Geological history of atmospheric CO2 variations and Earth's climate

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Outline

1. The global carbon cycle and climate
2. The Faint Young Sun and Precambrian CO_2
3. Snowball Earth
4. CO2 over the last 400 million years
5. The Paleocene-Eocene Thermal Maximum 56 million years ago
6. Glacial-interglacial cycles of the last 2.6 million years
7. Rapid climate changes of the last 50,000 years

Earth’s energy balance

At steady state:

Energy emitted by Earth = Energy absorbed by Earth

$$\sigma T_e^4 = S/4\,(1 - A)$$

Surface temperature depends on:

1) **S, solar flux at 1 AU (inverse-square law)**
2) **A, albedo**
3) **Warming provided by the atmosphere (greenhouse effect)**

Ice-albedo feedback: increasing average albedo leads to cooling, which will increase snow and ice, increasing average albedo, decreasing energy from Sun, increasing albedo…

Runaway ice albedo: theoretically may occur if sea ice extends into tropics (30° N and S latitude)

Earth's thermostat: chemical weathering of silicate rocks (igneous, most metamorphic, and siliciclastic sedimentary rocks)

<u>Basic reactions</u>

$$CO_2 + H_2O \rightarrow H_2CO_3$$

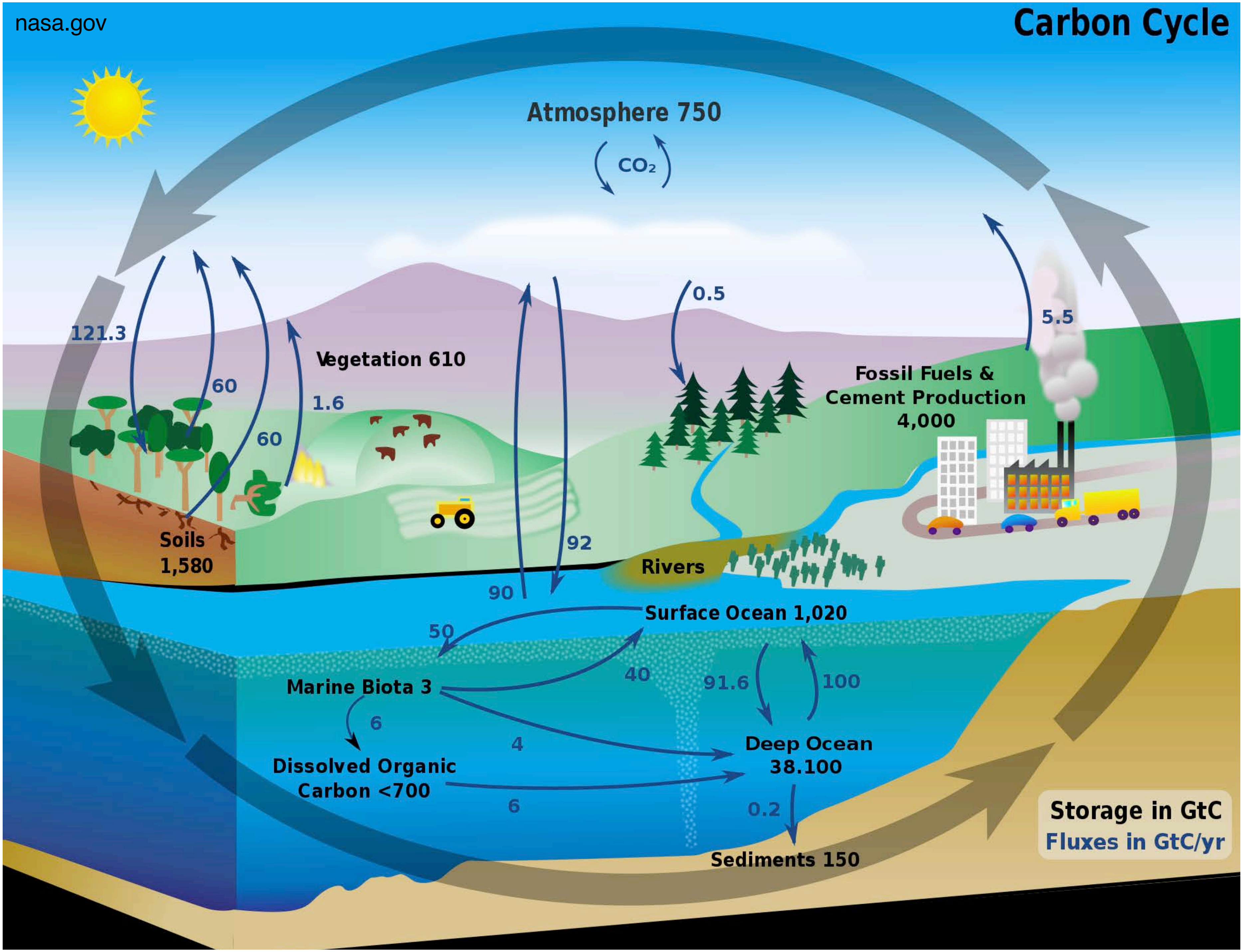
$$CaSiO_3 + 2H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$$

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + HCO_3^-$$

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

Chemical weathering of silicate rocks consumes atmospheric CO_2

If rate of CO_2 consumption is greater than rate of CO_2 supply by outgassing from volcanoes (really from mantle), CO_2 levels in the atmosphere will decrease

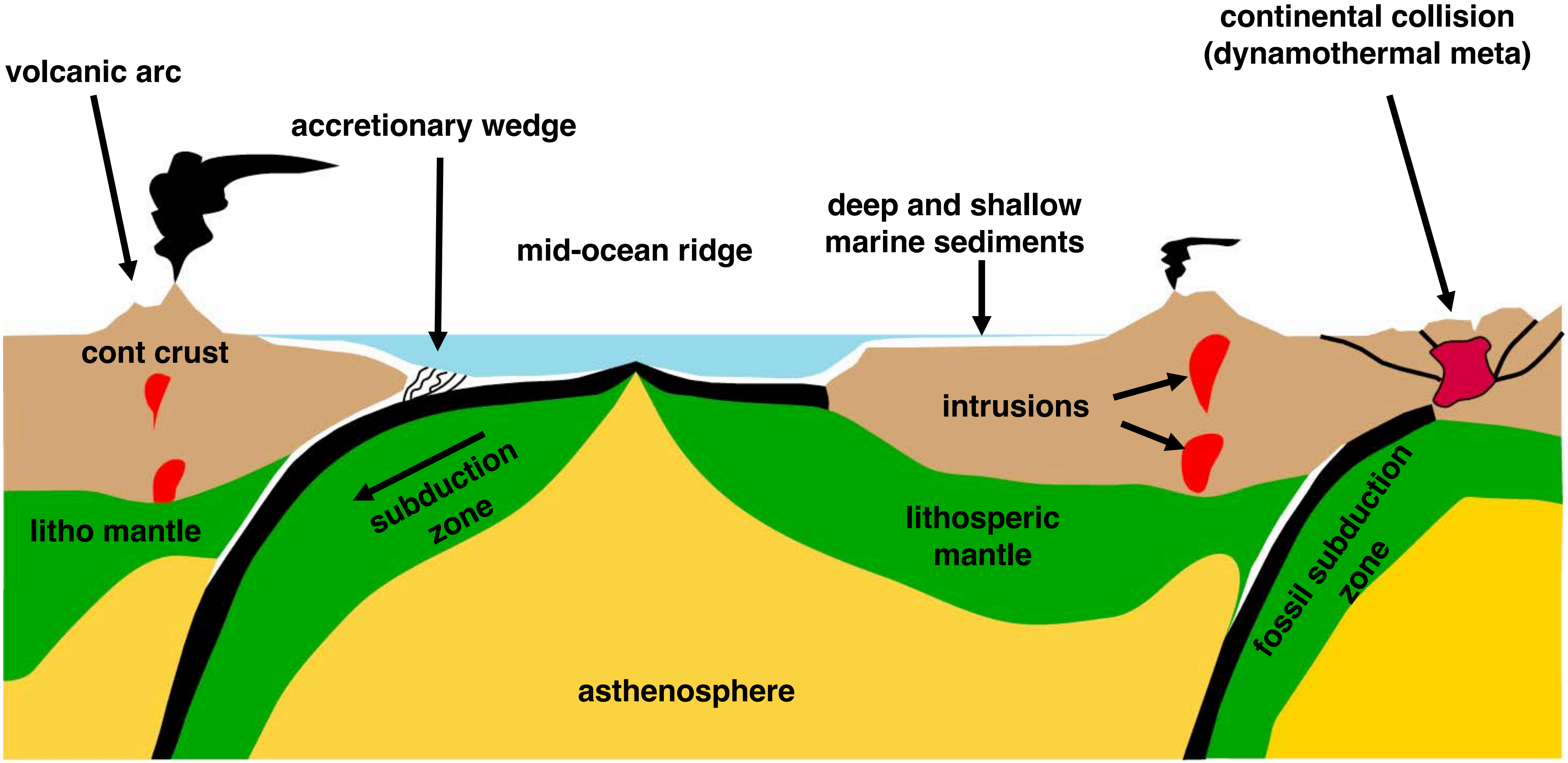


Marine sediments and crust: 100,000,000

1 Gigaton = 1,000,000,000 tons

Tectonics and the planetary carbon cycle

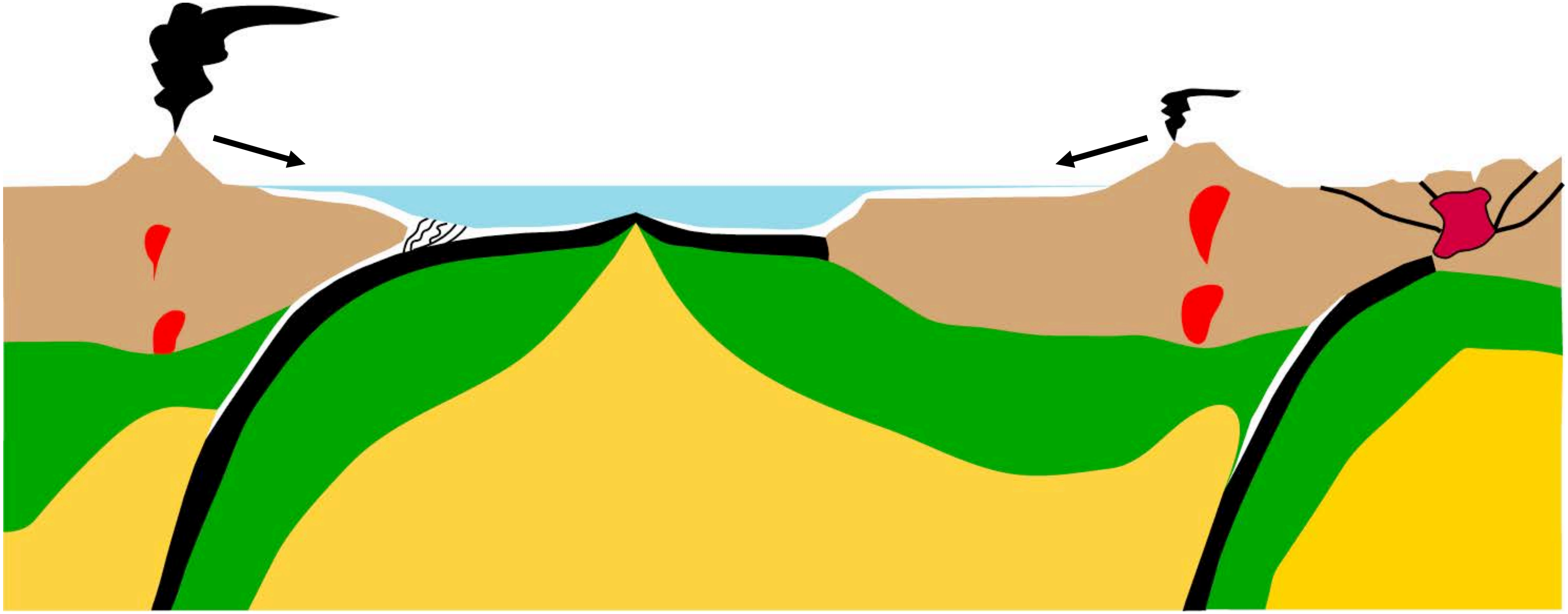
Basic components of Earth's plate tectonics



Tectonics and the planetary carbon cycle

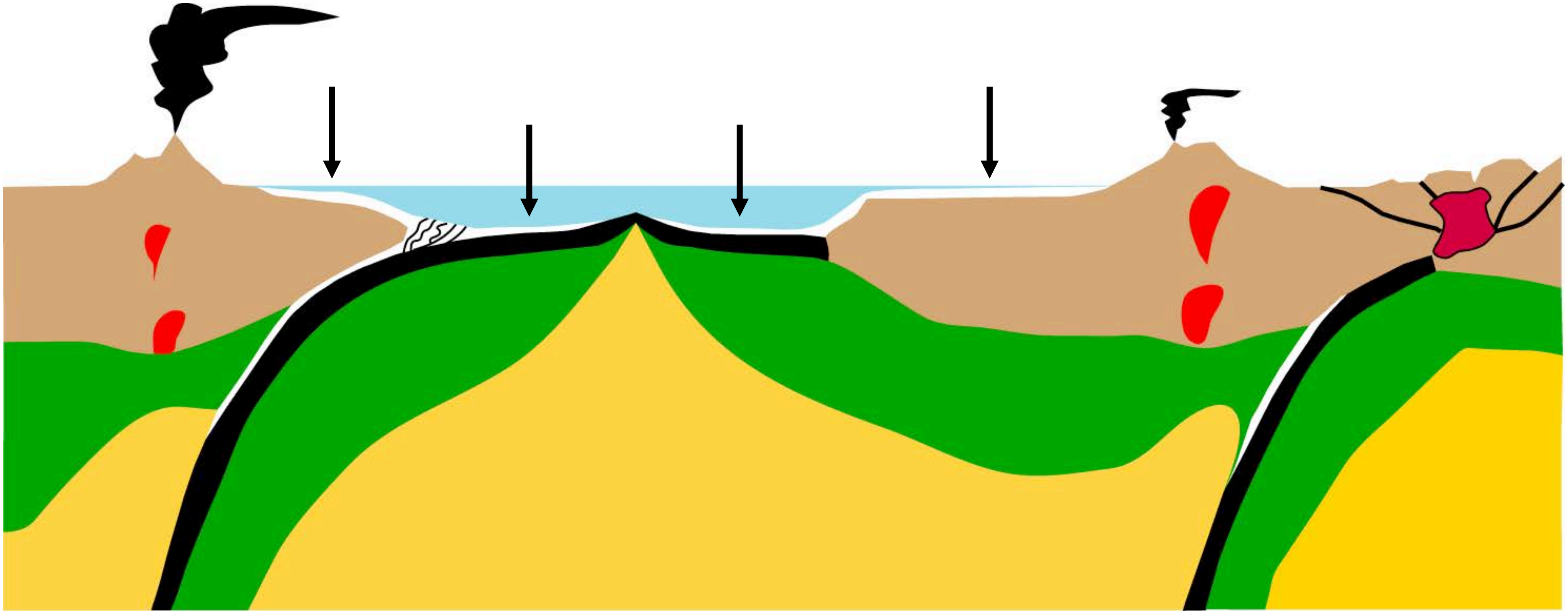
Chemical weathering of rocks consumes (reduces) atmospheric CO_2

Chemical and mechanical weathering of rocks delivers CO_3 and organic C to oceans

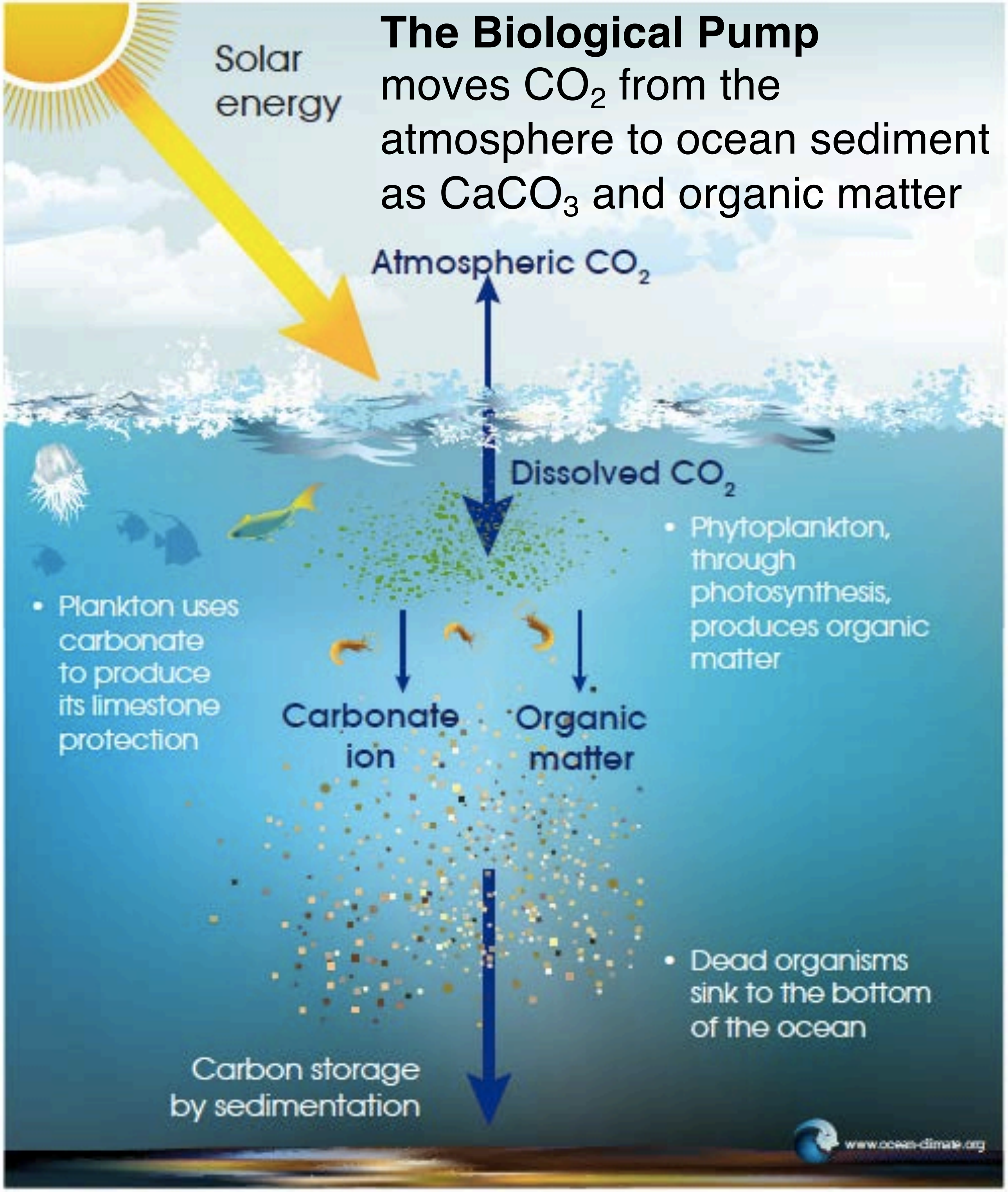


Tectonics and the planetary carbon cycle

Deposition of carbon on continental shelves and deep ocean floor as $CaCO_3$ and organic matter



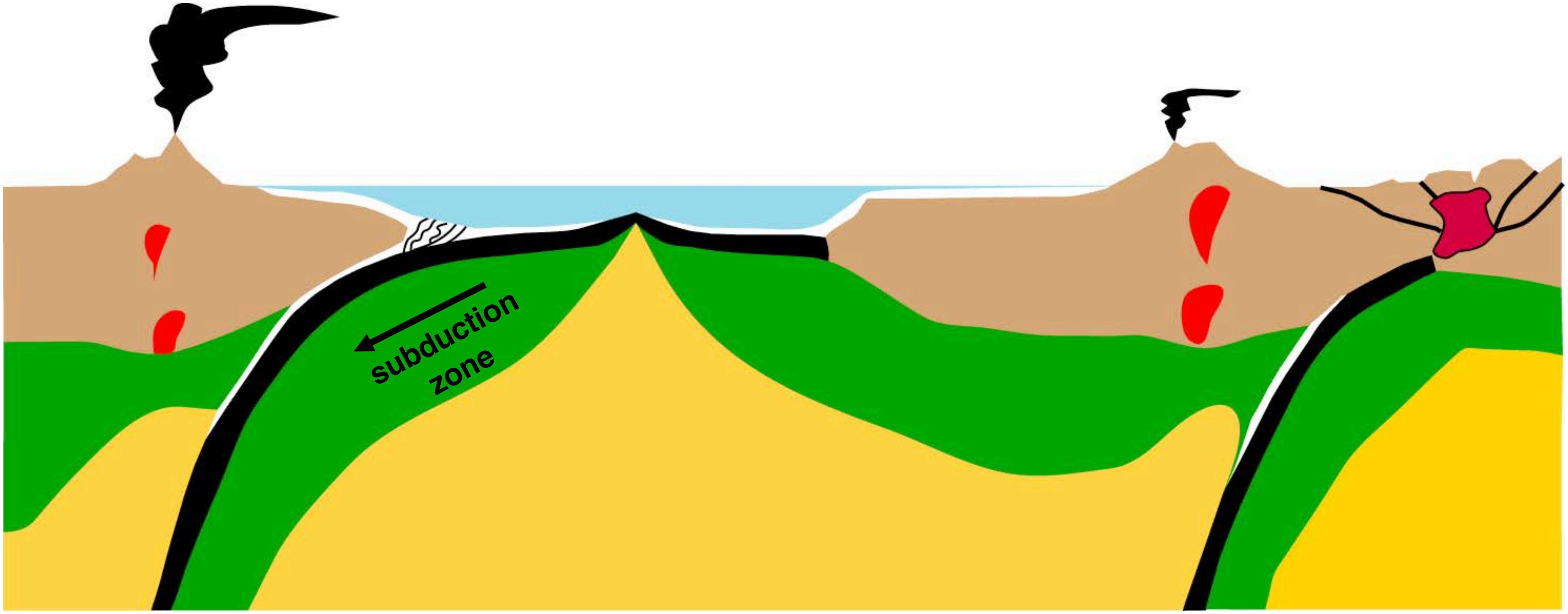
The Biological Pump
moves CO_2 from the atmosphere to ocean sediment as $CaCO_3$ and organic matter



2012

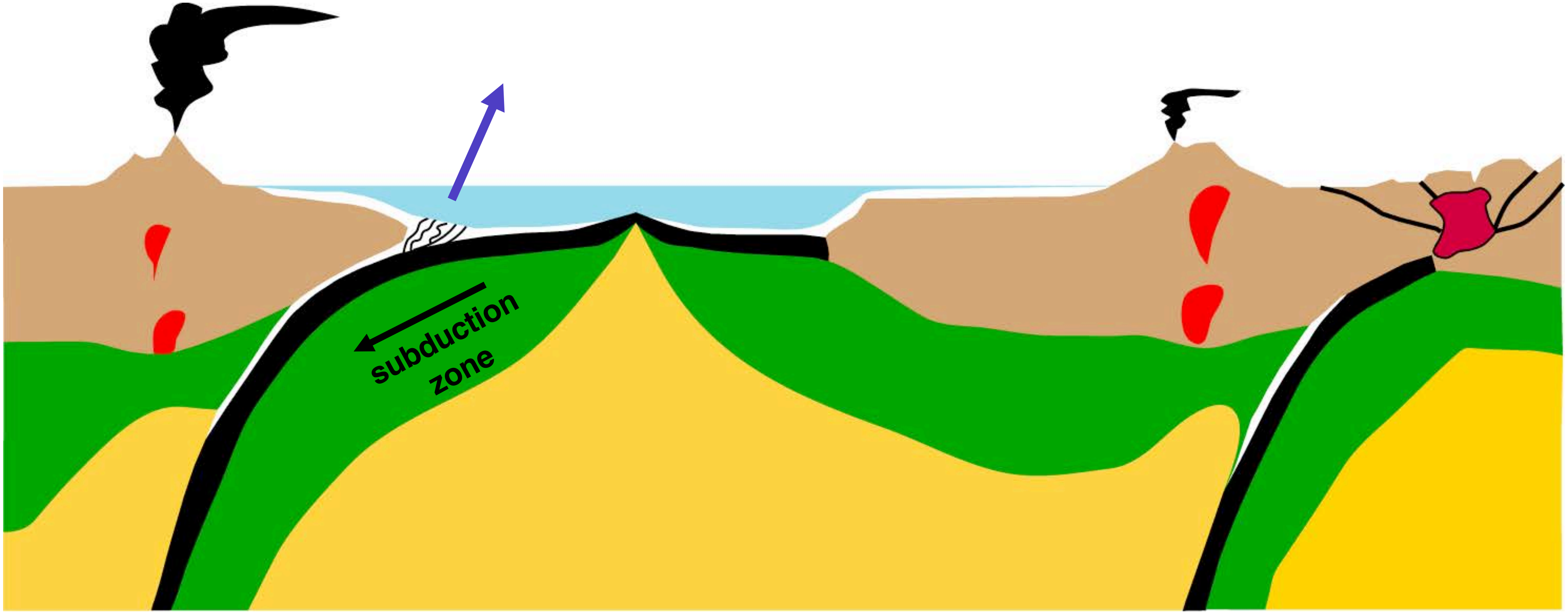
Tectonics and the planetary carbon cycle

