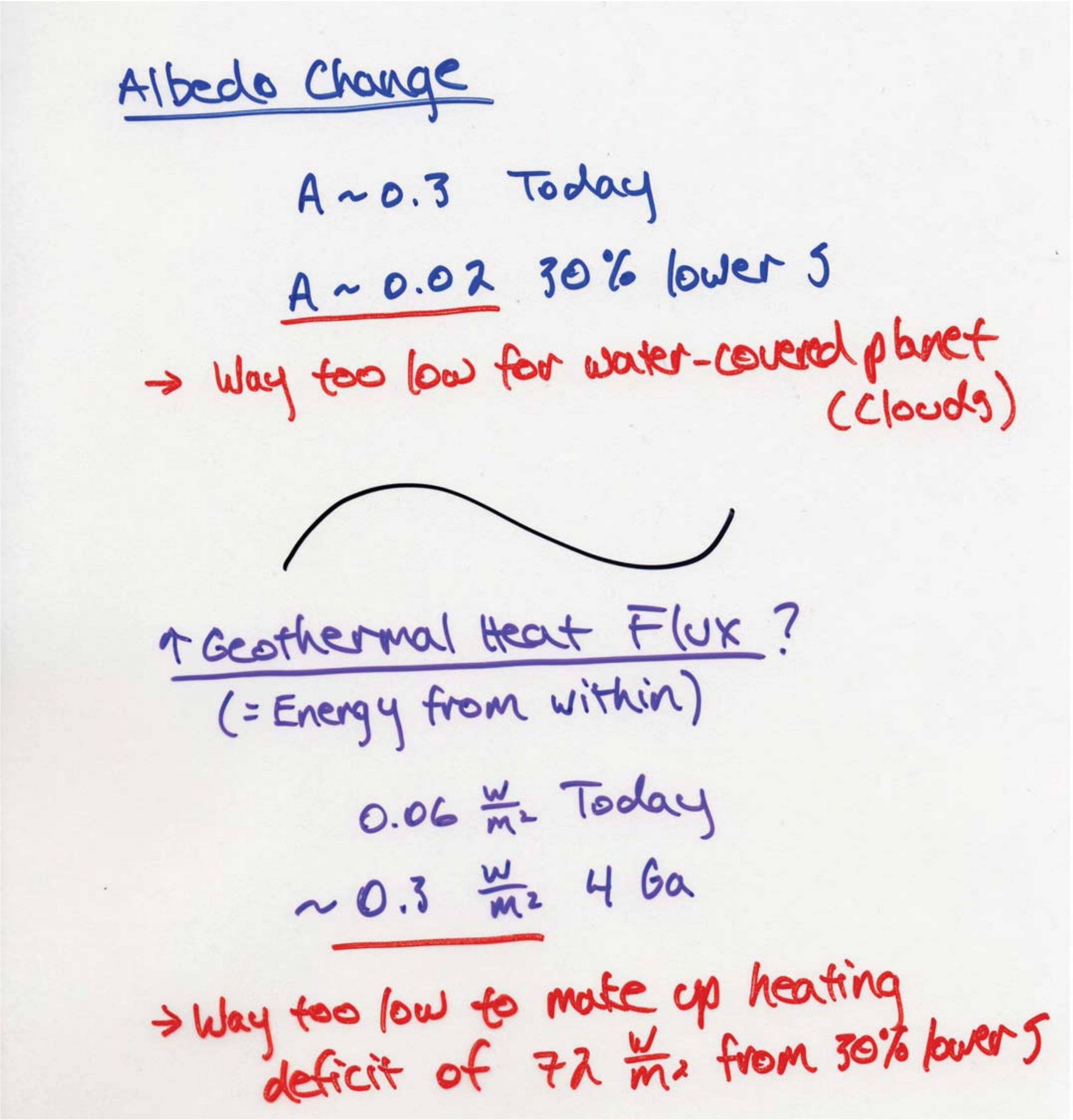
Please see Fig. 12.3 in Crowley, T. J., and North, G. R. *Paleoclimatology*. New York, NY: Oxford University Press, 1992. ISBN: 0195105338.



