Greenhouse Warming and Ocean Acidification in the Past: Lessons for the Future

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Climate–Carbon Cycle Feedback Analysis: Results from the C^{4}MIP Model Intercomparison

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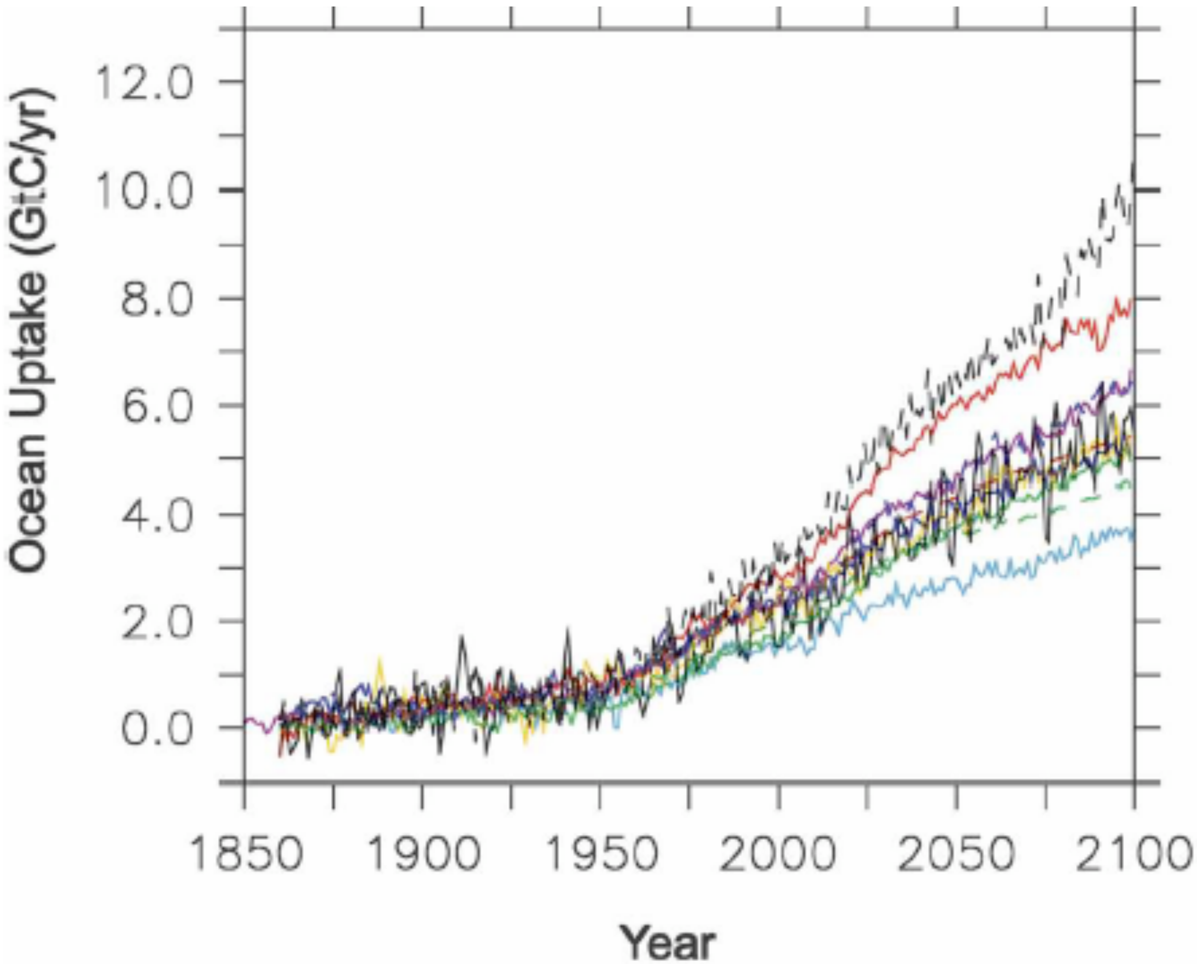
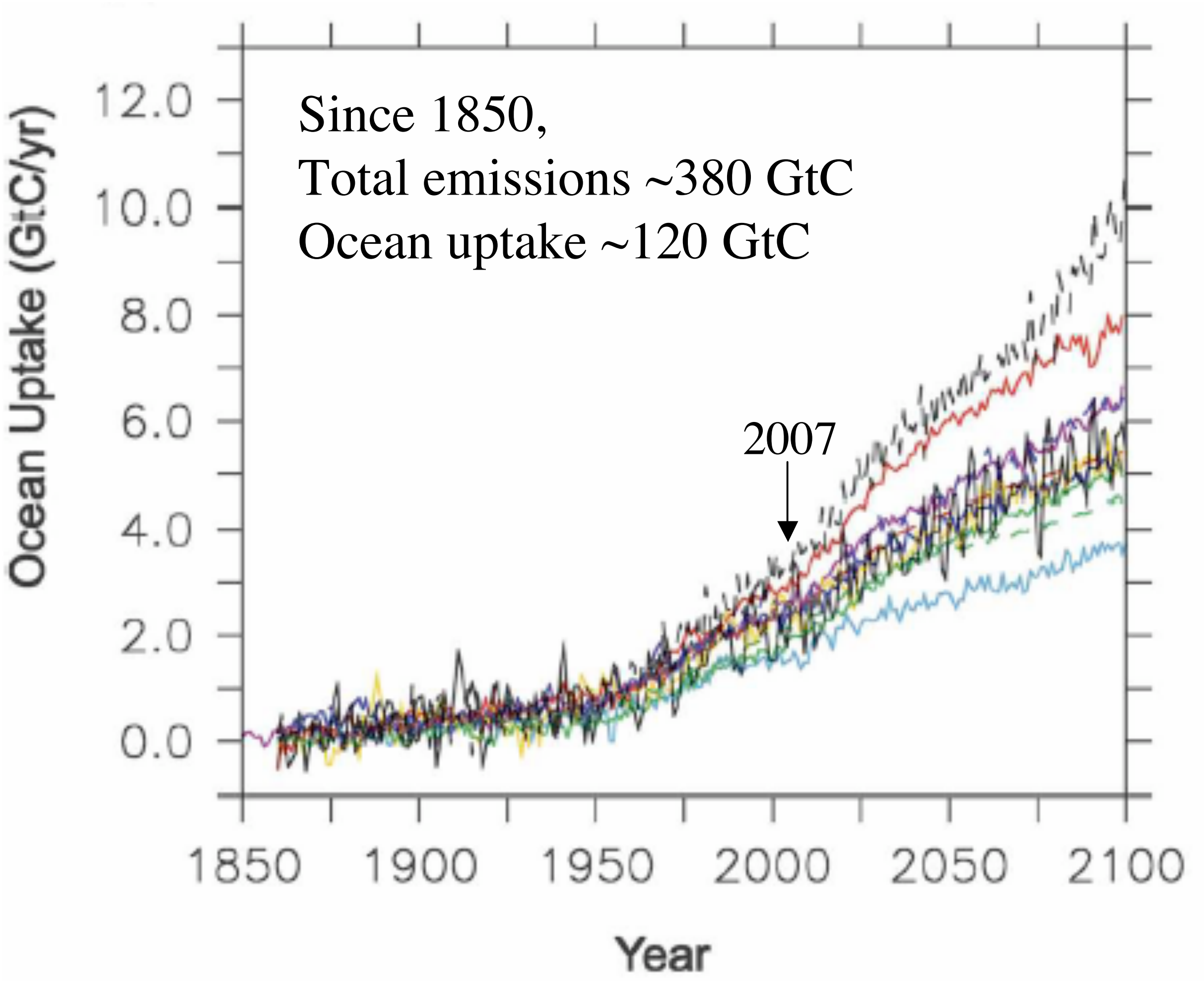


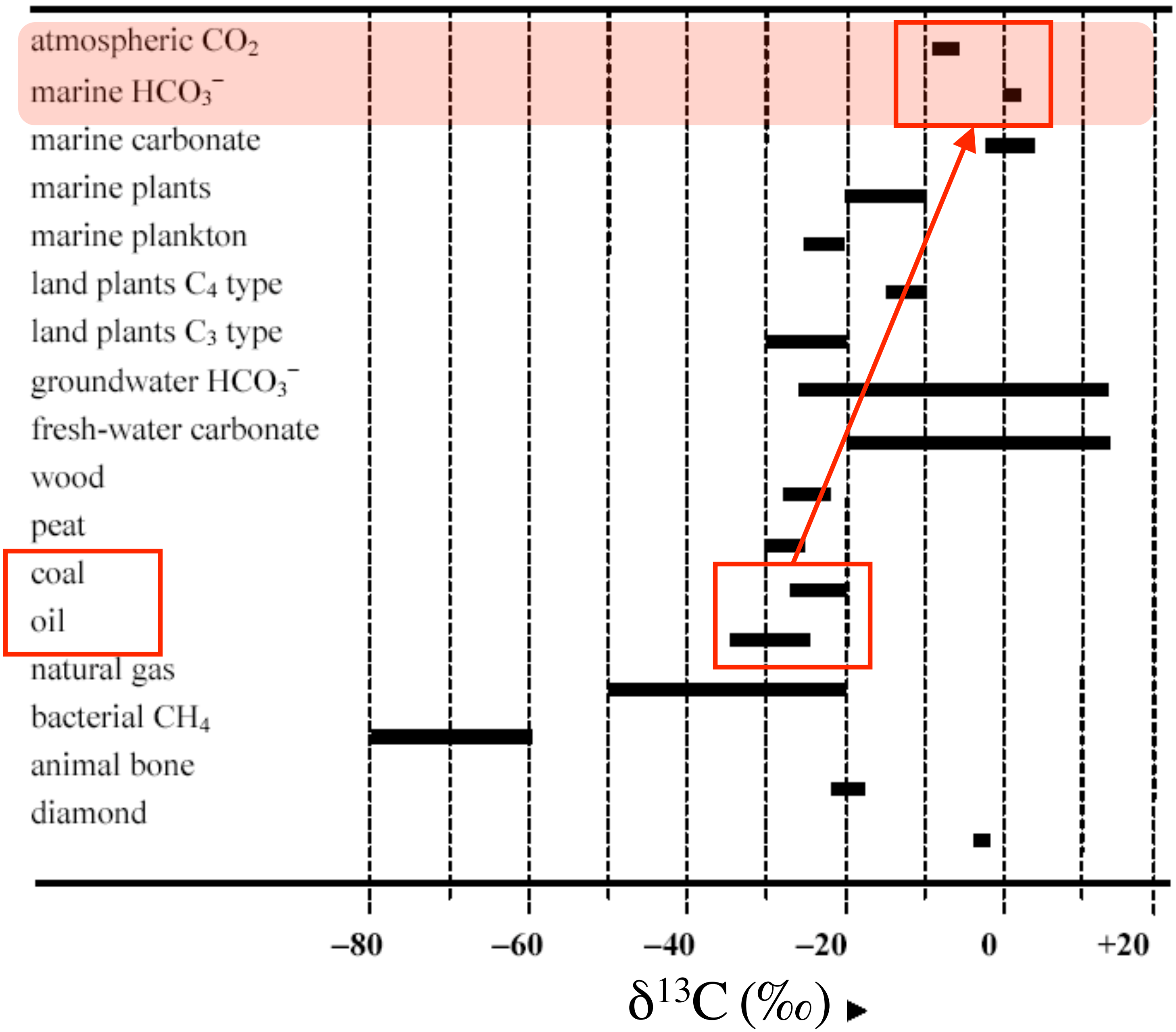
Short- and Long-Term Changes in pCO_2 & Global Warming

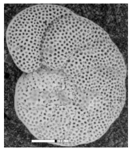
- Are there positive (amplifying) feedbacks that might accelerate the rate of rise in pCO_2?
  - ✓*Stratification/ocean mixing (~10^2y)*
  - ✓*Methane hydrates (~10^3y)*
- How fast will negative (damping) feedbacks sequester carbon & restore steady state?

Ocean Uptake of Anthropogenic CO_2

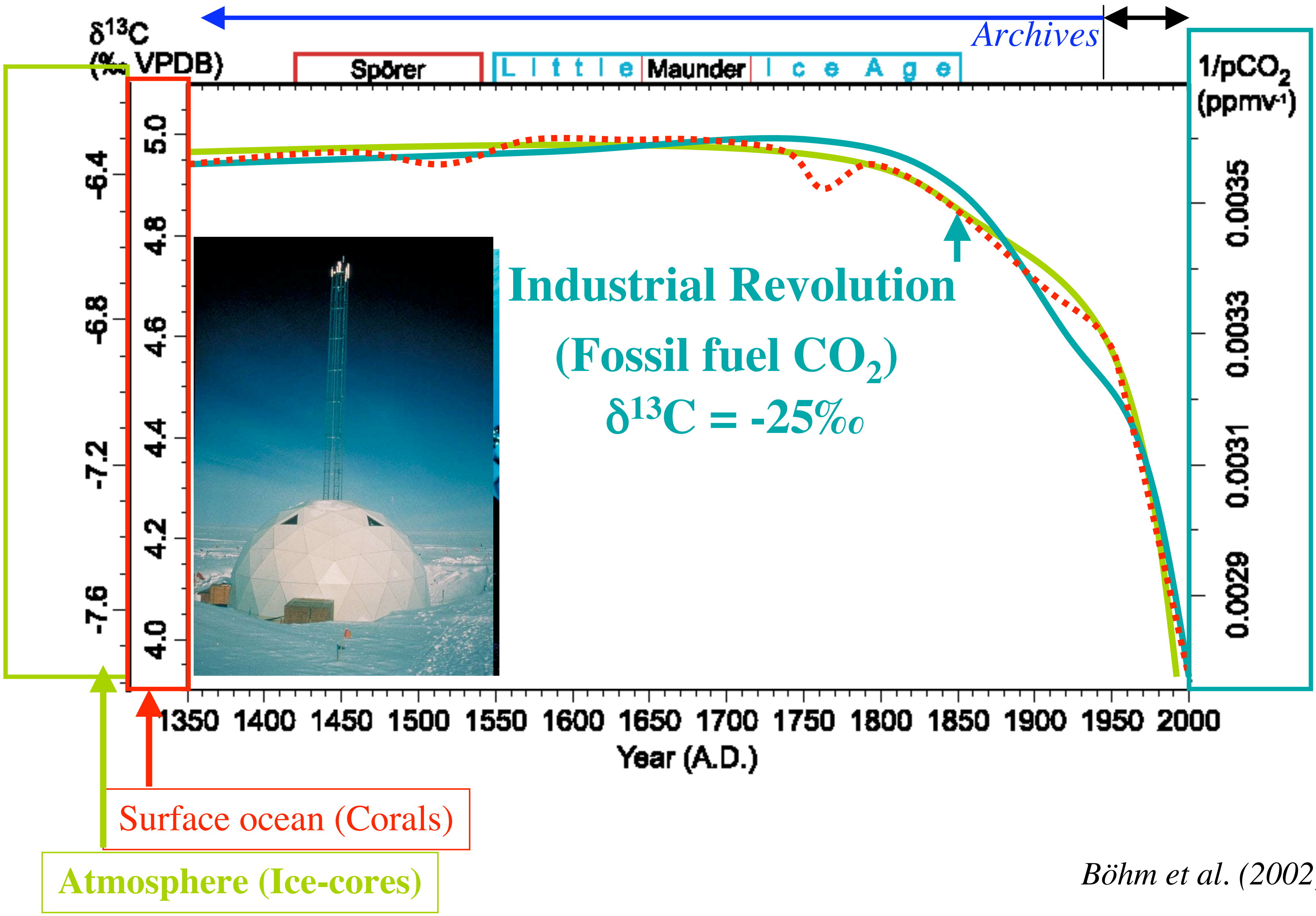


Carbon Isotope Signature of Fossil Fuel C





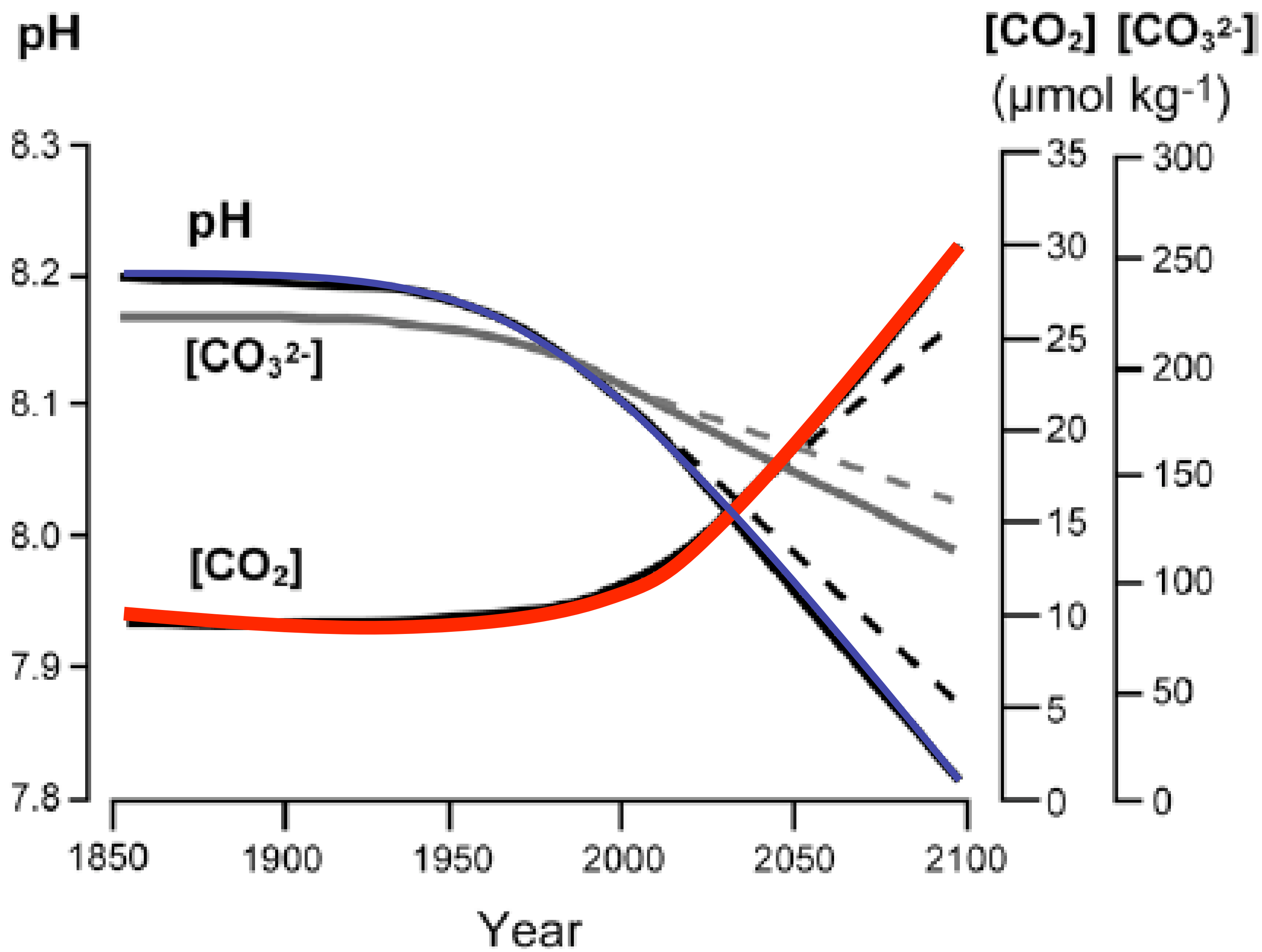
Atmosphere pCO_2/Surface Ocean $\delta^{13}C$
Last 650 y



Böhm et al. (2002)

