Surface Conditions on Earth Through Time

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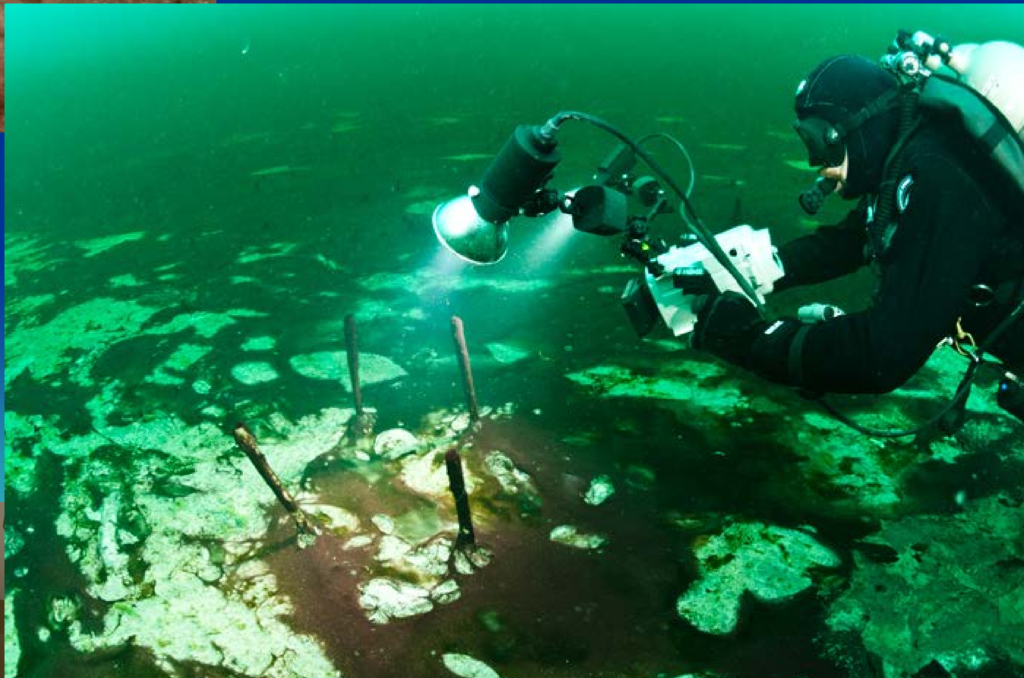
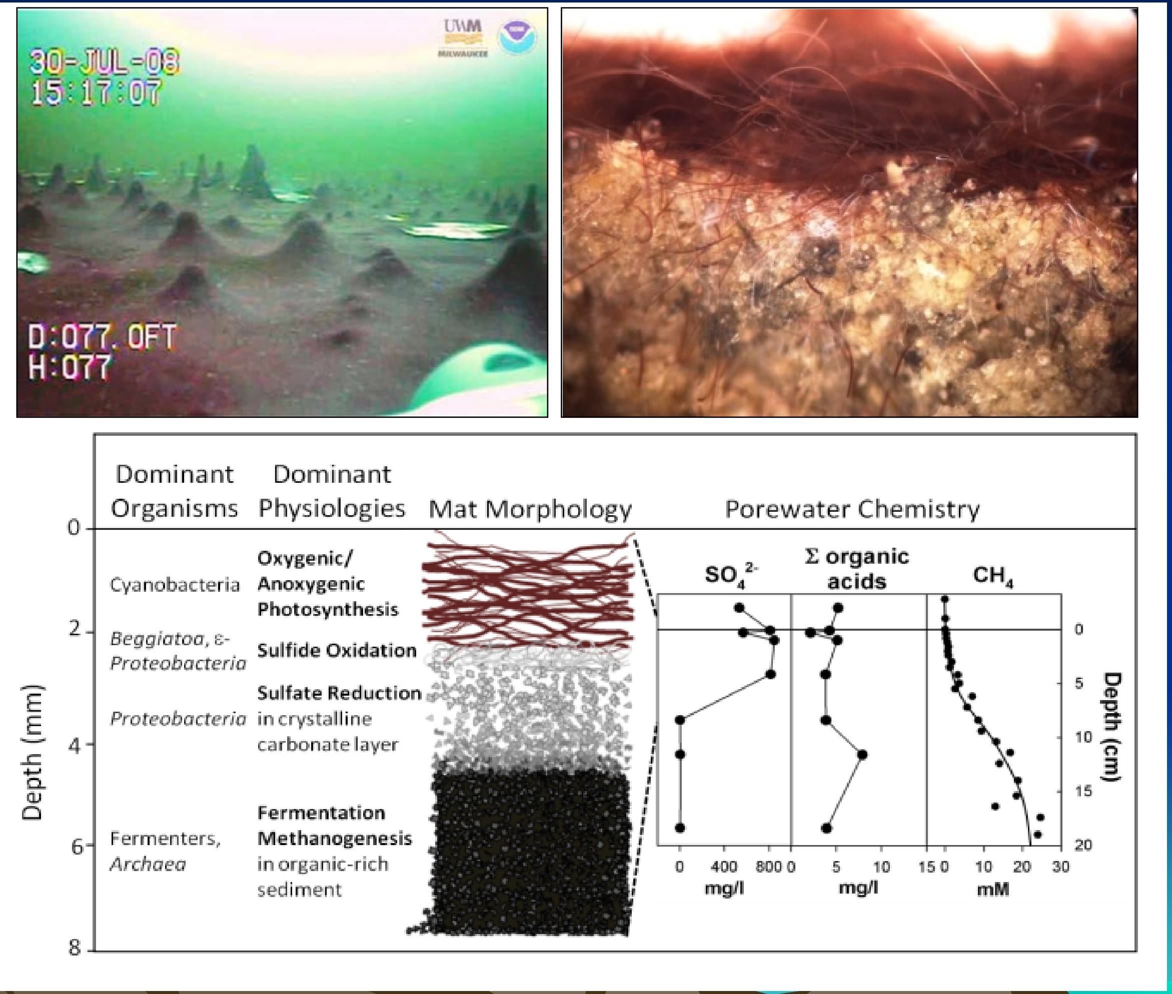
WHERE DISCOVERIES BEGIN

Acknowledgements:
Ria Mitchell, Michael Hren

Lake Huron near Alpena, MI

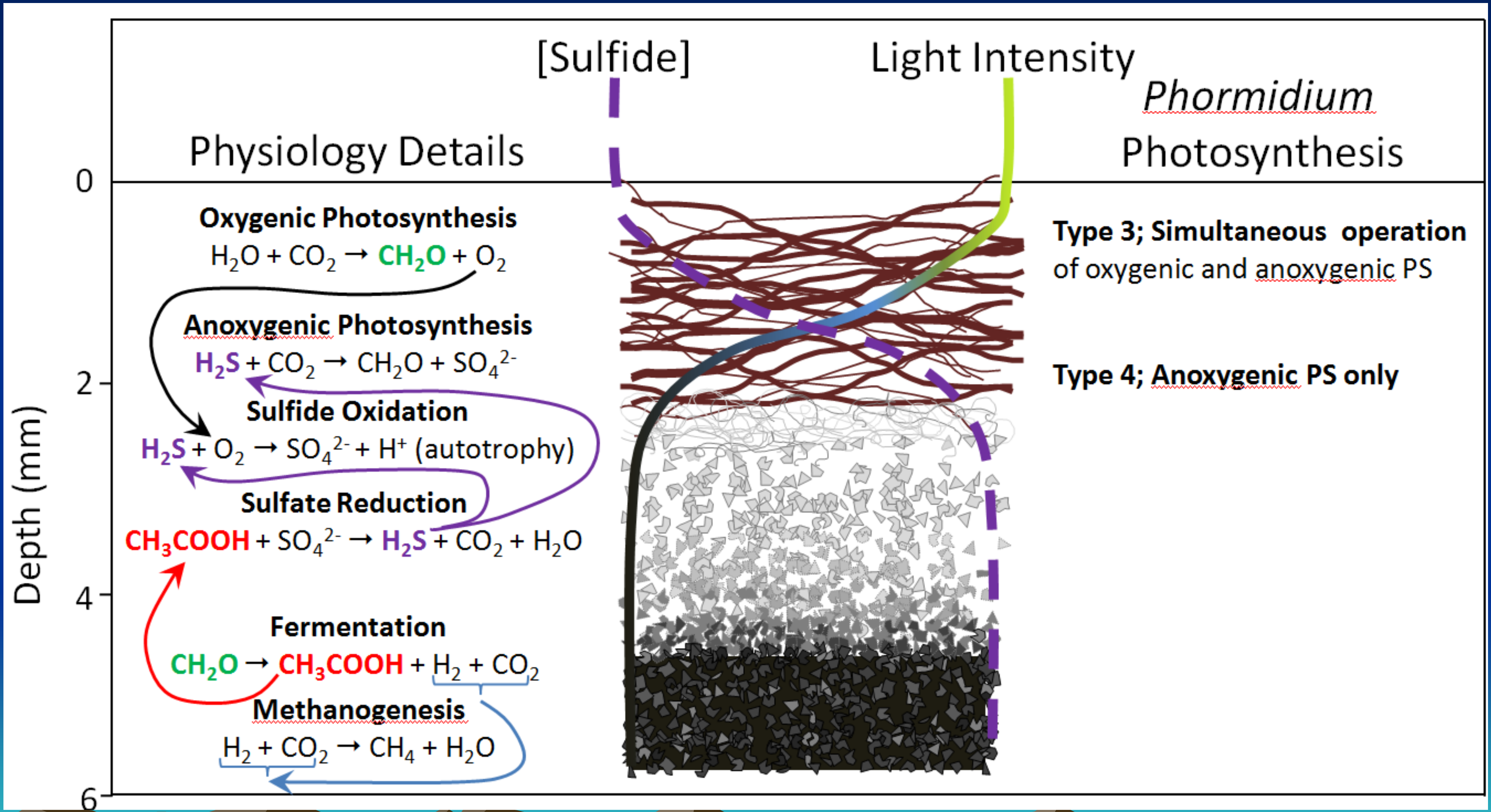


Proterozoic ocean…in modern Lake Huron at 8°C



Voorhies et al. (2012, Geobiology)

Metabolic Flexibility



Voorhies et al. (2012, Geobiology)

Life on Earth is Nearly Ubiquitous

Soil Crusts and Extremely Dry Environments

Cyanobacterial sheath holding together sand grains (SEM).

