Gaia Revisited:
The Interplay Between Climate and Life on the Early Earth

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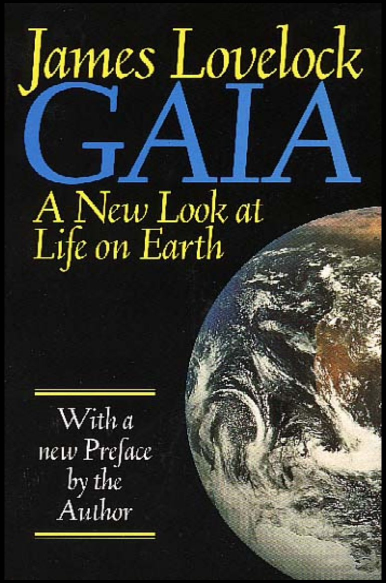
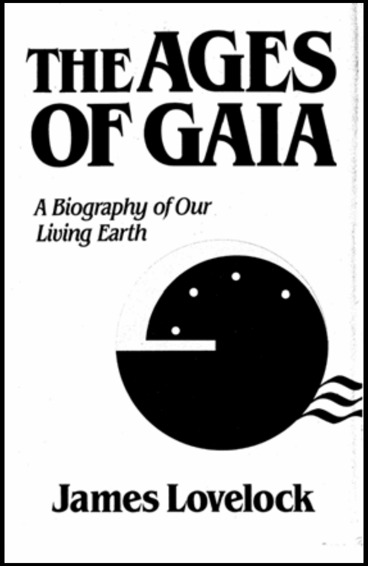
The Gaia Hypothesis

James Lovelock/
Lynn Margulis

- Earth's climate is regulated by (and for?) the biota



1979



1988

Geologic time

EON		ERA	Duration in millions of years	Millions of years ago
PHANEROZOIC		CENOZOIC	65	65
		MESOZOIC	183	248
		PALEOZOIC	295	543
PRECAMBRIAN	PROTEROZOIC	LATE	357	900
		MIDDLE	700	1600
		EARLY	900	2500
	ARCHEAN	LATE	500	3000
		MIDDLE	400	3400
		EARLY	400	3800
	HADEAN		800	4600

← First shelly fossils (Cambrian explosion)

← Snowball Earth ice ages

} Warm

← Rise of atmospheric O_2 (Ice age)

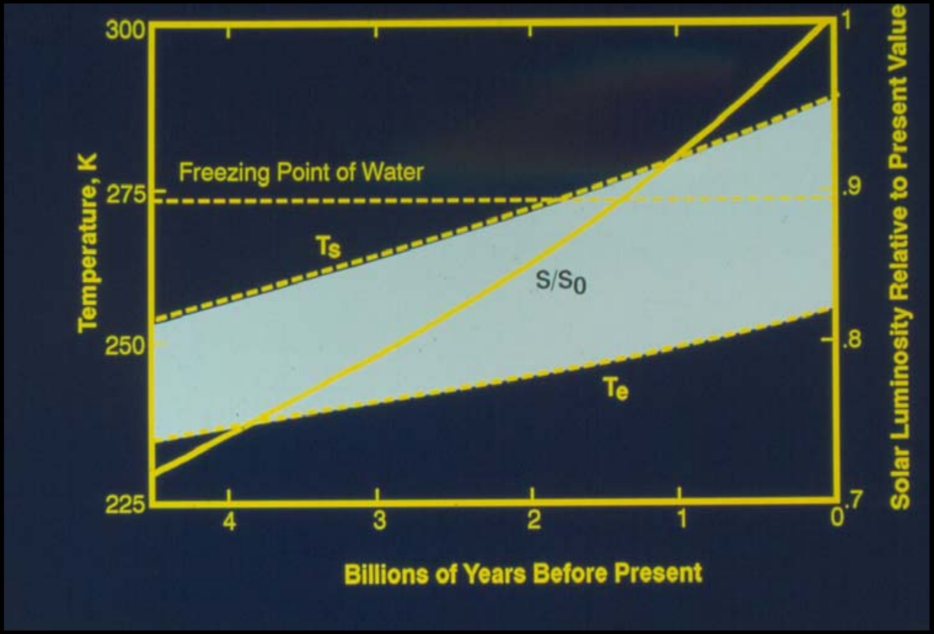
← Ice age (?)

} Warm (?)