Subduction of oceanic lithosphere
(plates) moves carbon into the geosphere



Tectonics and the planetary carbon cycle

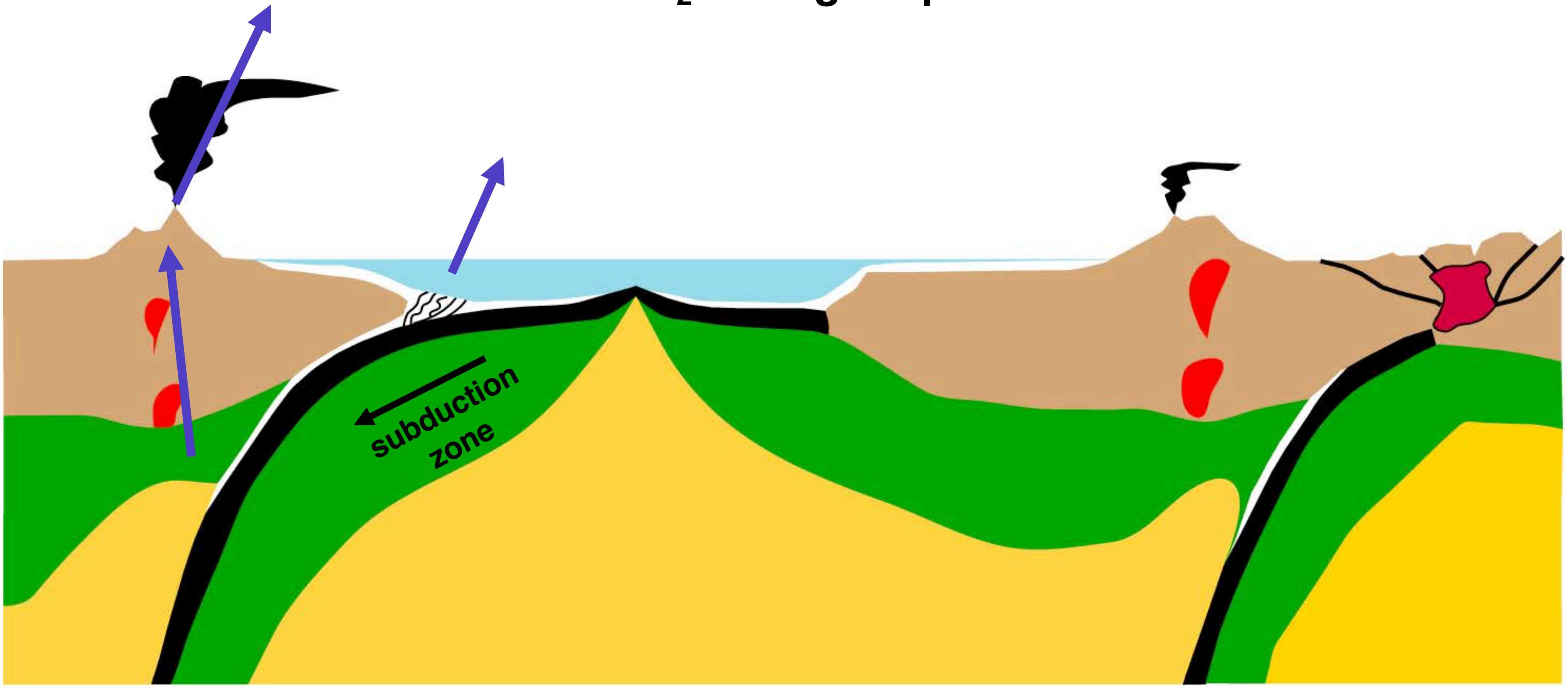
Heat and pressure in subduction zone alters rocks and releases some of the CO_2 to the atmosphere



Tectonics and the planetary carbon cycle

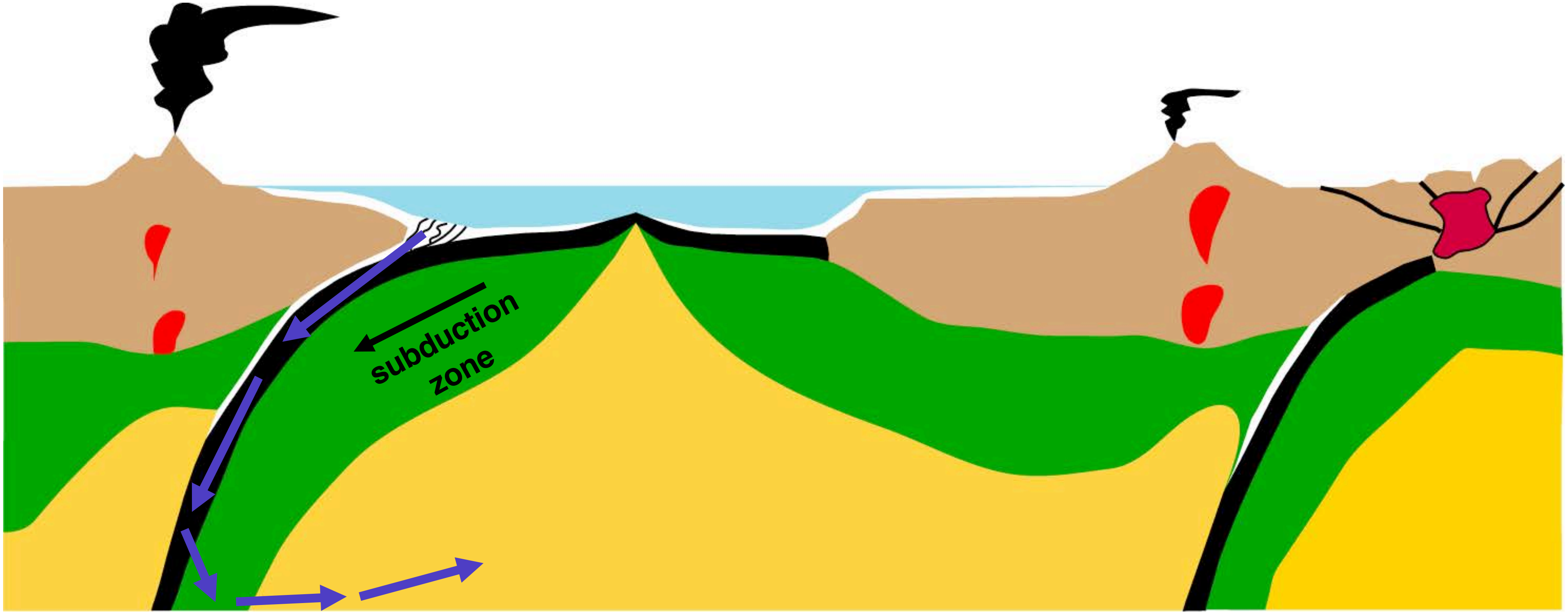
Heat and pressure in subduction zone alters rocks and releases some of the CO_2 to the atmosphere

Volcanoes above the subducted plate release more CO_2 during eruptions.



Tectonics and the planetary carbon cycle

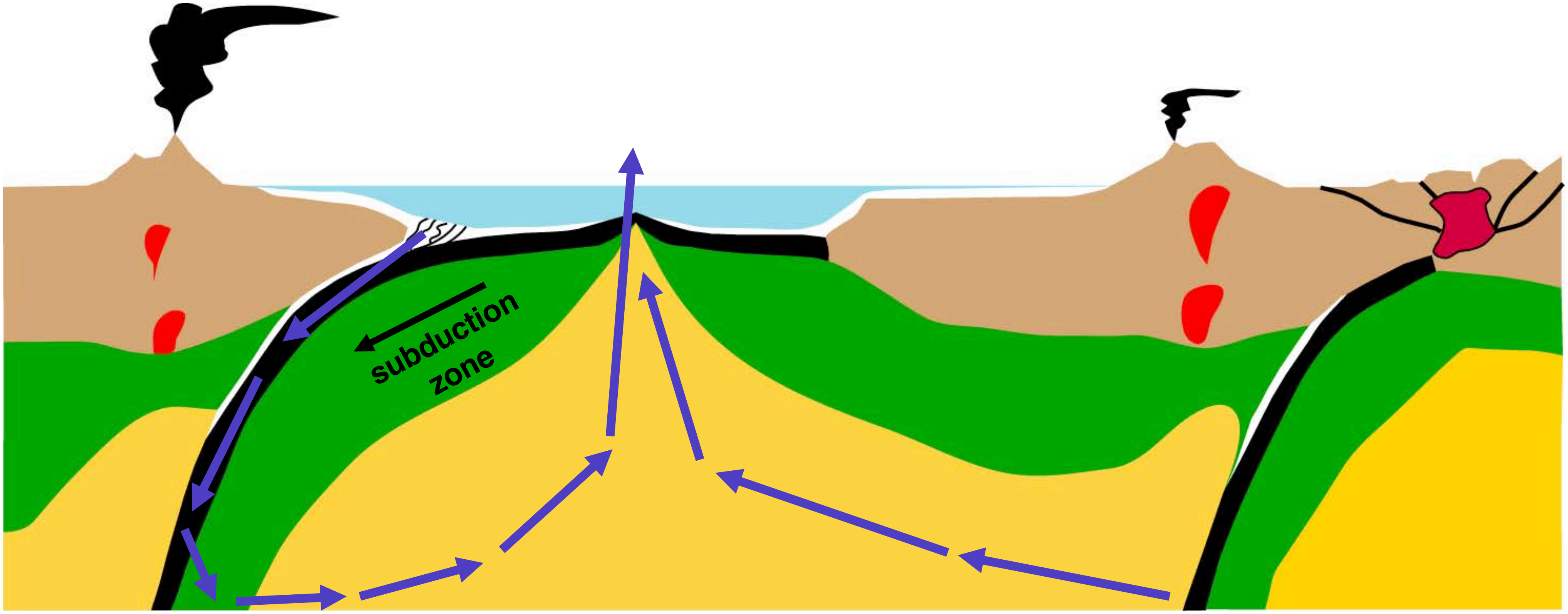
The subducted plate and its remaining carbon mixes into the convecting mantle



Tectonics and the planetary carbon cycle

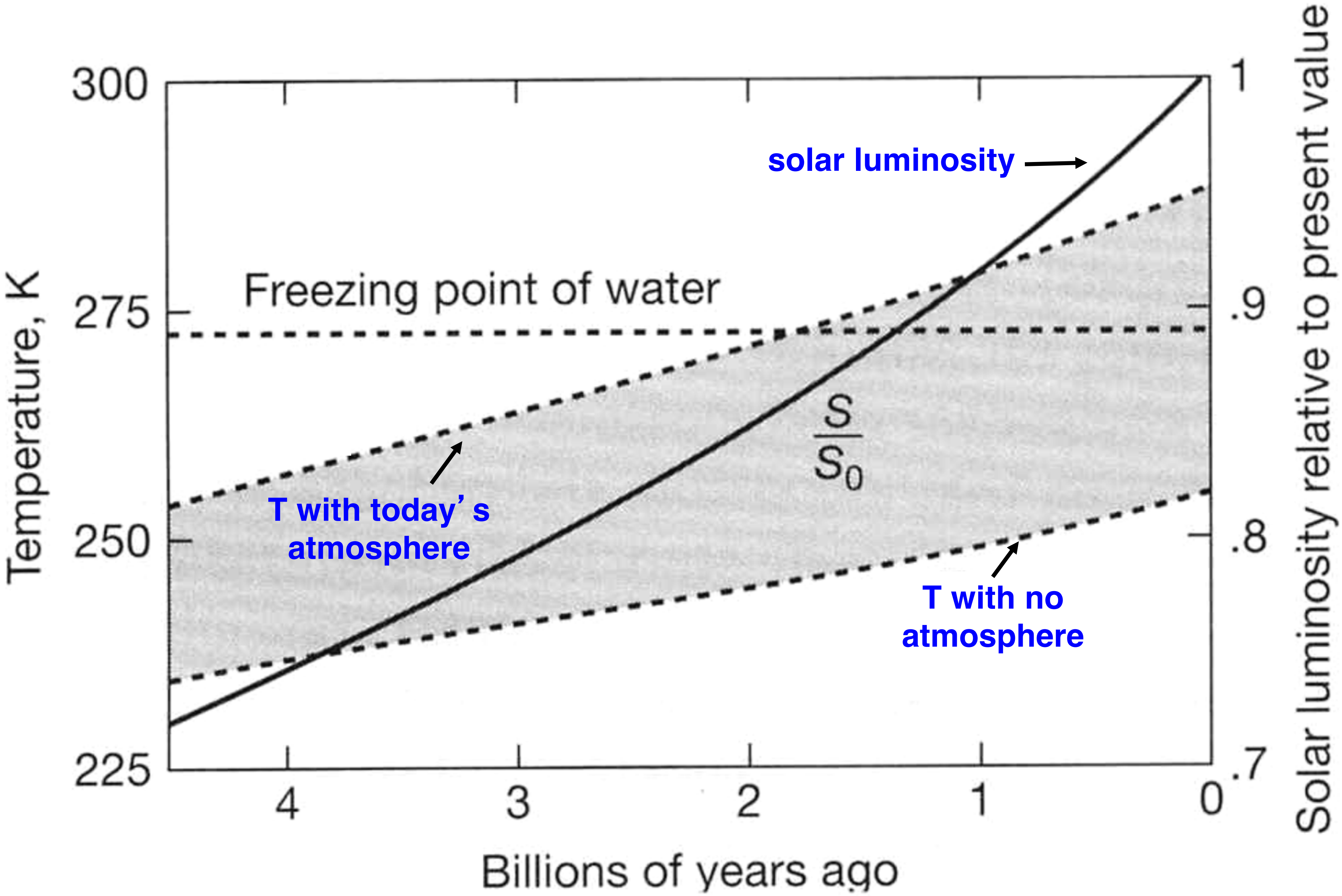
The subducted plate and its remaining carbon mixes into the convecting mantle

Volcanoes of the mid-ocean ridges release carbon to atmosphere during erutions as ocean basins grow wider

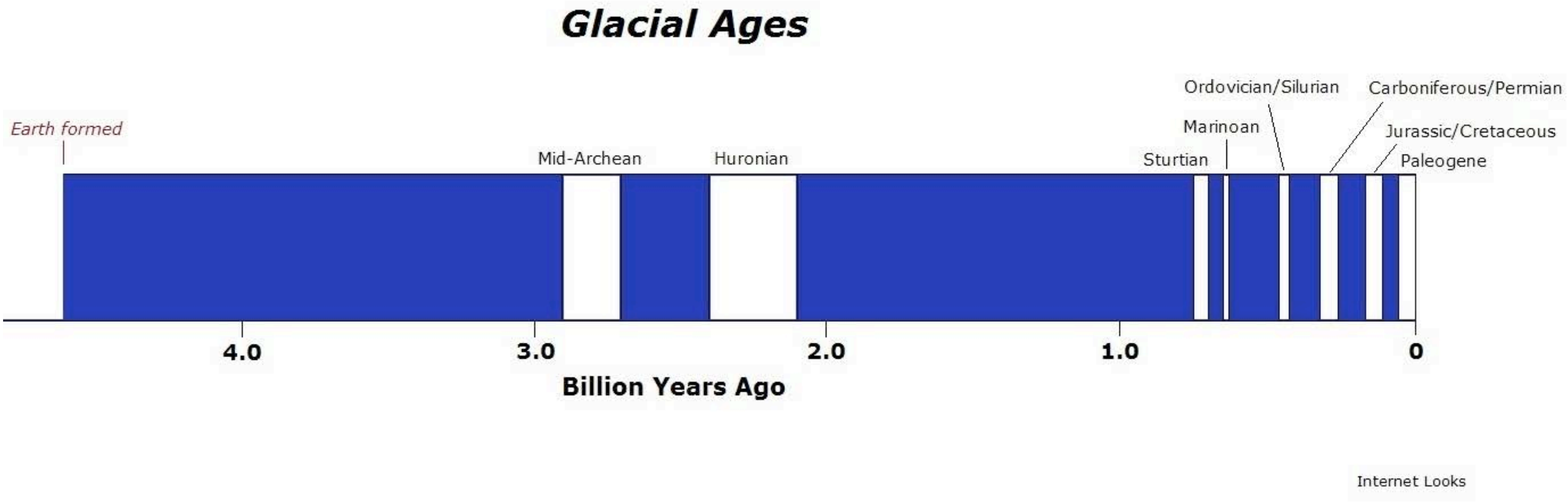


The Faint Young Sun Paradox

Young Main Sequence stars increase in luminosity over billions of years



Ice ages in Earth history



http://www.internetlooks.com/globaltempchange.html

Much higher pCO_2 as solution to FYS?

Moodies Group, Barberton Greenstone Belt, South Africa

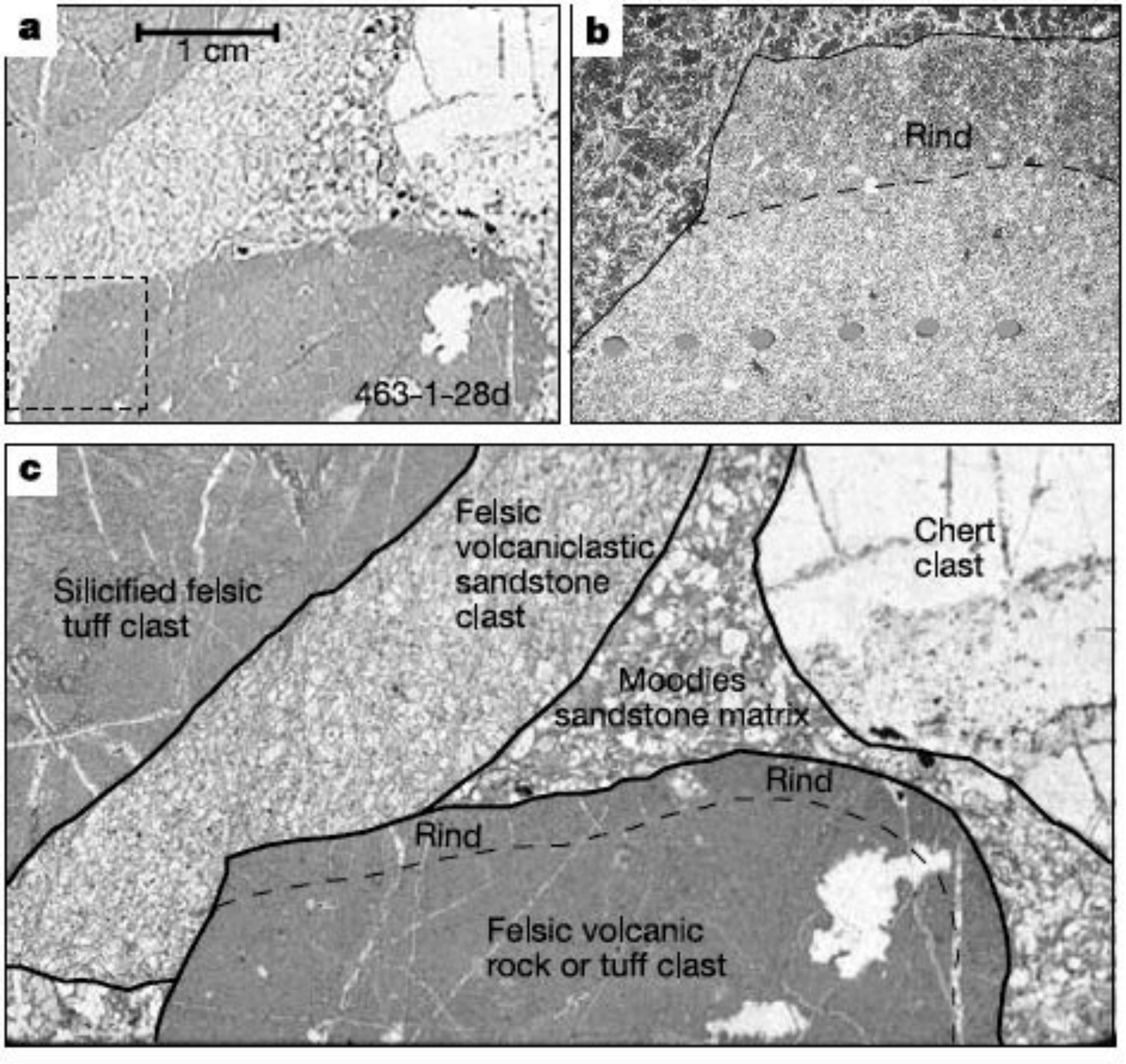
3.2 Ga siliciclastic alluvial fan and braided fluvial deposits

Oldest known non-marine deposits

Hessler et al., 2004

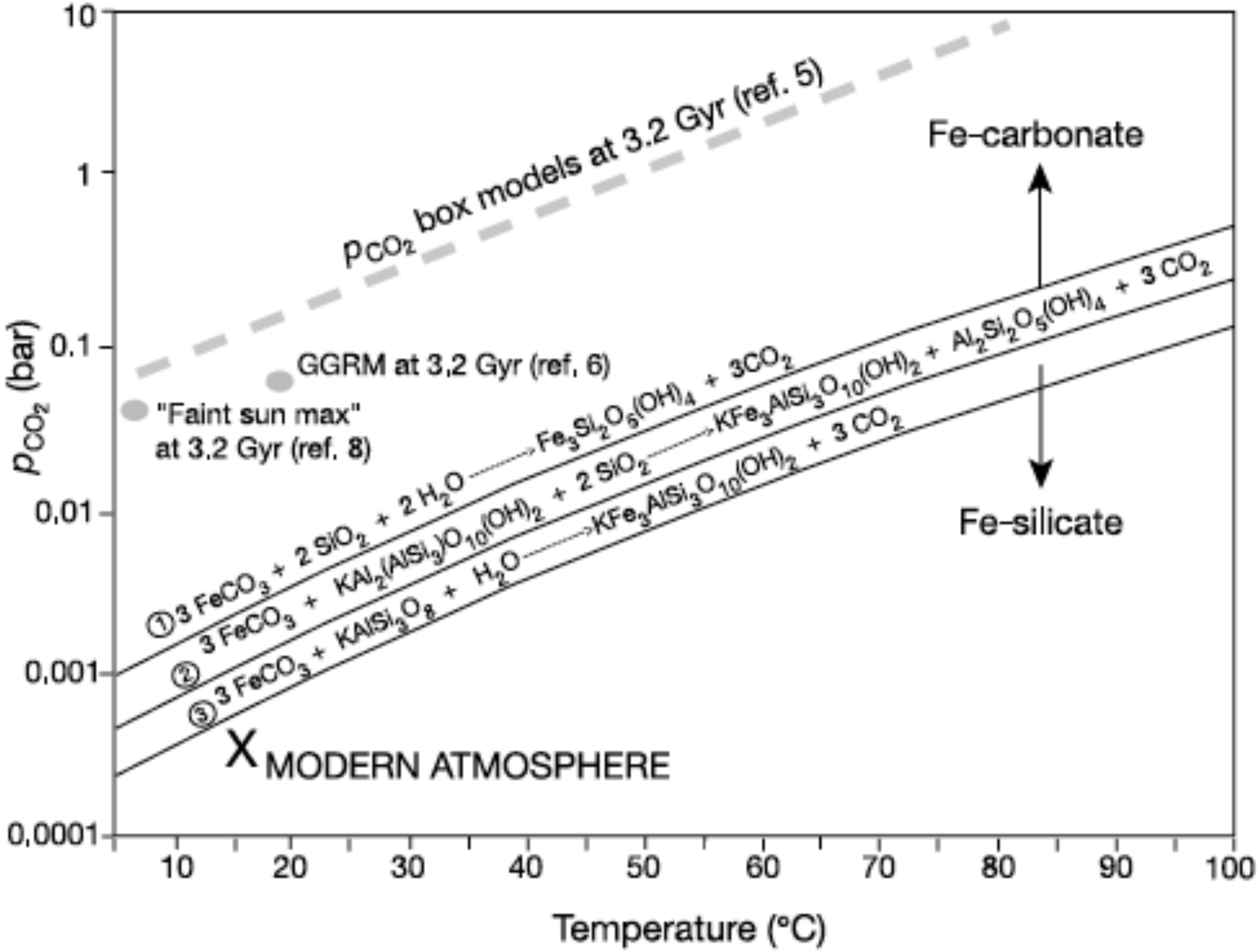
Pebbles with $Fe^{2+}CO_3$ siderite in weathering rinds

Implies anoxic surface environment



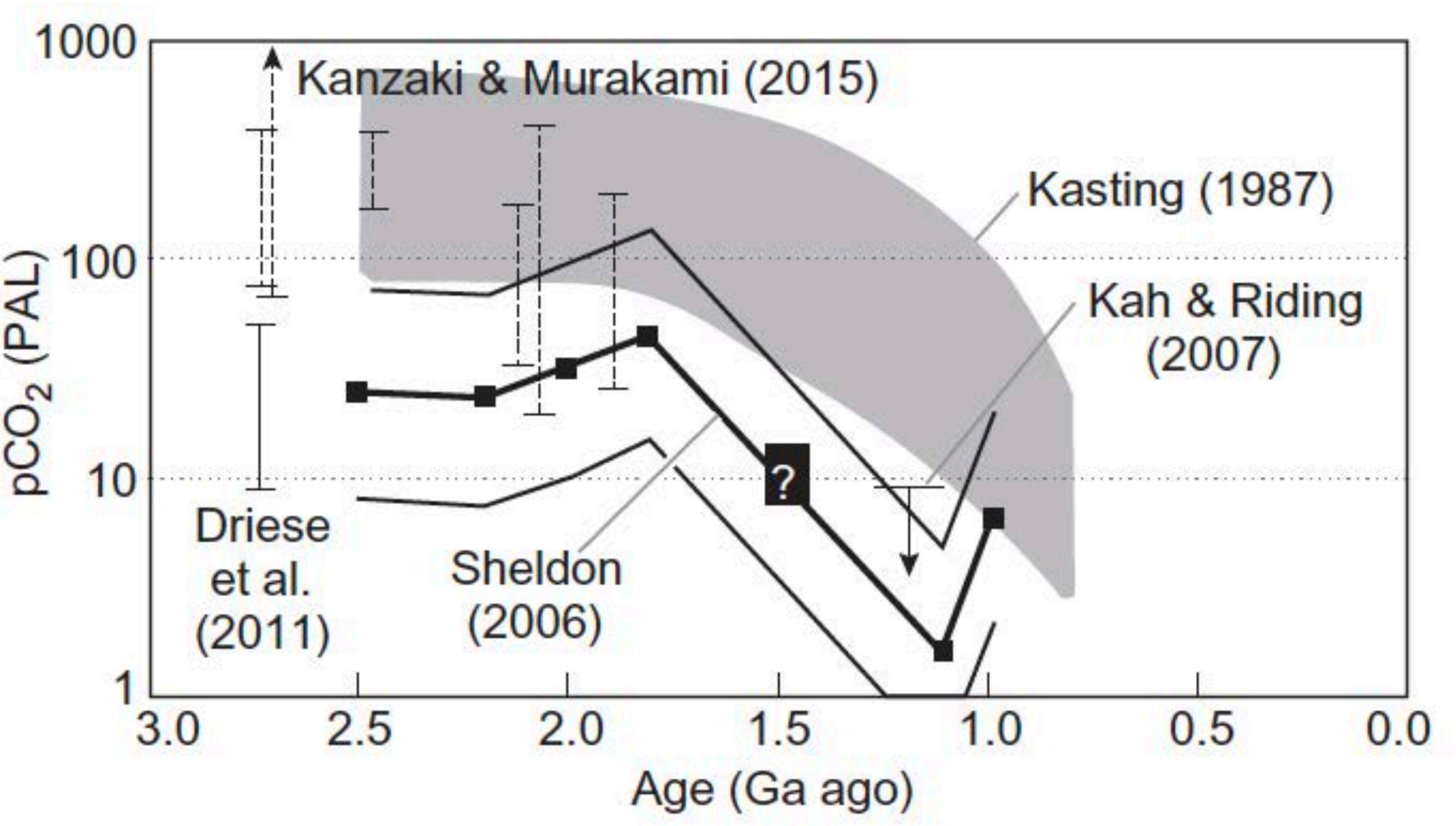
Thermodynamics of weathering reactions require minimum pCO_2 higher than modern over range of T and pCO_2