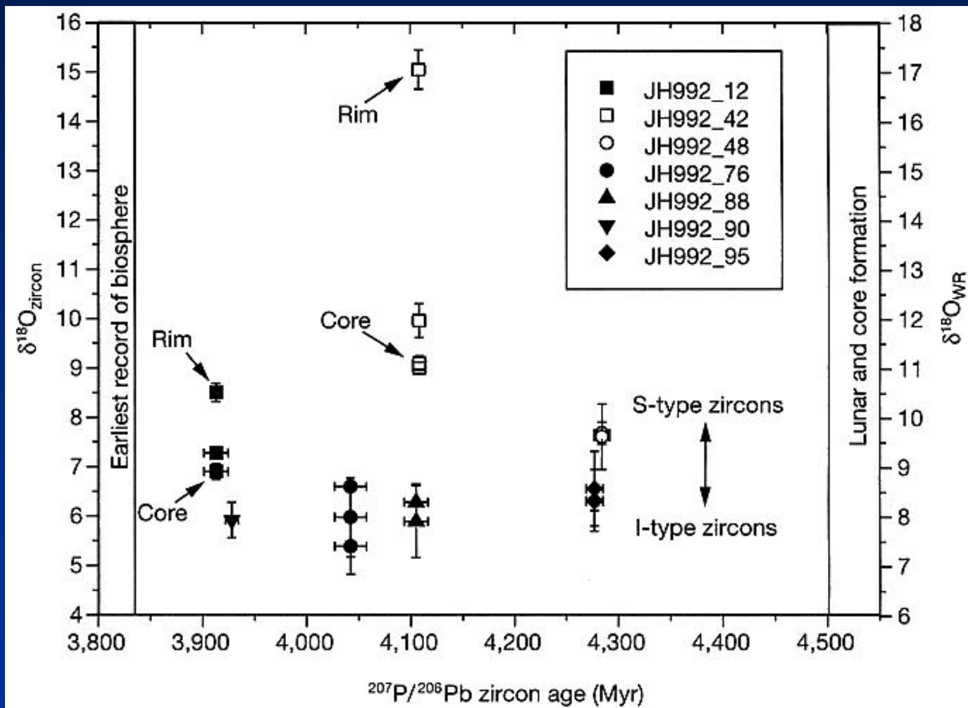
- Typically cyanobacteria
- Deserts, Antarctic Dry Valleys

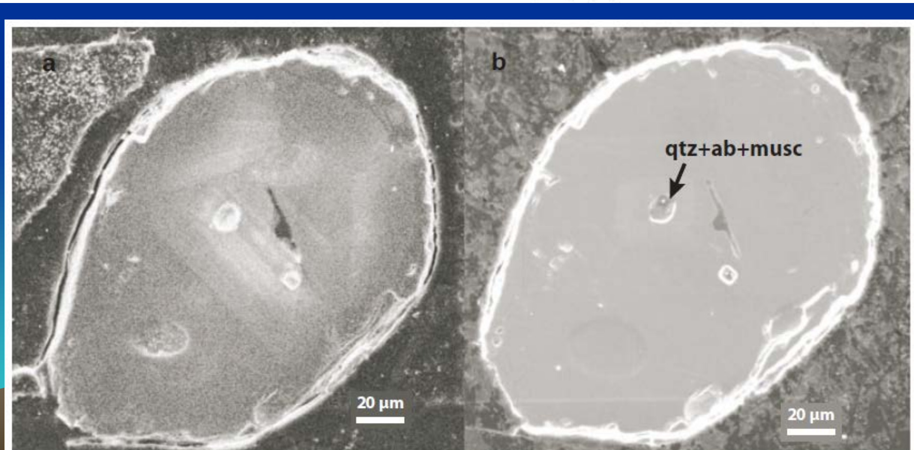
www.soilcrust.org/gallery.htm

Environmental Limits for Life

- Temperature -10°C - 121°C (230 °C?)
- Pressure up to gigapascals (10s of kbars)!
- Salinity up to 5 M NaCl (?)
- pH ~0-12 (?)
- Liquid water available
- O_2 available
- Only bacteria and archaea can withstand the highest T, P, etc.

Evidence for Liquid Water from Zircons





- Zircons from Jack Hills (Australia) and other Hadean sites record $\delta^{18}O$ values that indicate weathering in liquid water back to 4.4 Ga

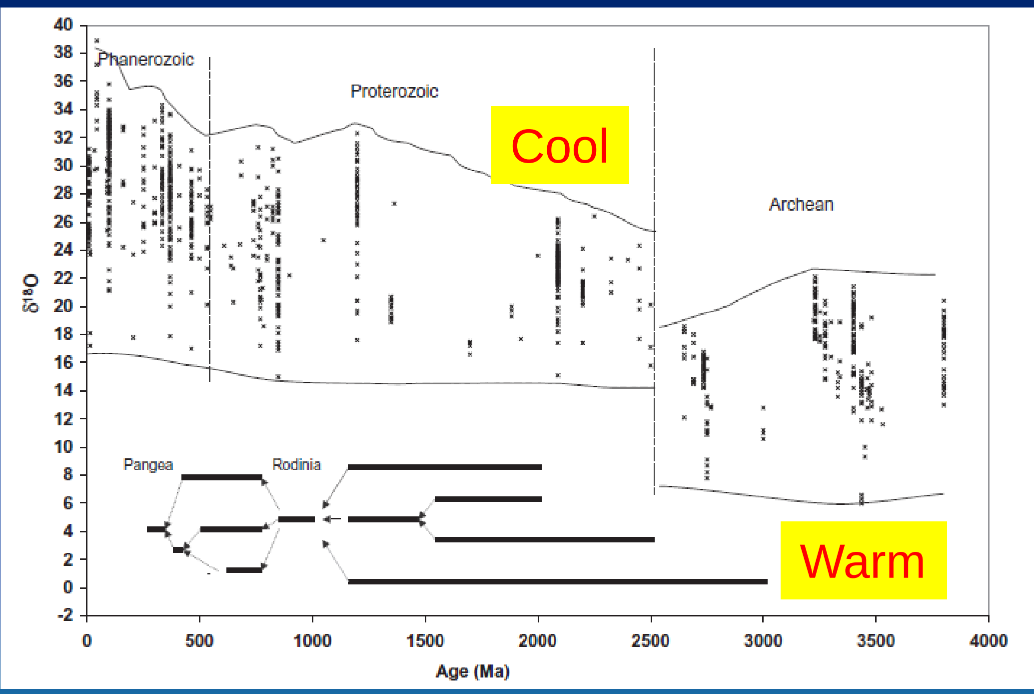
We simultaneously know much less about the Earth’s surface and much more about the history of its surface as compared with Mars!

Liquid water is nearly unique to Earth, but is it sufficient in and of itself to result in a habitable planet?

Habitability on the Earth

- To a first order, it depends on just three things:
  - Surface temperature (i.e., climate) was probably never substantially different than the present-day Earth
  - pO_2 (i.e., redox potential; constrains other greenhouse gases) rose twice, both times fundamentally changing the biosphere
  - pCO_2 (i.e., the organic-inorganic C cycle) is the ultimate control of Earth surface conditions and has both shaped the biosphere and been shaped by the biosphere

I. Arguments for Very Warm Early Earth

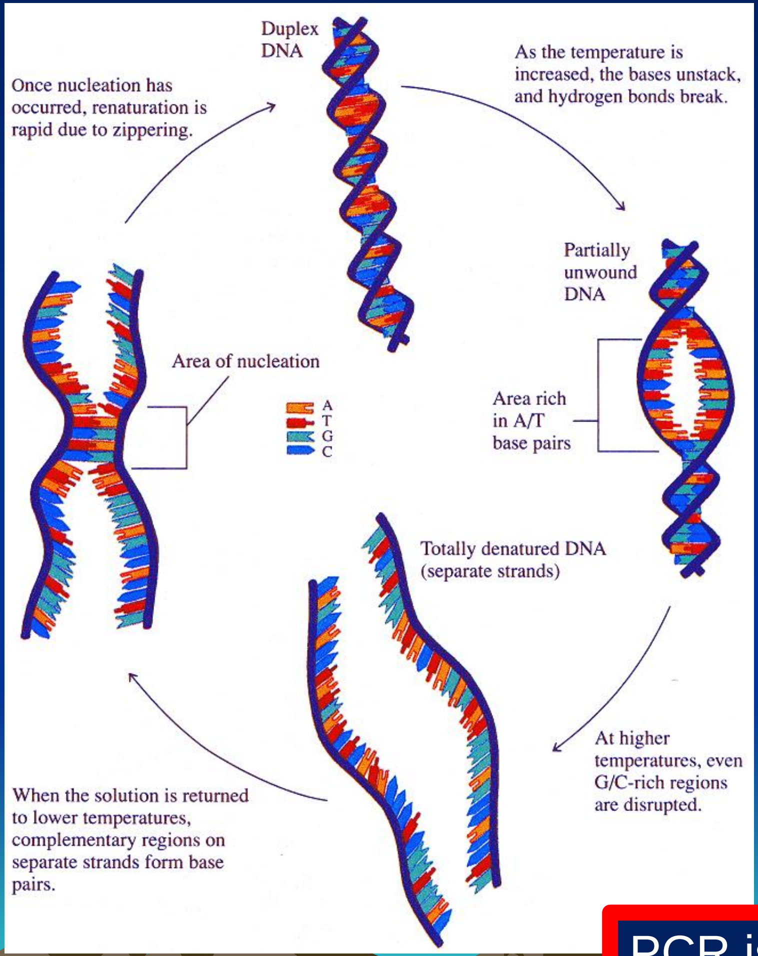


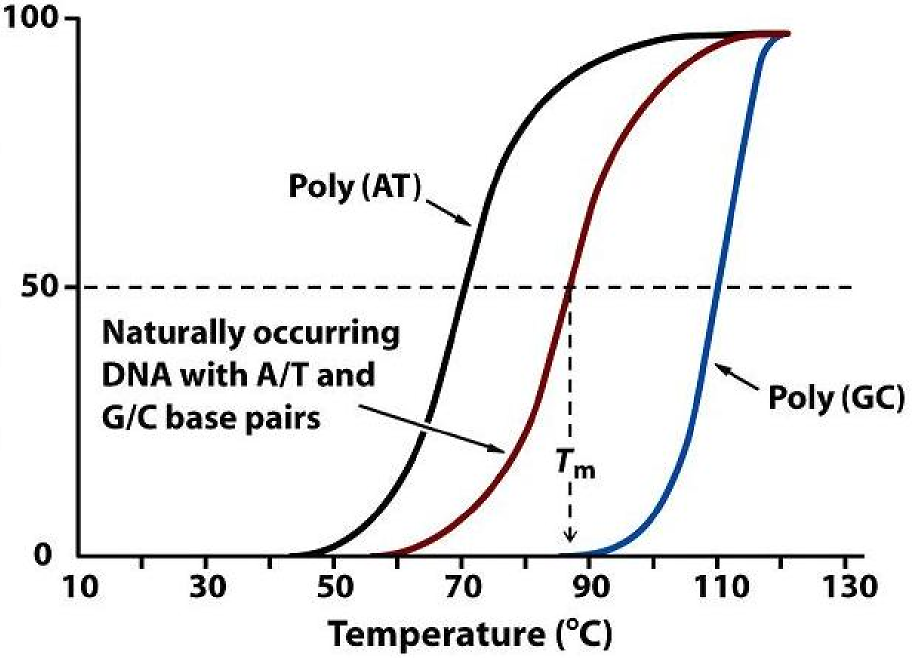
Knauth (2005, P-3)

Chert is an early diagenetic product derived from amorphous silica (cf. quartz)

- Archean (pre 2.5 Ga) cherts have very different $\delta^{18}O$ than Proterozoic and Phanerozoic cherts
- If sea water chemistry hasn't changed, this implies very warm early oceans **(55-85°C), which implies high CO_2, salinity, and P_{atm}**
- **Is this reasonable?**