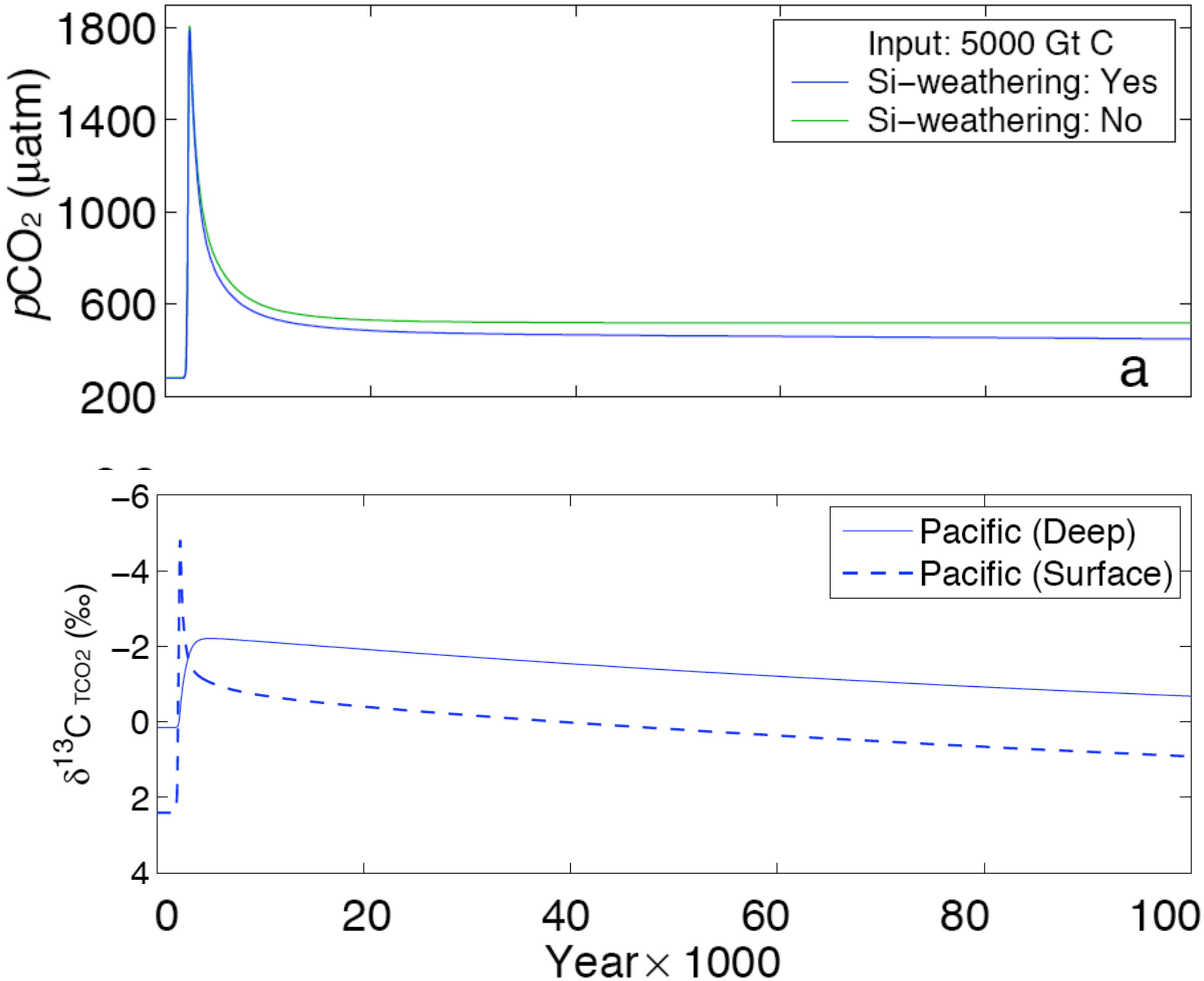
pCO_2, Ocean pH & Carbonate Ion

Next 100 years



Atmosphere pCO_2/Ocean pH & $\delta^{13}C$

Next 100,000 years

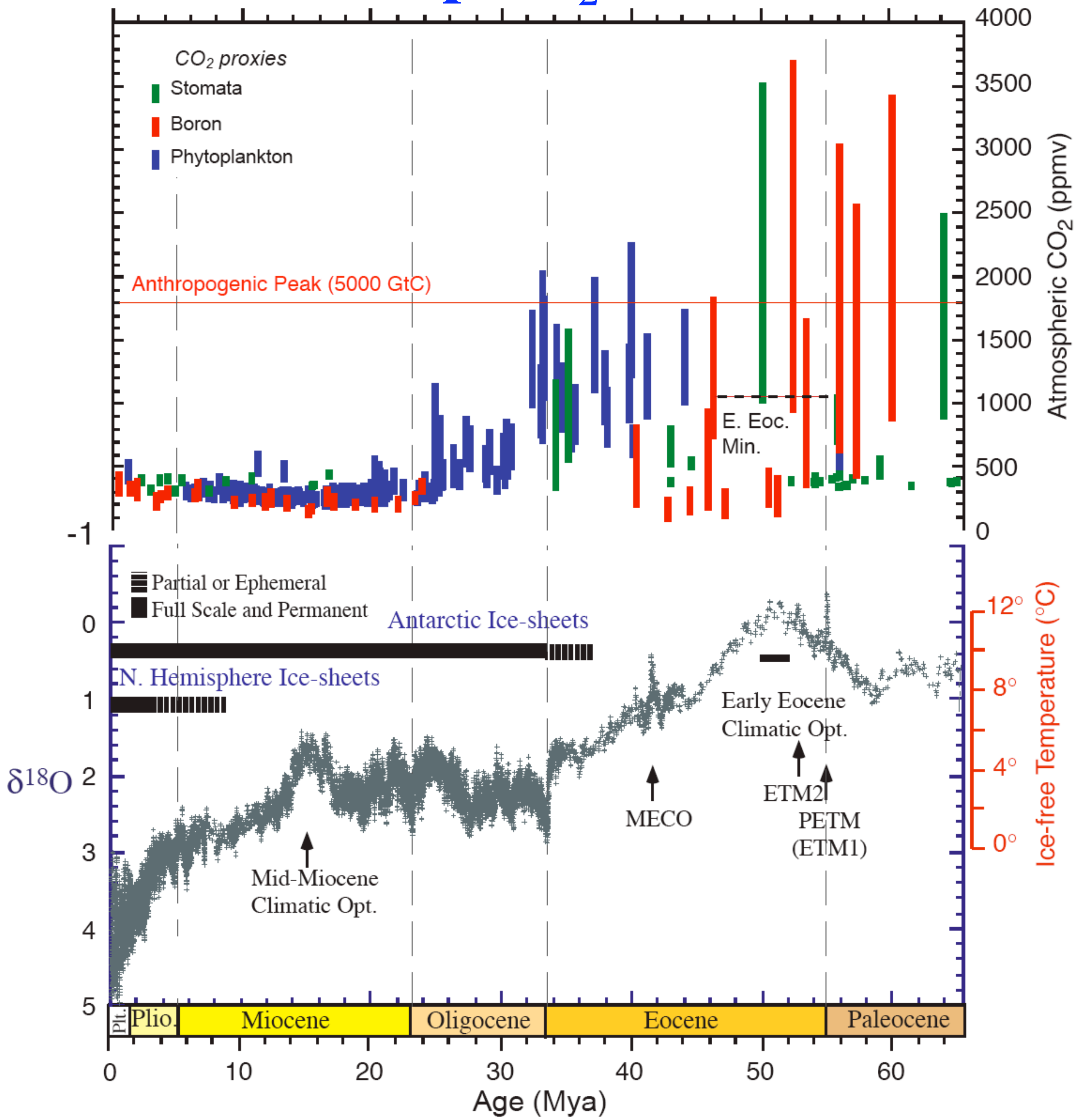


Zachos, Dickens, Zeebe,
(In press) *Nature*

How can we assess numerical predictions of short- and long-term changes in the carbon cycle?

Past greenhouse events with similar magnitude/rate of change in CO_2

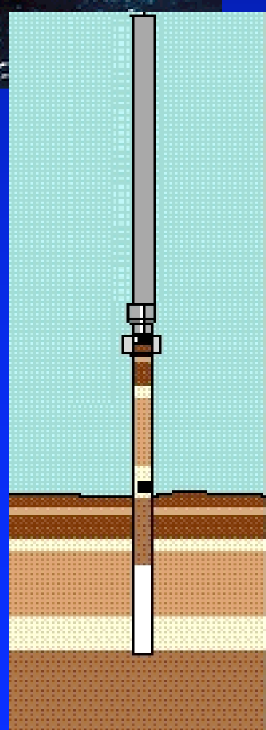
Cenozoic pCO_2 & Climate



IPCC (2007);
Zachos et al.,
(In press) *Nature*

Deep Sea Sediments: Archive of Ocean History

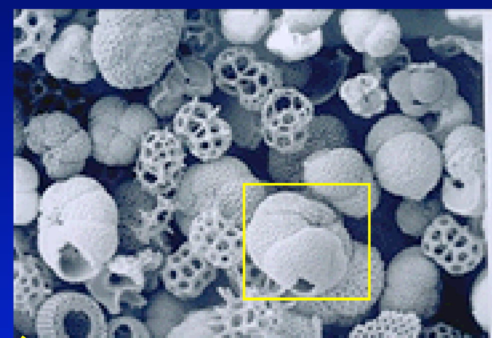
Microfossil shell chemistry provides information on ocean temperature & carbon chemistry

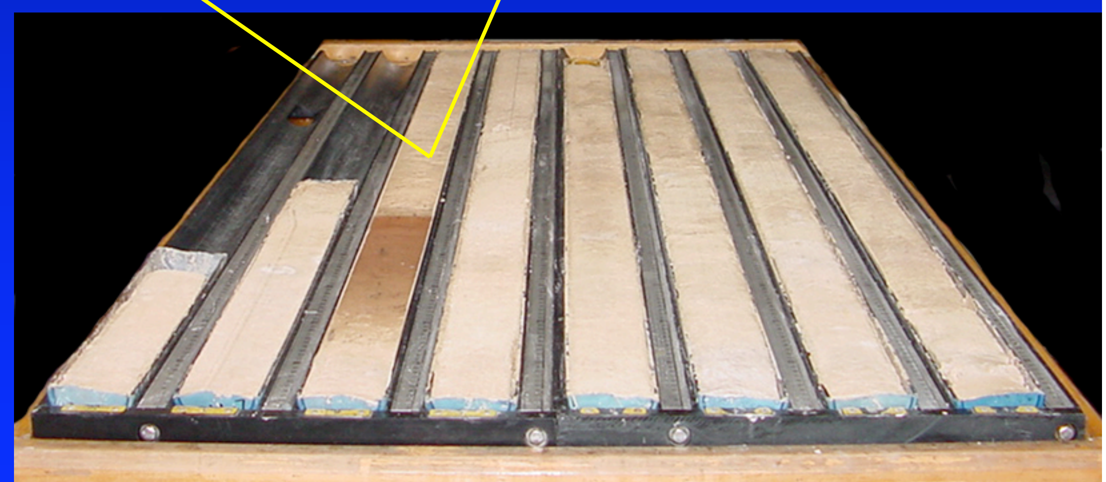


Meters below sea floor (mbsf)

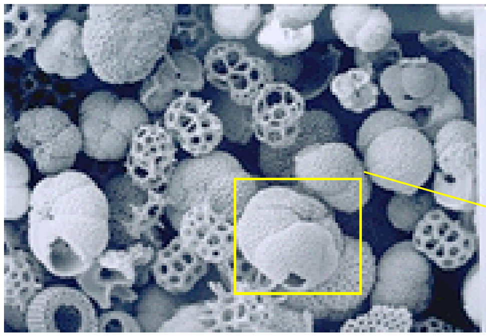
Present

Past





Reconstructing Ocean History with Stable Isotopes of Microfossils in Deep-sea Sediments



Foraminifera shells
~ calcite ($CaCO_3$)

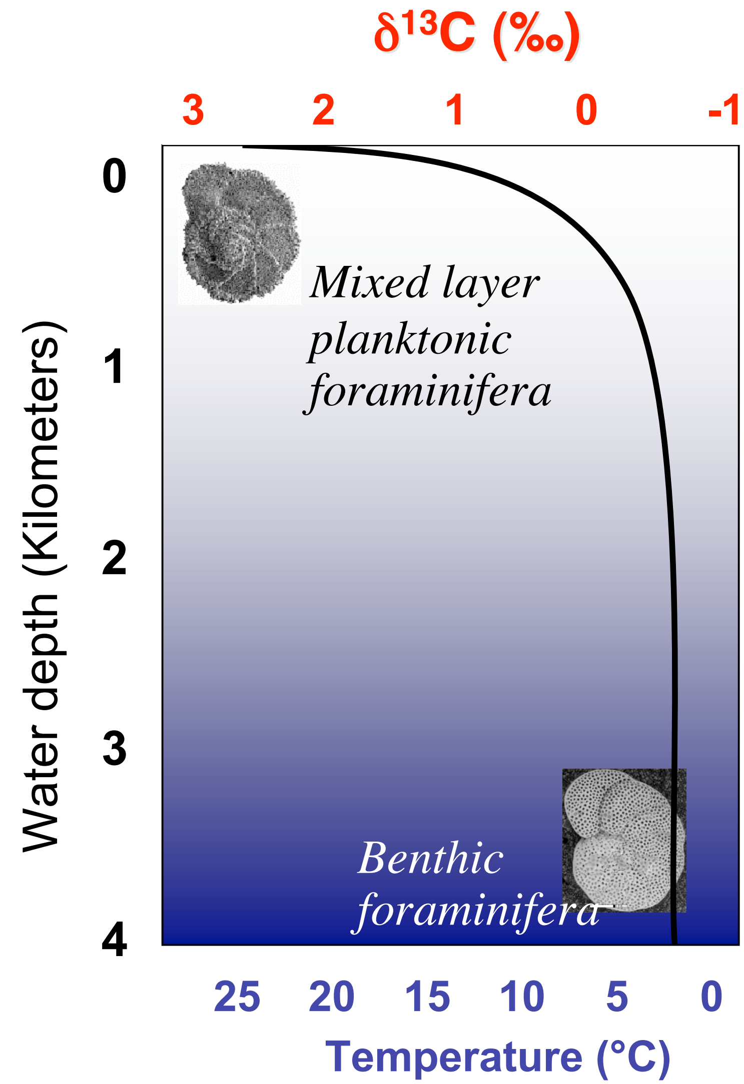
Mass Spectrometers

CO_2

Isotopes: $^{13}C/^{12}C$ $^{18}O/^{16}O$
Notation: $\delta^{13}C$ (‰) $\delta^{18}O$ (‰)

Δ Ocean Temperature
As T increases, $\delta^{18}O$ decreases 1‰ ~ 4°C

Dissolved inorganic carbon (DIC) of seawater. Mean $\delta^{13}C_{DIC}$ of the ocean varies with changes in the input and output of reduced and oxidized carbon

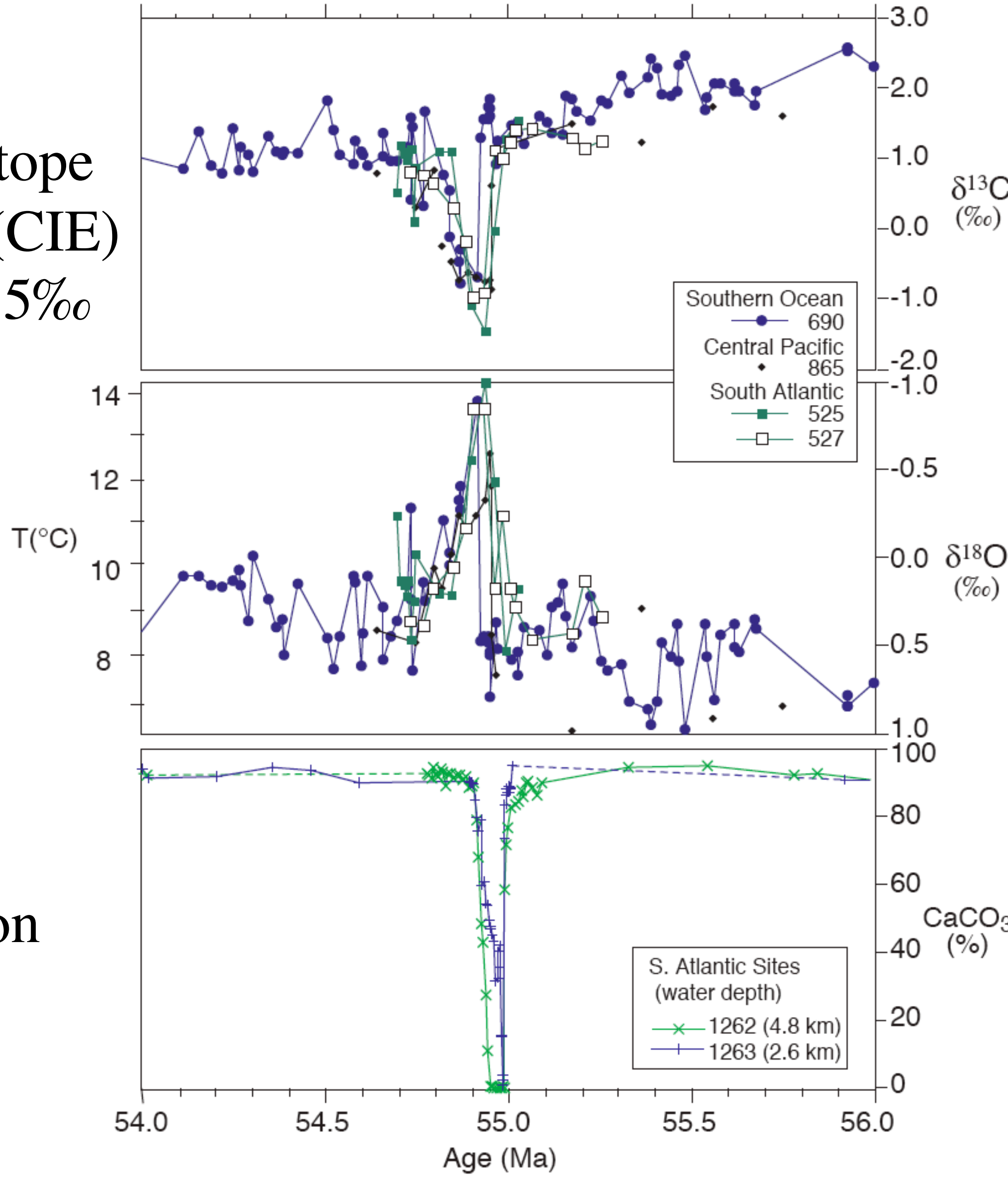


Paleocene-Eocene Thermal Maximum (PETM)

- Carbon Isotope Excursion (CIE)
- $\Delta\delta^{13}C$ = -2.5‰

- Warming
- ΔT = 5°C

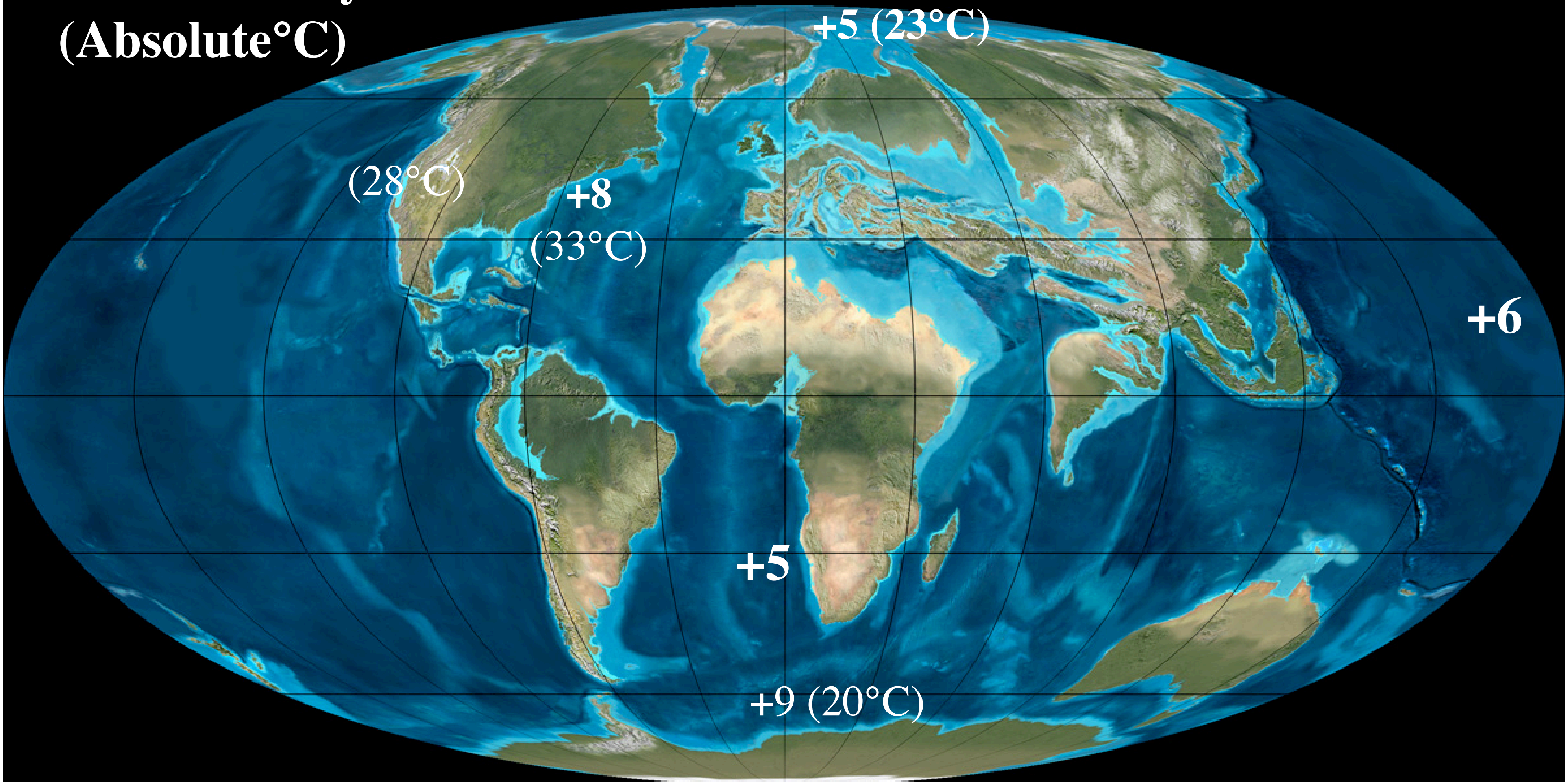
- Ocean Acidification



Zachos, Dickens, Zeebe, (In press) *Nature*

Paleocene-Eocene Thermal Maximum (PETM) ~ 55 Mya

SST Anomaly (Absolute°C)



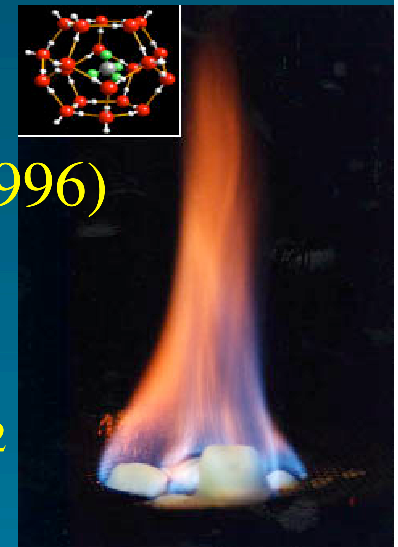
Temperature anomalies estimated from $\delta^{18}O$, Mg/Ca, and TEX_{86} Proxies

Kennett & Stott, 1991; Zachos et al., 2003; 2006; Thomas et al., 2002; Sluijs et al., 2006; John et al., submit.