Reaction 2 is most like weathering rinds and requires pCO2 higher than modern

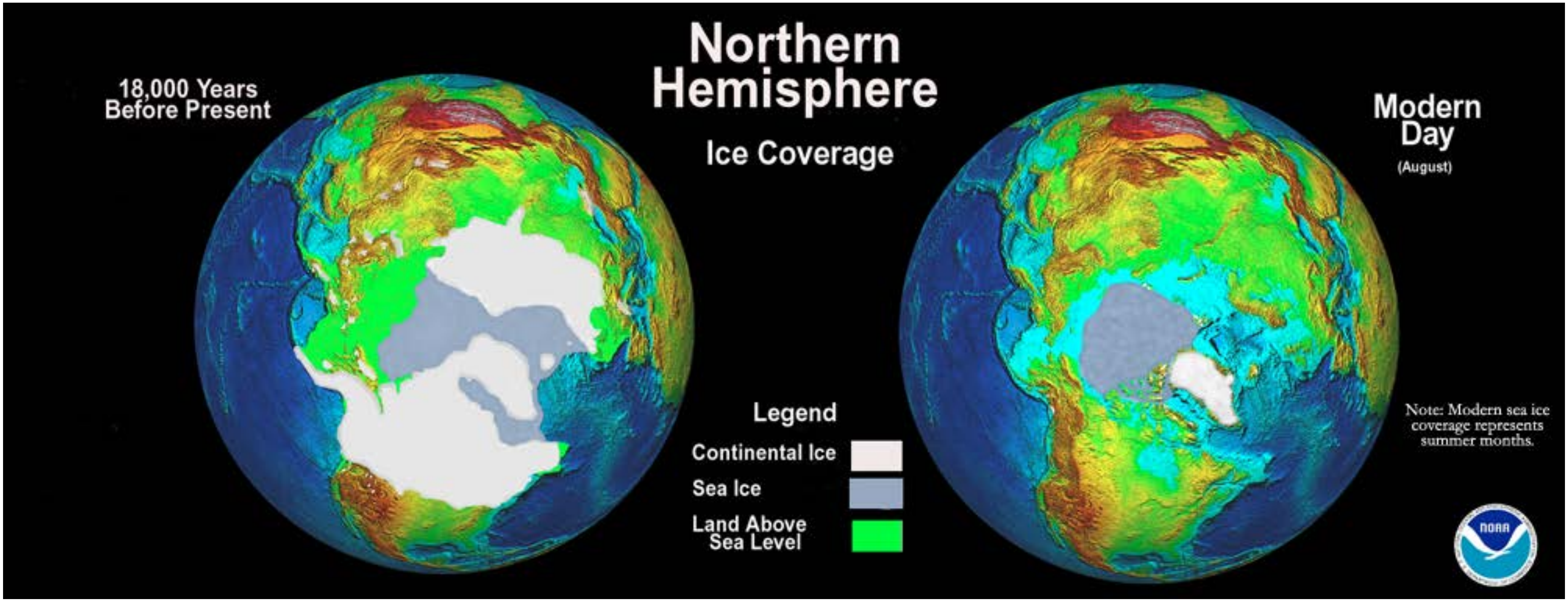


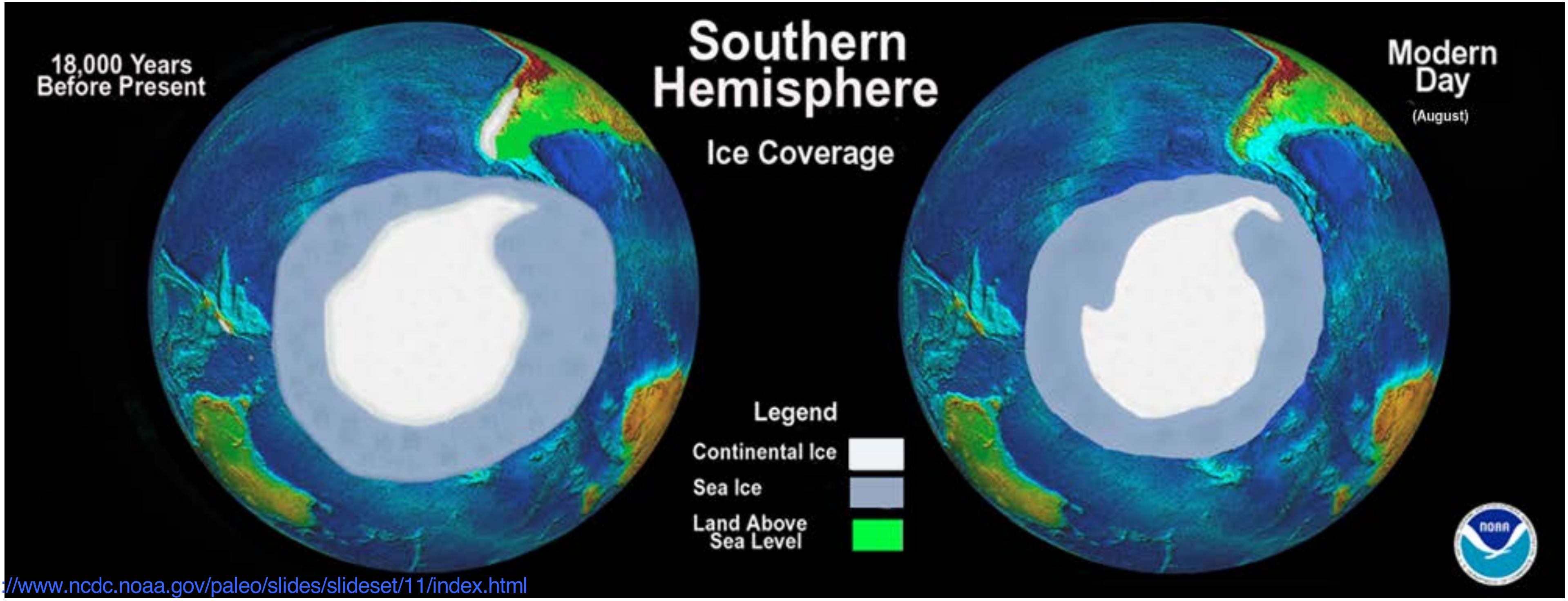
Hessler et al., 2004

Thermodynamics of weathering reactions require minimum pCO_2 higher than modern over range of T and pCO_2

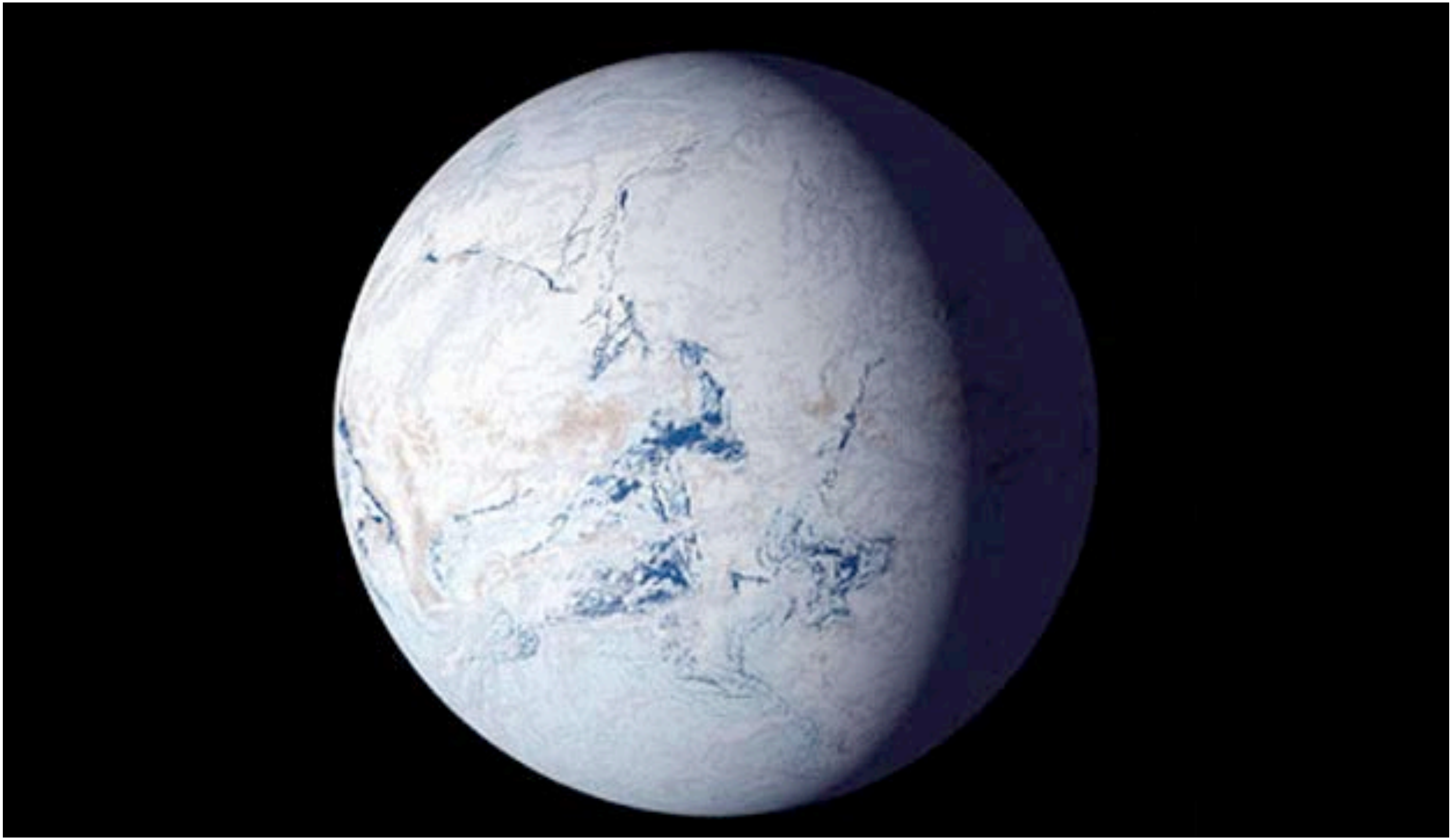


Kasting, 2018

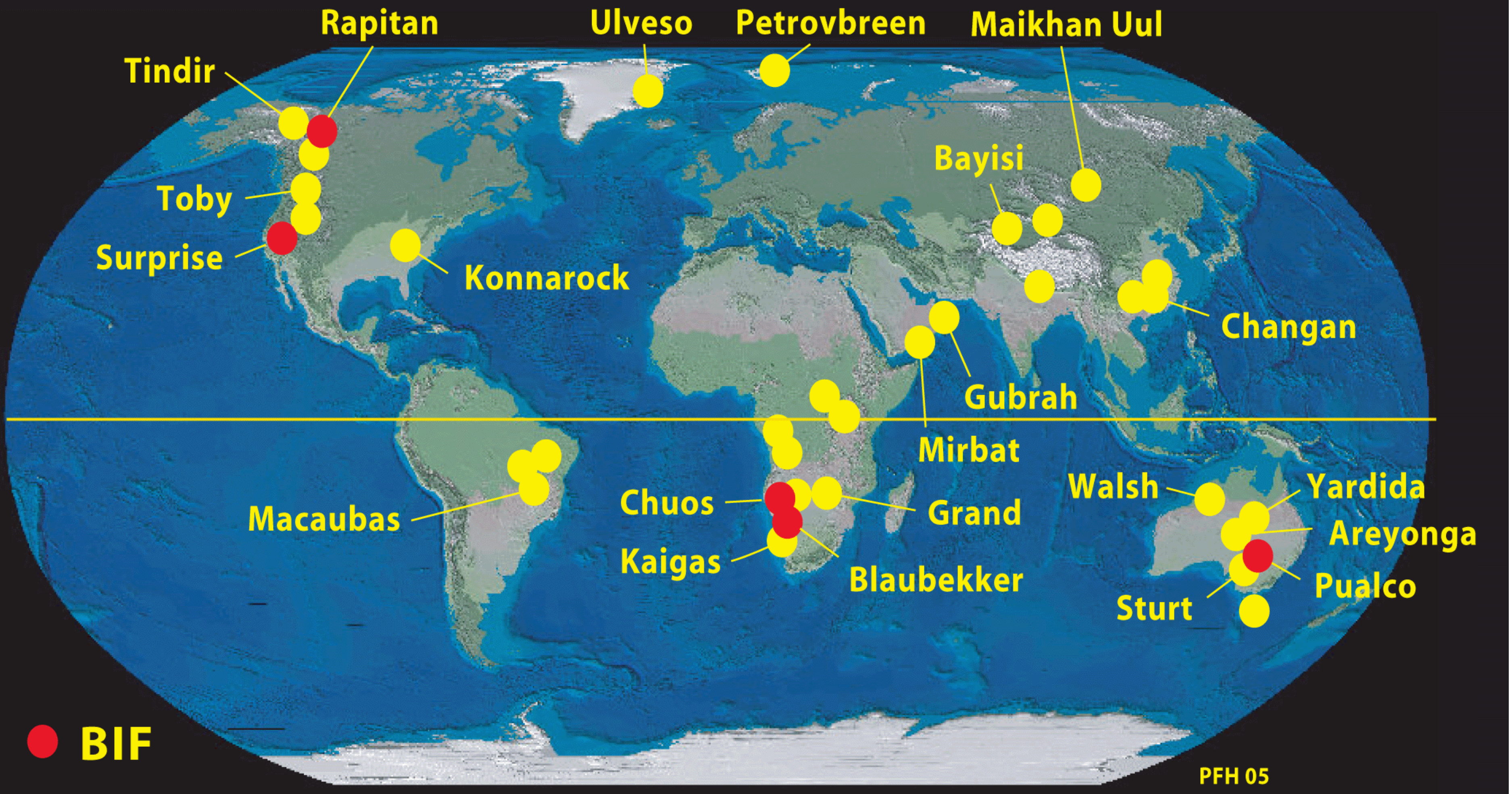




http://www.ncdc.noaa.gov/paleo/slides/slideset/11/index.html



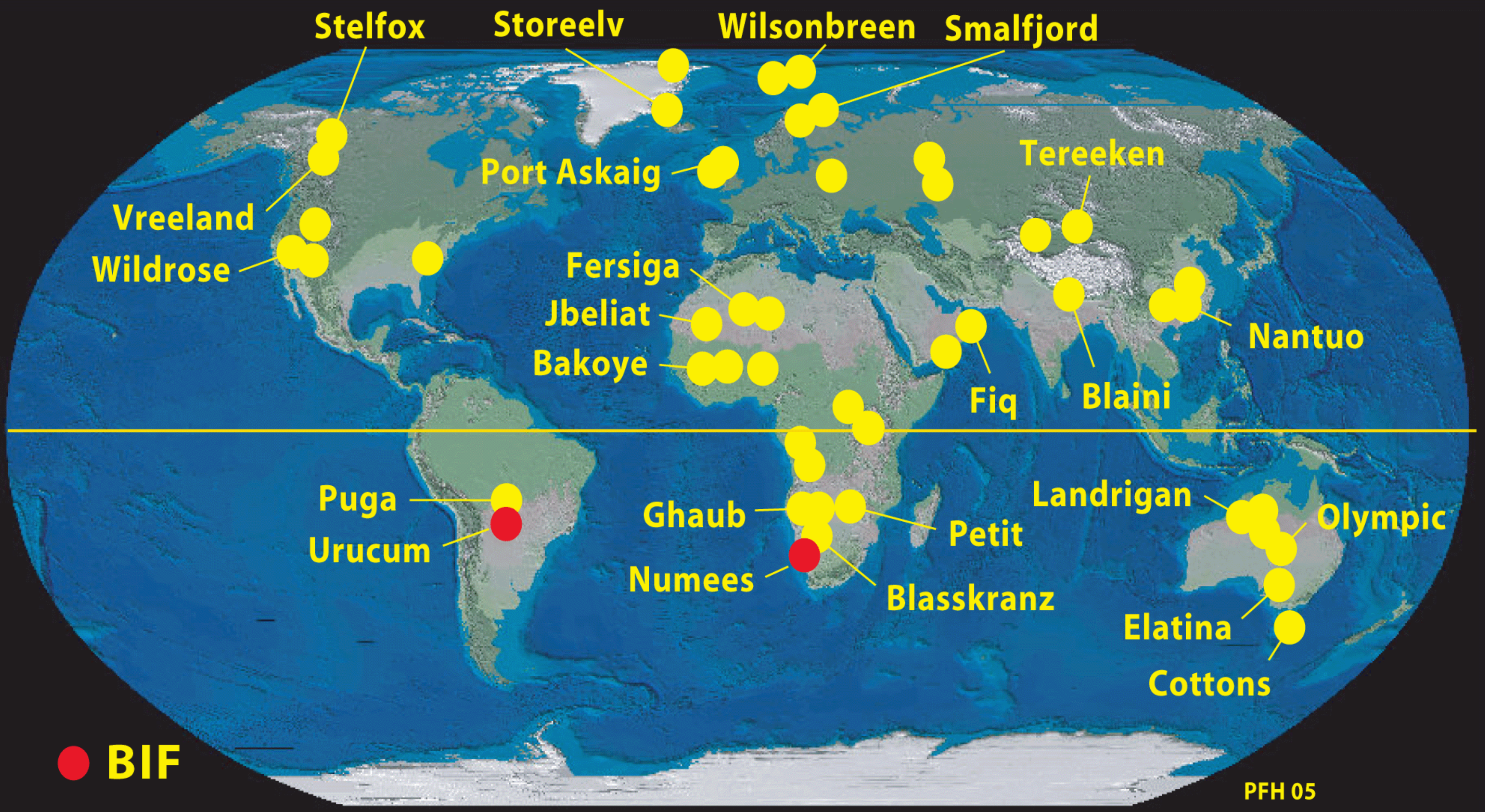
http://images.spaceref.com/news/oosnowball.earth.2.jpg



Older Cryogenian ('Sturtian') glacials

730 - 700 Ma

http://www.snowballearth.org/week1.html



Younger Cryogenian ('Marinoan') glacials

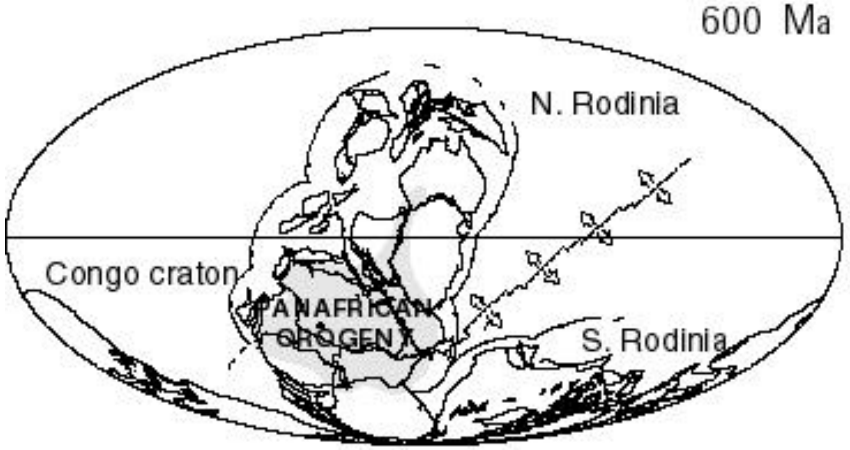
(665 - 635 Ma)

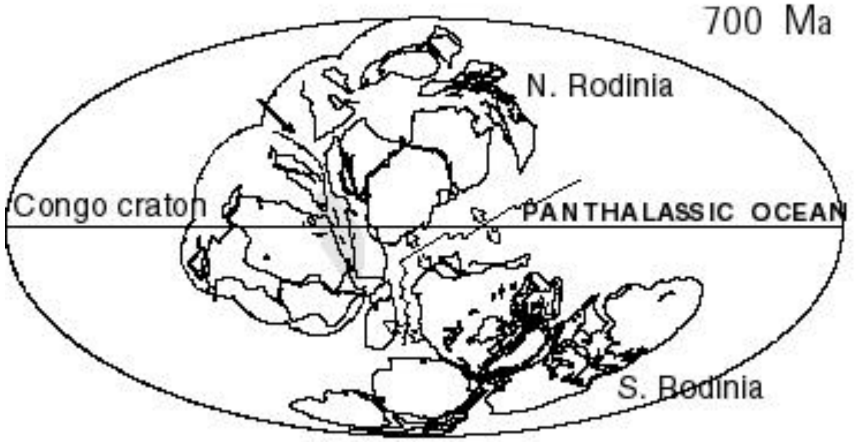
http://www.snowballearth.org/week1.html

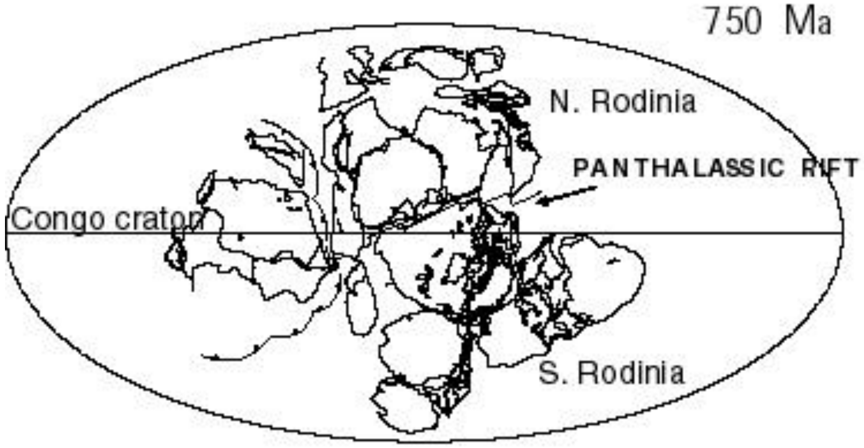
Paleogeography of Rodinia during Neoproterozoic