Albedo Change

$A \sim 0.3$ Today

$A \sim 0.02$ 30% lower S

→ Way too low for water-covered planet
(Clouds)

↑ **Geothermal Heat Flux** ?
(= Energy from within)

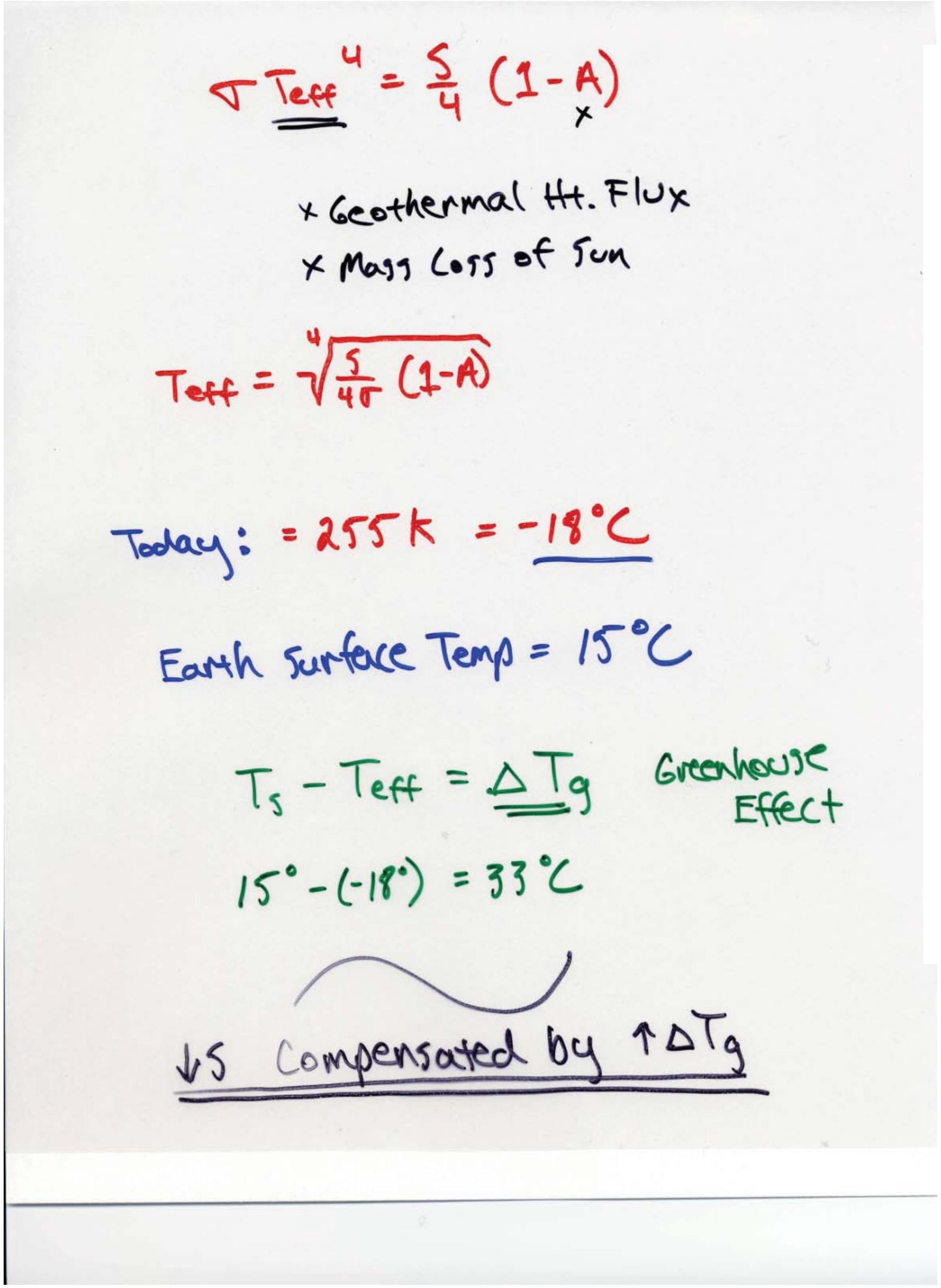
$0.06\ \frac{W}{m^2}$ Today

$\sim 0.3\ \frac{W}{m^2}$ 4 Ga

→ Way too low to make up heating deficit of $72\ \frac{W}{m^2}$ from 30% lower S

Neither albedo or geothermal heat flux changes can keep the Earth from freezing w/ 30% lower S

