Paleoclimate

source: NASA

Yesterday's Summary

- Paleoclimatology is very interdisciplinary
- many different archives and proxies, but data patchy and often uncertain

- long term climate determined by: insolation, albedo, and greenhouse gases

- Early Earth climate has changed completely
- Life and Evolution have shaped Earth's chemistry

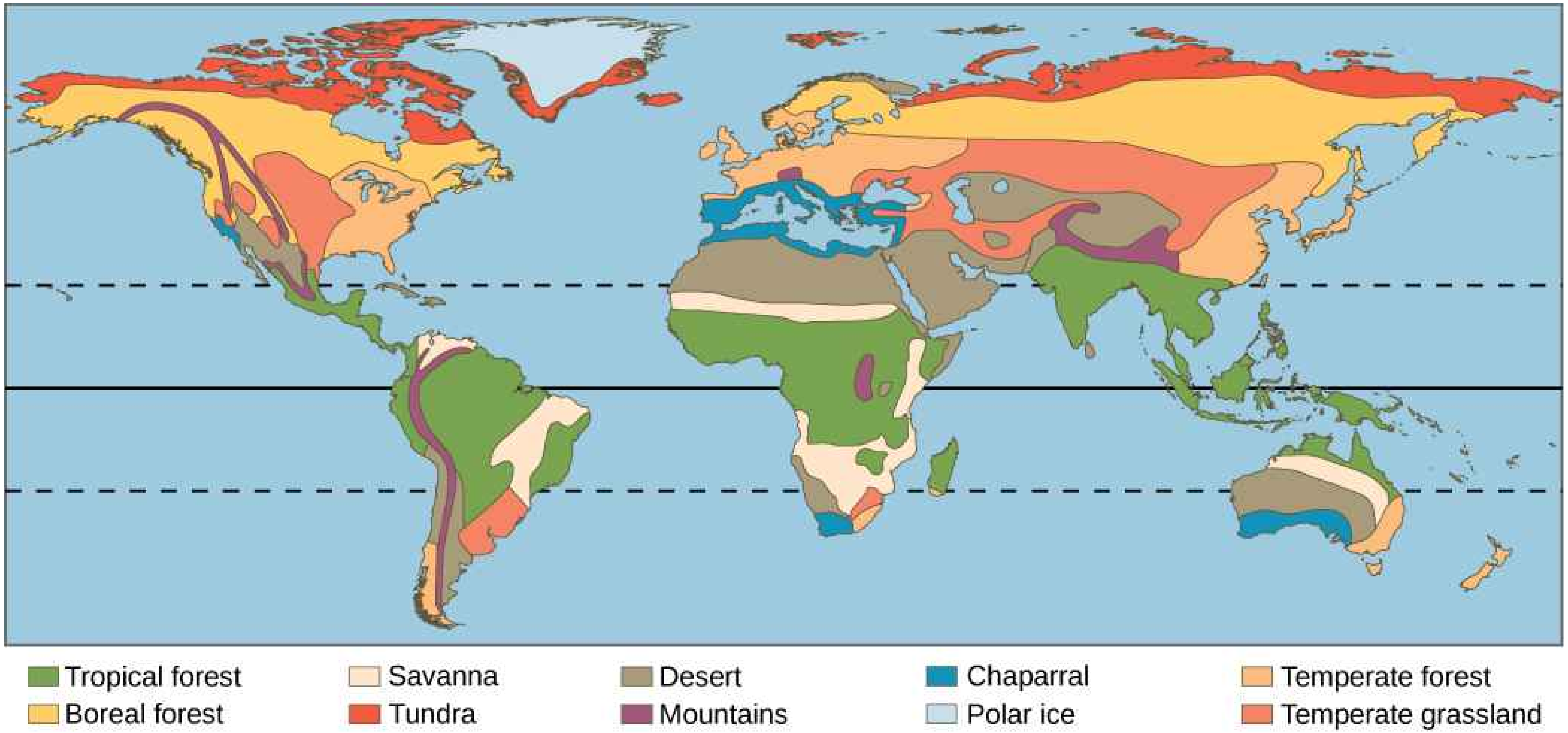
Lecture Progress

Today we finish 15 min early!

Monday	Introduction	Earth History
Tuesday	Proxies I	Cenozoic Hot & Warm House
Wednesday	Specific Climate System components	Pleistocene G-IG climate
Thursday	Proxies II & Climate System Interactions	Abrupt Climate Change
Friday	Current Climate Change	Future & Synthesis

modern biomes

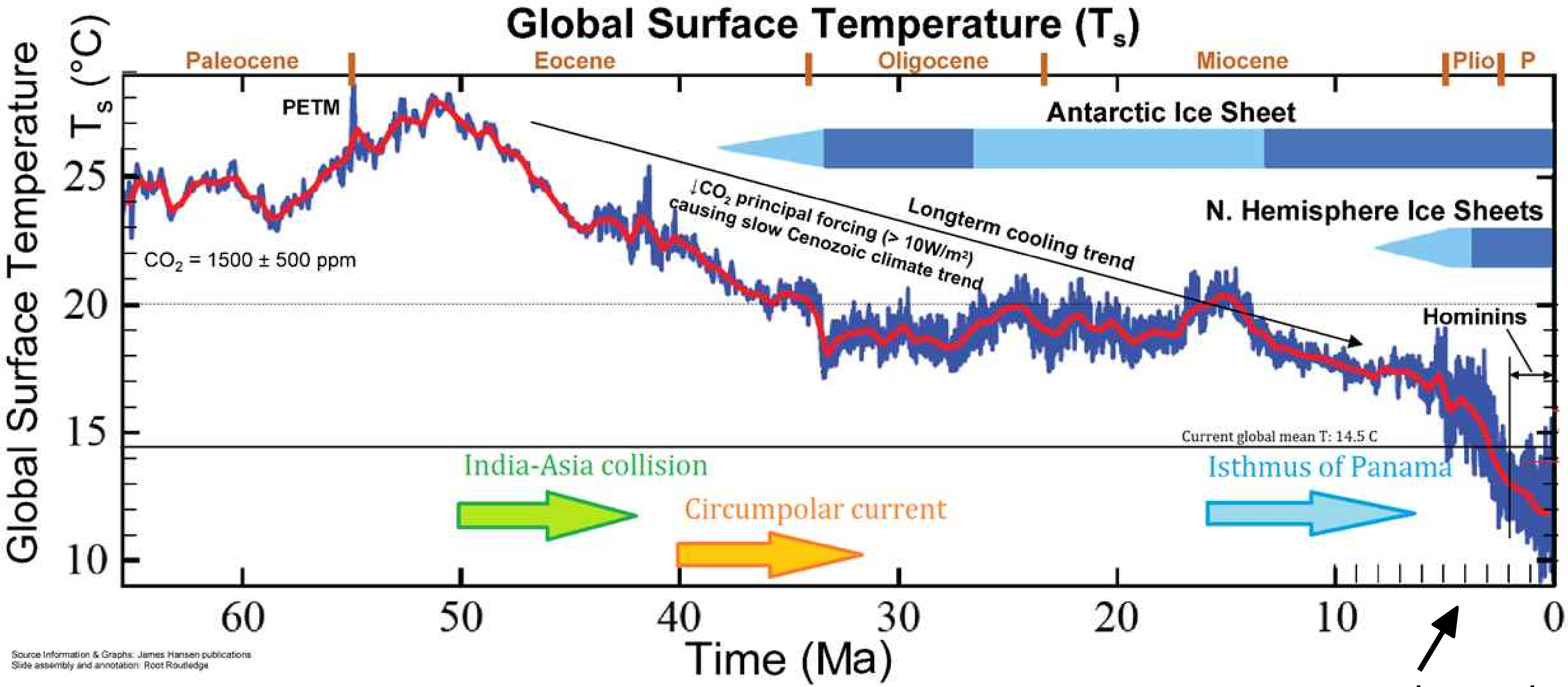
lumenlearning.com
Environmental Biology



Day 2 : Overview

- Overview of Cenozoic Climate
  - Marine Isotope Records
- Basics of Isotope Geochemistry
  - Oxygen Isotopes in Paleoclimatology
  - Clumped C-O Isotopes
  - Mg/Ca paleothermometer
  - TEX86 paleothermometer
- Hothouse “Equable Climate”
  - PETM hyperthermal
- Climate Sensitivity
- Mid-Late Cenozoic cooling