SWEAT: SouthWest US-East Antarctica

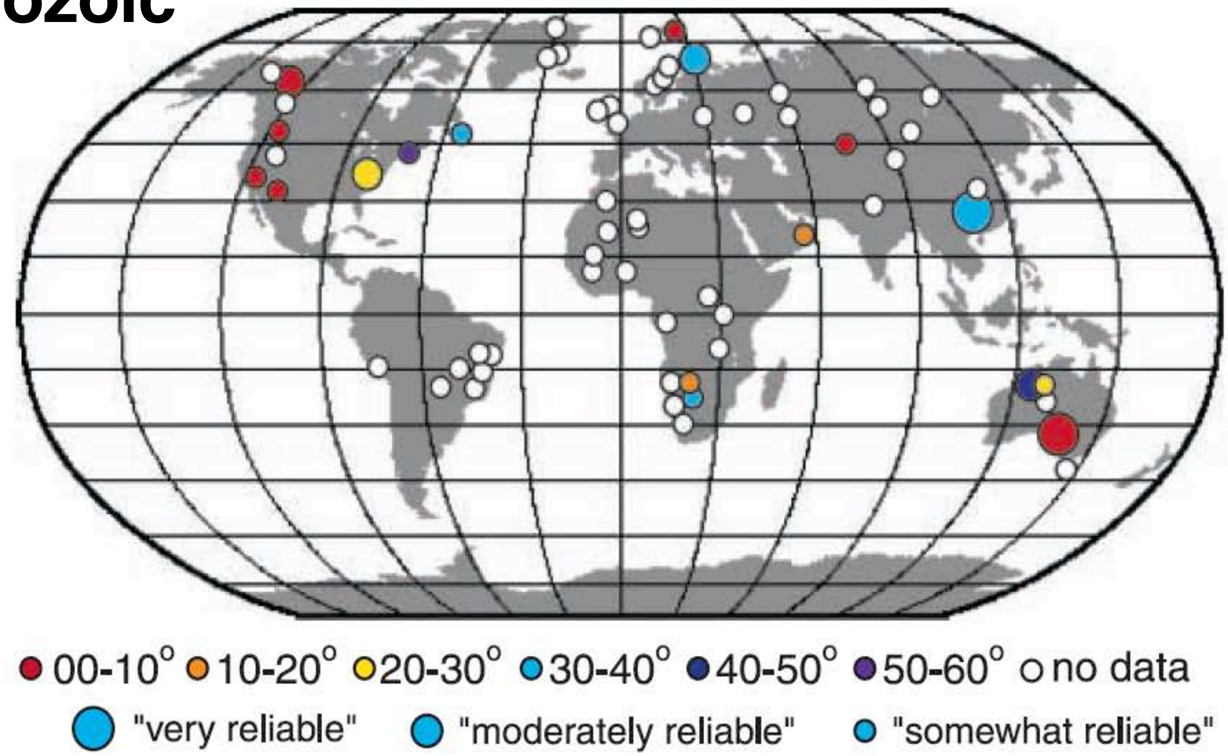
http://www.scotese.com/rodinia.jpg

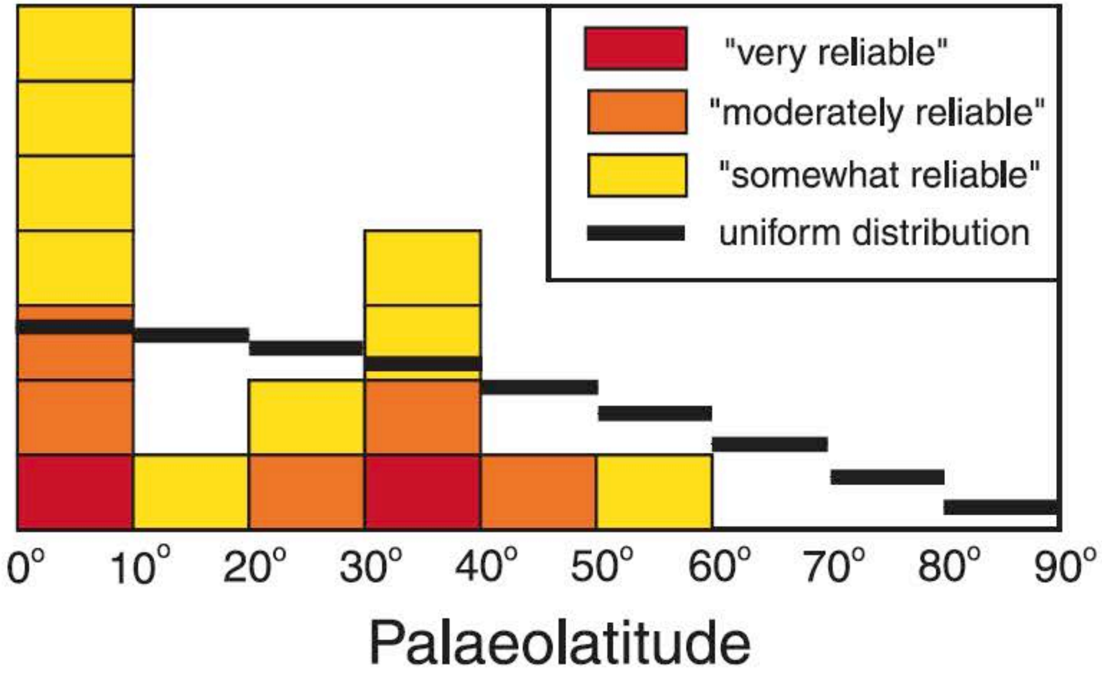




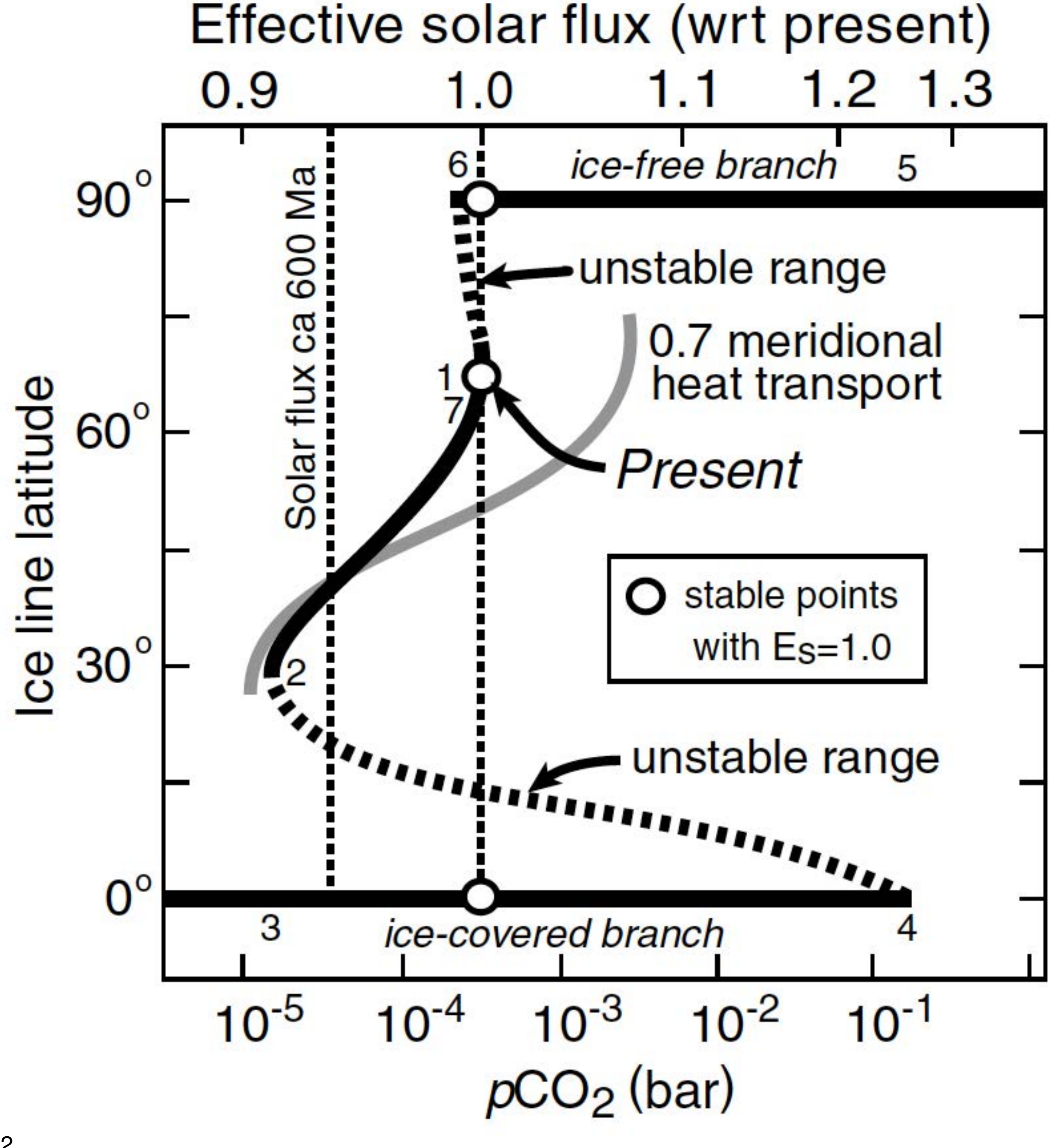


Low latitude Neoproterozoic global glaciations



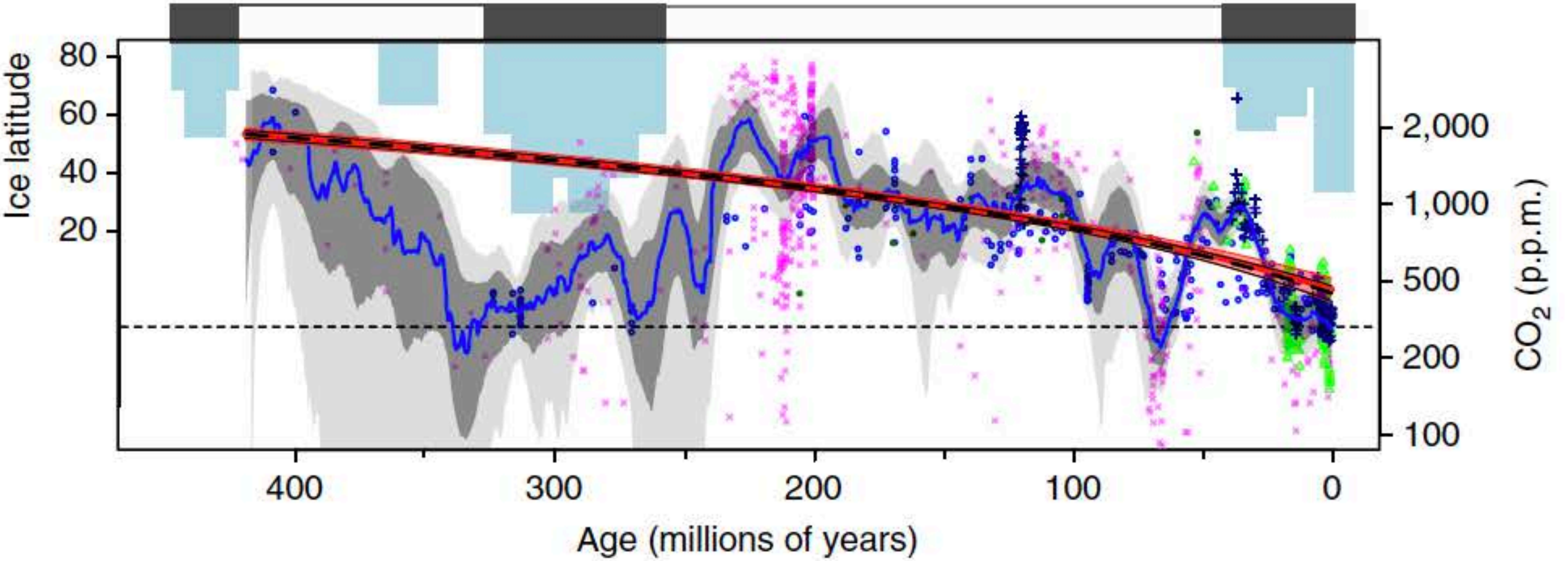


Hoffman and Schrag, 2002



Hoffman and Shrag, 2002

400 million year record of atmospheric CO_2 and climate

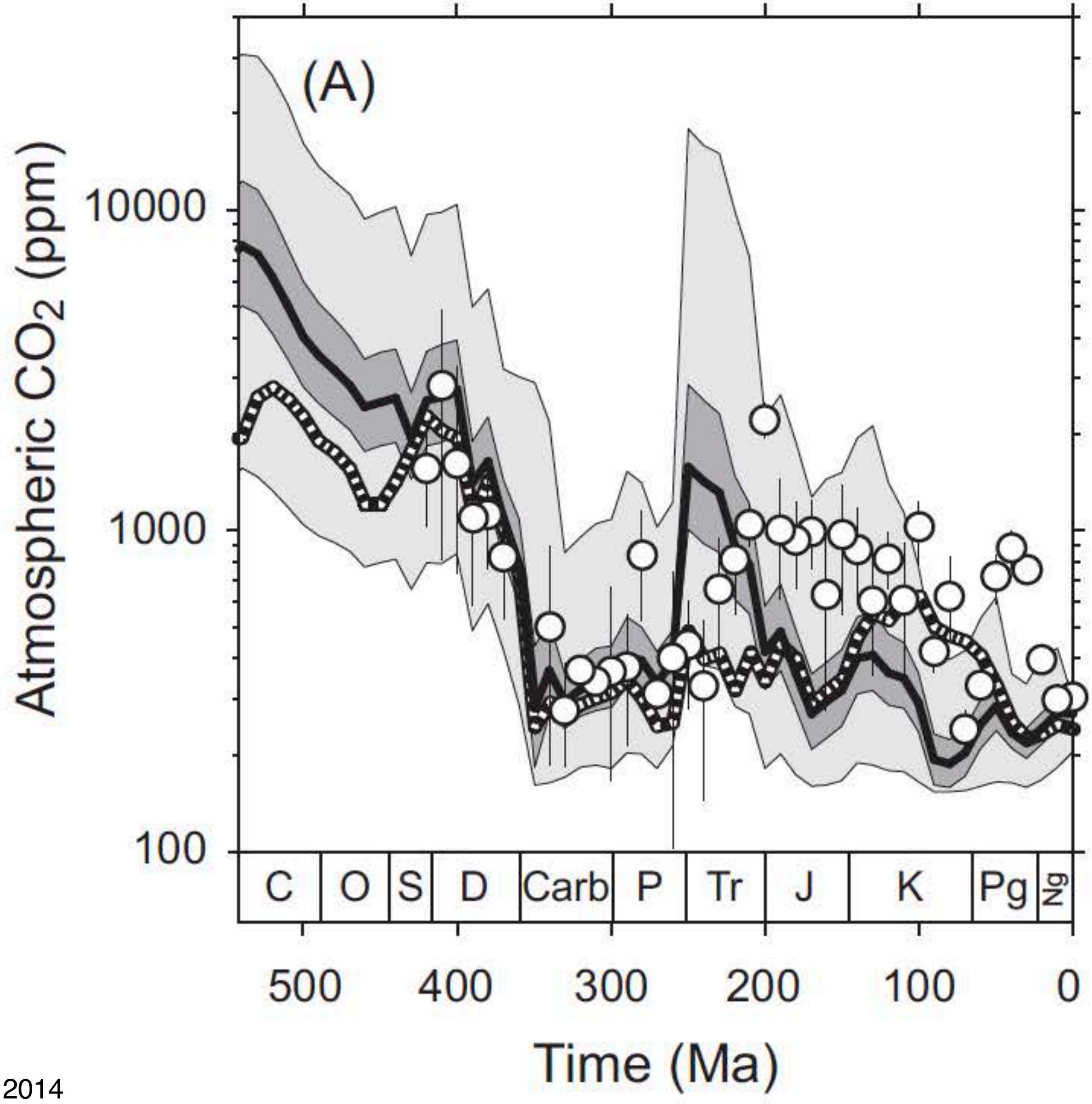


CO_2 record based on:
- fossil leaf anatomy
- chemistry of fossil soils
- chemistry of fossil plankton
- chemistry of fossil liverworts

Ice extent based on:
- geology
- paleogeography from paleomagnetic record

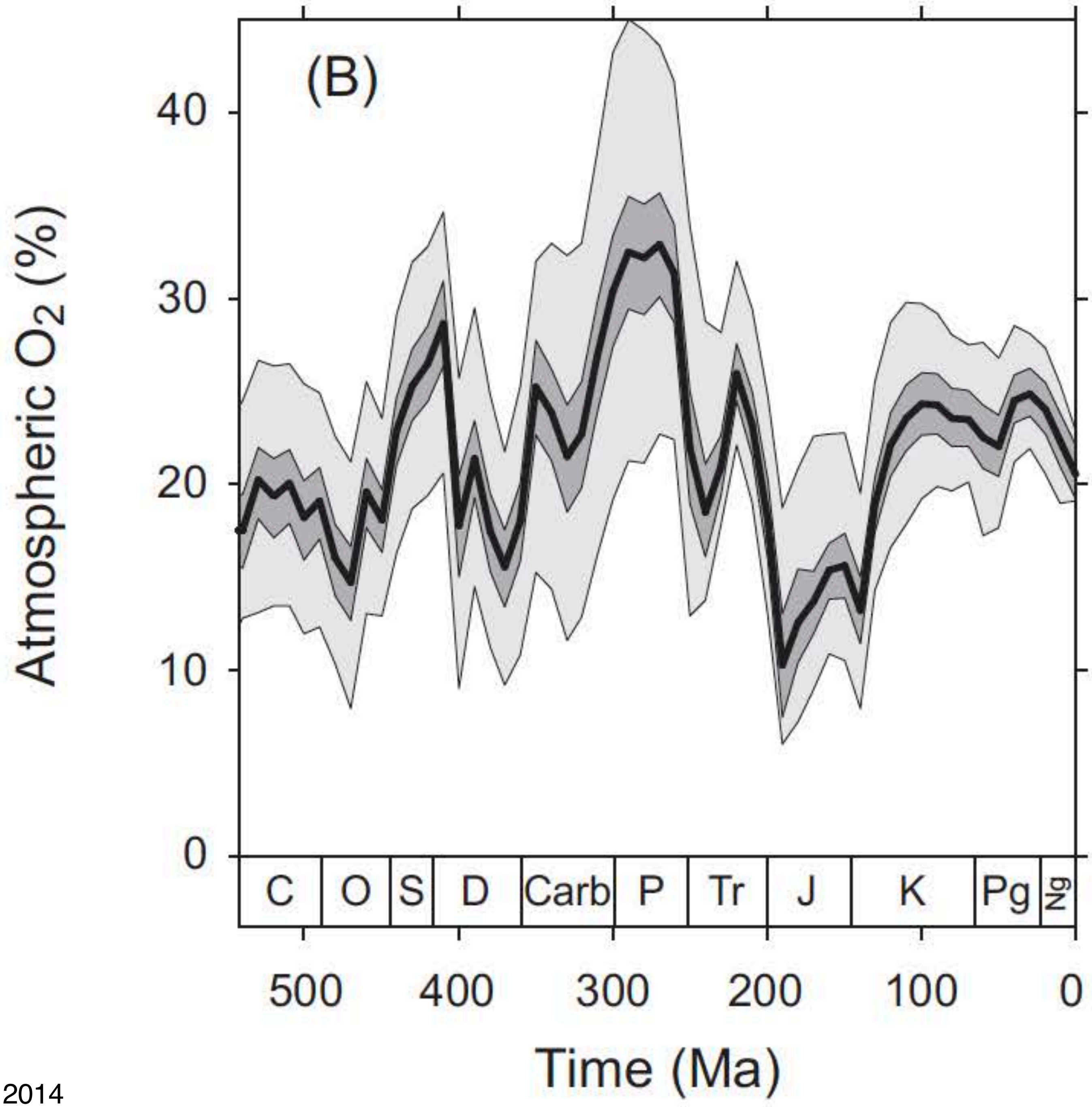
Foster et al., 2017. *Nature Communications*

Atmospheric CO_2 estimated by GEOCARBSULF



Royer et al., 2014

Atmospheric O_2 estimated by GEOCARBSULF



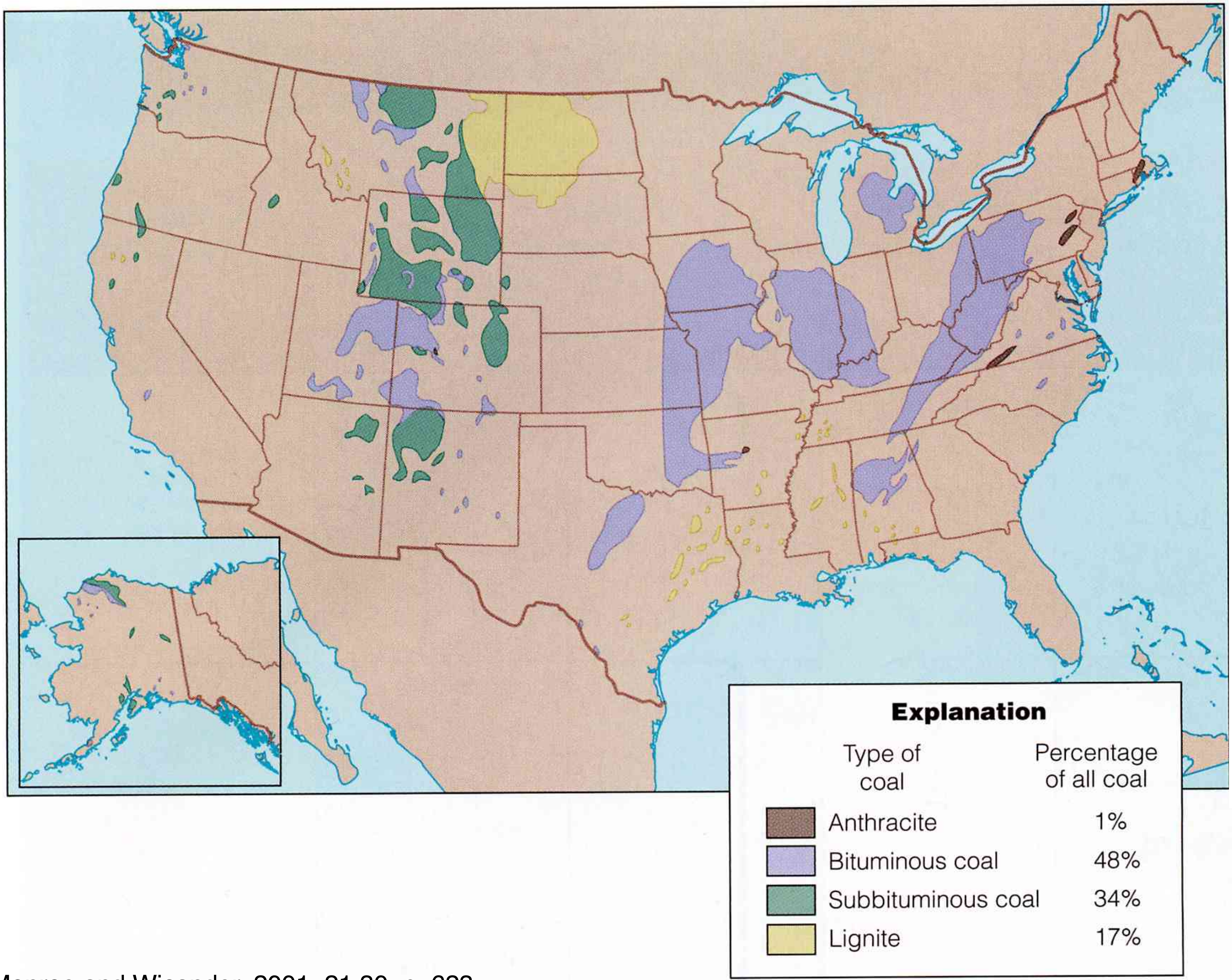
Royer et al., 2014

http://www.fmnh.org/research_collections/ecp/ecp_sites/NPI_web/models_coal.htm

Major coal deposits in the United States

Western: Cretaceous and Paleogene

Central and eastern: Pennsylvanian

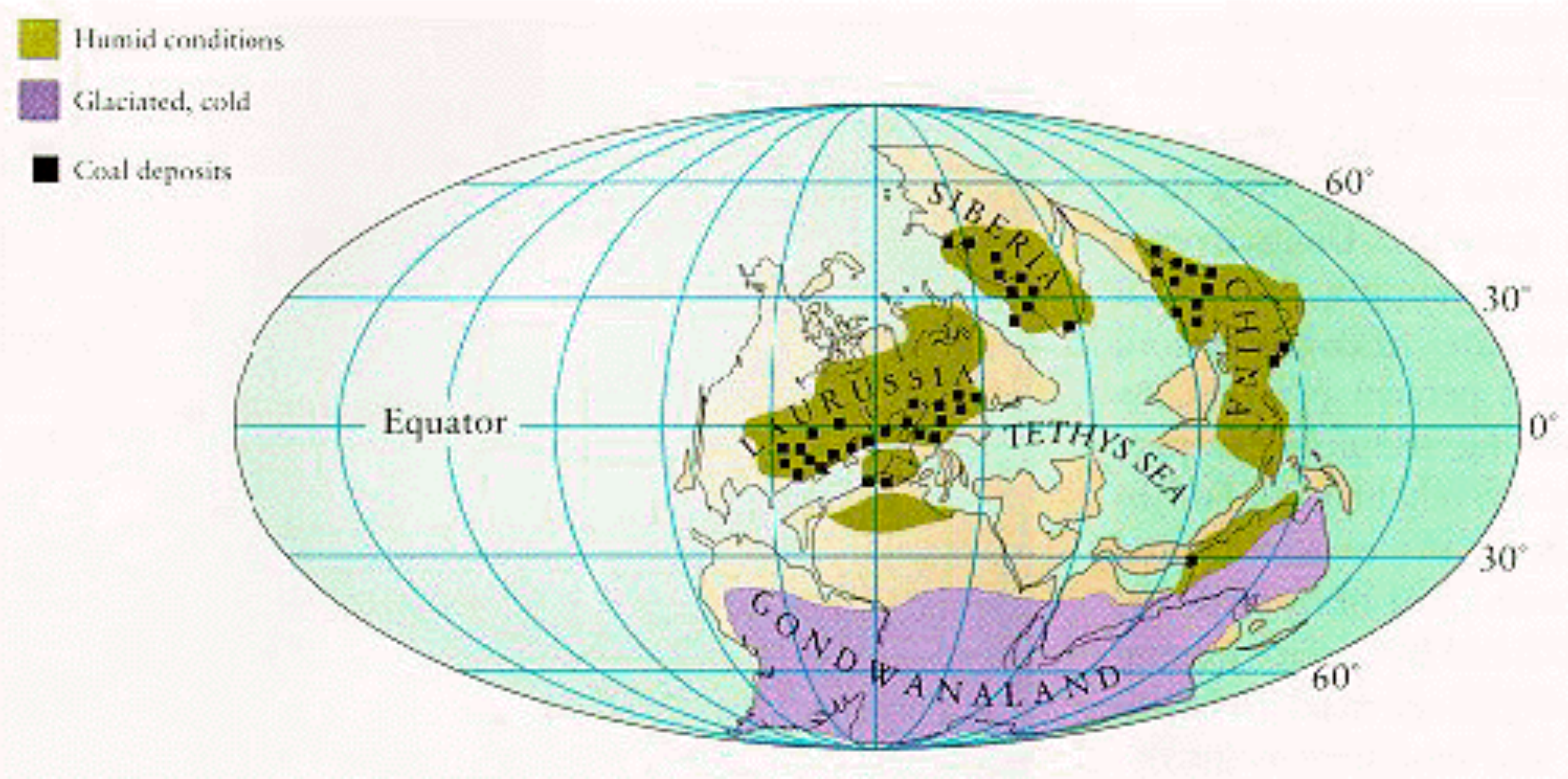


Explanation

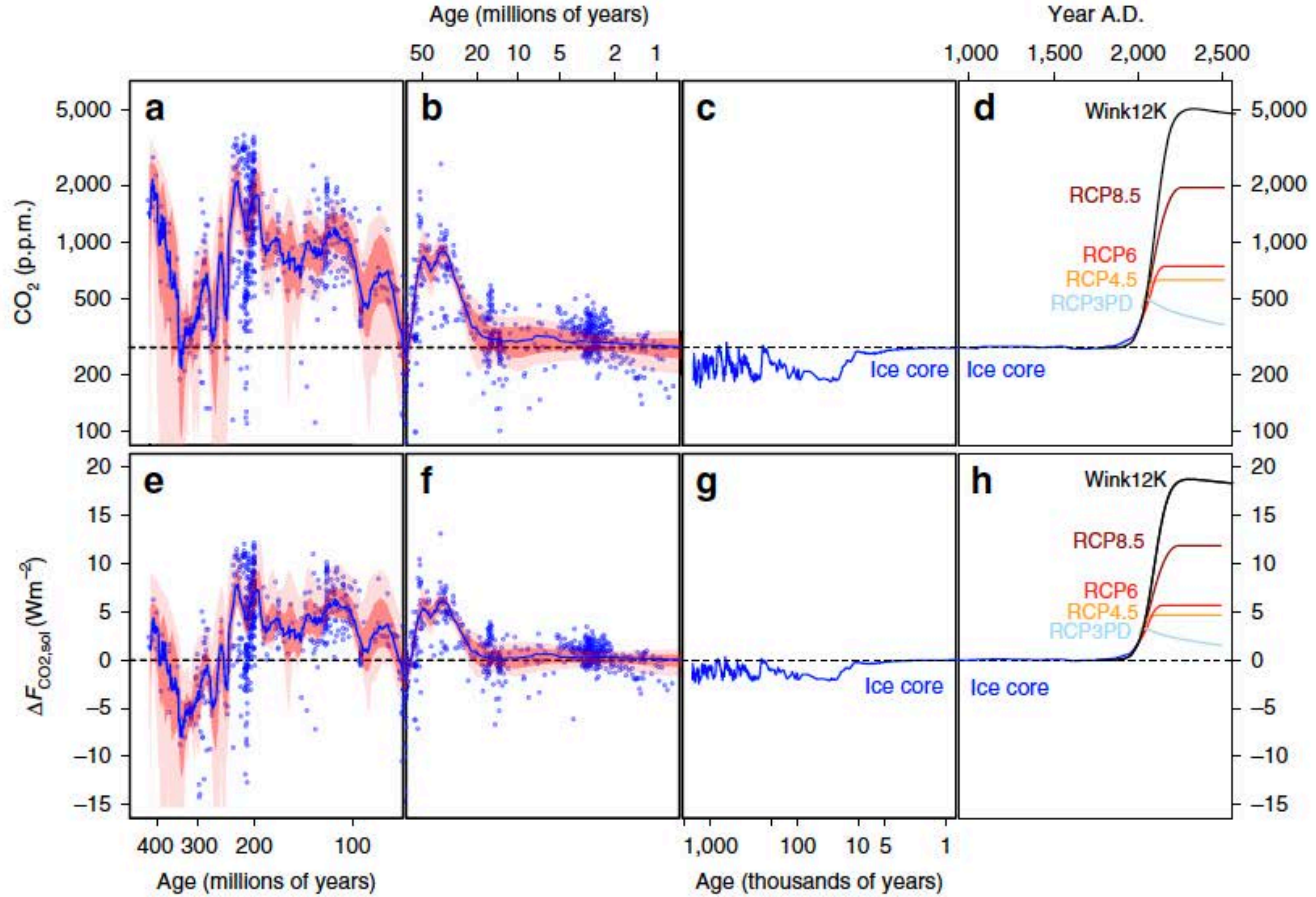
	Type of coal	Percentage of all coal
🟫	Anthracite	1%
🟪	Bituminous coal	48%
🟩	Subbituminous coal	34%
🟨	Lignite	17%