Some Climatic/Environmental Consequences of the PETM

- Increased aridity in low-latitudes
- Increased precipitation in high-latitudes
- Increased seasonality in precipitation
- Increased frequency of extreme weather events & wildfires
- Changes in the diversity/abundances of fauna & flora
  - Migration, extinction (minor), reduced diversity
  - biogeographic boundaries shift poleward
- Sea level rise of 15 meters
  - 3-5 meters thermal expansion

Primary Source of Carbon?



Decompositon of Methane Hydrate - (Dickens et al., 1996)

- Bacterial, $\delta^{13}C$ = -60‰.
- ~2000-10000 Pg C (modern reservoir)

Mantle Plume/Mid-ocean Ridge Volcanism - CH_4/CO_2 (Svensen et al., 2004)

- Thermal Corg decomposition, $\delta^{13}C$ = -7 to -25‰
- Emission rate? 0.1-0.5 Pg C/y

Dessication & Oxidation of Corg (soils/sediments

- Forest peats/bogs/swamps/other? - $\delta^{13}C$ = -20 to -25‰
- Collectively >5000 Pg C

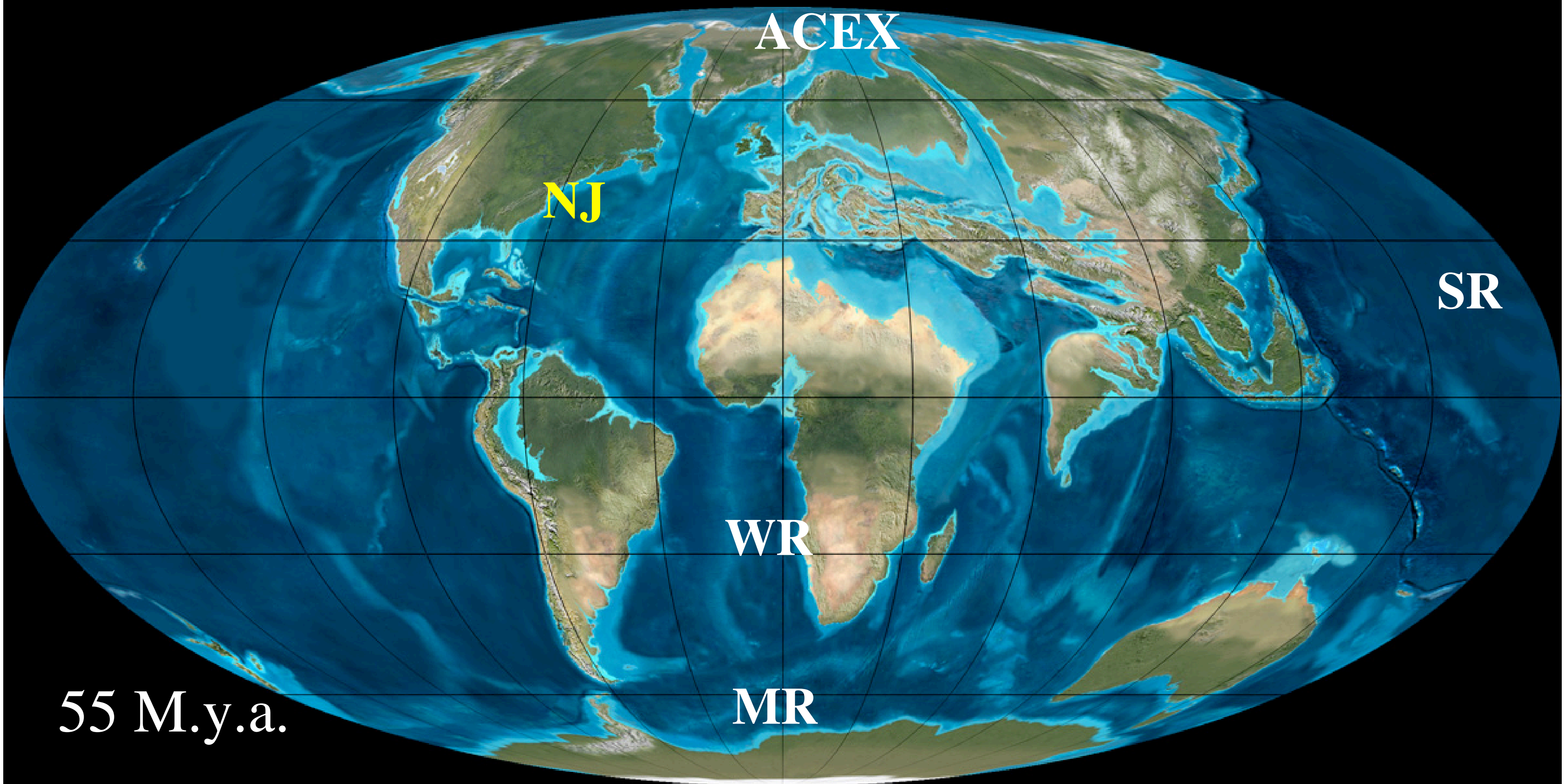
Positive Feedbacks?

e.g., gradual warming of the ocean destabilizes methane hydrates

Source of the Massive Carbon Flux?

- Single or multiple?
- Rate of release?
  - ✓Higher-fidelity records
  - ✓Single shell strategy
- Mass of carbon?
  - ✓Carbon isotope excursion (CIE)
  - ✓Carbonate saturation changes

Key PE Boundary Sections



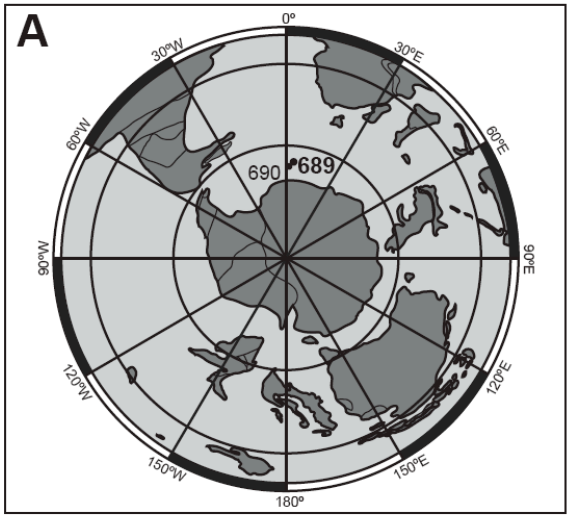
ACEX - Arctic coring expedition, Lomonosov Ridge

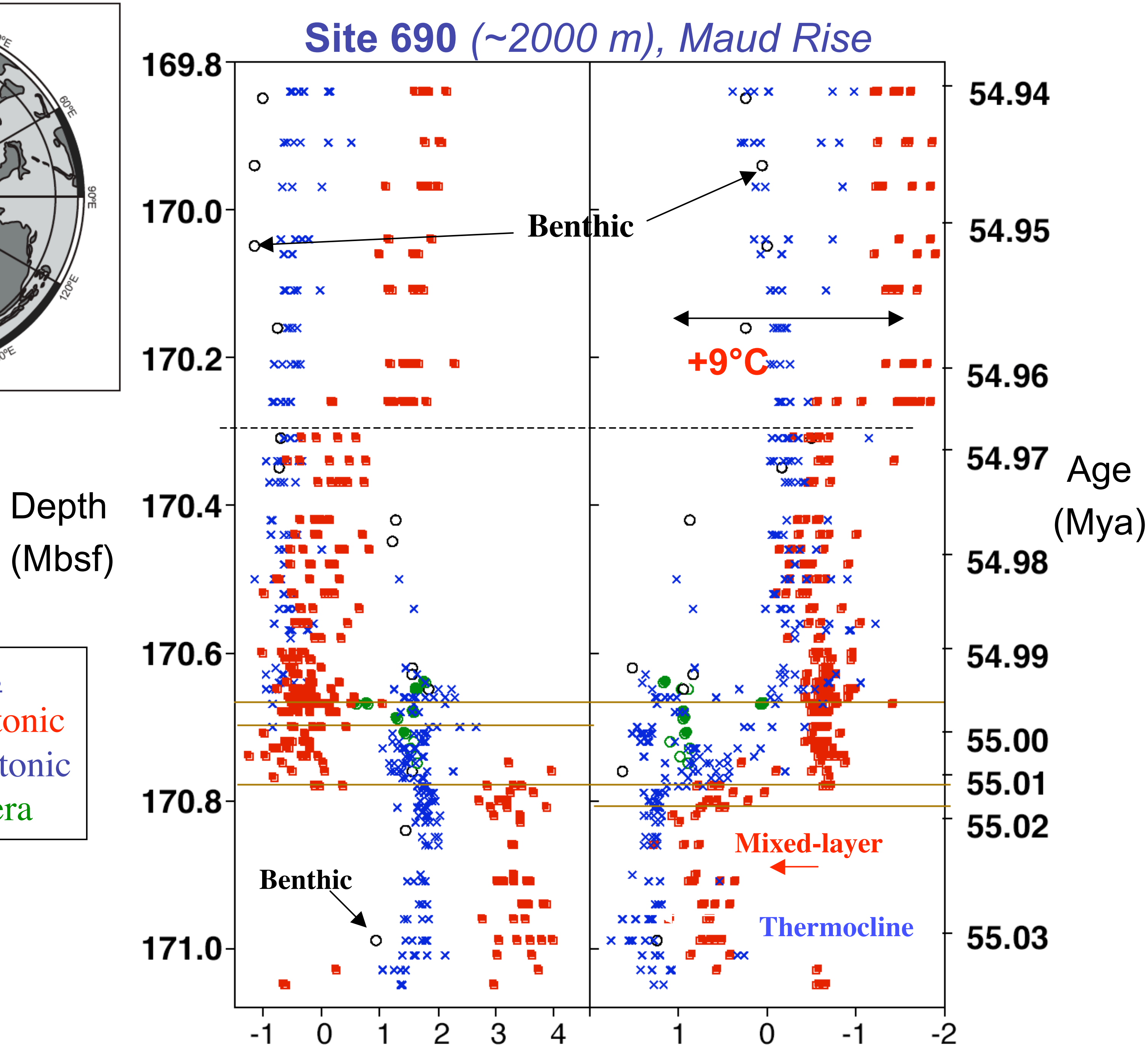
NJ - New Jersey Margin, *Bass River* and *Wilson Lake*

WR- Walvis Ridge (Leg 208), Sites 1262-1267

SR - Shatsky Rise (Leg 198) Sites 1209, 1210, 1211

MR - Maud Rise (Leg 113) Sites 689 and 690

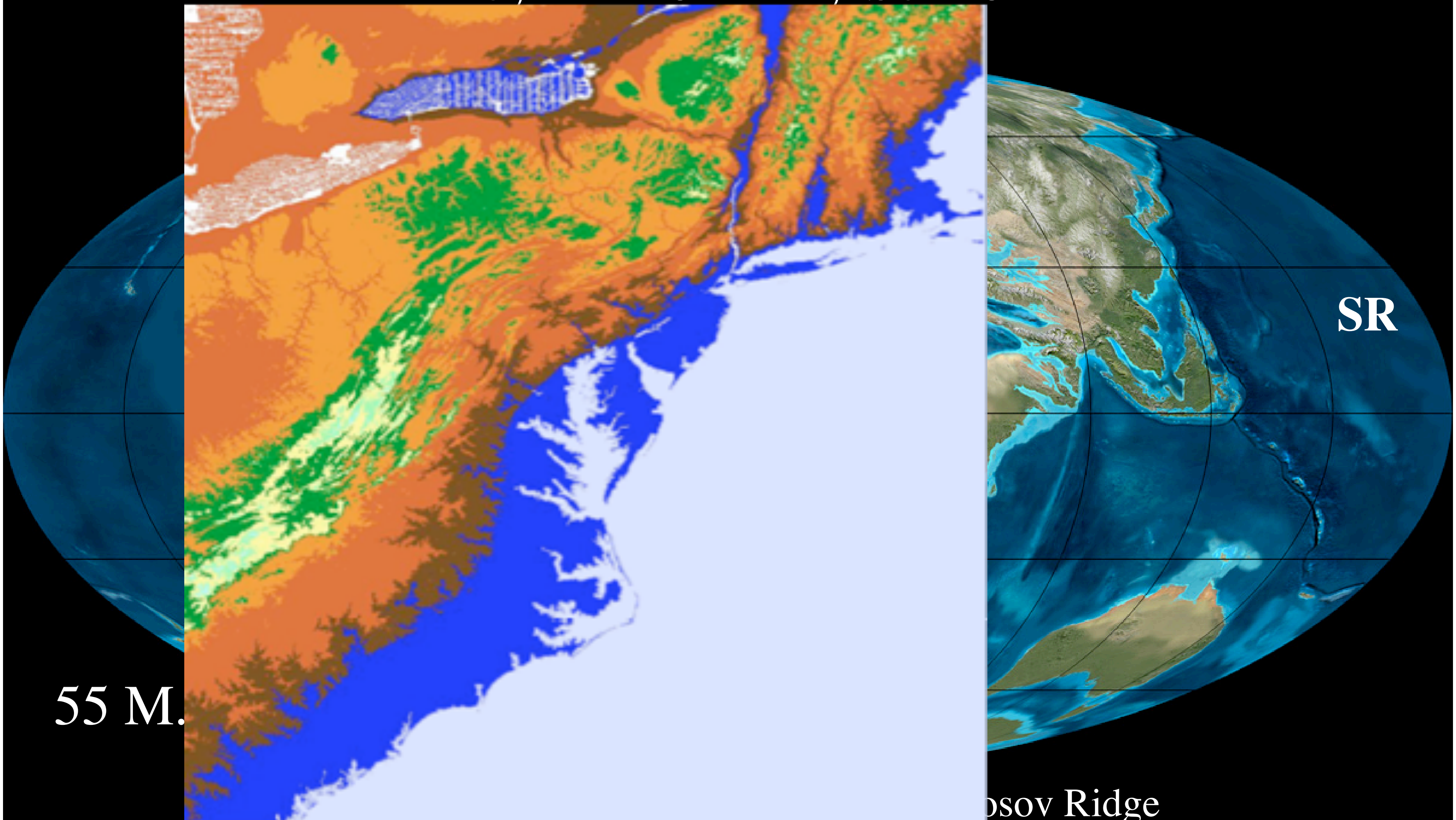




Single shell isotopes
- Mixed-layer Planktonic
- Thermocline Planktonic
- Benthic Foraminifera

Source: Thomas et al., Geology, 2002

Key PE Boundary Sections



55 M.

osov Ridge

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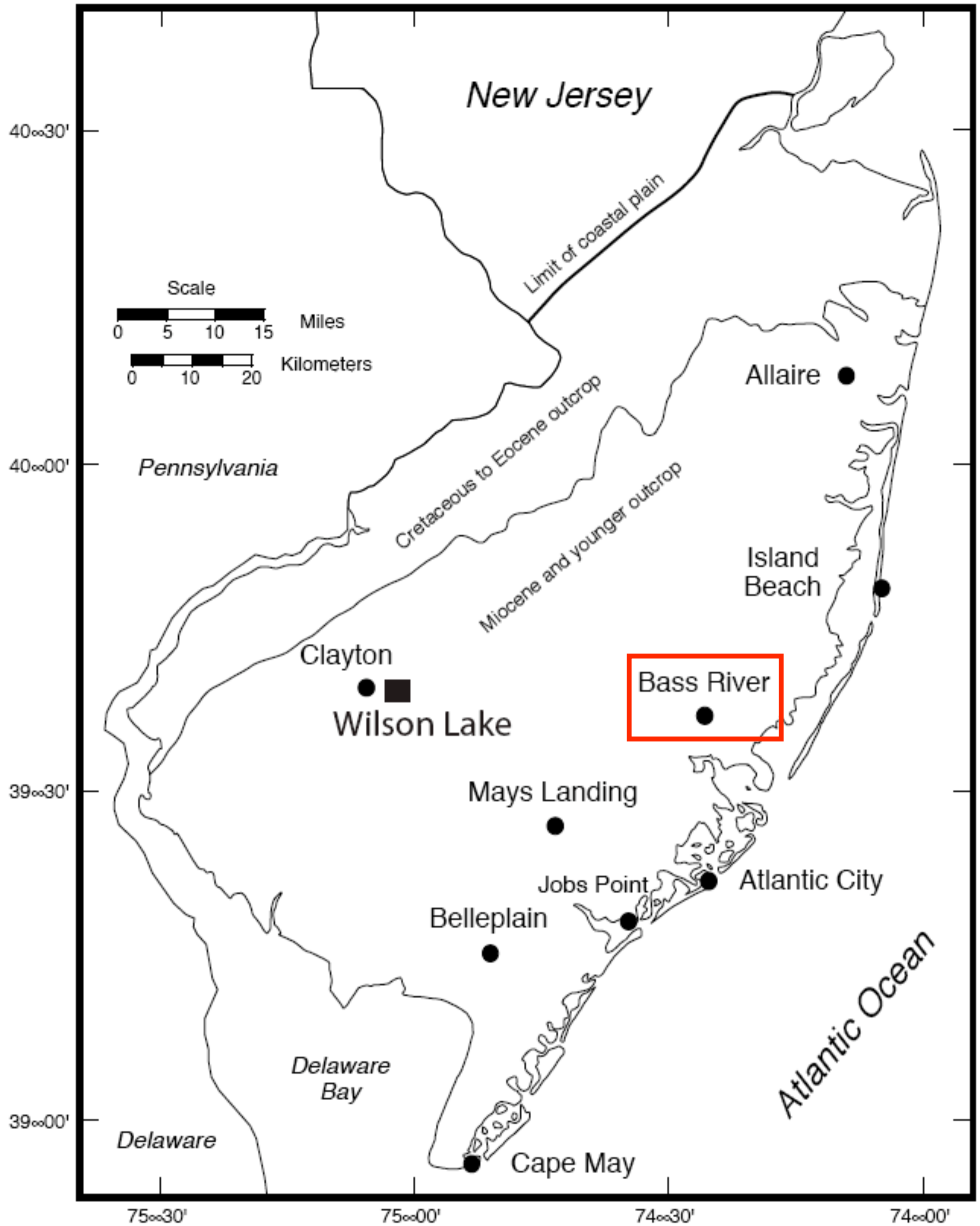
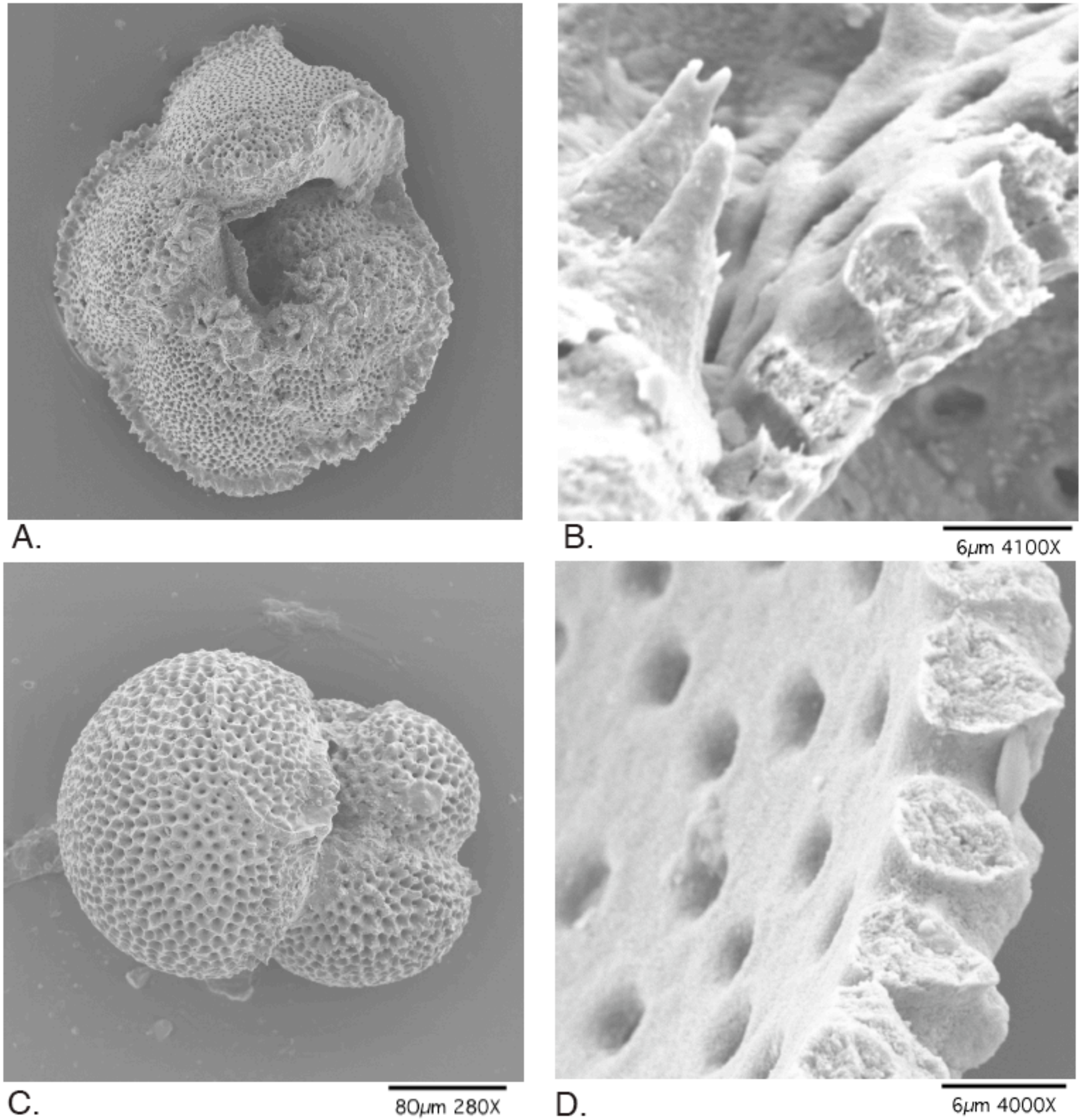
Bass River, NJ