Cenozoic Climate



modern mammals

mammoths and saber-toothed cats

better records with plenty marine sediment cores

Earle (2016), opentextbc.ca
after James Hansen and Root Routledge

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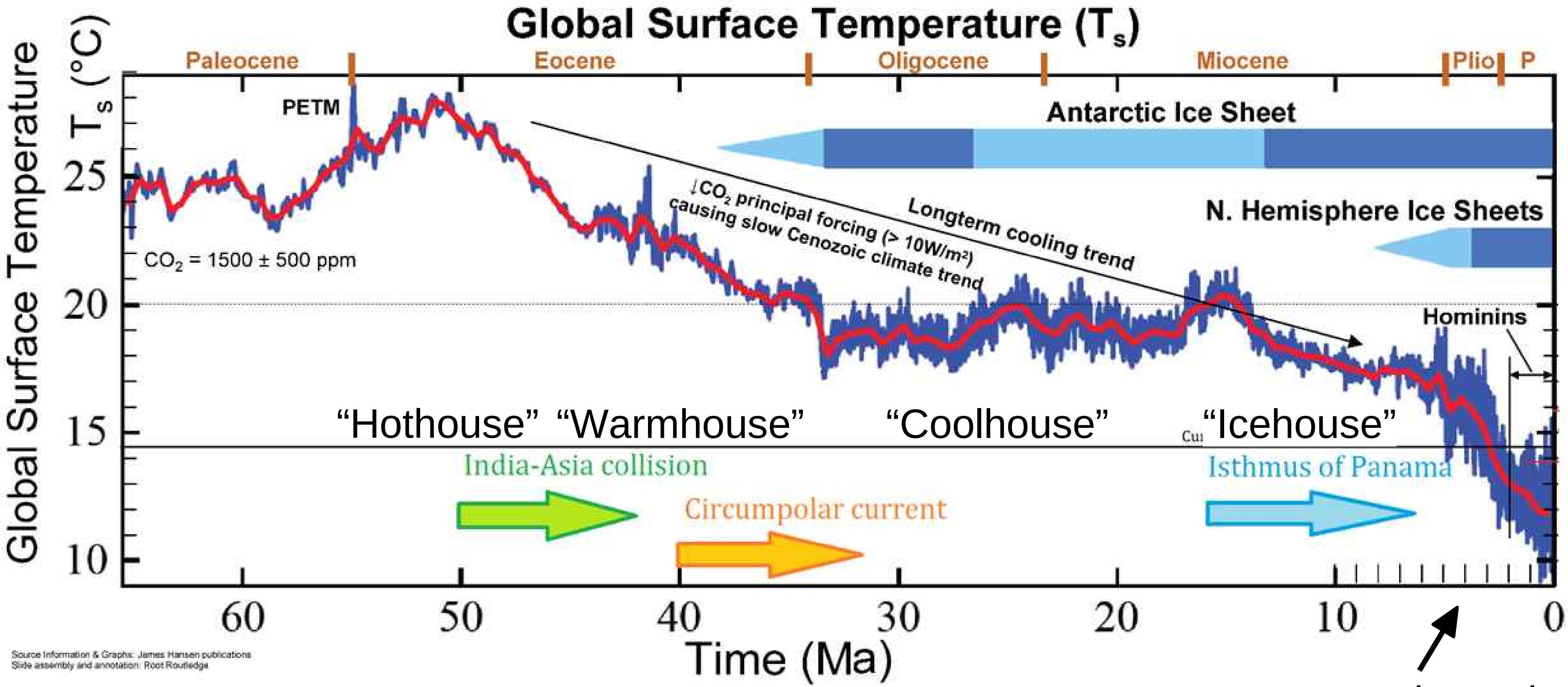
Cenozoic Climate