Biochemical Constraints on Ocean Temperatures

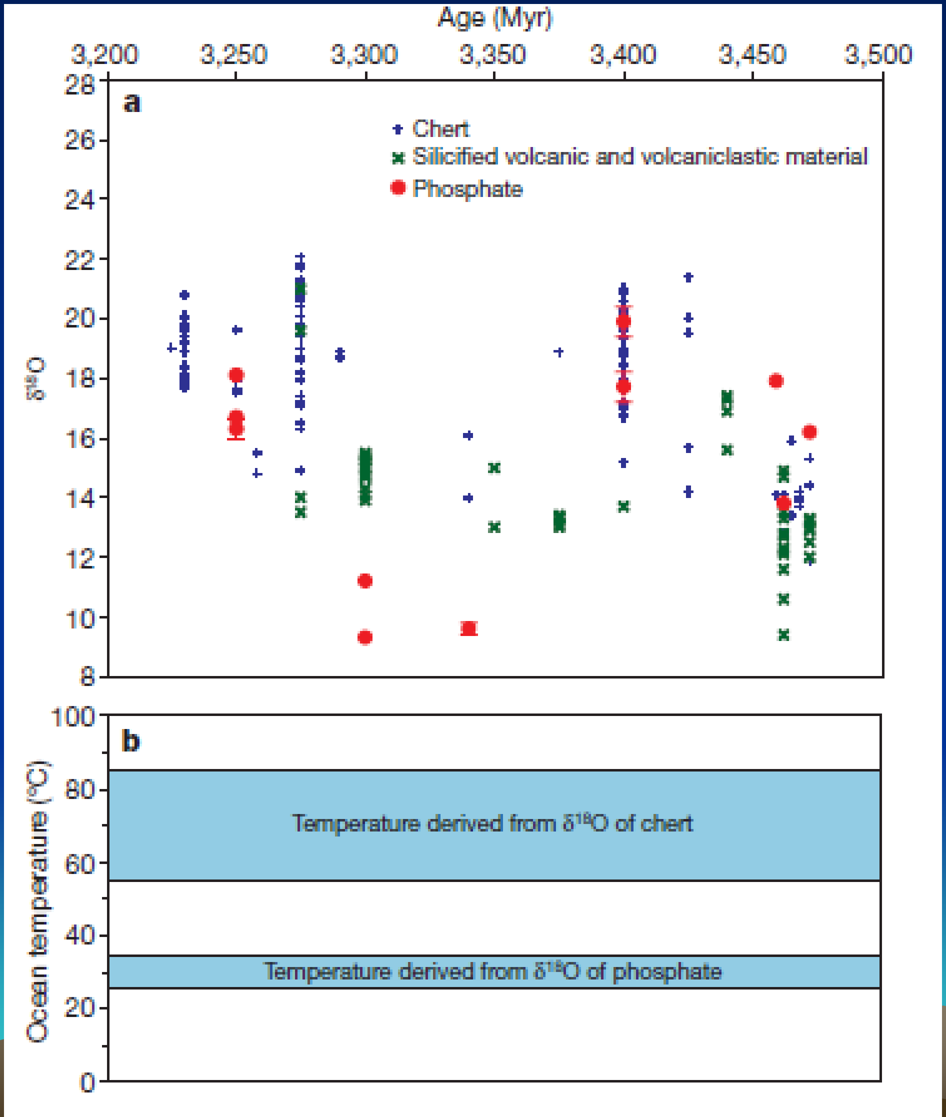




PCR is typically performed at 94°C, but depending on the base pair make up, the melting temperature of DNA/RNA can be as low as 70°C.

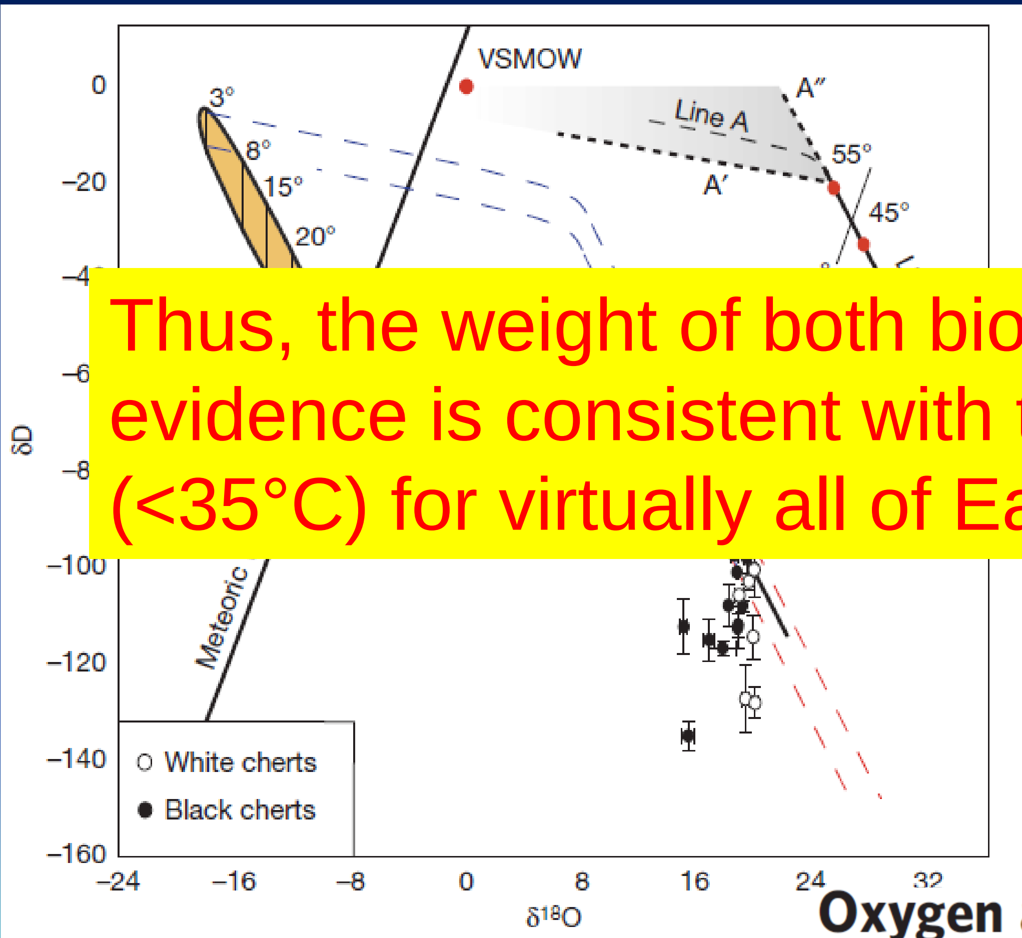
Images from Sandwalk

What do other minerals indicate?



- Blake et al. (2011, Nature) used the same rocks as Knauth and looked instead at phosphates
- Instead of warm temperatures, they found temperatures similar to the modern ocean
- Gypsum gives a similar constraint

Chert Revisited: Adding δD Lowers Temperatures



- Including δD from cherts adds a further constraint and precludes a straight … alues … cherts have been altered

- T_{max} < 40°C

Thus, the weight of both biological and mineral evidence is consistent with temperate conditions (<35°C) for virtually all of Earth's history

Oxygen and hydrogen isotope evidence for a temperate climate 3.42 billion years ago

M. T. Hren[1]†, M. M. Tice[2] & C. P. Chamberlain[3]

Vol 462 | 12 November 2009 | doi:10.1038/nature08518

II. History of pO_2

- Two competing models have developed:
  - Dimroth-Ohmoto model suggests that atmospheric pO_2 has not changed substantially during Earth's history
    - Fe mobility during surface weathering hasn't changed dramatically
    - BIFs (and other ore deposits) could all be hydrothermal, and therefore, tell us very little about surface conditions
    - C cycle changes don't correspond to proposed pO_2 changes and the two cycles should be linked

Additional Feedbacks in the Long-term Carbon Cycle

For organic matter:

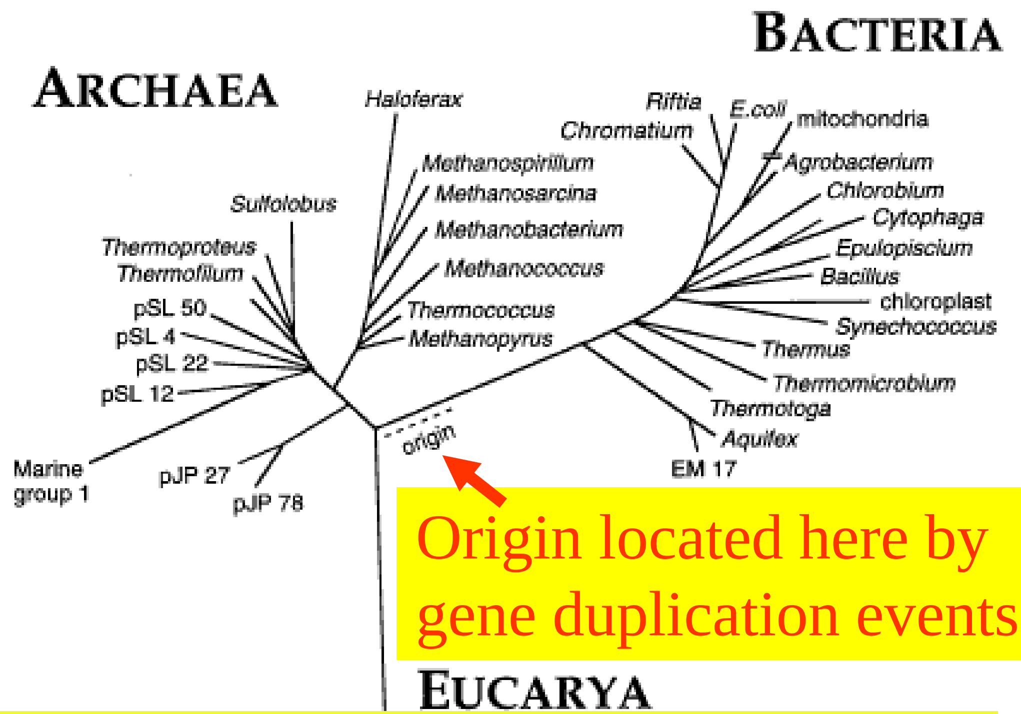
$$CO_2 + H_2O \underset{\text{weathering}}{\overset{\text{burial}}{\rightleftharpoons}} CH_2O + O_2$$

For pyrite:

$$2Fe_2O_3 + 16Ca^{2+} + 16HCO_3^- + 8SO_4^{2-} \underset{\text{weathering}}{\overset{\text{burial}}{\rightleftharpoons}} 4FeS_2 + 16CaCO_3 + 8H_2O + 15O_2$$

Berner and Canfield (1989, Am. J. Sci.)

Universal Tree of Life (based on RNA)

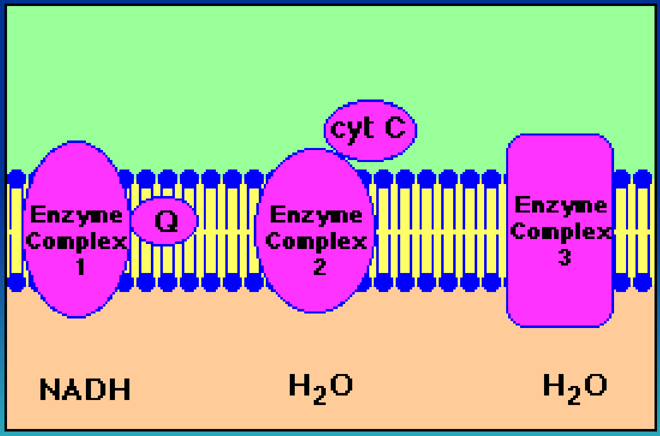


Origin located here by gene duplication events

Genomics: the last common ancestor had at least 4 respiratory Chains terminating in: O_2, nitrate, sulfate, and S.

