GEOS 22060/ GEOS 32060 / ASTR 45900

What makes a planet (unin)habitable?

Runaway greenhouse, moist greenhouse

Lecture 11

Thursday 9 May 2019

Course outline

Foundations (1-2 weeks)

- Earth history
- HZ concept, atmospheric science essentials
- Post-Hadean Earth system

Principles – how are habitable planets initiated and sustained? (4-5 weeks)

- Volatile supply, volatile escape
- Inner edge and outer edge of the habitable zone
- Long-term climate evolution **TODAY**
- **Specifics (2.5 weeks)**
- Hyperthermals on Earth
- Early Mars
- Oceans within ice-covered moons
- Exoplanetary systems e.g. TRAPPIST-1 system

Earth science

planetary science

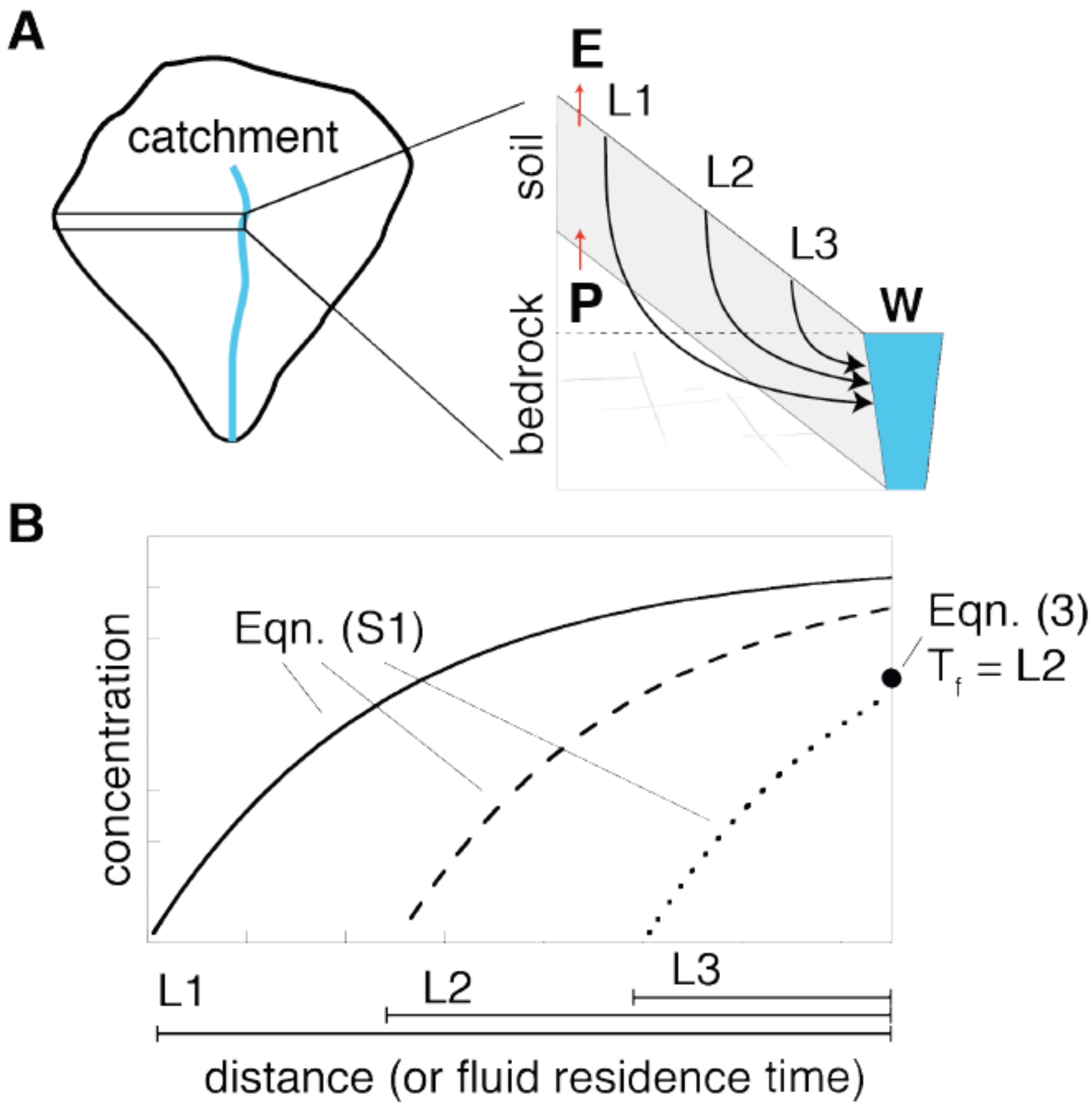
Logistics/Today

- Homework 3 is due tomorrow in my mailbox, 1st floor Hinds
- Homework 4 will be issued Saturday, due next Friday
- **Hinds 176**, 3:35p-4:30p, Tue May 14 for make-up lecture
- Presentation
- Earth-climate stabilization: looking under the hood of the carbonate-silicate feedback
  - The carbonate-silicate feedback hypothesis
  - Testing the hypothesis
  - Refining the hypothesis

What controls the weathering rate?

- **Water supply (to flush away dissolved products)**
- CO_2 concentration (acidity; thermodynamics)
- Temperature (→ kinetics)
- Reactive surface area (uplift/tectonics/erosion)

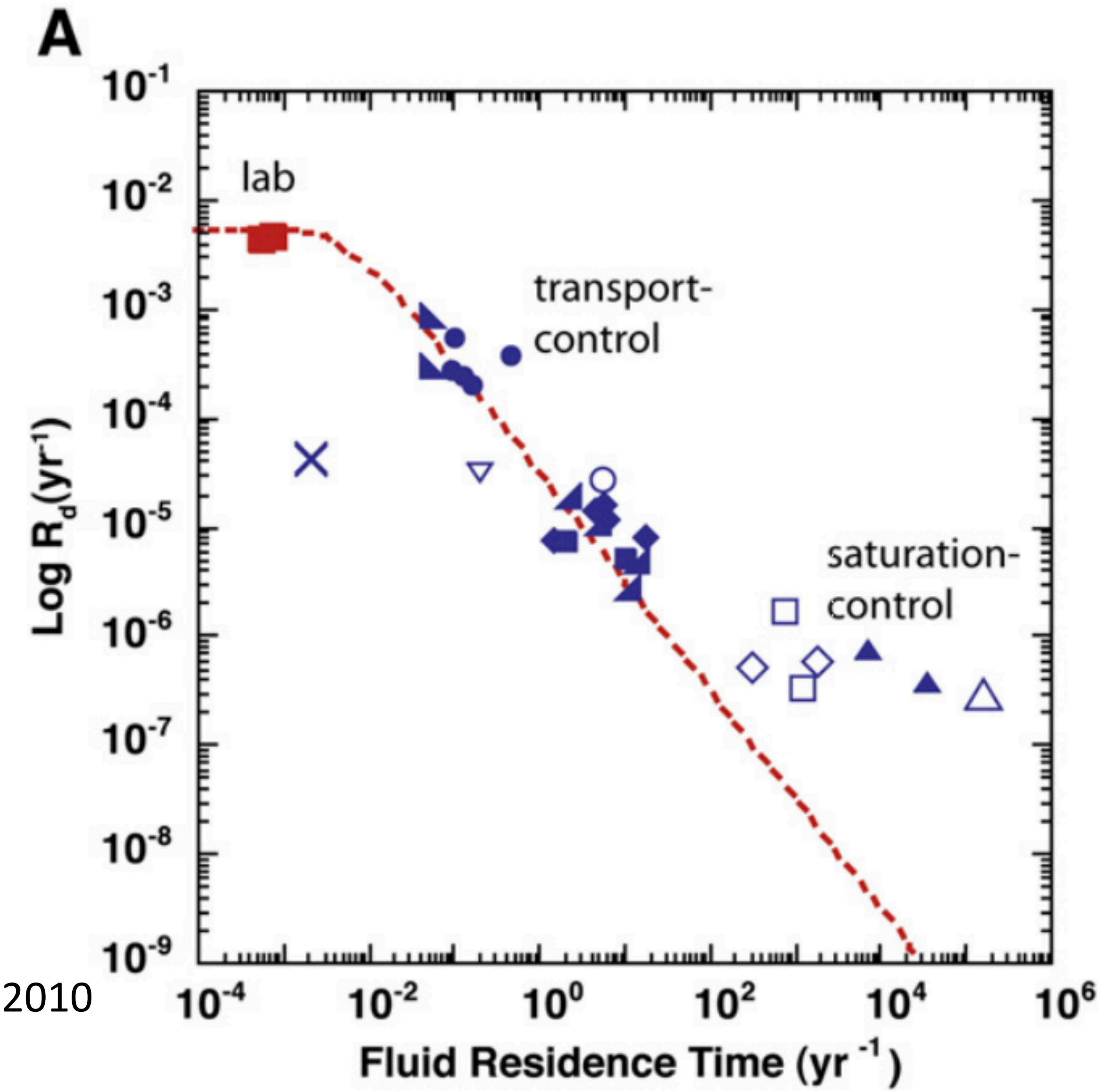
Refining the carbonate-silicate weathering feedback hypothesis: shift from direct T to indirect hydrologic control



The next part of today's lecture follows Maher & Chamberlain, "Hydrologic Regulation of Chemical Weathering and the Geologic Carbon Cycle," *Science*, 2014 (required reading)

What accounts for the lab-vs.-field discrepancy in weathering rates?
What is the role of flushing?

$$\frac{dc}{dz} = \frac{R_d}{q}\left(1 - \frac{c}{c_{eq}}\right)$$



Maher EPSL 2010

It takes time for the soil water to reach equilibrium with the soil.

$$c(x) = c_0 \exp\left(\frac{-R_n \phi x \tau}{q c_{eq}}\right) + c_{eq}\left(1 - \exp\left(\frac{-R_n \phi x \tau}{q c_{eq}}\right)\right)$$

τ is a constant (sic)

Advection-reaction equation (heterogenous, irreversible reactions)

$c\ [\mu mol/L]$ = concentration of a dissolving solute

$R_n\ [\mu mol/L/yr]$ = net dissolution rate (affected by availability of fresh minerals)

$q\ [m/yr]$ = flow rate

Damkohler number:

$$Da = \frac{R_n l \phi}{q c_{eq}} = \frac{t_f}{T_{eq}}$$

$$t_f = l\phi/q\ [yr]$$

$$T_{eq} = c_{eq}/R_n\ [yr]$$

Da → 0, c(x) → 0

Da → infinity, c(x) → c_eq

$$c(t_f) = c_0 \exp\left(\frac{-t_f \tau}{T_{eq}}\right) + c_{eq}\left(1 - \exp\left(\frac{-t_f \tau}{T_{eq}}\right)\right)$$

Need to integrate over the hillslope (with different travel times)

Damkohler number
(widely used)

"Damkohler Coefficient"
(used only by Maher & Chamberlin 2014)

$$Da = \frac{R_n l \phi}{q c_{eq}} = \frac{t_f}{T_{eq}} \xrightarrow{\text{multiply by } q} Dw[m/yr] = \frac{L\phi}{T_{eq}}$$

$$C = \frac{C_0}{1 + \tau Dw/q} + C_{eq} \frac{\tau Dw/q}{1 + \tau Dw/q}$$

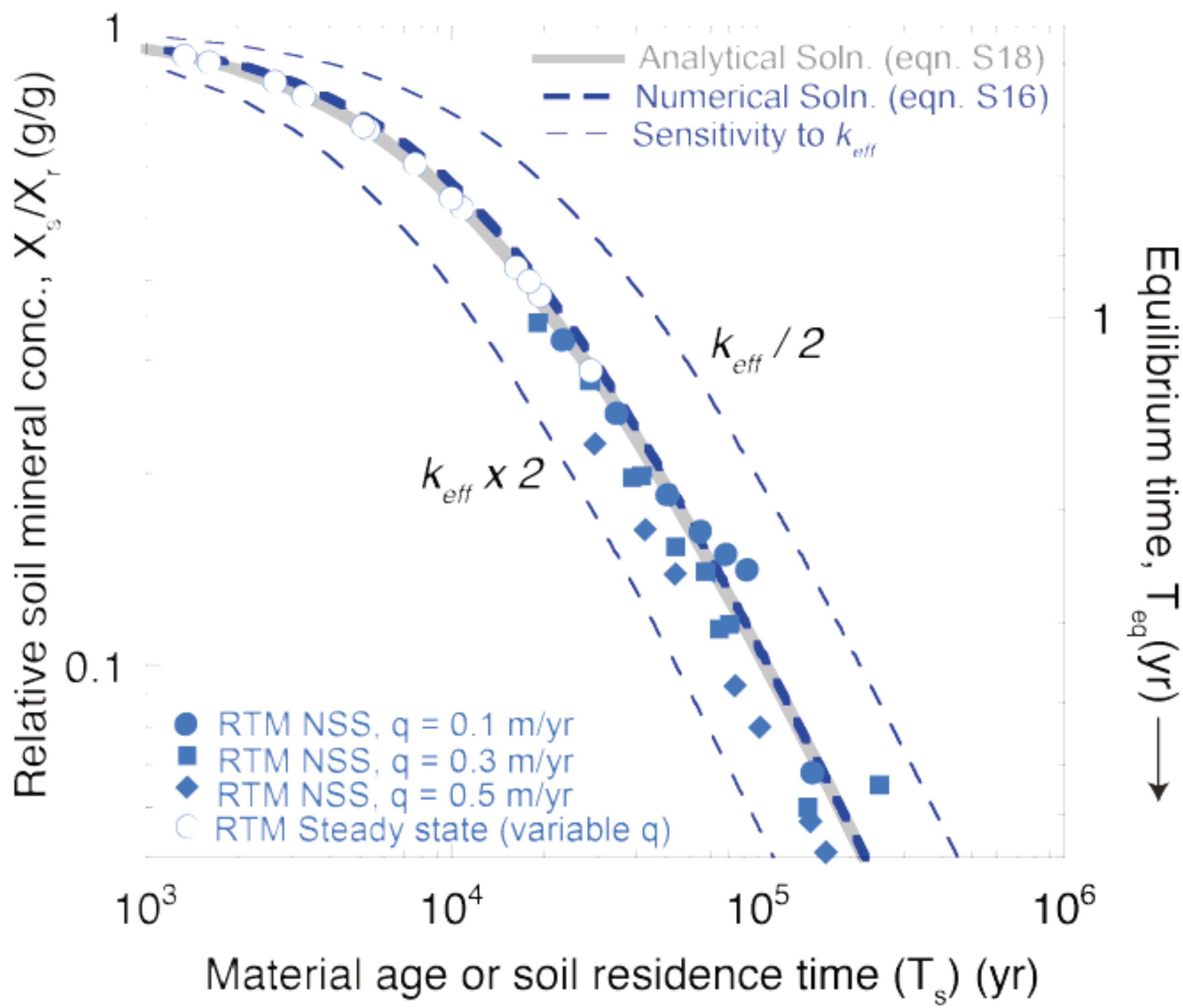
integration over an exponential distribution of travel times not shown (see Maher & Chamberlin 2014, supplementary equations S6-S8)

Main controls on solute flux: travel-time of fluid and <u>age of soil</u>

young soil, more reactive

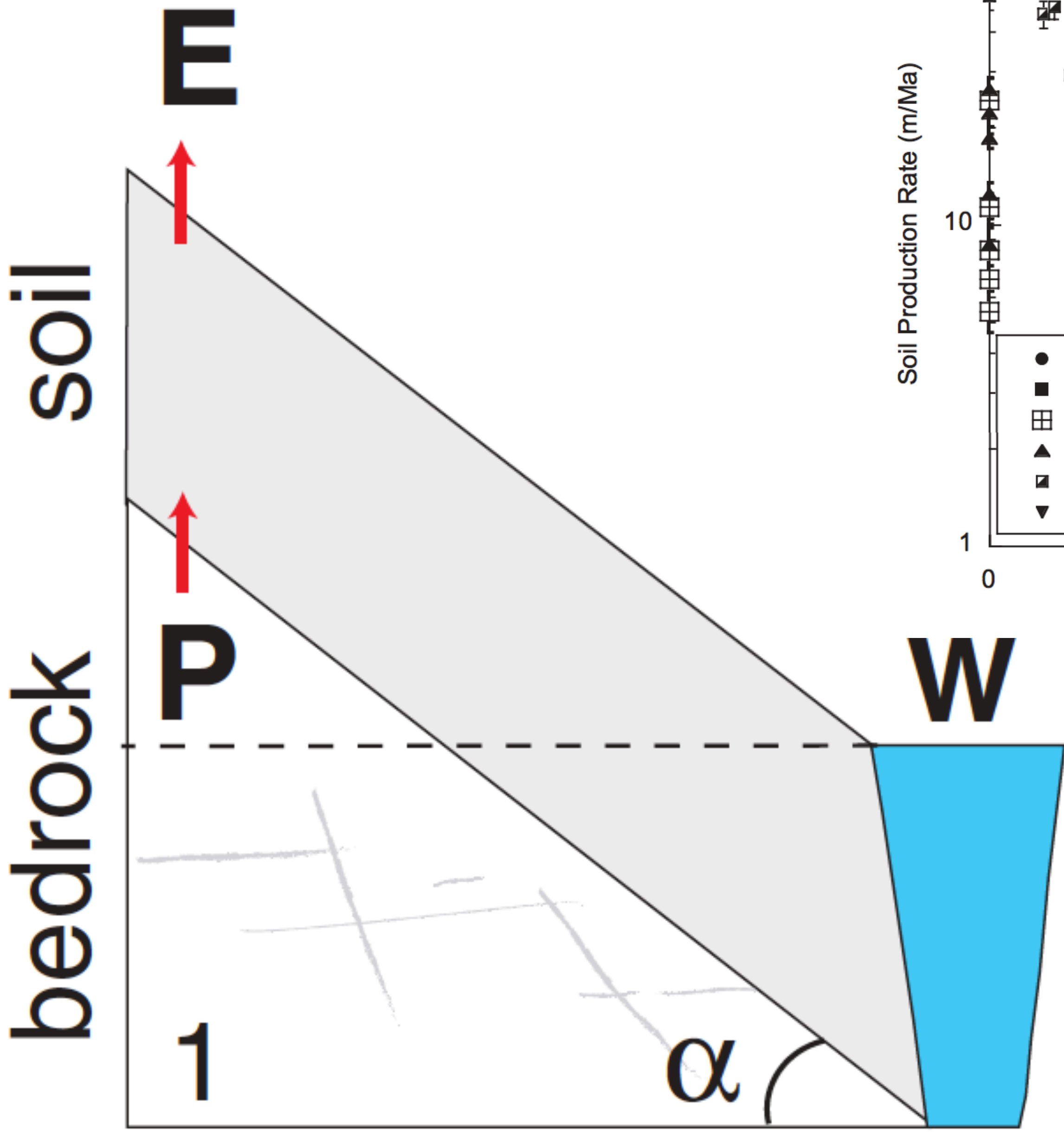
old soil, less reactive

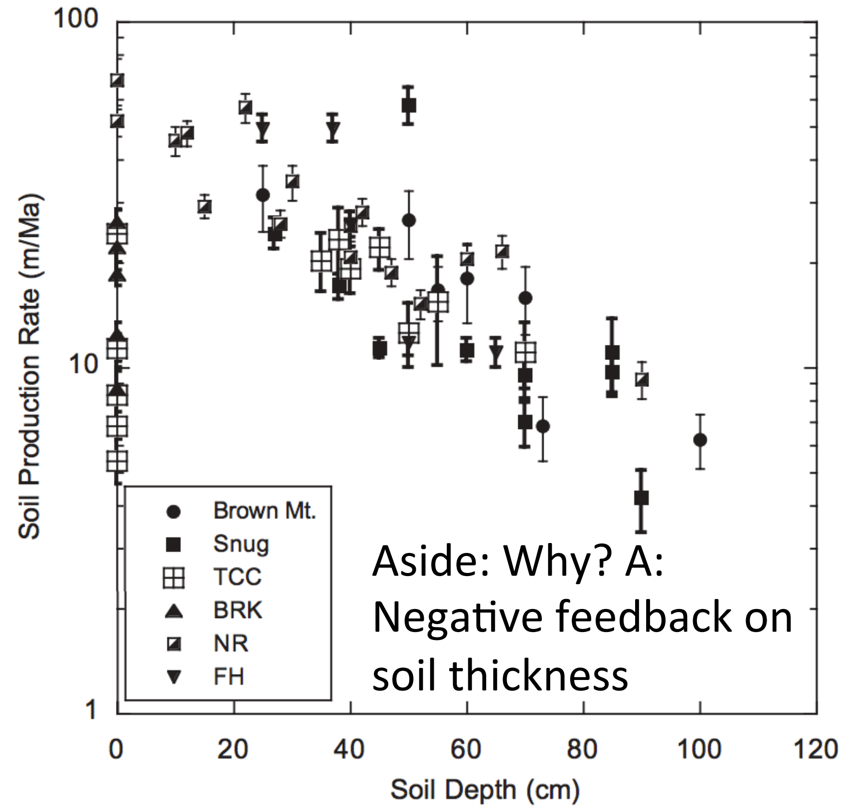
Symbols: output from a reaction-transport model
Curves: analytic fit



Soil **P**roduction rate approximately balances

Erosion rate (and, less precisely, rock uplift rate)