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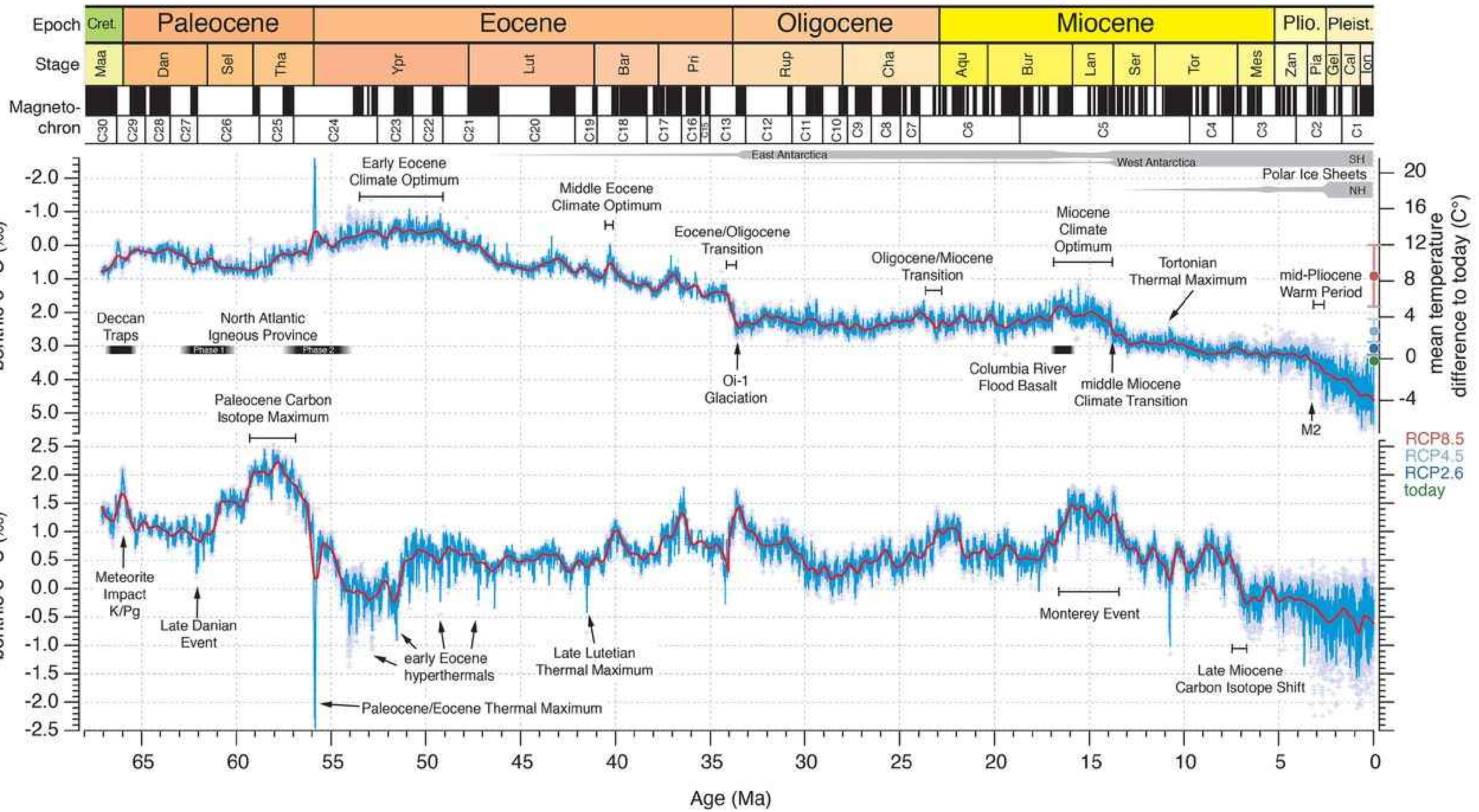
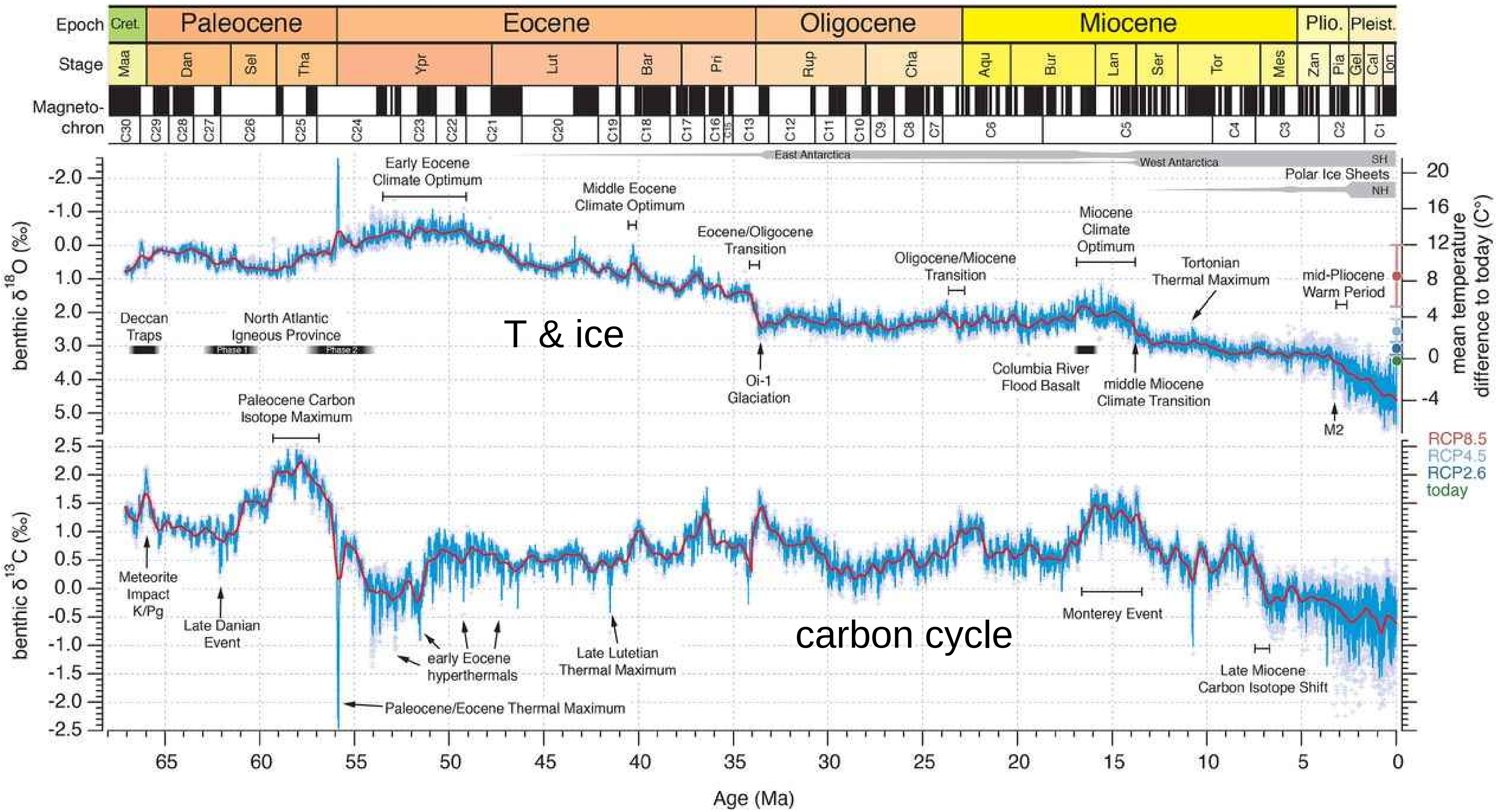
Cenozoic Climate



CENOGRID
Westerhold et al. (2020), Science

Cenozoic Climate



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Westerhold et al. (2020), Science

Isotope Geochemistry

Isotope Geochemistry

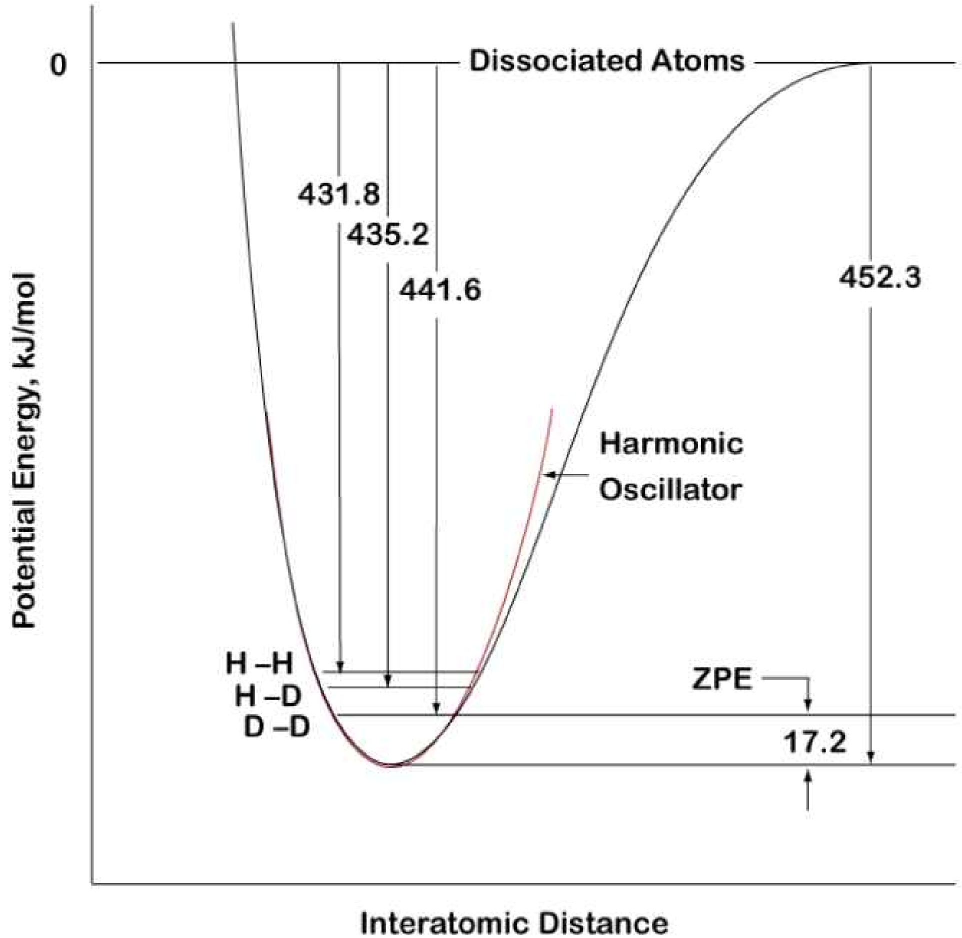
Isotope fractionation

^{16}O – 99.76 %
^{17}O – 0.04 %
^{18}O – 0.2 %

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)_{sam} - (^{18}O/^{16}O)_{SMOW}}{(^{18}O/^{16}O)_{SMOW}}\right] \times 10^{3}$$