Monroe and Wicander, 2001 21.30 p. 623

Carboniferous coal deposits globally

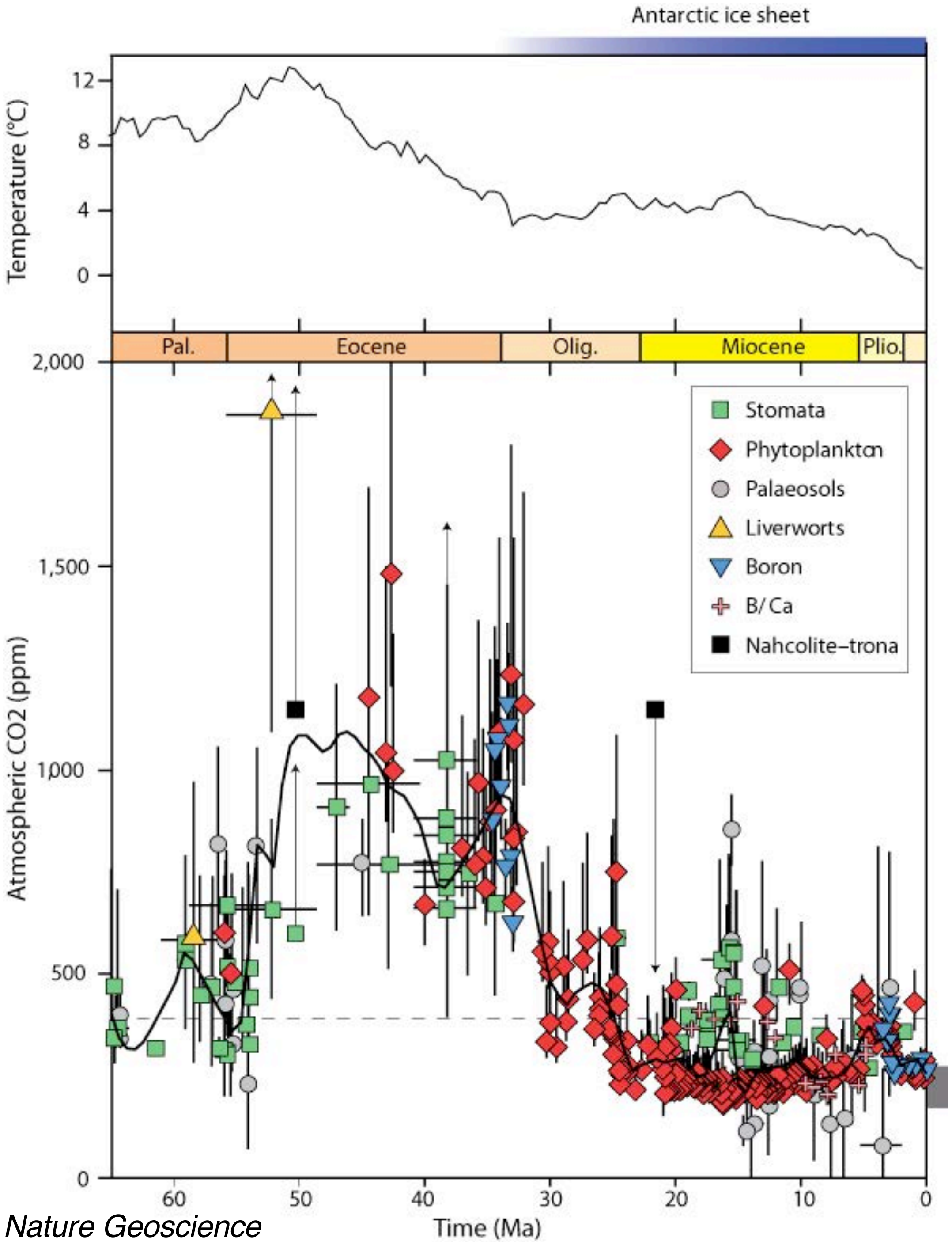


400 million year record of atmospheric CO_2 and climate



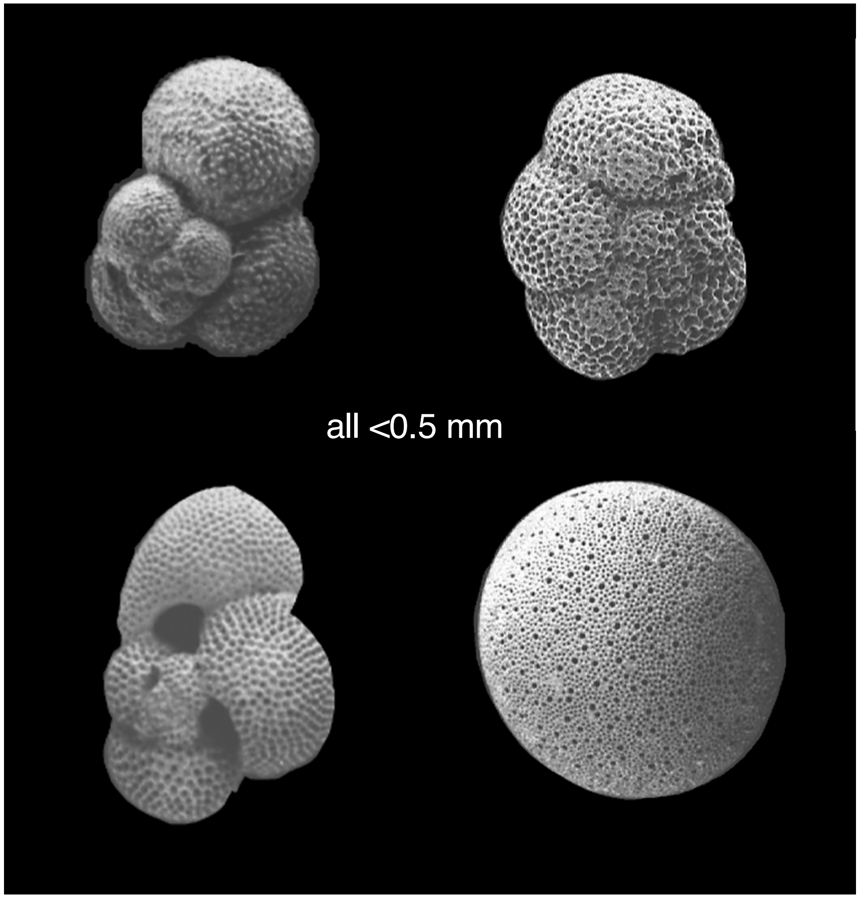
Foster et al., 2017. *Nature Communications*

65 million year record of armospheric CO_2 and climate



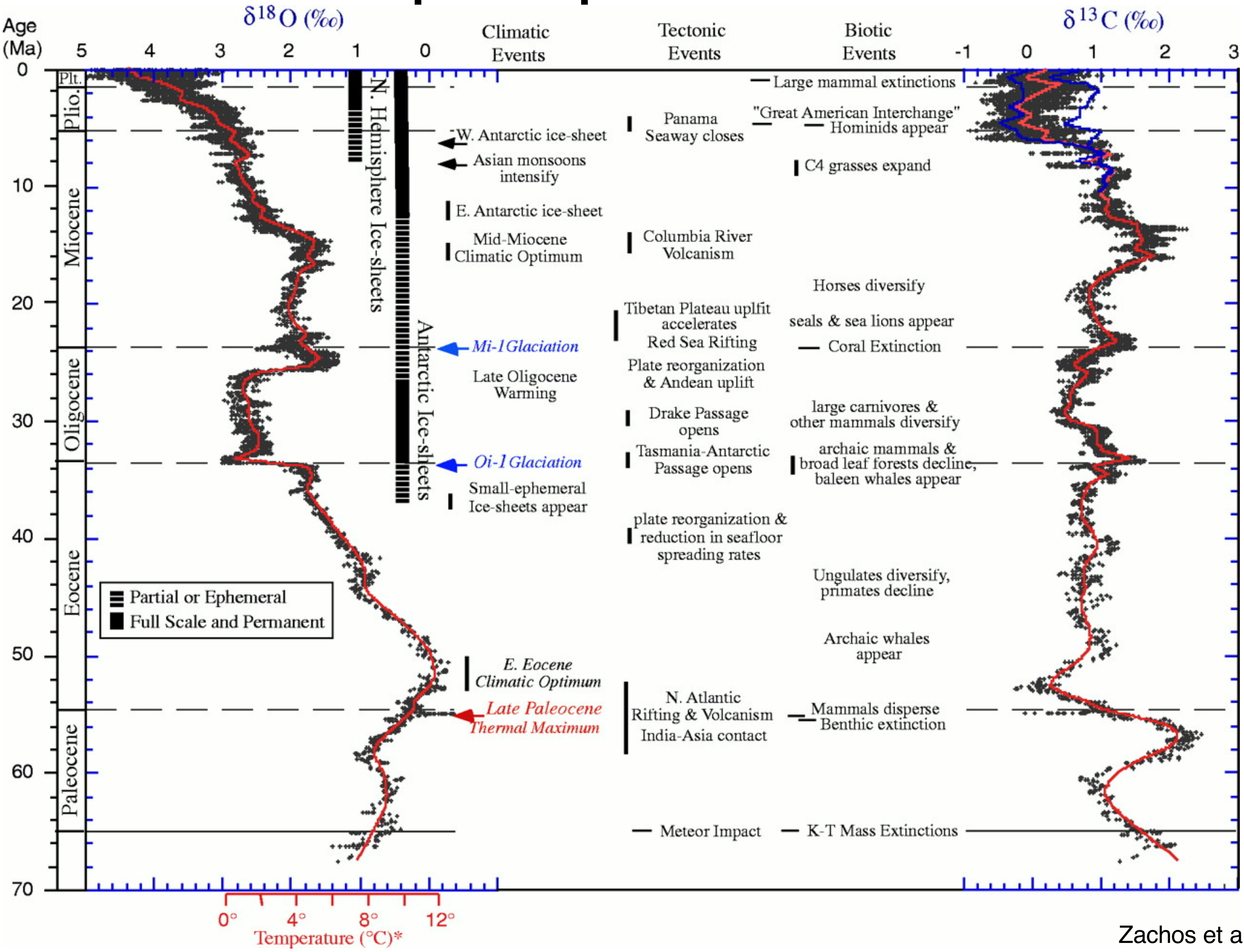
Beerling and Royer, 2011. *Nature Geoscience*

$^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios of benthic microfossils (foraminifera) record changes in the global carbon cycle and water temperature (± changes in ice volume)



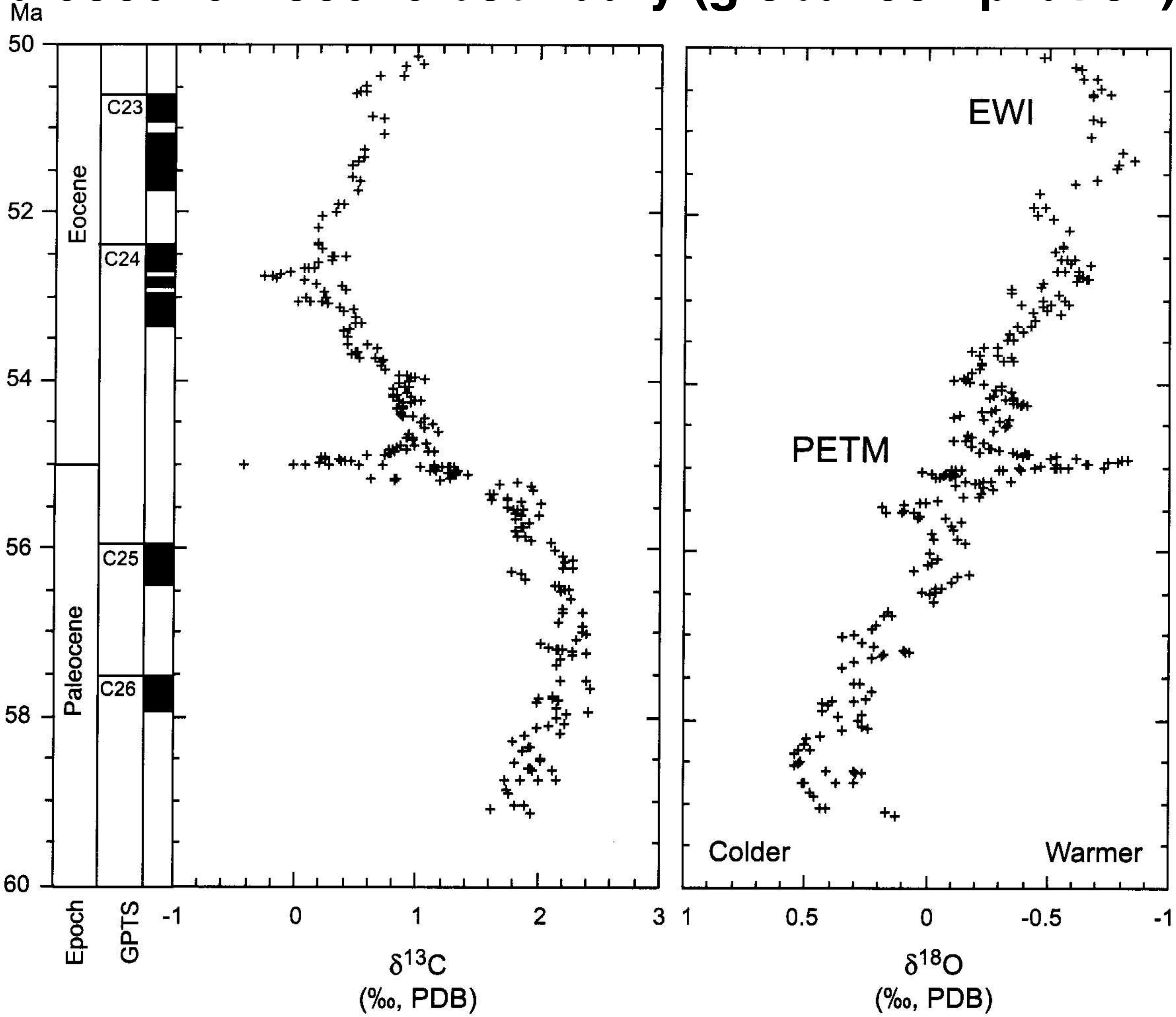
Ruddiman, 2000

Global compilation of benthic foraminifera oxygen and carbon isotope compositions

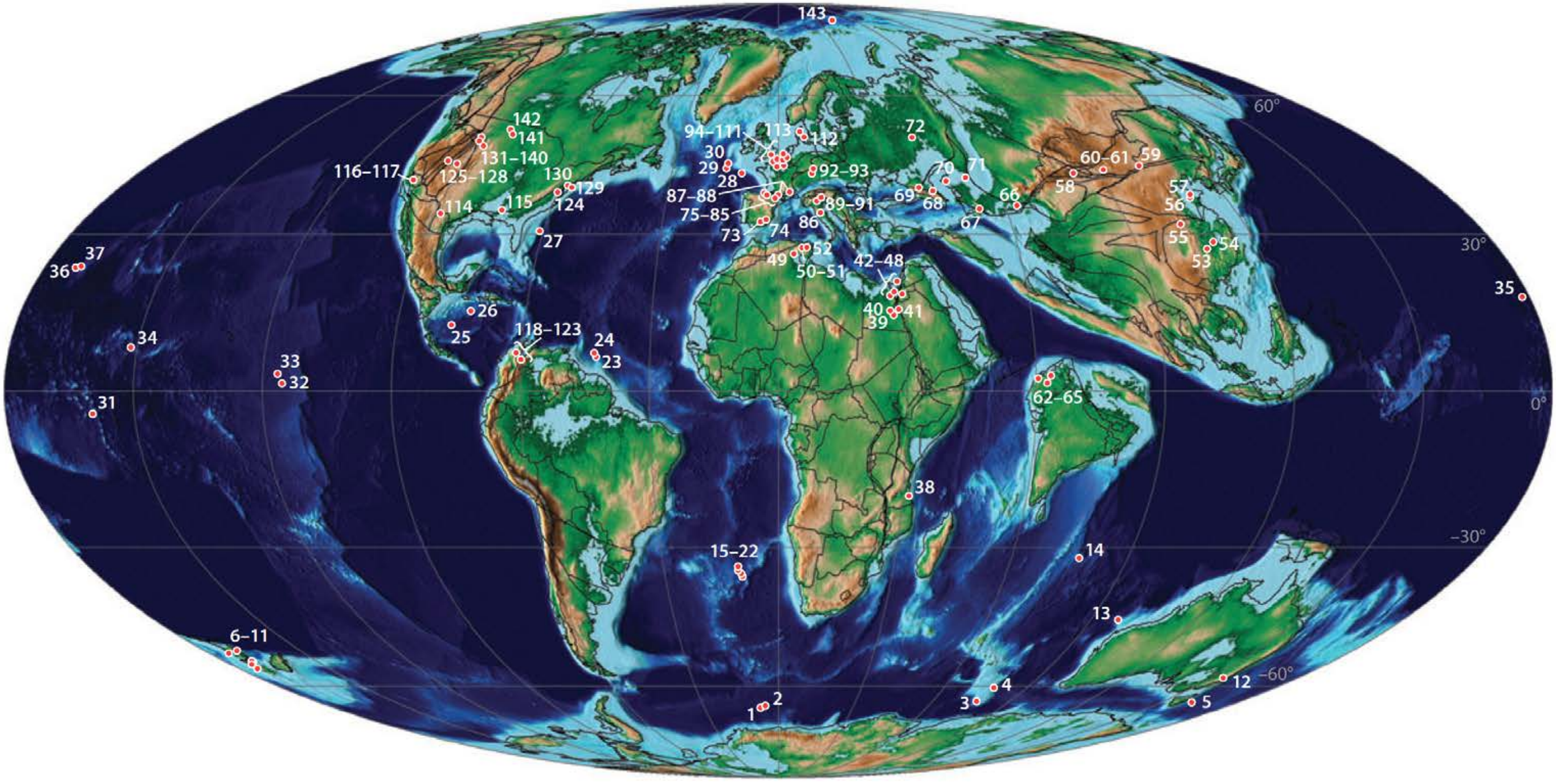


Zachos et al., 2008

Stable isotope composition of benthic foraminifera across the Paleocene-Eocene boundary (global compilation)

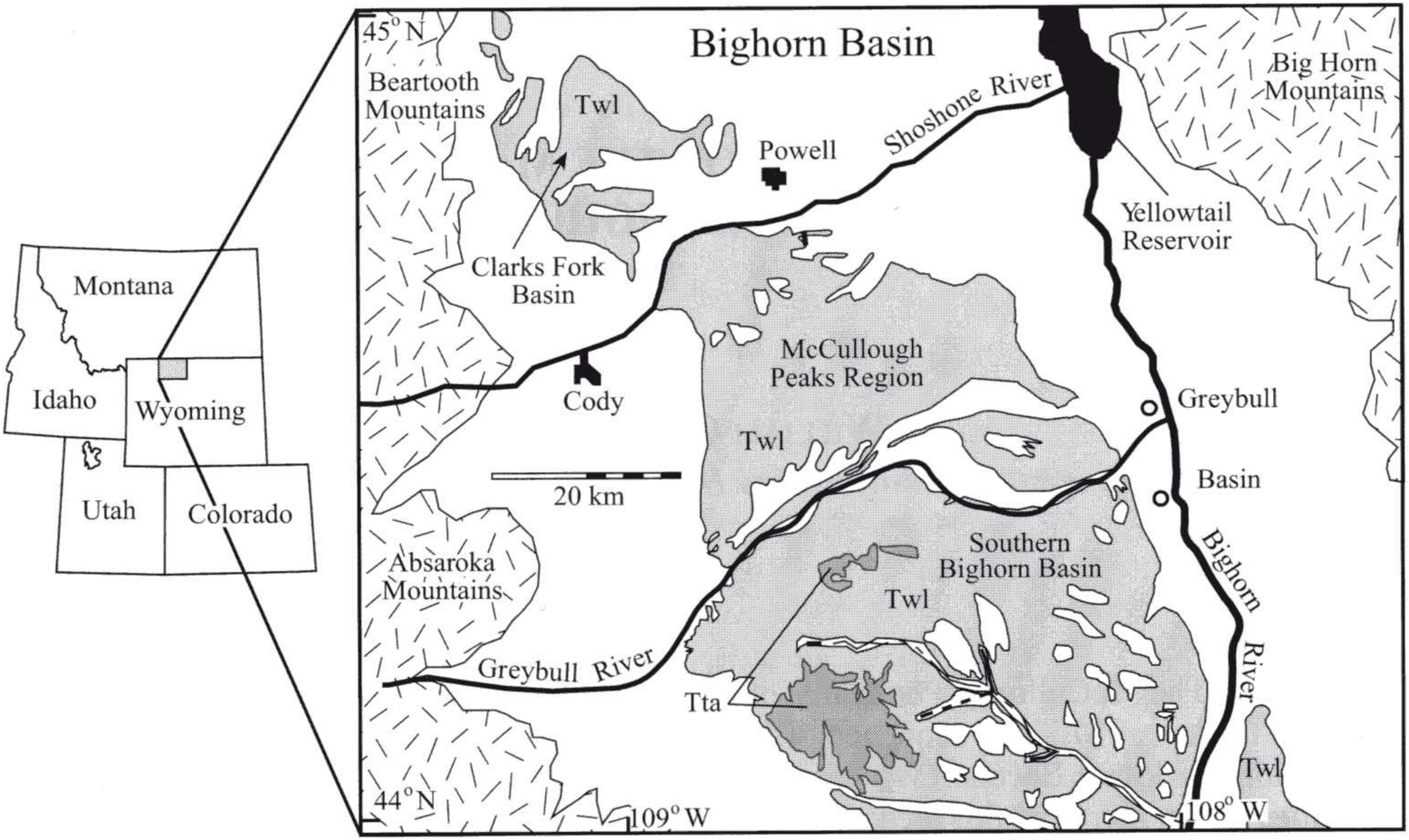


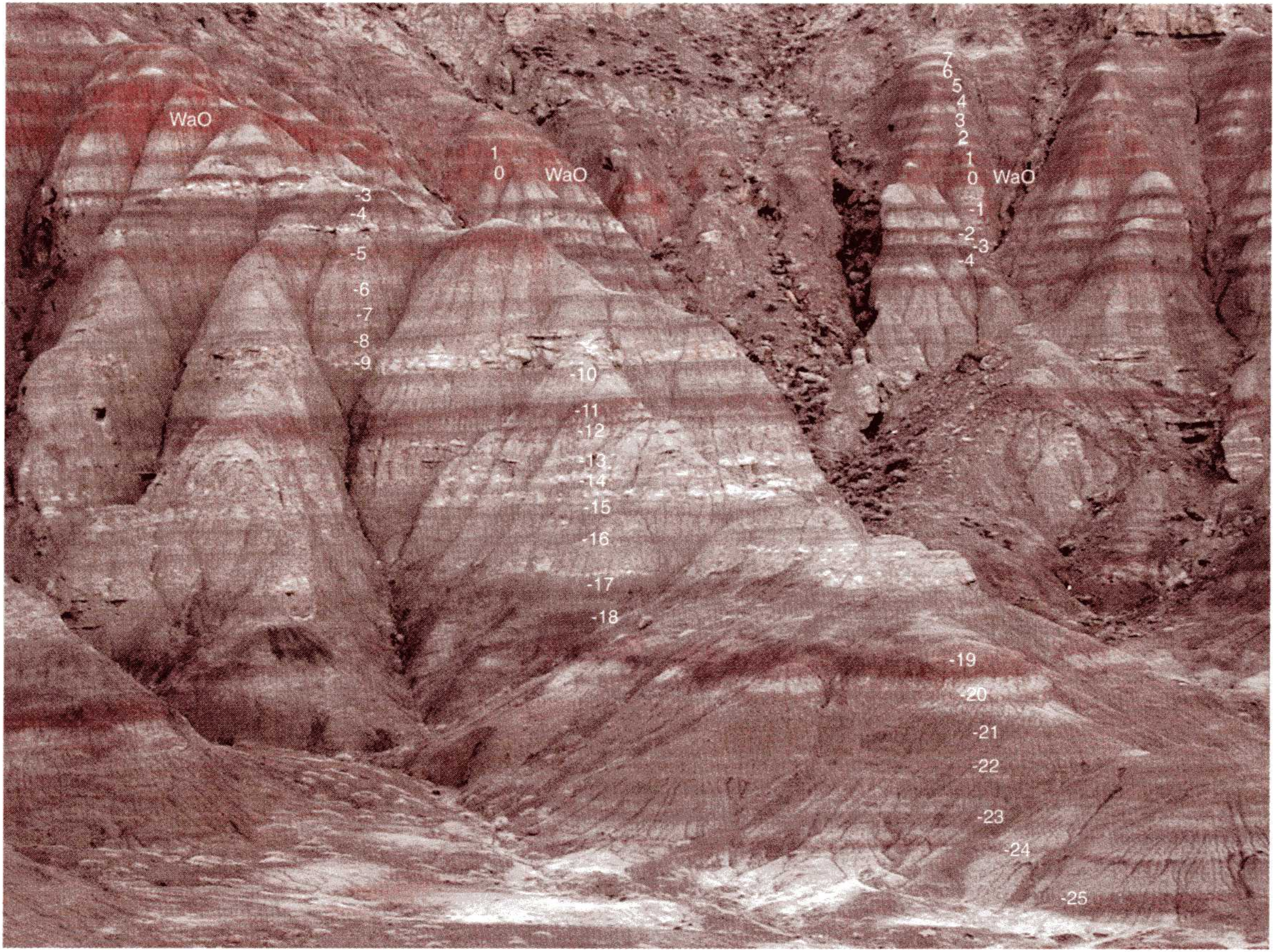
Paleogeographic map for 56 Ma with P-E boundary sites