} Origin of life

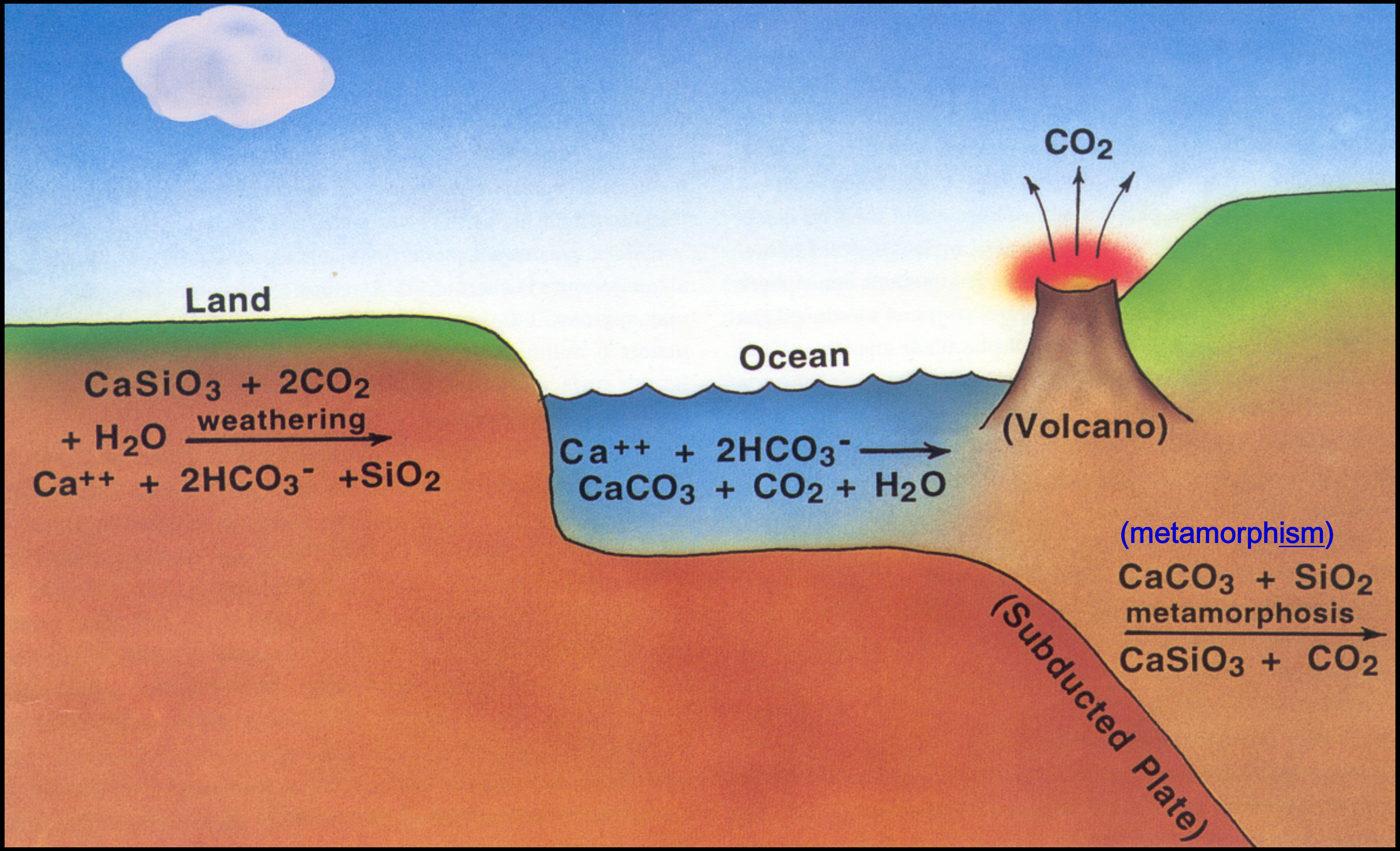
The Faint Young Sun Problem

- From a theoretical standpoint, it is curious that the early Earth was warm, because the Sun is thought to have been *less bright*
- This decrease in solar luminosity could have been offset either by higher CO_2, higher CH_4, or both



Kasting et al., *Sci. Amer.* (1988)

