12.842 / 12.301 Past and Present Climate

Fall 2008

Climate on Geologic Time Scales & The CO_2-Climate Connection

Where We've Been & Where We Will Go

- Reviewed what processes control CO_2 greenhouse effect over geologic time (i.e., geochem. C cycle).
- And what negative feedbacks (e.g., T-weathering, CO_2-weathering) might keep climate system from reaching &/or remaining in extreme states (e.g., Venus).
- But data (geologic evidence) to support the theory (strong control of climate by CO_2) is lacking*.
- Now turn to geologic evidence for CO_2-climate link during last 500 Myr.

* Prior to ~550 Ma the lack of animals with hard skeletons and vascular plants to date has resulted in little or no fossil evidence of atmospheric CO_2 levels.

CO_2-Climate Connection

→**Facts**:

- Trace atmospheric gas that efficiently traps outgoing IR

→**Hypotheses and theories:**

- Solution to FYSP
- Through influence on CO_2: weathering, tectonics and organic carbon burial/oxidation control climate on geologic timescales
- Negative feedbacks:
  1. Temp. – Weathering
  2. CO_2 - Weathering

→**Tests:**

- Comparisons between "proxies" for CO_2 and T

→**State of the science:**

- Substantial support for close link… with notable exceptions….

Image removed due to copyright restrictions.

Sarmientoand Gruber, 2005; Houghton et al., 1990.

Atmospheric CO_2 During the Phanerozoic (540-0 Ma)

Image removed due to copyright restrictions.

Low (CO_2+S) = Glaciation?

Crowley (2000)

Permo-Carboniferrous Glaciations (~300-275 Ma)

Image removed due to copyright restrictions.

Stanley (2000) Figure 11.11.

Phanerozoic CO_2 Evolution

Permo-Carboniferous Glaciations Followed a period of marked CO_2 decline

- The CO_2 decline likely resulted from the spread of rooted vascular plants in the Devonian, 400-360 Ma.

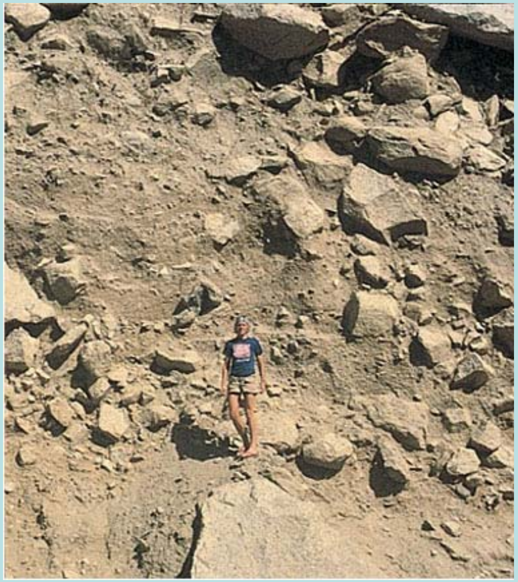
- Dissolution of bedrock (weathering) from: secreted acids, metabolic CO_2 from C_{org} decomposition, & anchoring of clay-rich soil to rock (which retains water).

Image removed due to copyright restrictions.

Stanley (2000)

Low CO_2 during Permo-Carboniferous Glaciations Resulted from Massive Burial of C_{org}

Image removed due to copyright restrictions.



High C_{org} Burial Results in High $^{13}C/^{12}C$ in Seawater & $CaCO_3$

Images removed due to
copyright restrictions.

Stanley (2000)

Image removed due to
copyright restrictions.