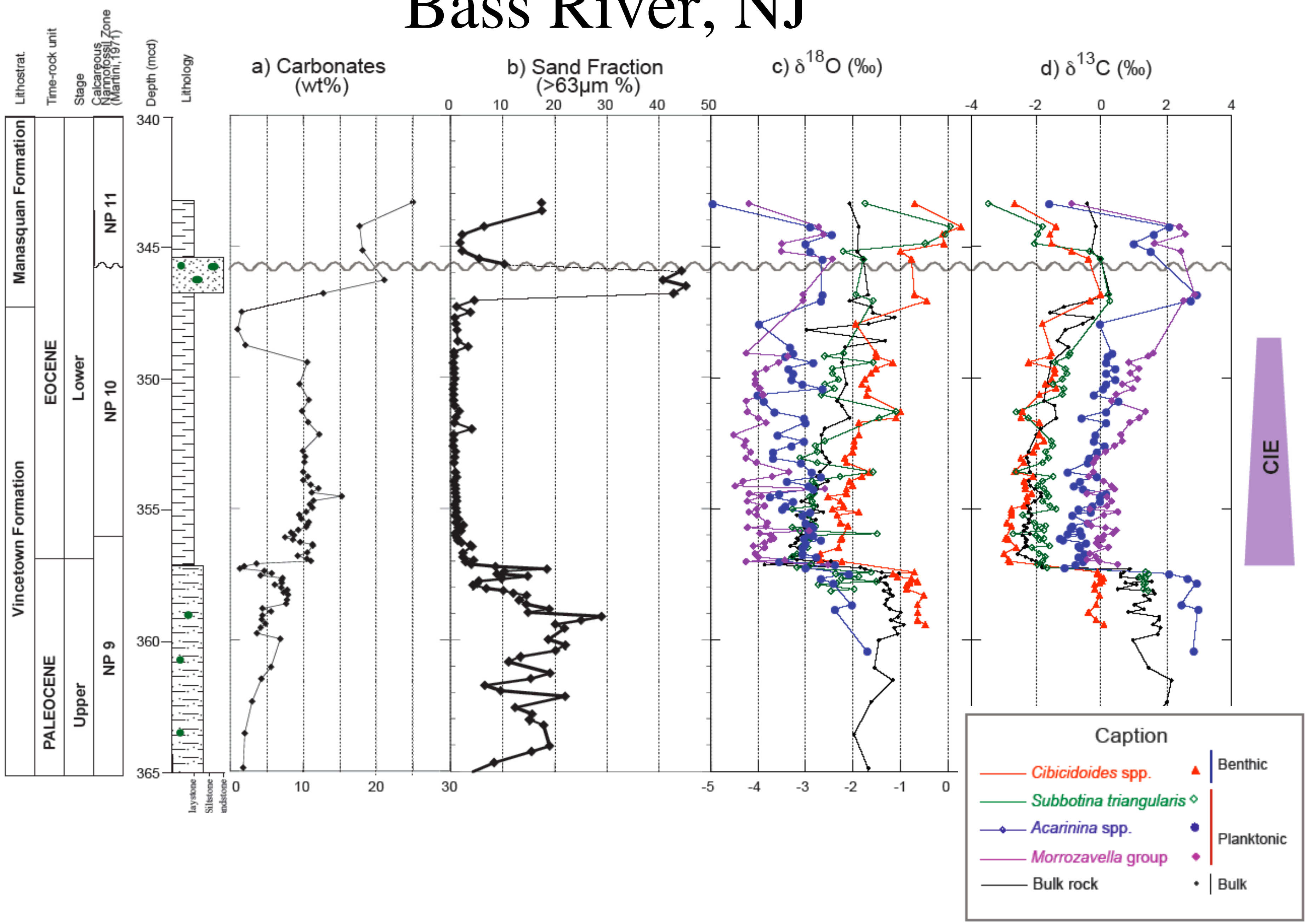
- <u>Mid-Shelf Environment;</u> unconsolidated silici-clastic silts & clay
  - *< 200 meters*
  - *Kaolinite* rich
  - P-E boundary is conformable
  - *Dinoflagellate* blooms
  - Foraminifera - scarce, but well preserved
- <u>High sedimentation rates</u>
  - 5-10x deep sea





Zachos et al., 2006

Bass River, NJ



John et al., submitted

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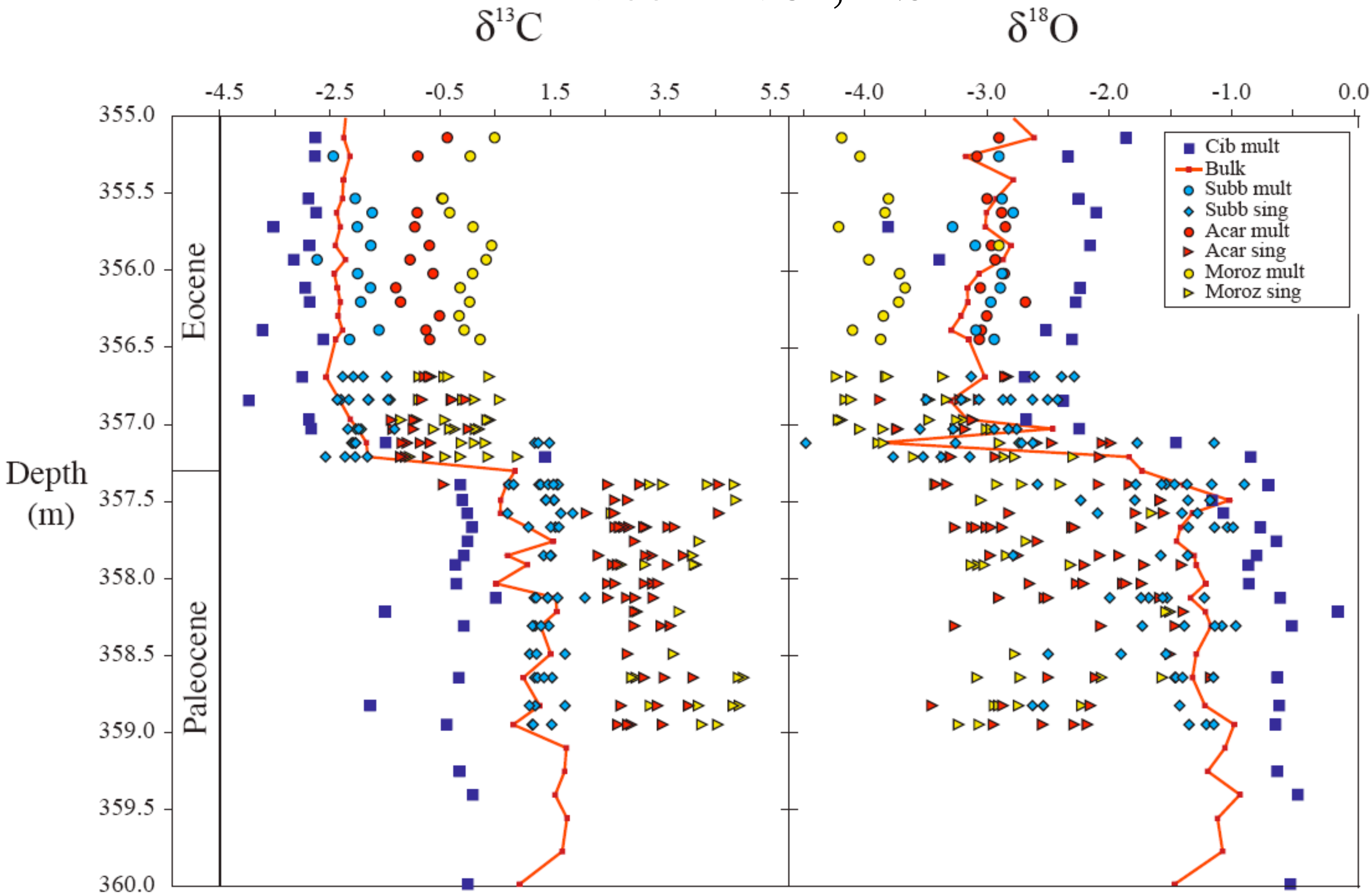
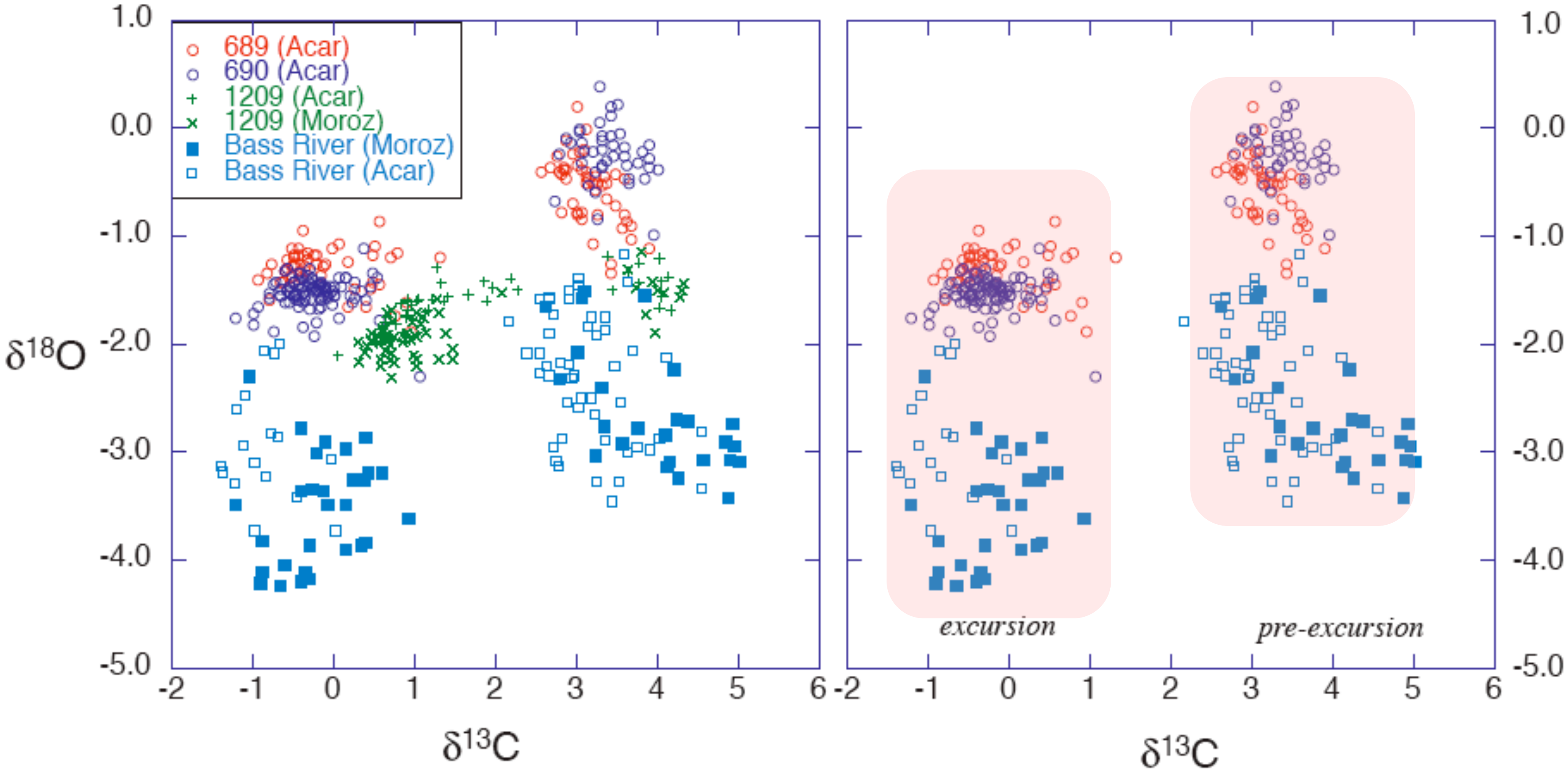


- Multiple/Single Shell Isotope Data

Zachos et al. (2007) Proc.Royal Soc.A

P-E Single Shell C & O-Isotope Data

(Southern Ocean, N. Pacific, N. Atlantic Shelf)



- CIE ~ 4.0‰ (surface ocean)
- Bi-Modal ~ No transitional values

Zachos et al. (2007) Proc.Royal Soc.A

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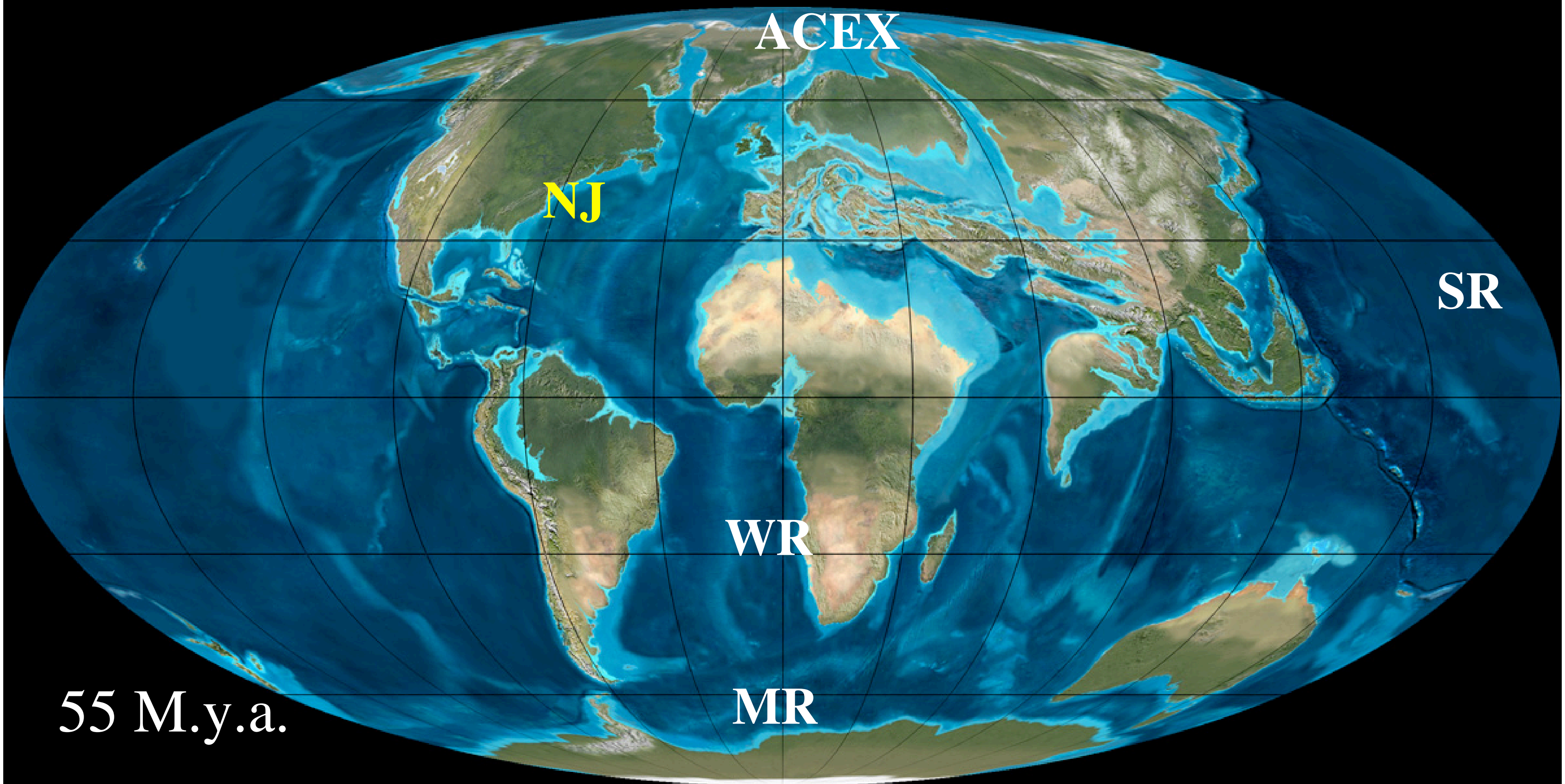

