XIII. natural variation of CO_2 and climate

clicker question

Which has the *longest* time scale for carbon exchange with the atmosphere?

A. above ground terrestrial biosphere (tree trunks, leaves)
B. below ground terrestrial biosphere (soil/plant litter)
C. upper ocean
D. deep ocean
E. carbon in rocks

clicker question

The ocean's biological pump

- a) describes the photosynthetic uptake and downward settling of carbon in the ocean
- b) describes the removal carbon from the sunlit surface by respiration
- c) quickly returns carbon from the deep ocean to the ocean surface and atmosphere
- d) all of the above
- e) none of the above

clicker question

Organic carbon stored as fossil fuels can be oxidized to produce CO_2 and

- a) this happens naturally as a consequence of weathering
- b) this happens during combustion of fossil fuels by humans
- c) *a)* and *b)* are both true but *a)* happens faster
- d) *a)* and *b)* are both true but *b)* happens faster
- e) neither *a)* or *b)* are true

review

- carbon cycle includes the atmosphere, ocean, terrestrial biosphere and rock reservoirs
- each of the reservoirs influences the atmosphere on different time scales, depending on *size of exchange* and *size of reservoir*
- the terrestrial biosphere is responsible for seasonal variations in CO_2
- other reservoirs must be responsible for longer time scale changes in CO_2
- *human activity and burning of fossil fuels connects the very long time scale of the "rock cycle" with the much shorter time scales of the atmosphere, ocean and biosphere*

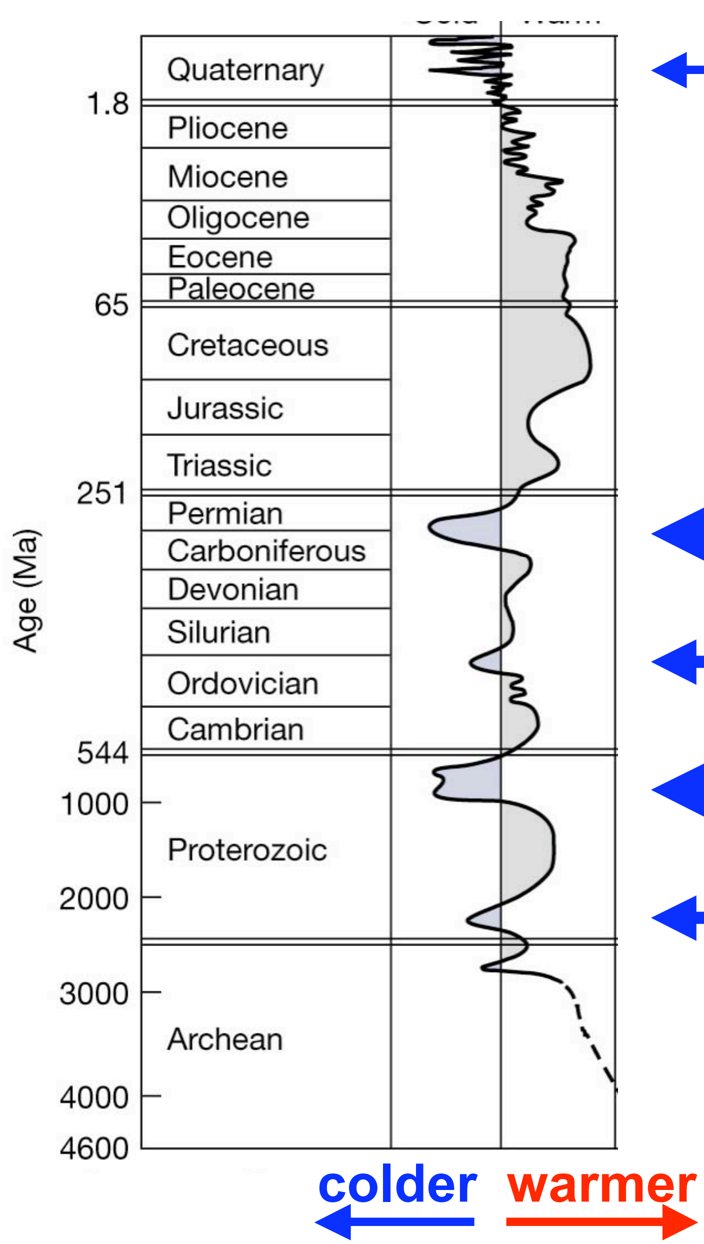
review

- emissions of CO_2 due to burning of fossil fuels have totaled ~250 GTC (by 1994) for since the 1800's
- a bit more than half has remained in the atmosphere
- about half has been taken up by the oceans (this is good!)
- closing the C budget suggests that the terrestrial biosphere has been a net source of C to the atmosphere
- the uptake of fossil fuel derived CO_2 into the oceans has led to ocean acidification (the dissolution of CO_2 into water produces carbonic acid) which impacts carbonate-shelled organisms (bad!)

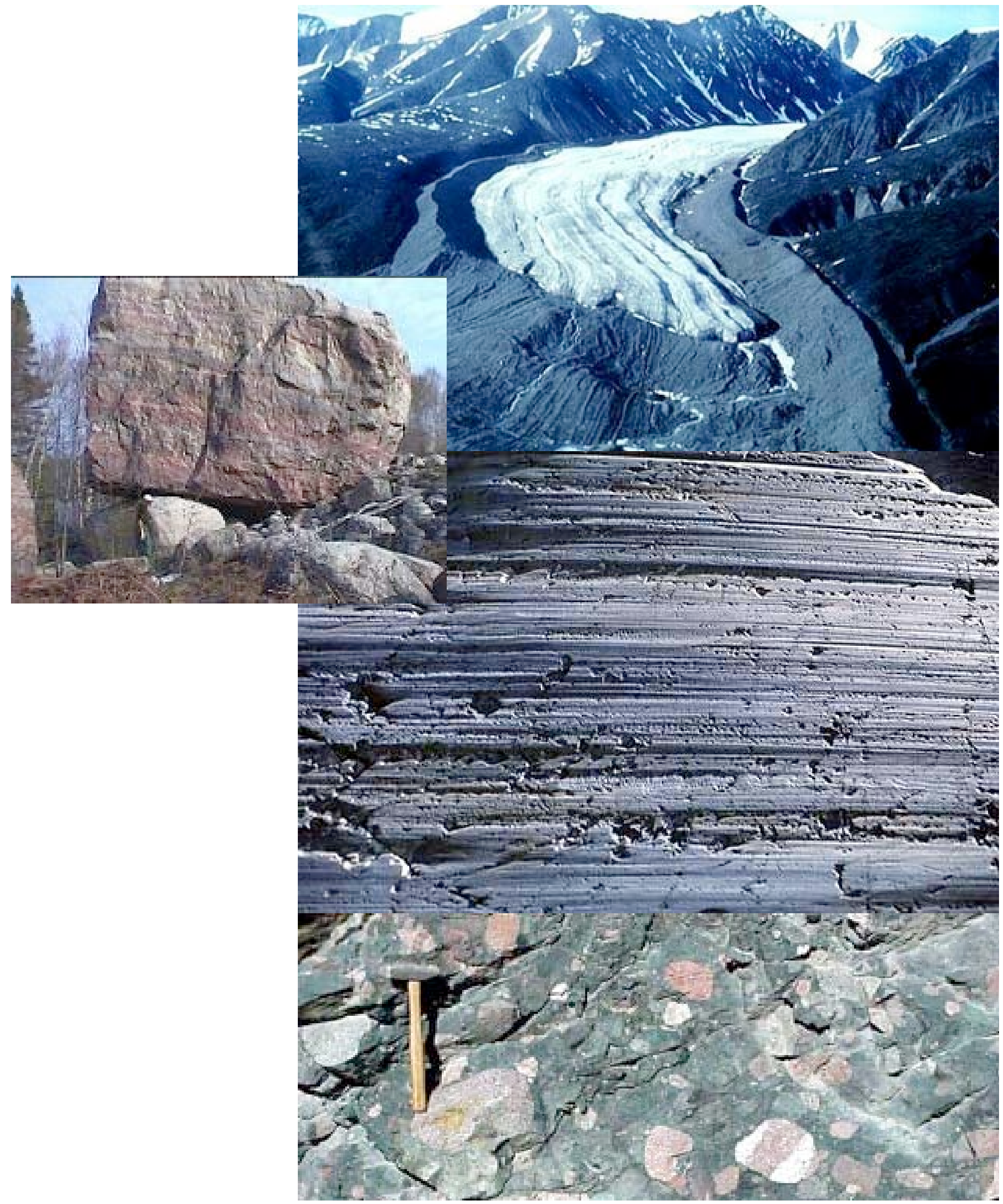
outline

- overview of Phanerozoic climate (last ~540 My)
- a mechanistic model of the long-term C-cyle
  -controls on C flows into and out of surface reservoirs
- modeled CO_2 vs. geologic observations
- CO_2 and climate in deep time
  - Mesozoic warmth
  - Cenozoic cooling
  - onset of Antarctic Glaciation (*CO_2 threshold?*)
- CO_2 and sea level
- the “Paleocene Thermal Maximum”