Isotope Geochemistry

Isotope fractionation



vibrational energy of hydrogen

Cornell University, after O'Neil (1986)

Isotope Geochemistry

Isotope fractionation

R_X – isotope ratio in reservoir X

α,ε – fractionation factor

$\alpha_{A\text{-}B} = R_A / R_B$ e.g. 1.0098 for ^{18}O in evap. @ 20°C

$\varepsilon = (\alpha - 1) * 10^3$

$\varepsilon_{A\text{-}B} \sim \delta_A - \delta_B$

Isotope Geochemistry

Isotope fractionation

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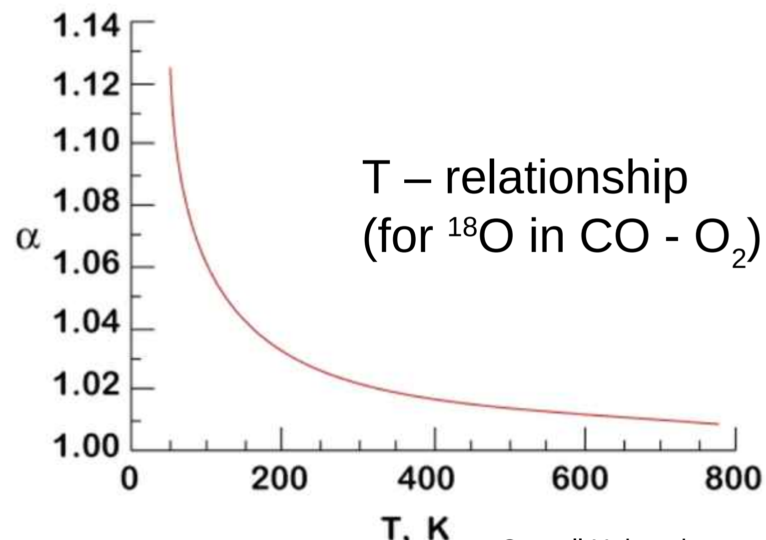
$$\alpha_{A\text{-}B} = R_A / R_B$$

e.g. 1.0098 for ^{18}O in evap. @ 20°C

$$\varepsilon = (\alpha - 1) * 10^3$$

$$\varepsilon_{A\text{-}B} \sim \delta_A - \delta_B$$

$$\alpha_{A\text{-}B} \sim 1/T^2$$



T – relationship
(for ^{18}O in CO - O_2)

Cornell University

Isotope Geochemistry

Equilibrium fractionation:

- slow complete equilibration
  (e.g. condensation @ 100% humidity)
- heavier isotopes enriched in colder phase

Kinetic fractionation:

- fast or incomplete reactions
  (e.g. condensation @ < 100% humidity or with immediate rain)
- unidirectional
- more complex

Isotope Geochemistry

Rayleigh fractionation:

- equilibrium fractionation with removal of product
- reservoir decreases in size
- e.g.: raining clouds

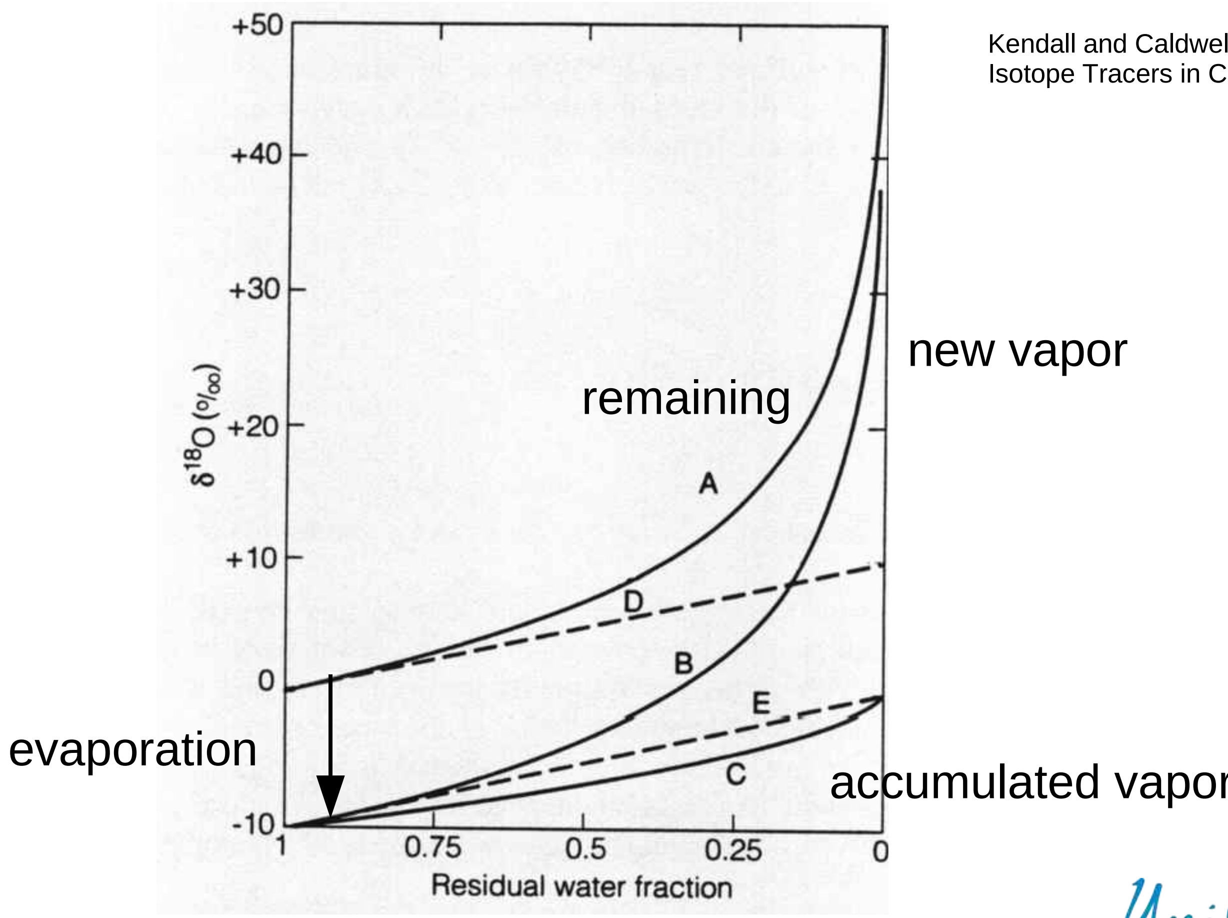
$R = R_0\, f^{(\alpha-1)}$ (f = fraction remaining)