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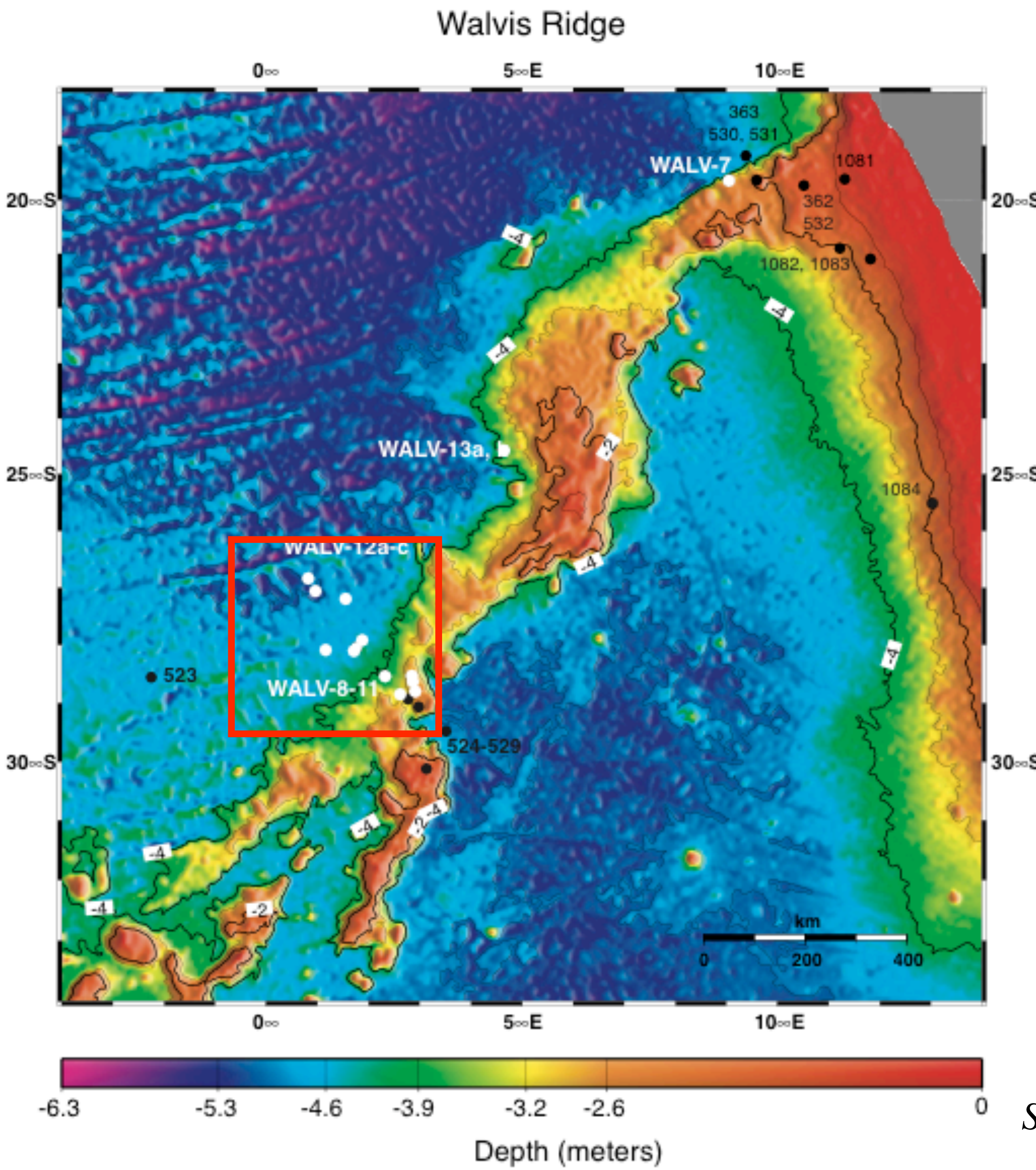
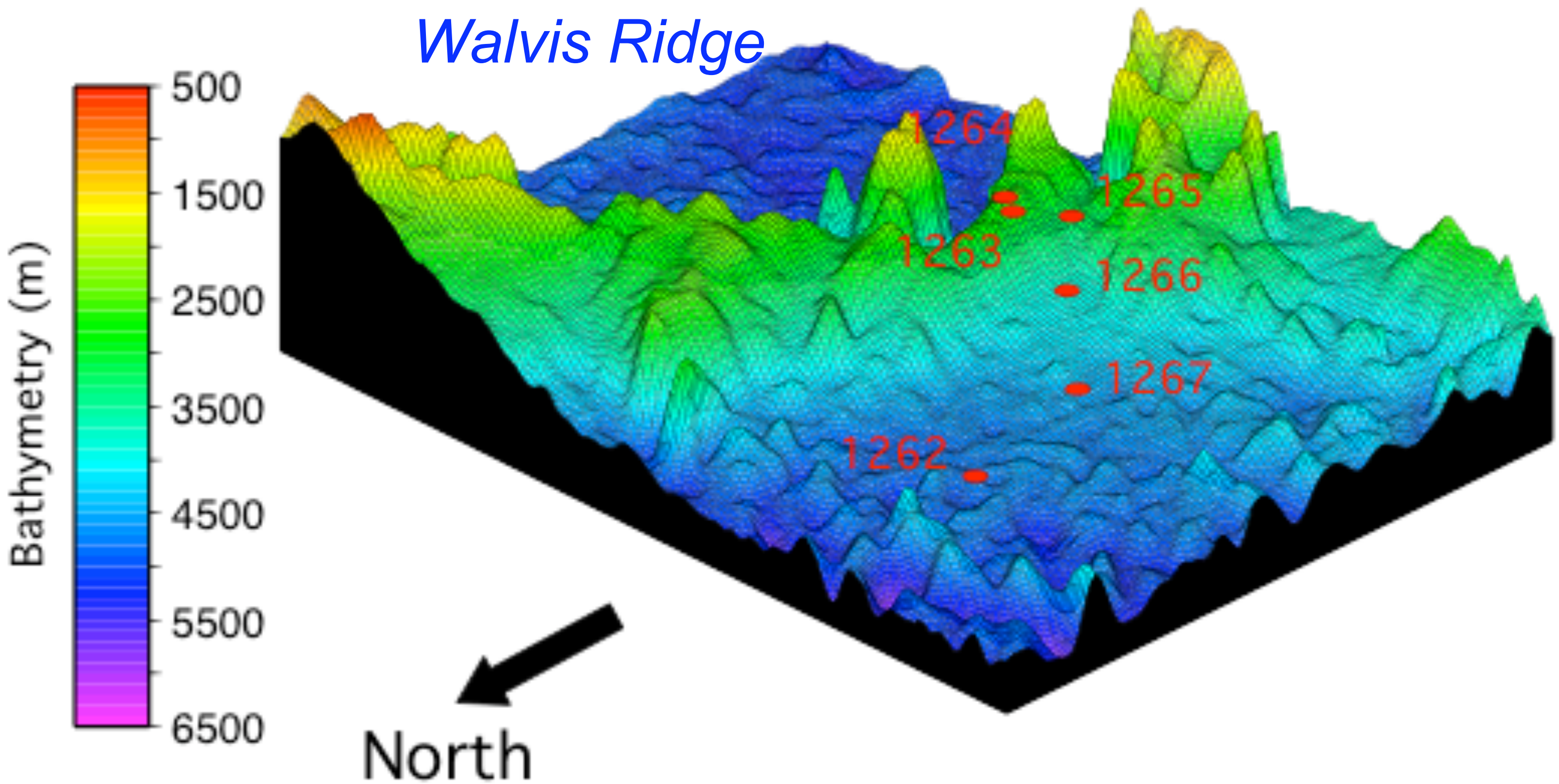
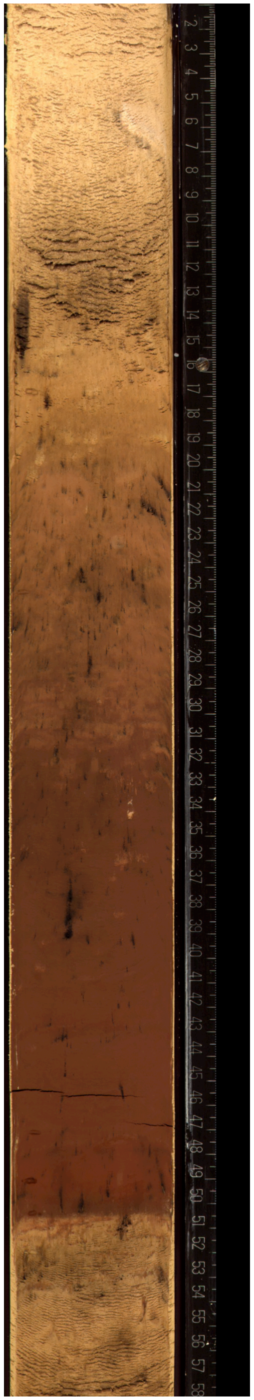


Spiess et al., 2003

ODP Leg 208 Sites

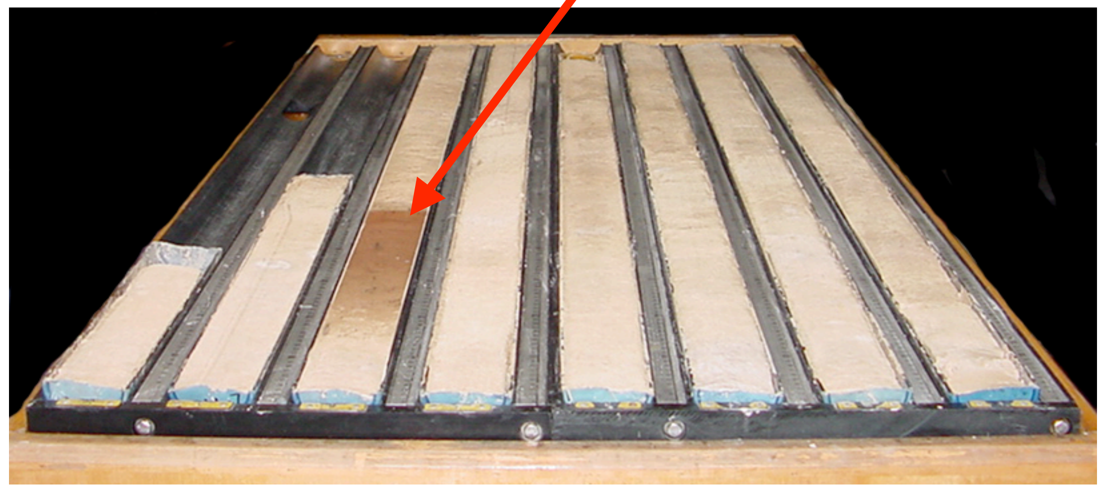


Zachos, Kroon, Blum et al. (2004)



nannofossil ooze

Carbonate Dissolution:
Ocean Acidification

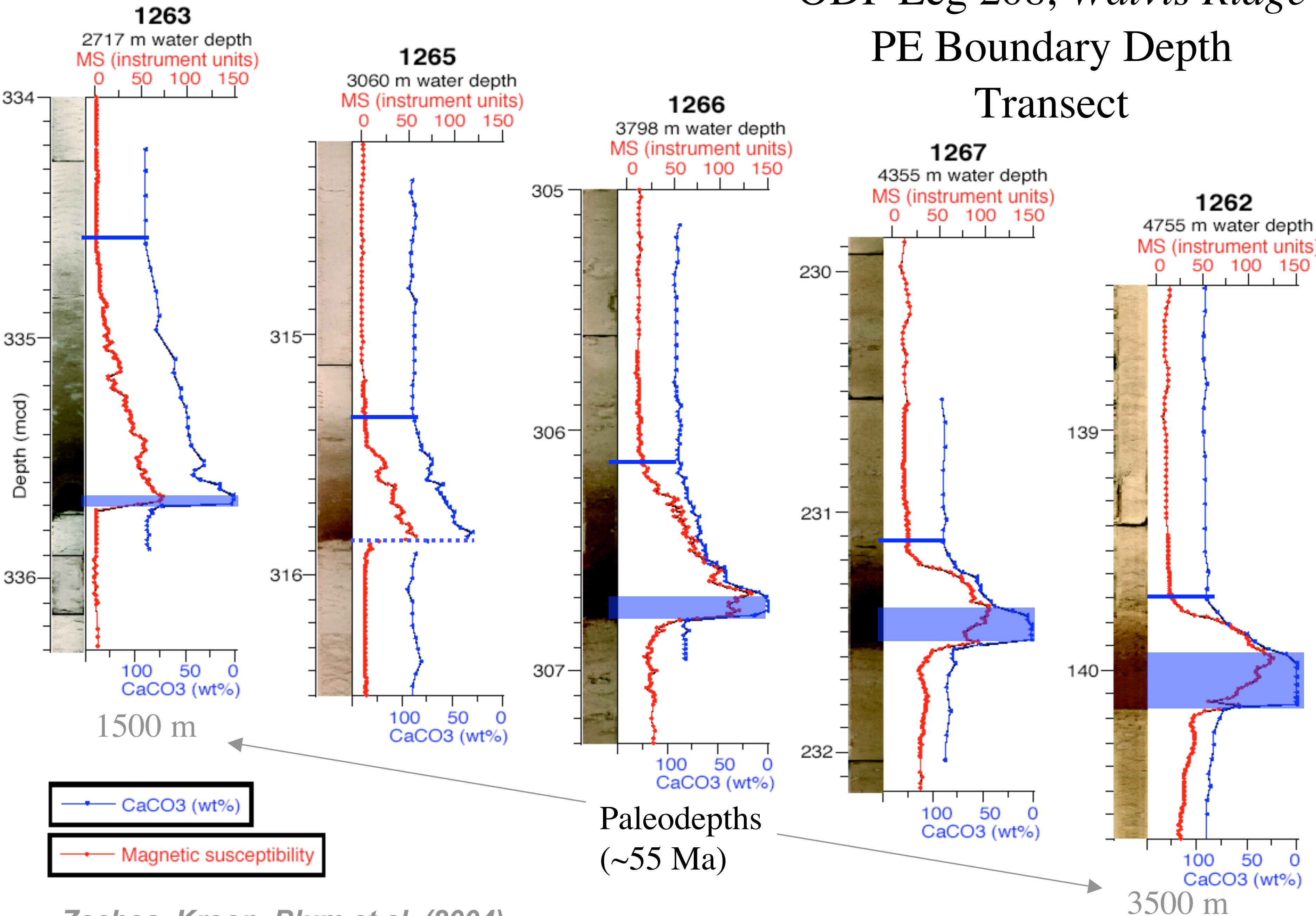


dusky-red clay

nannofossil ooze

Zachos, Kroon, Blum et al. (2004)

ODP Leg 208, *Walvis Ridge* PE Boundary Depth Transect



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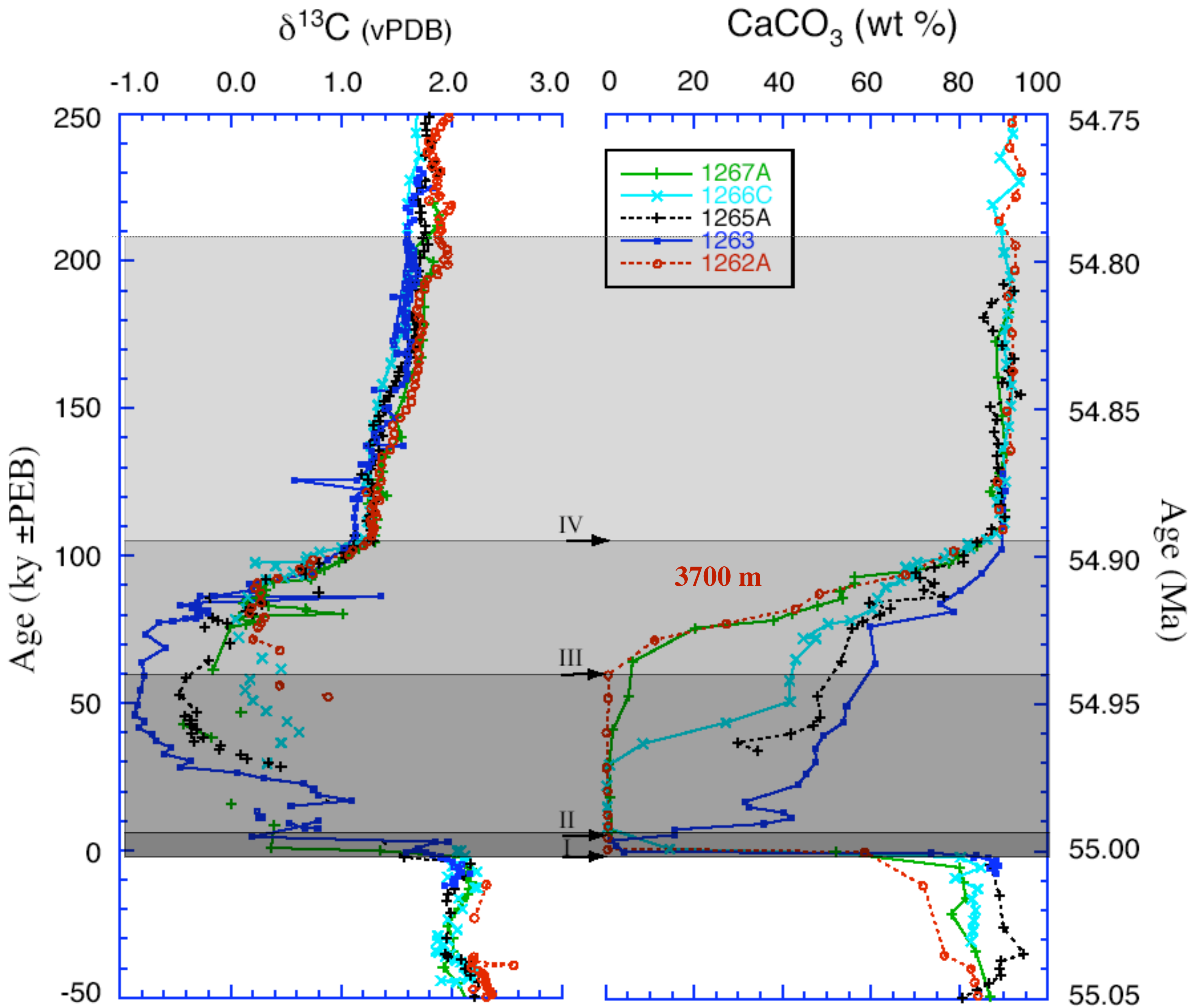
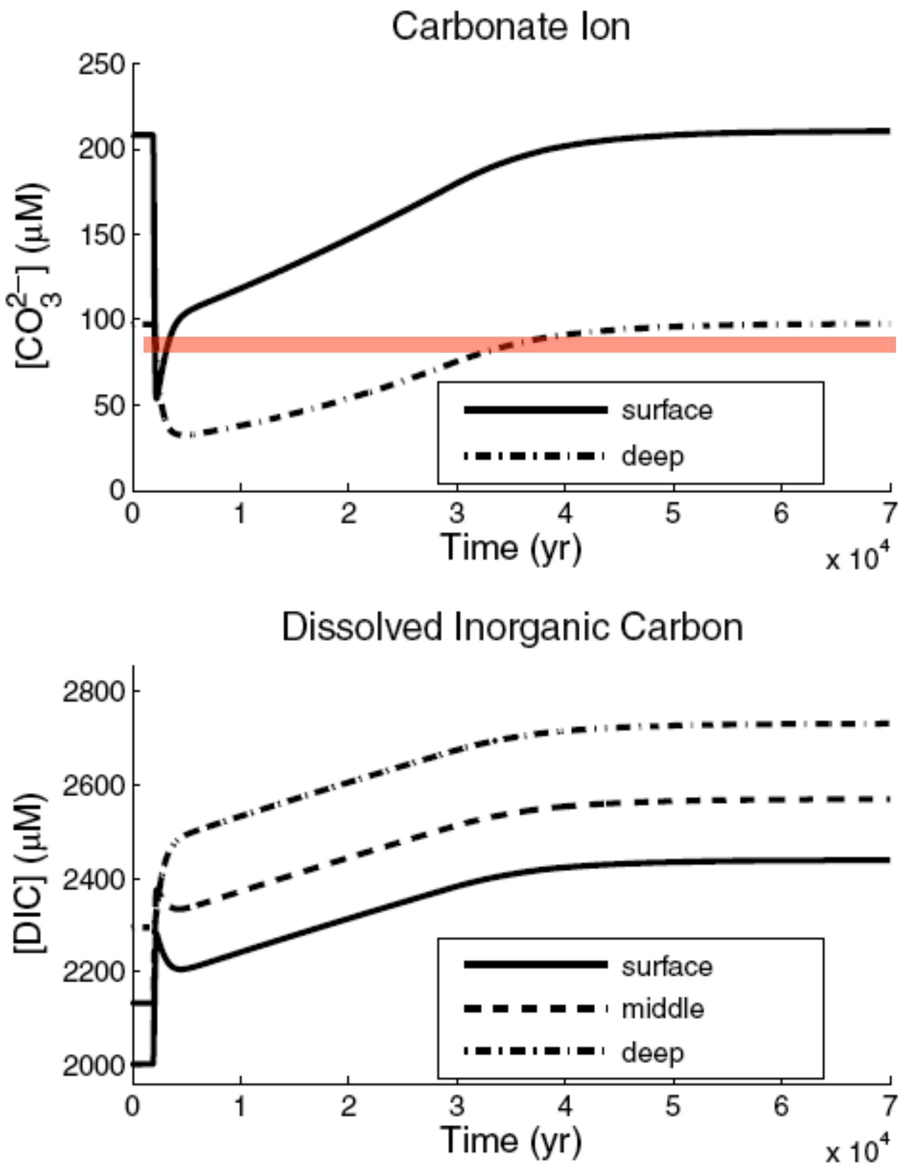