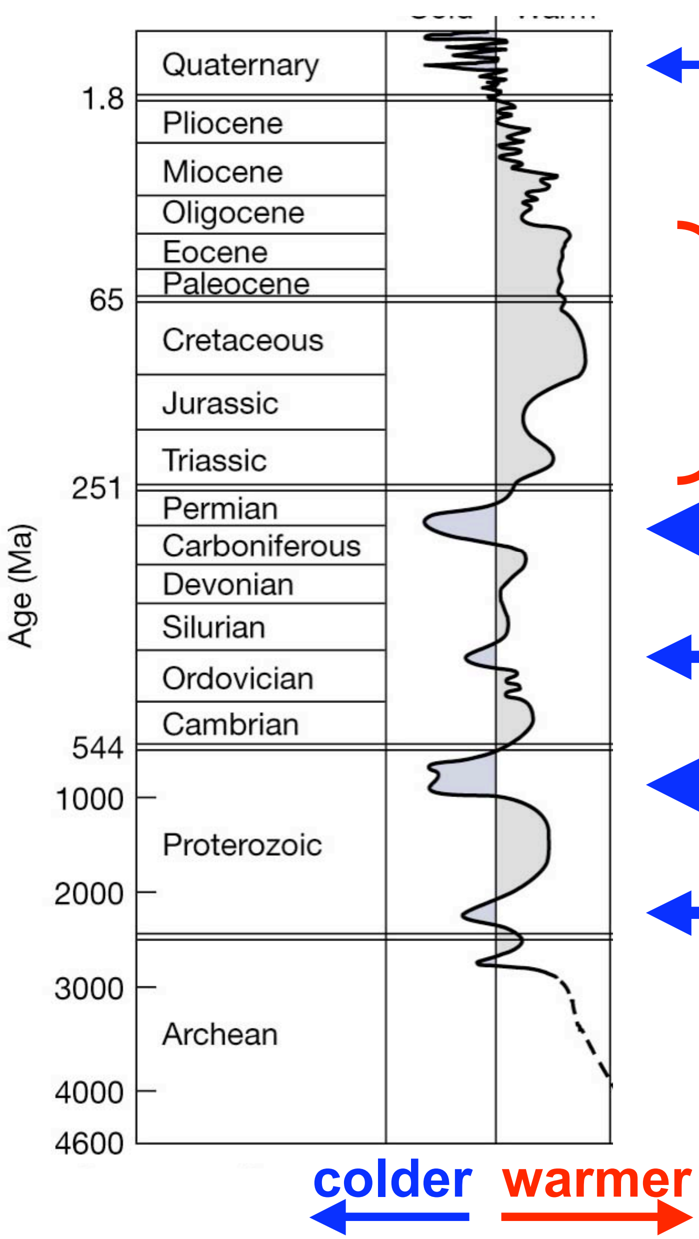
Earth temp. from geochem & fossils



major periods of glaciation



Earth temp. from geochem & fossils

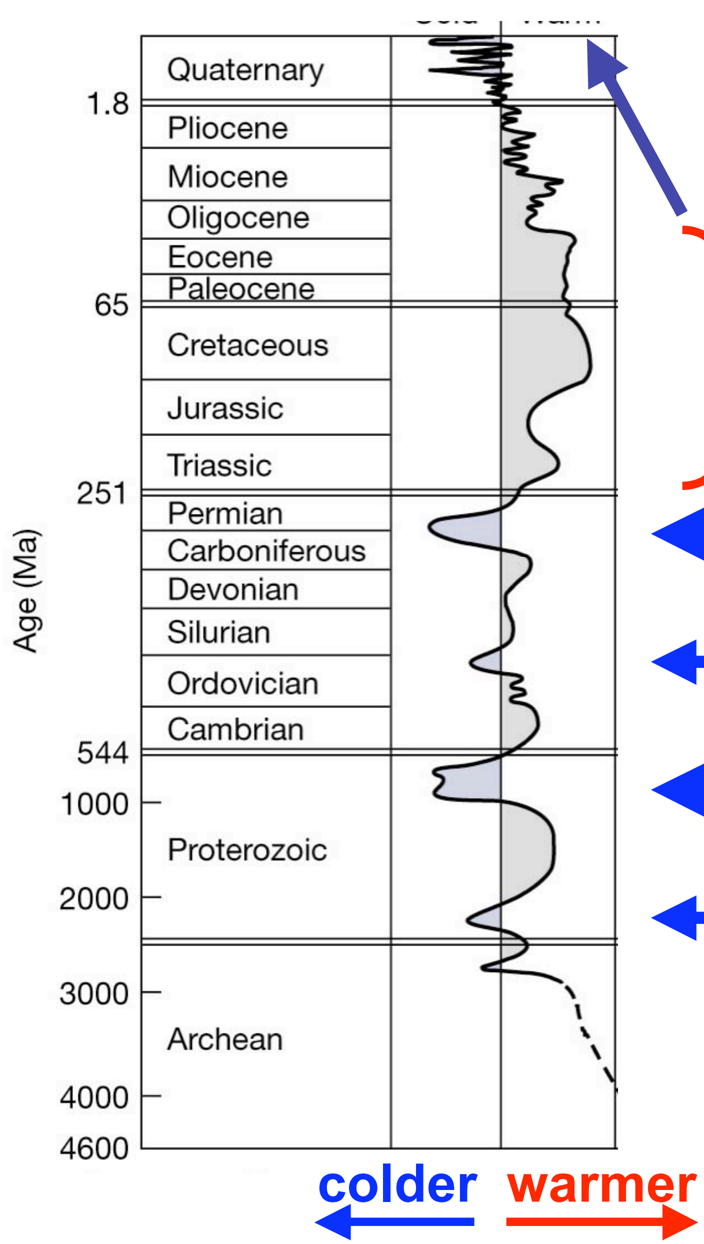


present Ice Age

Mesozoic and early Cenozoic warmth, +2 to +6°C at equator & +20 °C or more at poles!

mega-glaciations

Earth temp. from geochem & fossils



progressive Cenozoic cooling to Ice Age temperatures (0 to -6 °C)

Mesozoic and early Cenozoic warmth, +2 to +6°C at equator & +20 °C or more at poles!

mega-glaciations

(temperature estimates are given as departures from present)

Phanerozoic climate change

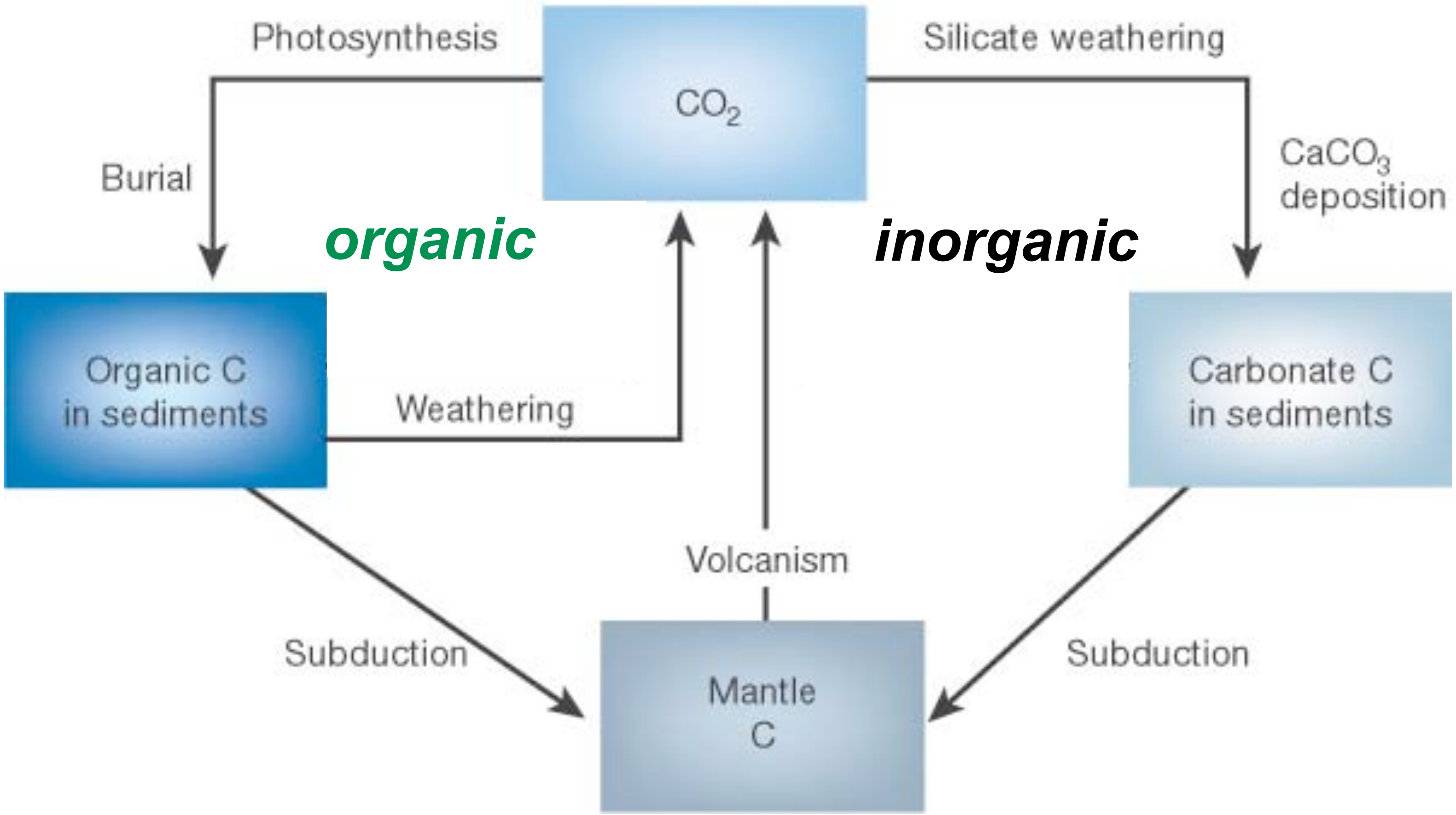
- *what factors might have contributed to long-term changes in Phanerozoic climate?*
  - tectonics, paleo-geography
  - solar luminosity (~ +1%/100 my)
  - atmospheric CO_2
  - other (galactic cosmic ray fluxes?)

- *changes in average latitude of continents and land-sea configuration important but not sufficient*

- *change in solar luminosity largely unidirectional*

- *CO_2 influences climate, but 4x changes or more (v. present) would be required*
  - need data or highly educated guess