Isotope Geochemistry

Rayleigh fractionation during water evaporation

Kendall and Caldwell (1998),
Isotope Tracers in Catchment Hydrology

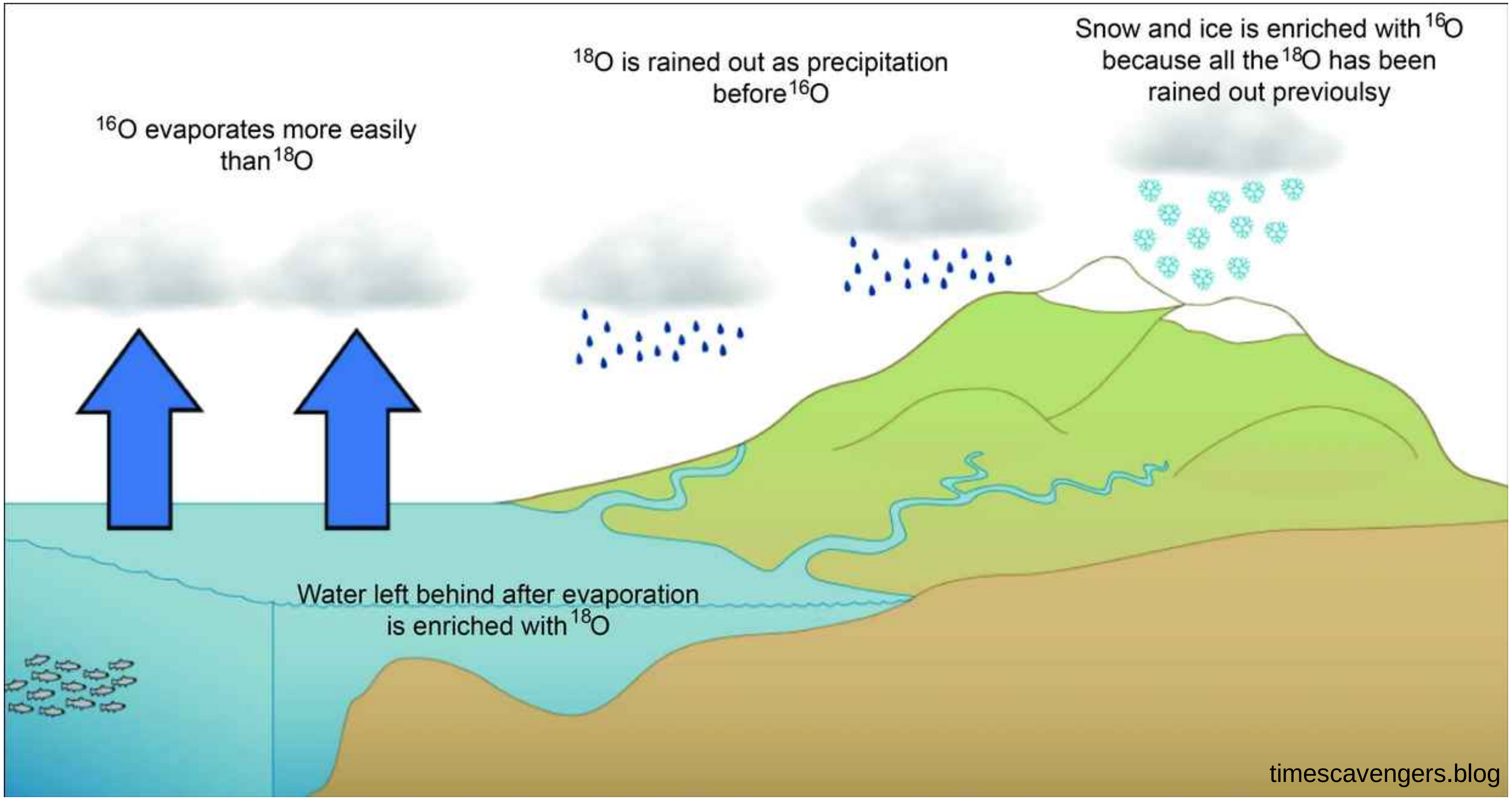
$\alpha = 1.01$



Oxygen Isotope Geochemistry

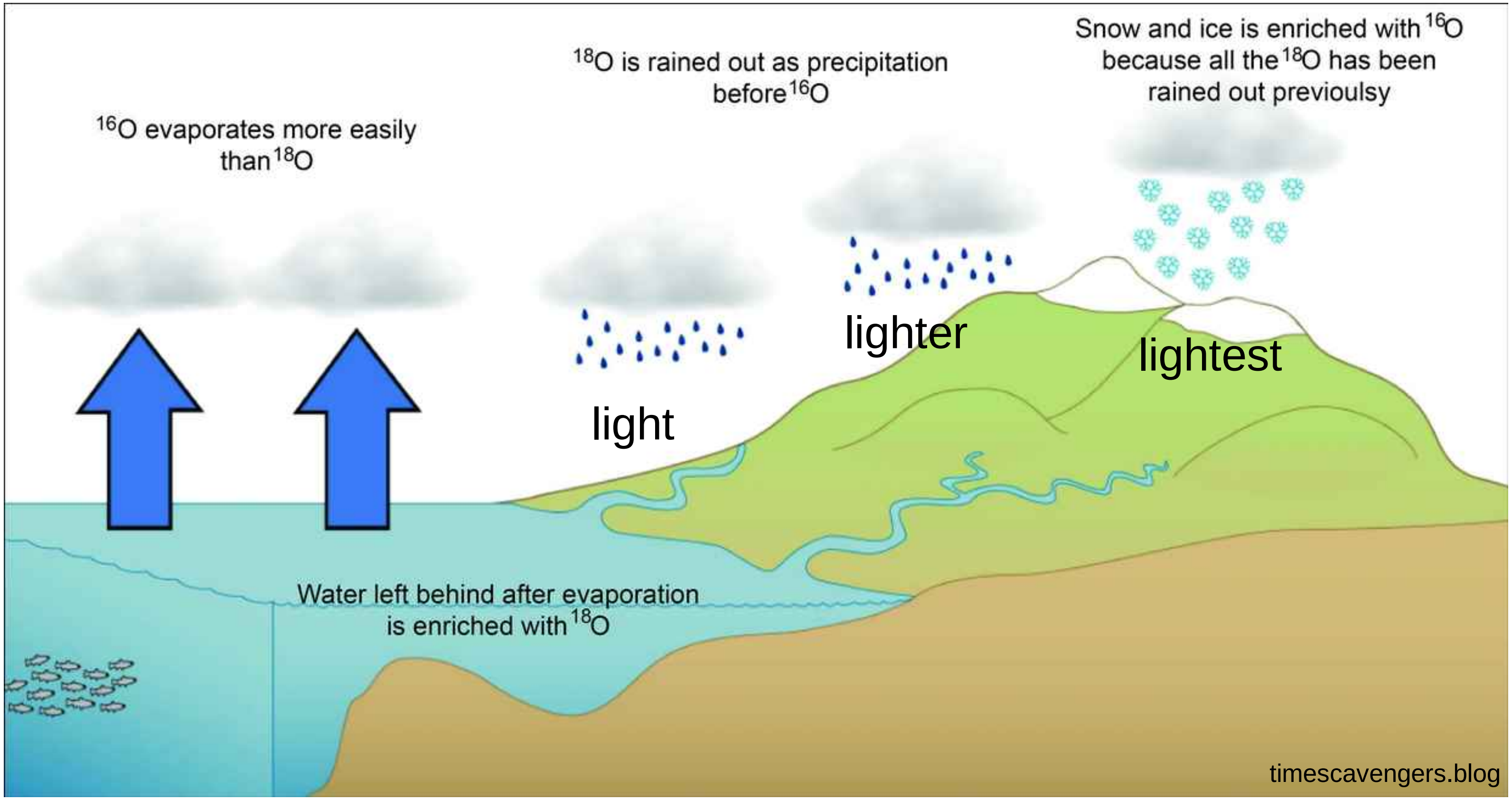
Oxygen Isotope Geochemistry

Rayleigh fractionation during water evaporation



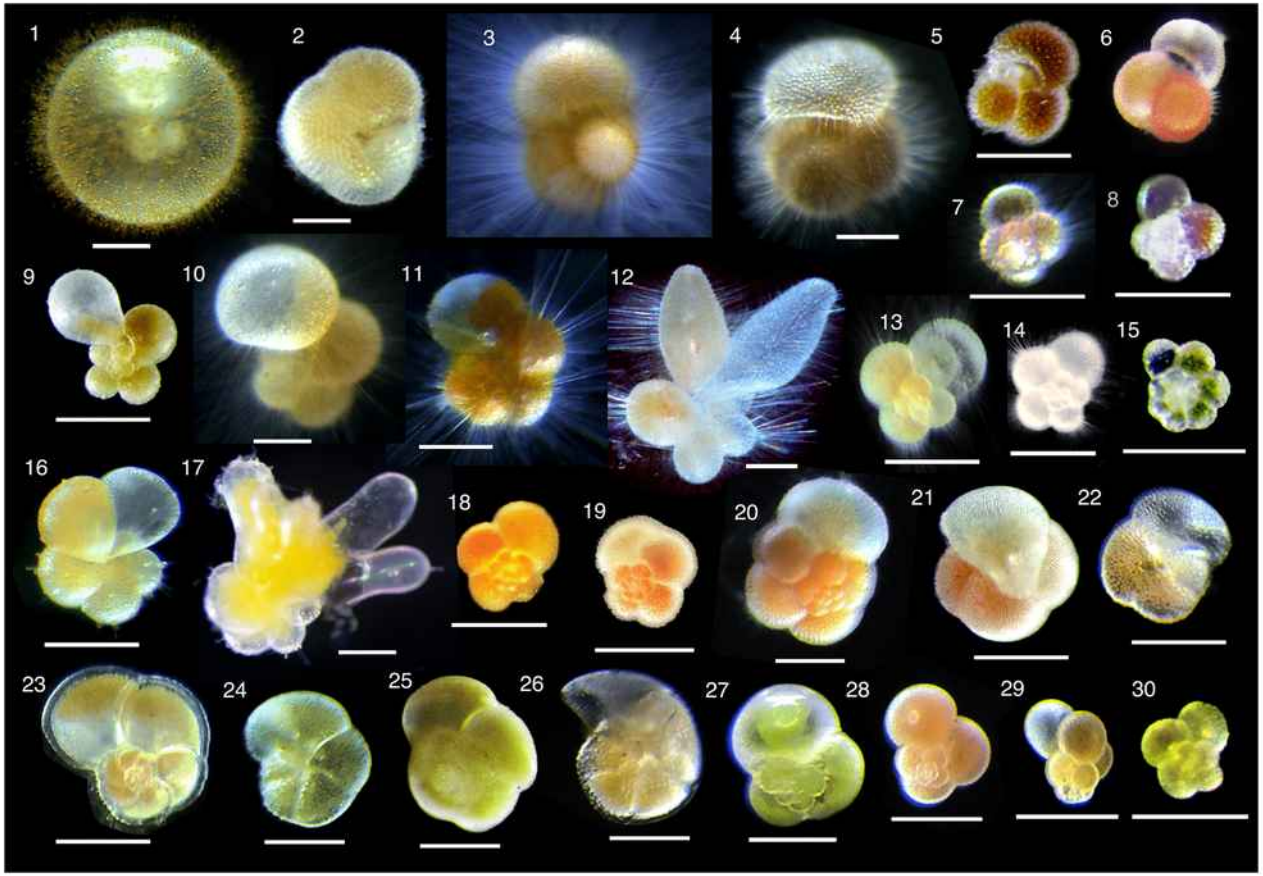