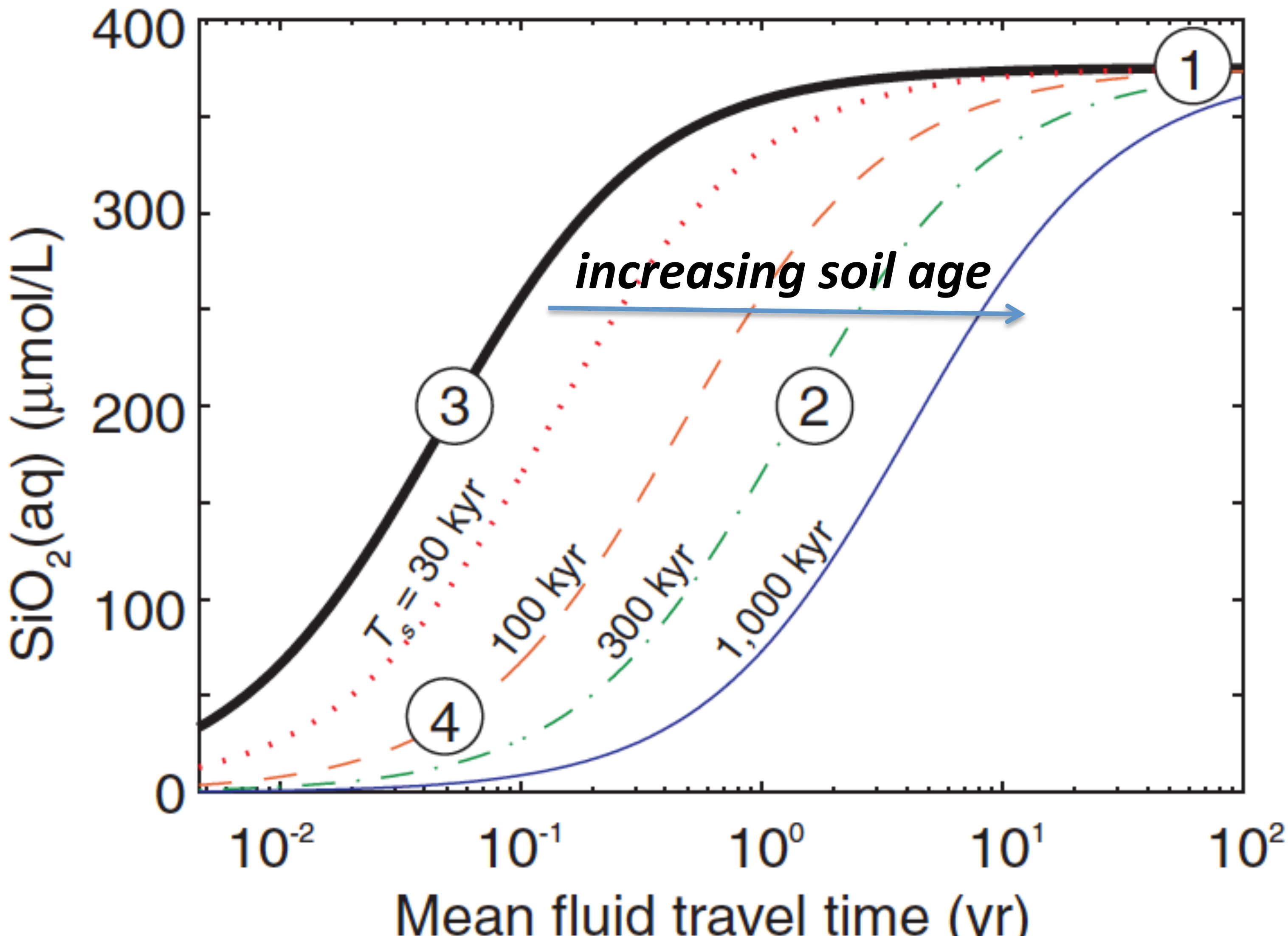


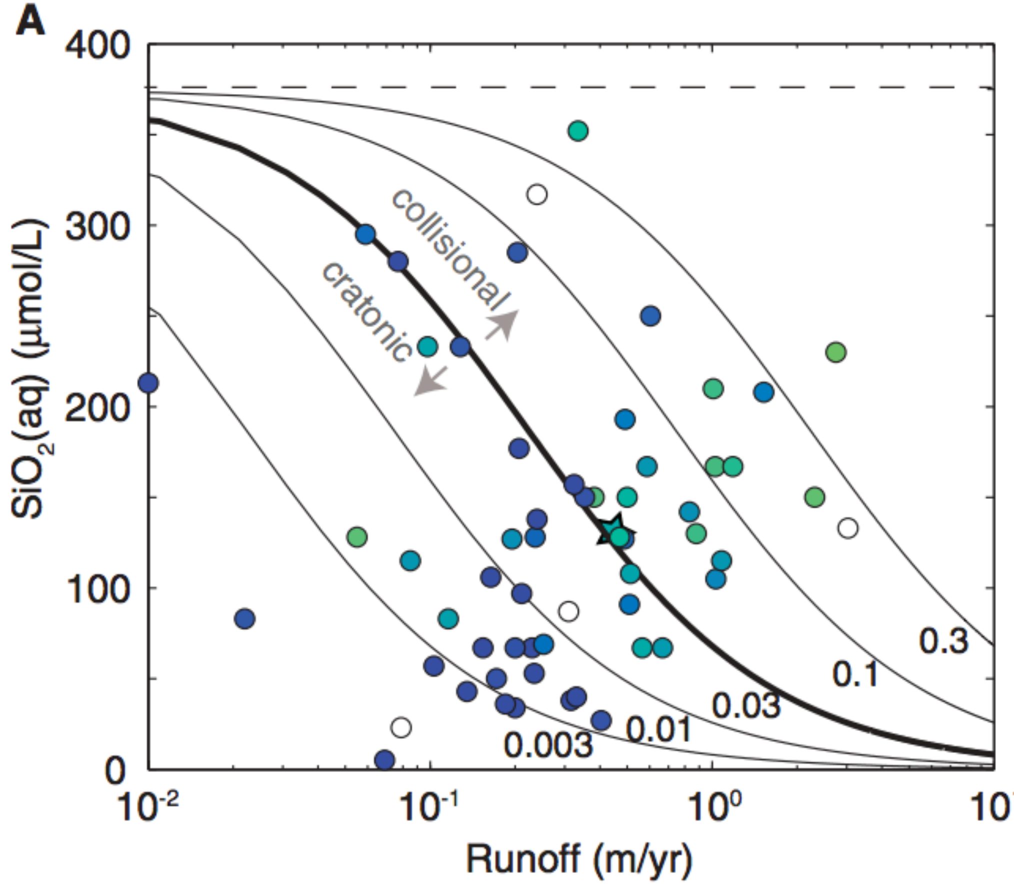
Aside: Why? A: Negative feedback on soil thickness

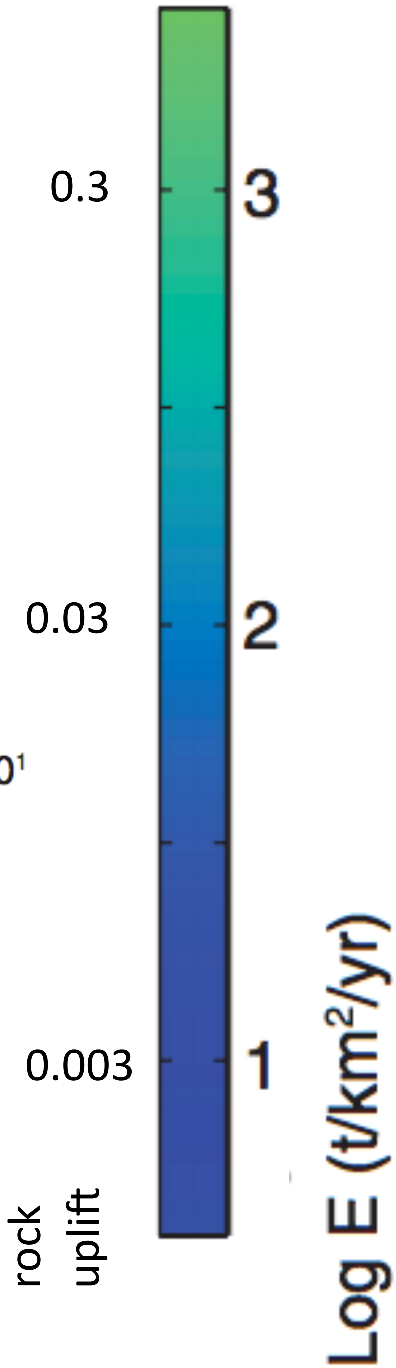
Heimsath et al.,
Earth Surf. Proc. & Landf.
2009

Mountain soil thicknesses are usually <~O(1) m

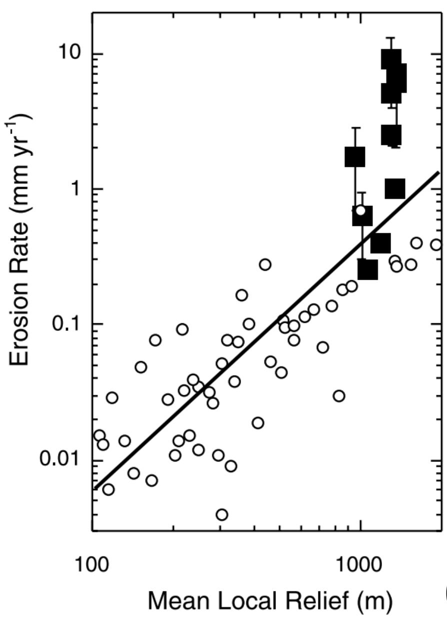
$$Dw(\mathrm{m/year}) = \frac{L\phi}{T_{\mathrm{eq}}} = \frac{L\phi R_{n,\max} f_{\mathrm{w}}}{C_{\mathrm{eq}}}$$







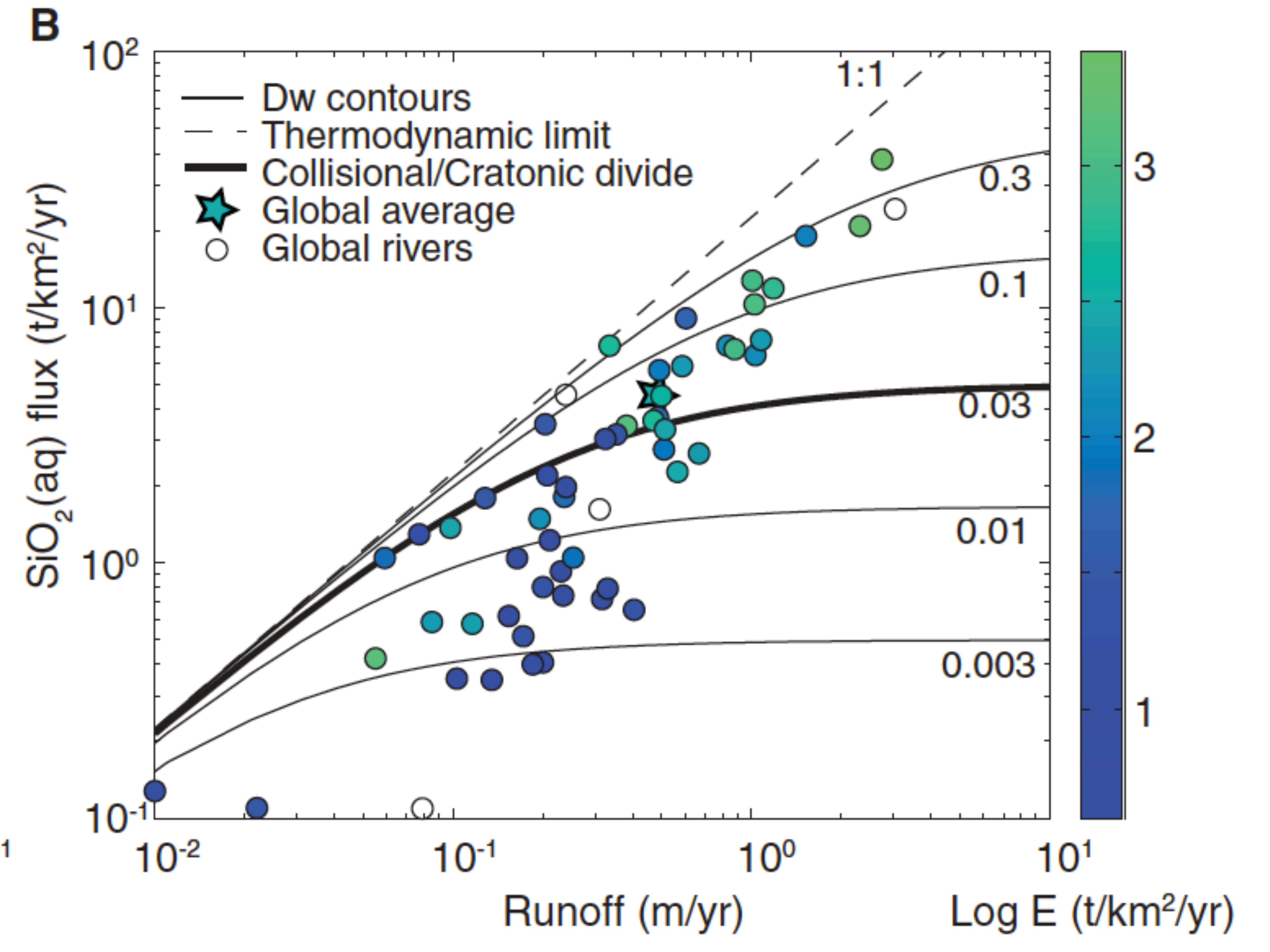
Note: effect of orographic precipitation



(local relief: 10 km window)

Montgomery & Brandon

EPSL 2002: negative feedback on mountain height



B
Dw contours
Thermodynamic limit
Collisional/Cratonic divide
Global average
Global rivers
1:1
0.3
0.1
0.03
0.01
0.003
SiO_2(aq) flux (t/km^2/yr)
Runoff (m/yr)
Log E (t/km^2/yr)
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
1
2
3

Where's the direct effect of temperature? A: It's small.

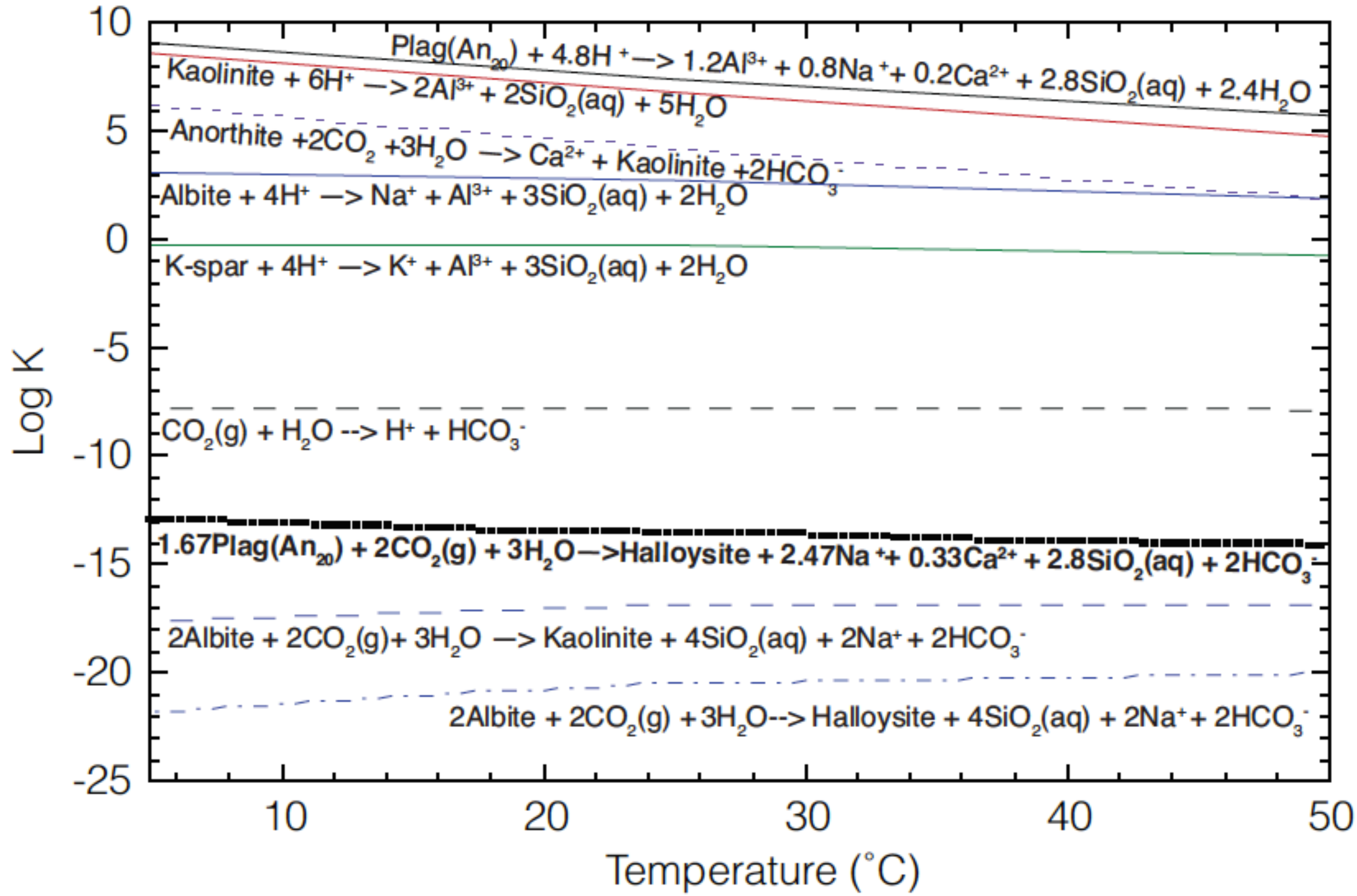
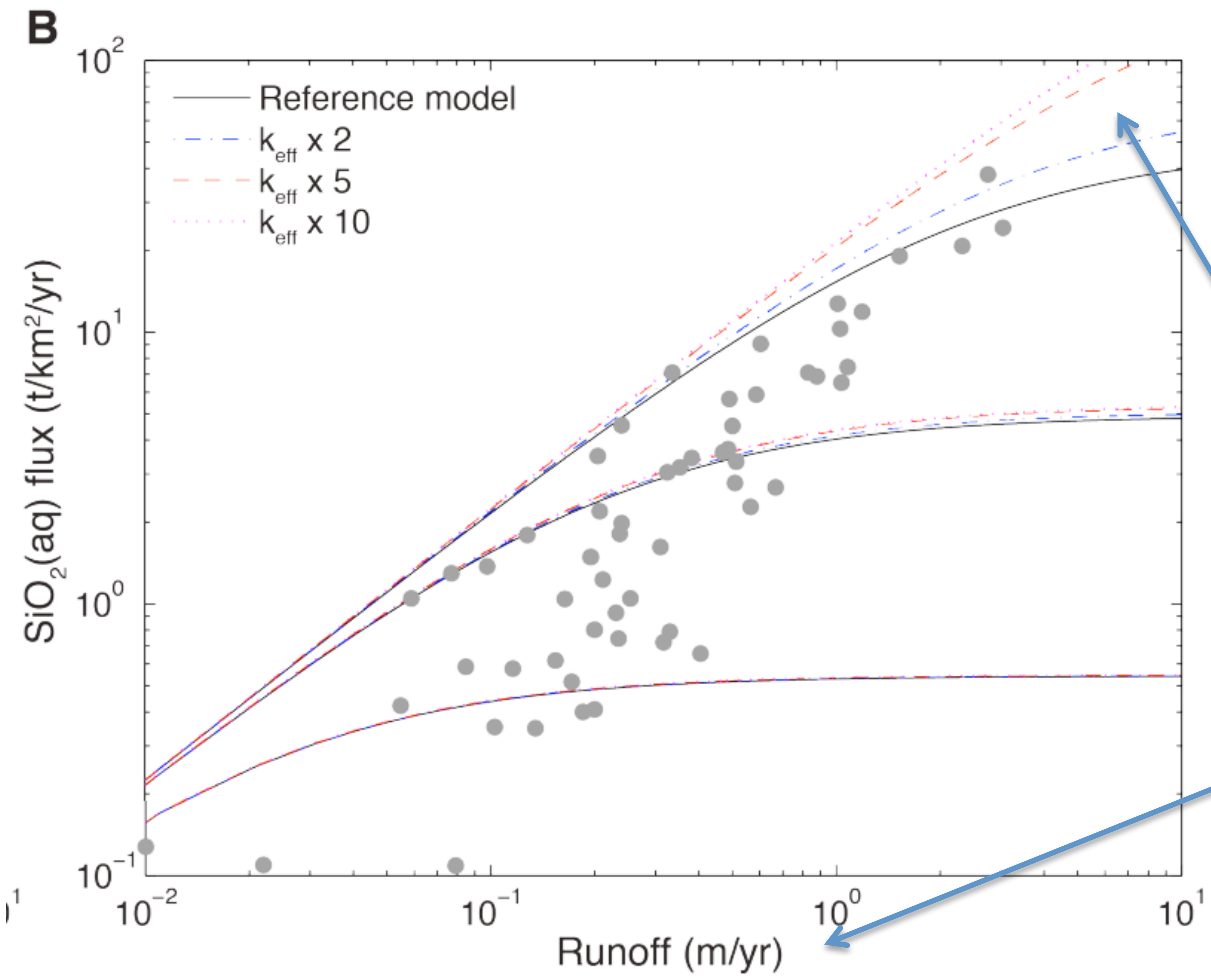


Fig. S7: Temperature sensitivity of weathering reactions. The primary mineral dissolution reactions and CO_2 dissociation reactions are show in solid lines, while the net reactions are shown in light stippled lines. The starred reaction in bold represents a simplified version of the one of the net reaction considered in the RTM simulation. Thermodynamic data is from ref. (*92*).

Where's the effect of temperature?

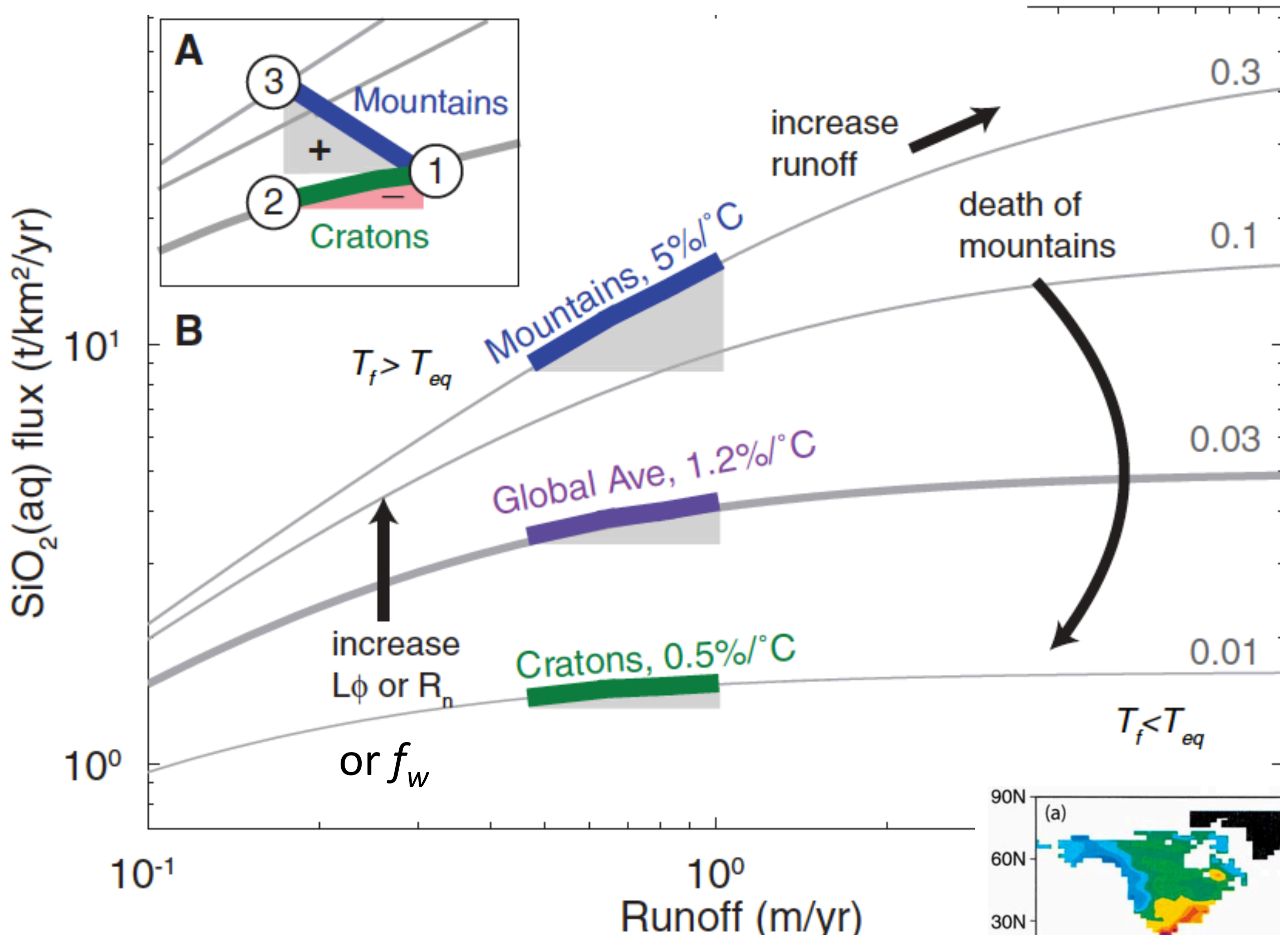


Direct effect of *T* is small; strong indirect hydrologic effect.