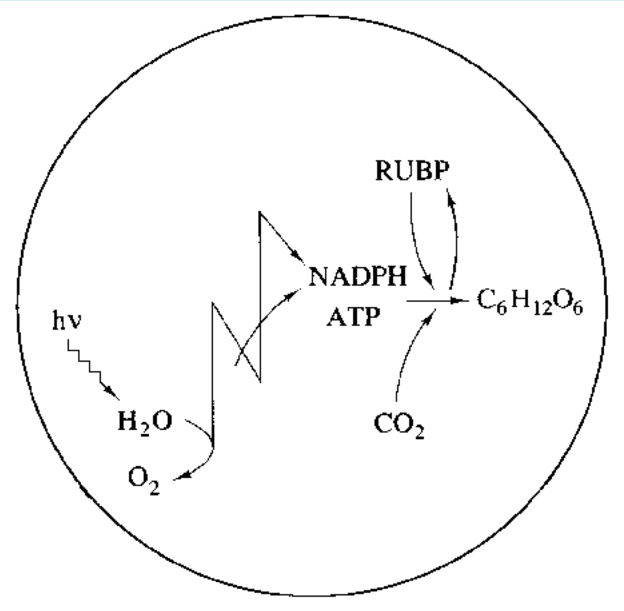
Kump et al. (1999) Figure 8-15.

20°-60° Warmer at Poles!

2°-6° Warmer at Equator

Decreased Equator-to-Pole Temperature Gradient

Photosynthetic fractionation of carbon isotopes depends on $[CO_2]_{aq}$



The Rubisco enzymatic photosynthesis pathway can be limited by available free CO_2 within a cell. It seems that many photosynthetic algae take up carbon by the diffusion of CO_2 across the cell wall. When CO_2 is abundant, this process results in a carbon isotope difference of ~30‰; it only uses a part of the available cellular CO_2 and shows maximal isotopic fractionation. In the limit of extremely scarce aqueous CO_2, the C fixation rate is diffusion limited, and the isotopic composition of the carbon entering the cell is the same as the aqueous dissolved CO_2 (i.e., ~ -7‰). So as aqueous CO_2 becomes more limiting, the isotopic composition of organic matter is shifted to heavier values.