Oxygen Isotope Geochemistry

Rayleigh fractionation during water evaporation



Oxygen Isotopes in Carbonate

foraminifera – protists with $CaCO_3$ shells



Wikipedia

Oxygen Isotopes in Carbonate

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Oxygen Isotopes in Carbonate

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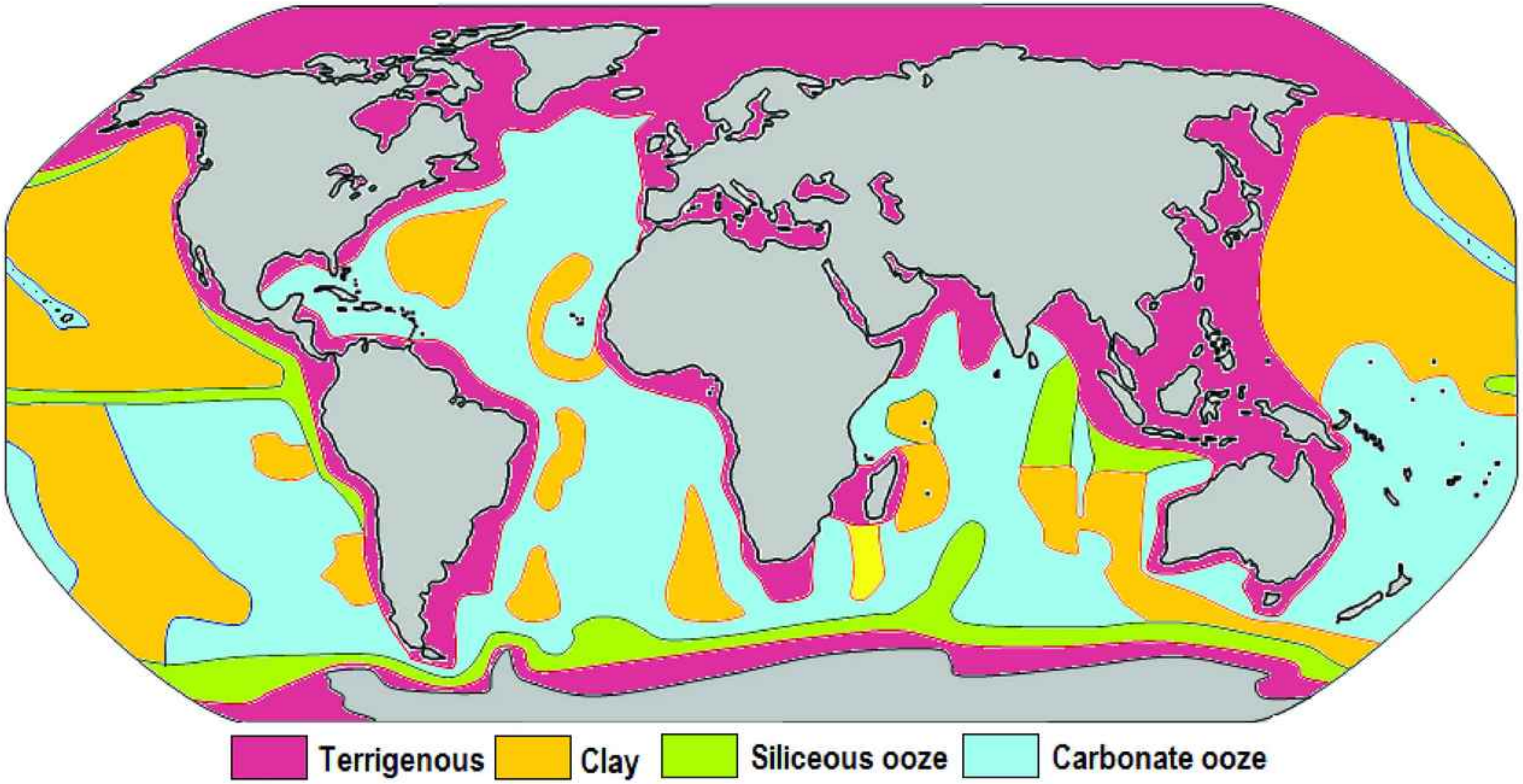
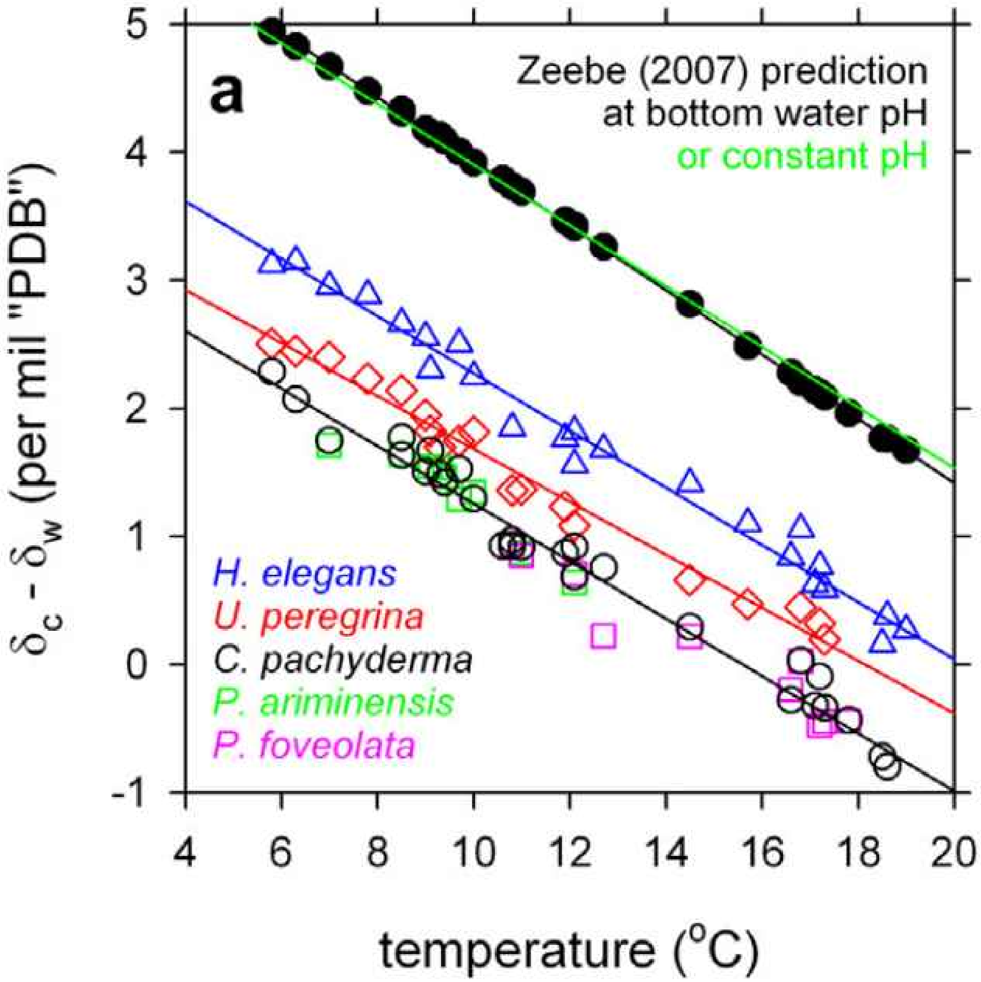