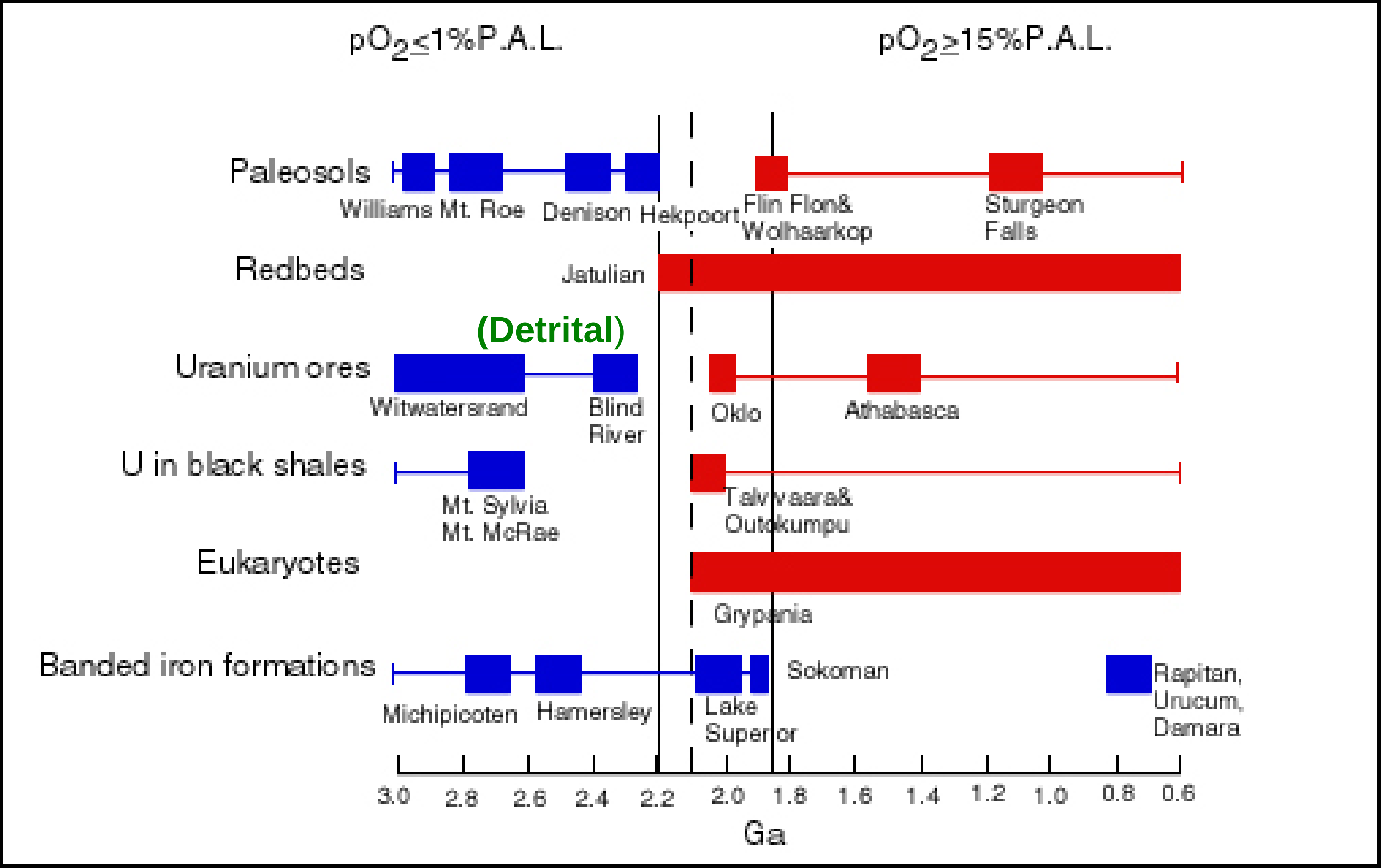
The Carbonate-Silicate Cycle



- Silicate weathering slows down as the Earth cools
  $\Rightarrow$ atmospheric CO_2 should build up

- Thus, atmospheric CO_2 levels may well have been higher in the distant past. However, there are good reasons for believing that CH_4 was abundant as well
- The first is that atmospheric O_2 levels were low…