Carbon Isotopic Fractionation Indicates $p\mathrm{CO}_2$

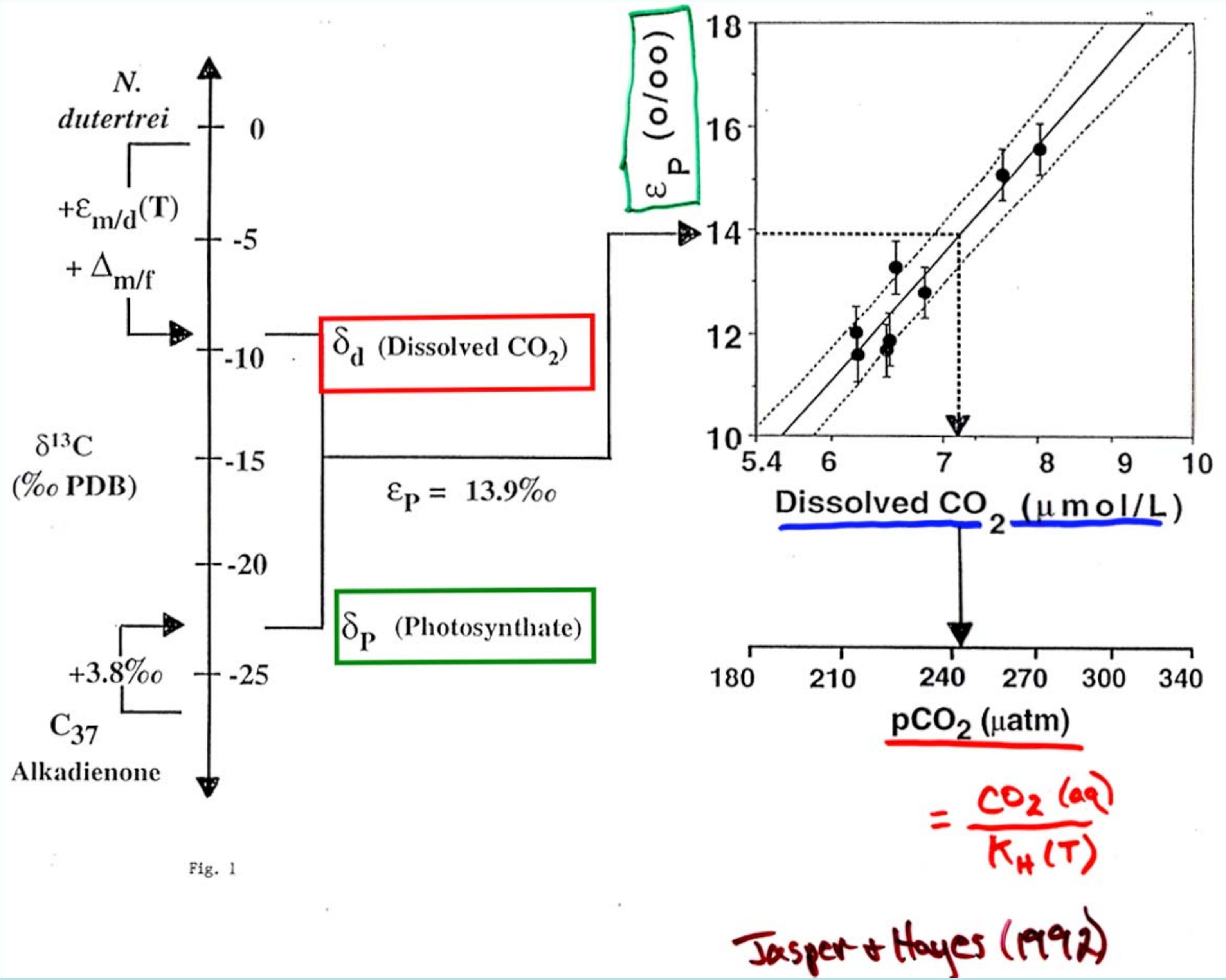


Fig. 1

$$= \frac{CO_2(aq)}{K_H(T)}$$

Jasper + Hayes (1992)

Paleo *p*CO2 Estimates from Carbon Isotopic Fractionation by Algae

Image removed due to copyright restrictions.

Royer et al. (2001) Figure 1.