Oxygen Isotopes in Carbonate



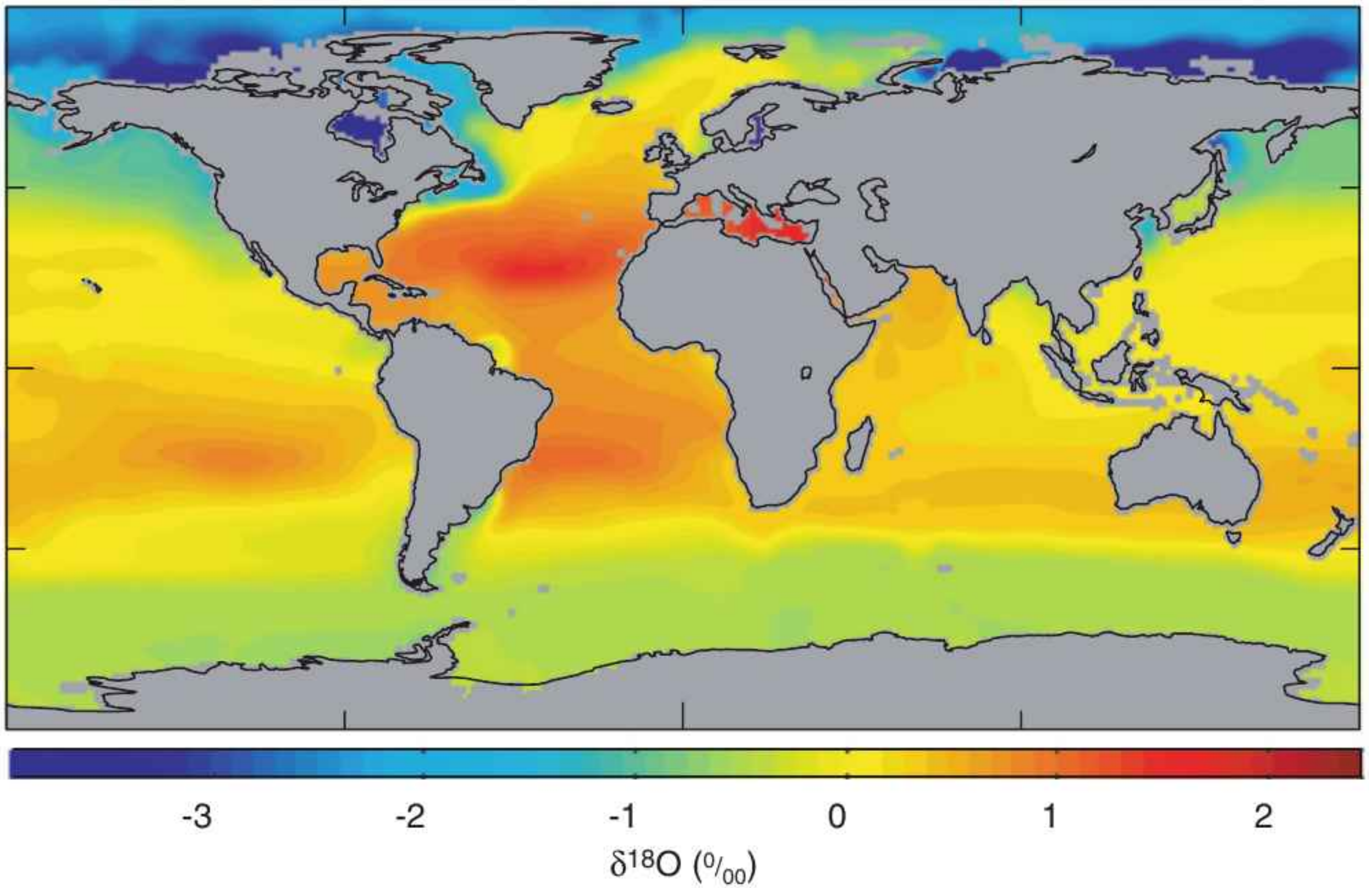
~ 0.20 – 0.25 ‰ per °C

uncertainty ~ 0.1 ‰

Marchitto et al. (2014)
Geochimica et Cosmochimica Acta

Oxygen Isotopes in the ocean

$\delta^{18}O$ in seawater: ~ salinity



Hillaire-Marcel and De Vernal (2007),
Proxies in late cenozoic paleoceanography

Oxygen Isotopes in the ocean

$\delta^{18}O$ in seawater: ~ salinity

$\delta^{18}O$ in carbonate: ~ salinity & temperature

→ ~ density

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Oxygen Isotopes in the ocean

$\delta^{18}O$ in seawater: ~ salinity

$\delta^{18}O$ in carbonate: ~ salinity & temperature

→ ~ density

BUT salinity in paleoceanography depends on global ice volume!