(Castresana & Moreira, 1999)

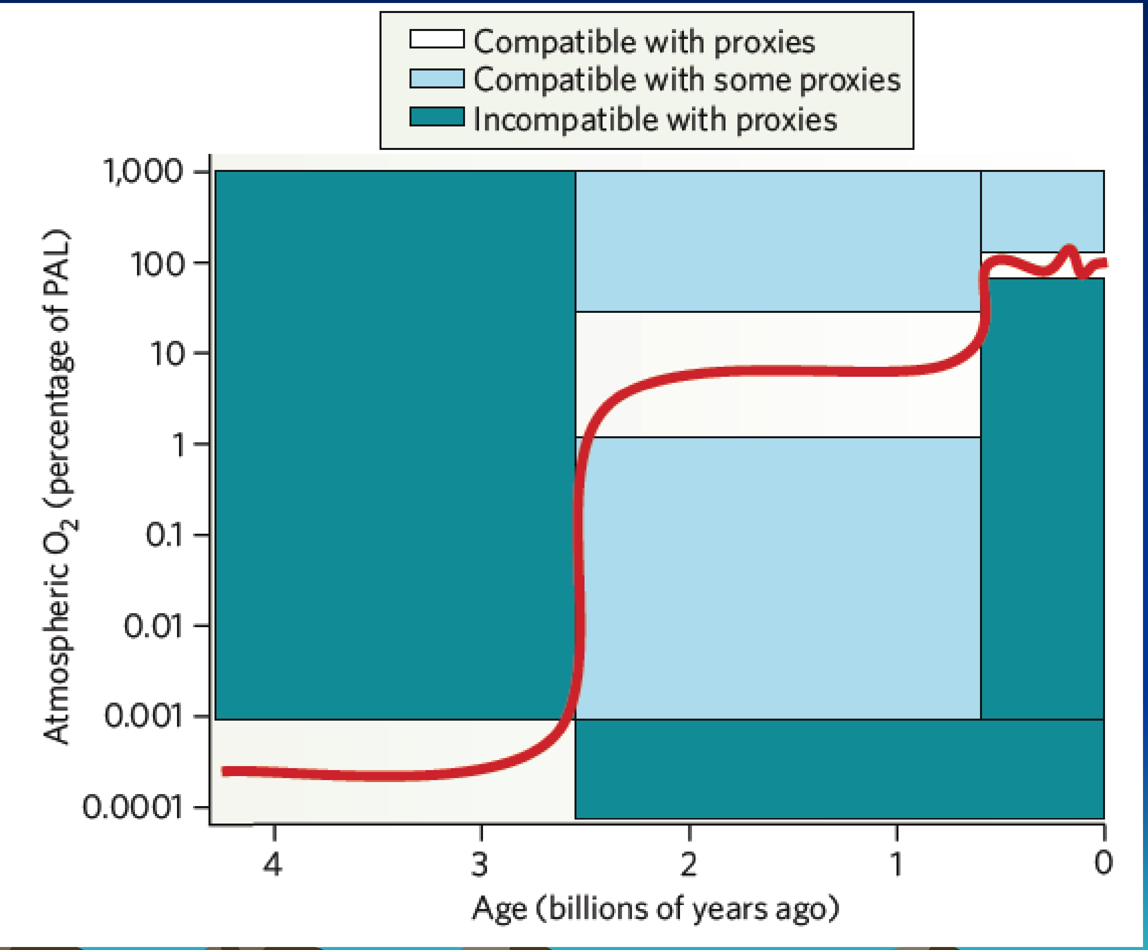
The last common ancestor lived on a planet with redox gradients extending down to molecular O_2!



II. History of pO_2

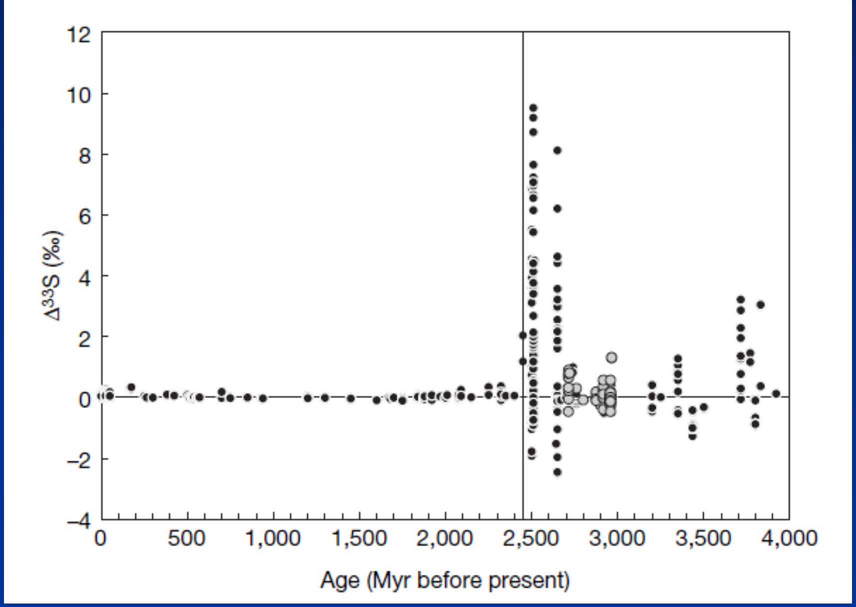
- Two competing models have developed:
  - Dimroth-Ohmoto model suggests that atmospheric pO_2 has not changed substantially during Earth's history
  - Cloud-Walker-Holland model suggests that early Earth was essentially anoxic and that pO_2 rose substantially early on in the Proterozoic → model is now canonical

Proxy Constraints on pO_2



Kump (2008)

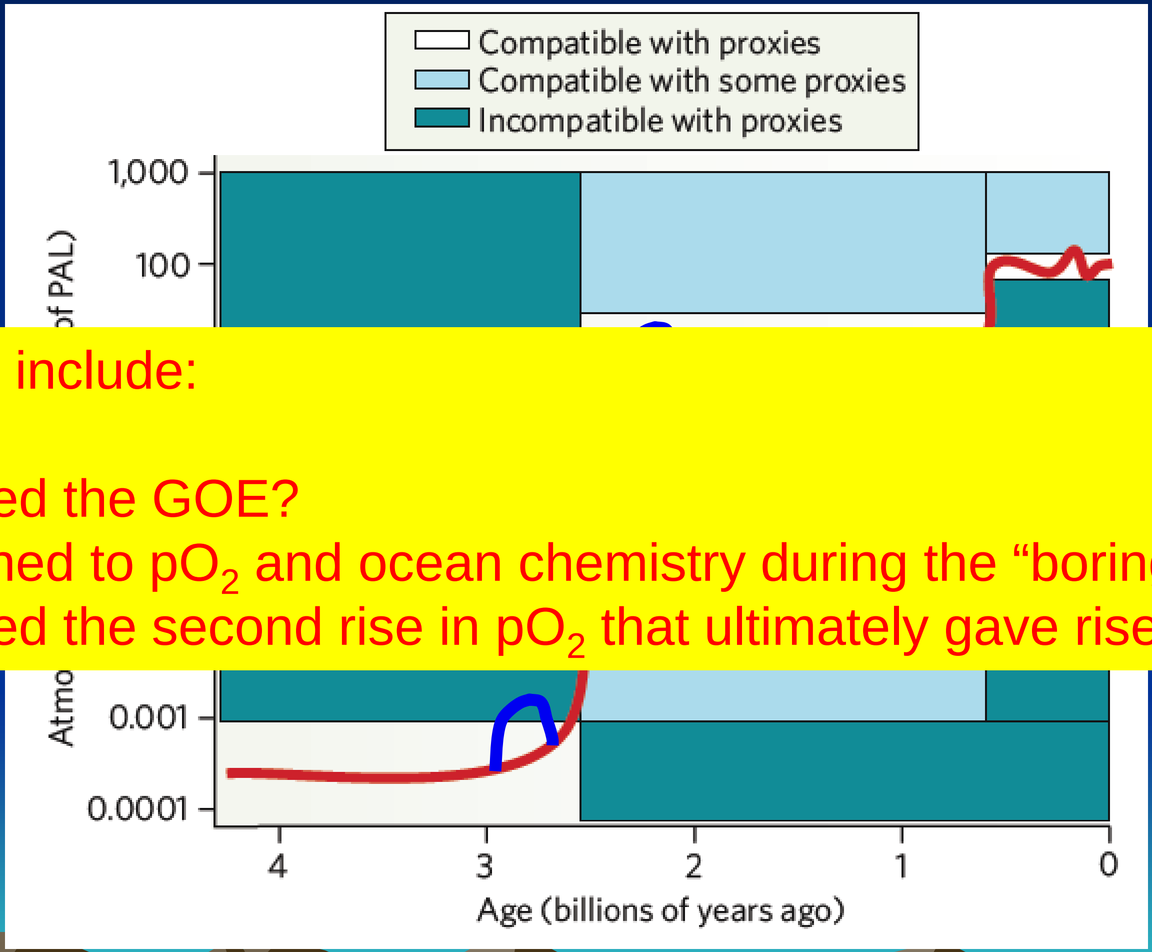
"Great Oxidation Event"



Farquhar et al. (2007, Nature)

- Various lines of evidence (red beds, detrital uraninite, paleosols, etc.) indicate a singular increase in pO_2
- MIF-S disappears after 2.45 Ga
- This implies a rise in pO_2 to > 10^{-5} bars
- There may have been a "whiff" of oxygen prior to the GOE
- Consequences: loss of CH_4, increase in biological niches

Proxy Constraints on pO_2

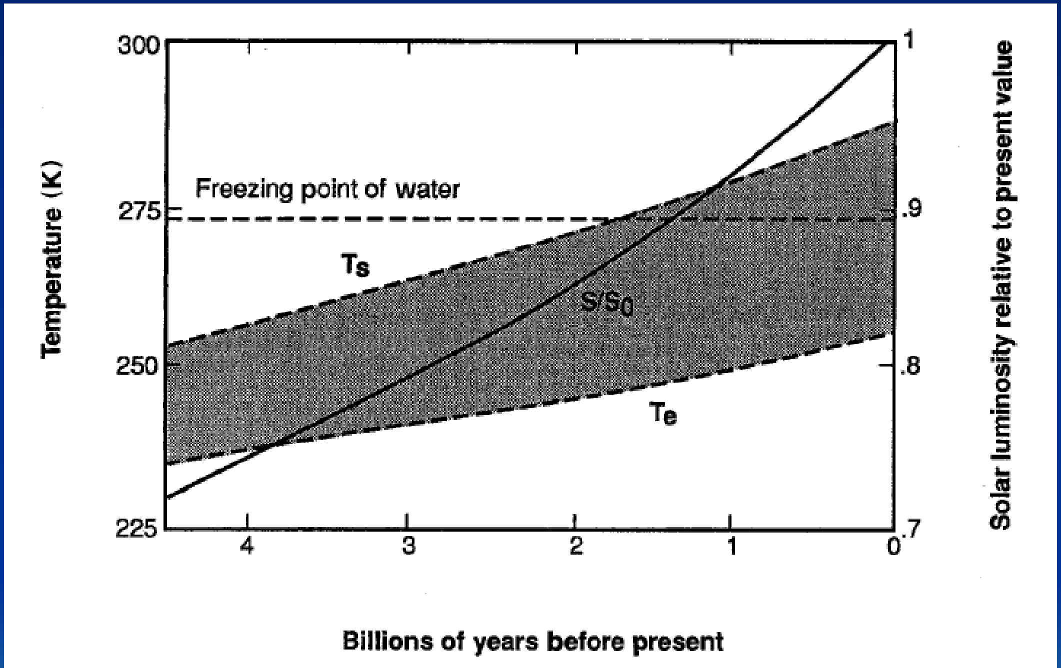


Open questions include:

1) What triggered the GOE?
2) What happened to pO_2 and ocean chemistry during the "boring billion?"
3) What triggered the second rise in pO_2 that ultimately gave rise to animals?