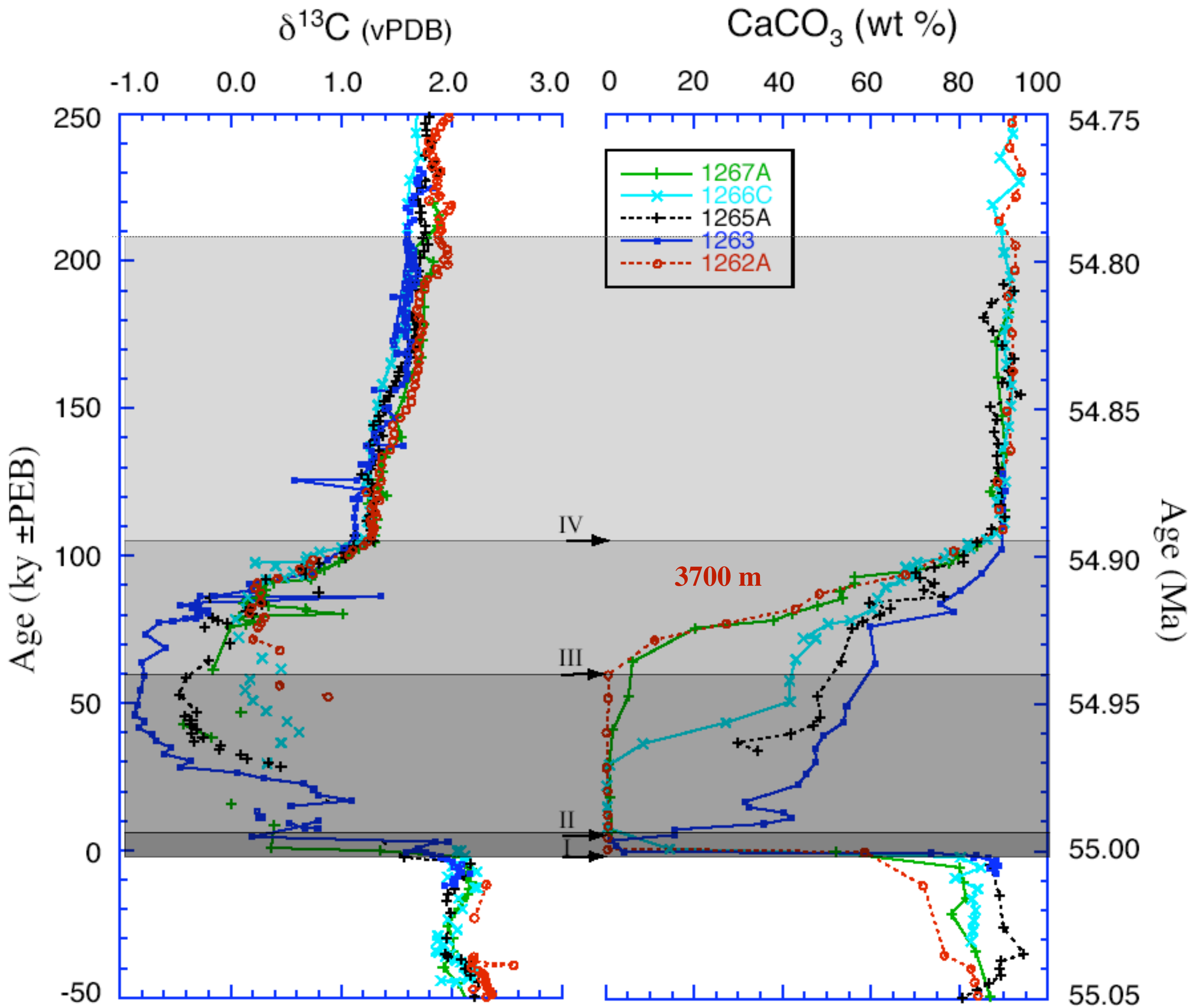
Zachos et al. *Science, 2005*

Ocean Acidification and Chemical Erosion (5000 Gt C)



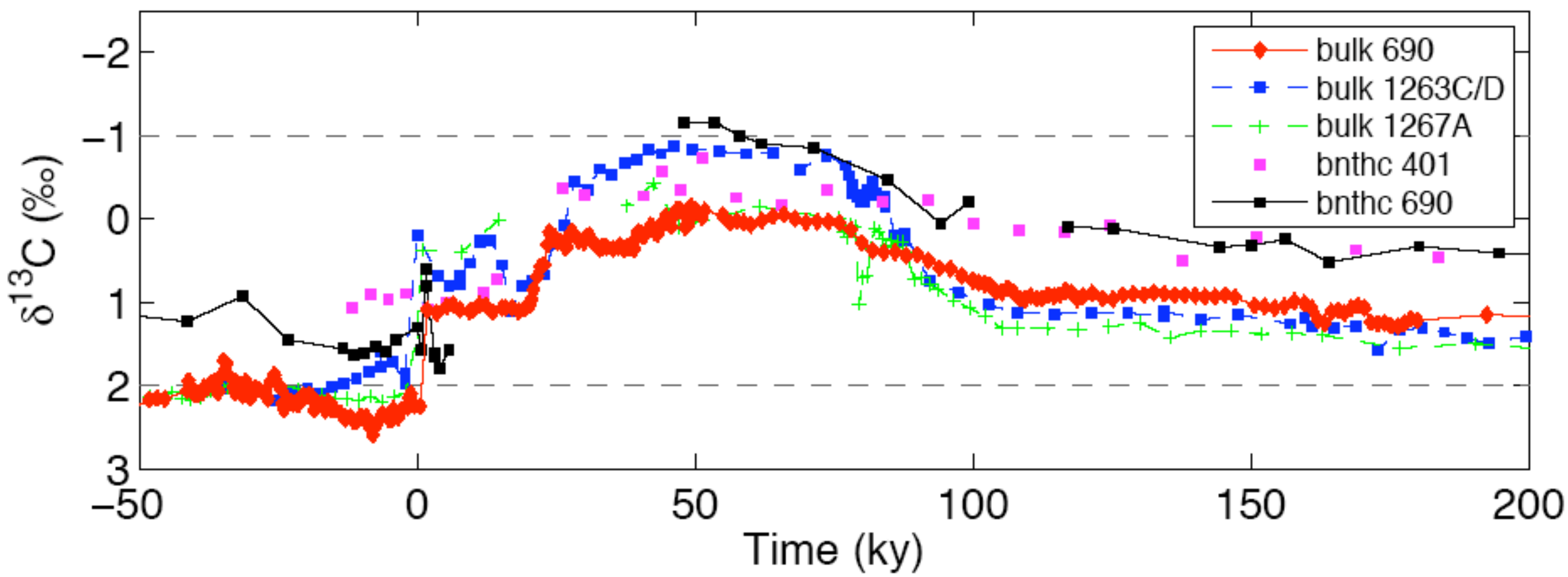
No $CaCO_3$ deposition

Tyrell et al, 2007



Zachos et al. *Science, 2005*

PE Carbon Isotope Excursion

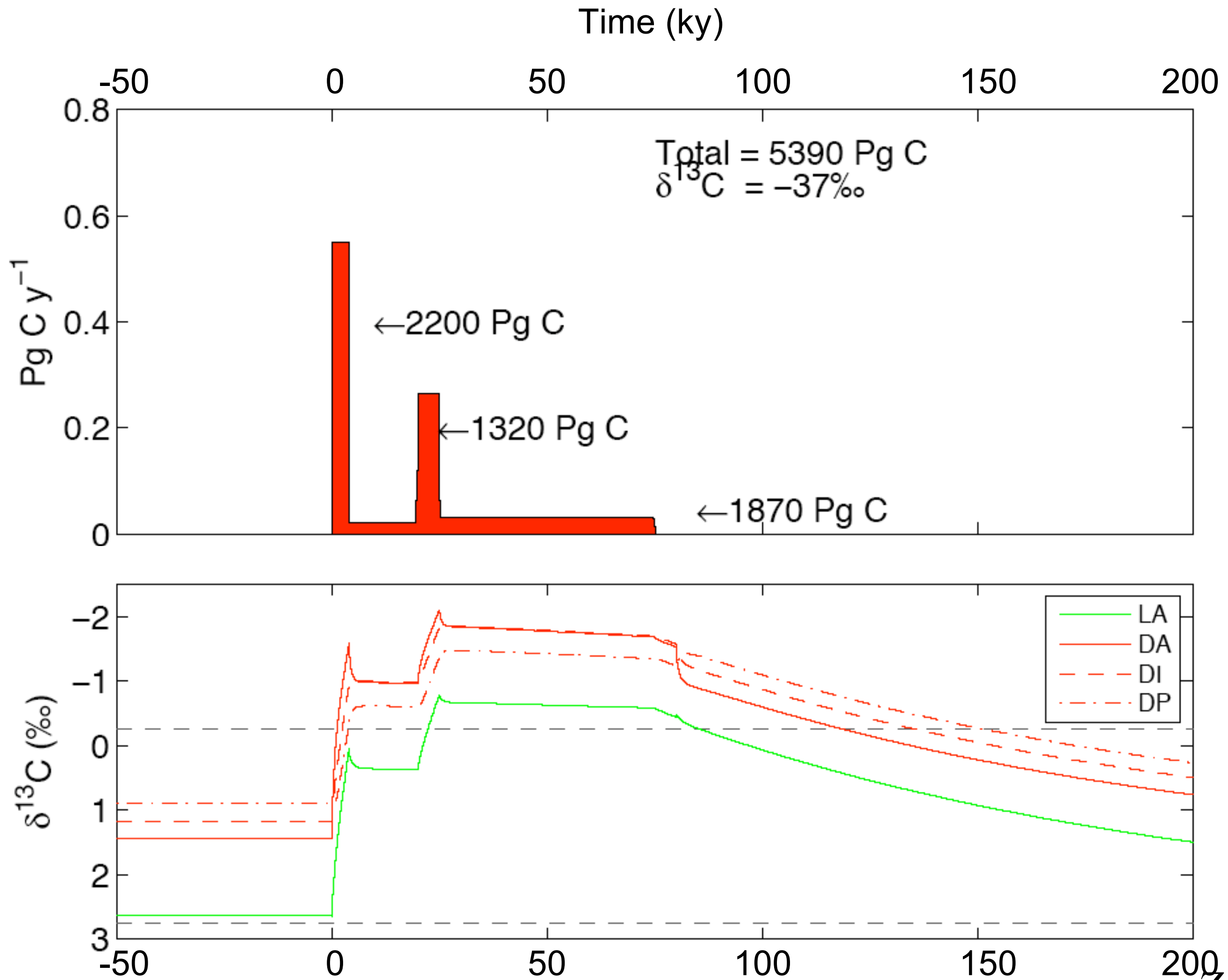


- Bulk Sediment C-Isotope Records
- Structure of CIE?
- Dissolution/Reworking

Zeebe et al, in prep

Simulating Massive Carbon Input

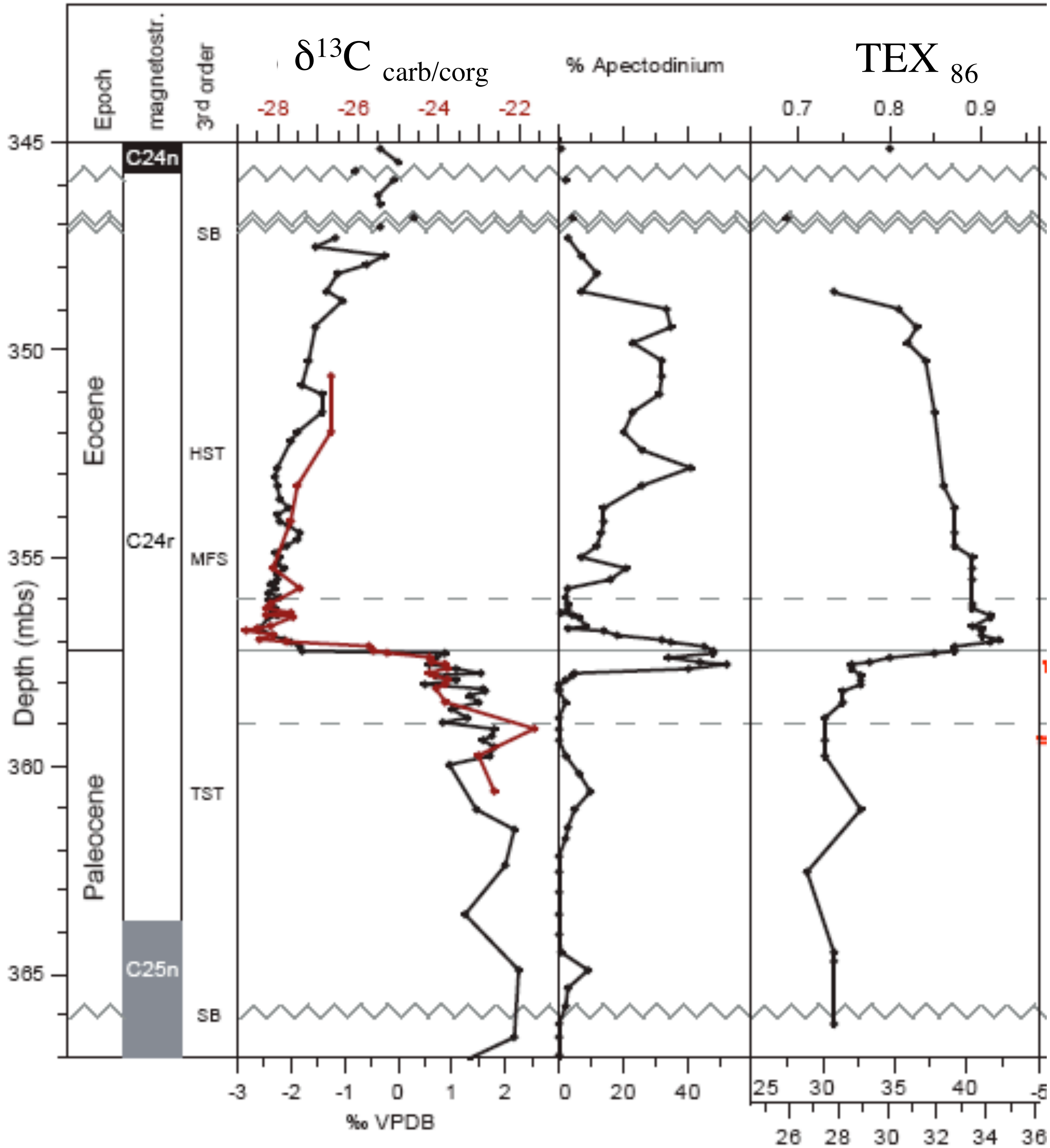
- Carbon Cycle Box Model (Walker & Kasting, 1993)
- Ocean/Atmosphere reservoirs



Zeebe et al, in prep

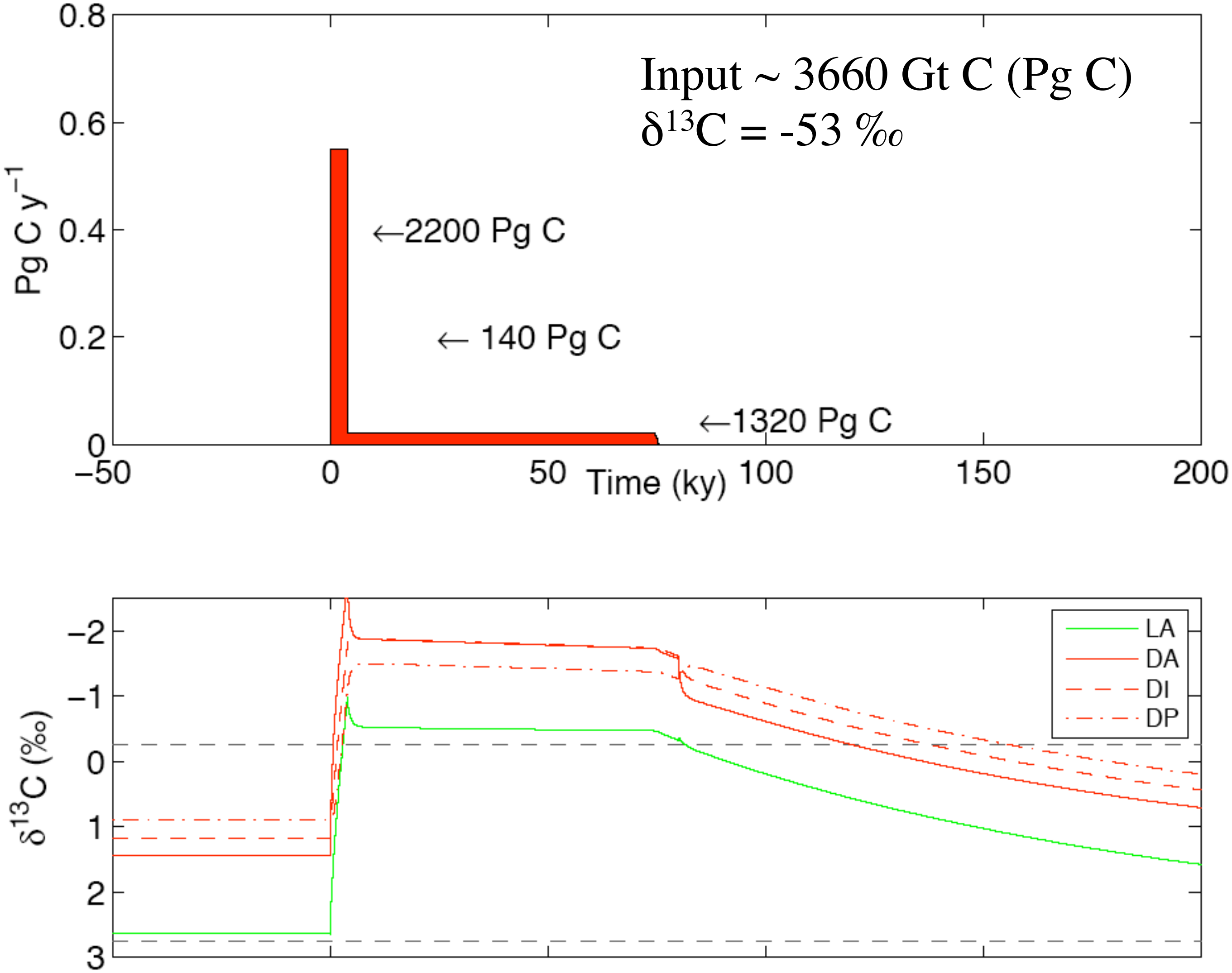
Bass River, NJ

- Siliciclastic Shelf Facies
- Multiple SST Proxies
  - Oxygen Isotopes
  - TEX$_{86}$