Carbon Isotopic Fractionation Indicates $p\mathrm{CO}_2$

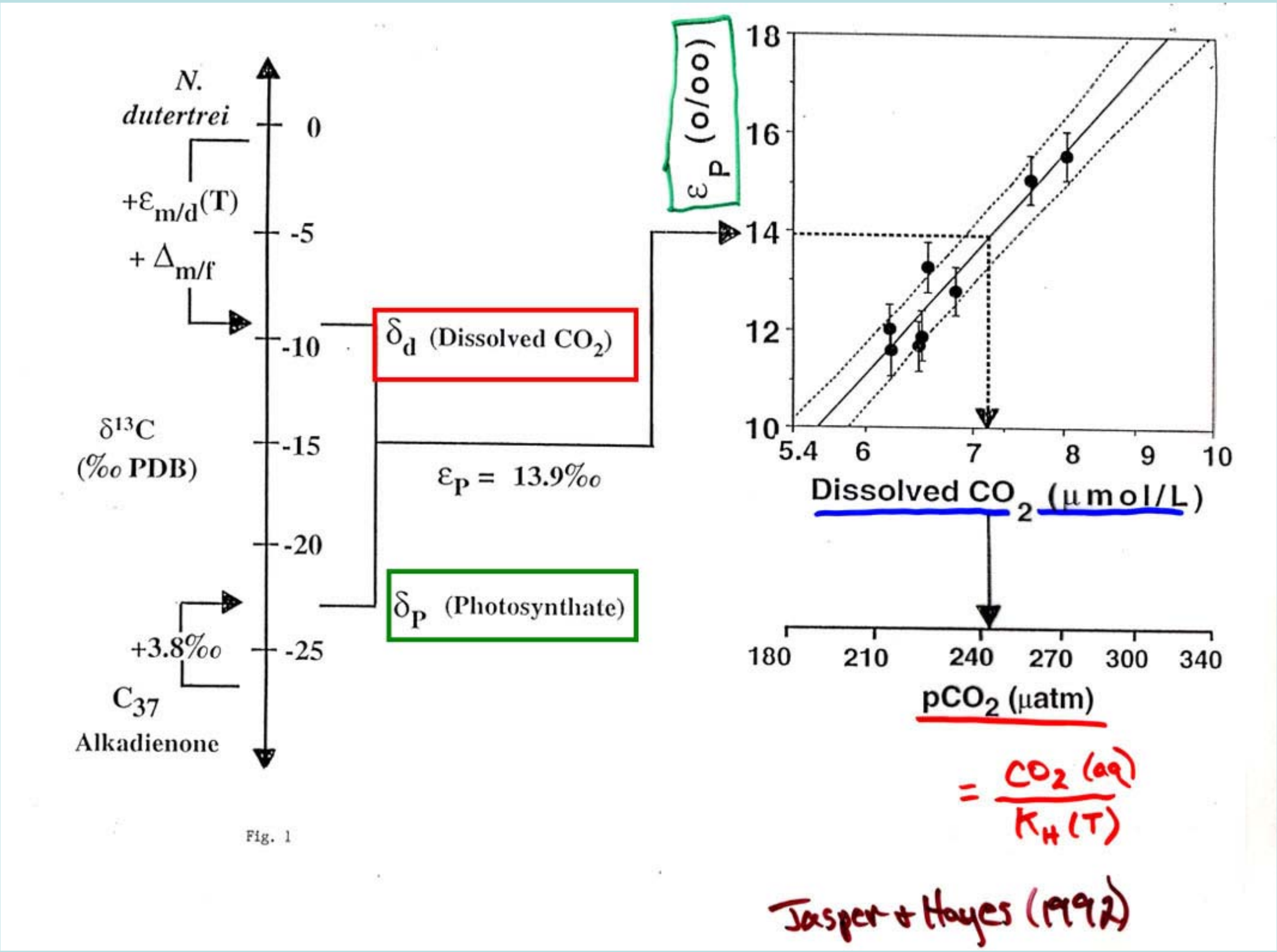


Fig. 1

$$= \frac{CO_2\,(aq)}{K_H(T)}$$

Jasper + Hayes (1992)

Fossil leaf cuticles provide evidence for elevated CO_2 during Mesozoic

3-6 x PAL
during
Mesozoic

Image removed due to copyright restrictions.
Citation: Retallack (2001), *Nature* 411: 287-290.

$SI(\%)=SD/(SD+ED)*100\%$

SD= stomatal density
ED=epidermal cell density

(i.e., the proportion of epidermal cells that are stomata

Calibrating the Leaf Stomatal "Paleo-barometer"

Image removed due to copyright restrictions.
Citation: Royer, et al. *Science* 292 (2001): 2310-2313.

Image removed due to copyright restrictions.
Citation: Retallack (2001), *Nature* 411: 287-290.

Extrapolation to high pCO_2 *not established by calibration data…*

Image removed due to copyright restrictions.
Citation: Figure 9. Royer, et al. *Earth-Science Reviews* 54 (2001): 349-392.

Response of stomata to [CO_2] is species-dependent

Limiting SI-derived paleo-CO_2 estimates to times and places when fossilized leaves from extant species exist…

Nevertheless, calibrations of the SI appear accurate for at least the last 9 kyr

Image removed due to copyright restrictions.
Citation: Figure 12. Royer, et al. *Earth-Science Reviews* 54 (2001): 349-392.

Royer et al. (2001)

organic ε_p CO_2 estimates

Image removed due to copyright restrictions.
Citation: Figure 3. Paganiet al. (2005) *Science* 309:600.

Boron Isotopes in Seawater Also Indicate Large Cenozoic CO_2 Decline

Image removed due to copyright restrictions.

$\delta^{11}B = [(^{11}B/^{10}B)_{smpl} / (^{11}B/^{10}B)_{std} - 1] \times 1000‰$