Kump (2008)

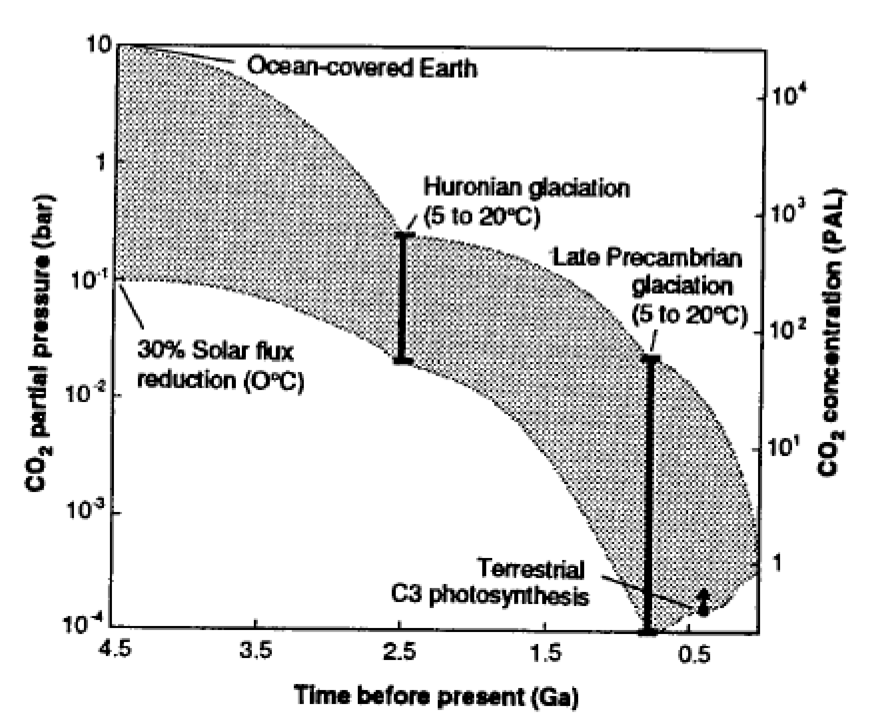
III. "Faint Young Sun" Paradox



- The Earth's surface appears to have been temperate
- The Sun was likely only 70% as luminous early in its history
- Therefore, significantly higher greenhouse gas levels are required

Kasting (1988, Scientific America)

pCO_2-only Solution to FYS

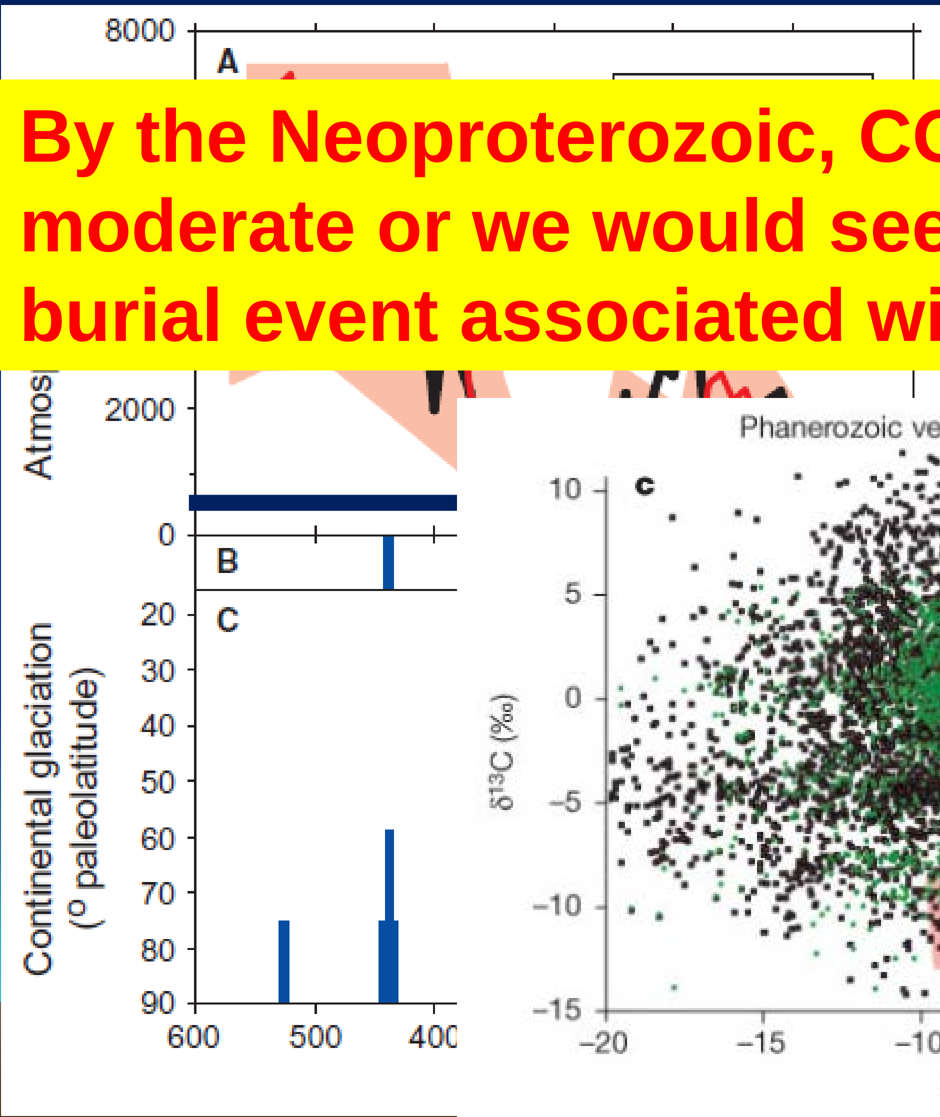


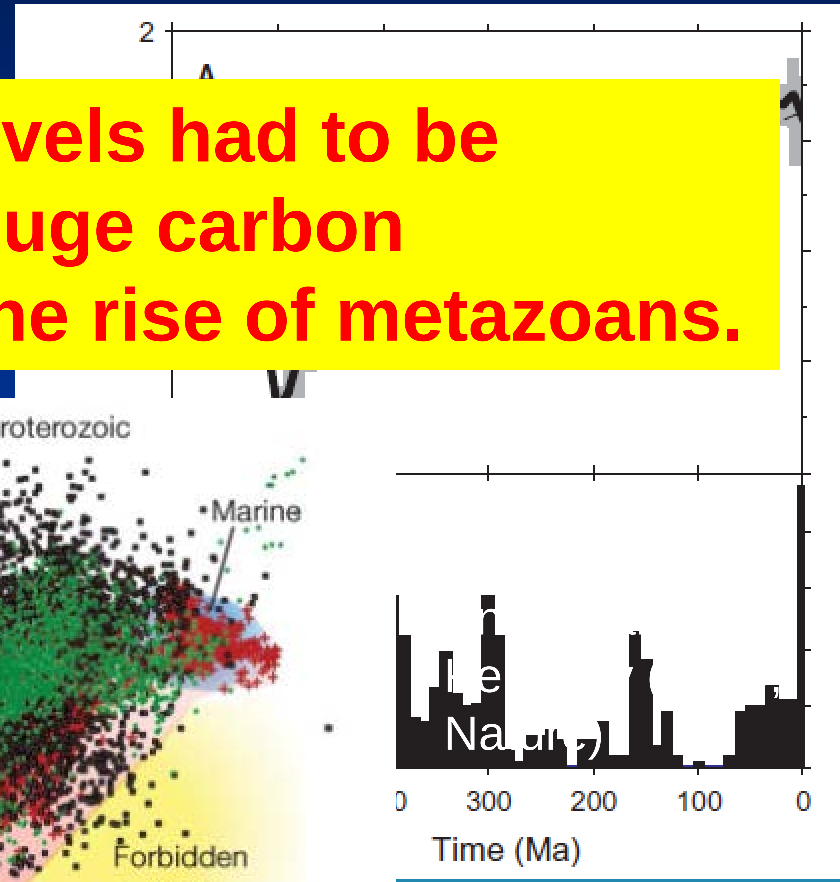
Kasting (1993, Science)

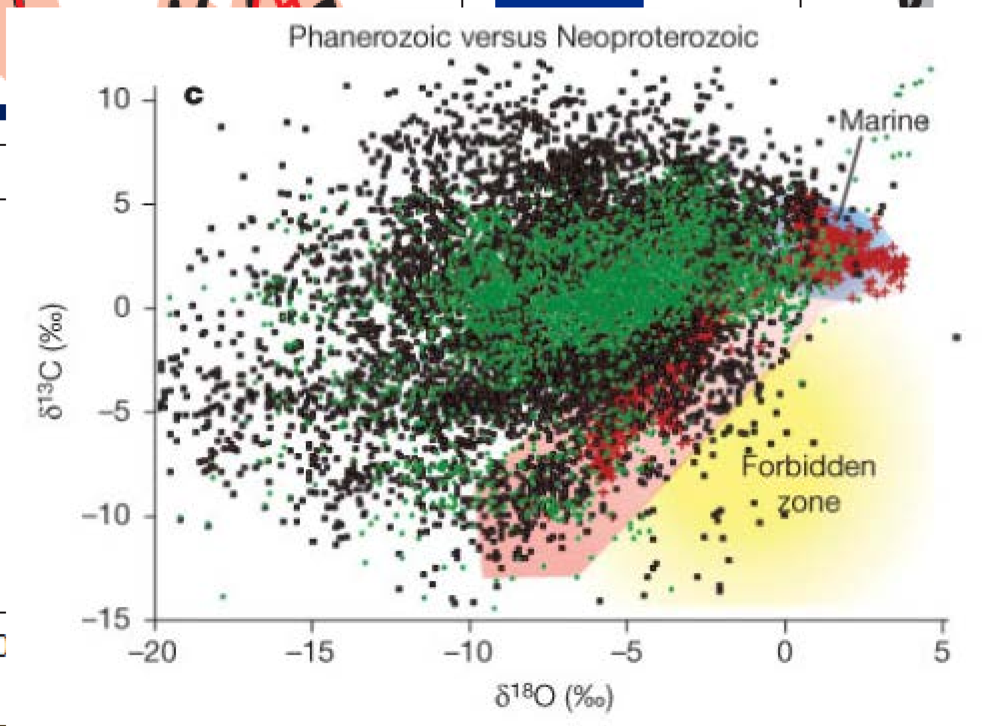
- Requires at least 0.1 bars of CO_2, whereas the pre-Industrial atmosphere had $10^{-3.5}$ bars
- This would result in extremely acidic rain and should have left an isotopic signature of the burial of that carbon

Constraints from the last 500 Ma

By the Neoproterozoic, CO_2 levels had to be moderate or we would see a huge carbon burial event associated with the rise of metazoans.