Sluijs et al., in press, Nature

Modeling massive carbon input



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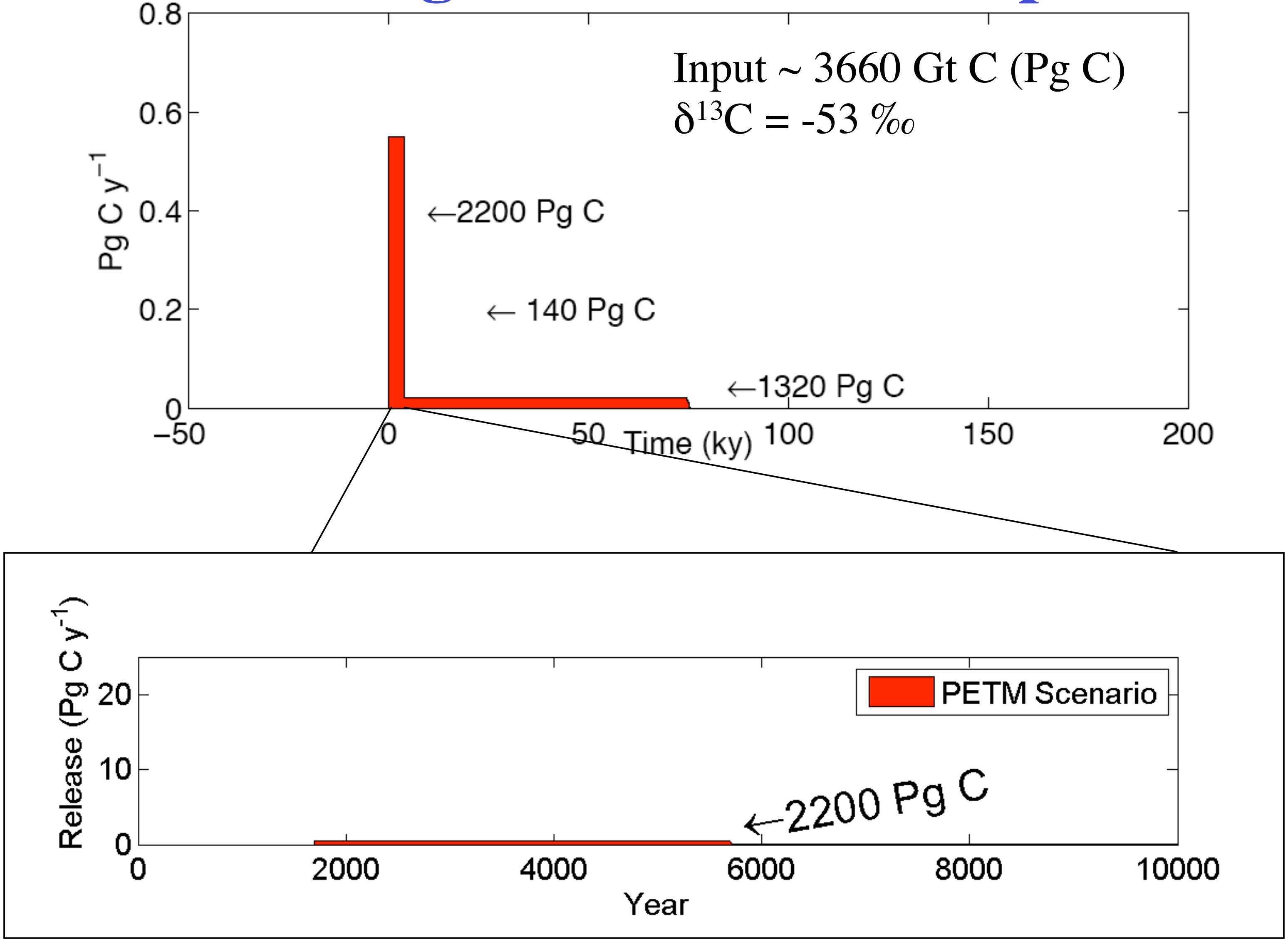
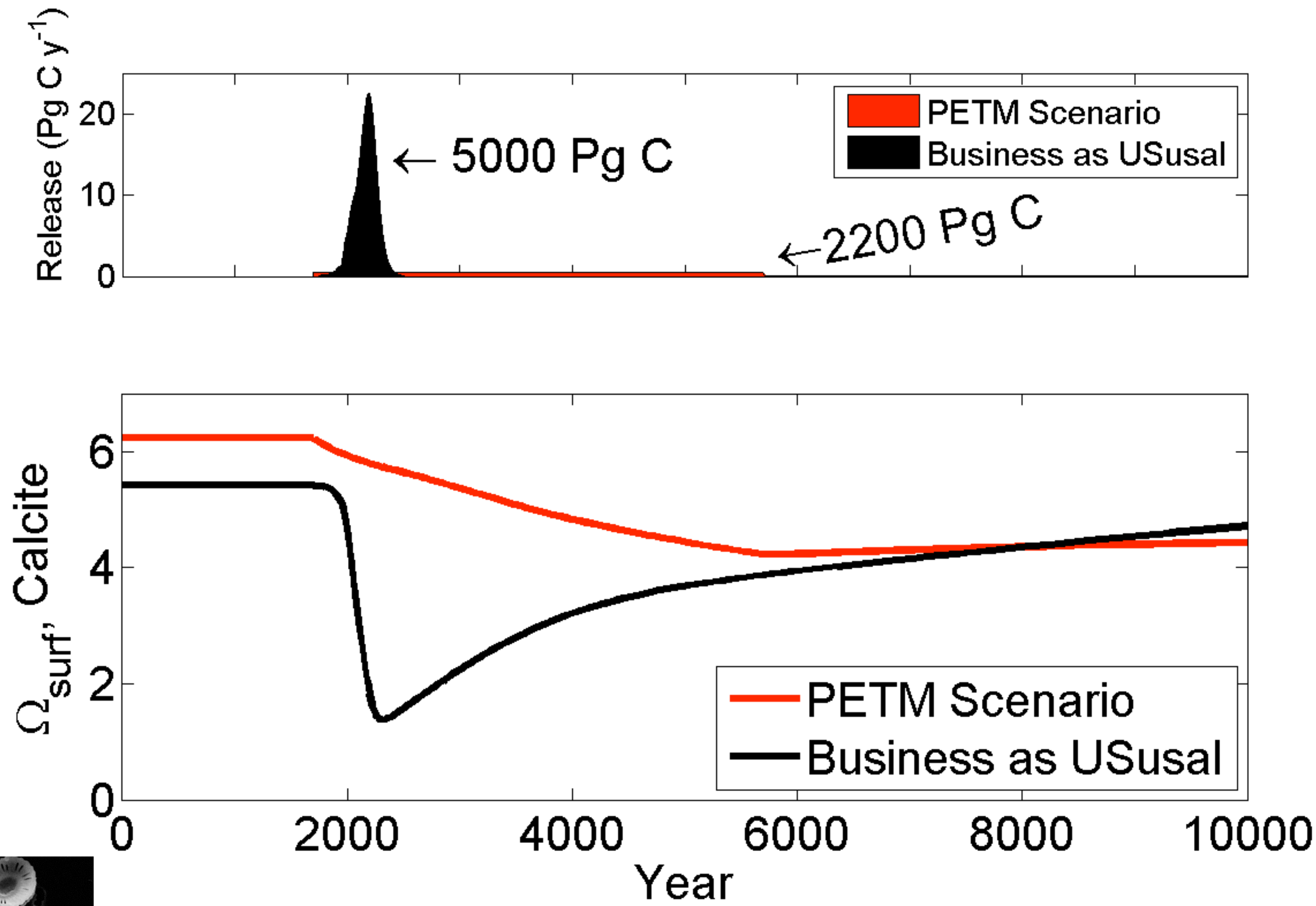
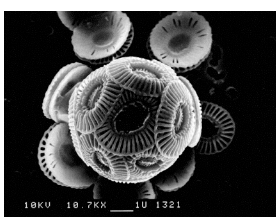


Zeebe et al, in prep

Ocean Acidification
PETM vs. Future





Zeebe et al, in prep

Future Impact on Marine Calcifiers?

NATURE | VOL 407 | 21 SEPTEMBER 2000 | www.nature.com

letters to nature

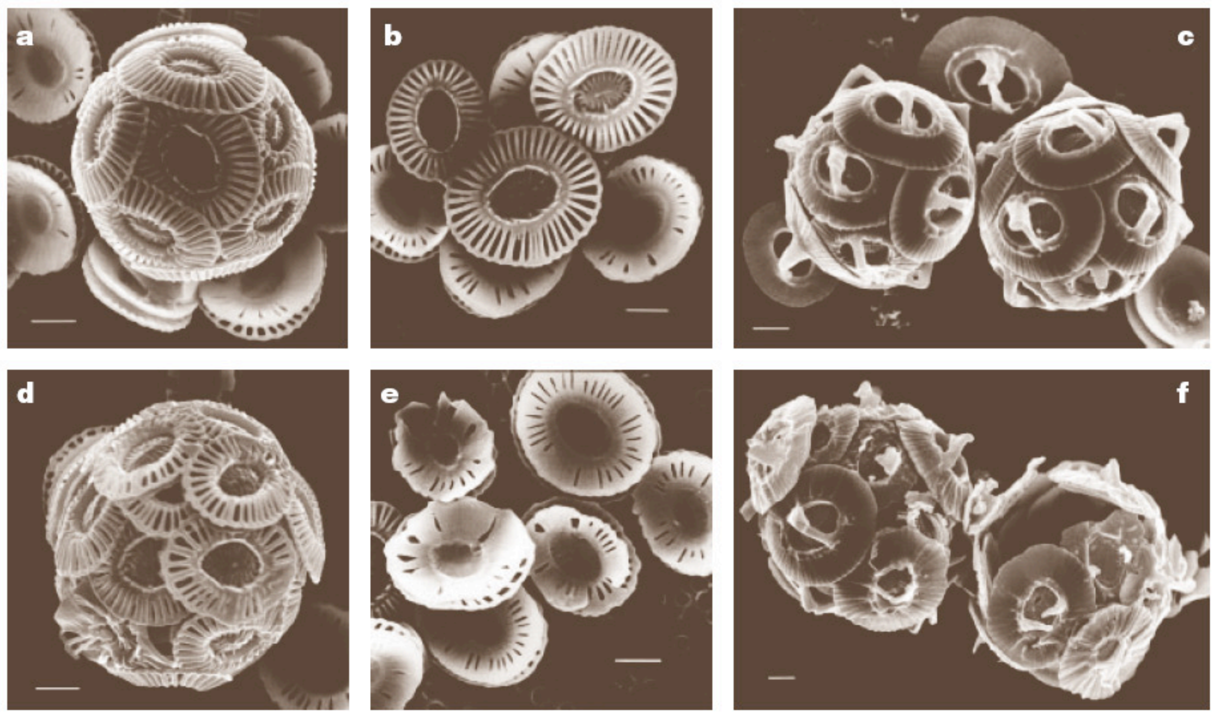
Reduced calcification of marine plankton in response to increased atmospheric CO_2

Ulf Riebesell *, Ingrid Zondervan*, Björn Rost*, Philippe D. Tortell†, Richard E. Zeebe*‡ & François M. M. Morel†

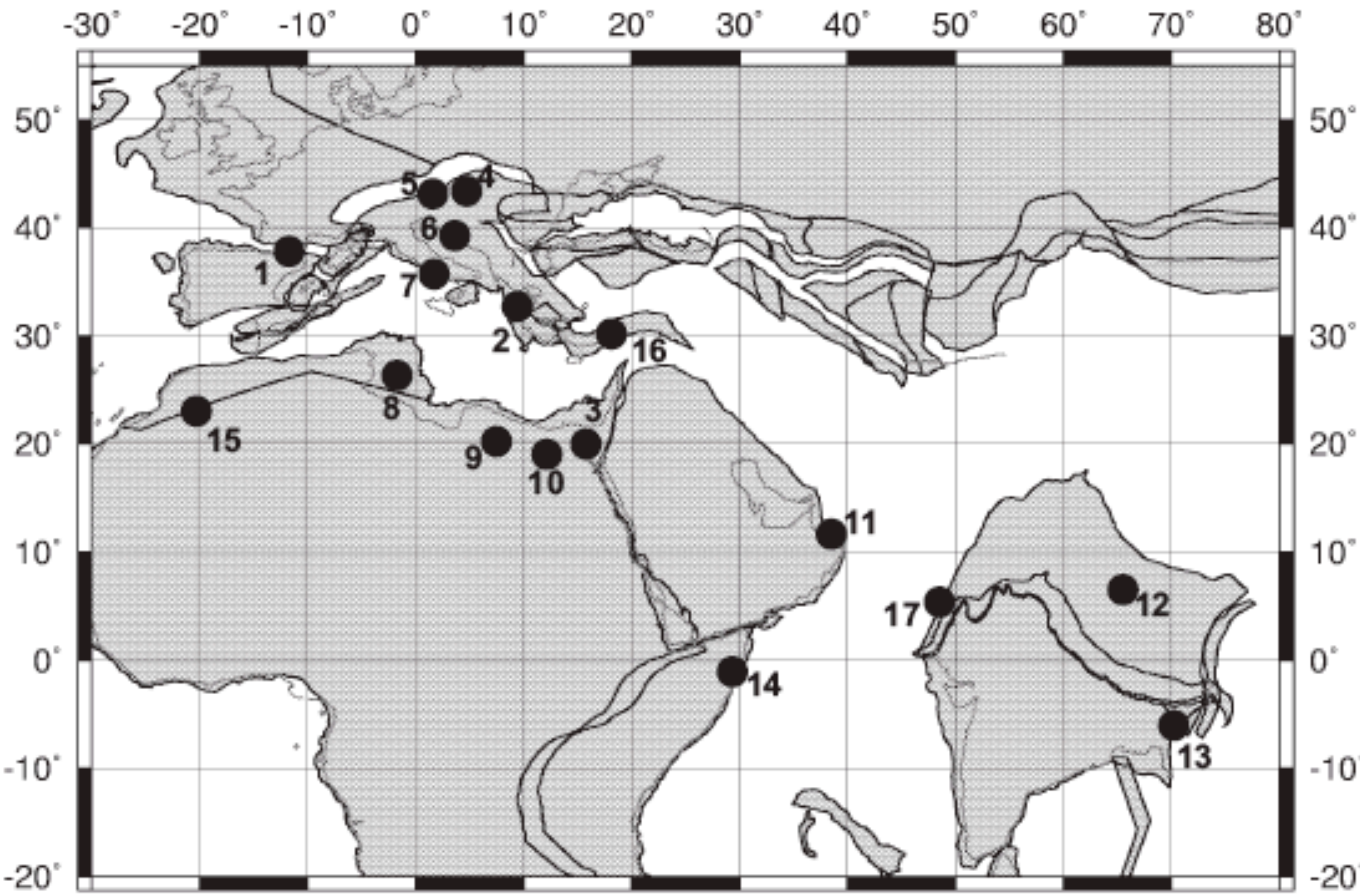
** Alfred Wegener Institute for Polar and Marine Research, P.O. Box 120161, D-27515 Bremerhaven, Germany*
† Department of Geosciences & Department of Ecol
Princeton University, Princeton, New Jersey 08544,
‡ Lamont-Doherty Earth Observatory, Columbia U
New York 10964, USA

300 ppmv →

800 ppmv →

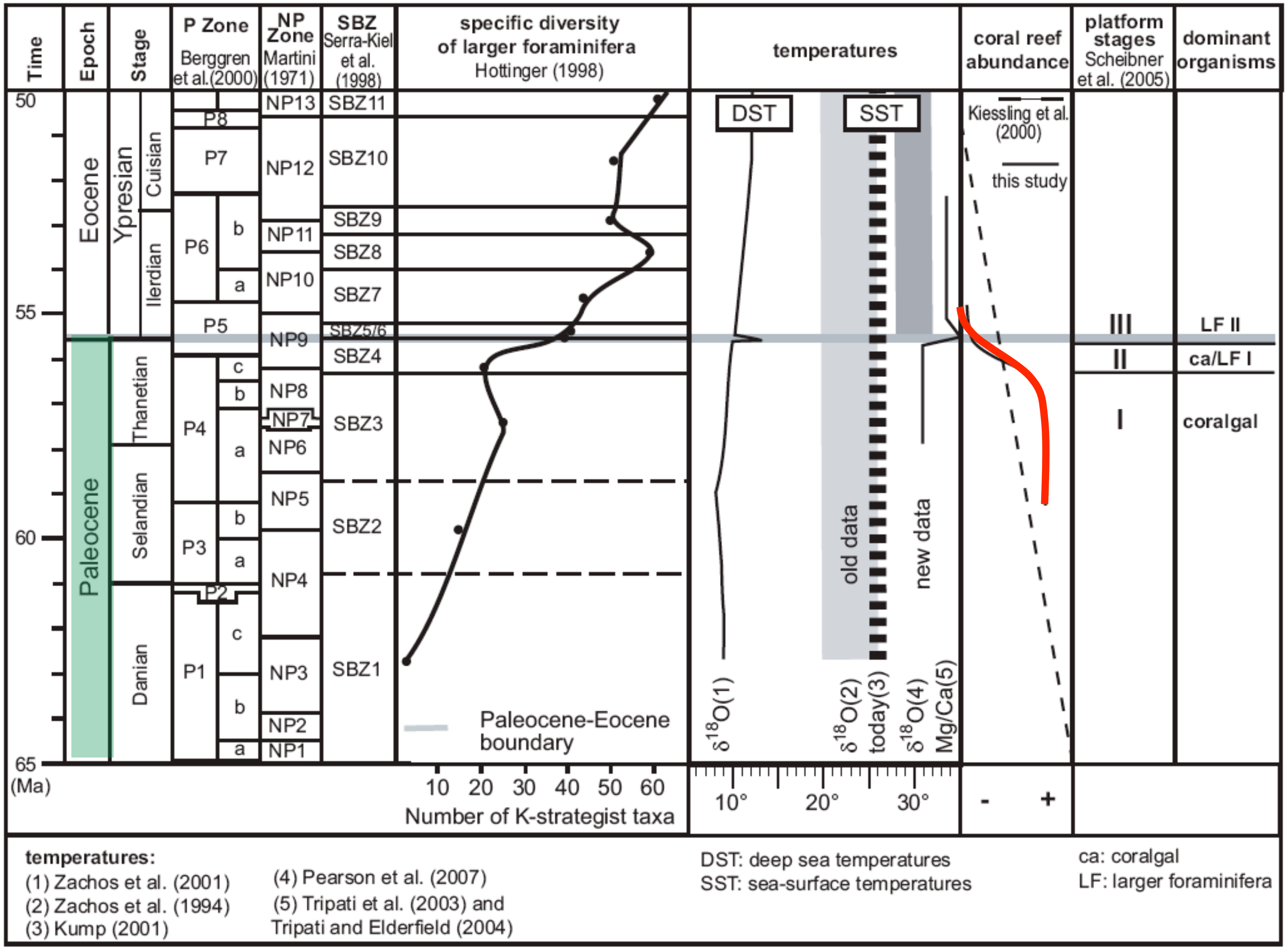


Impact of PETM on Calcifiers?
Early Paleogene Carbonate Platforms



Scheibner and Speijer, 2007, Earth

Decline in Diversity of Larger Foraminifer & Corals



Scheibner and Speijer, 2007, Earth

Summary

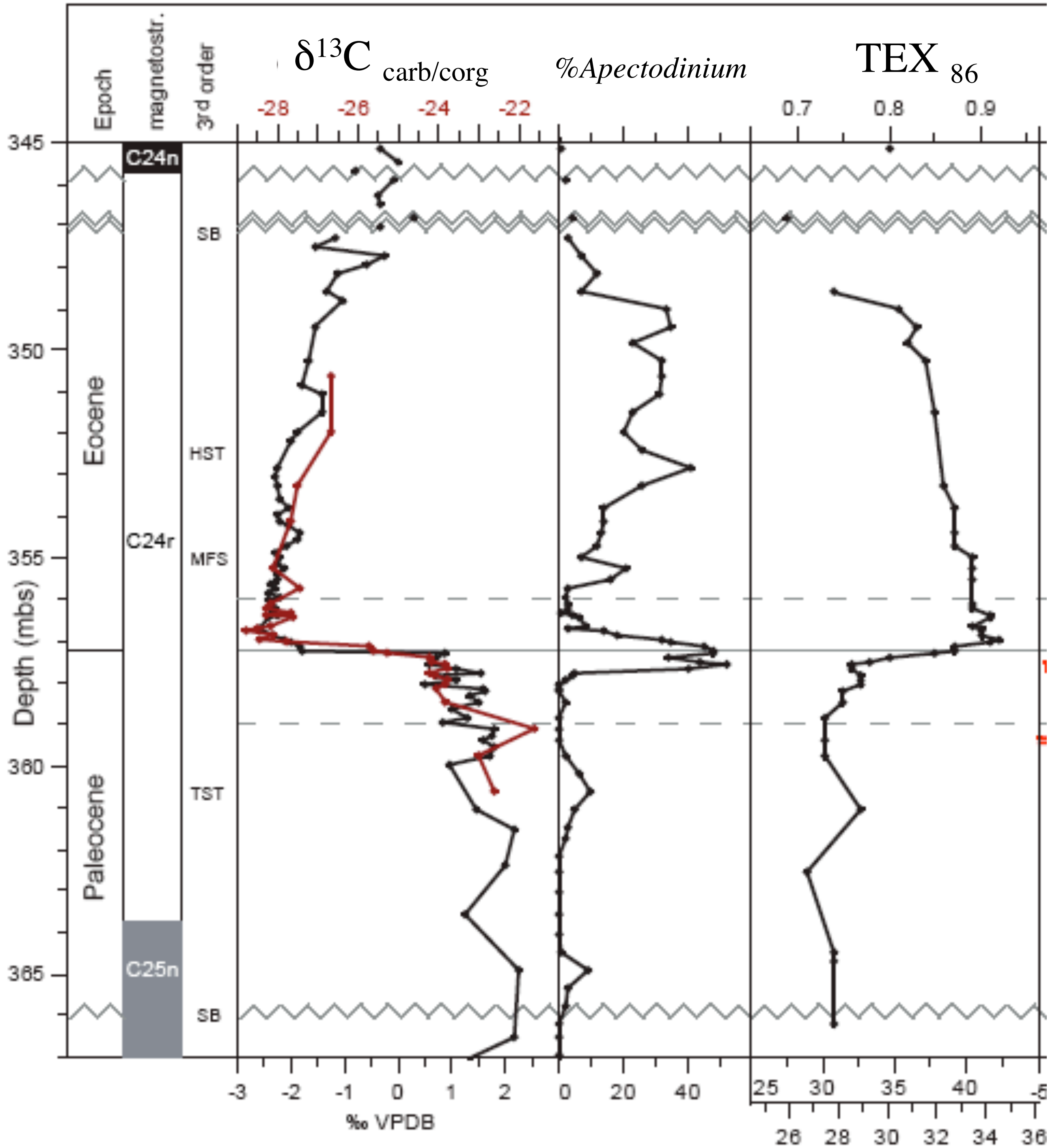
- CIE Magnitude ~ 4.0‰
- Mass of carbon released during the PETM >> 4500 Gt
- Multiple sources are required
  - ✓Volcanic (N. Atlantic)
  - ✓Methane hydrates (feedback)
  - ✓Terrestrial?
- Decreased pH/warming triggered end Paleocene decline in coral diversity

Implications for the future?