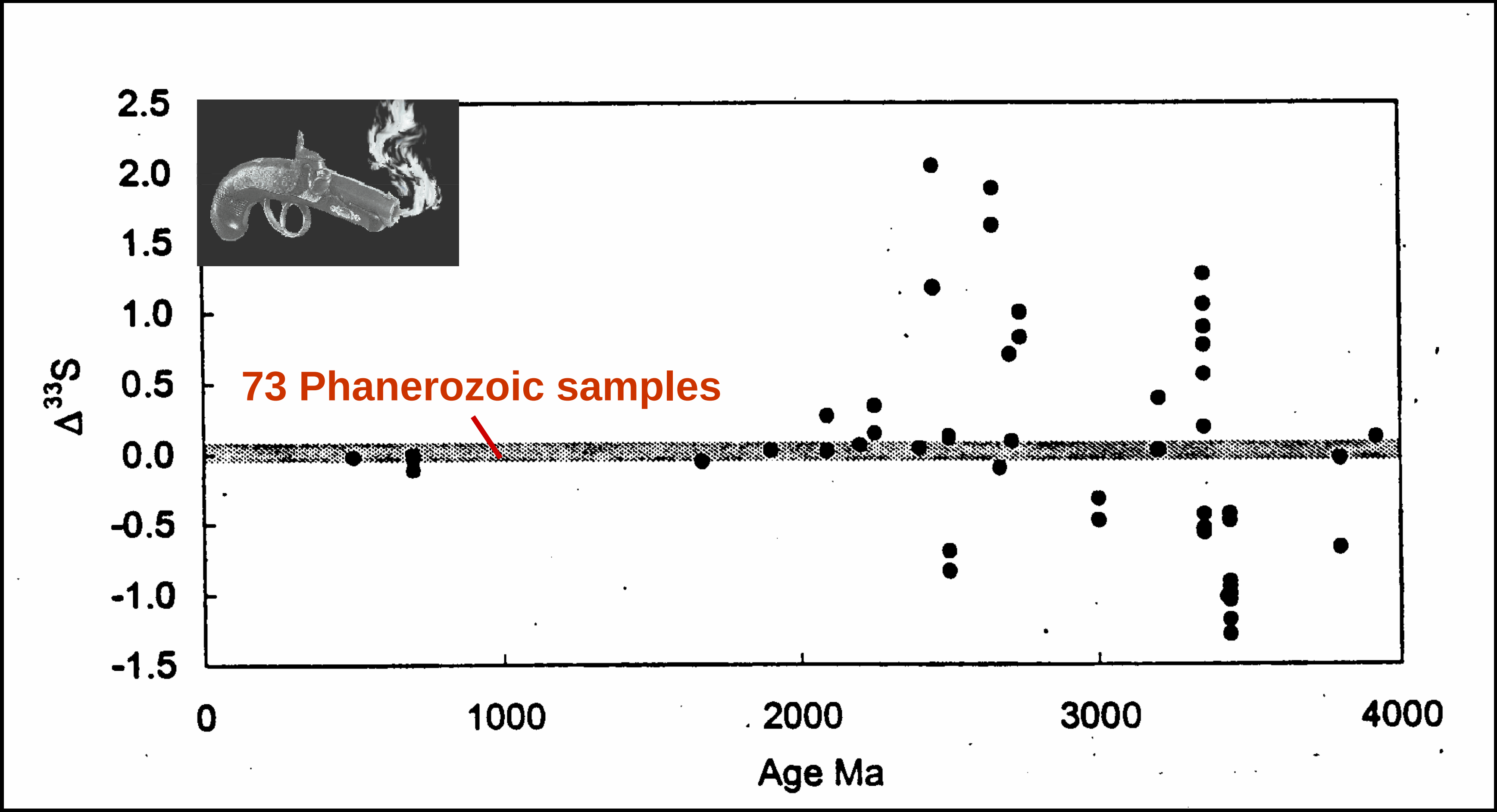
Geologic O_2 Indicators



H. D. Holland (1994)

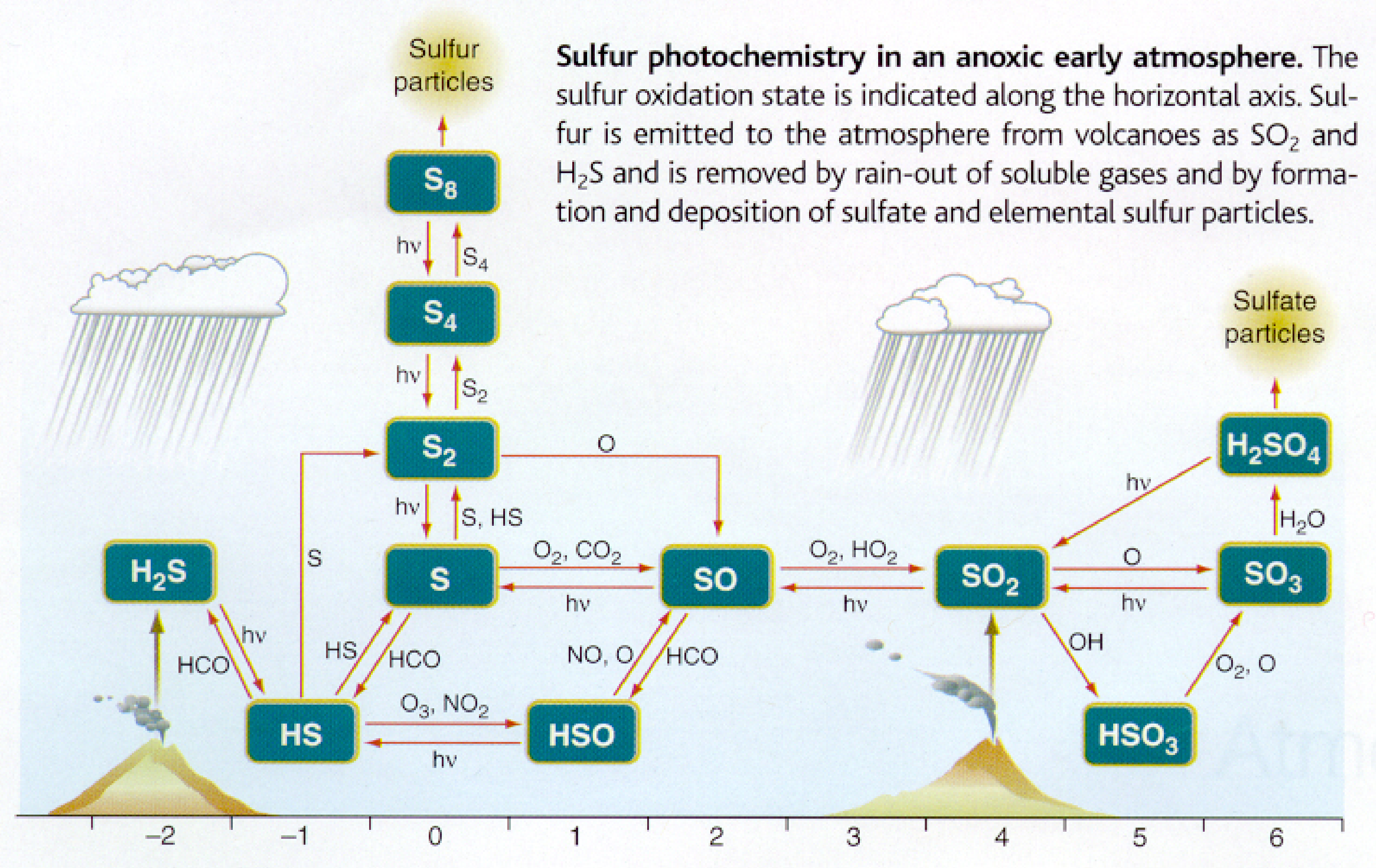
- Even better evidence for low O_2 during the Archean is provided by *mass-independent fractionation (MIF)* of sulfur isotopes in ancient rocks $\Rightarrow$

$\Delta^{33}S$ versus time



Farquhar et al., *Science*, 2000

Archean Sulfur Cycle



Sulfur photochemistry in an anoxic early atmosphere. The sulfur oxidation state is indicated along the horizontal axis. Sulfur is emitted to the atmosphere from volcanoes as SO_2 and H_2S and is removed by rain-out of soluble gases and by formation and deposition of sulfate and elemental sulfur particles.

Kasting, *Science* (2001)   Redrawn from Kasting et al., *OLEB* (1989)
Original figure drafted by Kevin Zahnle

- A second reason for suspecting that CH_4 was abundant on the early Earth is that the biological source of (most) methane is probably *ancient*

- Today, CH_4 is produced in restricted, *anaerobic* environments, such as the intestines of cows and the water-logged soils underlying rice paddies
  - Update (Keppler et al., *Nature*, Jan., ’06): Methane is also produced by plants!
- *Methanogenic bacteria* are responsible for most methane production

Archean CH_4 concentrations

- It can be shown that CH_4 production rates in an anaerobic biosphere could have been comparable to today (P. Kharecha et al., *Geobiology*, 2005)
- Because O_2 was low, the lifetime of methane would have been long (~10,000 yrs), and CH_4 could have accumulated to 1000 ppmv or more (as compared to 1.7 ppmv today)
- This is enough to produce a substantial *greenhouse effect* (~20-30 degrees) (Pavlov et al., *JGR*, 2000)

One of the most attractive features of the methane greenhouse model is that it correlates well with the *glacial record* ⇒