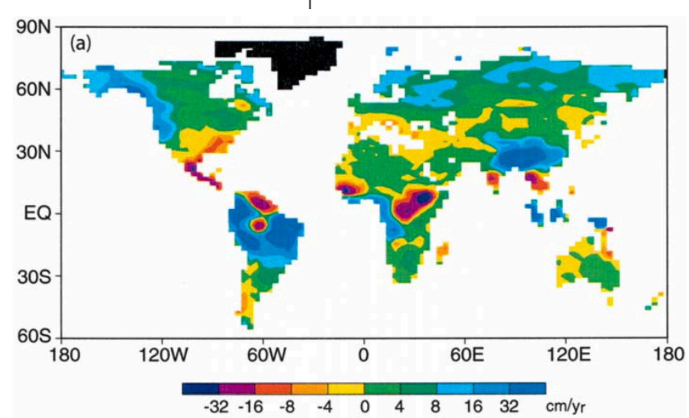
(black lines). **(B)** Increases in k_{eff} by a factor of 2, 5 and 10 (see legend) corresponding to temperature increases of 15 to 30°C and 15 to 40°C and 15 to 75°C, respectively. Because k_{eff} appears in both the R_n term and the f_w term (*i.e.*, in the numerator and the denominator of *Dw*) the effects of temperature are minimal at small *Dw*, but increase with increasing *Dw* as the numerator becomes larger. **(C)** and **(D)** Sensitivity analysis is shown in

$$Dw(\mathrm{m/year}) = \frac{L\phi}{T_{eq}} = \frac{L\phi R_{n,\max} f_w}{C_{eq}}$$

f_w = fraction of fresh minerals



Manabe et al.
Climatic Change
2004



runoff change (cm/yr)

Maher & Chamberlain Science 2014:

Earth's thermostat is mediated by wetting of mountain belts in response to global warming

Mountain belts also *release* CO_2 (via metamorphic decarbonation and by oxidation of C in uplifted shale, coal)

Colorado Front Range organic-rich shale

Figure 3. Photo of effervescing CO_2-rich spring along the Marsyandi River (sample MLB-51). $T_{fluid} = 55°C$, $\delta^{13}C_{DIC} = +11.6‰$, $P_{CO2} > 1$ bar. The spring is surrounded by extensive travertine ($CaCO_3$) deposits.

Evans et al., G^3, 2008

Bickle, Terra Nova, 1996

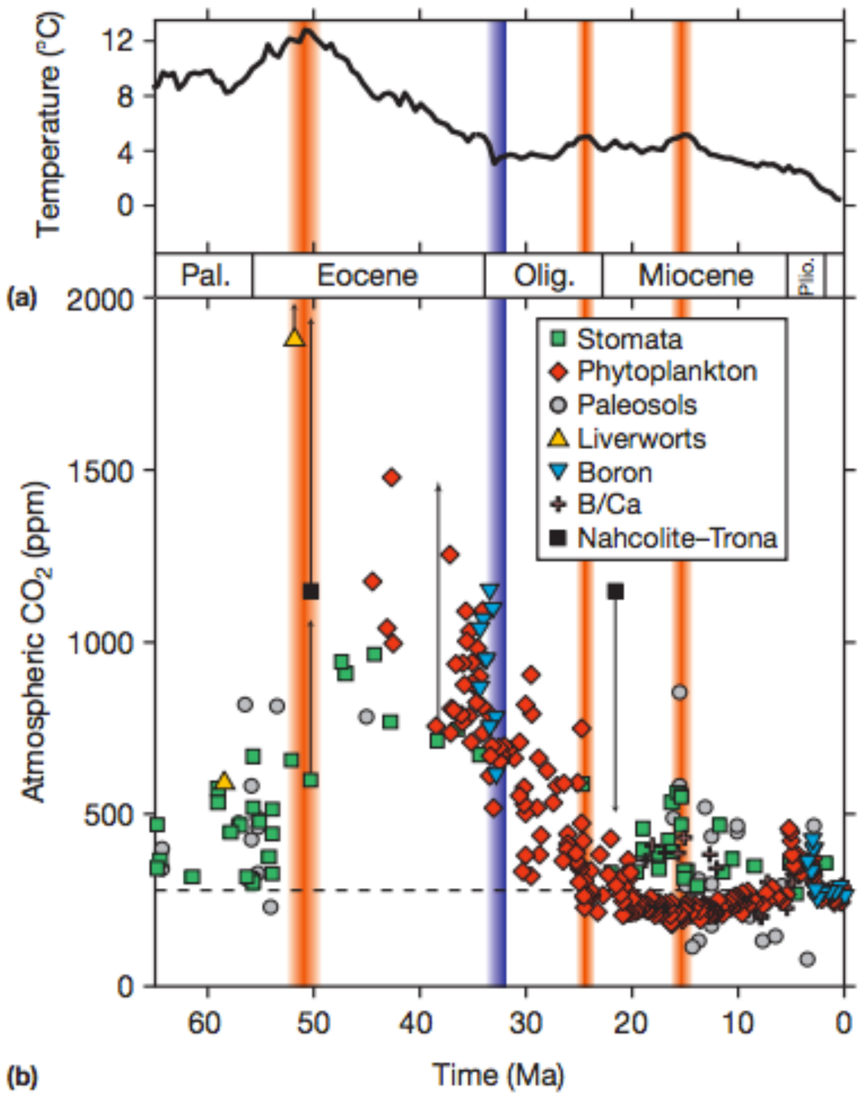
Tests for the carbonate-silicate weathering feedback hypothesis:

- Seek present-day gradients weathering corresponding to present-day gradients in temperature between watersheds.
- Seek evidence for weathering increases during geologically-sudden warm events.
- (Because of the Faint Young Sun) look for evidence of higher pCO2 in the distant geologic past.

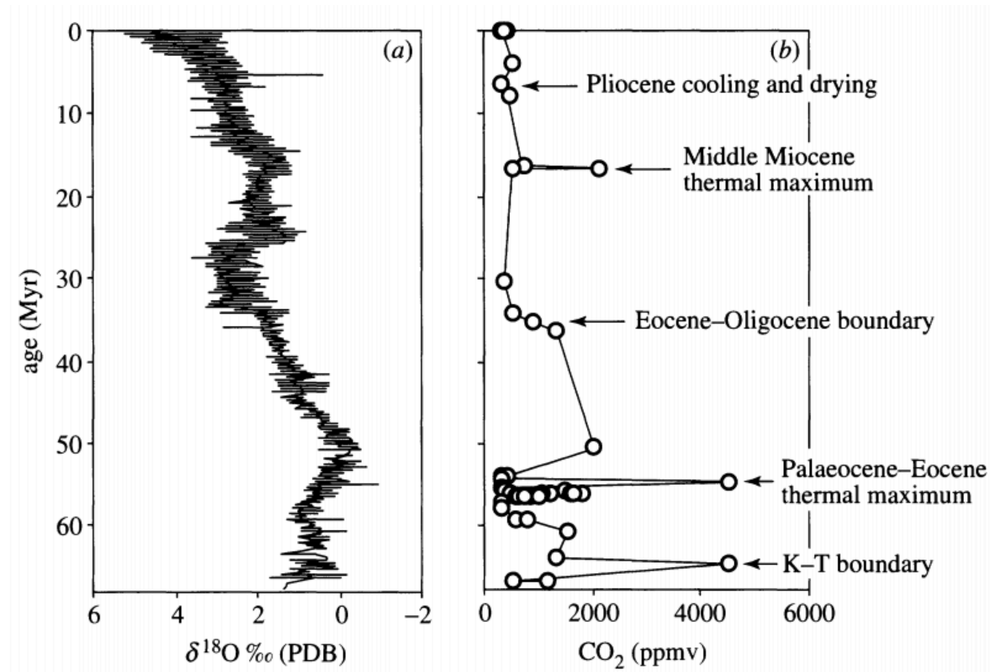
Q: When CO_2 goes up, does temperature go up?

A: Sudden rises in CO_2 are accompanied by temperature rises;
longer-term changes in temperature may have other controls, e.g. albedo.

Multiproxy



Stomatal indices



Retallack, Phil. Trans., 2002

Before 1 Mya, temperature records are more reliable than pCO_2 records.

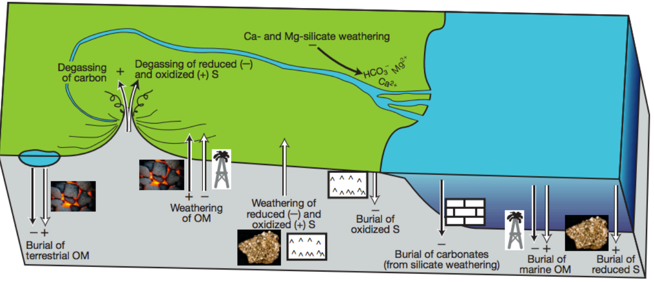


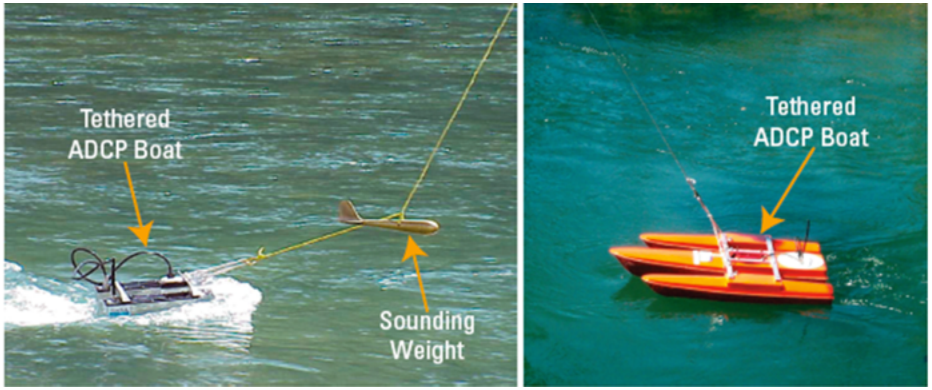
Figure 1 Major processes that control the long-term evolution of atmospheric CO_2 (black arrows) and O_2 (white arrows). Arrows linked to plus signs (+) cause an increase in the gas concentration, while those with minus signs (−) cause a decrease.

River input

- Composition of upper continental crust (UCC) ~ composition of shales ~ composition of river sediments.

- [Seawater] >> [UCC]: S, Cl, F, B, Mg, Na, K
- [Seawater] << [UCC]: Pb, Al, Si, Fe

How river input (discharge x concentration) is measured



Acoustic Doppler profiling (discharge)

Stream gages (discharge)

Sampling for chemistry (concentrations)

Concentration-discharge relationships show dilution trend at large discharge

This trend is also observed for the seasonal cycle of runoff in individual rivers. Therefore, constructing an annual-average budget requires many concentration measurements.

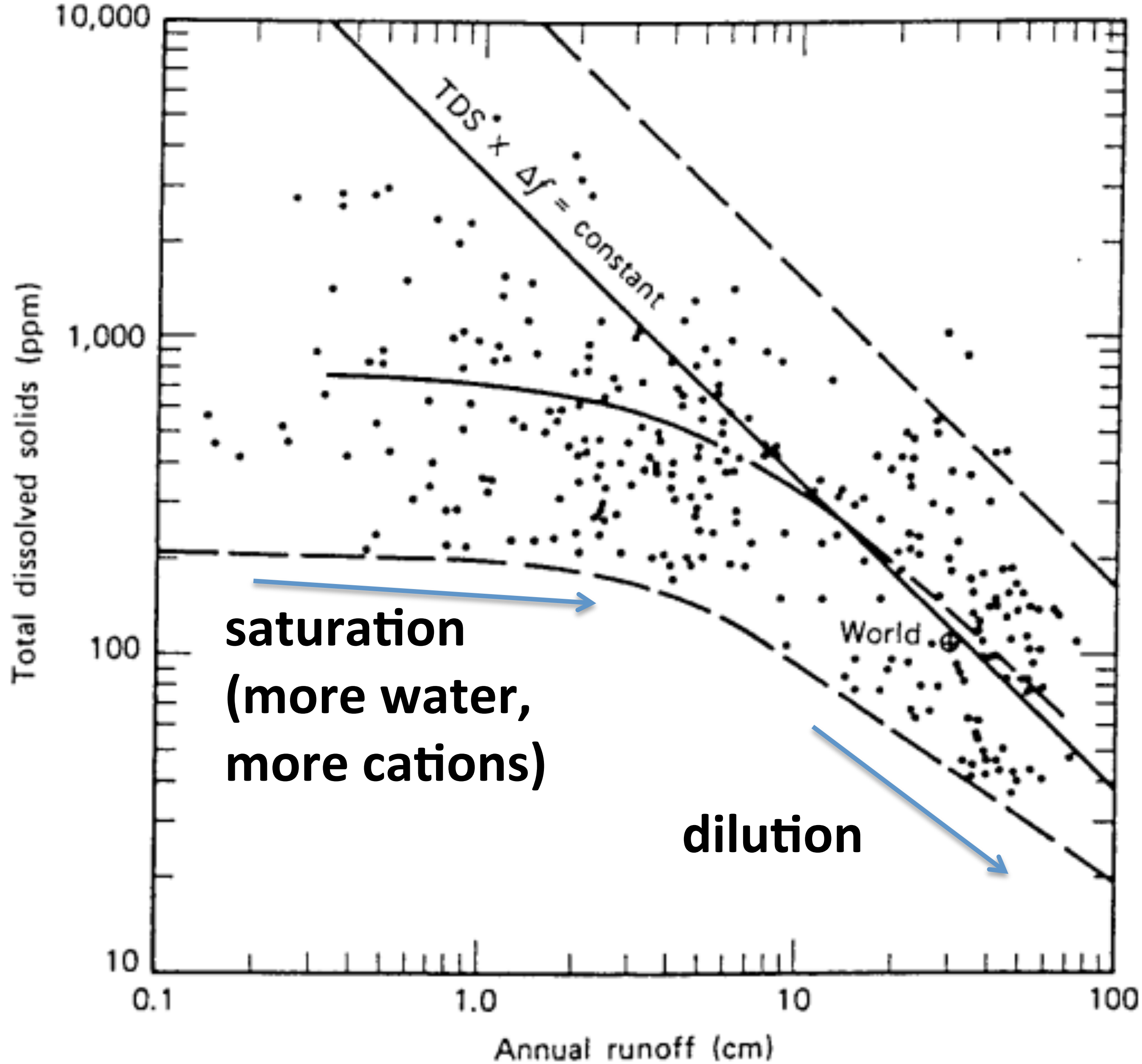
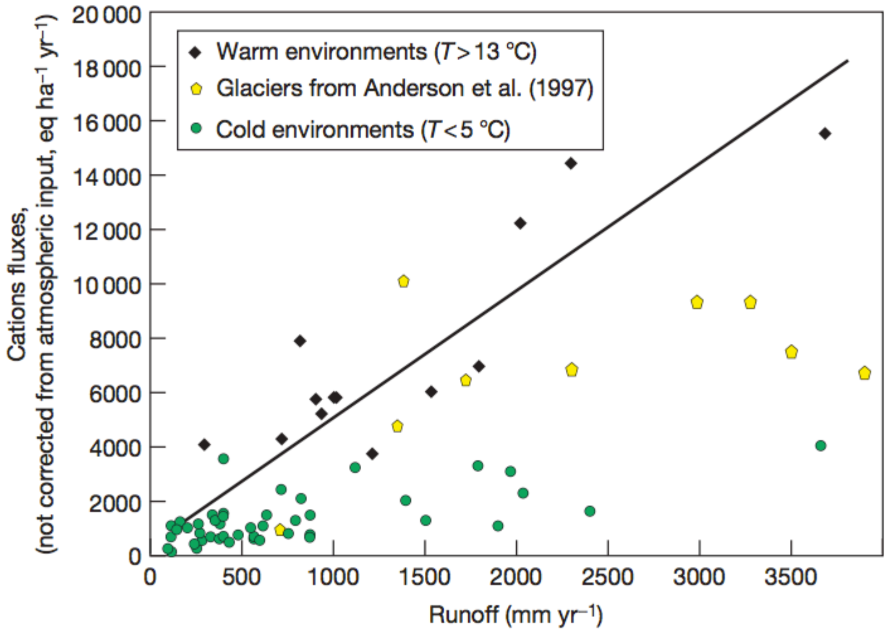


Figure 6 Holland's (1978) plot of total dissolved solids vs. runoff for the world's rivers. Solid curve shows general trend; solid line shows dilution trend.

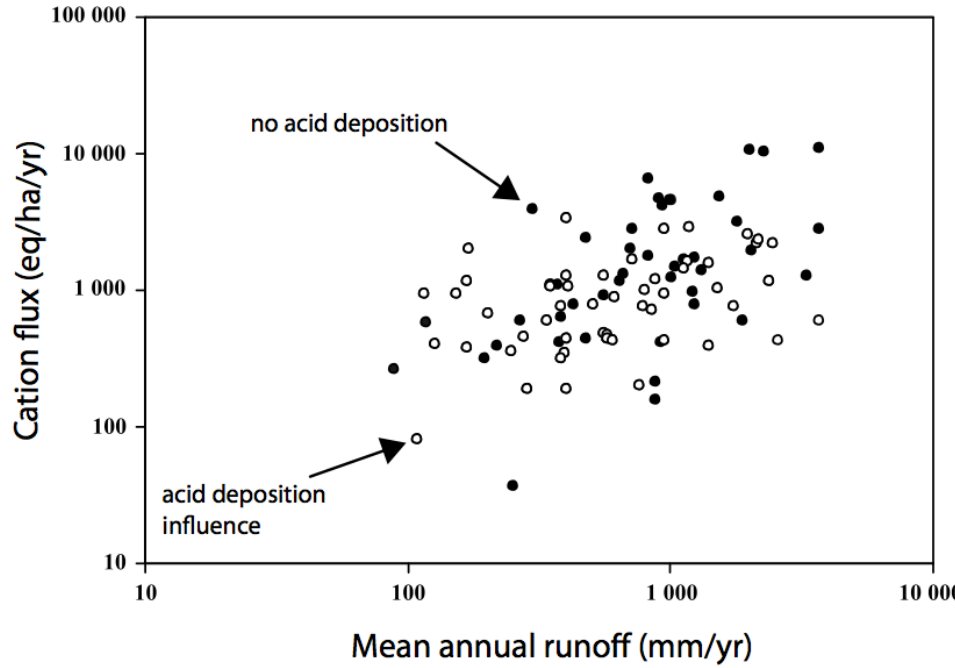
Some support for T and runoff control on weathering, but much scatter

$$F_{CO_2} = k \cdot Run \cdot \exp\left(\frac{-E_a}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_0}\right)\right)$$