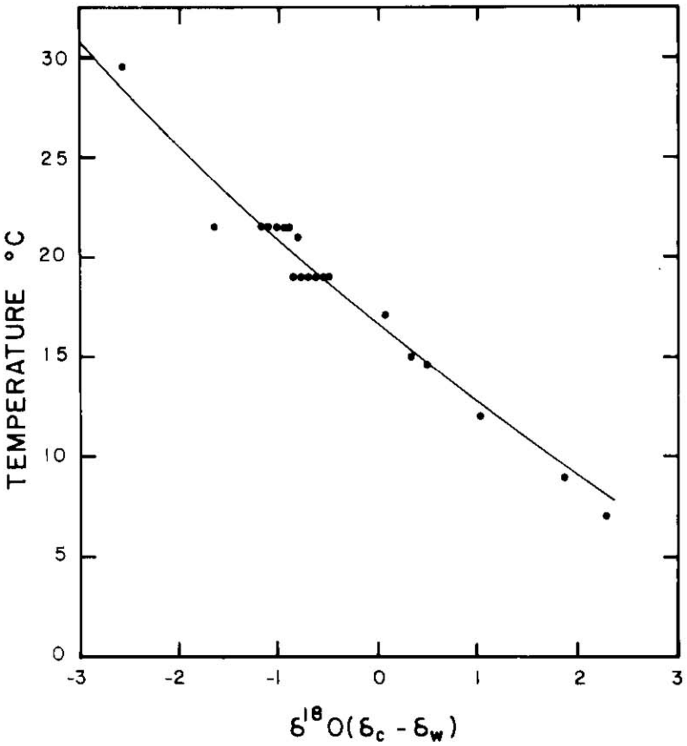
- B in seawater: $B(OH)_3$, $B(OH)_4^-$
- Relative abundance controlled by *p*H
- B incorporated into calcite: $B(OH)_4^-$
- Strong isotopic fractionation between ^{10}B & ^{11}B:
  ^{10}B = tetrahedral coordination, -19.8‰ relative to ^{11}B

in Zachos et al. (2001)

- Urey (1947) calculated that the oxygen isotope fractionation between calcium carbonate and water should be temperature-dependent.

$$\delta^{18}O = 1000\left[\frac{R_{sample}}{R_{s\tan dard}} - 1\right]$$

- Epstein (1953) grew molluscs in the laboratory and empirically determined the O18-T relationship:



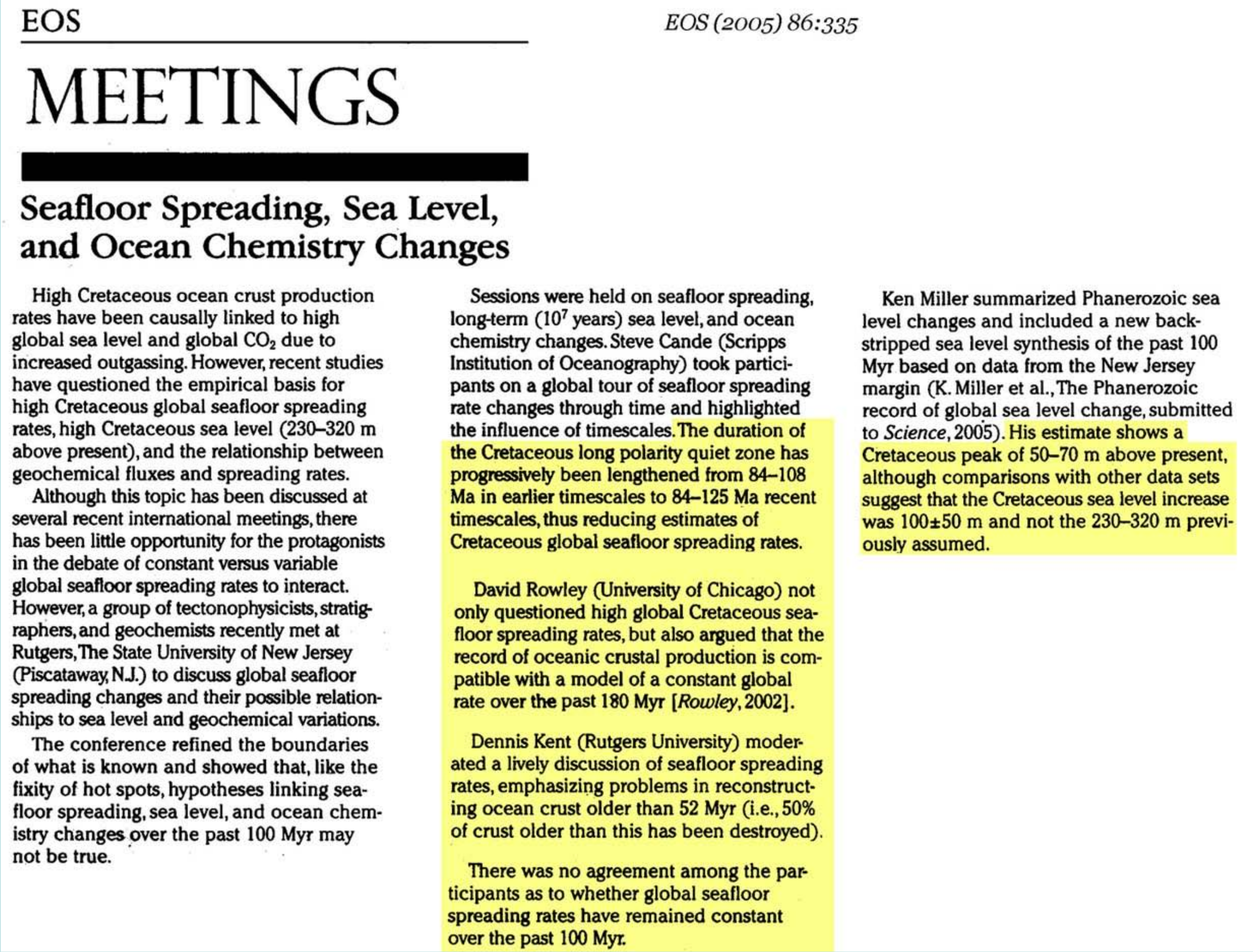
Isotopic temperature scale and original data points of Epstein *et al.* (1953). Temperature is in degrees Celsius. The δ values are the δ-corrected values, which are equal to $\delta_c - \delta_w$. After Epstein *et al.* (1953).