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Warm

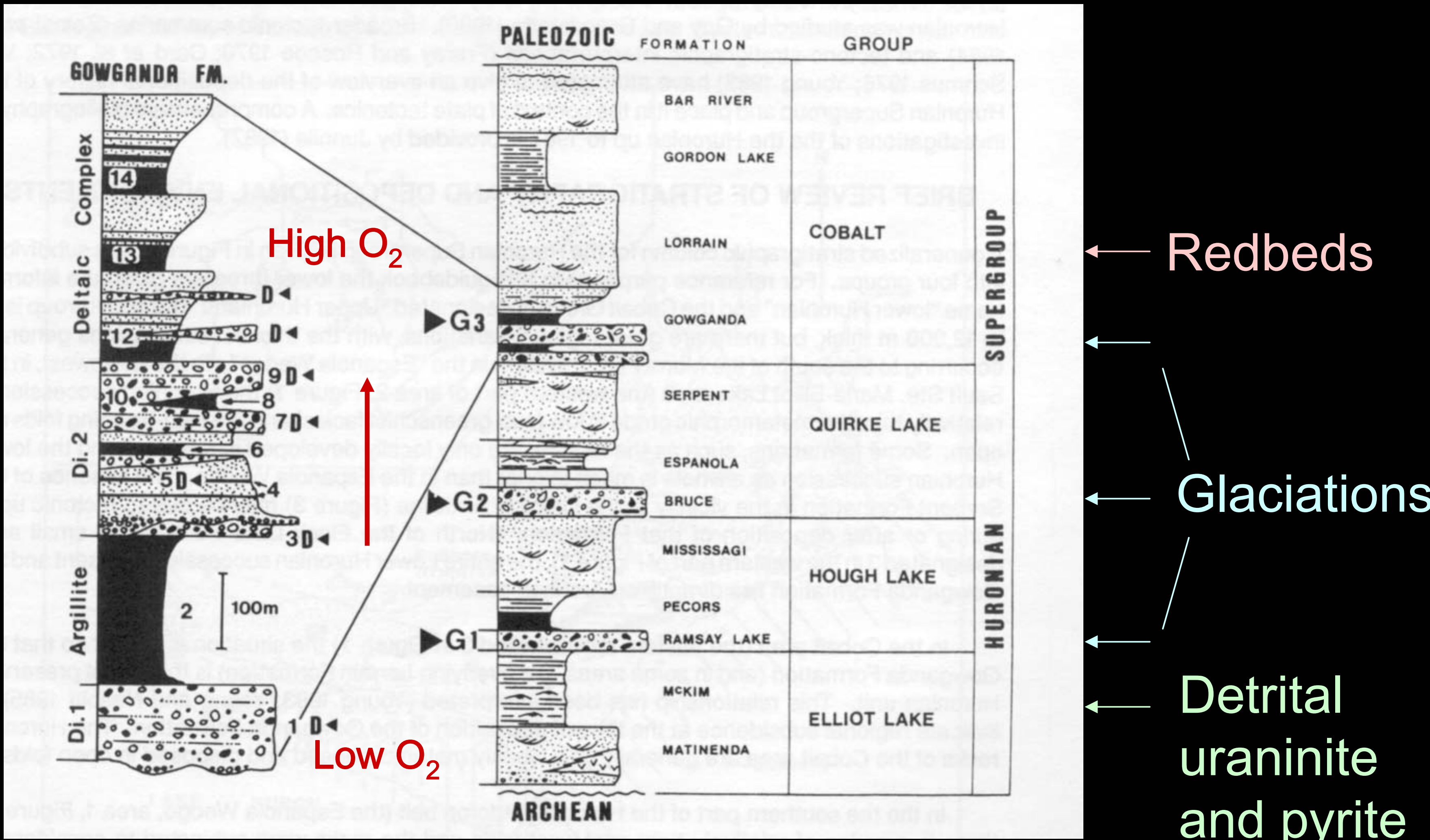
← Rise of atmospheric O_2 (Ice age) ~2.4 Ga

← Ice age (?) ~2.9 Ga

Warm (?)

Origin of life

Huronian Supergroup (2.2-2.45 Ga)



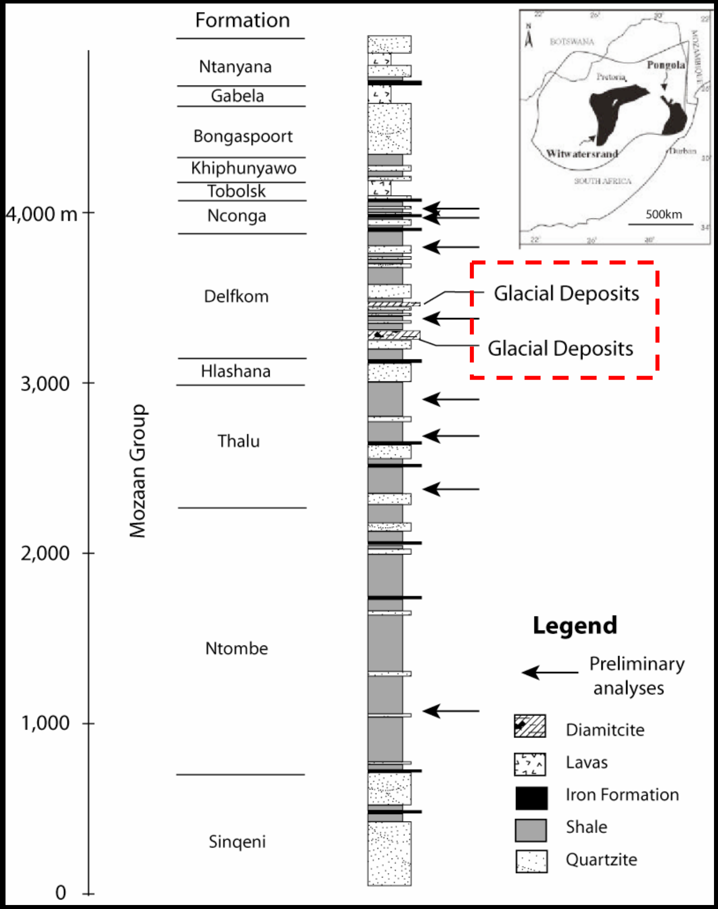
S. Roscoe, 1969

- The Paleoproterozoic glaciations (2.4-Ga) are nicely explained by the rise of atmospheric O_2 and the collapse of the methane greenhouse
- What about the mid-Archean glaciations (2.9-Ga) ?