Data: 99 small granitic catchments

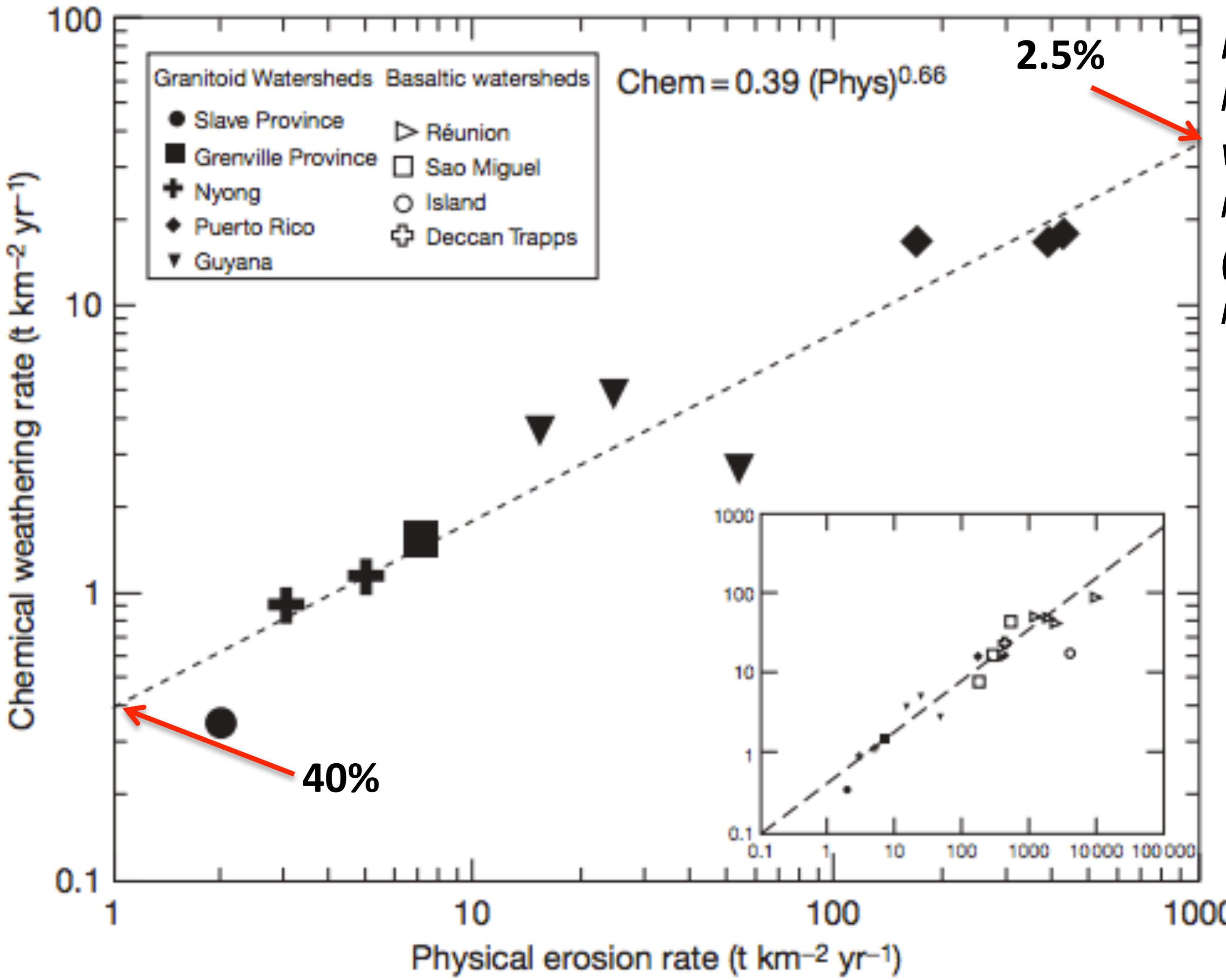


Oliva et al. 2003



Godderis et al. Rev. Min. Geochem. 2009

Kinetically-limited watersheds vs. supply-limited watersheds



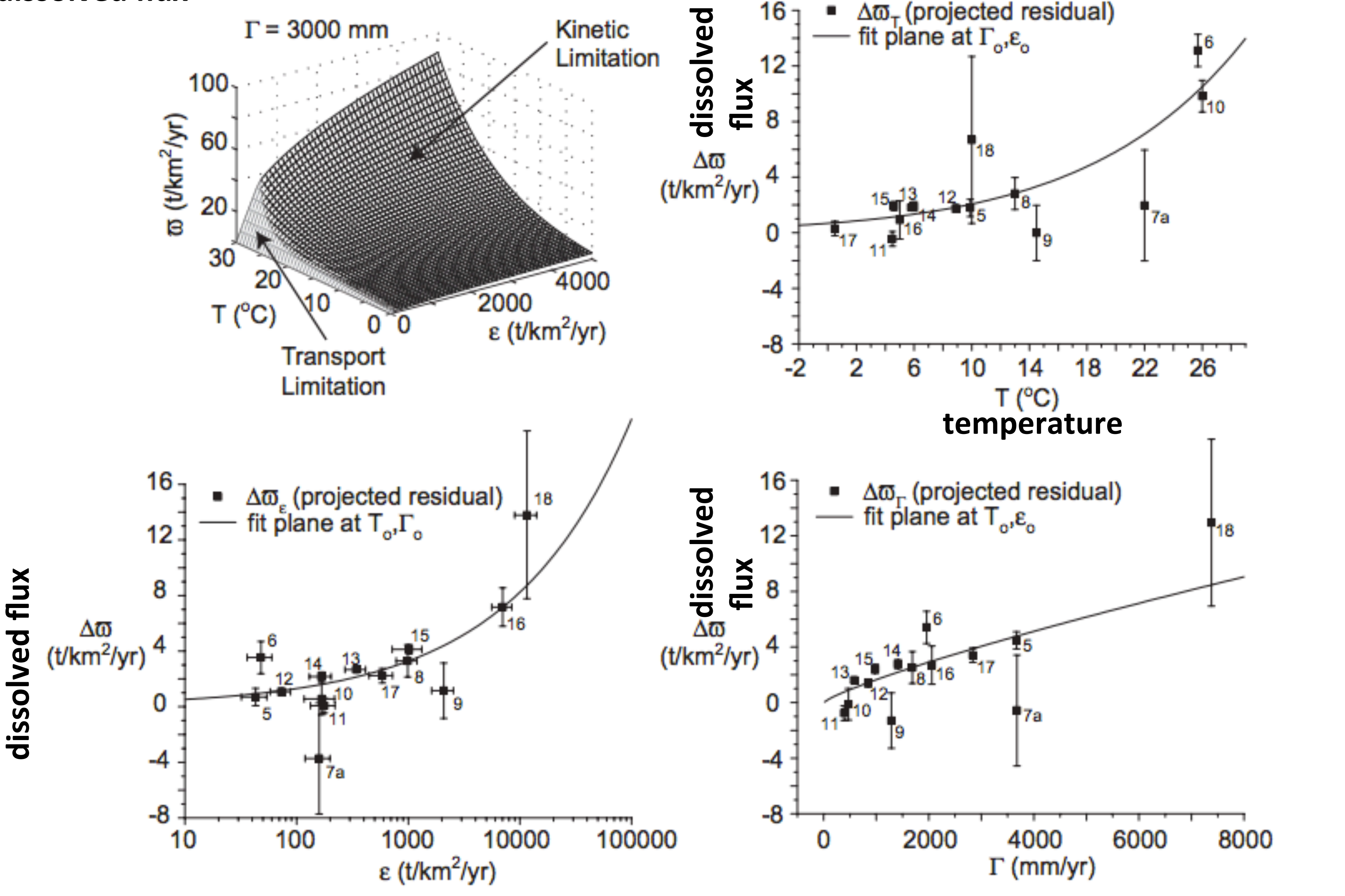
Kinetically-limited, low weathering intensity (steep mountains)

Earth's ability to recover from a hyper-thermal resides in the mountains

Transport-limited, High weathering intensity (plains)

"supply" limited

Putting it all together: combined effect of rainfall, temperature, and erosion rate on dissolved flux



West et al. 2005 EPSL

Testing the carbonate-silicate weathering feedback using present-day temperature gradients: Rivers and streams in Antarctica

Nezat et al. GSA Bulletin 2001

TABLE 1. LENGTHS, DISCHARGES, AND CALCULATED H_4SiO_4 AND HCO_3^- DENUDATION RATES FOR TAYLOR VALLEY STREAMS

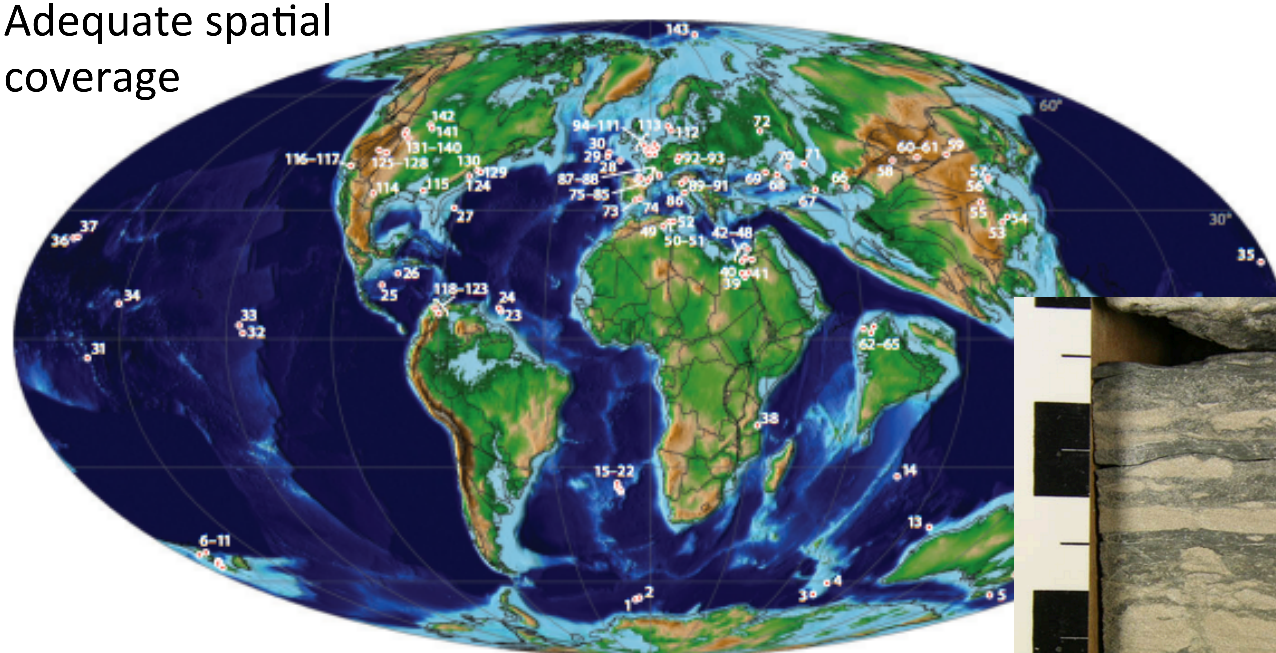
	Length* (km)	(1994–1995) Discharge (m^3)	(1994–1995) H_4SiO_4 (μM)	(1994–1995) H_4SiO_4 denudation† 4 m stream width (10^3 mol·km^{-2}·yr^{-1})	(1994–1995) H_4SiO_4 denudation† 24 m stream width (10^3 mol·km^{-2}·yr^{-1})	(1995–1996) Discharge (m^3)	(1995–1996) H_4SiO_4 (μM)	(1995–1996) H_4SiO_4 denudation† (10^3 mol·km^{-2}·yr^{-1})	(1995–1996) HCO_3^- (mM)	(1995–1996) HCO_3^- denudation (10^3 mol·km^{-2}·yr^{-1})
Fryxell Basin										
Canada Stream	1.5	41 710	27.8	146	24	75 350	30.6	298	0.20	2520
Lost Seal Stream	2.2	20 630	46.5	93	16	56 480	34.0	175	0.49	3140

TABLE 2. CHEMICAL DENUDATION RATES CALCULATED FROM STREAM H_4SiO_4 AND HCO_3^- FLUXES

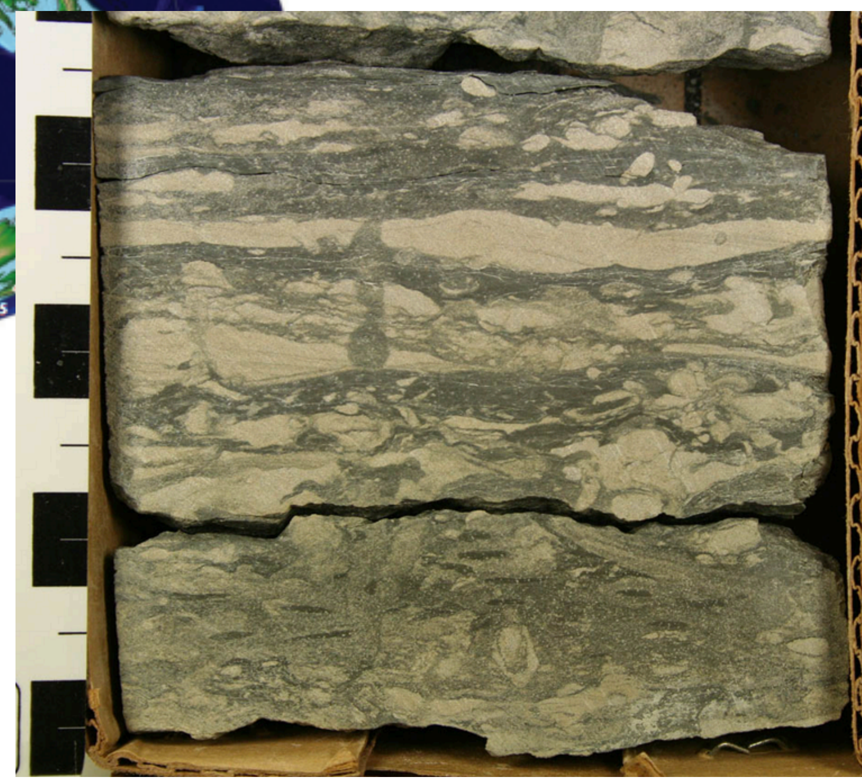
River	H_4SiO_4 (10^3 mol·km^{-2}·yr^{-1})	HCO_3^- (10^3 mol·km^{-2}·yr^{-1})	Source
World average	64	300	Hu et al. (1982)
Tisa (Eastern Europe)*	90	640	Lyons et al. (1992)
Mekong (Southeast Asia)†	100	680	Hu et al. (1982)
Amazon (South America)§	130	300	Hu et al. (1982)
Cahaba (Alabama, USA)*	55	736	Lyons et al. (1998)
Alabama (Alabama, USA)	51	No data	Lyons et al. (1998)

Paleocene-Eocene Thermal Maximum
A hyperthermal 55 Mya

Adequate spatial coverage

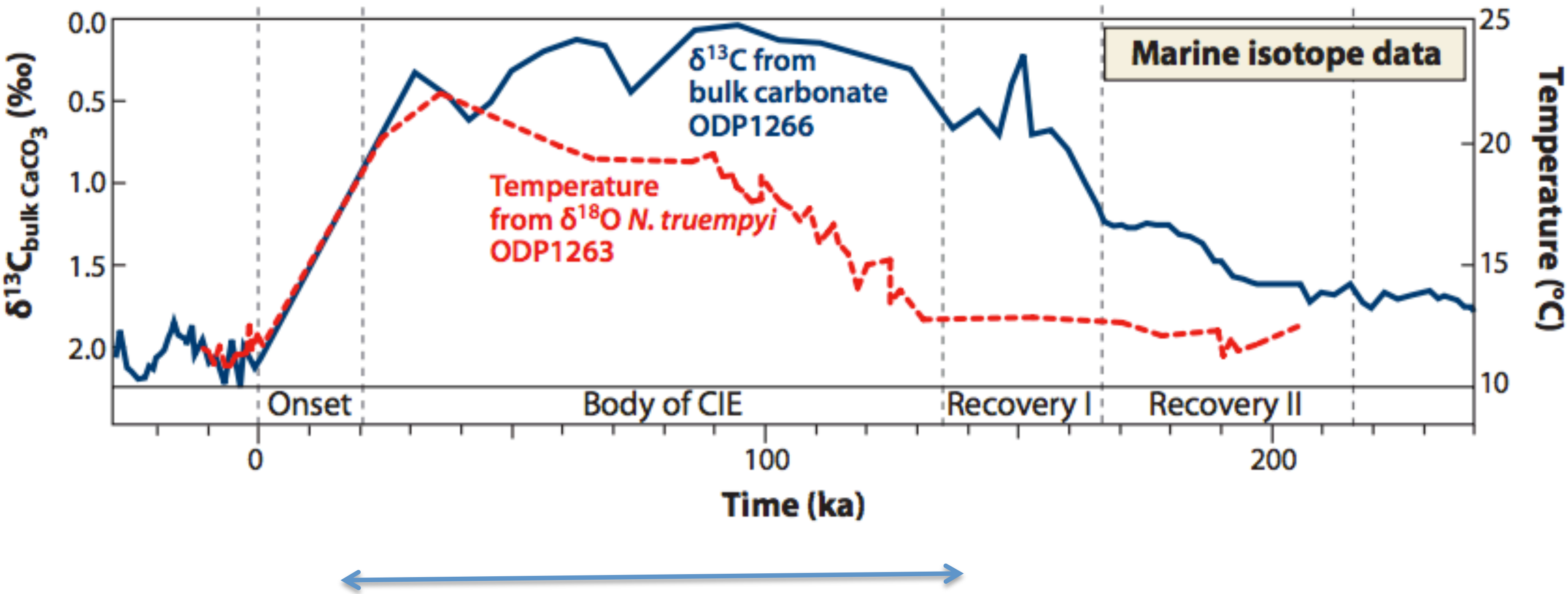


Time resolution limited to > 1 Kyr by bioturbation



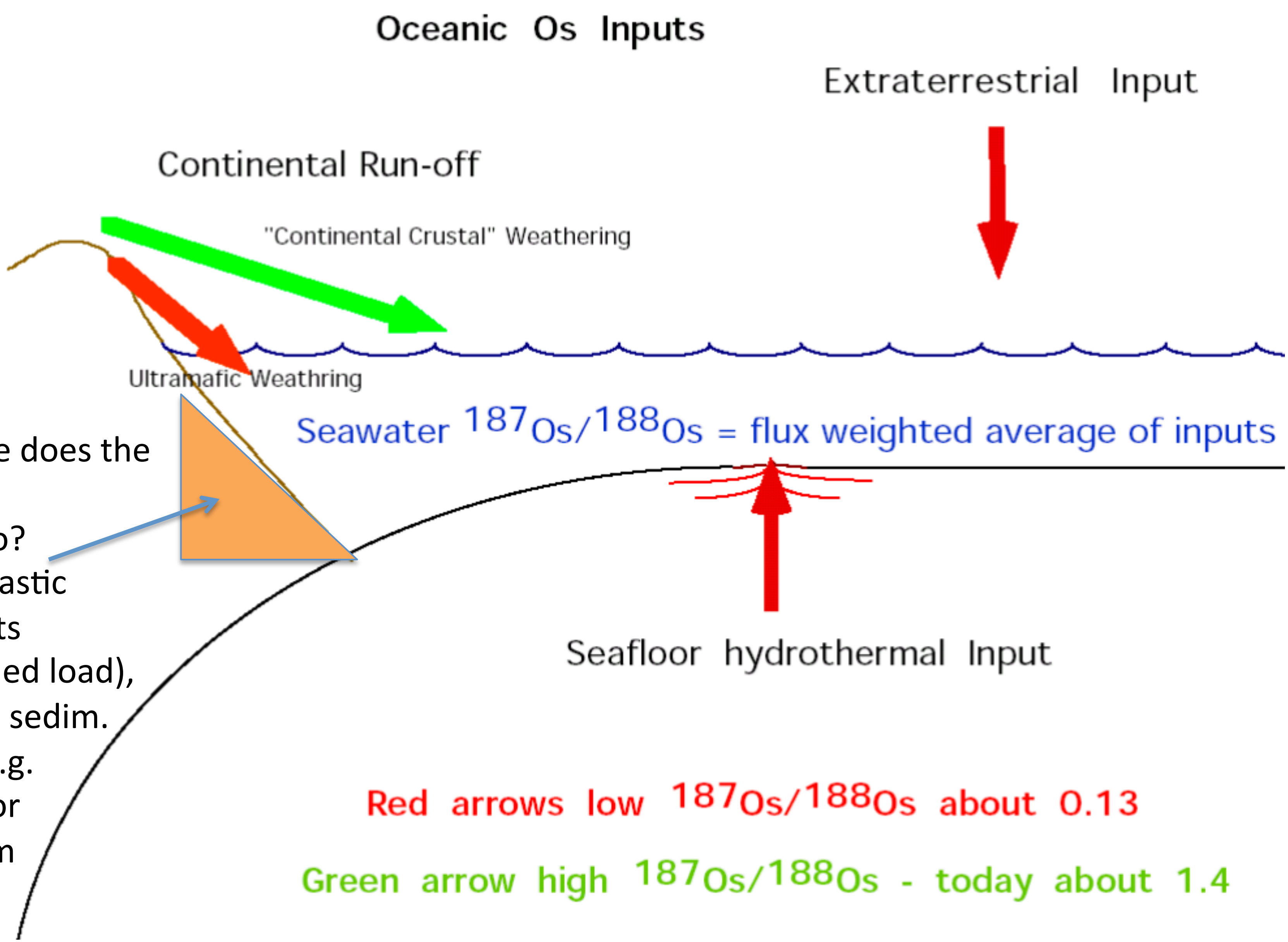
Though brief relative to the ~100 Kyr timescale of the weathering feedback, the CO_2 release that triggered the PETM was much more prolonged than anthropogenic CO_2 release.

Sustained temperature rise:
expect – increased weathering; intensified hydrologic cycle; CO_2 drawdown on ~100 Kyr timescale



Time interval estimated using cyclostratigraphy and helium-3 accumulation

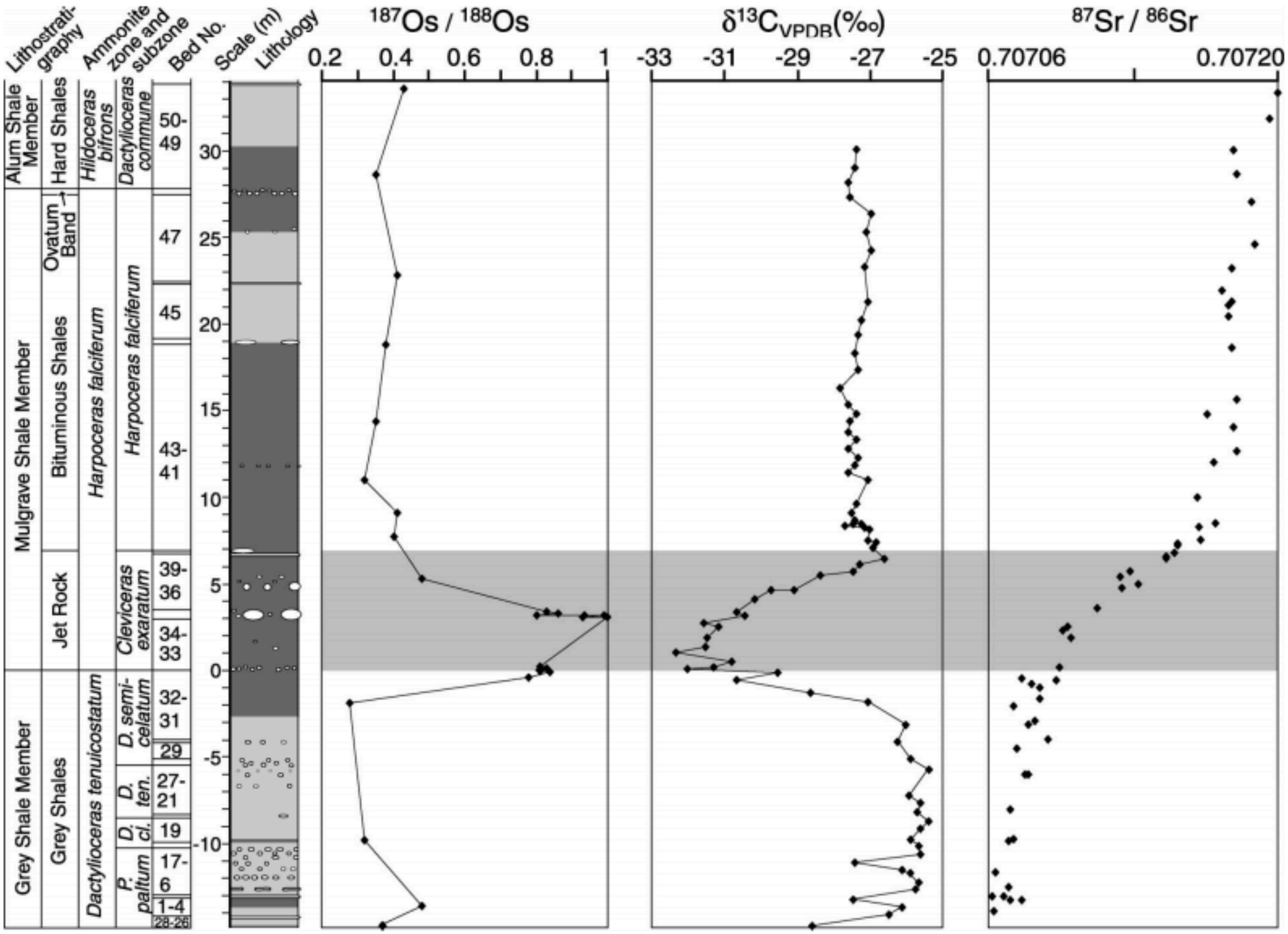
Osmium-isotope systematics



Q: Where does the "rest" of the Os go?
A: into clastic sediments (suspended load), and then sedim. basins (e.g. deltas) for long-term storage

Example of Os-isotope response to a hyperthermal (0.18 Ga, non-PETM)

Cohen et al. Geology 2004, "Osmium isotope evidence for the regulation of atmospheric CO_2 by continental weathering."