the long-term C-cycle

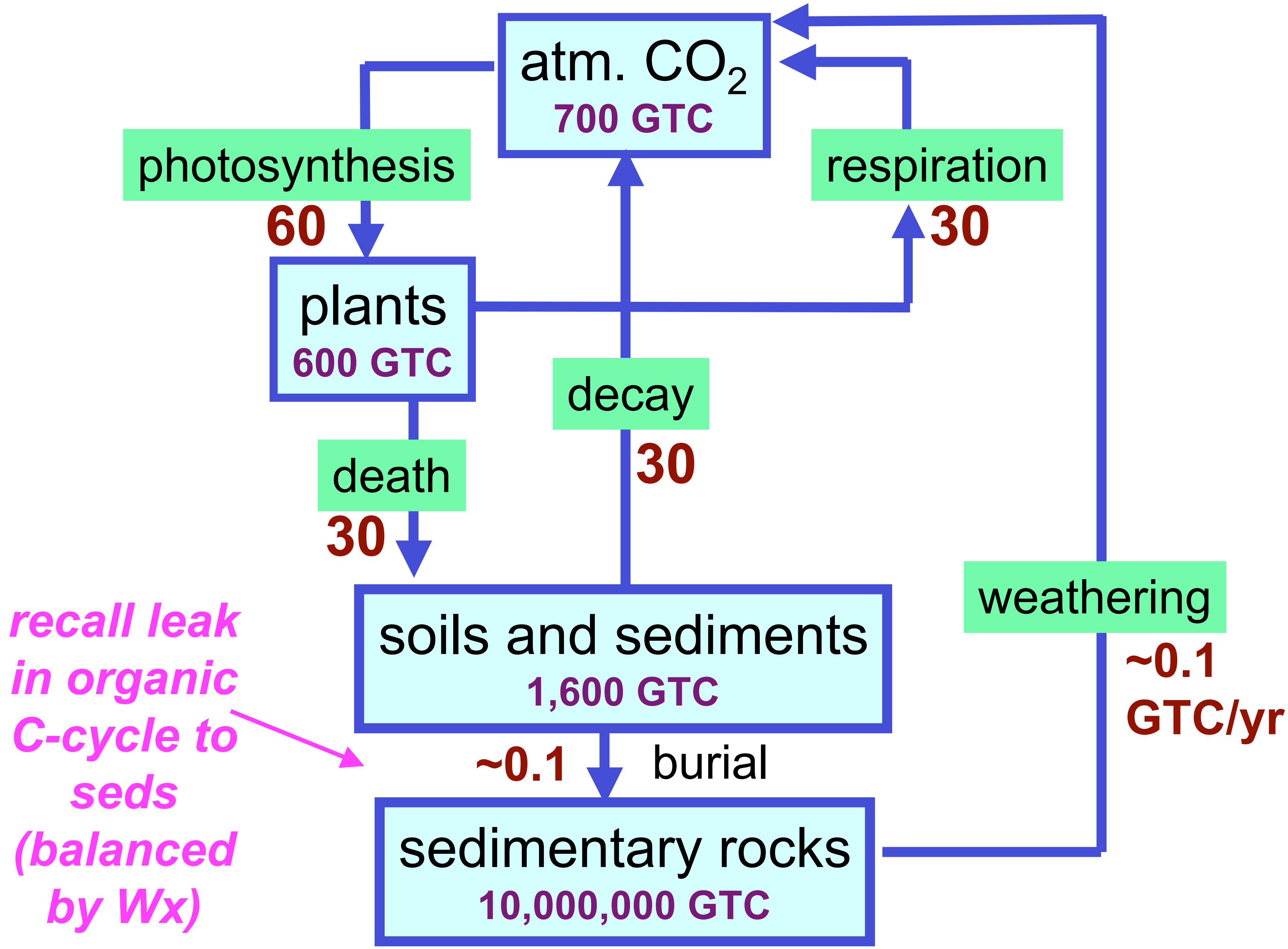


$CO_2 + H_2O \longleftrightarrow CH_2O + O_2$

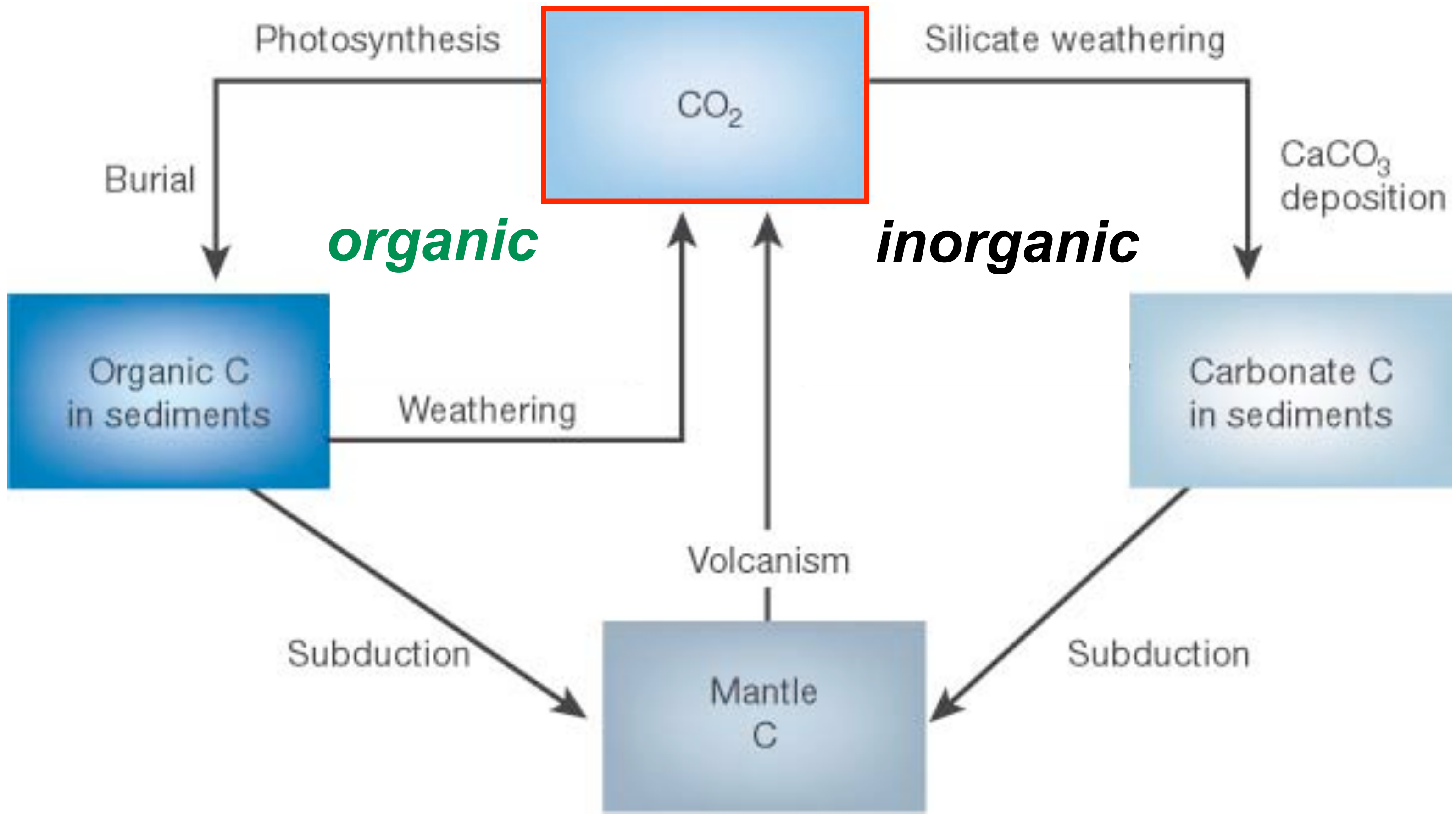
$CaSiO_3 + CO_2 \longleftrightarrow CaCO_3 + SiO_2$

Berner '03

the organic carbon cycle



mechanistic model of C-cycle...

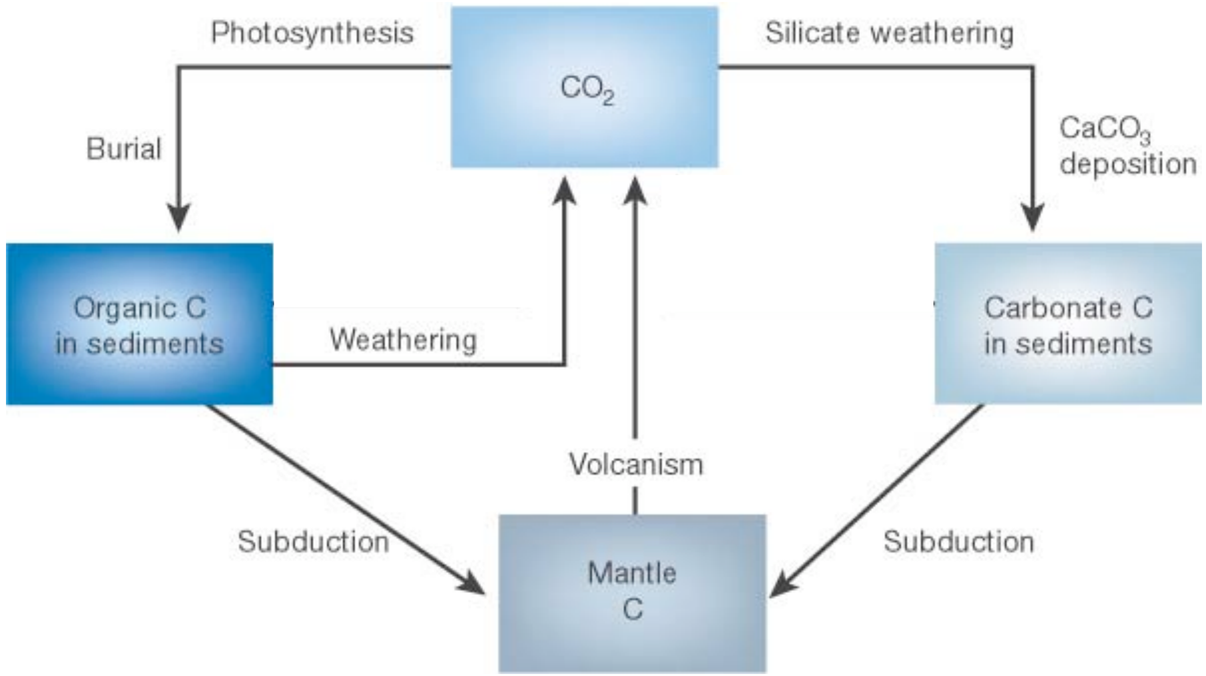


$CO_2 + H_2O \longleftrightarrow CH_2O + O_2$

$CaSiO_3 + CO_2 \longleftrightarrow CaCO_3 + SiO_2$

what changes to flows might influence CO_2 in surface reservoir?

mechanistic model of C-cycle...



$CO_2 + H_2O \longleftrightarrow CH_2O + O_2$

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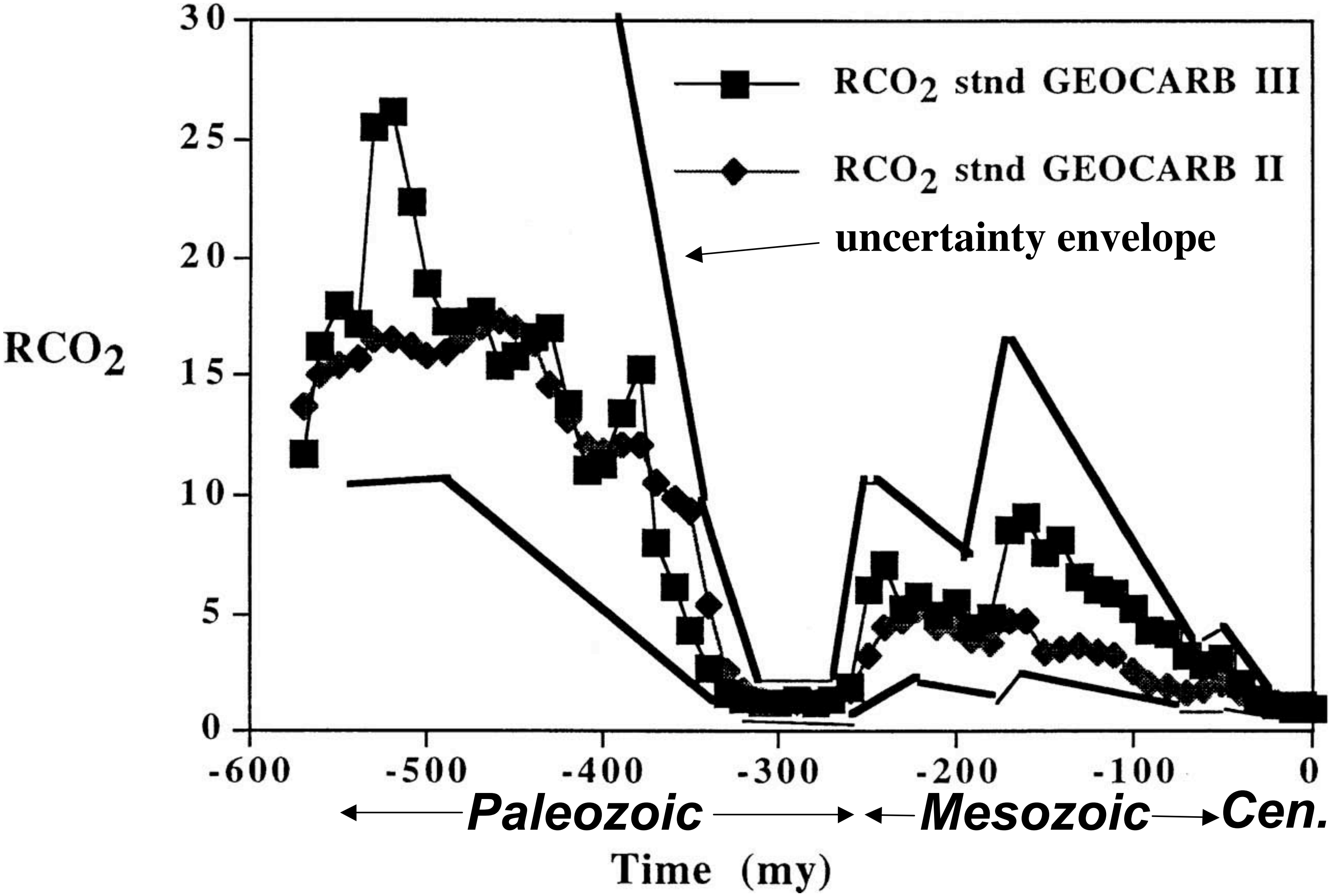
factors influencing key flows (Wx, burial, subduction, volc.)