McInerney and Wing, 2011

Bighorn Basin, north central Wyoming




WaO
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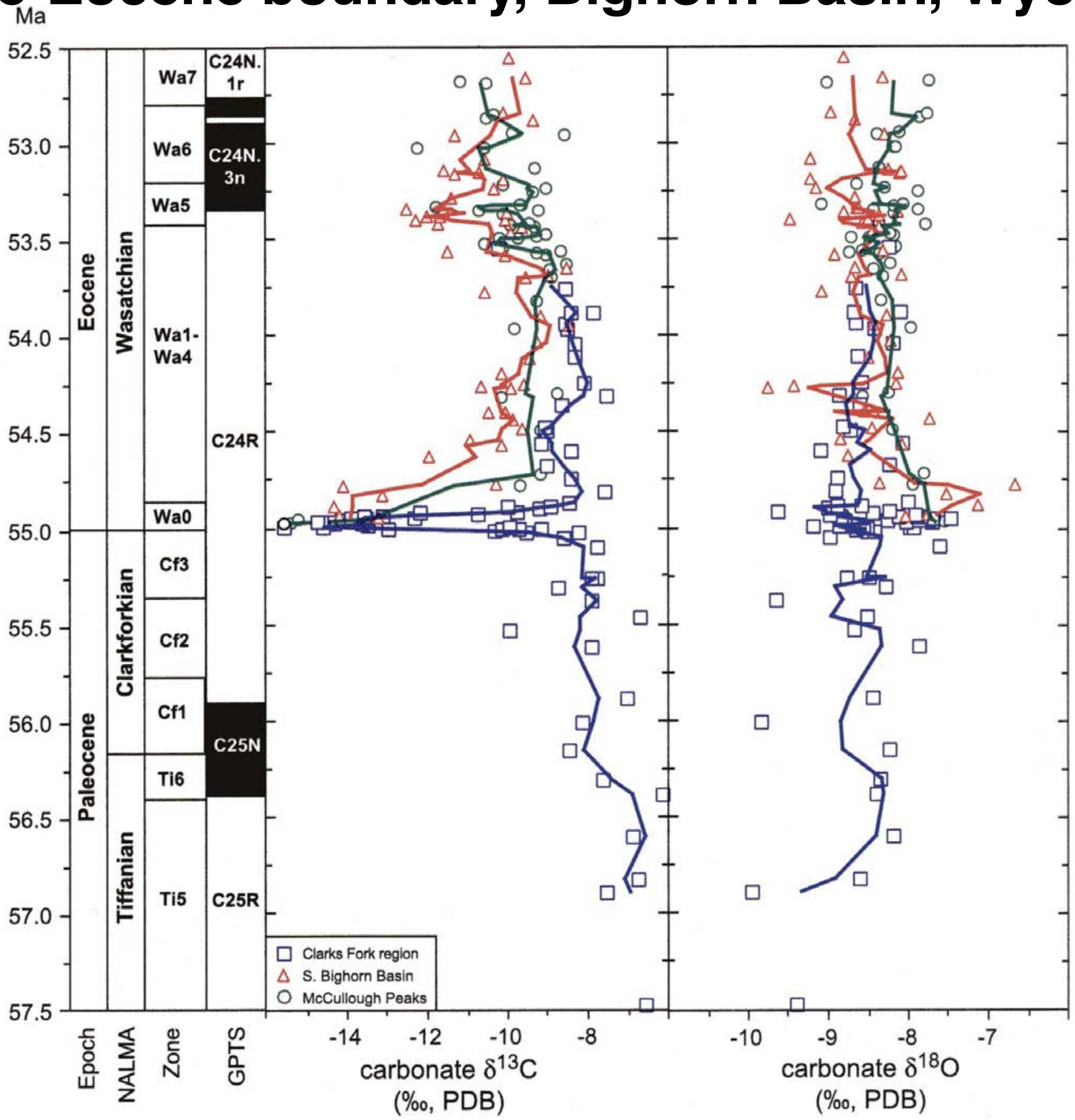
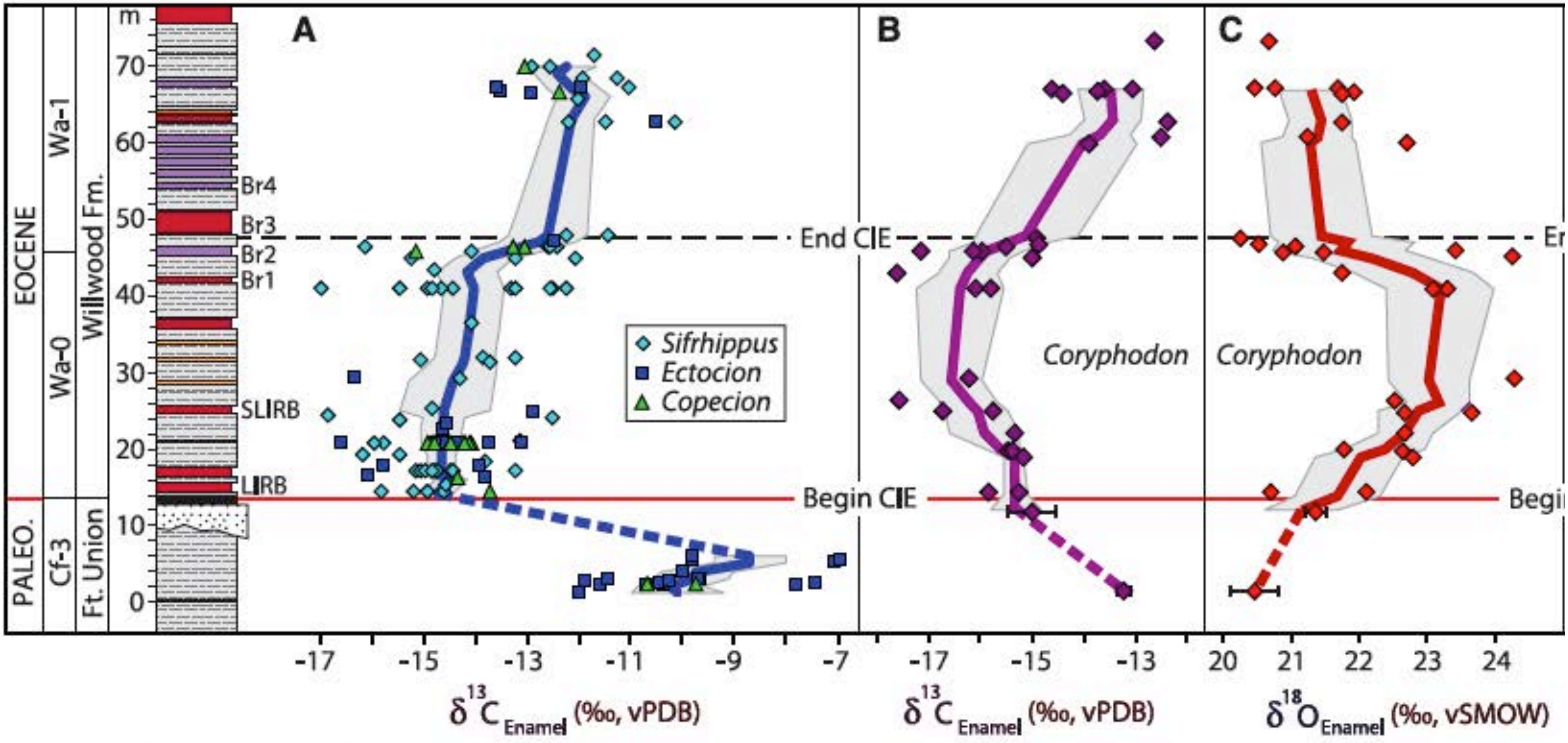
Stable isotope composition of paleosol carbonates at the Paleocene-Eocene boundary, Bighorn Basin, Wyoming



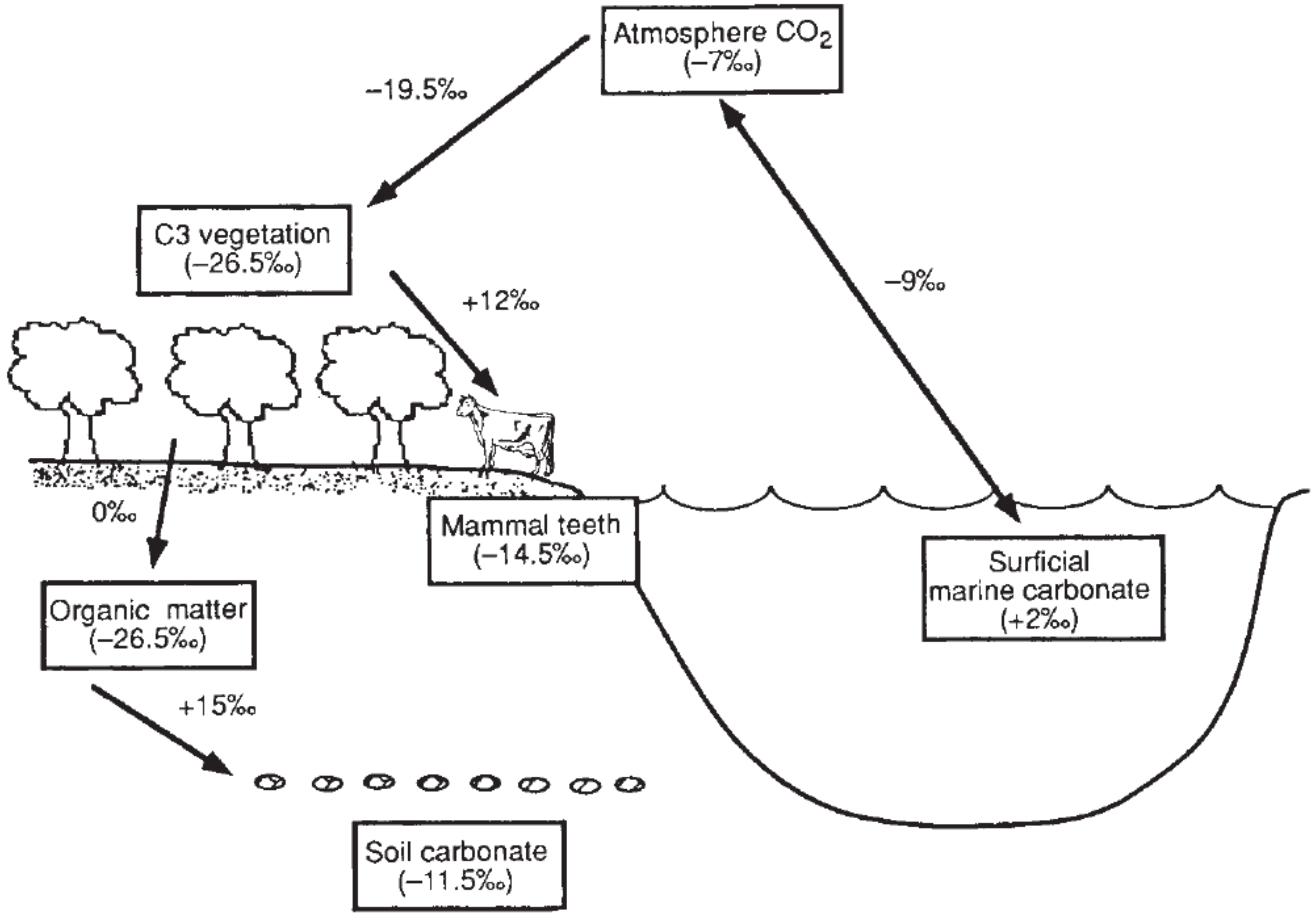
Bowen et al., 2001

Isotopic signal of CIE and PETM in mammalian tooth enamel



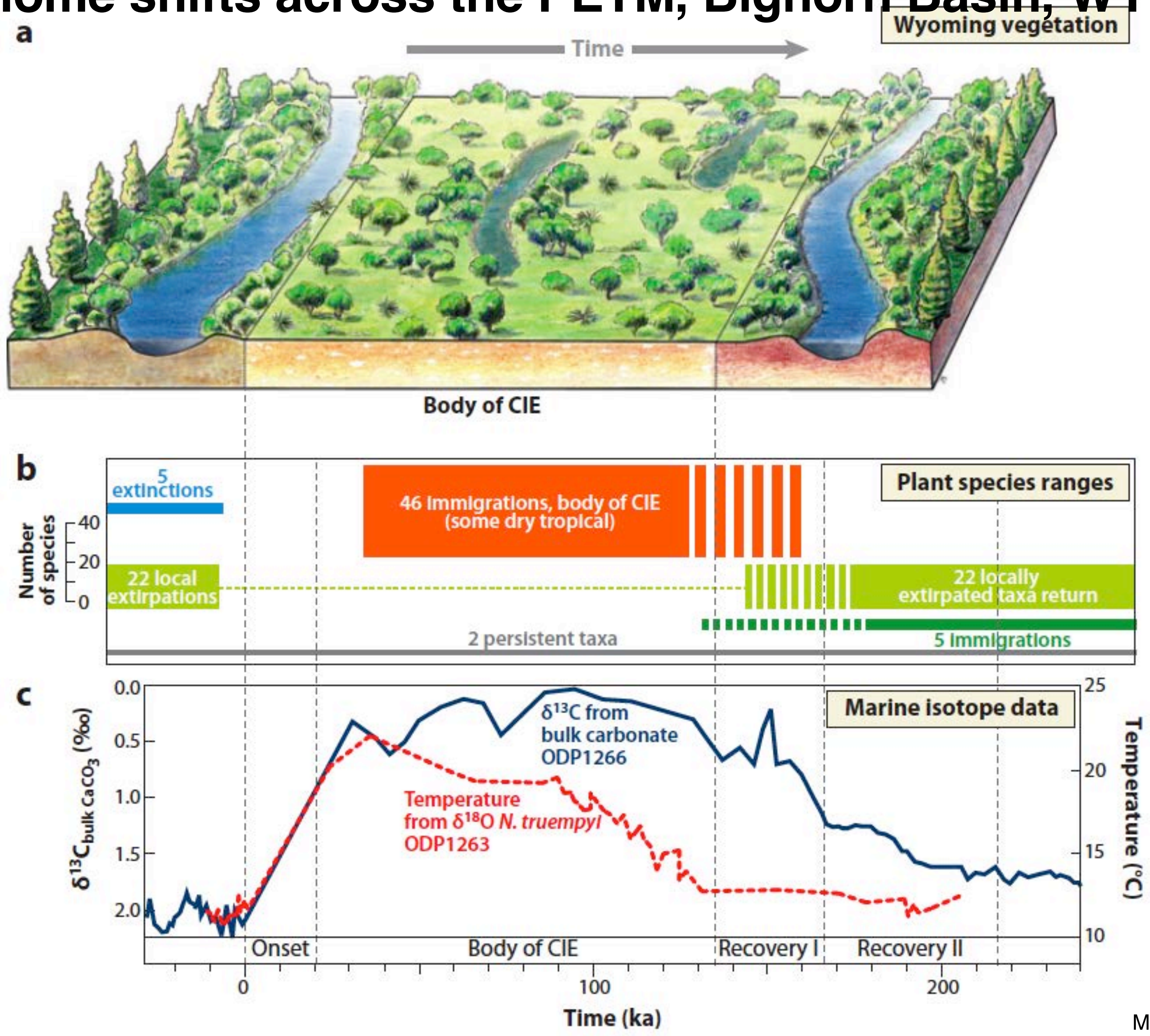
Secord et al., 2012

Carbon isotope excursion in the linked ocean-atmosphere-terrestrial biosphere system



Koch et al., 1989

Biome shifts across the PETM, Bighorn Basin, WY



McInerney and Wing, 2011

Mass balance and the amount of carbon added

$$(M_{\text{final}}) \times (\delta^{13}C_{\text{final}}) = (M_{\text{initial}}) \times (\delta^{13}C_{\text{initial}}) + (M_{\text{added}}) \times (\delta^{13}C_{\text{added}}).$$

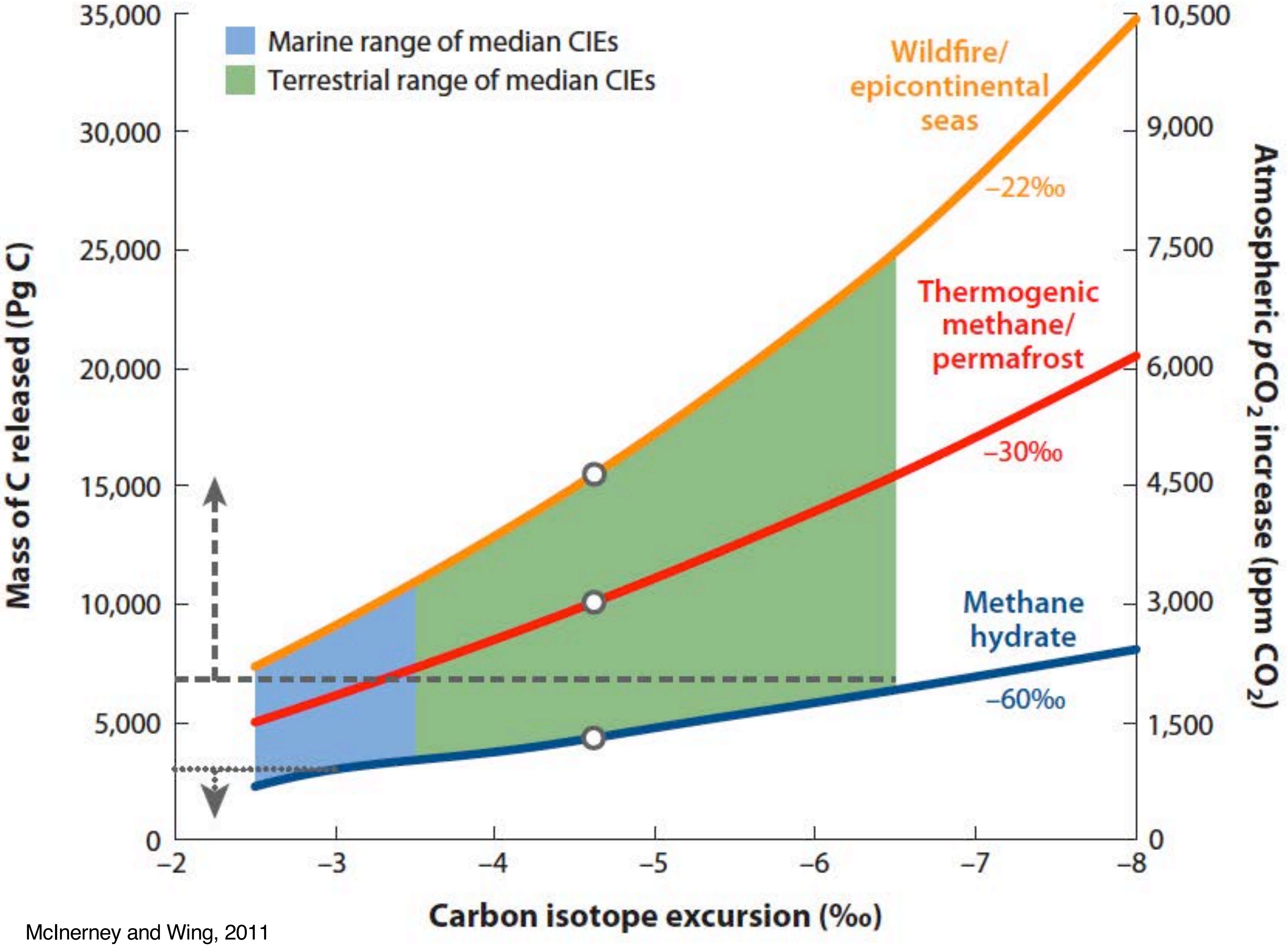
$$M_{\text{final}} = M_{\text{initial}} + M_{\text{added}},$$

$$\text{CIE} = \delta^{13}C_{\text{final}} - \delta^{13}C_{\text{initial}}.$$

$$M_{\text{added}} = -\text{CIE} \times M_{\text{initial}}/(\delta^{13}C_{\text{final}} - \delta^{13}C_{\text{added}}).$$

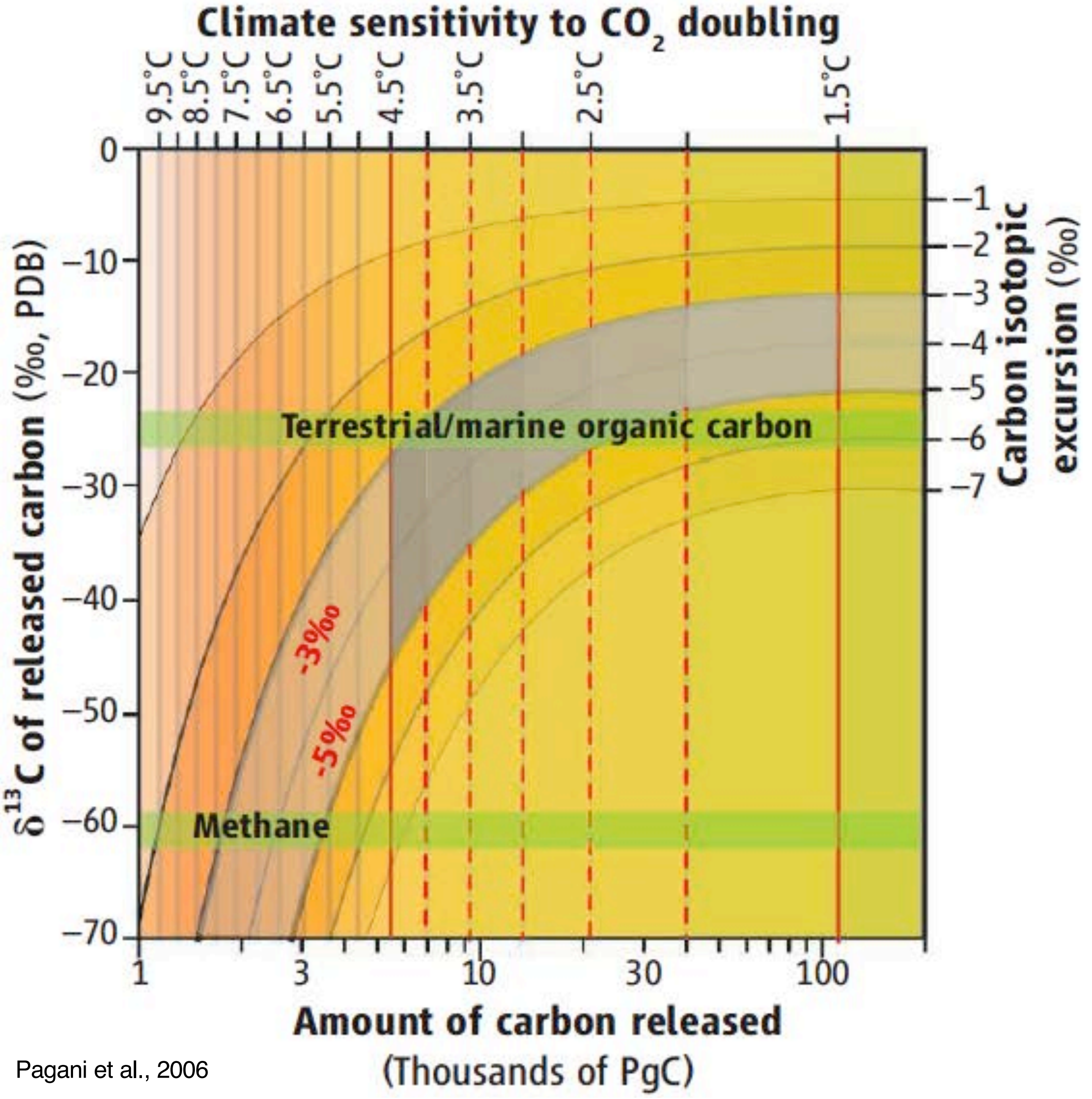
McInerney and Wing, 2011

Size of carbon release in relation to sources and CIE size



McInerney and Wing, 2011

Climate sensitivity and the PETM CIE



Pagani et al., 2006

C input to atmosphere to explain 5° C warming depends on…

Pre-PETM conditions

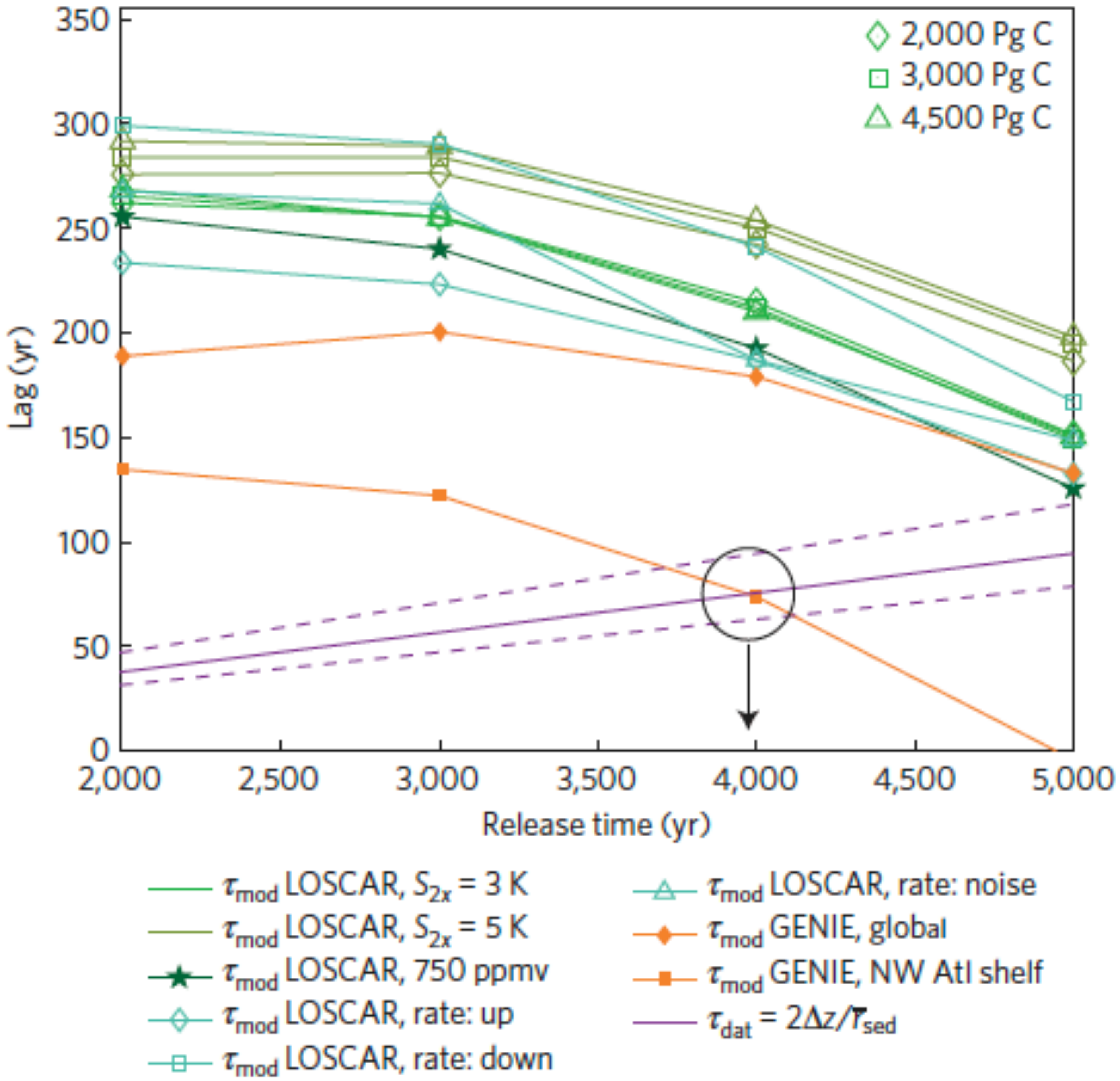
5° C warmer than recent pre-industrial

pCO_2 = 280 ppm

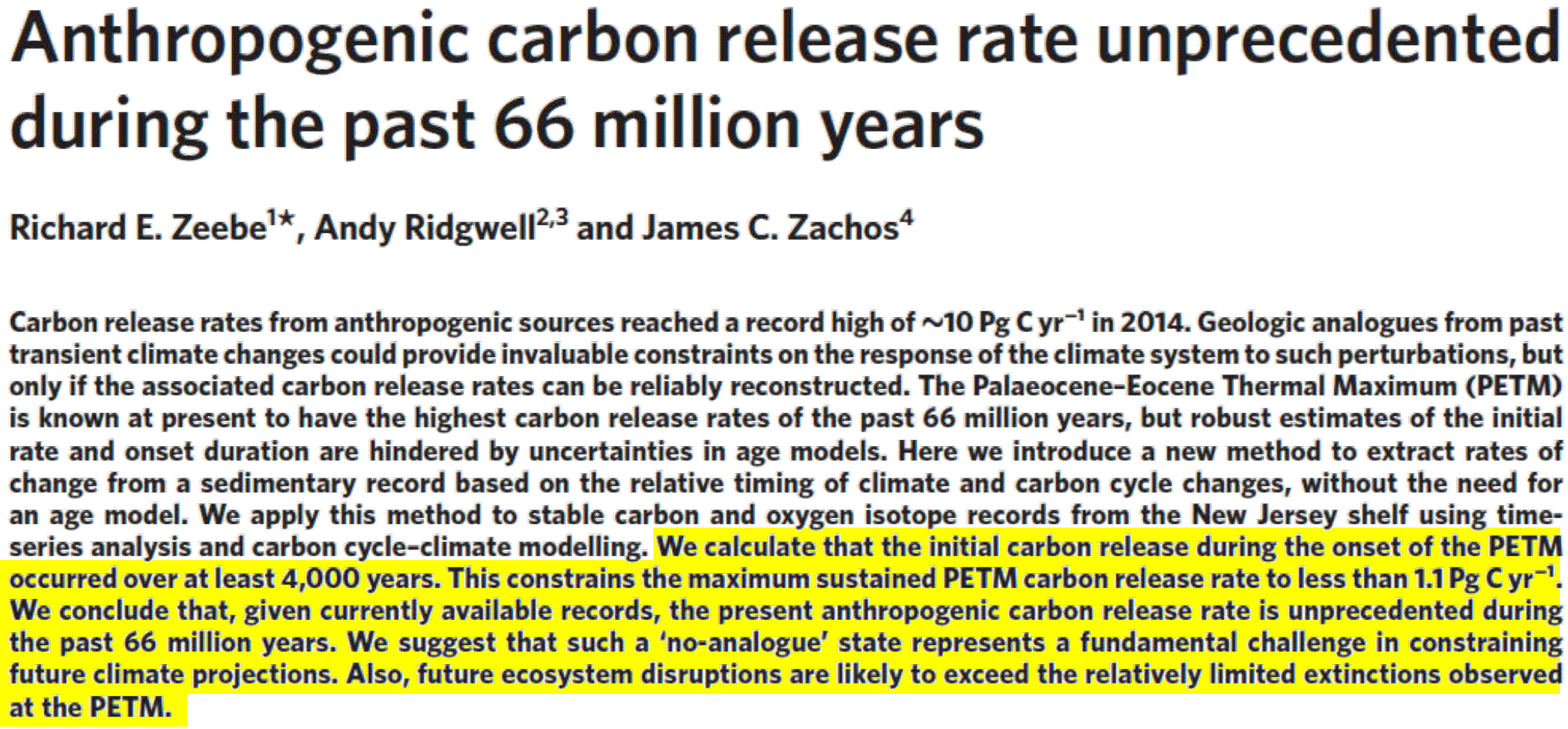
Climate sensitivity to doubling of CO_2

Source and isotope composition of C

Duration of CO_2 release during PETM



Zeebe et al., 2016



Anthropogenic carbon release rate unprecedented during the past 66 million years

Richard E. Zeebe[1]*, Andy Ridgwell[2,3] and James C. Zachos[4]