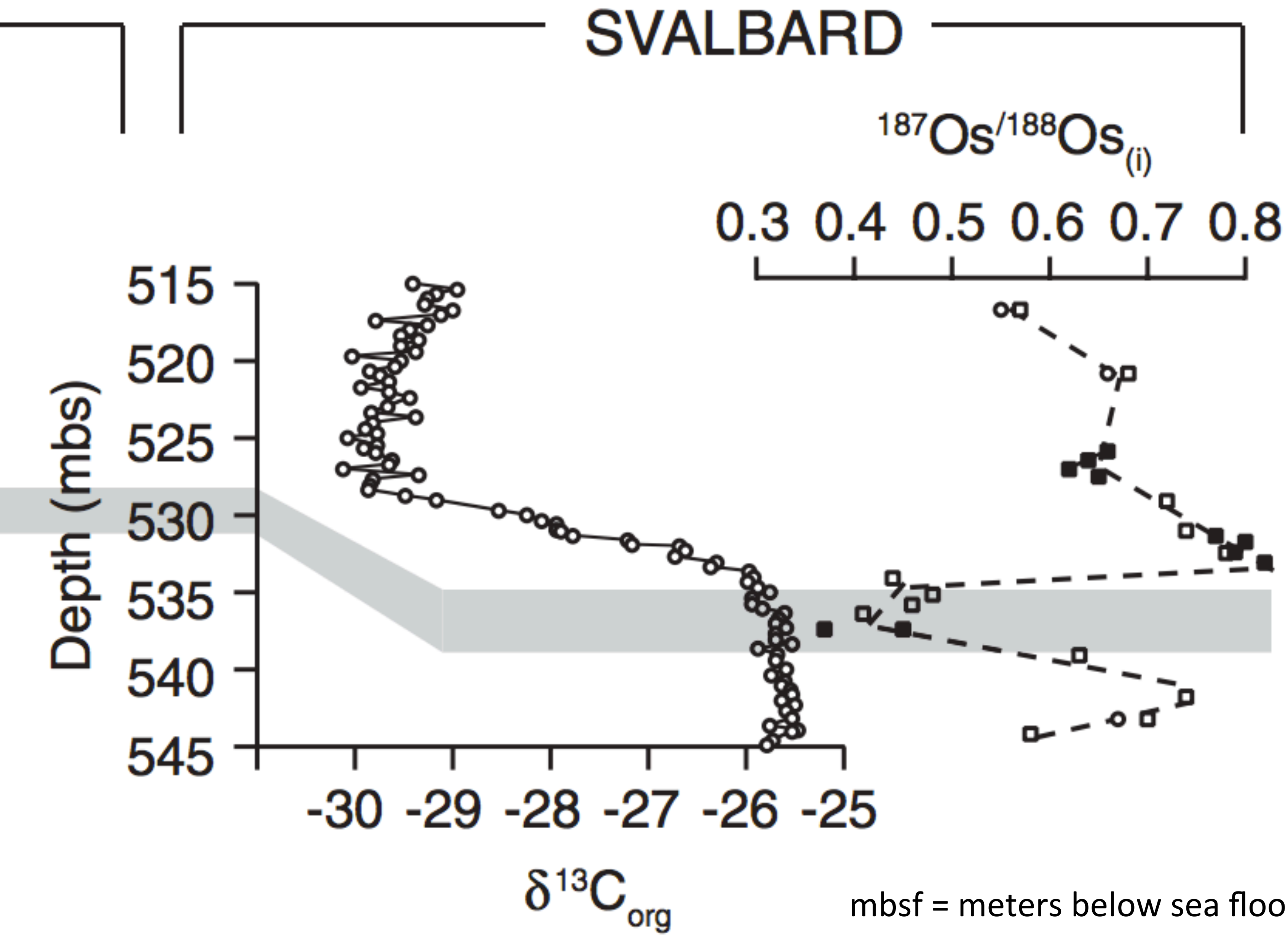
Jet Rock

Evidence for increased chemical weathering at the PETM Dickson et al., P^3, 2015

Other potential proxies for weathering intensity include ^7Li and ^{40}K

Evidence for increased chemical weathering at the PETM

Dickson et al., P3, 2015

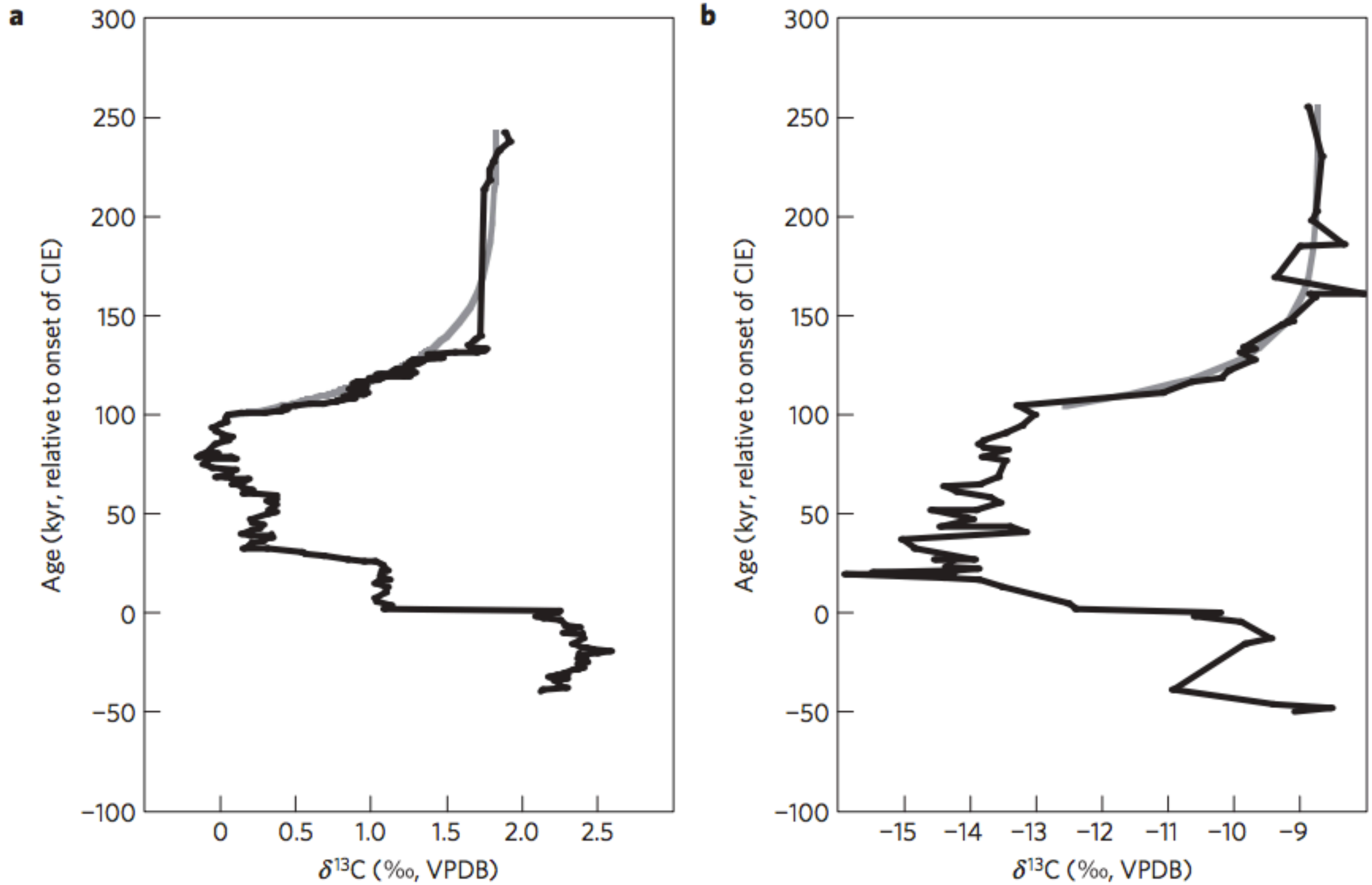


mbsf = meters below sea floor

Return to the Paleocene-Eocene Thermal Maximum (55 Mya): consistent with Maher & Chamberlin?

PETM: geologically-rapid injection of isotopically light C → global warming.

how did Earth's climate recover?



Bowen & Zachos, Nature Geoscience 2010

Predictions of M&C 2014 for the PETM:

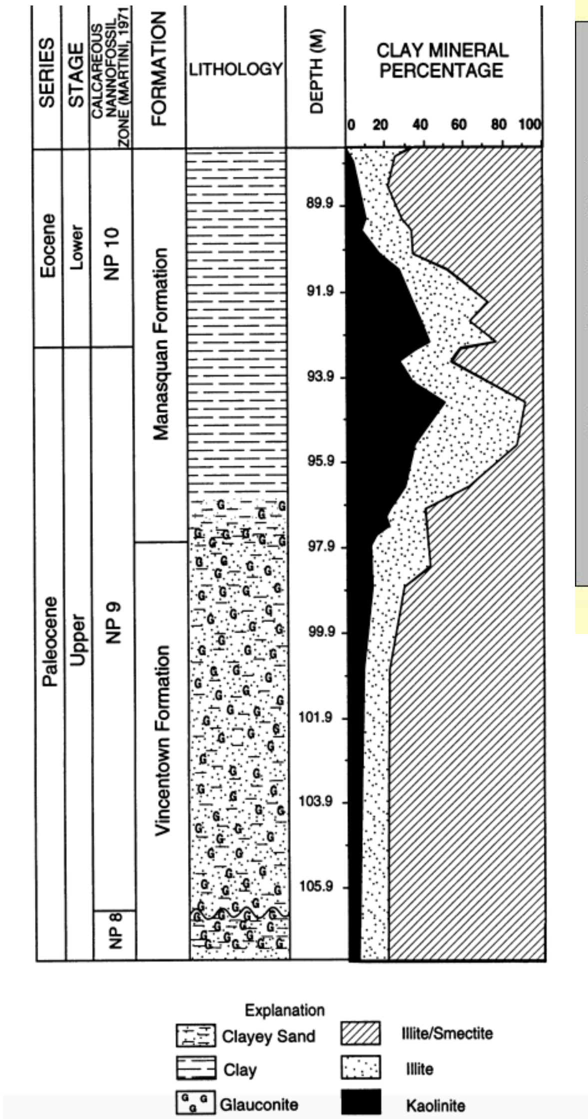
- Extent of weathering should increase

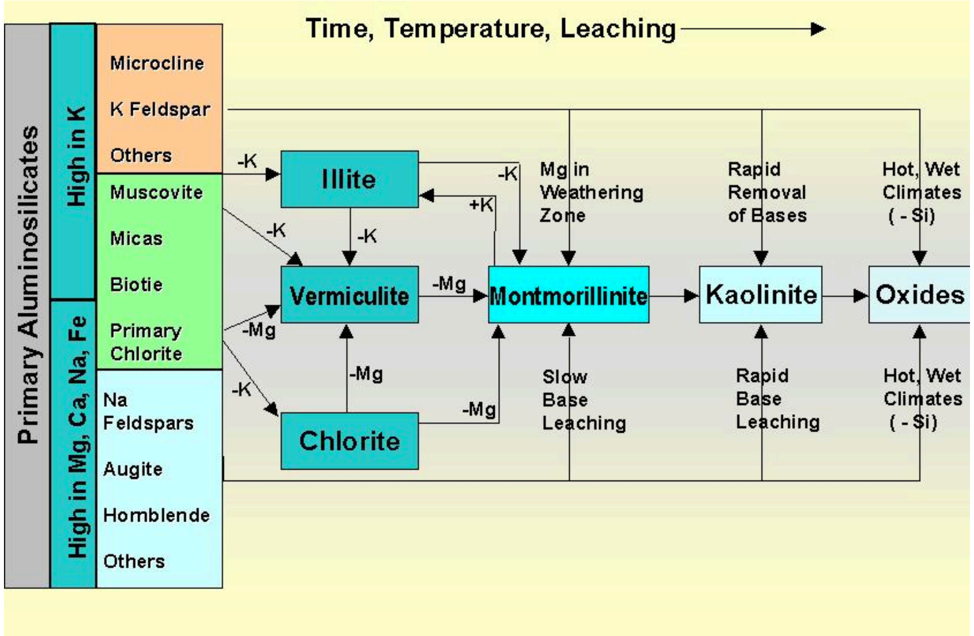
  (clay mineralogy reflecting deeper weathering)
- Rainfall should increase (at least in mountainous zones relevant to weathering).

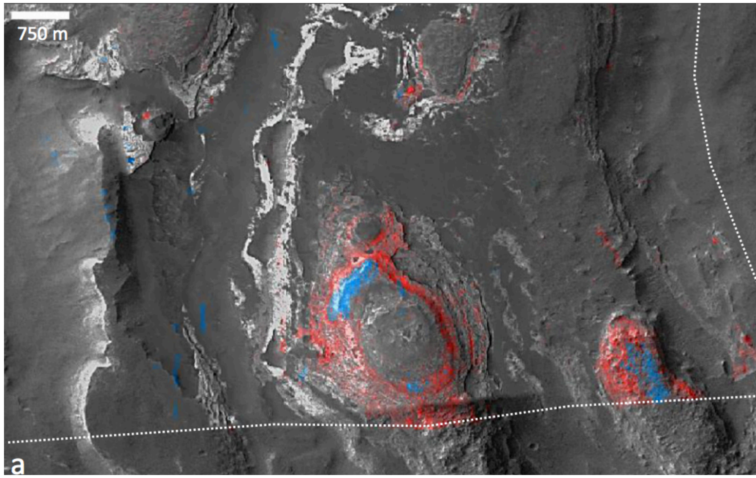
There is a global kaolinite spike at the PETM

Kaolinite = clay formed from thorough intense leaching of parent rock; associated with humid climates

Gibson et al. Sedimentary Geology 2000





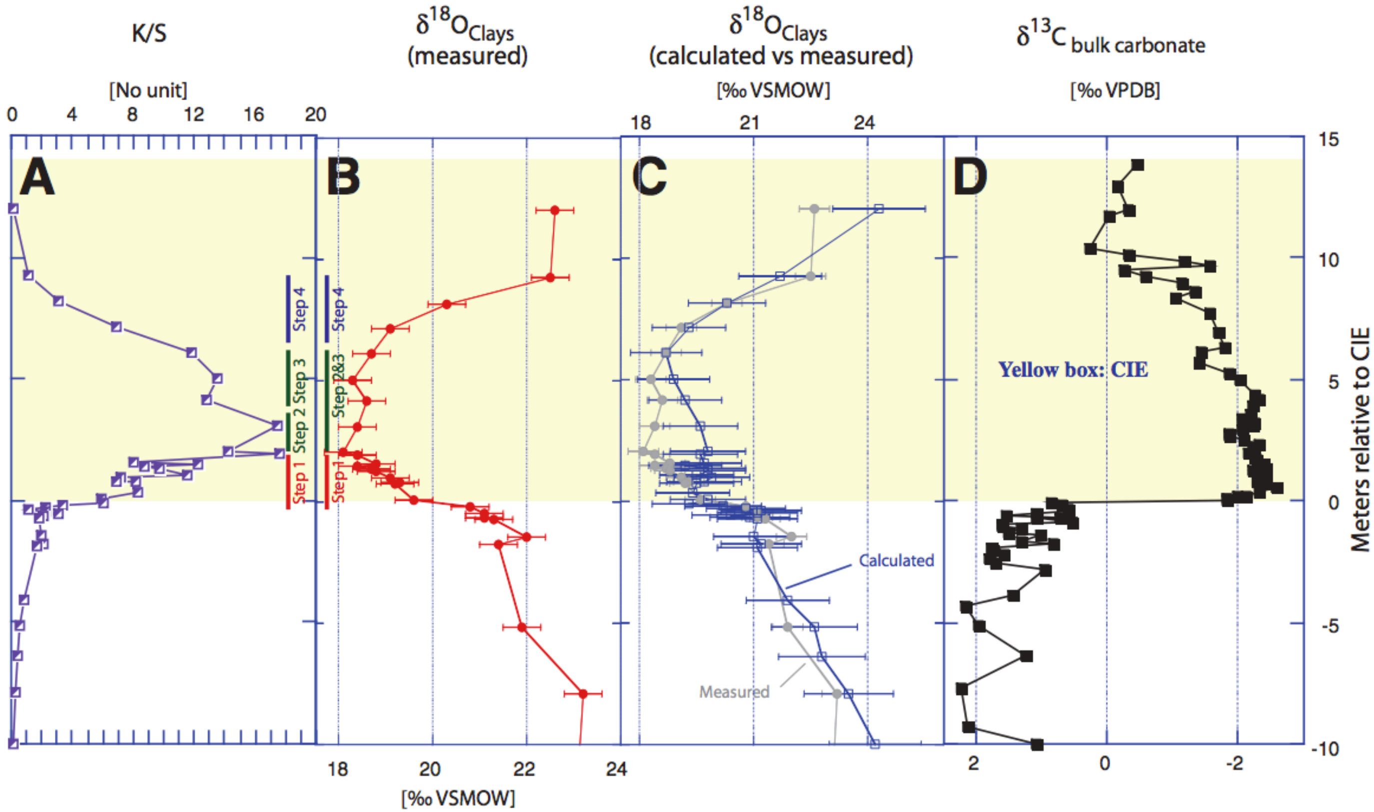


blue: kaolinite
red: smectite

Also found on Mars (Carter et al. Icarus 2015)

The *age* of the kaolinite is uncertain

John et al. Geology 2012



Massive increase in physical erosion
(stripping of previously-leached laterites)
John et al. Paleoceanography 2008

Physical removal of Cretaceous laterites at the PETM?

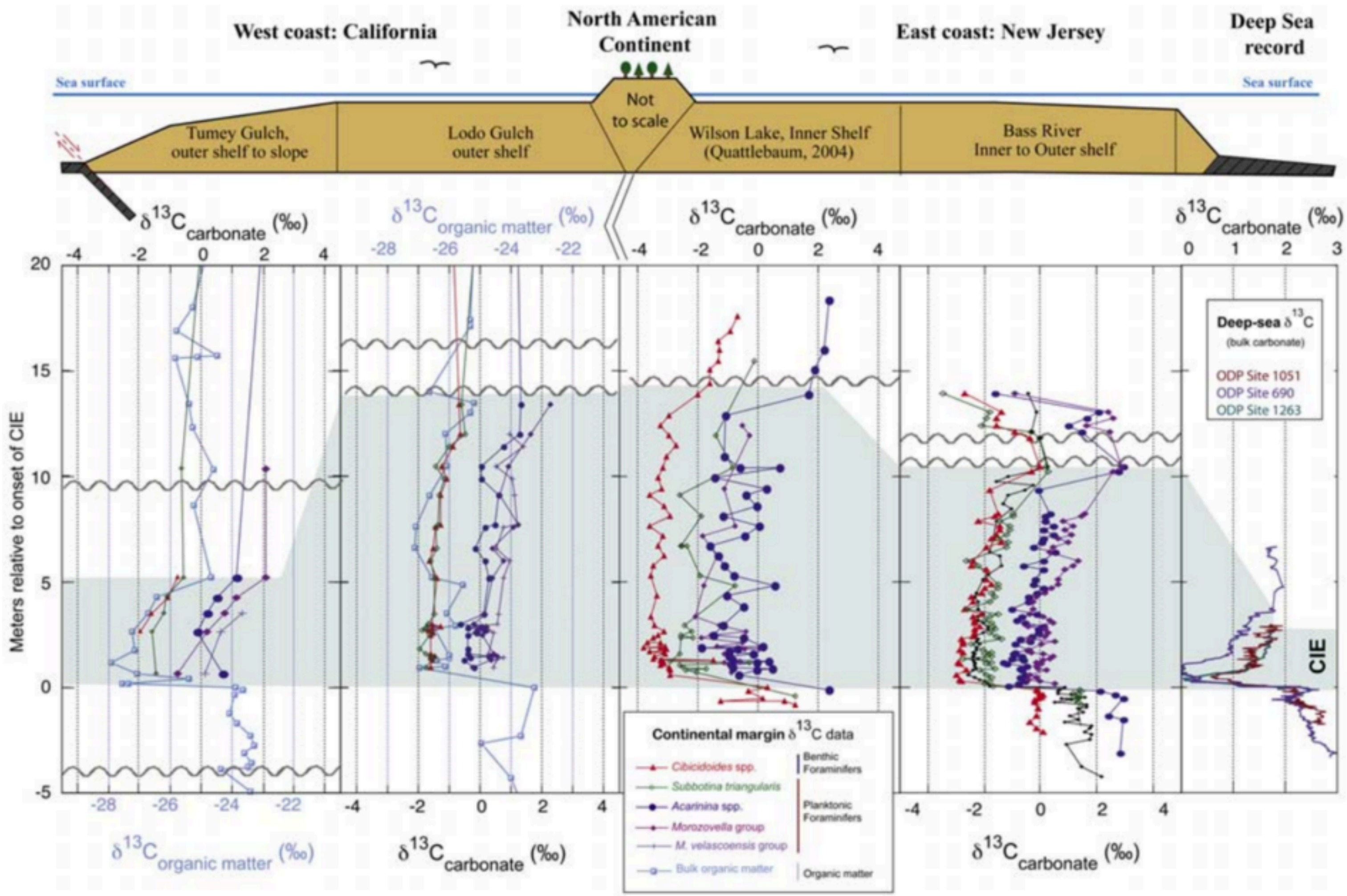


Figure 9. Summary of the carbon isotope results obtained in this and other studies and conceptual cross section from the continent to the deep sea. Data from left to right are for Tumey Gulch (continental slope, California), Lodo Gulch (outer shelf, California), Wilson Lake (inner shelf, New Jersey), Bass River (inner to outer shelf, New Jersey), and various deep-sea records (ODP Sites 1051, 690, and 1263).