- ***tectonics***
  - *continental relief/position*
  - *sea-floor spreading/subduction/volc.*
- ***climate***
  - *T, P*
- ***plants***
  - *abundance, type*

GEOCARB model

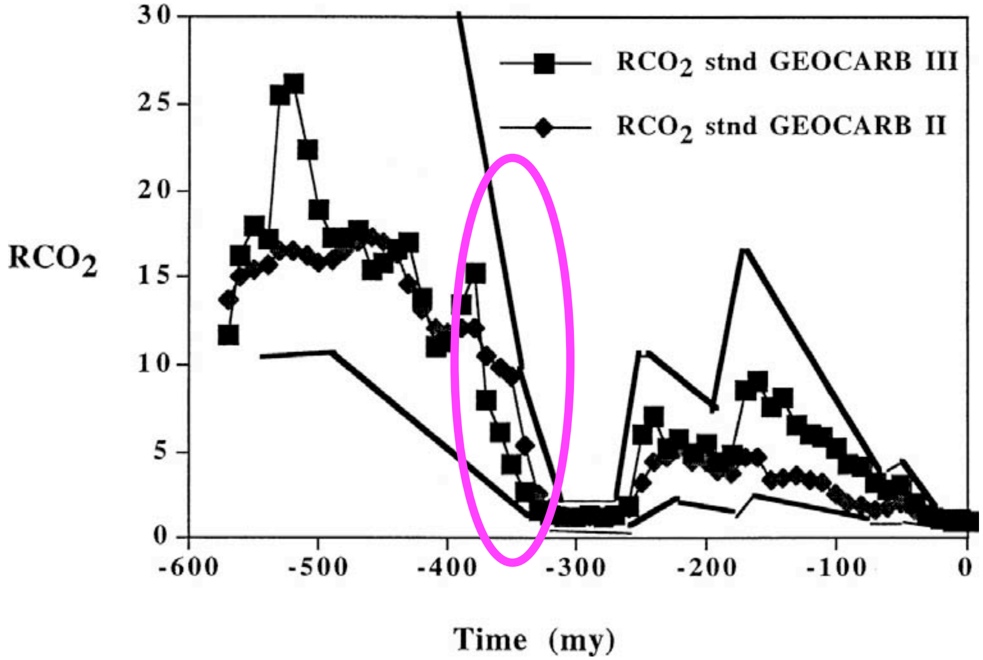
- *Yale's Bob Berner considered the evolution (based on independent geologic observ-ations) of these various factors over time in a mechanistic model of the long-term C-cycle*
- *this enabled Berner to estimate changes in* CO_2 *across the Phanerozoic (last 540 MY)*
- *what did he find?*

GEOCARB model



RCO_2 = model CO_2/"present" (300 ppm)

clicker



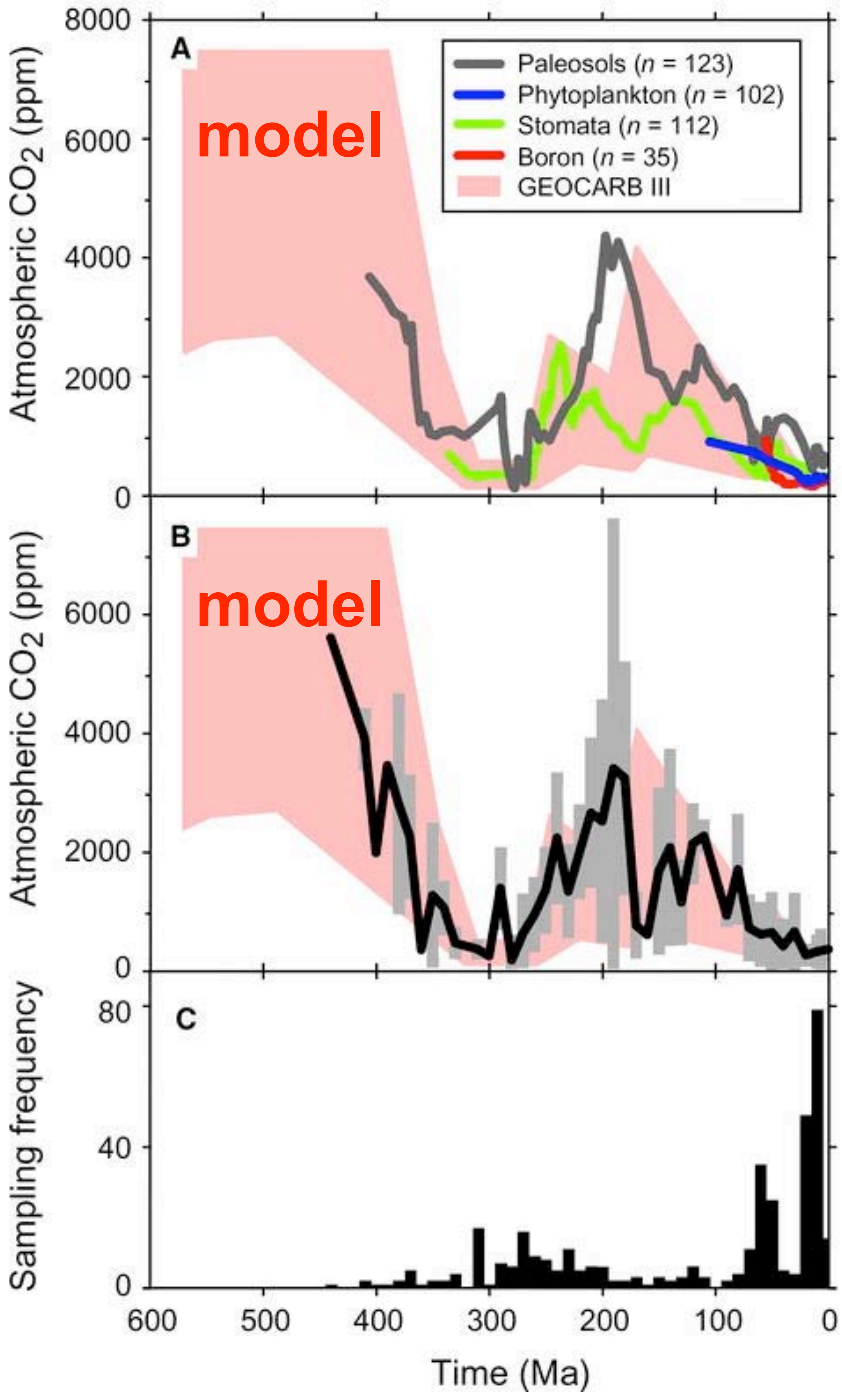
the decline in modeled CO_2 accelerated ~350 MY ago and some driving factors might be.....

a) appearance/expansion of vascular (woody) plants, b) formation and burial of organic C in poorly oxygenated swamps, c) increased silicate weathering, d) increased volcanism, e) all but d)

answer

- *woody plants appeared, expanded 350 - 300 MY ago*
  - *plants promote silicate weathering (via root respiration)*
  - *woody plant tissue resistant to oxidation, more likely to survive 'til burial*
- *continental position, low relief and warm, humid climate led to development of large inland swamps*
  - *swamps allow growth and then preservation (due to low oxygen levels) of organic matter*
- *increased formation, preservation and burial of plant remains led to formation of massive "<u>Carbon</u>iferous" coal beds (300-250 MY)*

CO_2 estimates



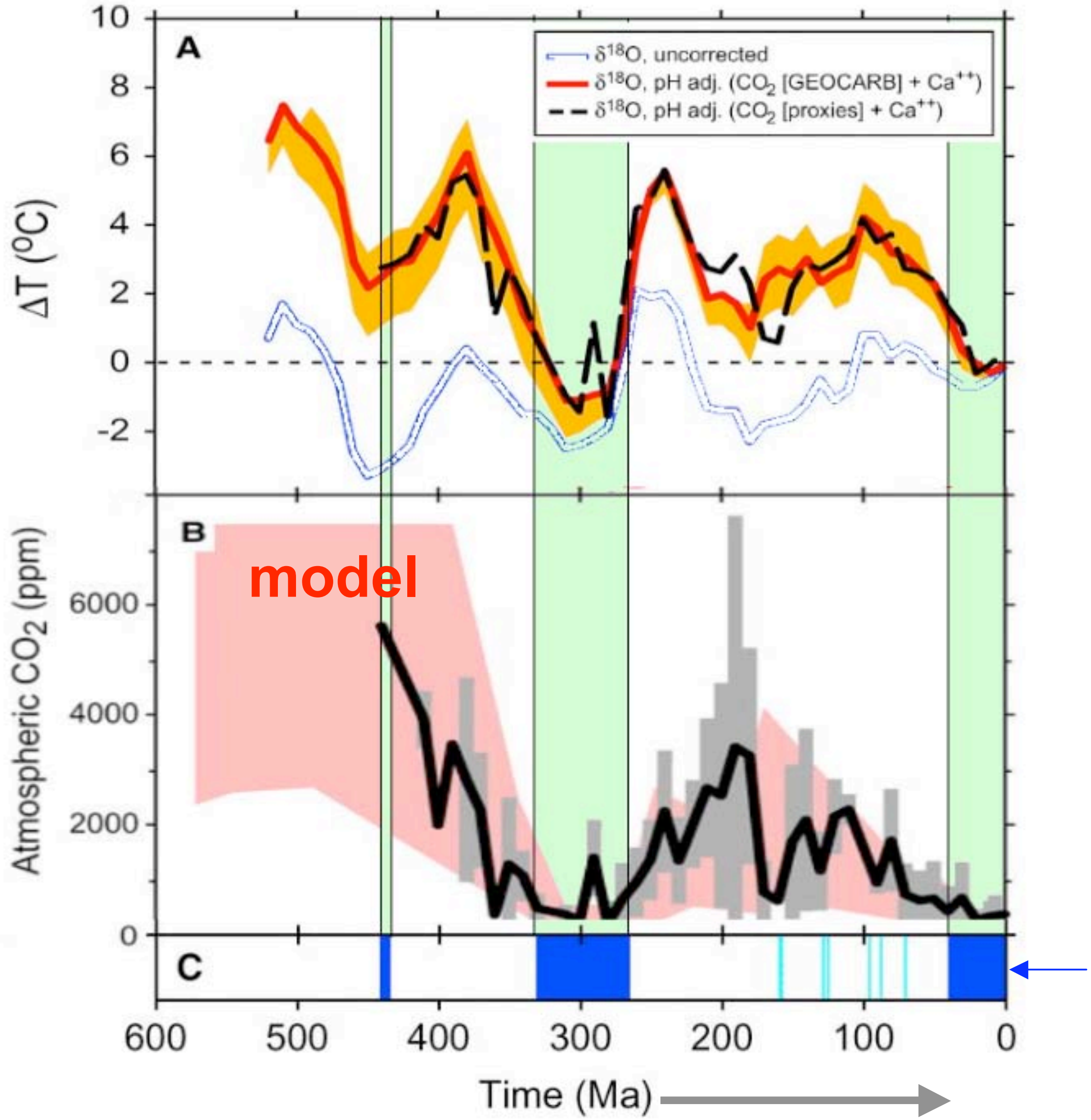
estimates from various proxies (colored lines)

all estimates (grey) and their 10 MY average (black)

substantial data - model agreement suggests reconstructions reliable despite uncertainties in both