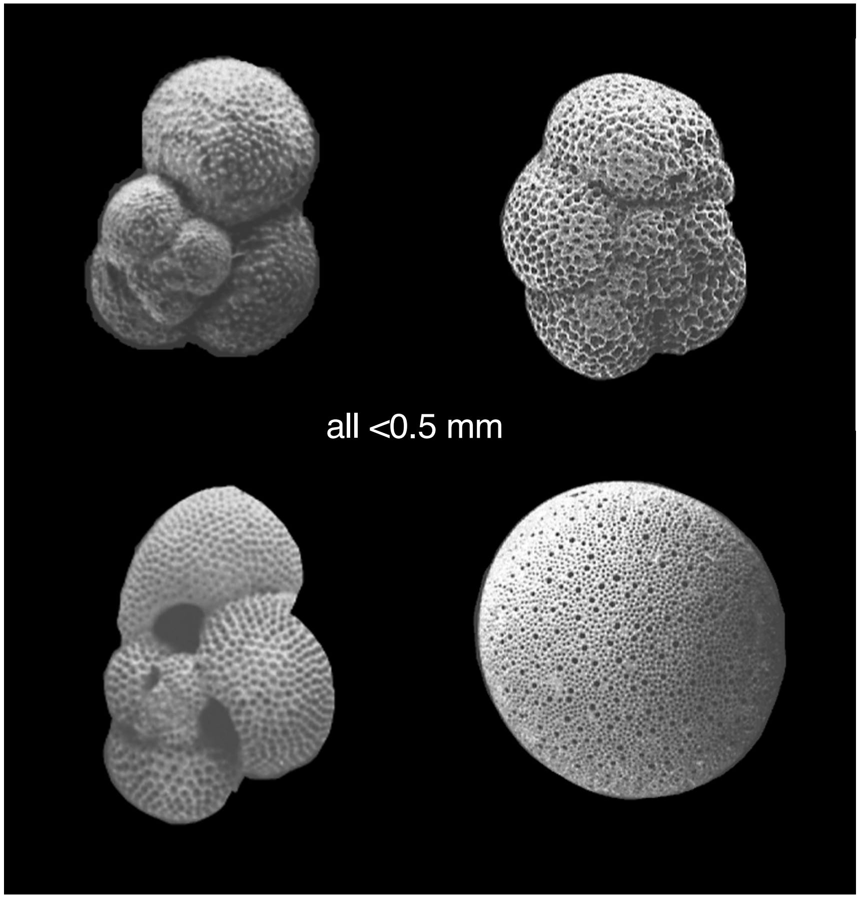
Carbon release rates from anthropogenic sources reached a record high of $\sim$10 Pg C yr^{-1} in 2014. Geologic analogues from past transient climate changes could provide invaluable constraints on the response of the climate system to such perturbations, but only if the associated carbon release rates can be reliably reconstructed. The Palaeocene–Eocene Thermal Maximum (PETM) is known at present to have the highest carbon release rates of the past 66 million years, but robust estimates of the initial rate and onset duration are hindered by uncertainties in age models. Here we introduce a new method to extract rates of change from a sedimentary record based on the relative timing of climate and carbon cycle changes, without the need for an age model. We apply this method to stable carbon and oxygen isotope records from the New Jersey shelf using time-series analysis and carbon cycle–climate modelling. We calculate that the initial carbon release during the onset of the PETM occurred over at least 4,000 years. This constrains the maximum sustained PETM carbon release rate to less than 1.1 Pg C yr^{-1}. We conclude that, given currently available records, the present anthropogenic carbon release rate is unprecedented during the past 66 million years. We suggest that such a 'no-analogue' state represents a fundamental challenge in constraining future climate projections. Also, future ecosystem disruptions are likely to exceed the relatively limited extinctions observed at the PETM.

Zeebe et al., 2016

^{18}O/^{16}O ratios of benthic microfossils (foraminifera)

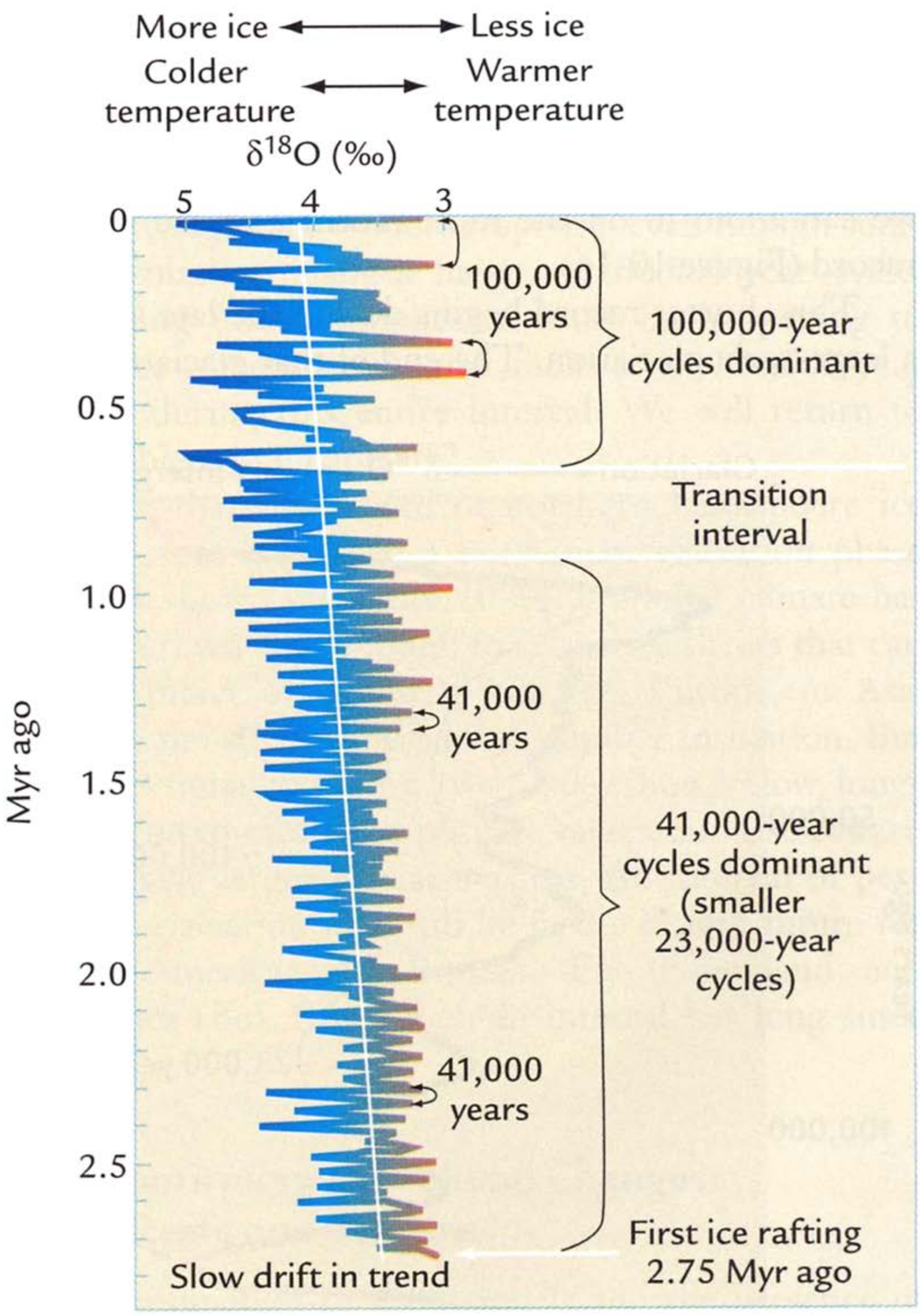
Repeated, periodic ice ages over the last 2.6 Ma

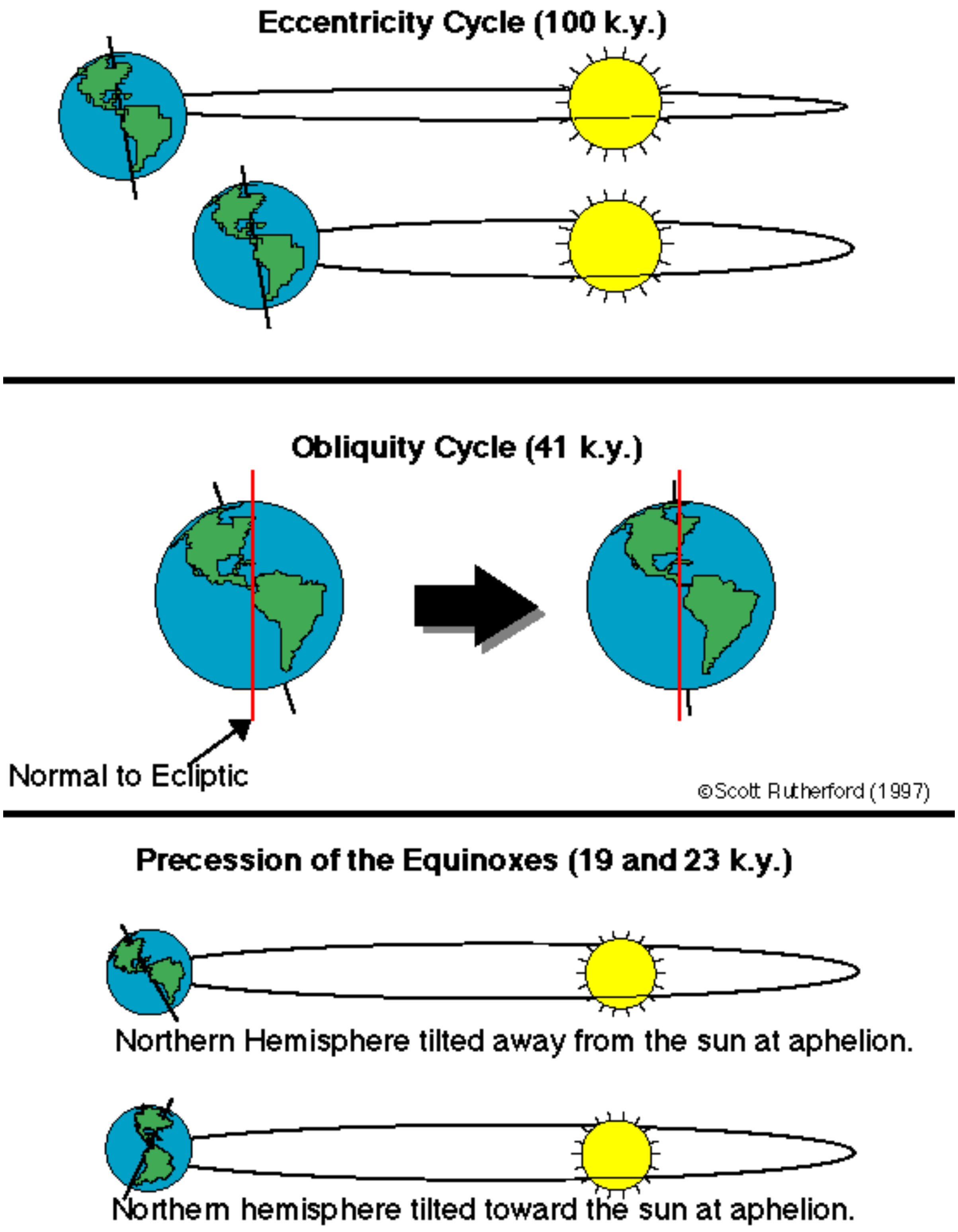
Globigerina bulloides *Neogloboquadrina pachyderma*



Globigerinoides sacculifer *Orbulina universa*

Ruddiman, 2000





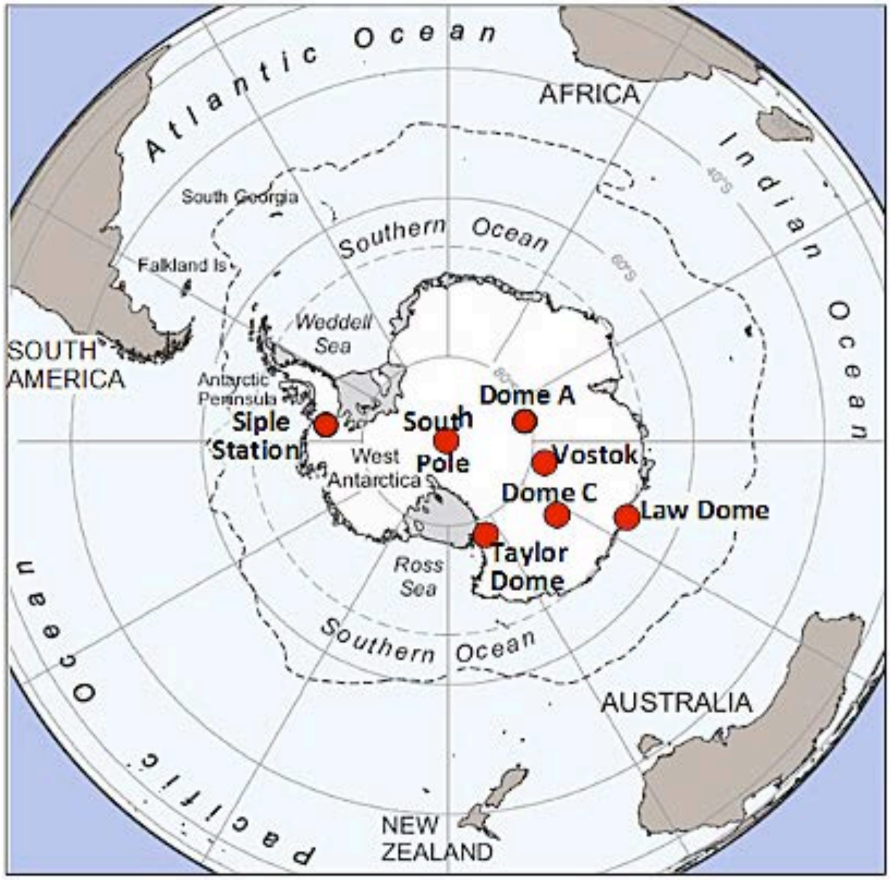
Energy at the surface varies with changes in…

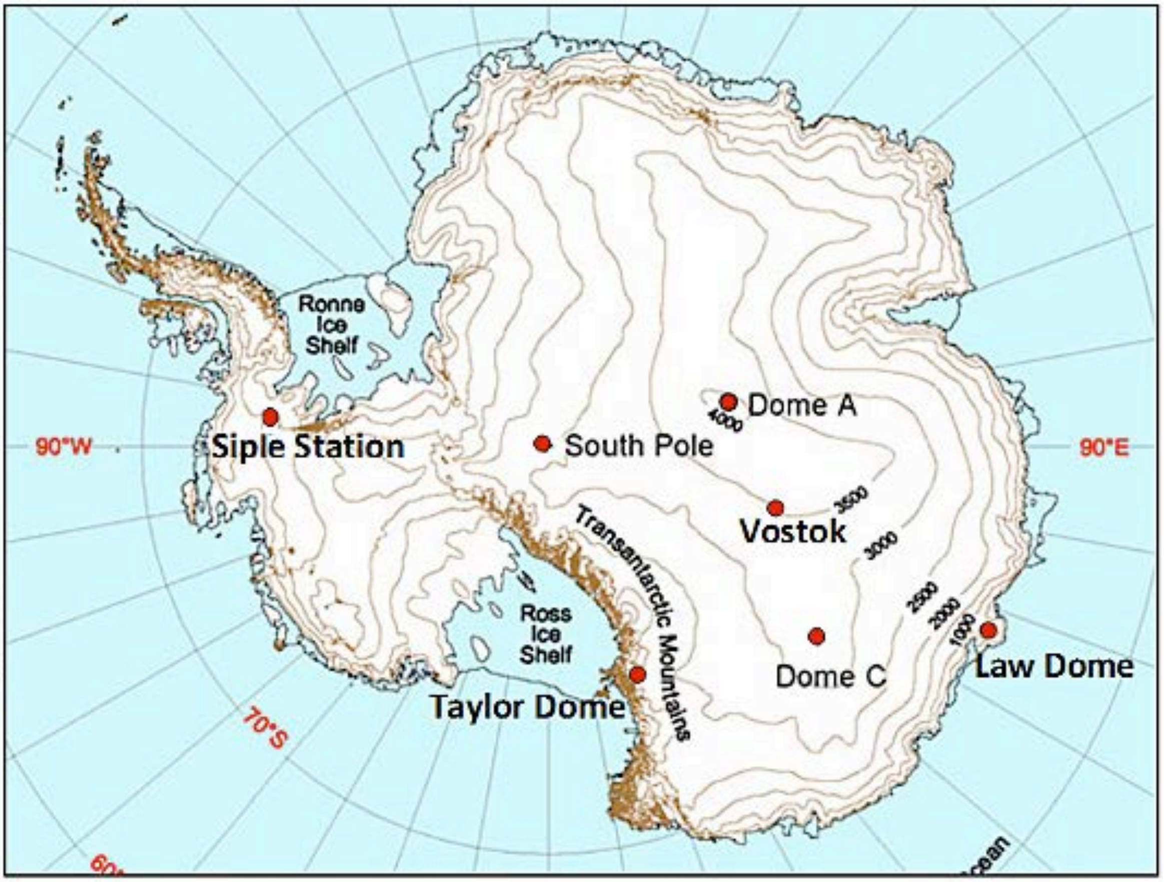
- Earth’s orbit around the sun
- orientation of the spin axis relative to the plane of the orbit

Three major frequencies:

- Eccentricity (100 ka): shape of orbit varies from more elliptical to more circular
- Obliquity (41 ka): tilt of rotational axis varies from 24-21° from plane of orbit around Sun
- Precession (ca. 20 ka): rotational axis wobbles like a spinning top so that seasons change in relation to position in orbit around Sun

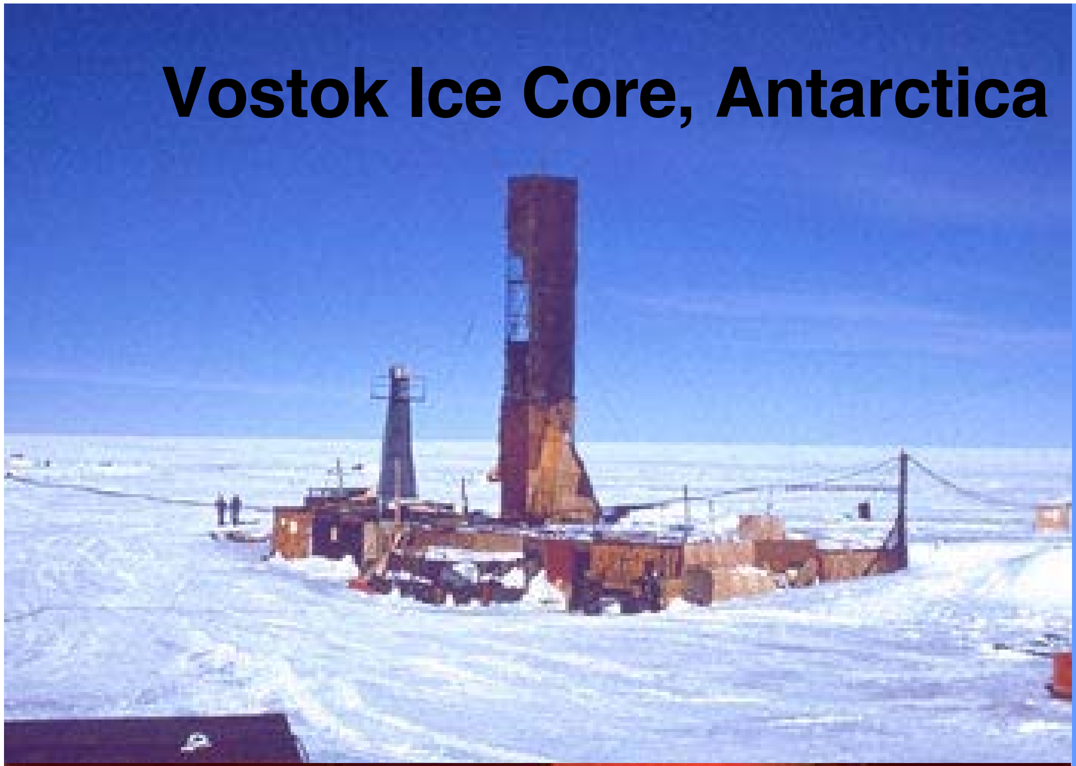
Antarctic ice sheet drilling sites

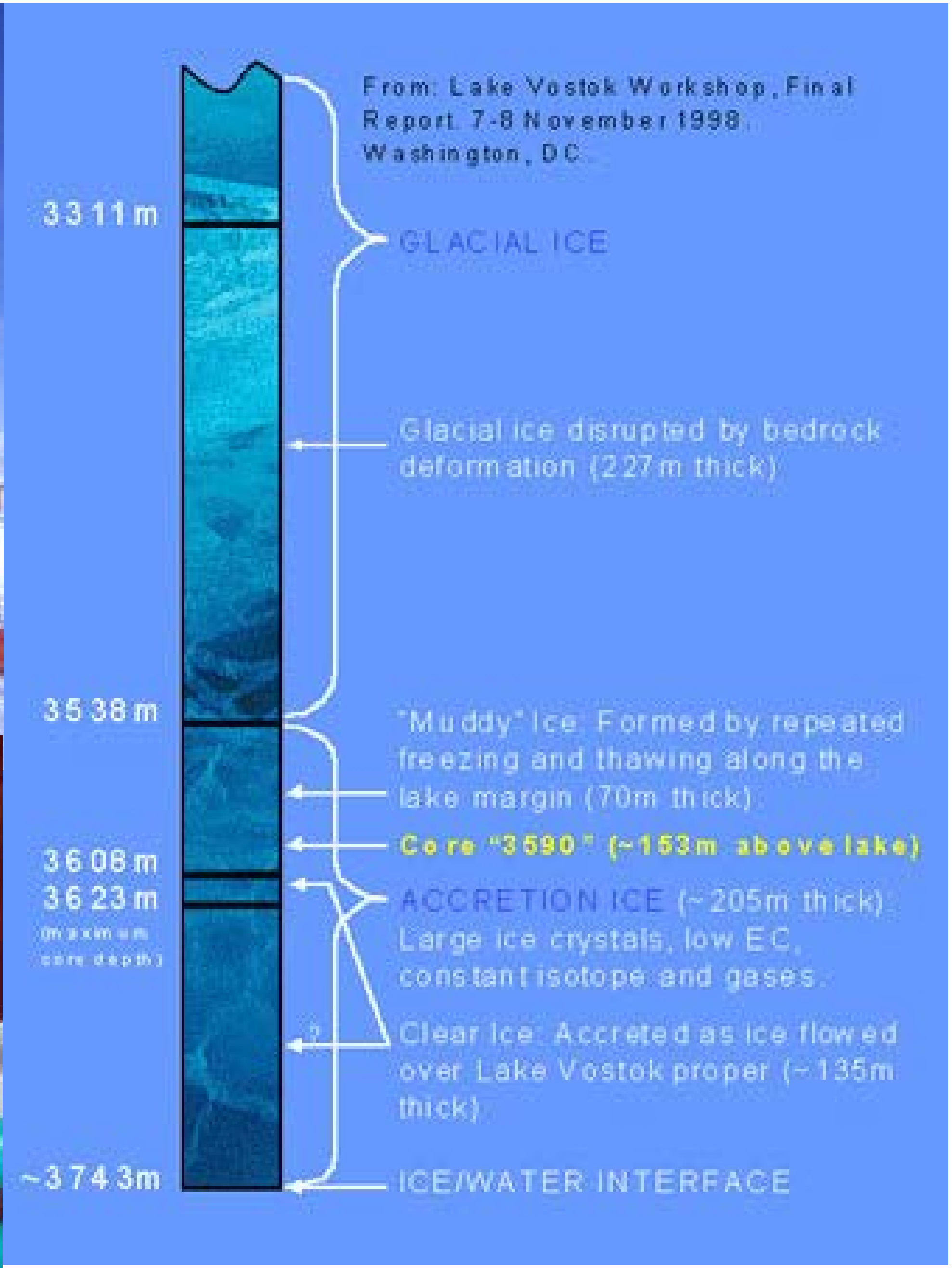




http://cdiac.ornl.gov/trends/co2/ice_core_co2.html

Vostok Ice Core, Antarctica





From: Lake Vostok Workshop, Final Report. 7-8 November 1998. Washington, DC.