John et al. Paleoceanography 2008

LETTER

Evidence for hydrological change in mountainous regions

doi:10.1038/nature11513

Fluvial response to abrupt global warming at the Palaeocene/Eocene boundary

Brady Z. Foreman[1], Paul L. Heller[1] & Mark T. Clementz[1]

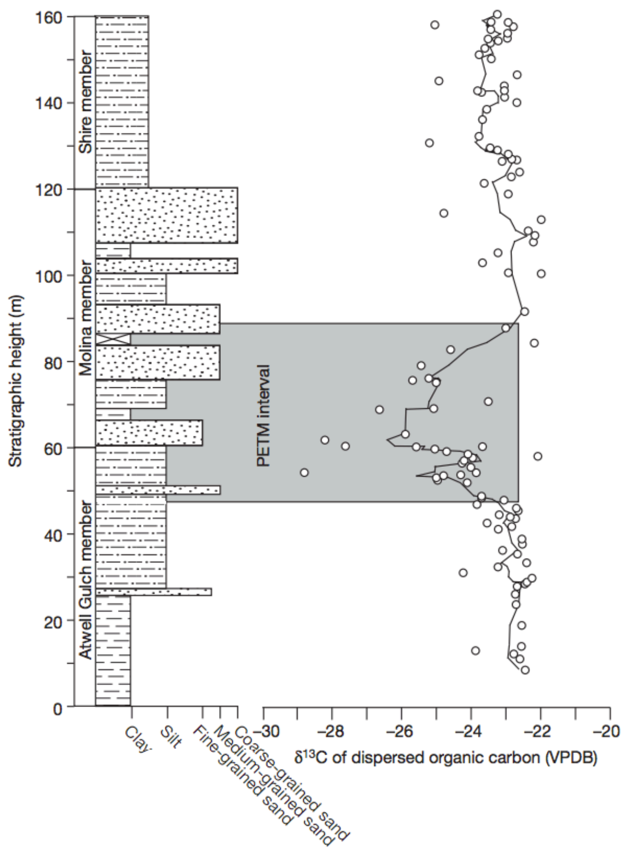
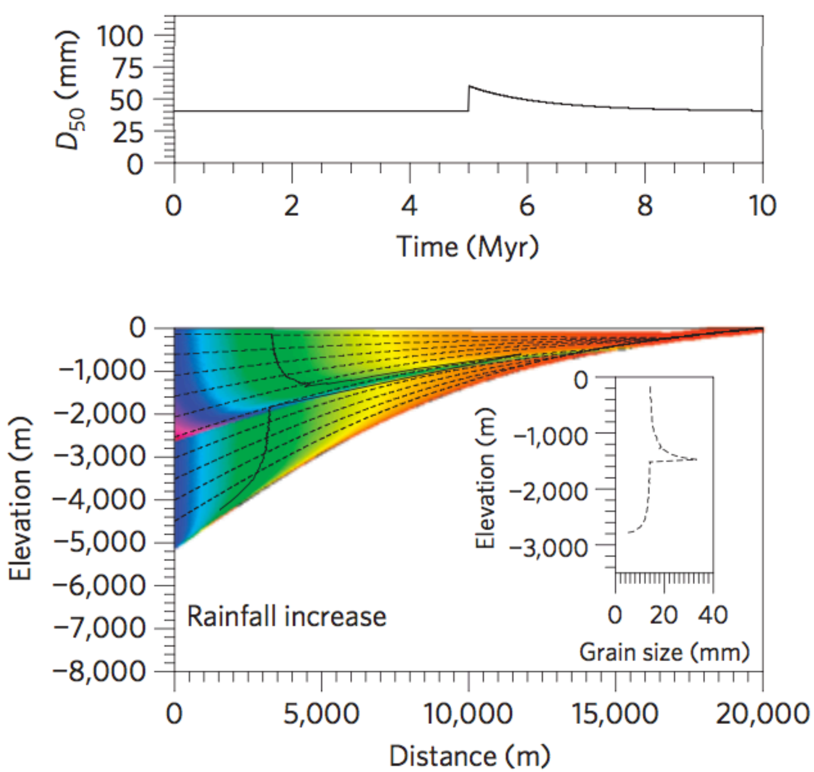
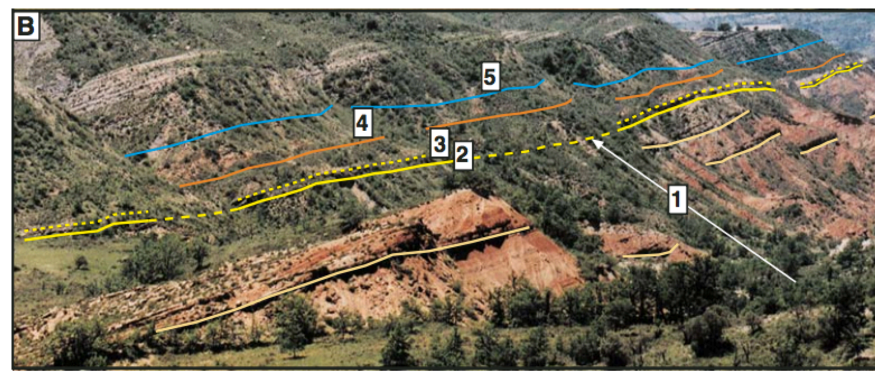


Figure 1 | Generalized geologic map showing major Laramide structures and associated basins. The Uinta and Piceance Creek basins were separate during the Palaeocene and the earliest Eocene epochs, and Cenozoic volcanic fields substantially post-date the deposition of the Wasatch formation.

Polecat Bench, Wyoming: excellent floral record
(Wing et al. Science 2005)
- floral indications of initial drying followed by return to wetter conditions

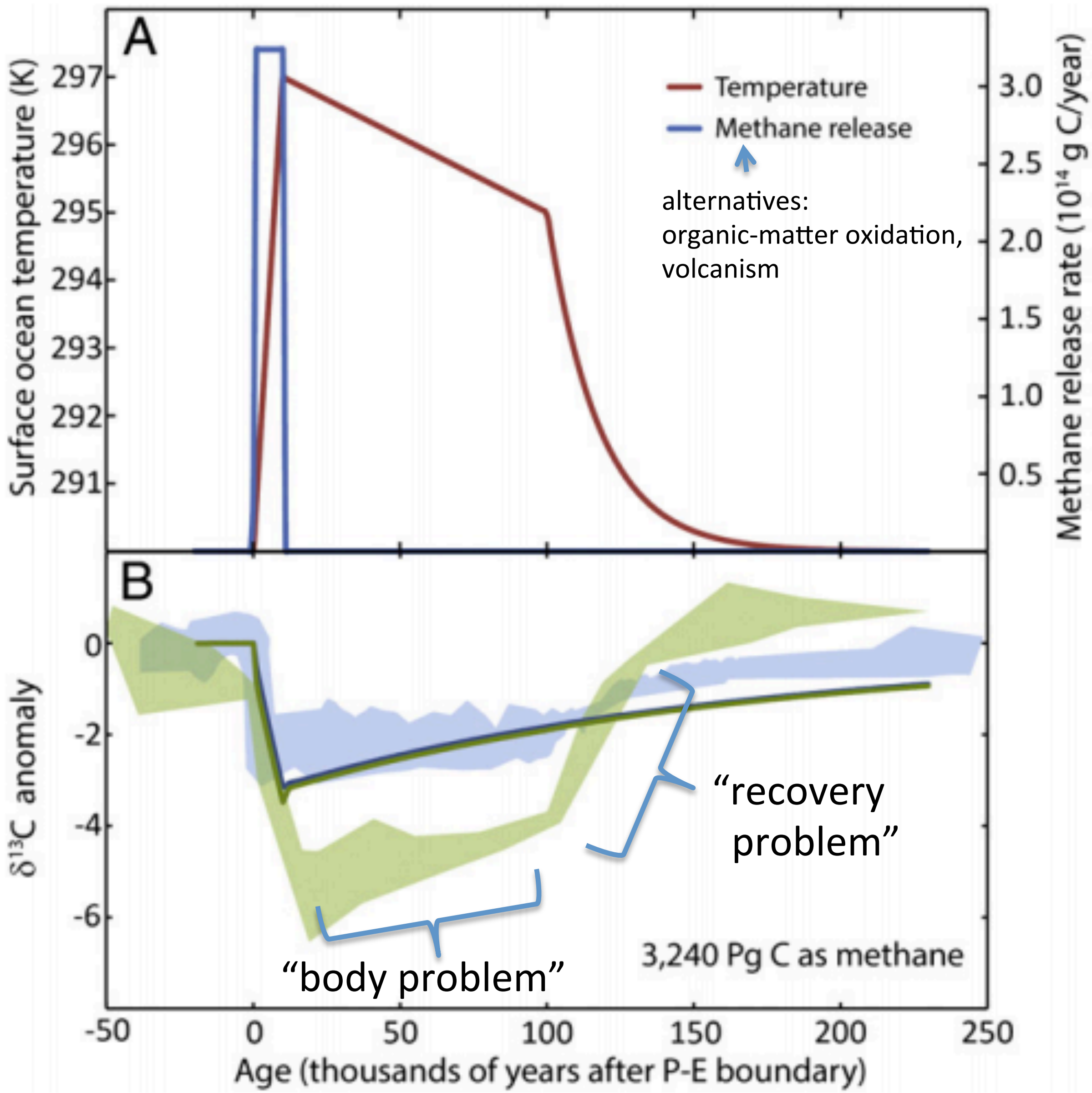


Pyrenees: Schmitz & Pujalte, Geology 2007



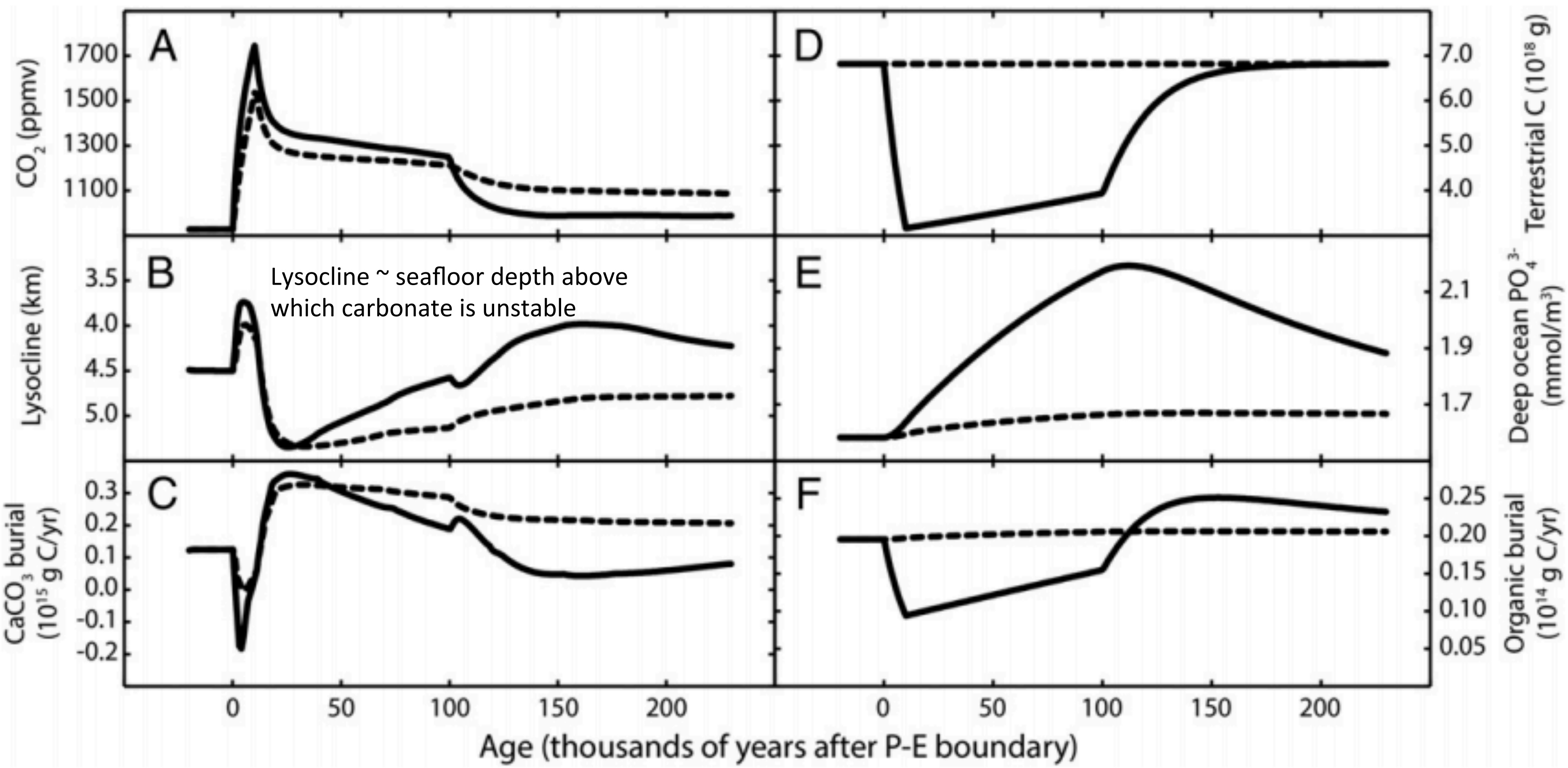
Model: Armitage et al. Nature Geoscience 2011

Severe data-model mismatch when only temperature-dependent silicate weathering is considered



Bowen 2013

Is the carbonate-silicate weathering feedback enough to explain the data?



Dashed lines: without organic matter feedbacks
Solid lines: with organic-matter feedbacks

Bowen 2013

Key points from the required reading

- Transport limitation vs. kinetic limitation
- Conceptual understanding of hillslope- and watershed-scale weathering, controls on fluxes, relative timescales

Key points – a look under the hood of the carbonate-silicate feedback hypothesis

- Main fluxes and reservoirs in the long-term carbon cycle: what is the evidence for a negative feedback?
- Testable elements of the carbonate-silicate weathering hypothesis: how well do they hold up to testing?
- Evidence from past shocks to the Earth system and present-day weathering bearing on the carbonate-silicate weathering hypothesis.

  - Testing hydrologic control on silicate weathering rates as an explanation for recovery from the PETM
  - Alternative, organic-carbon explanations

- Possible explanations for the lab-vs.-field discrepancy in weathering rates: the role of flushing.

Backup slides

A new proxy for weathering: ^{7}Li

Input/output	Lithium flux (10^9 moles/year)	Average δ^7Li (‰)
Inputs		
Rivers, F_{Riv}	10	23
Hydrothermal vents, F_{HT}	13	8.3
Subduction reflux, F_{Reflx}	6	15
Total input, F_{Input}	29	15
Outputs		
Basalt alteration (AOC), F_{AOC}	8	15
Sediment uptake (MAAC), F_{MAAC}	20	15
$\Delta_{Seawater-Sediment}$ ($\delta^7Li_{SW} - \delta^7Li_{Sink}$)		16
Total reverse weathering, F_{Sink}	29	15

Misra & Froelich, Science 2012

$$\delta^7\mathrm{Li}\ (‰) = \left\{\left[\frac{\left({}^7\mathrm{Li}/{}^6\mathrm{Li}\right)_{\mathrm{Sample}}}{\left({}^7\mathrm{Li}/{}^6\mathrm{Li}\right)_{\mathrm{Standard}}}\right] - 1\right\} 1000$$

Seawater

[Li] = 26 μM

$\delta^7Li_{SW} = 31‰$

$\tau \approx 1.2$ Ma

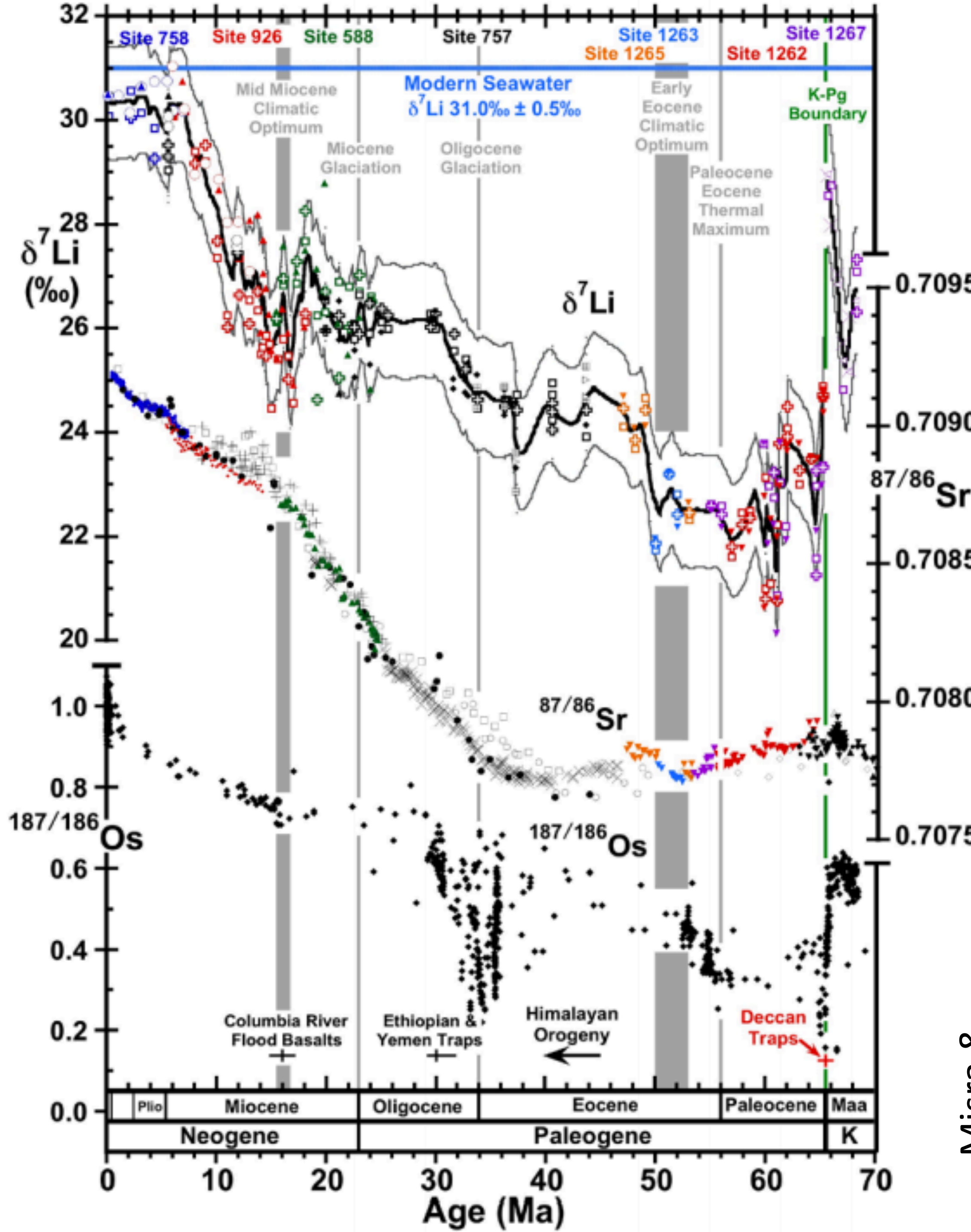
Lithium cycle is mostly in silicate rocks and aluminosilicate clays; none in carbonates.
High weathering intensity: Low riverine ^{7}Li concentrations.
Low weathering intensity (e.g. mountains): High riverine ^{7}Li concentrations.

0.9% increase

Dissolved Li 50 Ma
→ suspended Li today?

(Other interpretations possible).