Royer et al., '04

Phanerozoic climate & CO_2



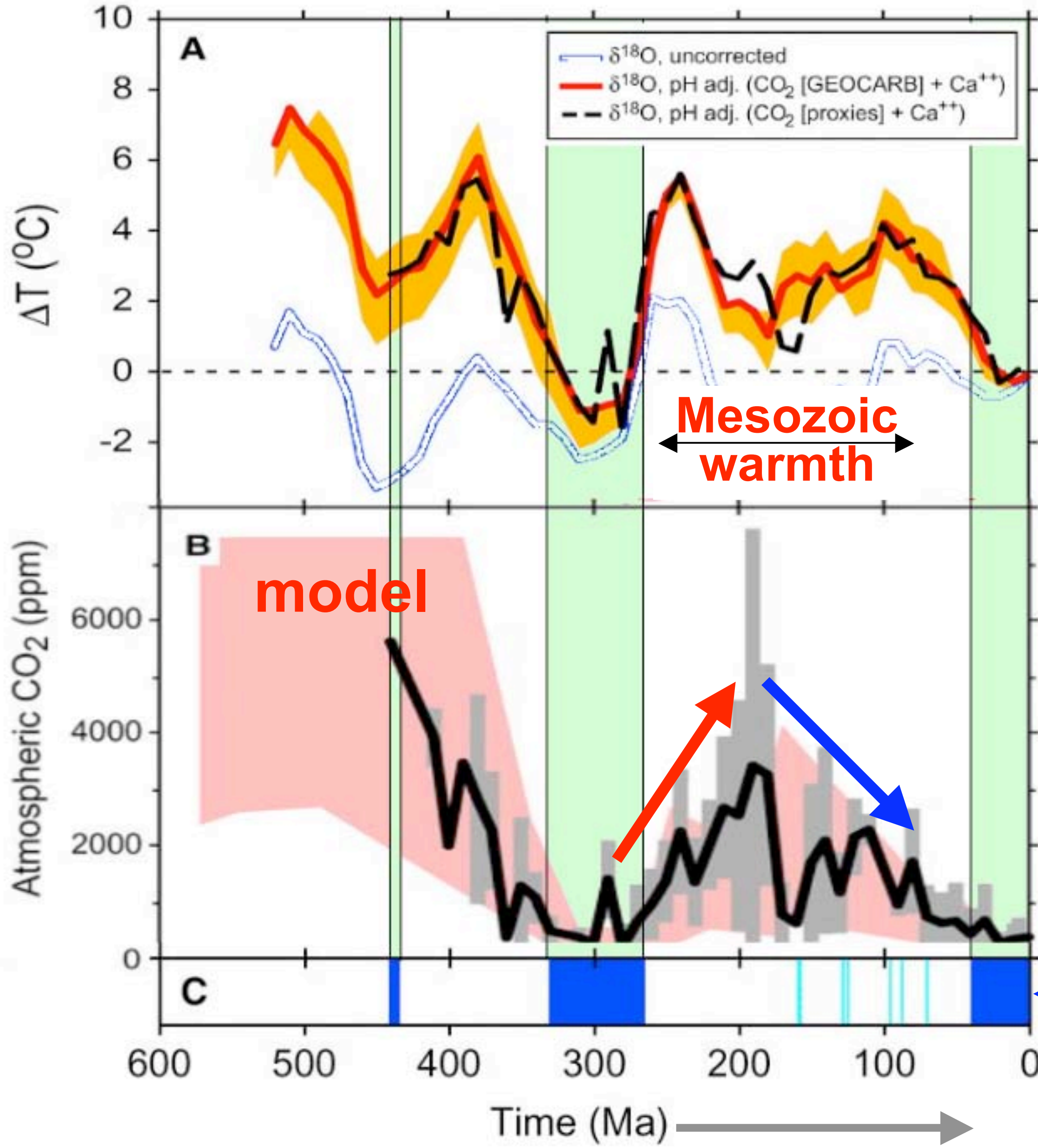
^{18}O geo-thermometer corrected for geo-chemical effects

CO_2 estimated from various proxies and model (pink)

major glaciations (assoc. w/ low CO_2)

after Royer et al., '04

Phanerozoic climate & CO_2



^{18}O geo-thermometer corrected for geo-chemical effects

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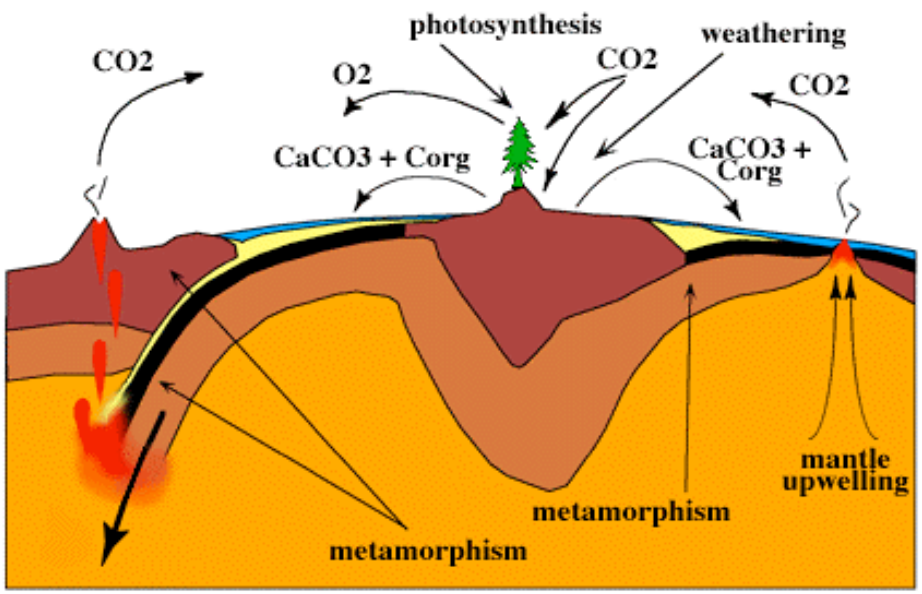
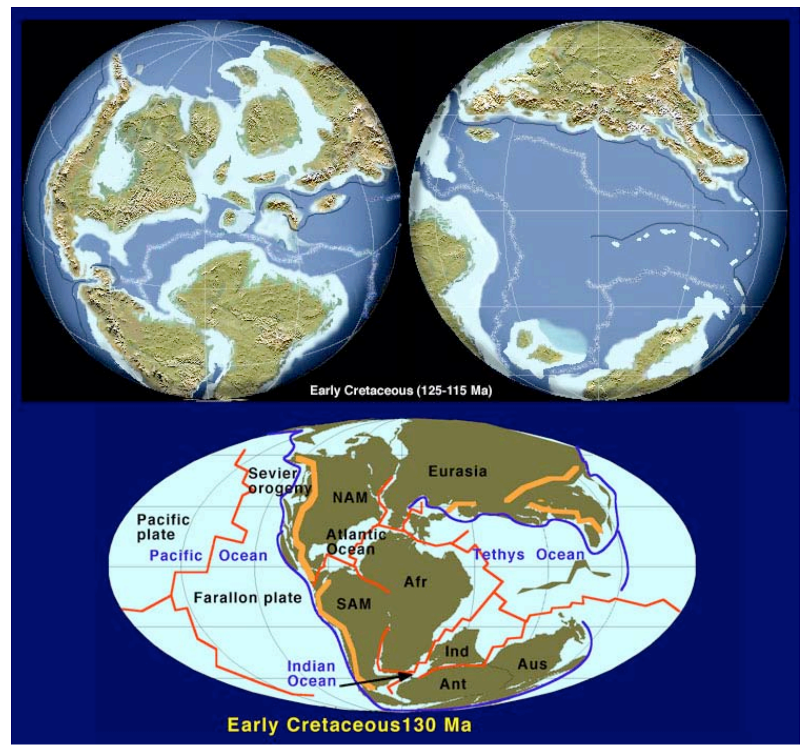
Mesozoic

increased sea-floor spreading rates:

= increased subduction of C in seds (yellow) → <u>increased metamorphosis</u> & <u>volcanism</u> (stronger CO_2 source)

= decreased land area (more ocean crust, black) → <u>decreased silicate weathering</u> (weaker CO_2 sink)





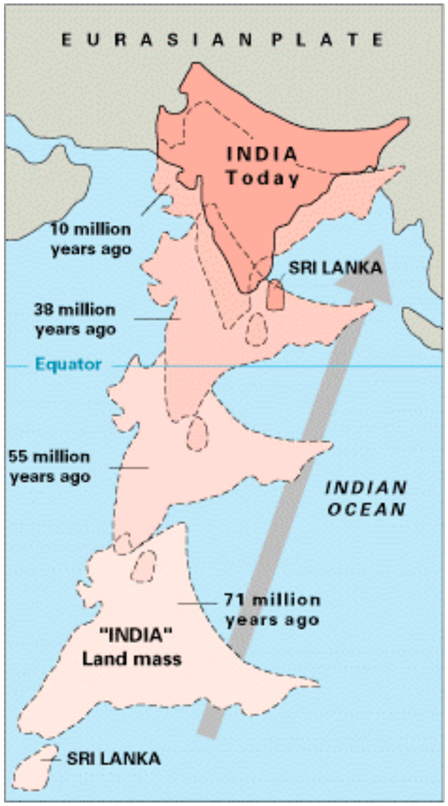
Cenozoic

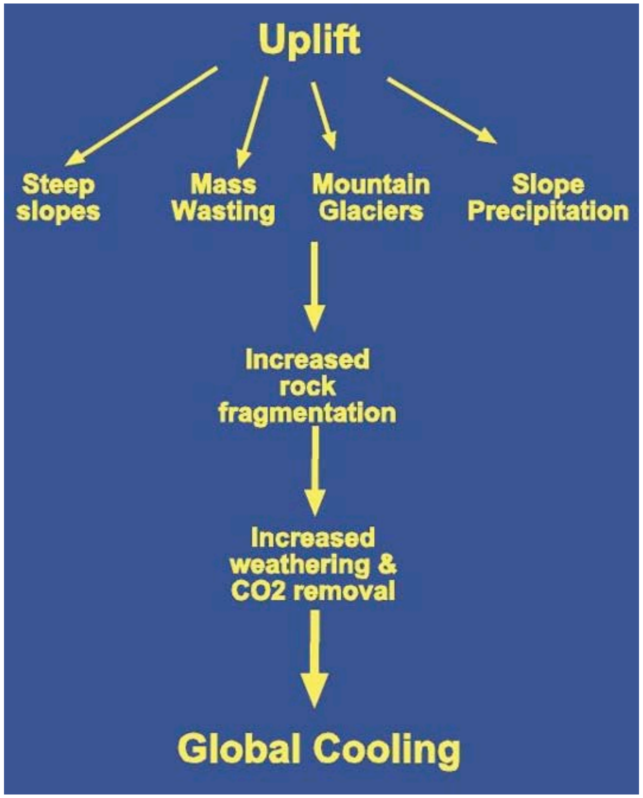
decreased sea-floor spreading rates (early Cenozoic):