?Declining Seafloor Spreading Rates 80-40 Ma?

Image removed due to copyright restrictions.

Declining seafloor spreading rates are consistent with decreasing CO_2 in early Cenozoic (more continental area to weather as sea-level fall, less subducted $CaCO_3$ recycling)

But sea-level and sea-floor spreading rates in the past are uncertain…



EOS

EOS (2005) 86:335

MEETINGS

Seafloor Spreading, Sea Level, and Ocean Chemistry Changes

High Cretaceous ocean crust production rates have been causally linked to high global sea level and global CO_2 due to increased outgassing. However, recent studies have questioned the empirical basis for high Cretaceous global seafloor spreading rates, high Cretaceous sea level (230–320 m above present), and the relationship between geochemical fluxes and spreading rates.

Although this topic has been discussed at several recent international meetings, there has been little opportunity for the protagonists in the debate of constant versus variable global seafloor spreading rates to interact. However, a group of tectonophysicists, stratigraphers, and geochemists recently met at Rutgers, The State University of New Jersey (Piscataway, N.J.) to discuss global seafloor spreading changes and their possible relationships to sea level and geochemical variations.

The conference refined the boundaries of what is known and showed that, like the fixity of hot spots, hypotheses linking seafloor spreading, sea level, and ocean chemistry changes over the past 100 Myr may not be true.

Sessions were held on seafloor spreading, long-term (10^7 years) sea level, and ocean chemistry changes. Steve Cande (Scripps Institution of Oceanography) took participants on a global tour of seafloor spreading rate changes through time and highlighted the influence of timescales. The duration of the Cretaceous long polarity quiet zone has progressively been lengthened from 84–108 Ma in earlier timescales to 84–125 Ma recent timescales, thus reducing estimates of Cretaceous global seafloor spreading rates.

David Rowley (University of Chicago) not only questioned high global Cretaceous seafloor spreading rates, but also argued that the record of oceanic crustal production is compatible with a model of a constant global rate over the past 180 Myr [*Rowley*, 2002].

Dennis Kent (Rutgers University) moderated a lively discussion of seafloor spreading rates, emphasizing problems in reconstructing ocean crust older than 52 Myr (i.e., 50% of crust older than this has been destroyed).

There was no agreement among the participants as to whether global seafloor spreading rates have remained constant over the past 100 Myr.

Ken Miller summarized Phanerozoic sea level changes and included a new backstripped sea level synthesis of the past 100 Myr based on data from the New Jersey margin (K. Miller et al., The Phanerozoic record of global sea level change, submitted to *Science*, 2005). His estimate shows a Cretaceous peak of 50–70 m above present, although comparisons with other data sets suggest that the Cretaceous sea level increase was 100±50 m and not the 230–320 m previously assumed.