Mid-Archean glaciations

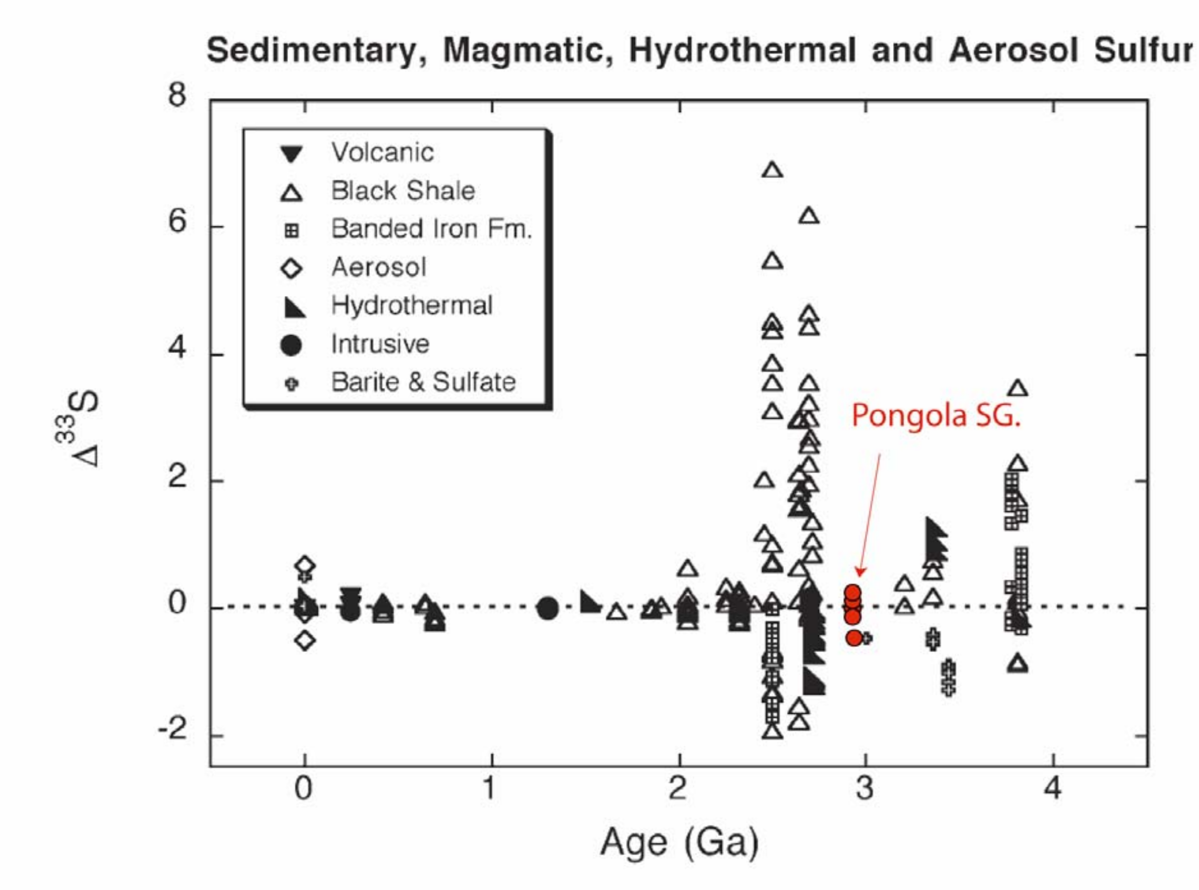
Diamictites dated at ~2.9 Ga are found in several different localities:

- Pongola Supergroup of S. Africa
- Witwatersrand Basin, also in S. Africa
- Belingue greenstone belt in Zimbabwe



Courtesy of S. Ono

$\Delta^{33}S$ vs. time (compiled by S. Ono)



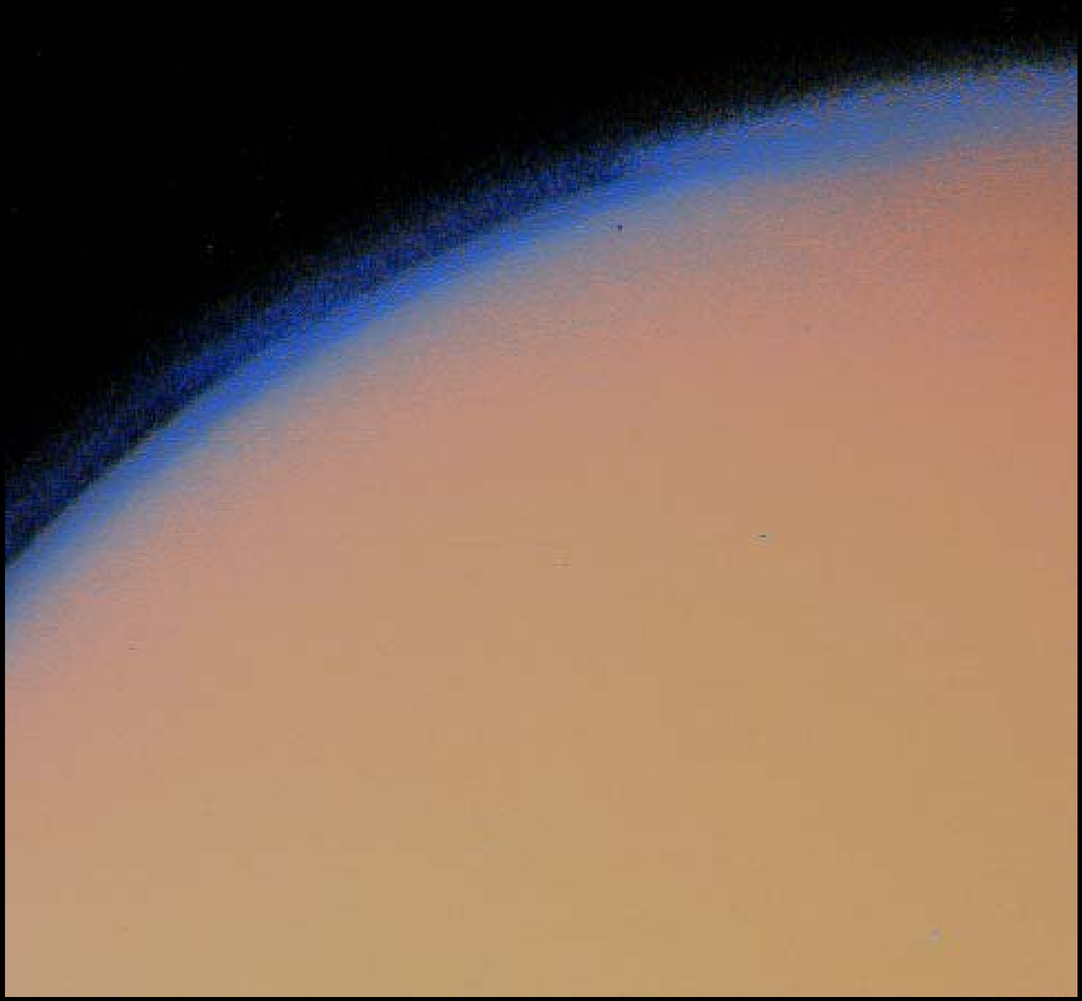
- H. Ohmoto and Y. Watanabe also have low-$\Delta^{33}S$ pyrite from the 2.76-Ga Hardey formation and the 3.0-Ga Mosquito Creek formation in Australia (*Tokyo, May, 2005*)
- H. Strauss also has low-MIF sulfur from the Kaapvaal craton in South Africa from about this same time