= *<u>decreased</u> <u>metamorphosis</u> & <u>volcanism</u> of C (weaker CO_2 source)*

increased mountain uplift (late Cenozoic):

= *<u>increased</u> <u>silicate</u> <u>weathering</u> (stronger CO_2 sink)*





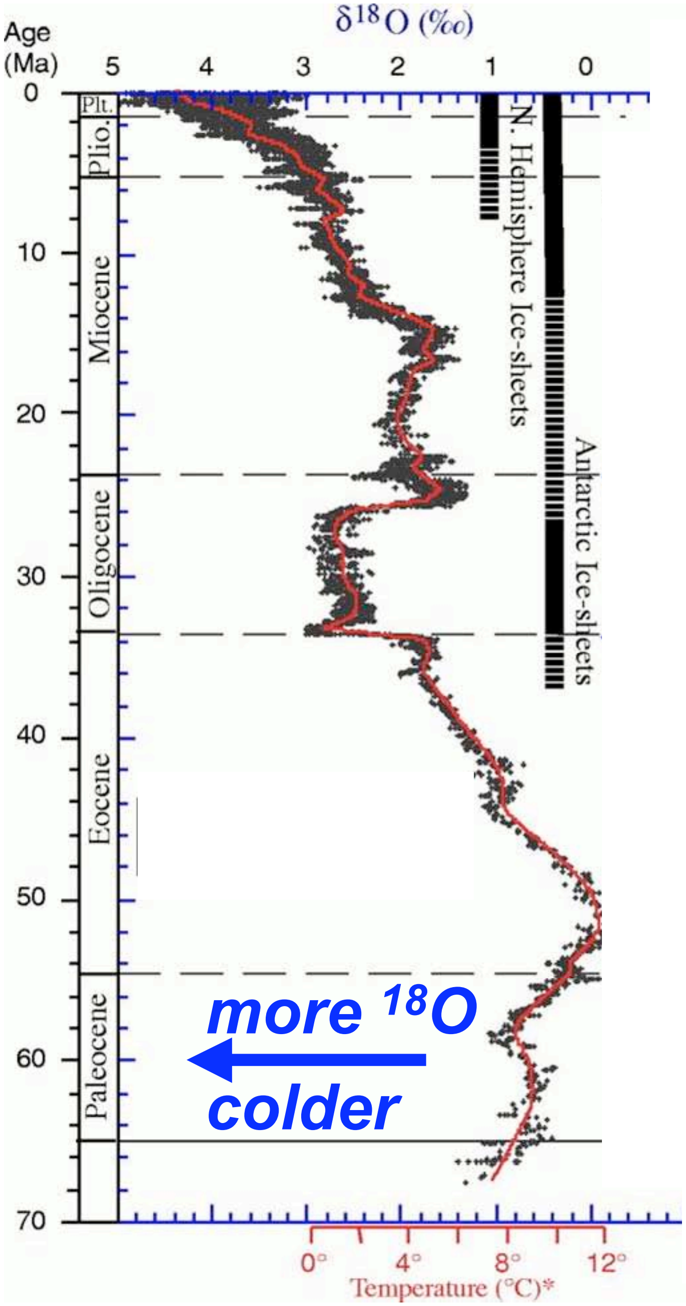
summary points (so far)

- *major changes of Phanerozoic climate and CO_2 appear related*

- *magnitude of CO_2 changes (>>4X "modern") consistent with role as major climate forcing agent*

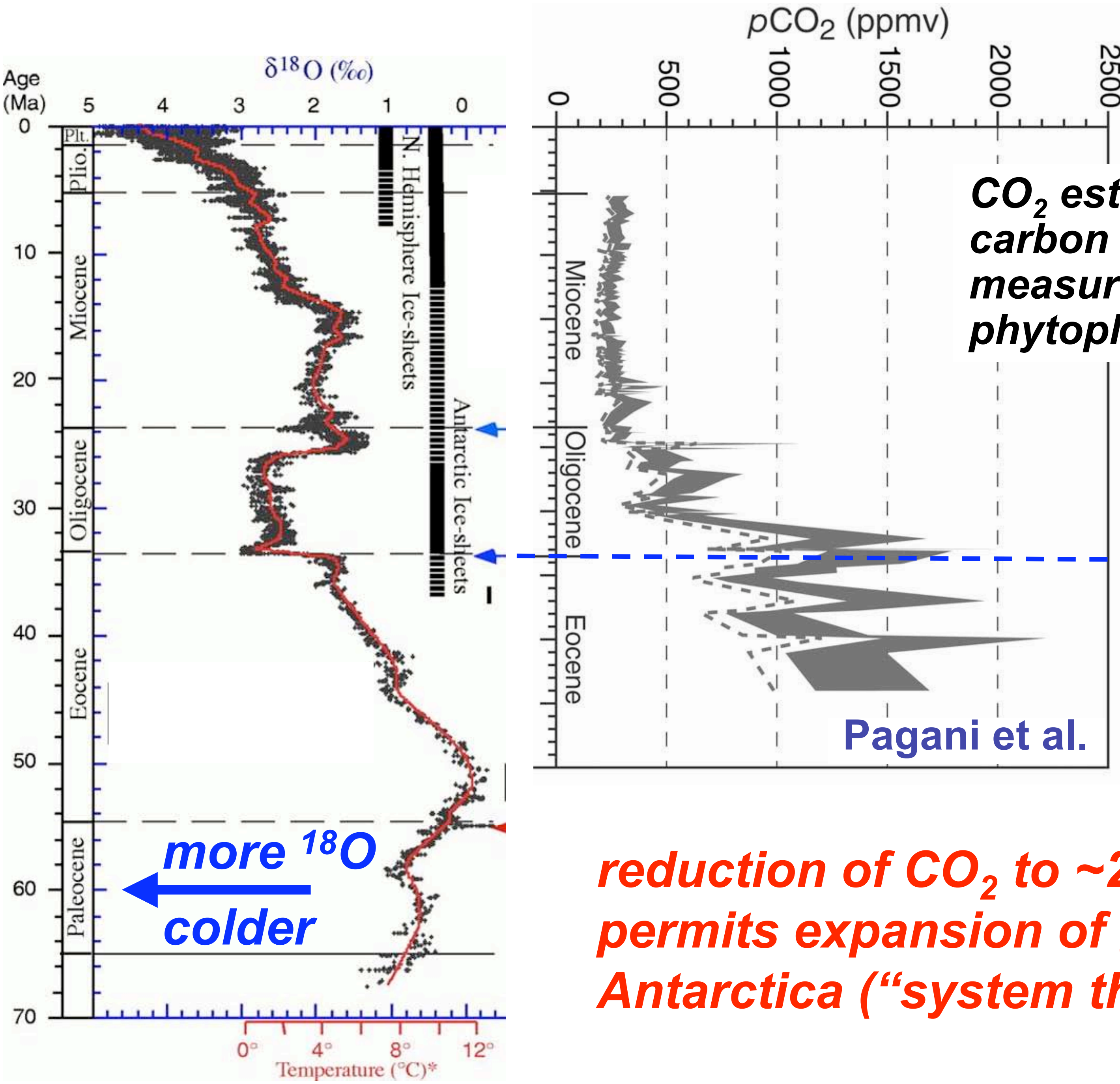
- *"observed" CO_2 from proxies well explained by mechanistic / process model of the long-term C-cycle*

Cenozoic T



from relative abundance of a heavy isotope of oxygen (^{18}O) in benthic (ocean bottom) carbonate shells