Raymo et al. suggest that Increasing Strontium Isotopic Composition of Seawater During Cenozoic Implies Increasing Weathering Rates:

SW $^{87}Sr/^{86}Sr$ is balance between:

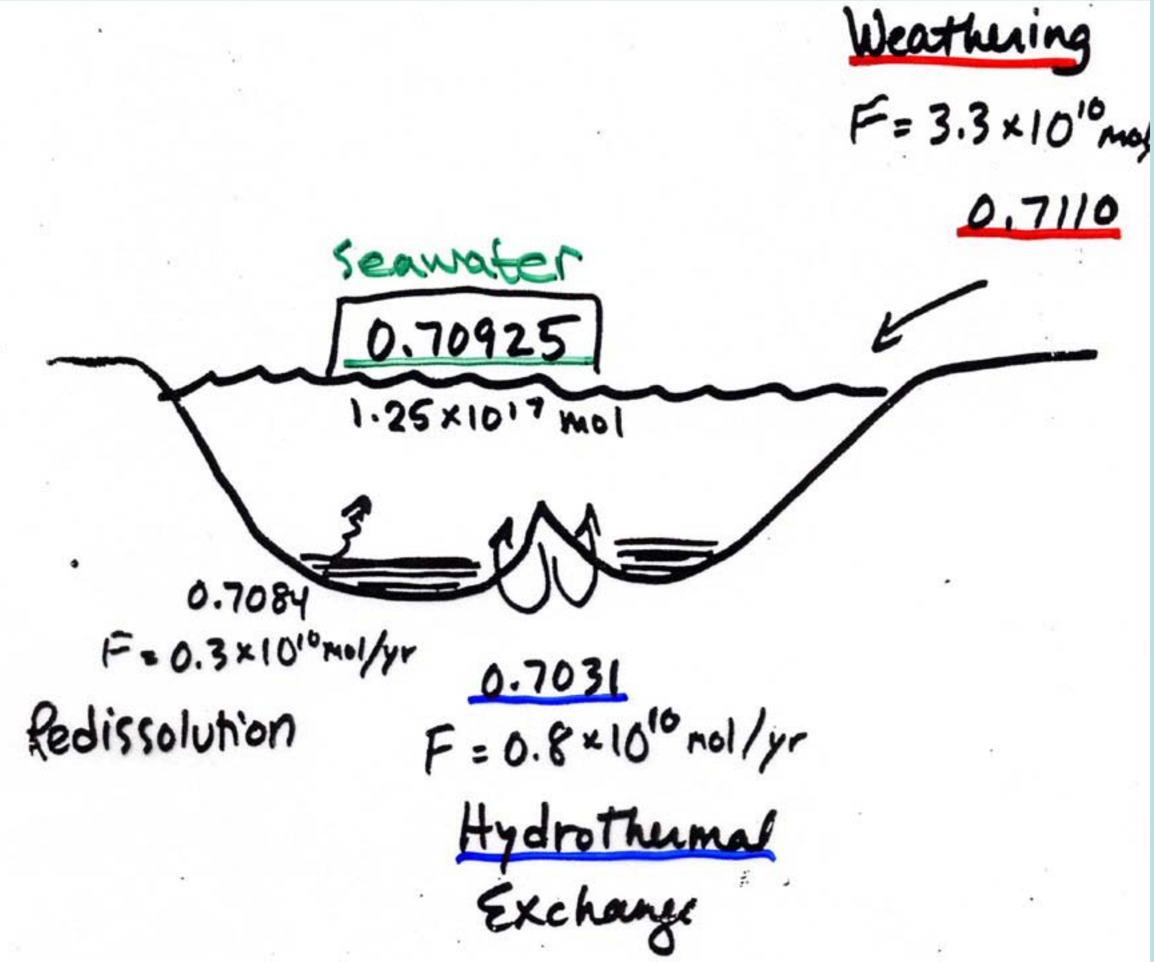
1. Deep-sea hydrothermal input of non-radiogenic Sr (0.7035)
2. More radiogenic input riverine flux from continental weathering (0.712)

Image removed due to copyright restrictions.