Glacial ice disrupted by bedrock deformation (227m thick)

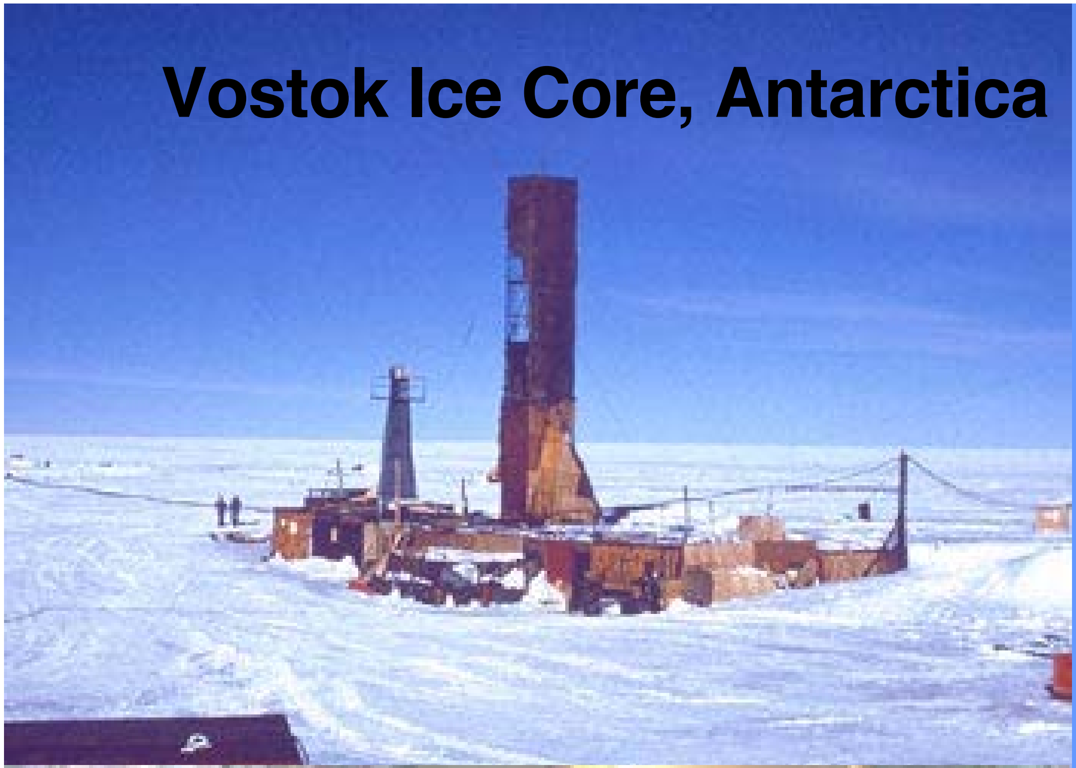
"Muddy" Ice: Formed by repeated freezing and thawing along the lake margin (70m thick).

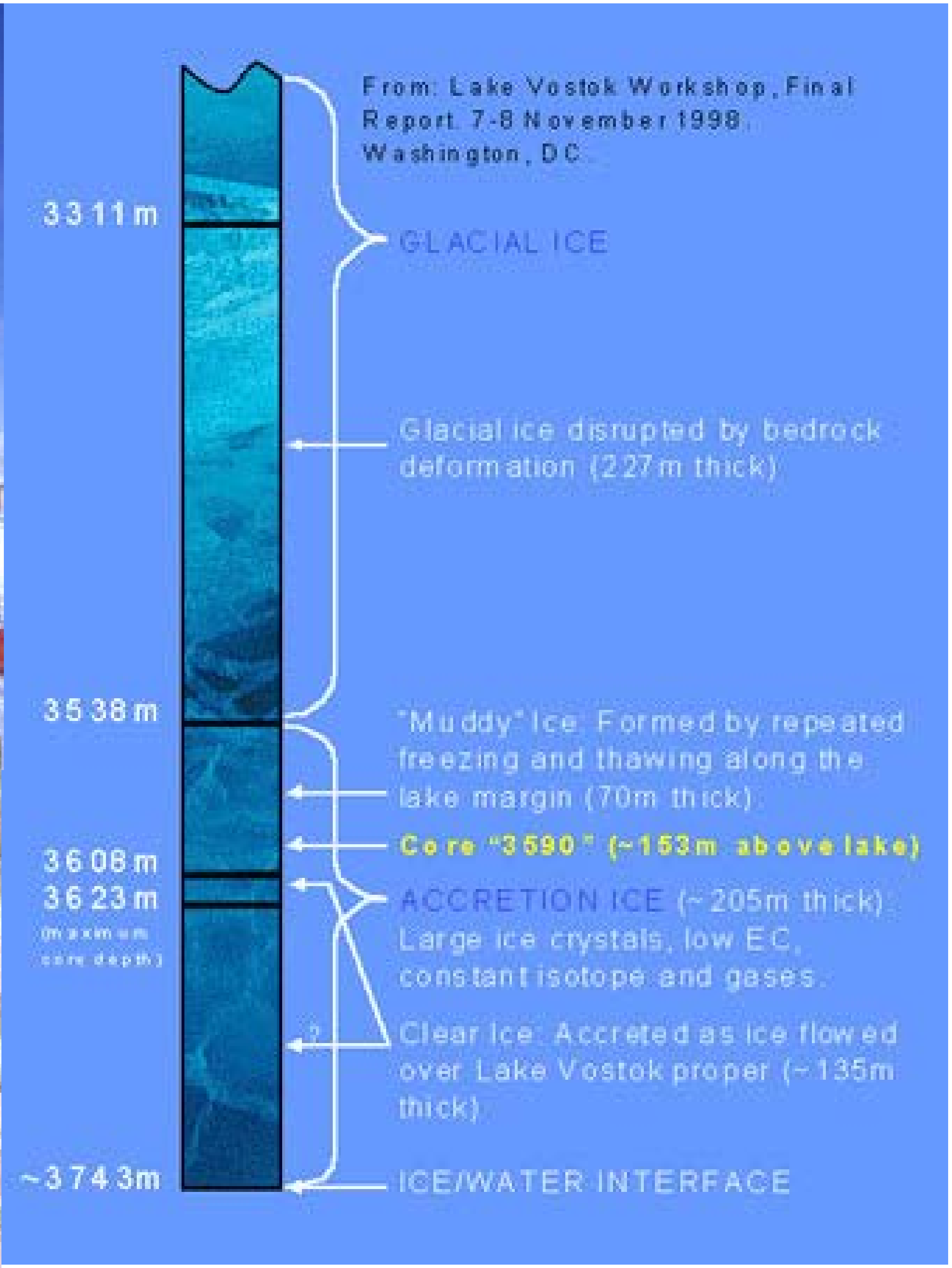
Core "3590" (~153m above lake)

ACCRETION ICE (~205m thick): Large ice crystals, low EC, constant isotope and gases.

Clear Ice: Accreted as ice flowed over Lake Vostok proper (~135m thick).

Vostok Ice Core, Antarctica





From: Lake Vostok Workshop, Final Report. 7-8 November 1998. Washington, DC.

3311m

GLACIAL ICE

Glacial ice disrupted by bedrock deformation (227m thick)

3538m

"Muddy" Ice: Formed by repeated freezing and thawing along the lake margin (70m thick).

Core "3590" (~153m above lake)

3608m

3623m

(maximum core depth)

ACCRETION ICE (~205m thick). Large ice crystals, low EC, constant isotope and gases.

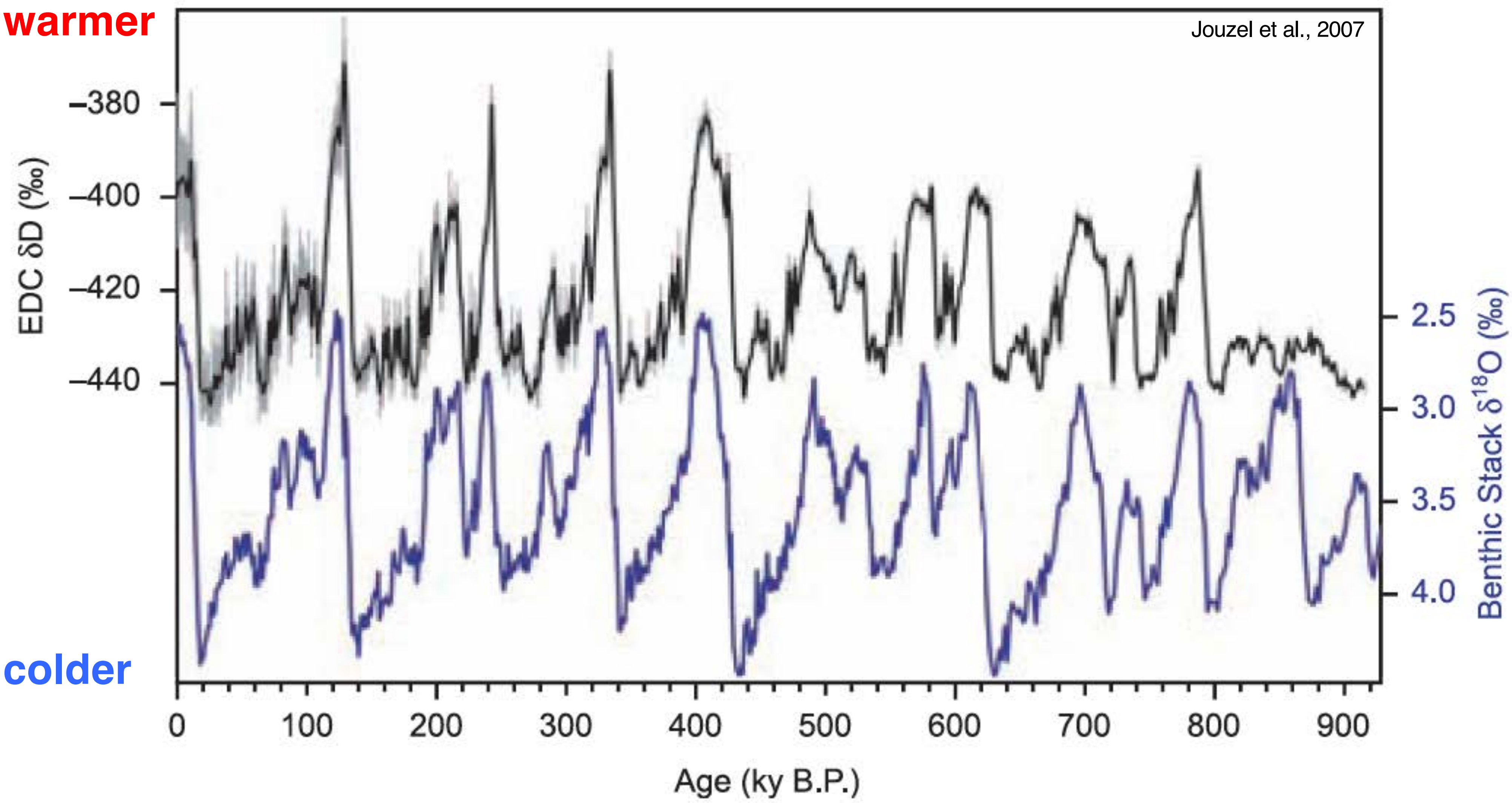
?

Clear Ice: Accreted as ice flowed over Lake Vostok proper (~135m thick).

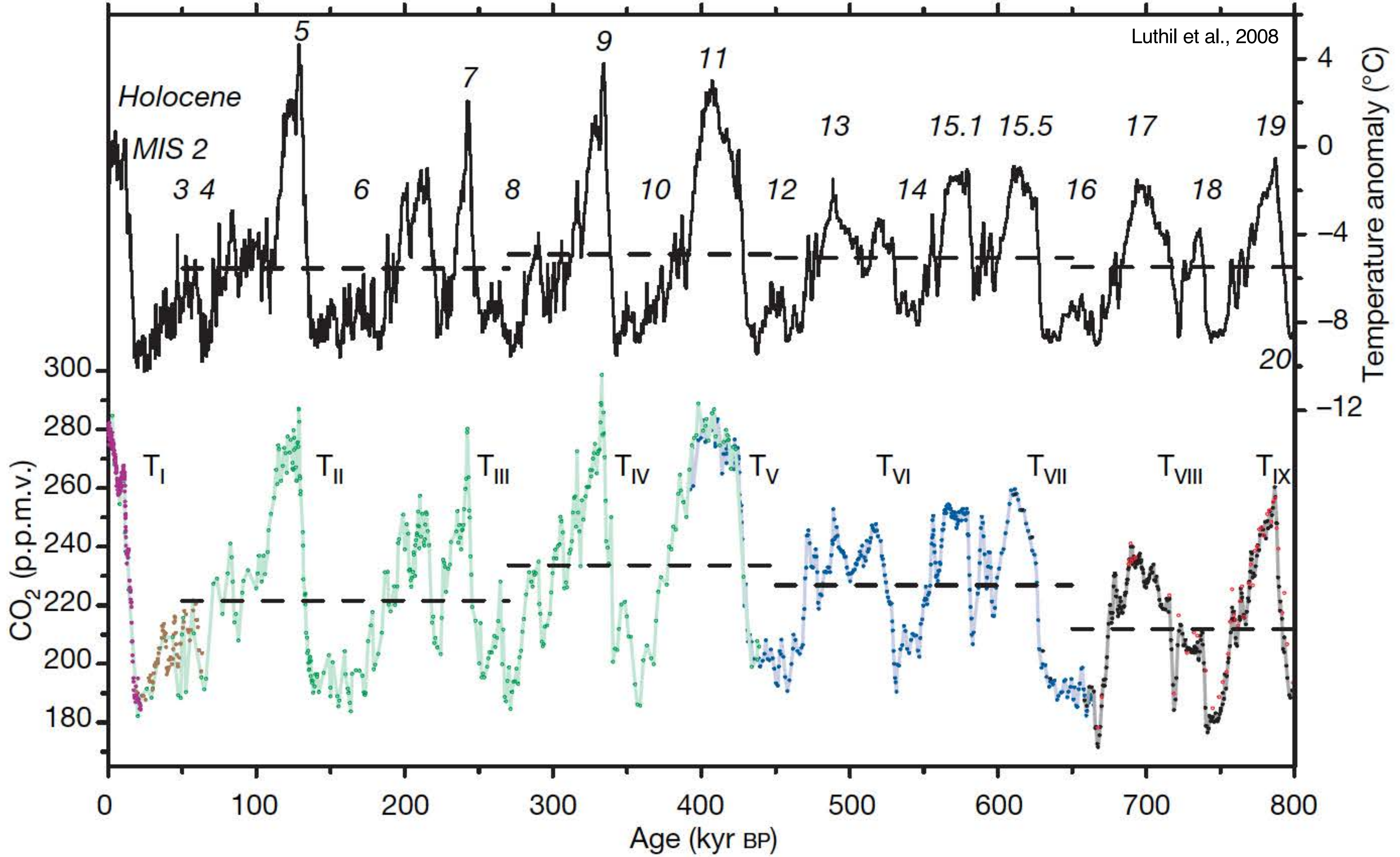
~3743m

ICE/WATER INTERFACE

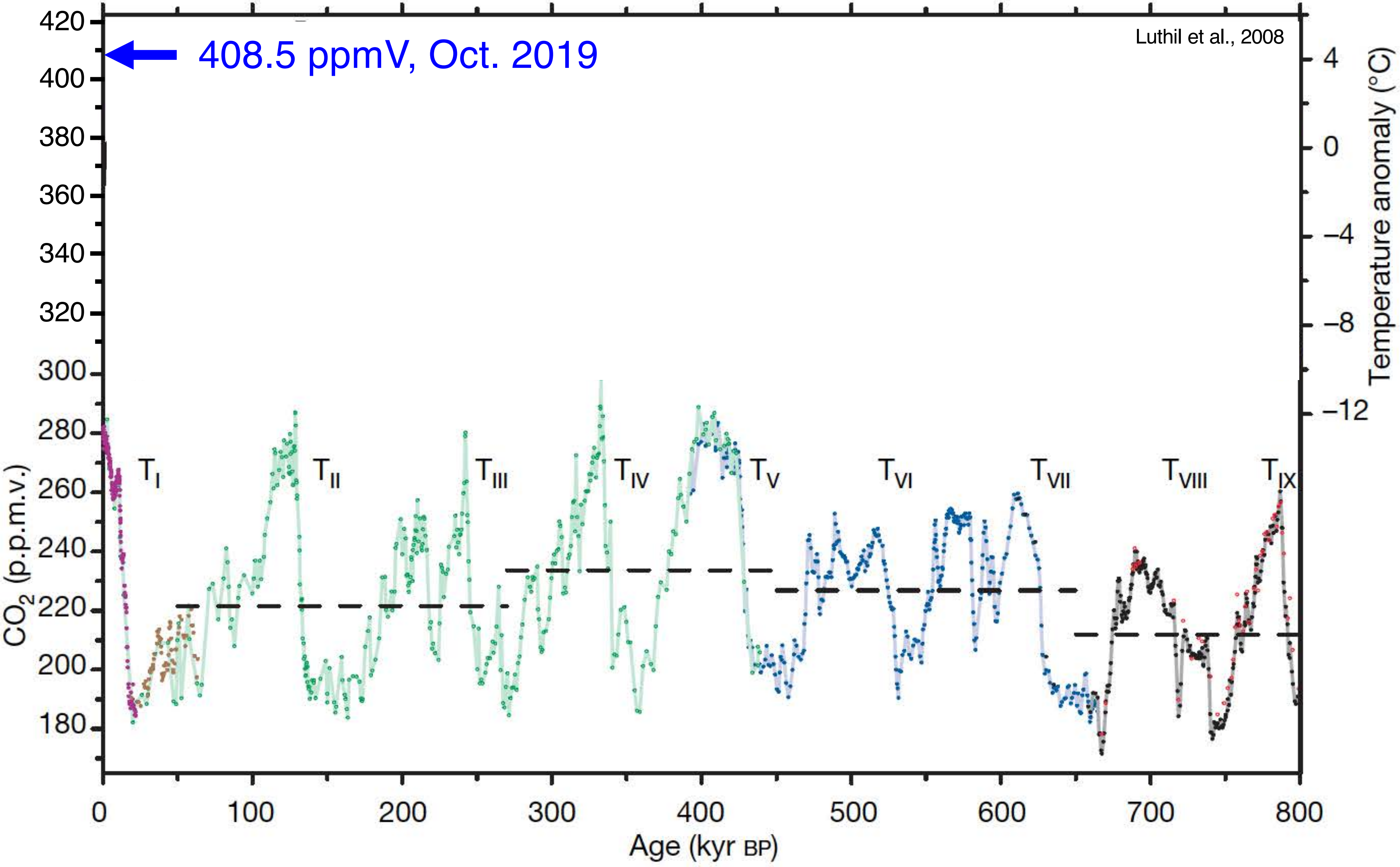
Dome C ice temperature (δD) and ocean temperature/ice volume ($\delta^{18}O$)



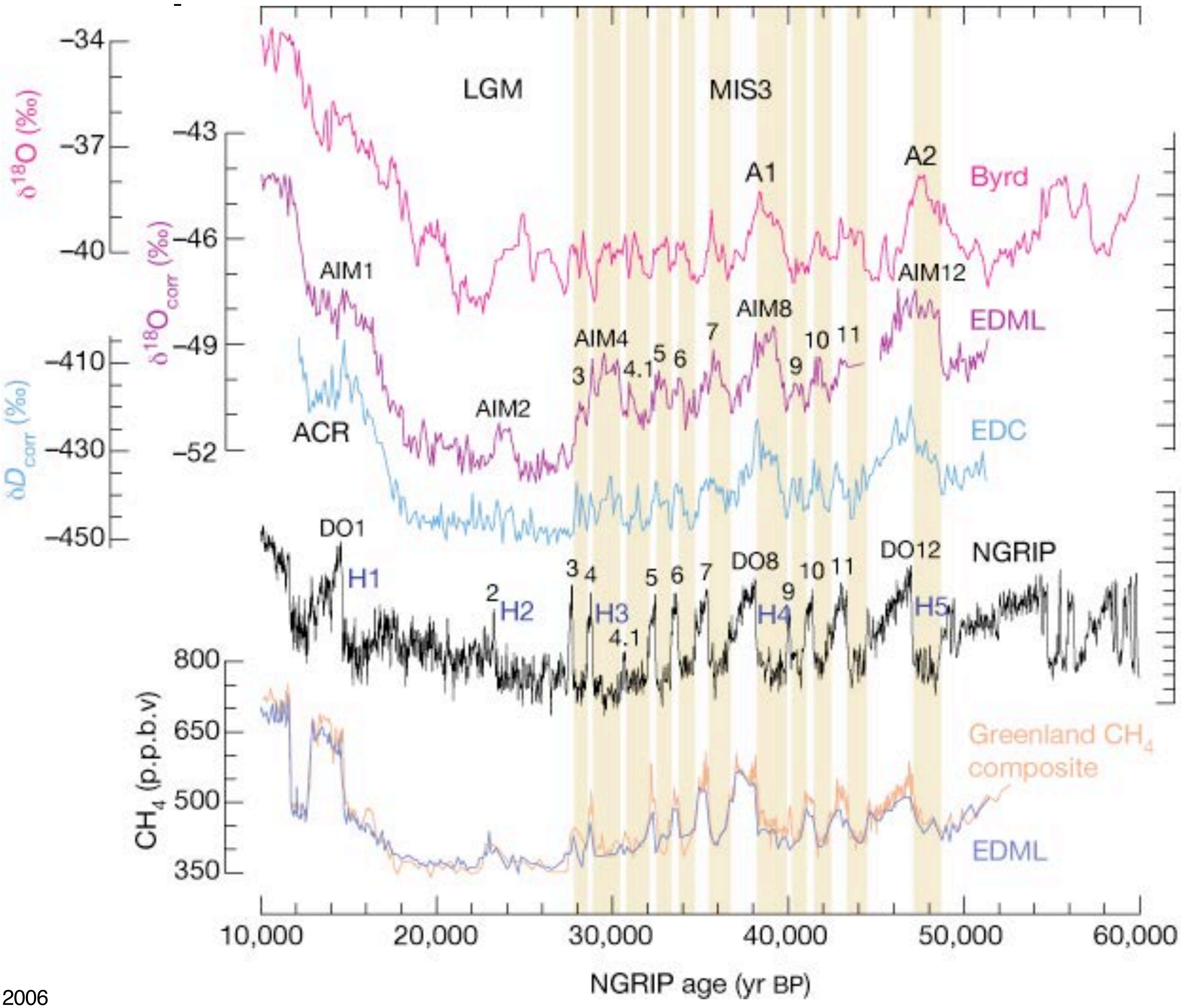
Dome C ice temperature and atmospheric CO_2 trapped in ice bubbles



Dome C ice temperature and atmospheric CO_2 trapped in ice bubbles

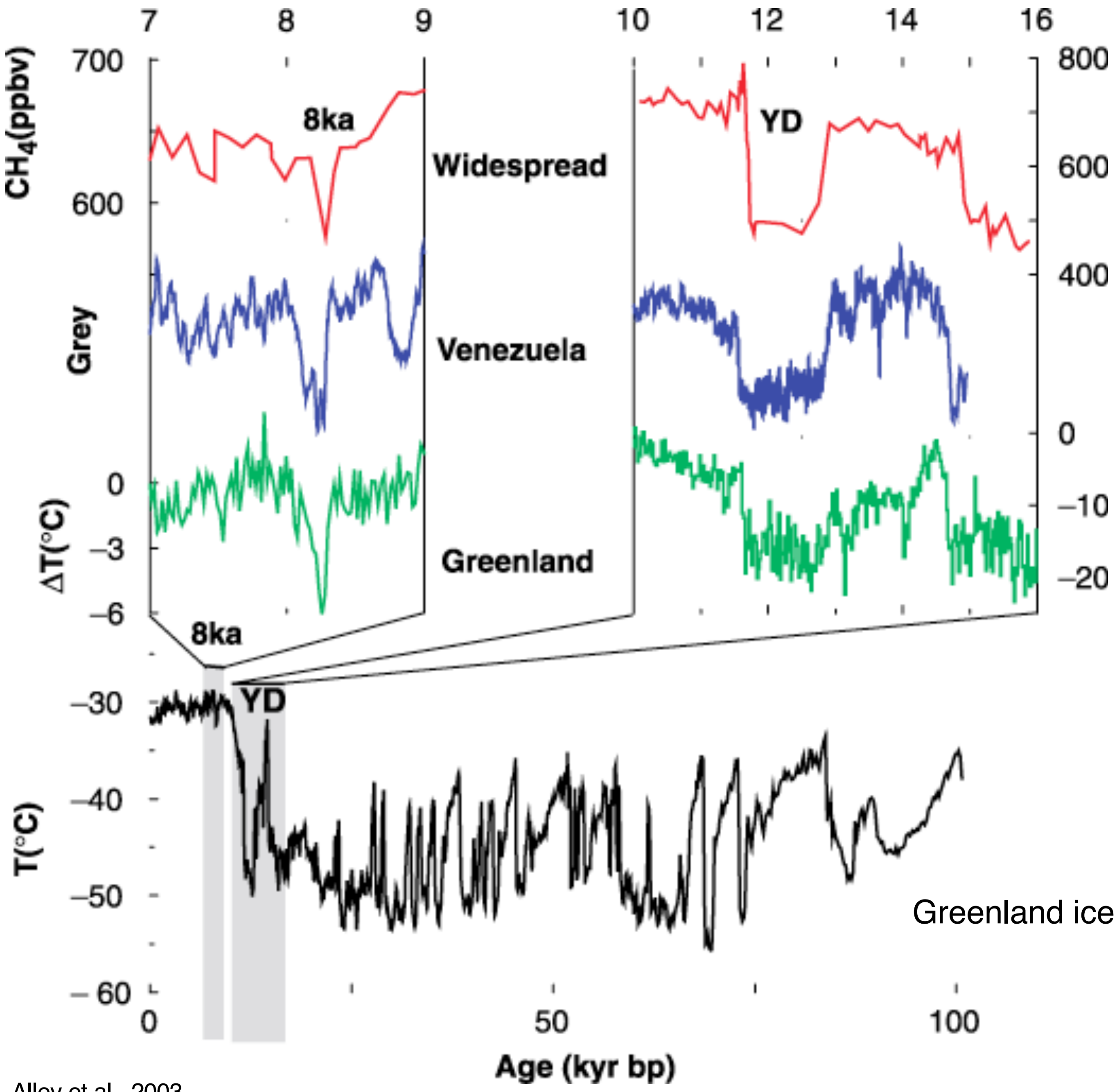


Comparison of Antarctic and Greenland ice core



EPICA, 2006

Abrupt climate changes in the last 15,000 years



Greenland ice record

Alley et al., 2003

Younger Dryas

- 11.5-13 ka
- widespread, rapid global cooling during deglaciation
- followed by rapid warming

8200 event

- 8.2 ka
- very brief, widespread cooling
- not as prominent as YD