GSA Today; 2007,

Part IV. Constraining CO_2 History

A. Equilibrium models for CO_2 and their limitations

B. A mass balance model for pCO_2 based on paleosols

C. Towards a Precambrian CO_2 Curve

D. 1-D Climate model results

A. Equilibrium Model: Rye et al. (1995, Nature)

- Greenalite is a good analogue mineral for the actual assemblage
- *In situ* measurements of CO_2 from BIFs give comparable values to the calculations
- If CO_2 levels were high enough, siderite would form, thus no siderite in Precambrian paleosols implies lower CO_2 levels

$$\underset{\text{greenalite}}{Fe_3Si_2O_5(OH)_4} + 2H_2O + 3CO_2 = \underset{\text{siderite}}{3FeCO_3} + 2H_4SiO_4$$

$$\therefore$$

$$P_{CO_2} = \sqrt[3]{\frac{a^2_{H_4SiO_4}}{K_{RXN}}}$$

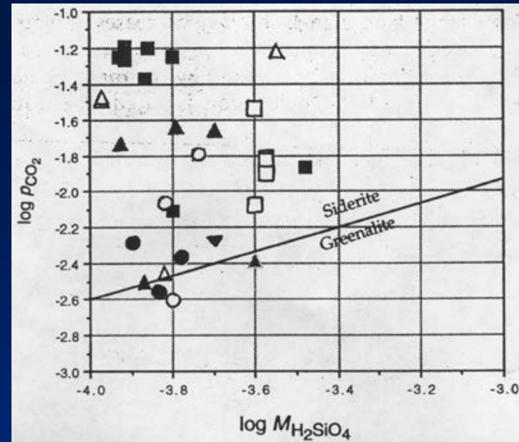
Equilibrium Models for Precambrian pCO_2

Atmospheric carbon dioxide concentrations before 2.2 billion years ago

Rob Rye, Philip H. Kuo & Heinrich D. Holland

Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, Massachusetts 02138, USA

Paleosols

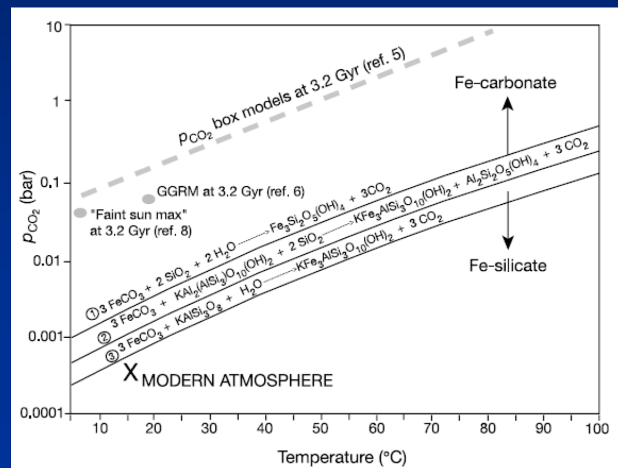


A lower limit for atmospheric carbon dioxide levels 3.2 billion years ago

Angela M. Hessler*, Donald R. Lowe, Robert L. Jones & Dennis K. Bird

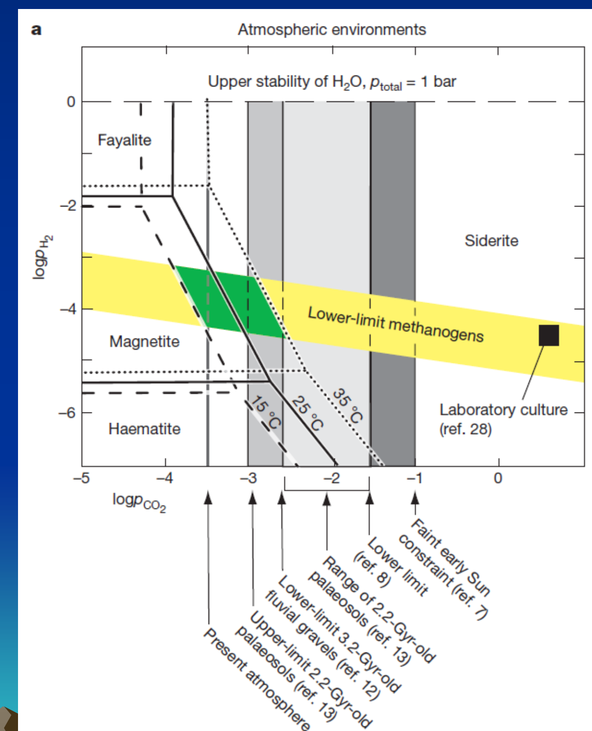
Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115, USA

Carbonate Rinds



No climate paradox under the faint early Sun

Minik T. Rosing[1,2,4], Dennis K. Bird[1,4], Norman H. Sleep[5] & Christian J. Bjerrum[1,3]

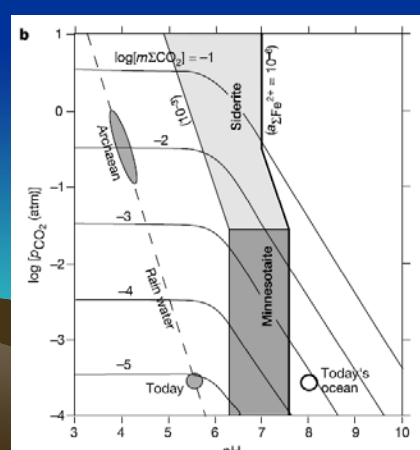


BIFs

Evidence from massive siderite beds for a CO_2-rich atmosphere before ~1.8 billion years ago

Hiroshi Ohmoto[1], Yumiko Watanabe[1] & Kazumasa Kumazawa[2]

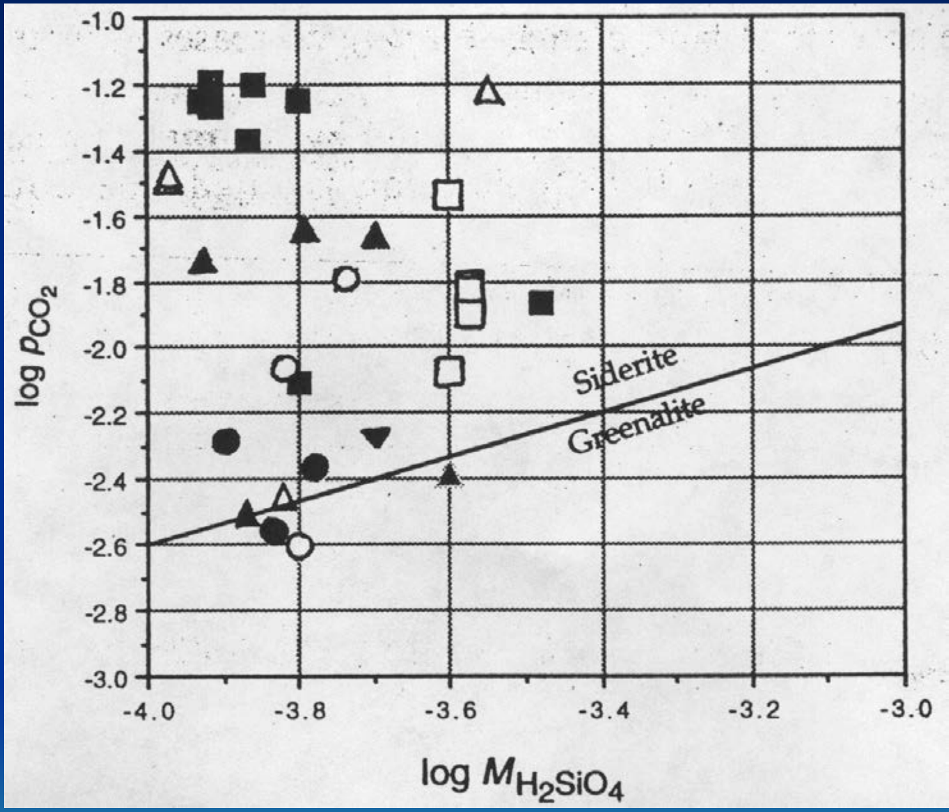
[1]*Astrobiology Research Center of the NASA Astrobiology Institute and Department of Geosciences, The Pennsylvania State University, University Park, PA 16802, USA*
[2]*Oyo Corporation, Miyazaki Branch, Oshima-cho, Miyazaki City, 0995-61, Japan*



BIFs

Problems

- BIF "proof" is irrelevant
- Thermodynamic data used is out of date
- First occurrence of siderite in a Precambrian paleosol is <1Ga ago
- Greenalite doesn't form authigenically in soils and isn't present at all in the Precambrian paleosols they examined



Rye et al. (1995, Nature)

Alternative Equilibrium Model: Berthierine

- Berthierine is a part of the mineral assemblage of the Hekpoort paleosol (Retallack, 1986; Retallack and Krinsley, 1993) and forms under reducing conditions (Sheldon and Retallack, 2002)

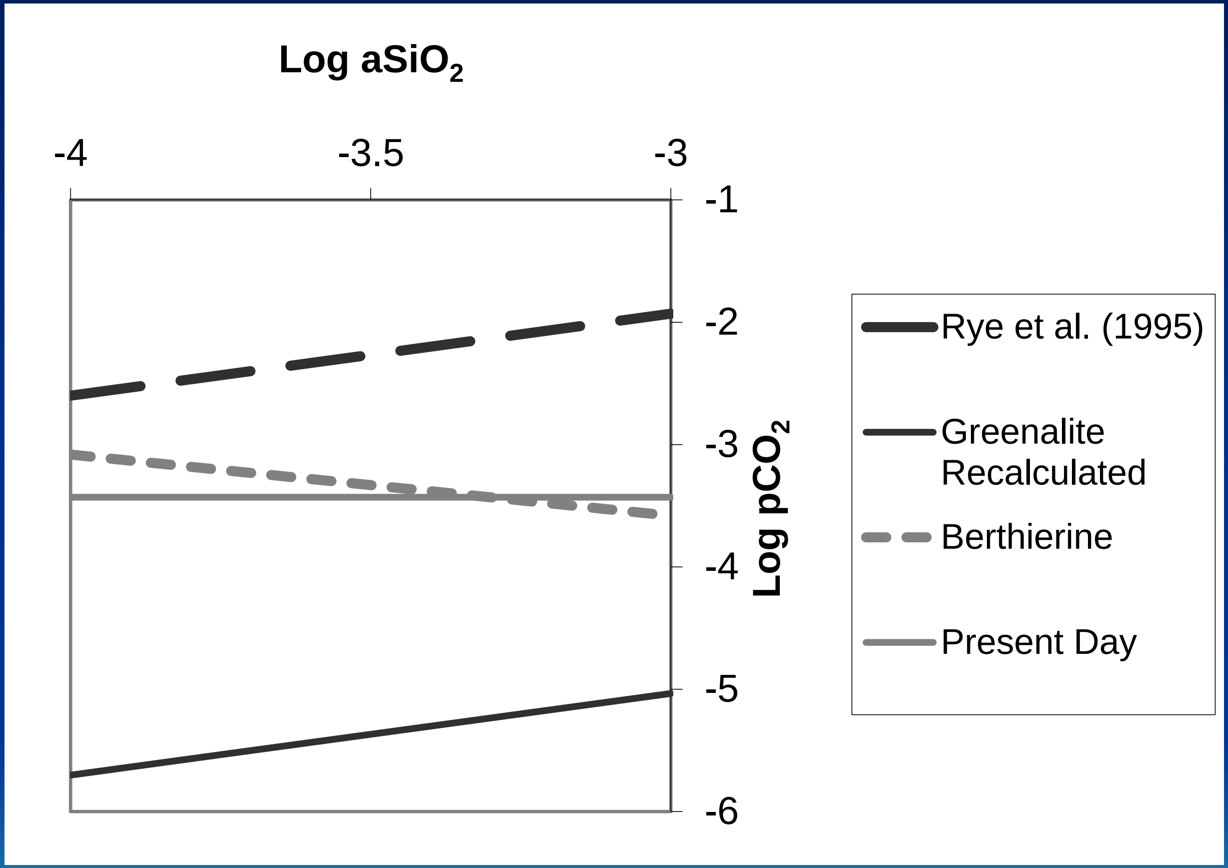
$$2FeCO_3 + Al_2Si_2O_5(OH)_4 = Fe_2Al_2SiO_5(OH)_4 + SiO_{2\,(aq)} + 2CO_{2\,(g)}$$