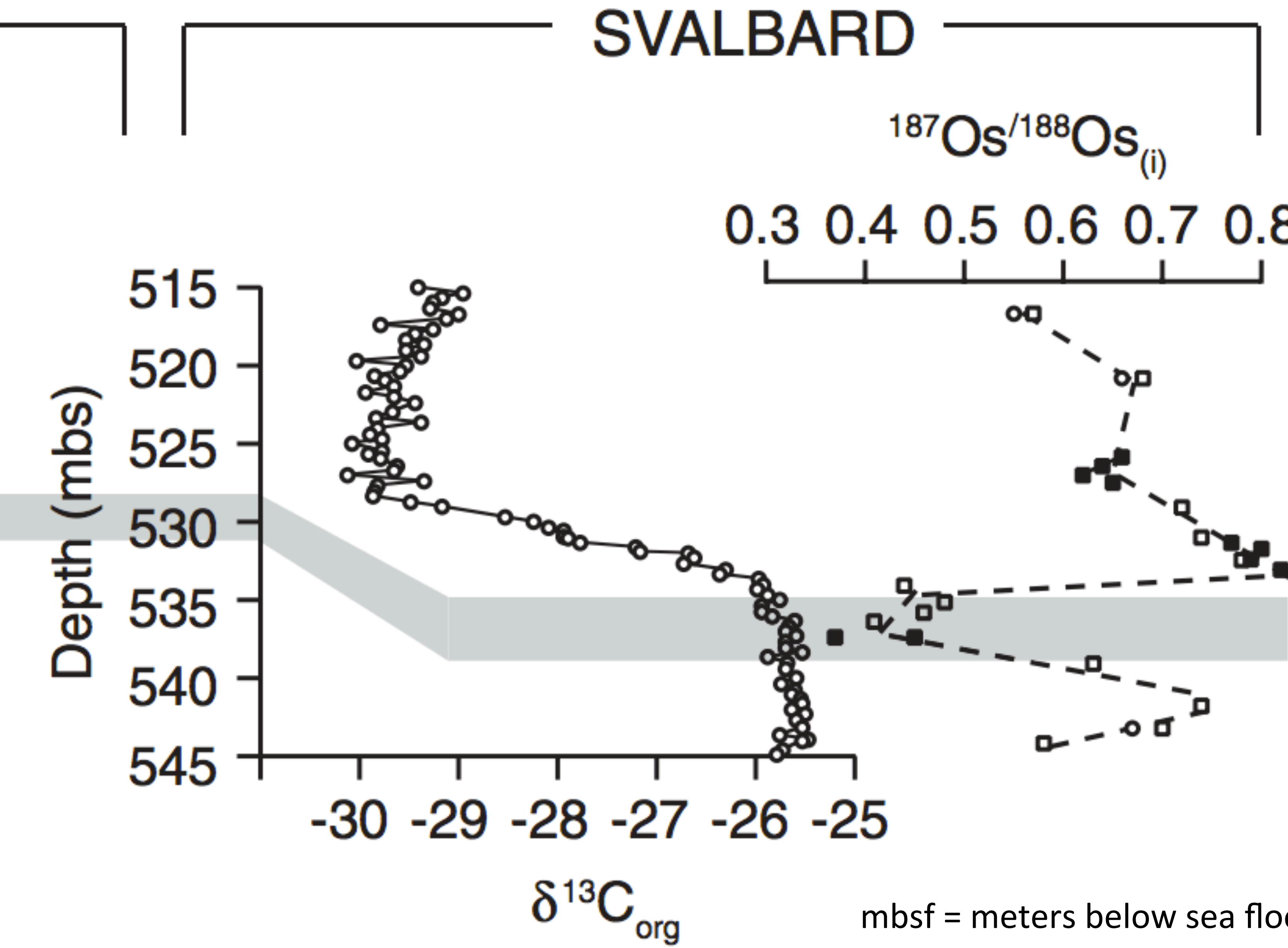

Ocean Drilling Program



Misra & Froelich 2012

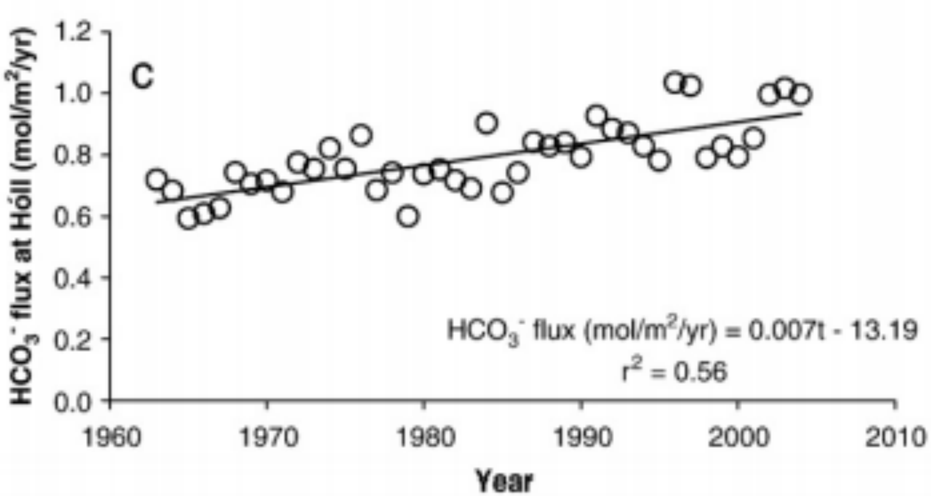
Evidence for increased chemical weathering at the PETM

Dickson et al., P^3, 2015

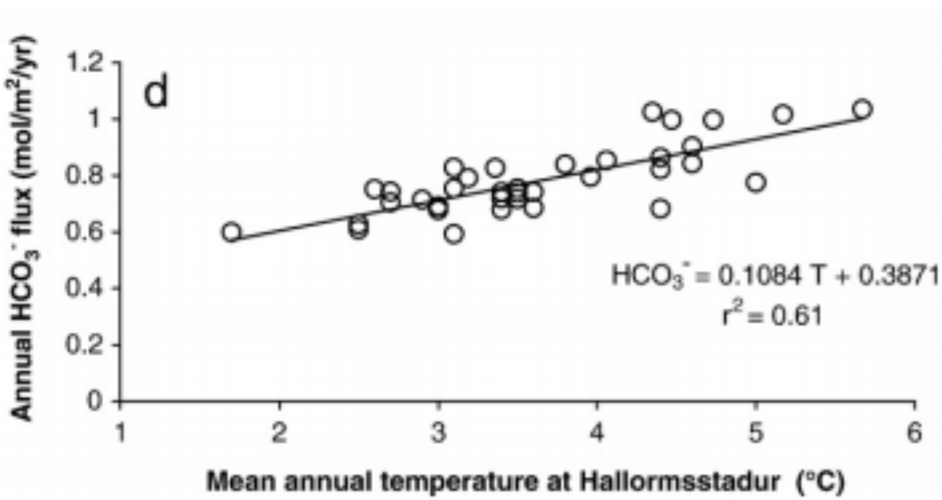


mbsf = meters below sea floor

Seasonal and interannual variability



Gislason et al. 2009



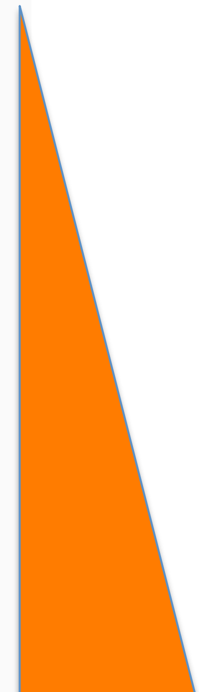
Icelandic watersheds showing a large, recent temperature increase (natural experiment)

Testing the prediction of a pole-to-equator increases in weathering rates

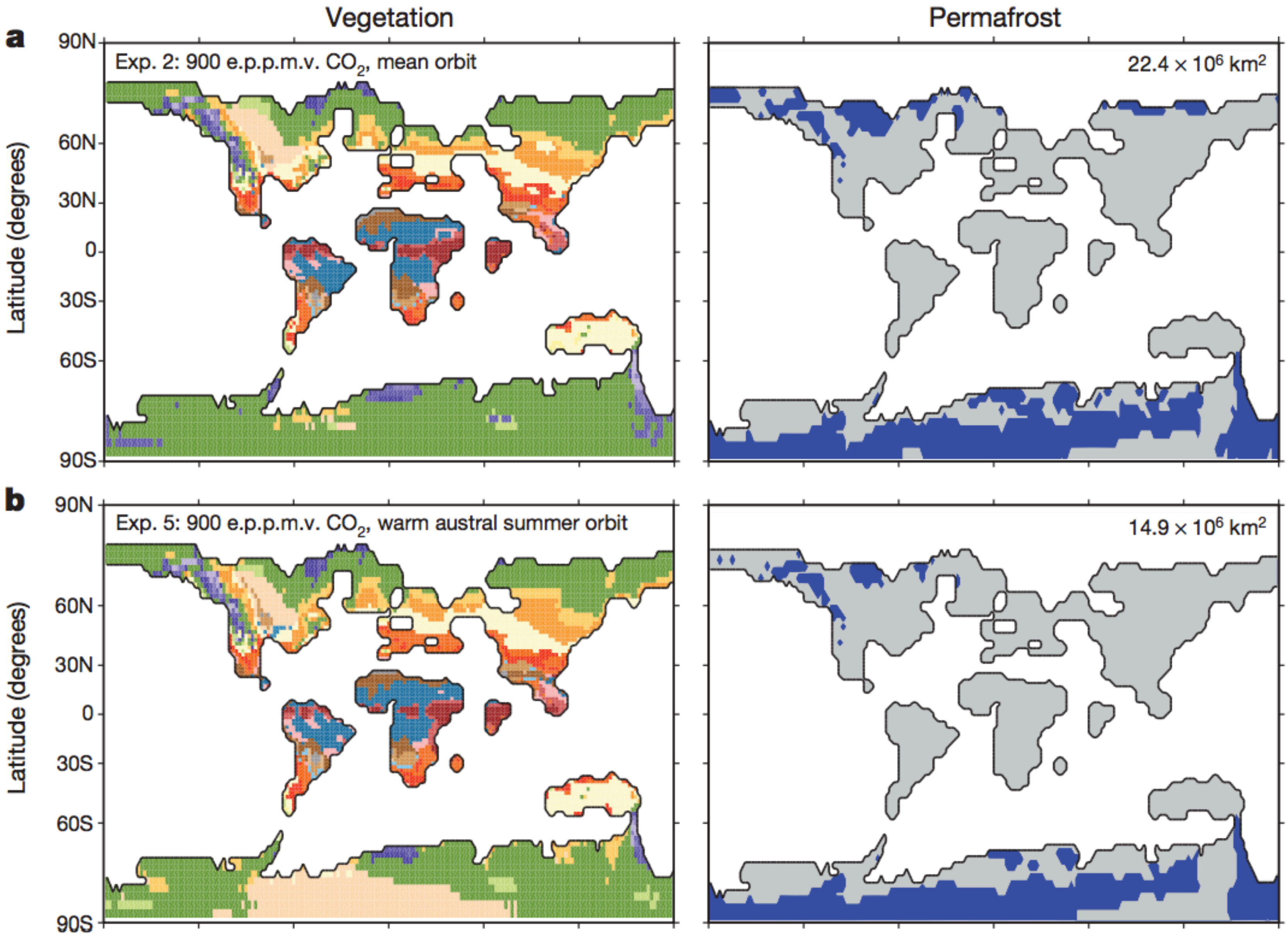
TABLE 1. Morphoclimatic Classification and Silicate Weathering Rates [Meybeck, 1979]

	Runoff, mm yr^{-1}				
Temperature, °C	<30	30–120	120–280	280–630	>630
<4			tundra and taiga, (0.75)	wet taiga, 1.6	very wet taiga (high relief), 5.75
4–15		semi-arid temperate, (0.8)	temperate, 1.4	wet temperate, 2.35	very wet temperate (high relief), (10)
15–25	arid, 0.25				
>20		mixed tropical, 2.35	mixed tropical, 2.35	wet tropical, 4.15	very wet tropical (plains), 11.4 very wet tropical (mountains), 16.4

Weathering rates are expressed in 10^6 gm km^{-2} yr^{-1} of dissolved SiO_2. Parentheses signify poorly determined values.



DeConto et al., Nature 2012: polar permafrost as a carbon capacitor



Large-scale organic carbon burial offshore in deltas today

Sequestration of petrogenic C moderates C release from eroding coal, org.-rich shale

Sequestration of biospheric C draws down CO_2 from atmosphere/ocean.

Galy et al. Nature 2007

Galv et al. Nature 2015*

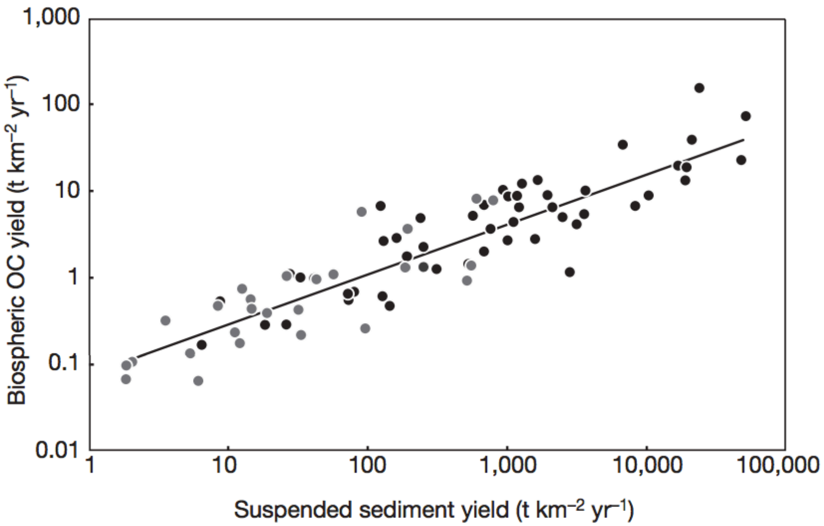
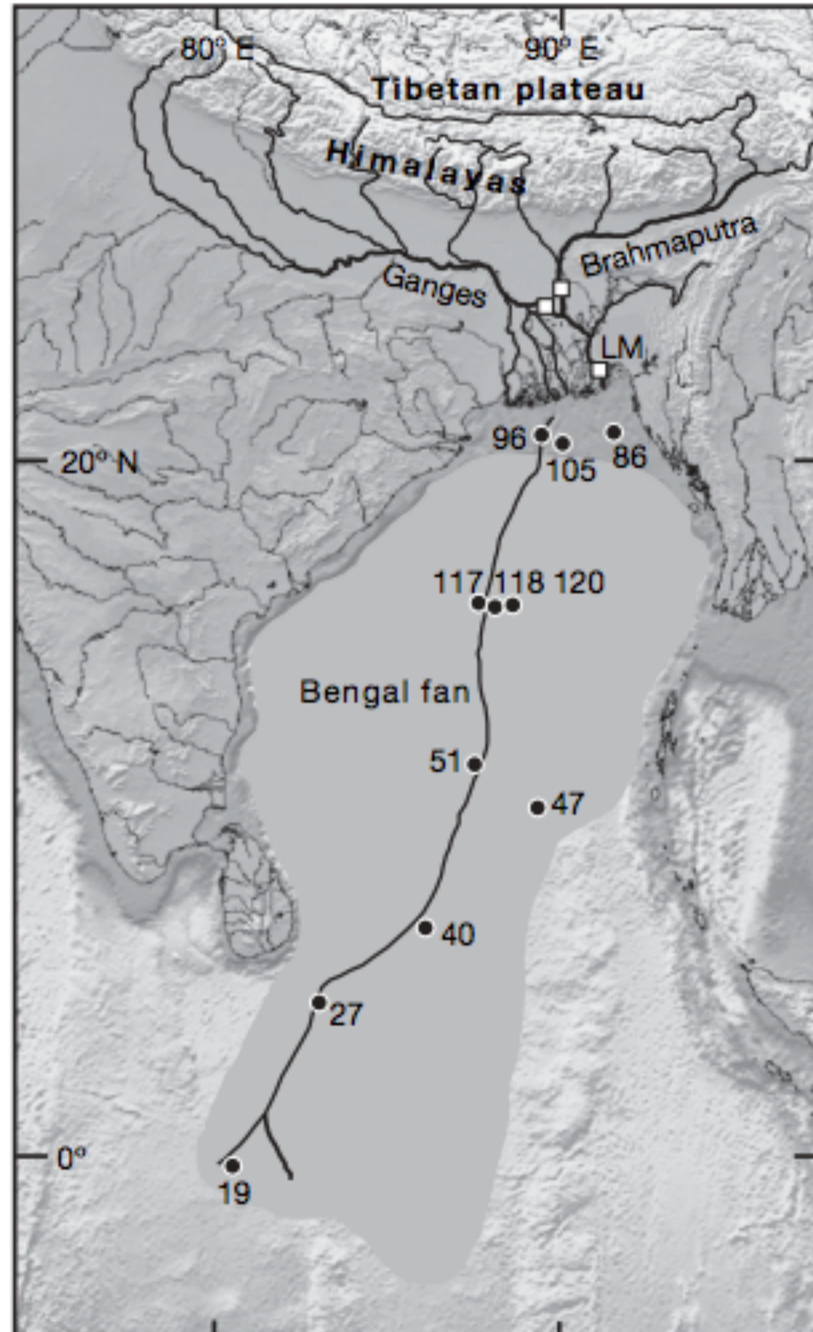
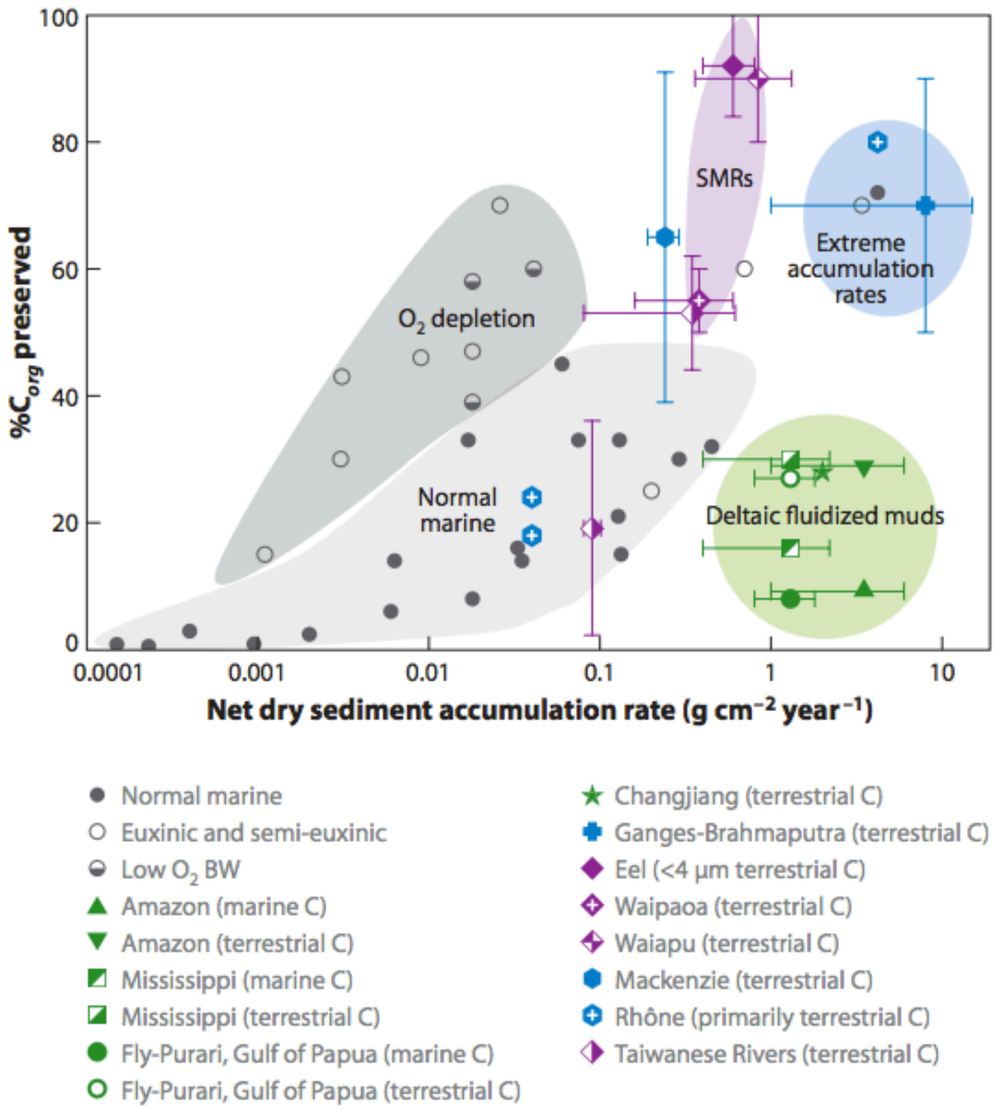


Figure 2 | Relationship between biospheric POC yield (Y_{bios}) and suspended sediment yield. Data obtained by subtracting measured petrogenic OC fluxes from riverine POC fluxes (black dots) and those obtained using petrogenic OC fluxes inferred from the relationship shown in Fig. 1 (grey dots) plot on the same trend. The regression line is $Y_{bios} = 0.081\,Y_{sed}^{0.56}$; $r^2 = 0.78$; $P < 0.001$.

* Optional reading this week



Survival chances of terrestrial organic matter are slight unless deposition is fast (usually only for the deltas of rivers draining fast-eroding mountain belts)



Because re-oxidation of organic matter (both terrestrial and marine) is usually efficient, oil and coal are rare in the rock record.

Snowball Earth catastrophe can be modeled using a 1D (latitudinal) Energy Balance Model (EBM)

divergence of
poleward heat transport

$$\underbrace{\frac{Q}{4}S(x)}[1-\alpha(x)] = \underbrace{A+BT(x)} + \underbrace{\nabla \cdot \mathbf{F}},$$

normalized latitudinal distribution of insolation (depends on obliquity)

linearization of Outgoing Longwave Radiation

x = sin(latitude)

x_s = ice line latitude

Suppose
α = 0.6, T < T_s
α = 0.3, T > T_s

Budyko 1969: $\nabla \cdot \mathbf{F} = C(T - \overline{T}).$

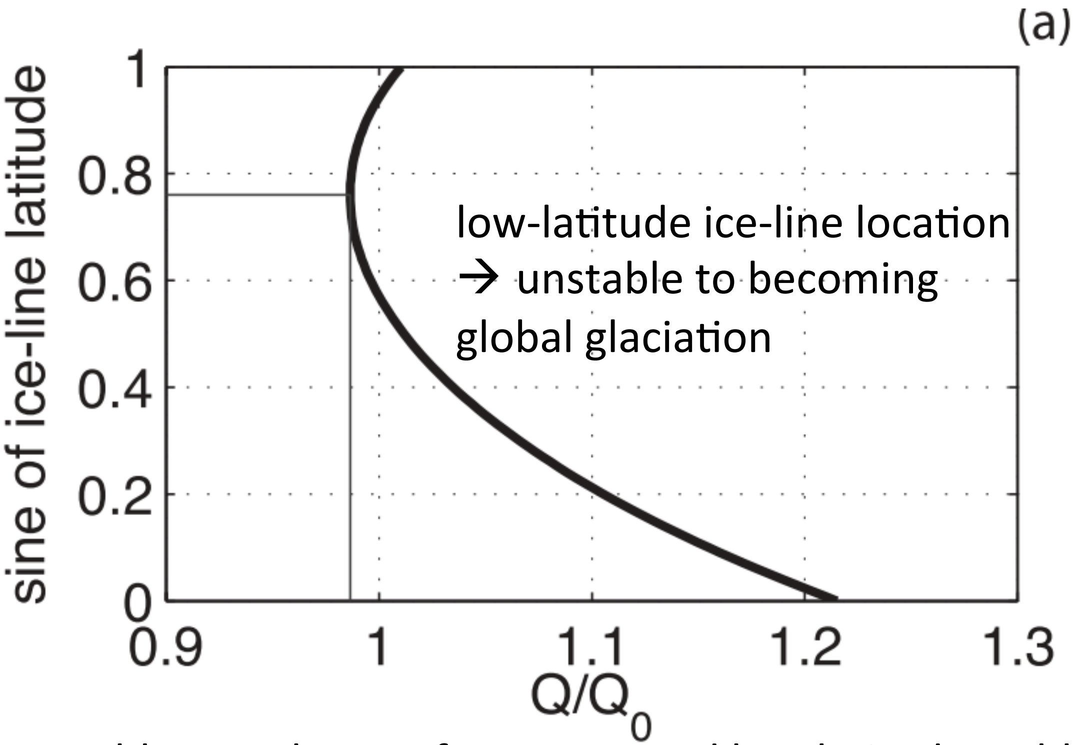
North 1975: $\nabla \cdot \mathbf{F} = -D\frac{d}{dx}(1-x^2)\frac{dT}{dx}.$

Following Roe & Baker 2010
(optional reading, pdf on website)