Abyssal carbonate $^{87}Sr/^{86}Sr$
$^{87}Rb \text{-->} ^{87}Sr$, $t_{1/2}$~48 Gyr

DePaolo & Ingram (1985)
in Edmond (1992)

Strontium Isotope Systematics



(Crust)

(Mantle)

World Average River $^{87}Sr/^{86}Sr$ ~ 0.711

Ganges-Brahmaputra $^{87}Sr/^{86}Sr$ ~ 0.8

Albarede, F; Michard, A; ***Minster***, J F; Michard, G (1981) **Earth Planet. Sci. Lett. 55:229-236**

Co-Variation of $^{87}Sr/^{86}Sr$ & CO_2 through the Phanerozoic

$$\varepsilon_p \sim \varepsilon_{toc} = \delta^{13}C_{CaCO3} - \delta^{13}C_{org}$$

$$\varepsilon_p \sim pCO_2$$

High weathering &/or **Low** magmatism

High CO_2

- **Weathering & magmatism may control CO_2, but does CO_2 control climate?**

Image removed due to copyright restrictions.
Citation: Figure 1. Rothman (2002) *PNAS*, Vol 99(7):4167.

Did a Gas Hydrate Release of Methane (2600 Gt) caused Late Paleocene Thermal Maximum?

Image removed due to copyright restrictions.

Benthic foraminifera from Atlantic & Pacific

- CO_2 not the only greenhouse gas we need to consider when evaluating warm episodes.

Zachos et al. (2001)

Substantial evidence exists for a link between CO_2 & climate on a variety of timescales….
With some notable exceptions!

Additional paleoclimate reconstructions & numerical model simulations are necessary. But the biggest (non-controlled) experiment ever attempted is now underway…

Chicxulub Crater
Gulf of Mexico

- 200 km crater
- 10-km impactor
- 65 Myr BP
- Extinction of 75% of all species!

Images removed due to copyright restrictions.

But:

Stigler and Wagner (1987) Science 238:940 say that the 26 million year period is an artifact of how the time scale is organized.

Cosmic Ray Forcing of Climate?

Image removed due to copyright restrictions.
Citation: Shaviv. *Phys Rev Lett* 89, no. 5 (2002): 051102-1-4.

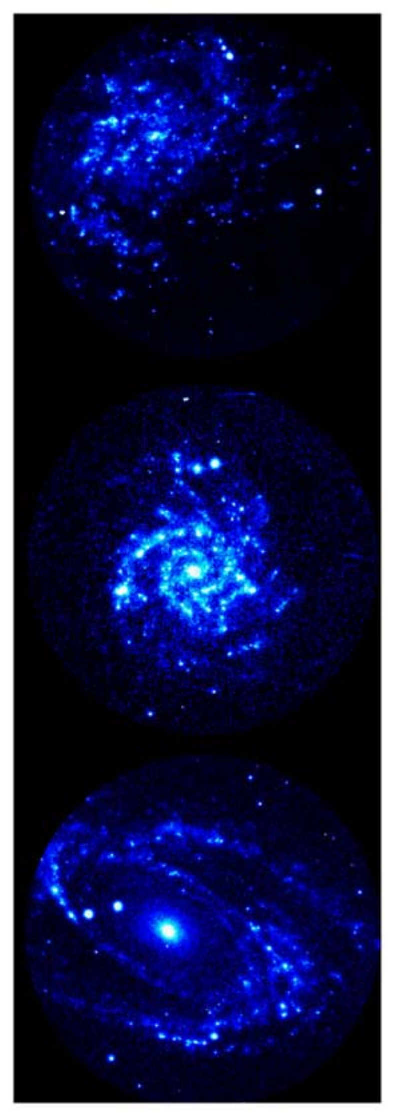


Image courtesy of NASA.

http://antwrp.gsfc.nasa.gov/apod/ap960409.html

Cosmic Ray Influence on Climate?

Image removed due to copyright restrictions.

Carslaw et al. (2002) *Science* Vol. 298: 1732-1737.

Image removed due to copyright restrictions.

Svensmark (1998) *Phys. Rev. Lett.* Vol. 81(22): 5027-5030.

Correlation does not require Causation