Siderite Kaolinite Berthierine

$$\therefore$$

$$P_{CO_2} = \sqrt{\frac{K_{RXN}}{a_{SiO_{2(aq)}}}}$$

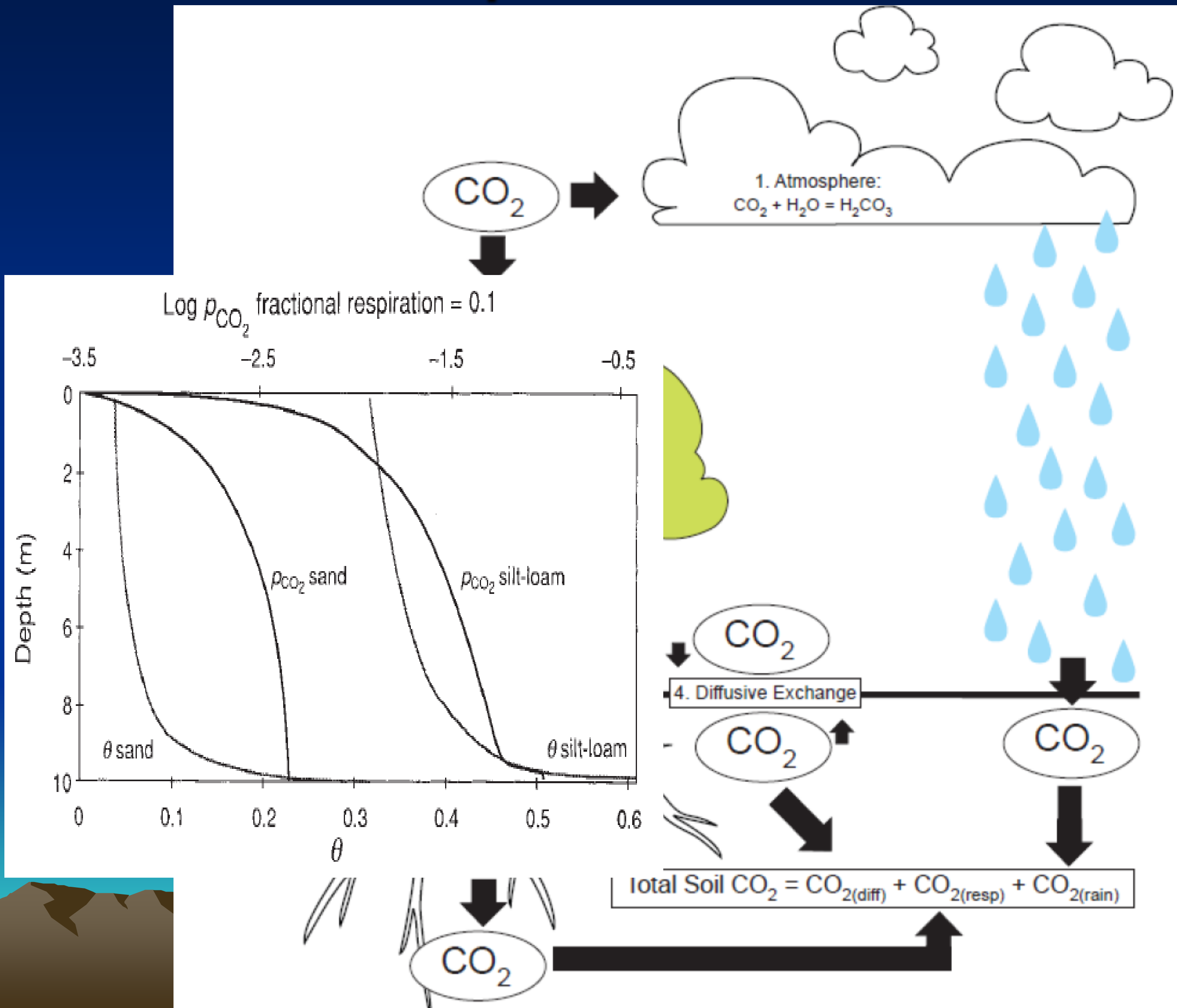
Recalculated pCO_2



Sheldon (2006, Precambrian Research)

If you take nothing else away from this part of the talk, please realize that thermodynamic models only provide **very, very weak guidance** about pCO_2 levels!

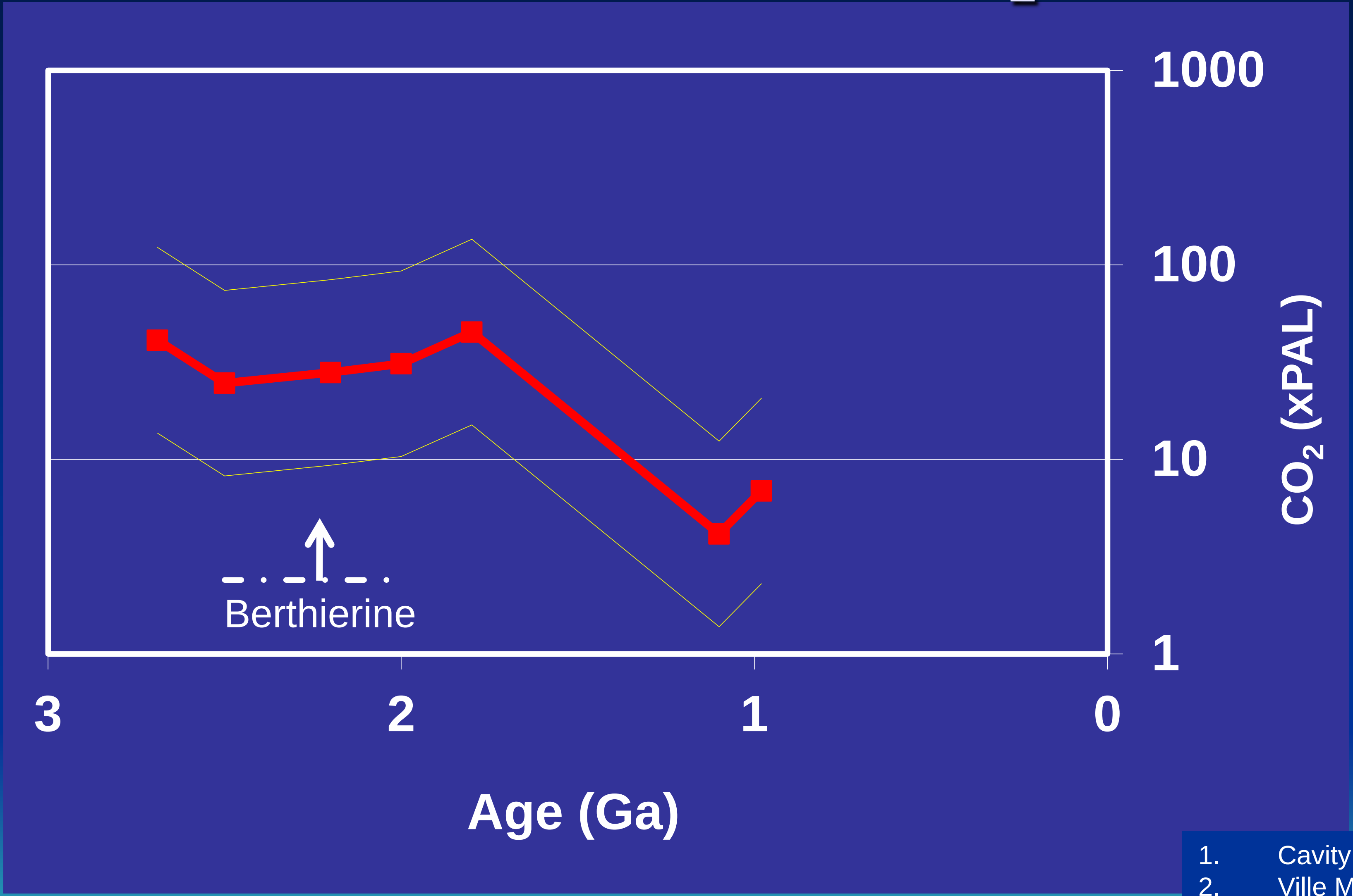
Conceptual Framework



Sheldon and Tabor (in press)

Keller and Wood (1993, Nature)

C. Towards a Precambrian CO_2 Curve



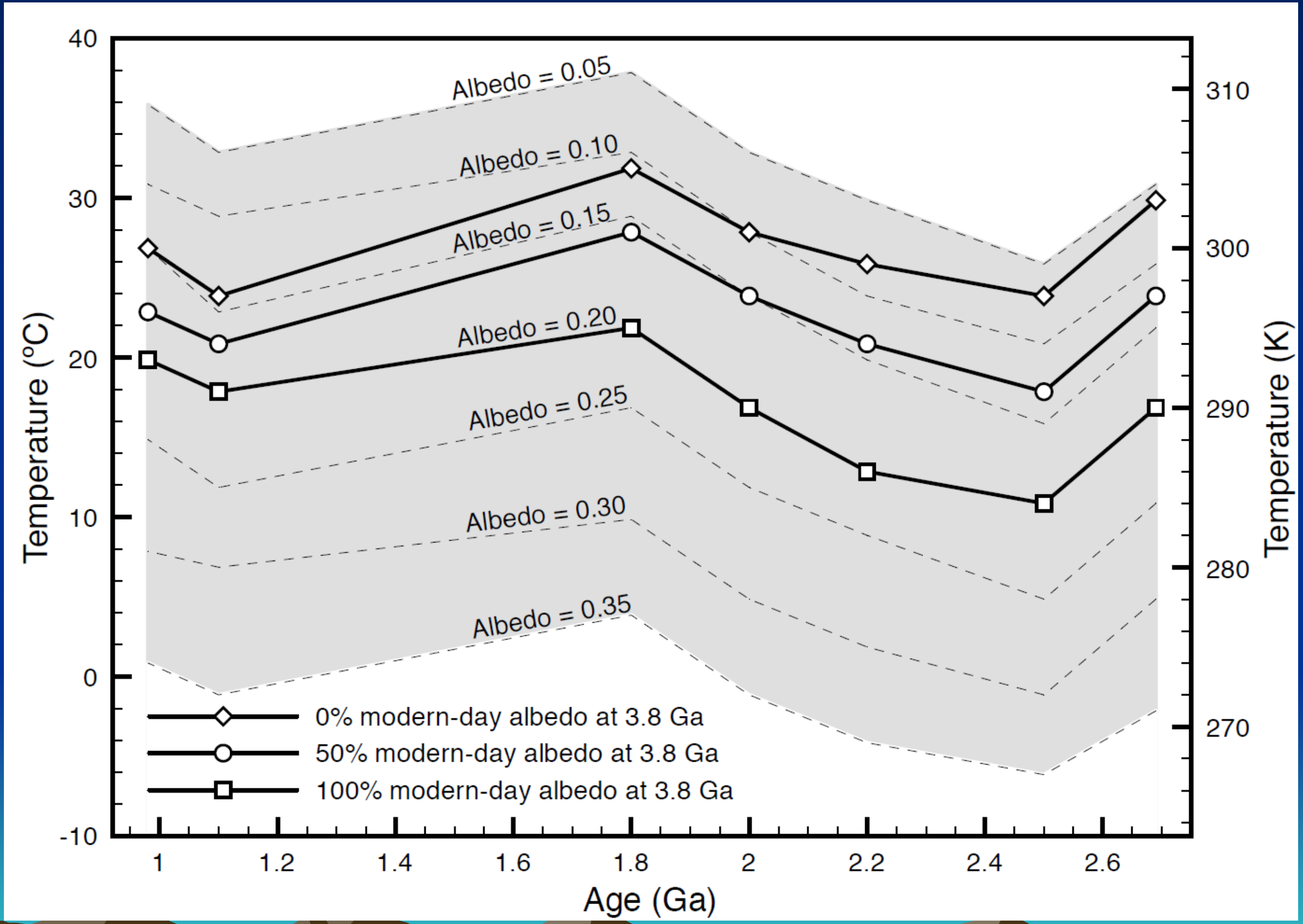
1. Cavity Lake
2. Ville Marie
3. Hekpoort
4. Drakenstein
5. Flin Flon
6. Sturgeon Falls
7. Sheigra

Compiled from Sheldon (2006, PC Res.), Mitchell and Sheldon (2010, PC Res.), and Driese et al. (2011, PC Res.)