- Unabated CO_2 emissions will lead to a severe drop in pH of the surface ocean
- Positive feedbacks will likely accelerate the rise in pCO_2
  - ✓Reduced vertical mixing
  - ✓Saturation state of the ocean surface
- Will methane hydrates dissociate?
  - ✓Depends on magnitude of warming & propagation of heat into the upper ocean

Bass River, NJ

- Siliciclastic Shelf Sequence
- Multiple SST Proxies
  - Oxygen Isotopes
  - TEX_{86}



Sluijs et al., in press, Nature

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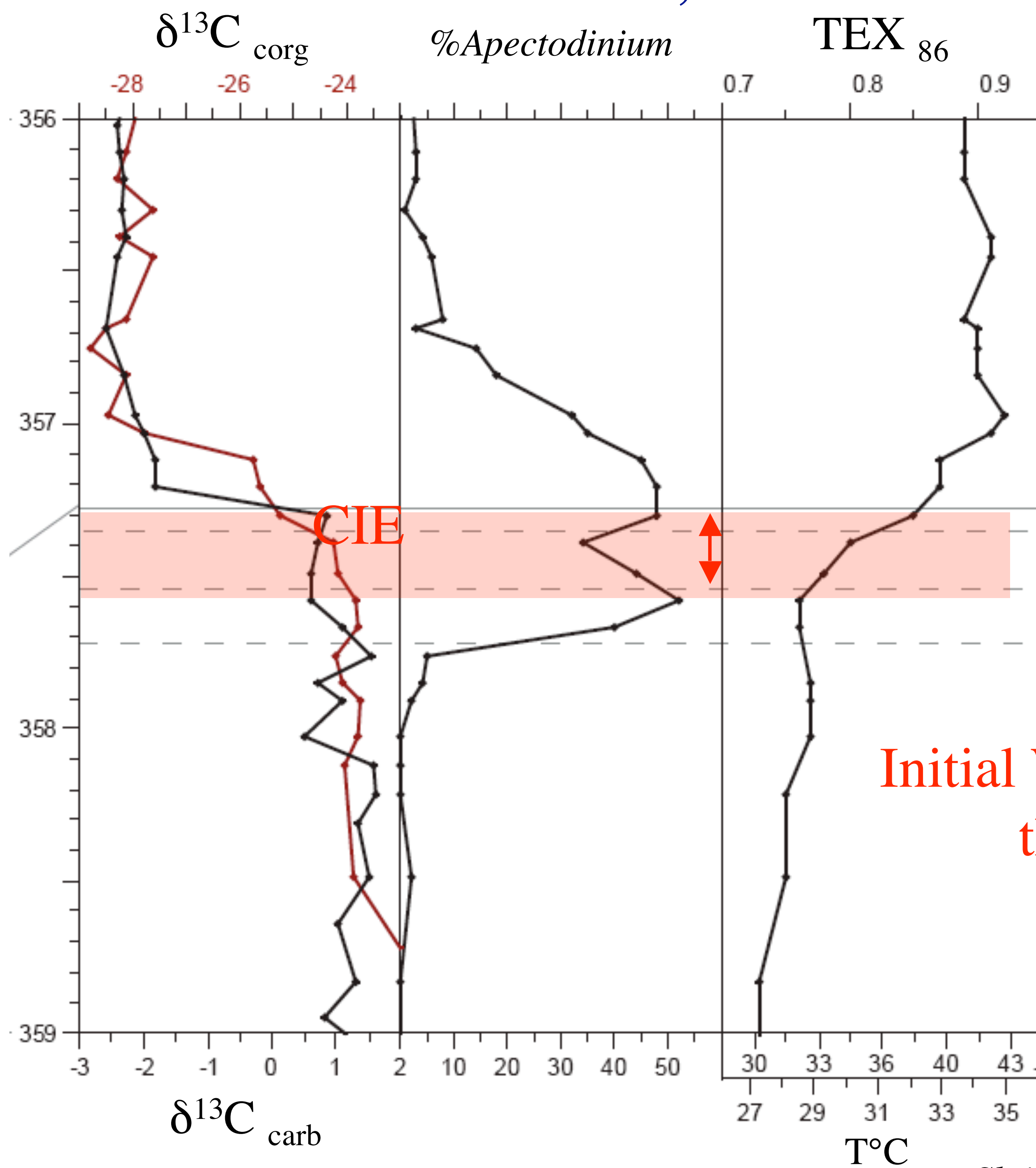


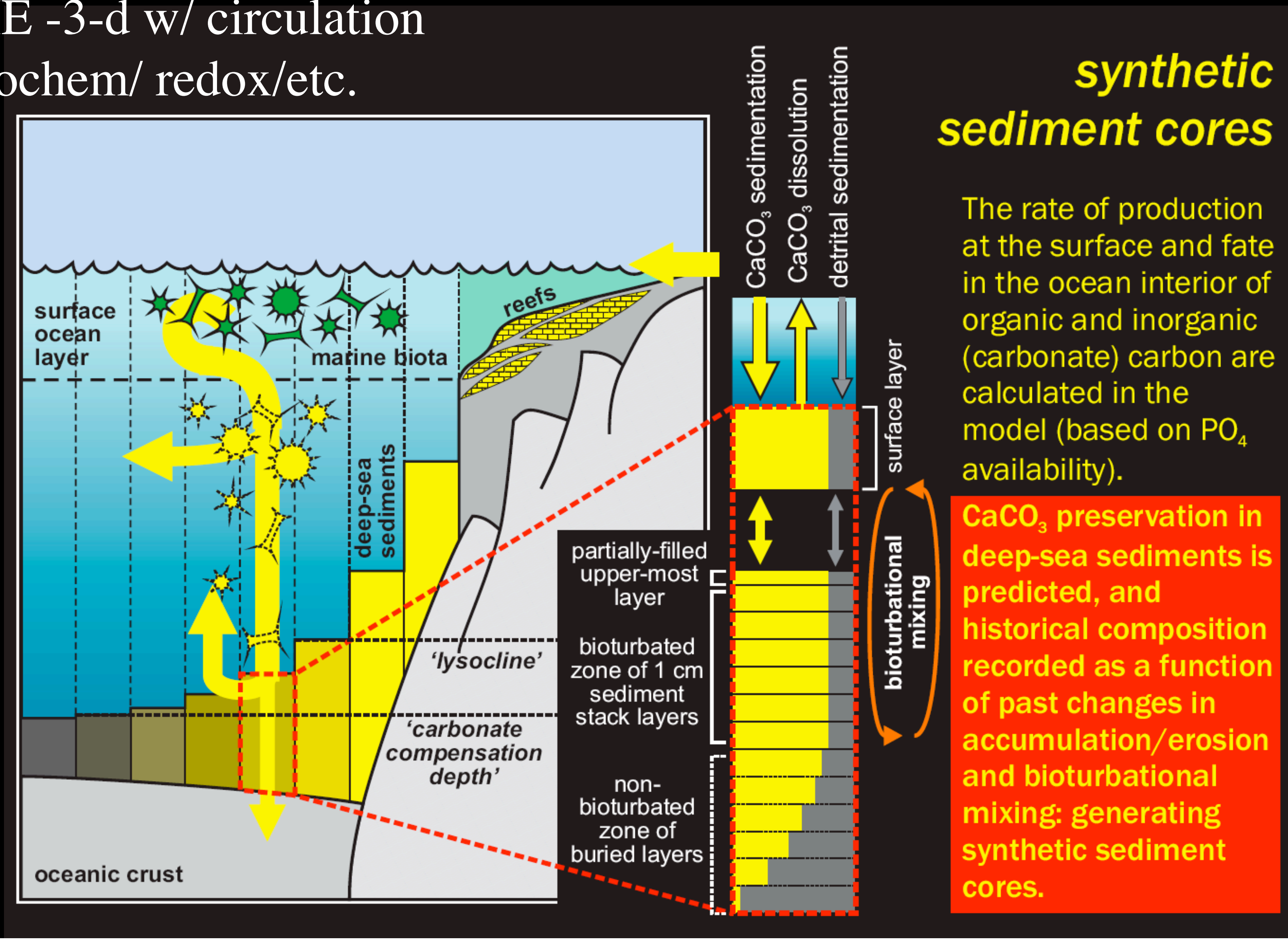
Initial Warming Leads the CIE!?!

Sluijs et al., in press, Nature

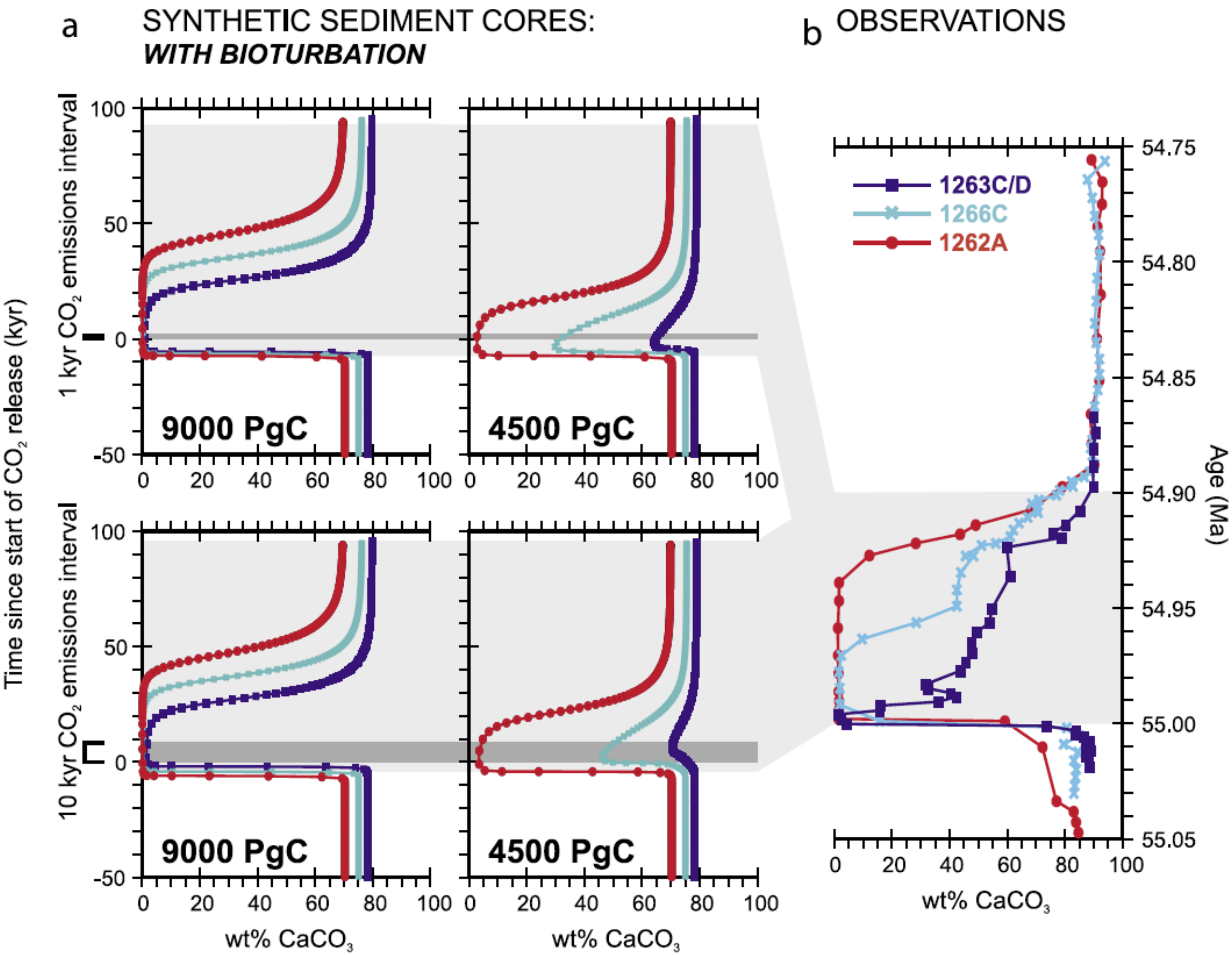
Earth System Models

Ridgwell, 2006; Panchuk, Kump, Ridgwell, in review

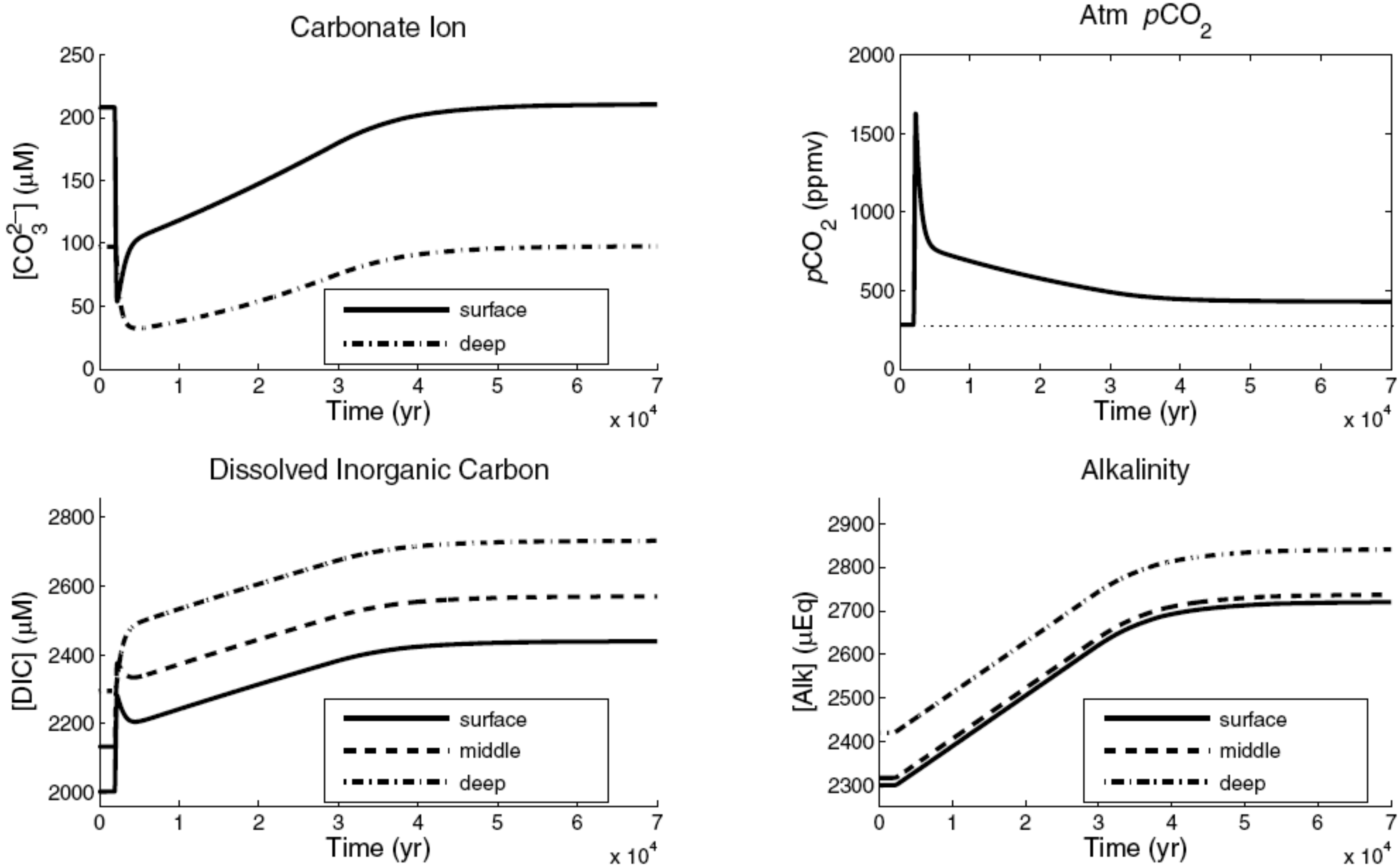
- GENIE -3-d w/ circulation
- biogeochem/ redox/etc.



Earth System Models



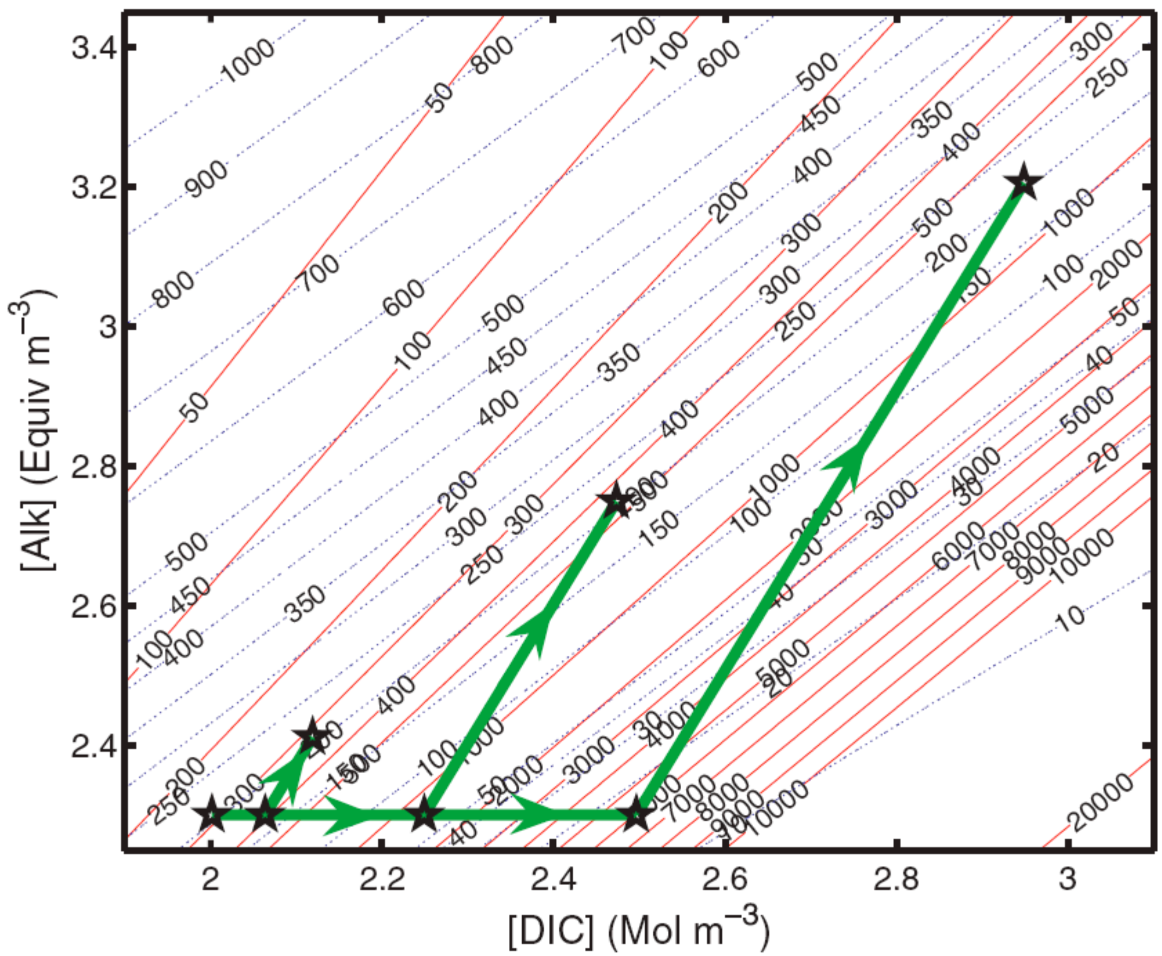
Long Term CO_2 Legacy



Tyrrell et al., 2007

Long Term CO_2 Legacy

$$Ca^{2} + 2HCO_3^- \underset{\text{dissolution}}{\overset{\text{precipitation}}{\rightleftharpoons}} CaCO_3 + CO_2(aq) + H_2O$$



Tyrrell et al., 2007