Adapted from Kump et al. (1999)



$$\sigma \underline{\underline{T_{eff}}}^4 = \frac{S}{4}(1-\underset{\times}{A})$$

× Geothermal Ht. Flux

× Mass Loss of Sun

$$T_{eff} = \sqrt[4]{\frac{S}{4\sigma}(1-A)}$$

Today: = 255 K = $\underline{-18°C}$

Earth surface Temp = 15°C

$T_s - T_{eff} = \underline{\underline{\Delta T_g}}$ Greenhouse Effect

15° − (−18°) = 33°C

$\underline{\downarrow S \text{ compensated by } \uparrow \Delta T_g}$

Therefore:

Lower S must have been compensated by larger greenhouse effect

Adapted from
Kump et al. (1999)

http://www.scotese.com/precambr.htm

Image removed due to copyright restrictions.

Please see http://www.scotese.com/images/650.jpg

This map illustrates the break-up of the supercontinent, Rodinia, which formed 1100 million years ago. The Late Precambrian was an "Ice House" World, much like the present-day.

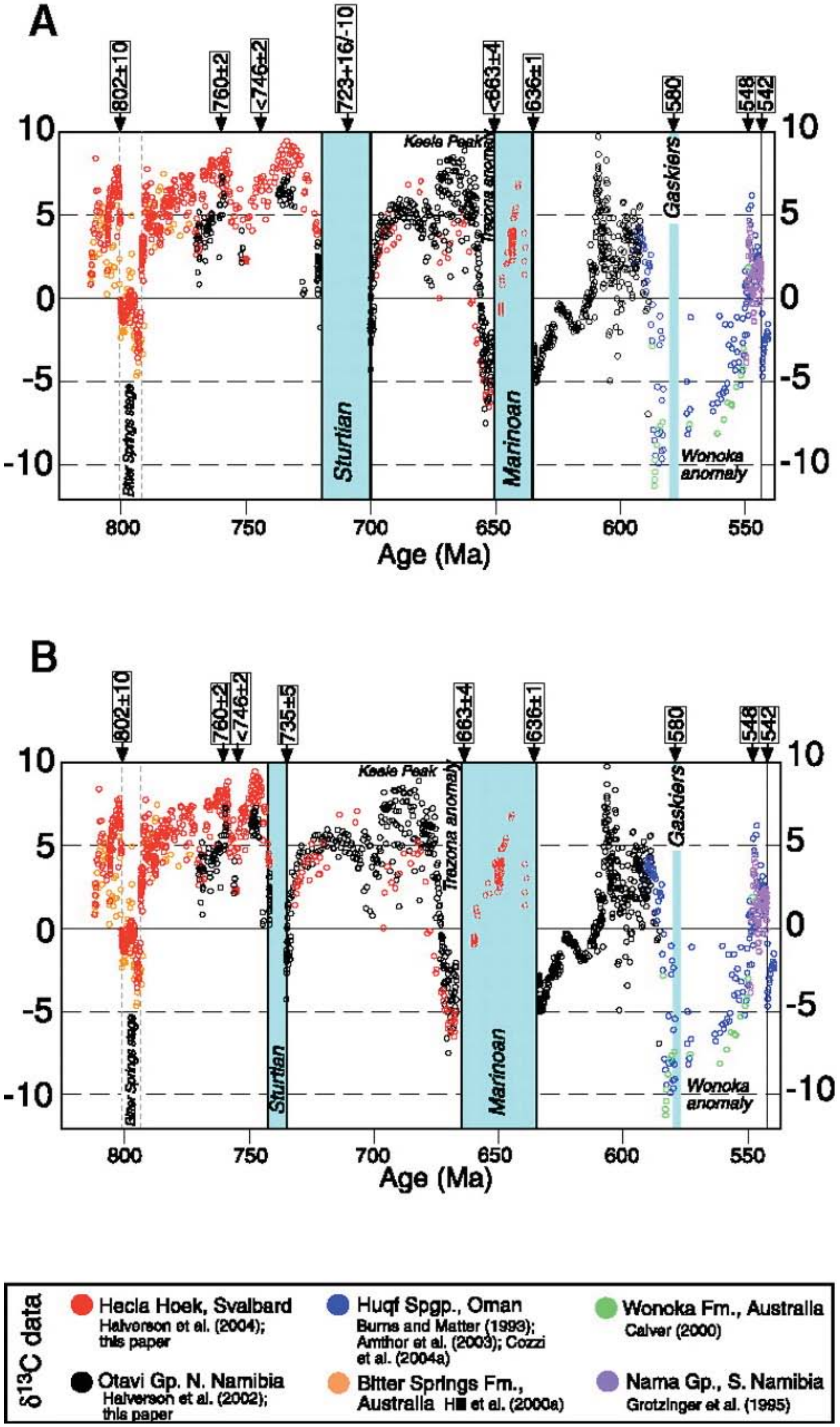


Figure 15. Two permissible calibrations of the composite carbon-isotope record in Figure 14 based on available radiometric dates and {delta} 13C data that can be correlated into the record and contrasting interpretations of the age and duration of the Sturtian and Marinoan glaciations.

GSA Bulletin; September 2005; v. 117; no. 9-10; p. 1181-1207;
Toward a Neoproterozoic composite carbon-isotope record
Galen P. Halverson, Paul F. Hoffman, Daniel P. Schrag, Adam C. Maloof and A. Hugh N. Rice

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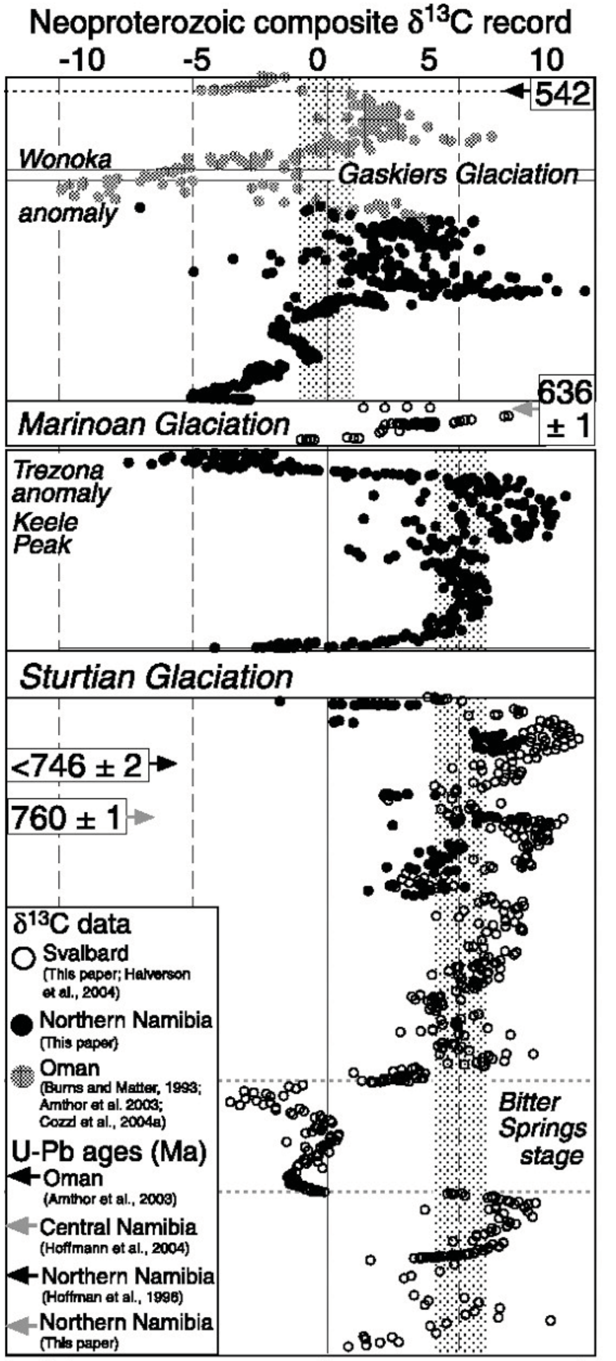

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