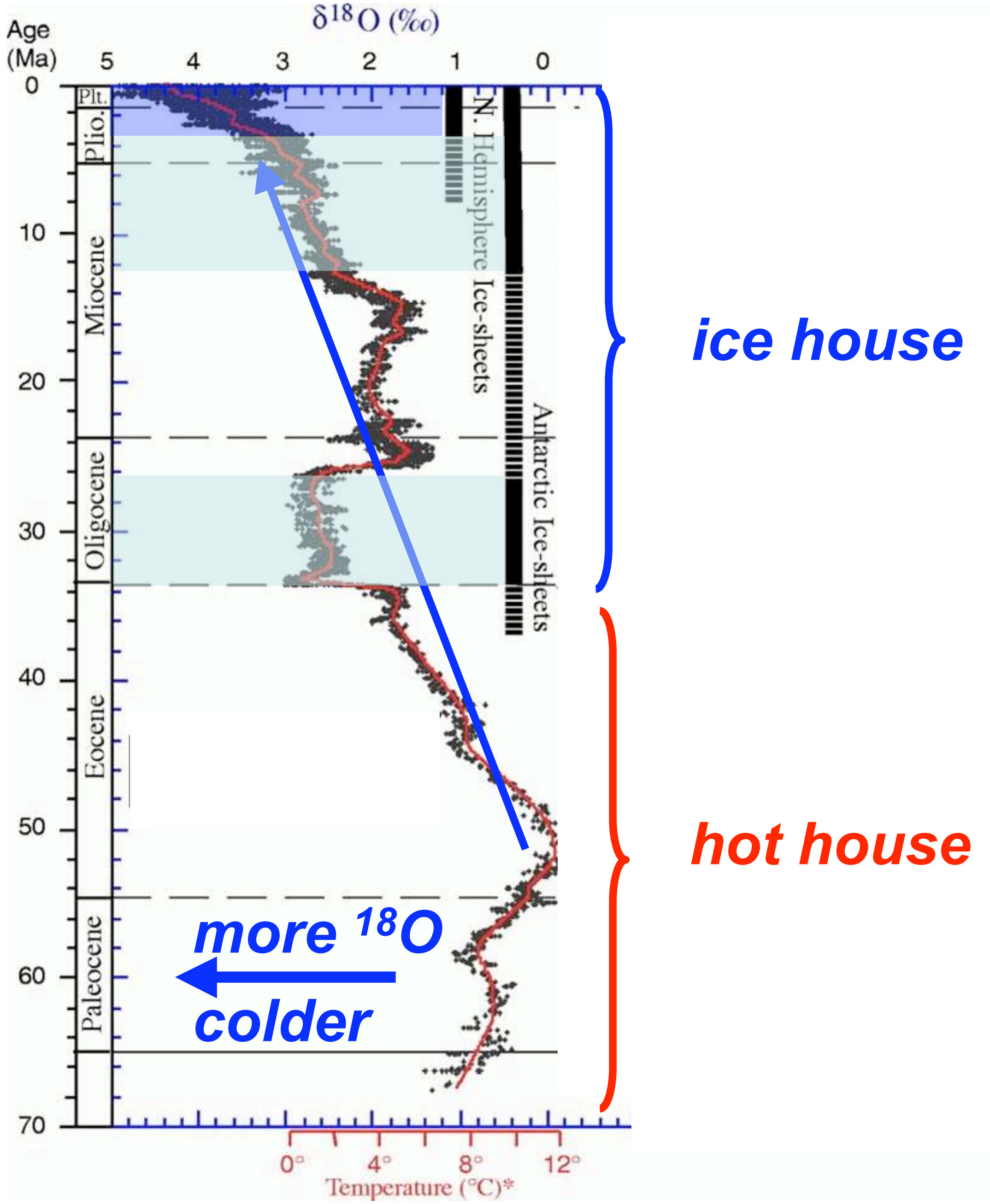
Zachos et al. '01



inception of continental-scale glaciation in Antarctica

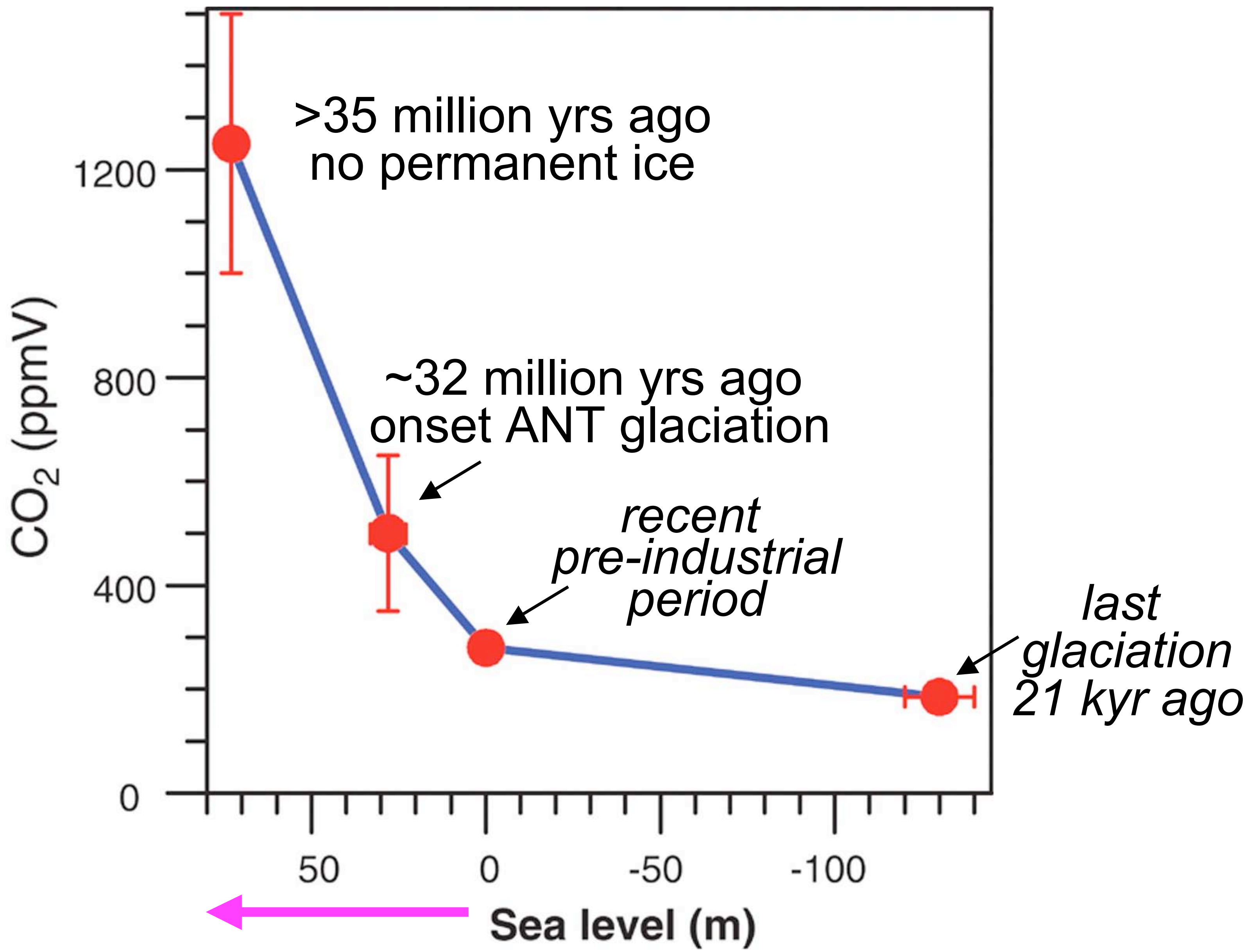
reduction of CO_2 to ~2.5X modern permits expansion of glaciers in Antarctica ("system threshold")

Cenozoic T



Zachos et al. '01

Cenozoic sea level & CO_2

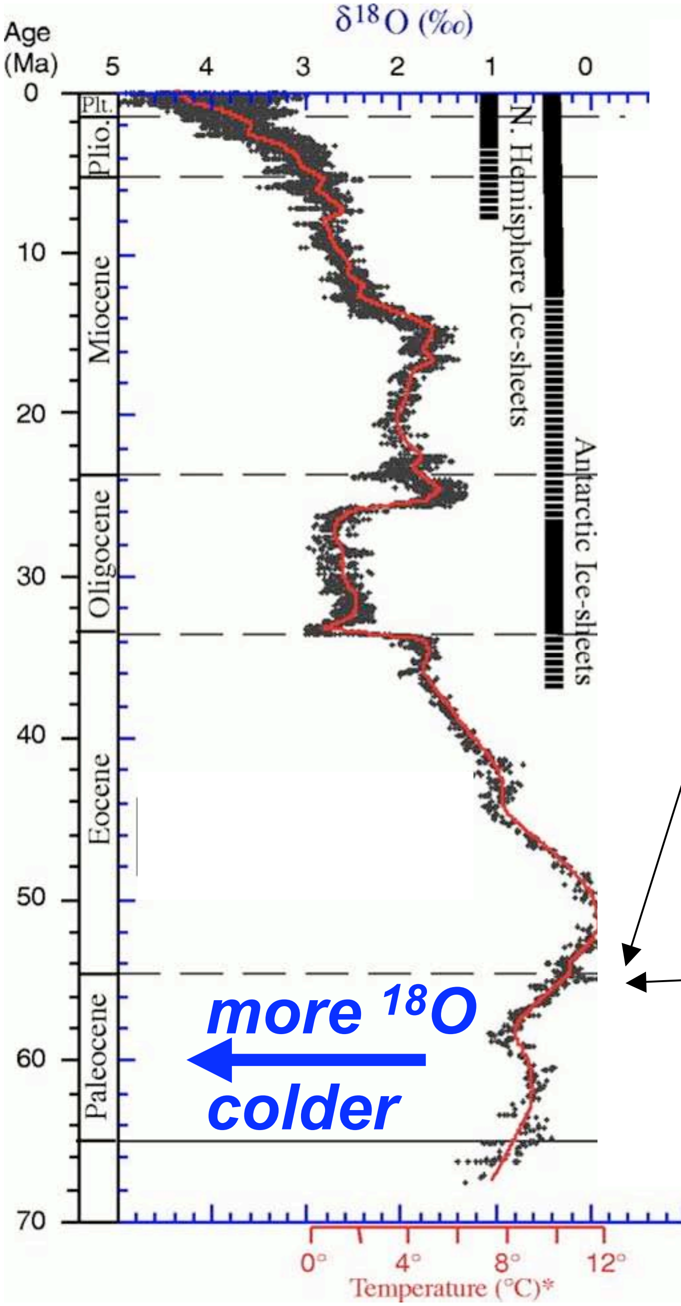


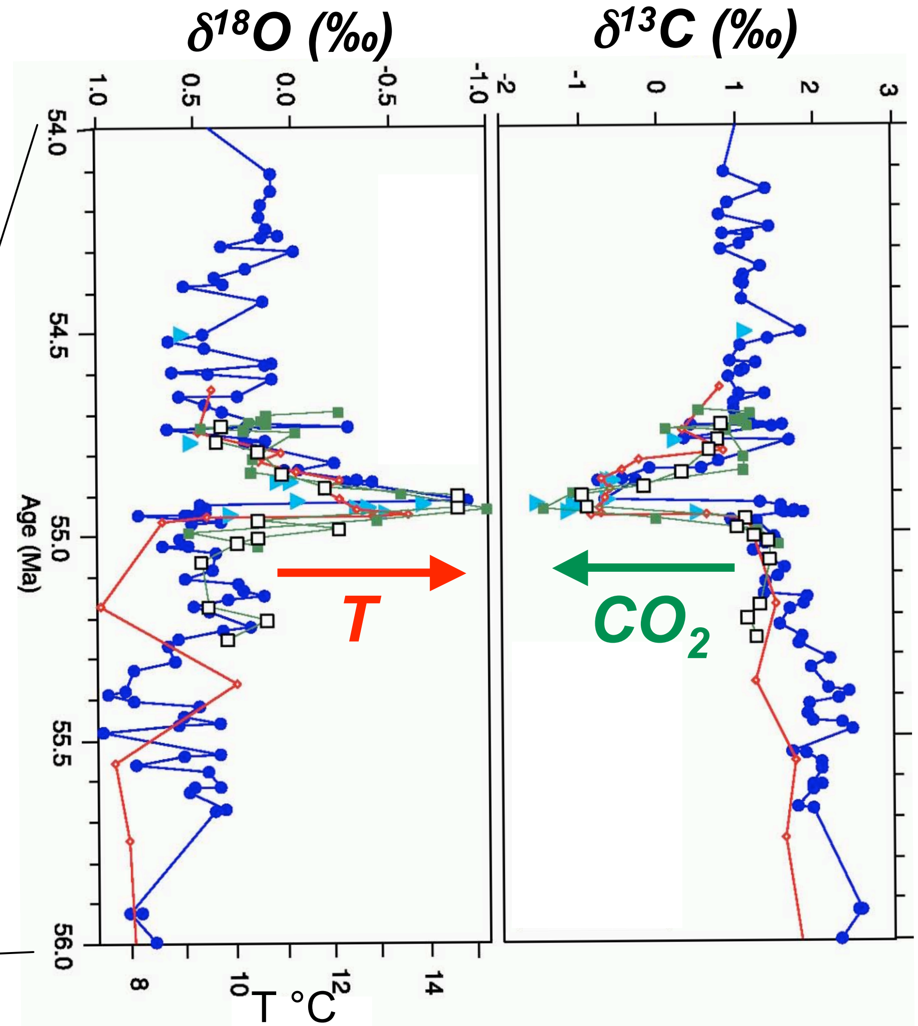
Paleocene Thermal Maximum

- *an abrupt perturbation of the C-cycle and T*
- *~ 5000 GTC released in a few 1000 years**
- *deep ocean warmed by 5 °C*
- *lead to severe ocean acidification (marine carbonate dissolved)*
- *and, extinction of benthic organisms*
- *recovery of T and ocean chemistry takes ~100,000 years*