Snowball Earth catastrophe can be modeled using a 1D (latitudinal) Energy Balance Model (EBM)

$$\underbrace{\frac{Q}{4}S(x_s)(1-\alpha_s)}_{\text{absorbed shortwave}} - \underbrace{C(T_s - \overline{T})}_{\text{flux divergence}} = A + BT_s,$$

$$\frac{Q}{4}(1-\alpha_s)S(x_s) + \frac{Q}{4}\frac{C}{B}(1-\alpha_p) = \text{constant}.$$



Due to spherical geometry for a rapidly-rotating planet:

At lower latitudes,

- local insolation (negative feedback) increases more slowly with decreasing latitude
- local divergence of the heat flux (+ve feedback) leads to more cooling with decreasing latitude

Following Roe & Baker 2010 (optional reading, pdf on website)

but see Abbot et al. 2011 for a proposed low-latitude stable-ice-line glacial state

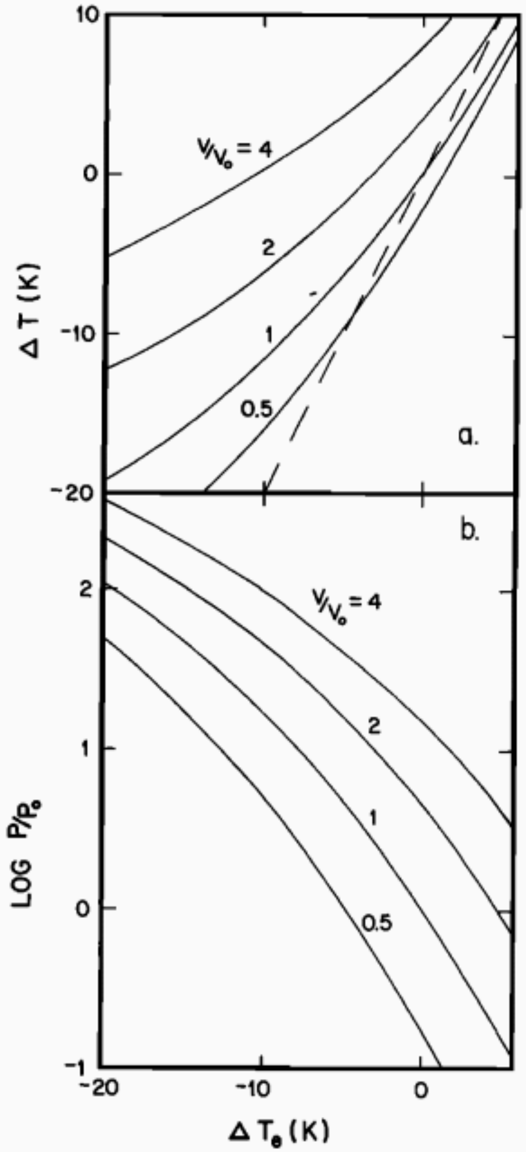
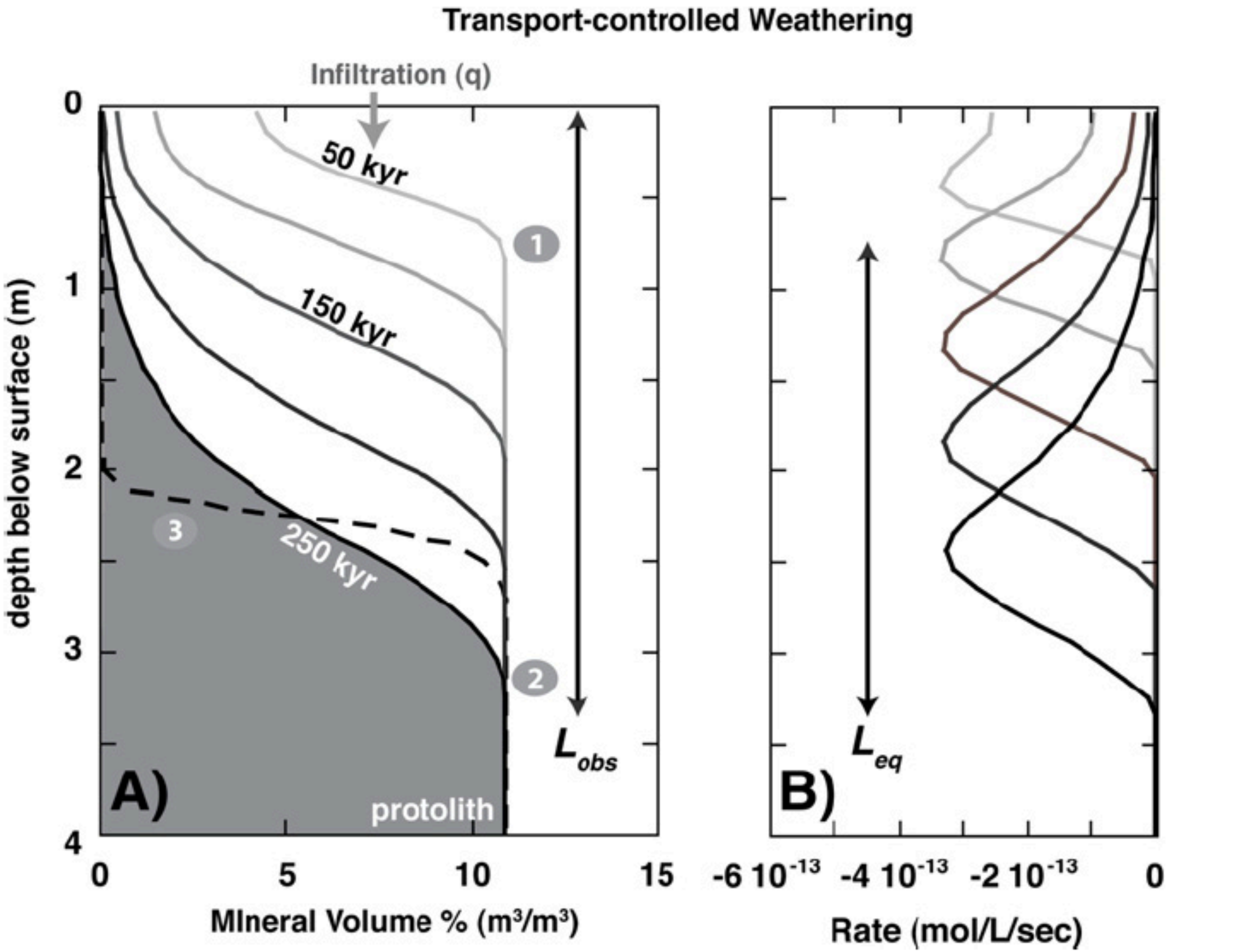
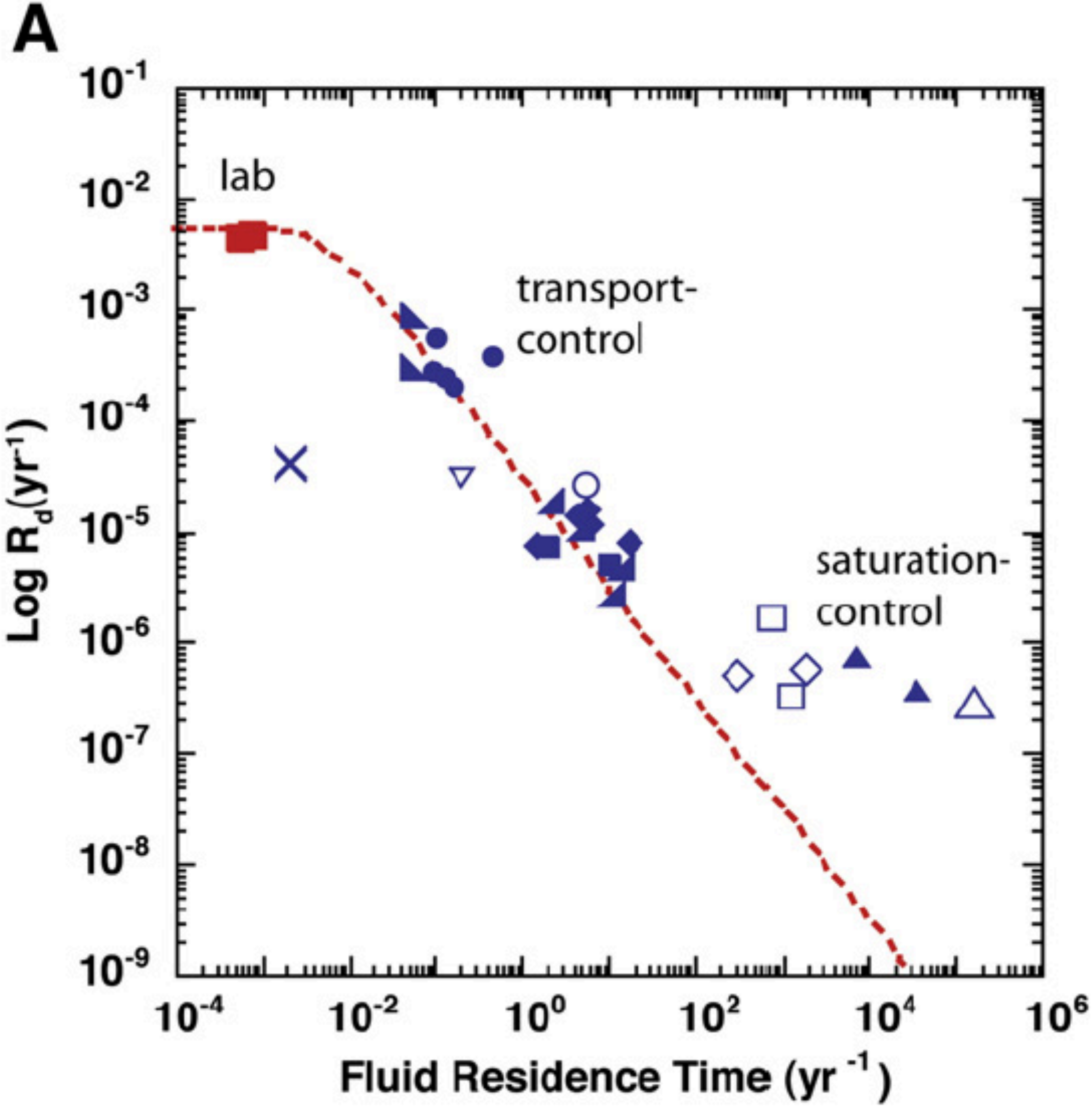


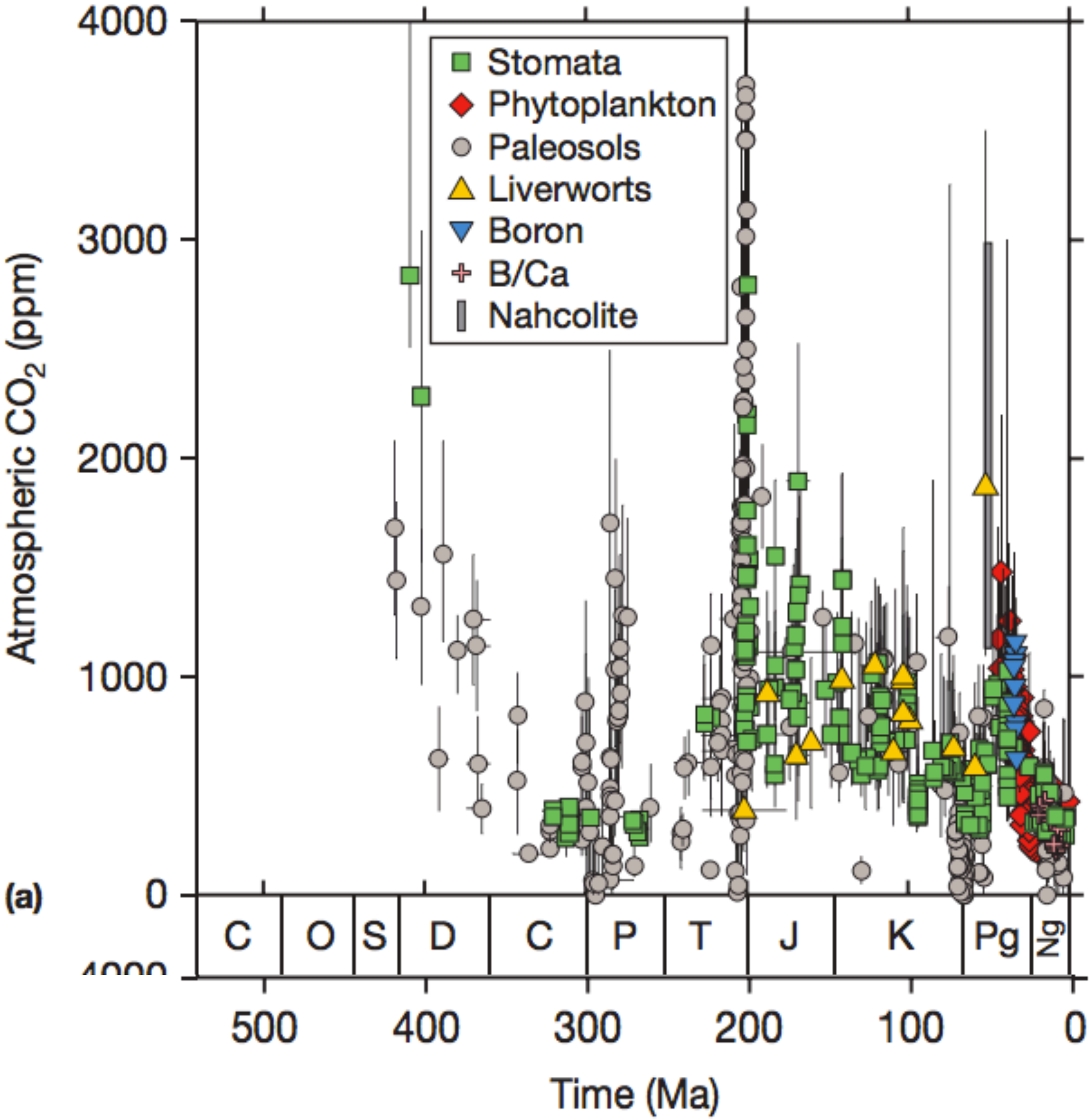
Fig. 2. Change in surface temperature ($\Delta T = T_s - 285°K$) and carbon dioxide partial pressure (P) as functions of change in effective temperature ($\Delta T_e = T_e - 253°K$) for several values of the volcanic and metamorphic source of CO_2. Present day values are designated P_o and V_o. The broken line shows the surface temperature variation for constant CO_2 pressure.

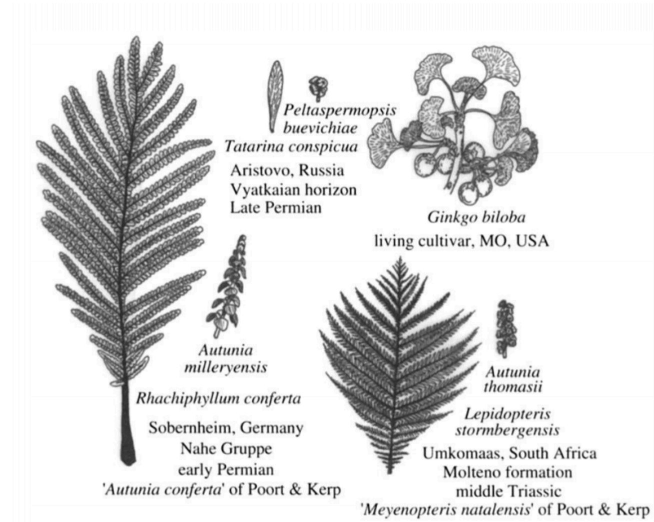

Transport-controlled Weathering
Infiltration (q)
0
1
2
3
4
depth below surface (m)
50 kyr
150 kyr
250 kyr
1
2
3
protolith
L_{obs}
A)
0
5
10
15
MIneral Volume % (m³/m³)
L_{eq}
B)
-6 10^{-13}
-4 10^{-13}
-2 10^{-13}
0
Rate (mol/L/sec)



A
lab
transport-
control
saturation-
control
Log R_d (yr^{-1})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Fluid Residence Time (yr^{-1})

CO_2 versus time for the last 0.5 Gyr



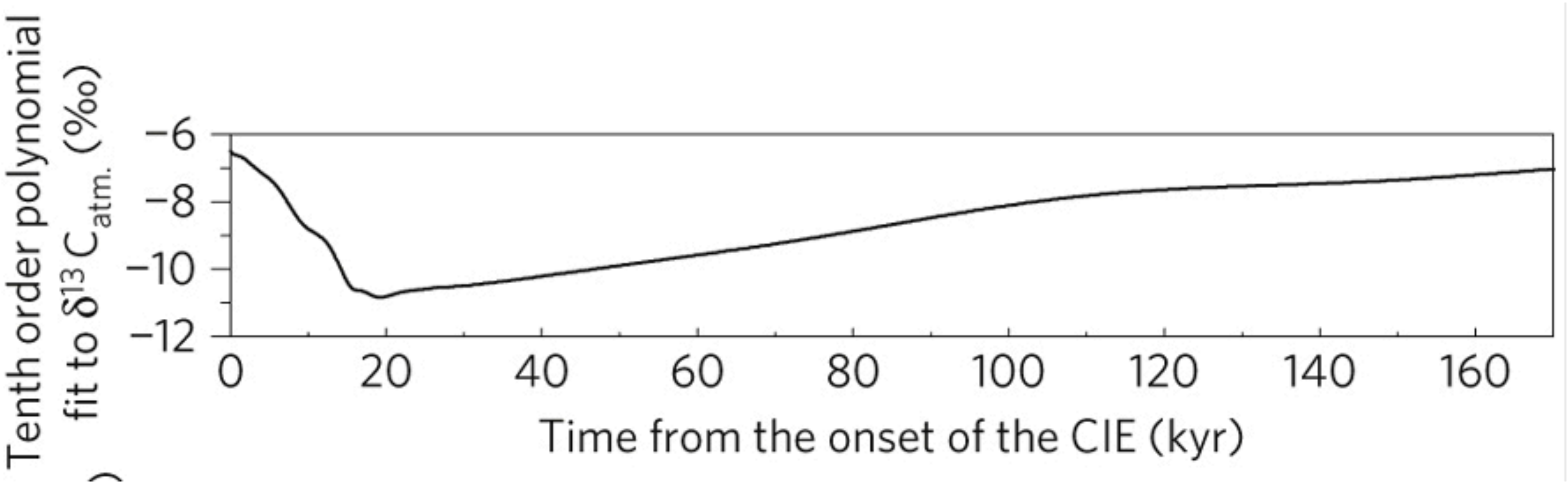


Stomatal indices

Gastornis in earliest Eocene forest

Major radiation of mammals at the PETM
(e.g., horses double in size)

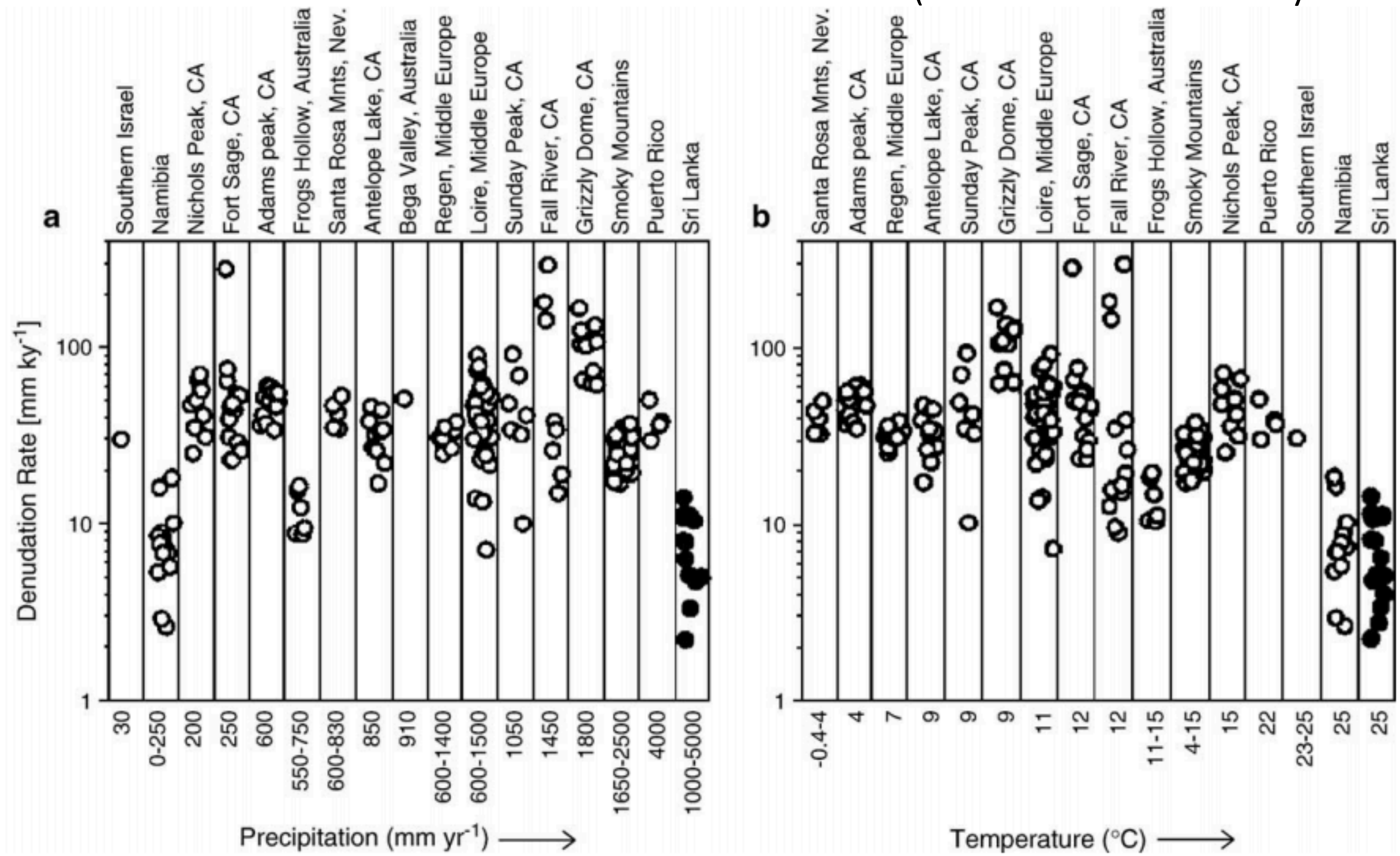
Testing the silicate-weathering feedback hypothesis with hyperthermals



Cui et al. Nature Geoscience 2011

No evidence for T or runoff control on physical erosion from ^{10}Be data

^{10}Be: spallation product of ^{16}O, 1 Myr half-life, formed by neutron bombardment <~1 m from Earth surface (Neutrons are cosmic-ray secondaries)



von Blanckenburg EPSL 2006