D. 1-D Climate Models (w/ S. Domagal-Goldman)

- Use revised upper limit pCO_2 curve from paleosols
- Use two coupled models, one for photochemistry (CO_2, CH_4, O_2, O_3, C_2H_6, H_2O, particles (mostly S compounds), which is then fed into a 1-D climate model to calculate temperatures
  - Sim. to Haqq-Misra et al. (2008, Astrobiology) and Domagal-Goldman et al. (2011, Astrobiology)
- Assumptions:
  - Well-mixed atmosphere
  - After 2.4 Ga ago, 5% O_2 concentration and modern CH_4 flux to atmosphere; no O_2 flux to atmosphere, instead controlled by other species
  - Modern-day volcanic sources of H_2, SO_2, and H_2S
  - Variable albedo and different continental growth scenarios considered

1-D Climate Model Results

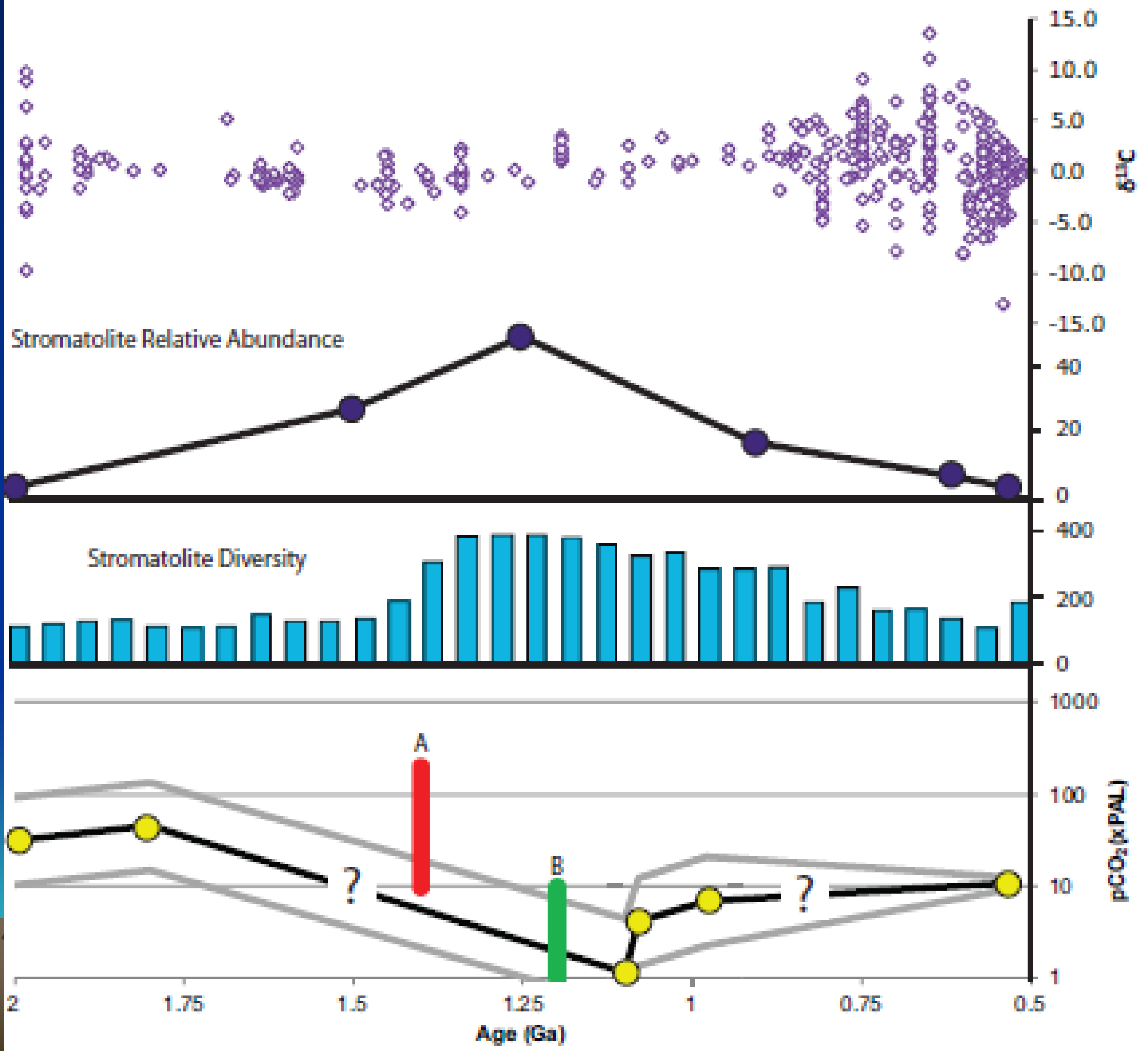


Domagal-Goldman and Sheldon (in prep)

So, if moderate pCO_2 were able to maintain equable conditions, it really must have been a "boring billion"…or was it?

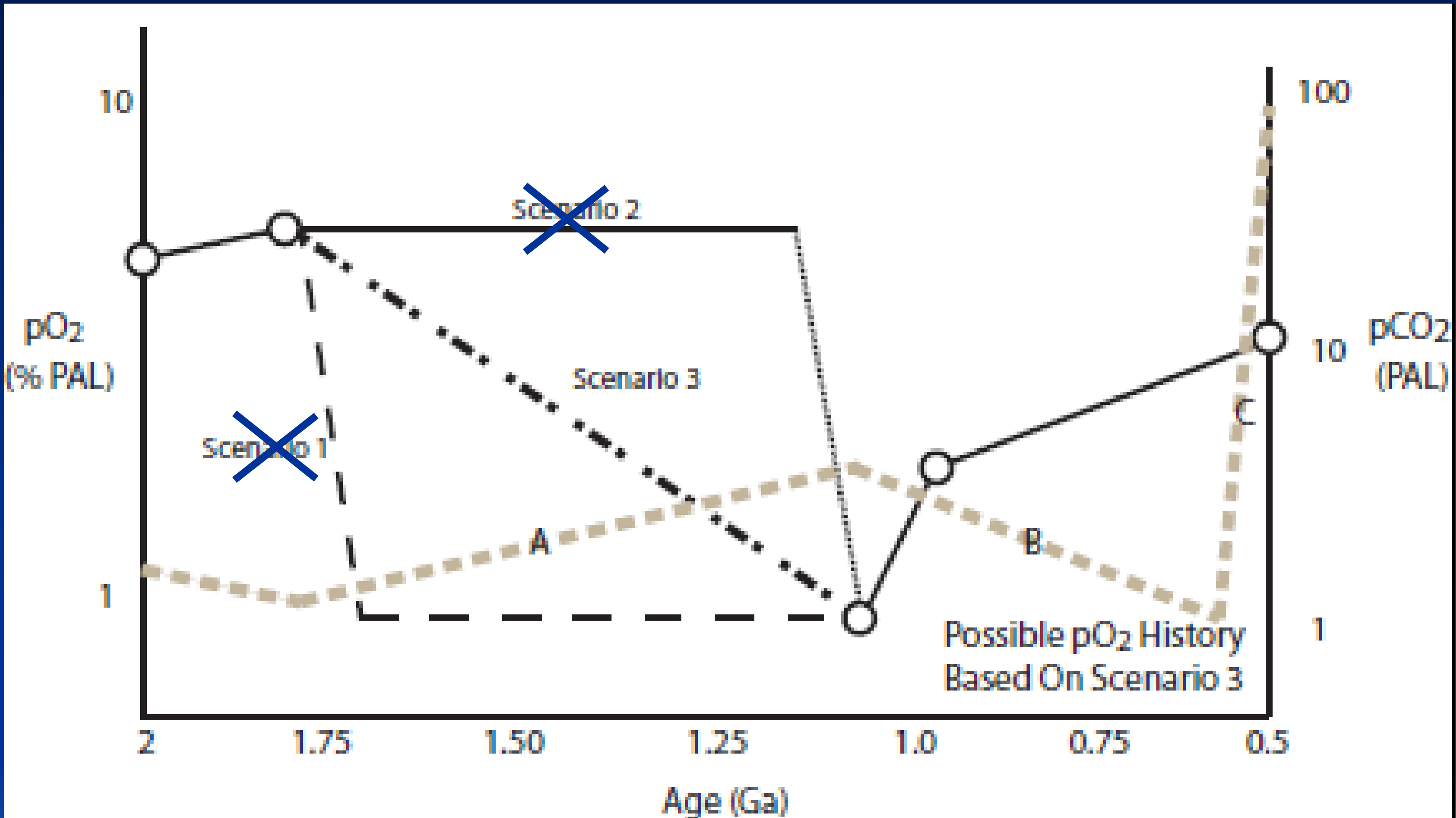
Earth's Middle Ages

Sheldon, in review



Earth's Middle Ages II

Sheldon, in review



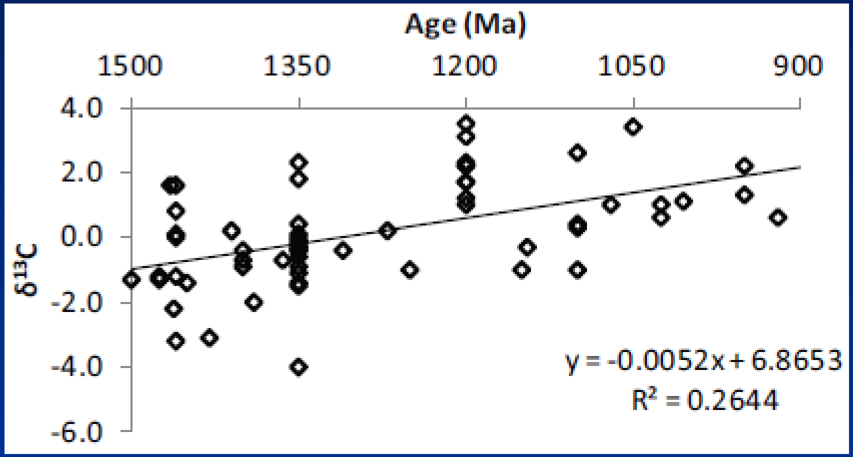
For organic matter:

$$CO_2 + H_2O \underset{\text{weathering}}{\overset{\text{burial}}{\rightleftharpoons}} CH_2O + O_2$$

For pyrite:

$$2Fe_2O_3 + 16Ca^{2+} + 16HCO_3^{-} + 8SO_4^{2-} \underset{\text{weathering}}{\overset{\text{burial}}{\rightleftharpoons}} 4FeS_2 + 16CaCO_3 + 8H_2O + 15O_2$$

Earth's Middle Ages III



$$F_{org} = F_{tot} \frac{\delta^{13}C_{carb} - \delta^{13}C_{input}}{\Delta^{13}C}$$

- If scenario three is correct, then we should see evidence for gradual C burial
- Based upon simple mass balance, 6×10^{14} moles of excess C are buried
- Corresponds to rise of calcifying algae, which store C in their sheaths

Conclusions

- Temperatures have been equable since at least 3.5 Ga ago, but probably 4.0 Ga
- Oxygen levels rose twice, between 2.45-2.22 Ga and 0.7-0.54 Ga
- Another greenhouse gas such as methane had to be present to account for the "faint young Sun" paradox, but both glaciation and equable conditions are possible with known constraints; albedo could be moderately important
- The "boring billion" actually represents a time of significant environmental change