**based on ^{13}C proxy (^{13}C discriminated against during photosynthesis and methanogenesis, so organic matter is low in ^{13}C- low values in carbonates indicate addition of organic C as CO_2 to ocean & atmosphere*

Paleocene Thermal Maximum



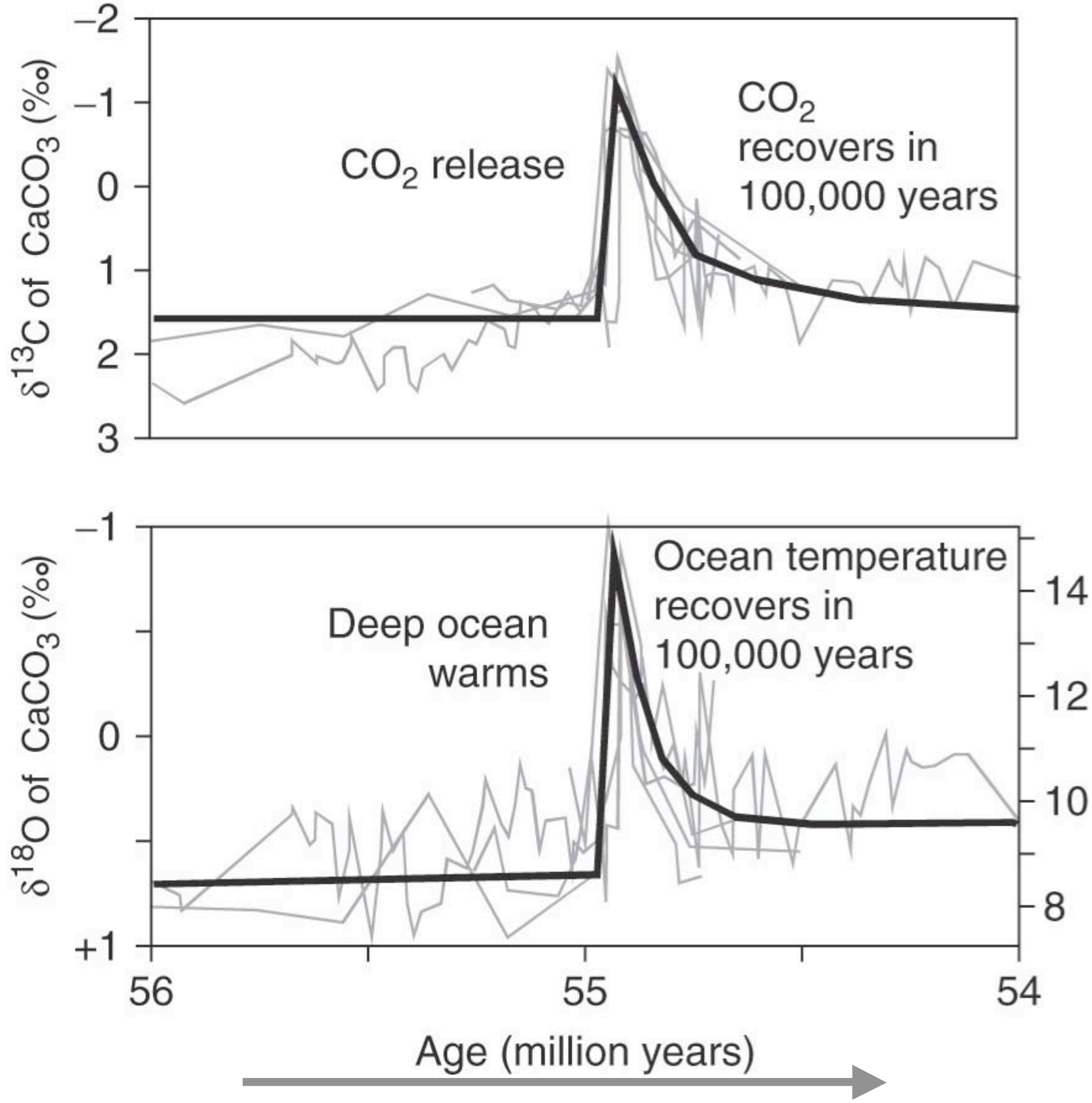


5 °C warming of deep sea

~5000 GTC released

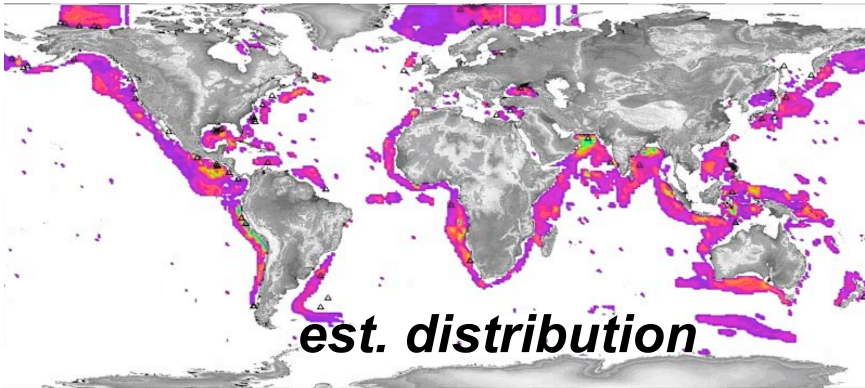
Zachos et al. '01

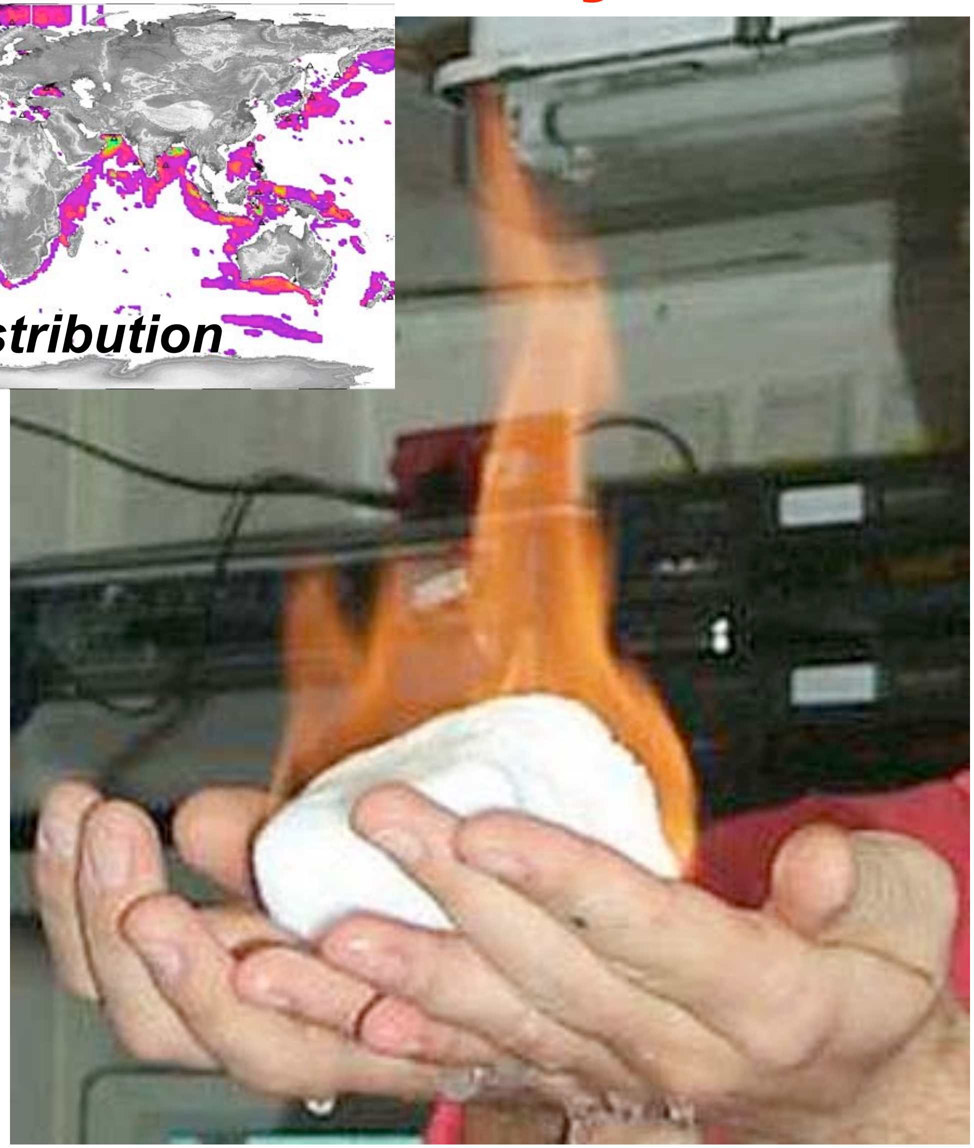
Paleocene Thermal Maximum



is the implied rate of C release consistent with a source in the hard rock reservoir?

methane hydrate





possible source of low ^{13}C carbon during LPTM

methane held in water ice by high pressure and low temperature beneath sea floor

recall

- *current inventory of fossil fuels is ~5000 GTC*
- *at current rates of consumption it would take ~500 years to burn it all*
- *the LPTM is a strong indication from the geologic record that it would be a mistake to do so*
- *consequences (?):*

summary

- flows of inorganic and organic C into and out of the "rock reservoir" control atmospheric CO_2 on long time scales
- these flows are influenced by tectonic forces, climate, and biology
- changes in these factors can be used to estimate CO_2 variations in deep time
- such estimates are largely consistent w/ geologic "proxy" evidence of past CO_2 amount
- variations of CO_2, climate, glaciation and sea level during the Phanerozoic appear to be causally related
- at the end of the Paleocene a marked perturbation of CO_2 and climate occurred that appears to be unique in the Cenozoic

learning goals

- be able to describe the primary flow paths of C in the long-term (“rock”) C-cycle and some of the factors that influence the strength of these flows
- use your understanding of the above to explain or “predict” the evolution of CO_2 through the Phanerozoic (last 540 MY)
- describe the relationship between Cenozoic cooling, CO_2 change and continental scale glaciation in the N and S Hemispheres
- outline the events of the PTM and consider how they might inform our understanding of the timescales of recovery from a large release of C
- establish your own summary view of the overall relationship between CO_2, climate and sea level in deep time