data compiled from various sources
(Farquhar et al., 2000, 2002; Ono et al., 2003, Mojzsis et al., 2003; Hu et al., 2003; and studies in prep by Ono, Wing, Johnston)

Possible mechanisms for causing the mid-Archean glaciations

1. "Yo-yo" atmosphere (Ohmoto; S. Ono)
   – O_2 levels go up briefly, then go back down
2. Highly reduced atmosphere (A. Pavlov)
   – H_2 and/or CH_4 levels are very high, so that all the sulfur exits the atmosphere as H_2S
3. Organic haze hypothesis (Goldman & Kasting; Peters,Farquhar, & Strauss)
   – Organic haze produced from CH_4 photolysis produces an *anti-greenhouse effect* that cools the climate

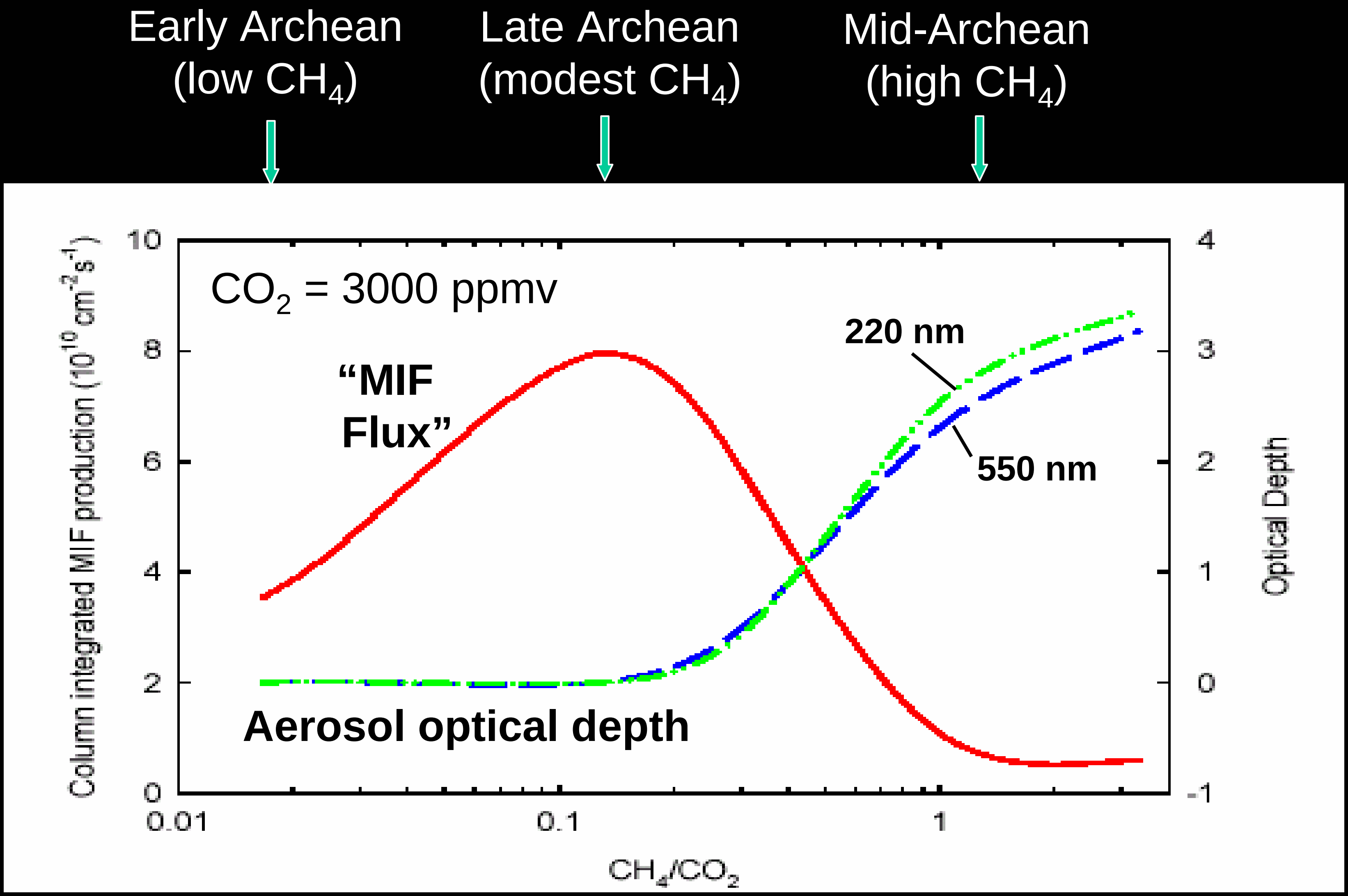
Titan's organic haze layer



Haze is thought to form from photolysis (and charged particle irradiation) of CH_4

(Picture from Voyager 2)

- Organic haze is predicted to form in Earth's early atmosphere when the CH_4/CO_2 ratio is > 1



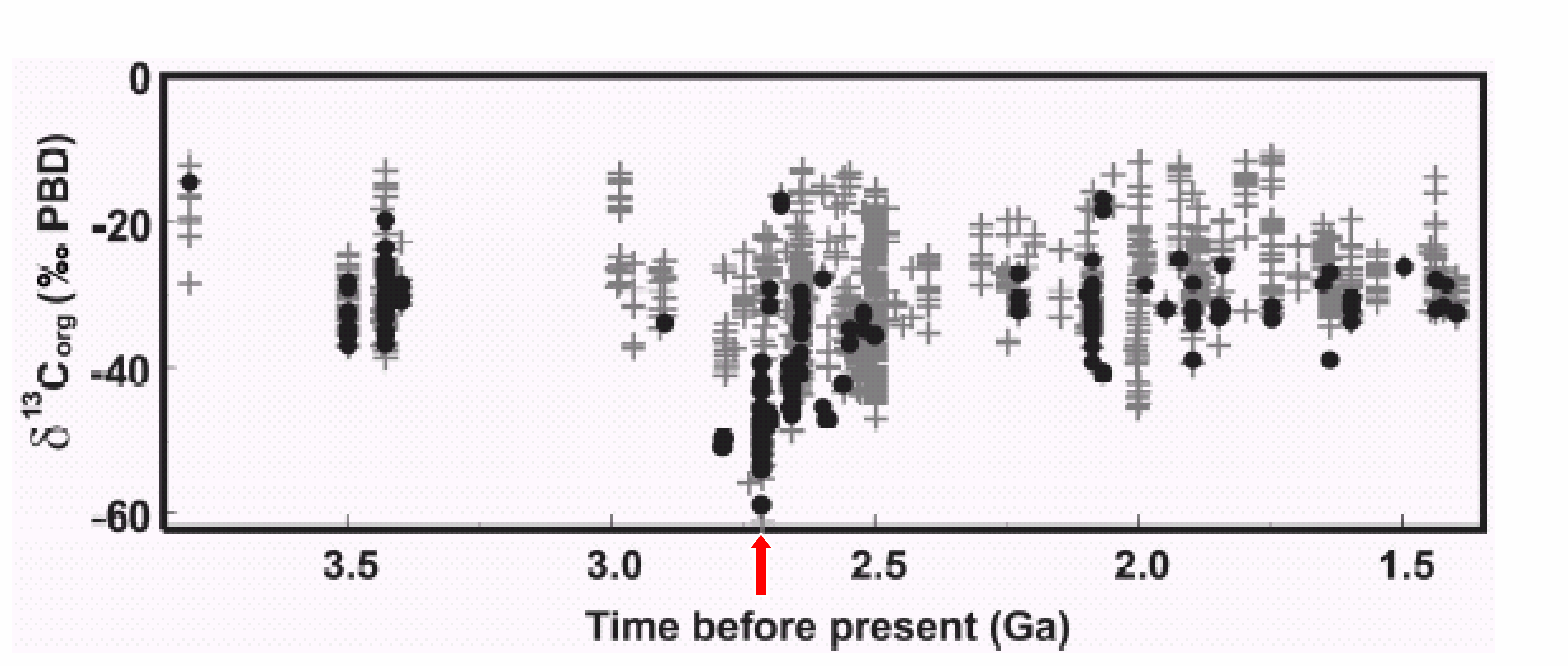
Goldman and Kasting, in preparation

- "MIF flux" = column-integrated dissociation rate of SO_2 at $\lambda < 220$ nm

Possible Evolutionary Sequence

> 3.2 Ga	$CH_4 << CO_2$. No haze. Methan-ogens evolve during this time
3.2 Ga	CO_2 levels drop so that $CH_4 \approx CO_2$. Thick organic haze forms, glaciation occurs
2.7 Ga	Cyanobacteria evolve, O_2 appears in water column (oxygen oases), sulfate increases, CH_4 production goes down, organic haze becomes thinner, climate warms
2.4 Ga	Atmospheric O_2 goes up, new episode of glaciation

Organic carbon isotopic record



Pavlov et al., *Geology* (2001) [Data from J. Eigenbrode and K. Freeman]

- The extremely light kerogens at 2.6-2.8 Ga have been interpreted (by John Hayes) as evidence for the onset of oxygenic photosynthesis

Conclusions

- CH_4 was probably an important greenhouse gas during the Archean (1000 ppmv or greater)
- The Paleoproterozoic glaciations at ~2.4 Ga were likely triggered by the rise of O_2 and a corresponding decrease in CH_4
- The mid-Archean glaciations at 2.9 Ga may have been triggered by an increase in CH_4 and the corresponding development of a thick organic haze layer
- All of this is very "Gaian". Score one for James Lovelock!