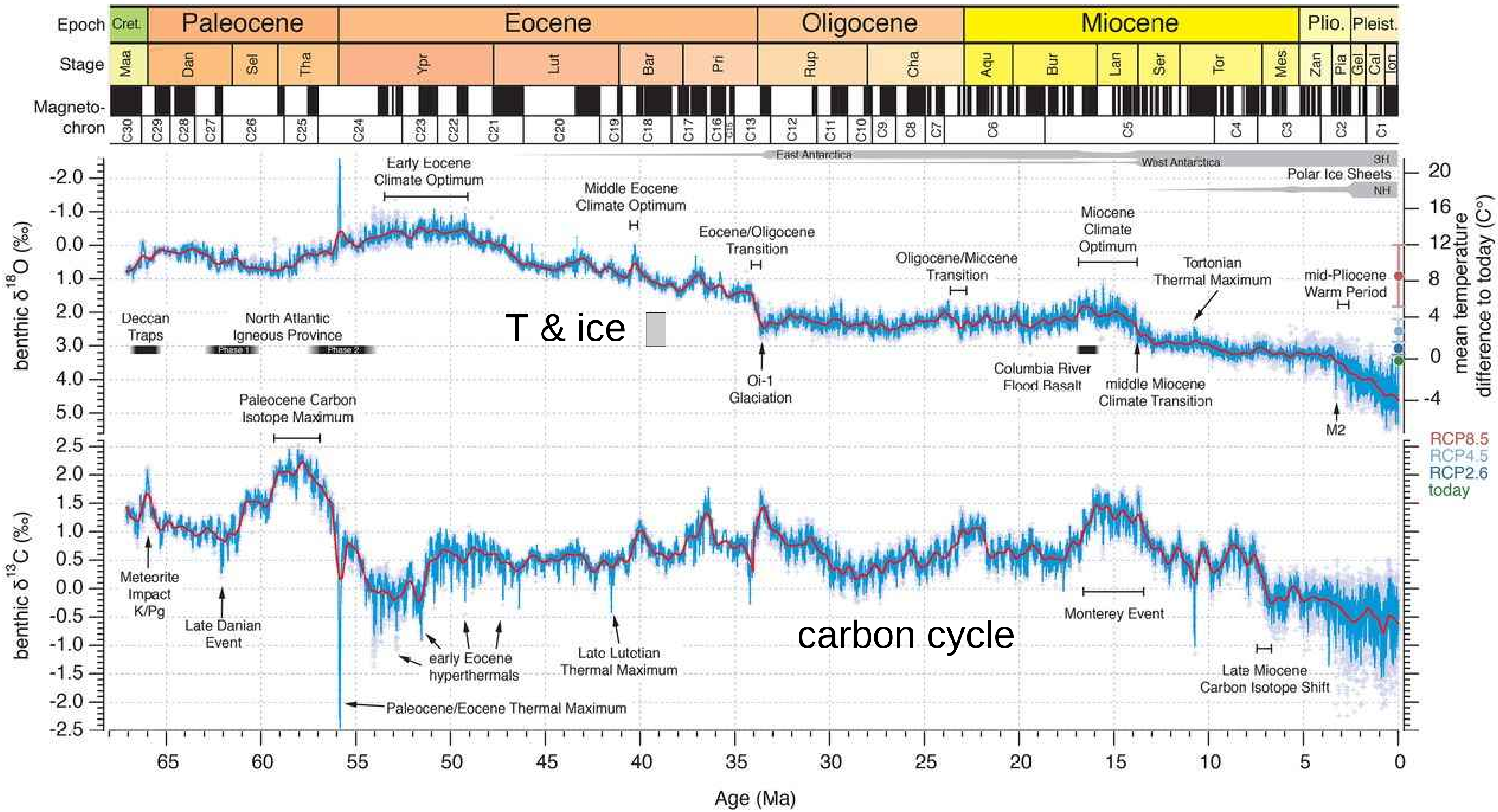
~ +1 ‰ per 100m sea level as ice

Today's continental ice ~ 0.6 ‰

Last Glacial Maximum ice ~ + 1 ‰

Hillaire-Marcel and De Vernal (2007),
Proxies in late cenozoic paleoceanography

Cenozoic Climate



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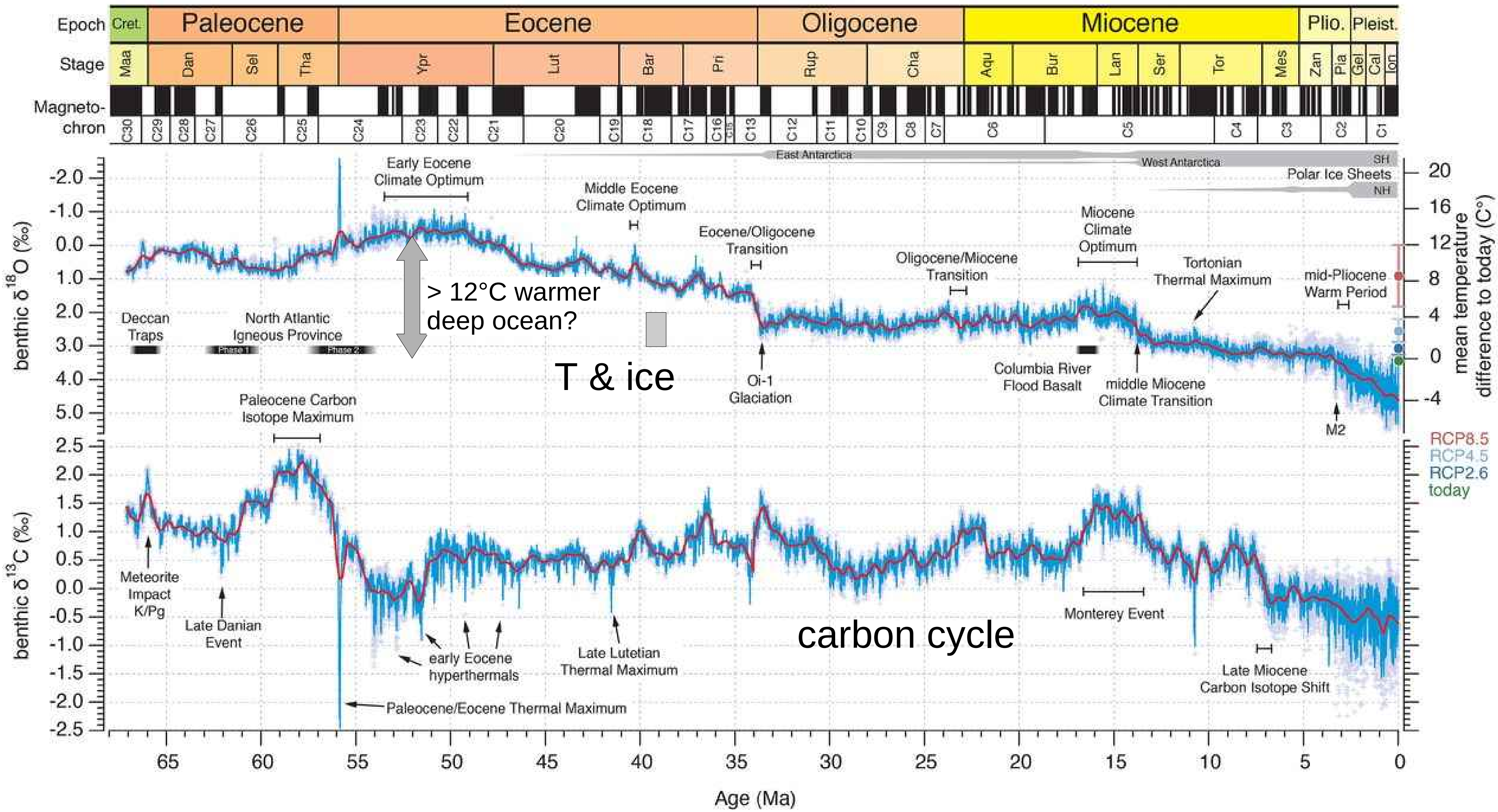
Westerhold et al. (2020), Science

Cenozoic Climate

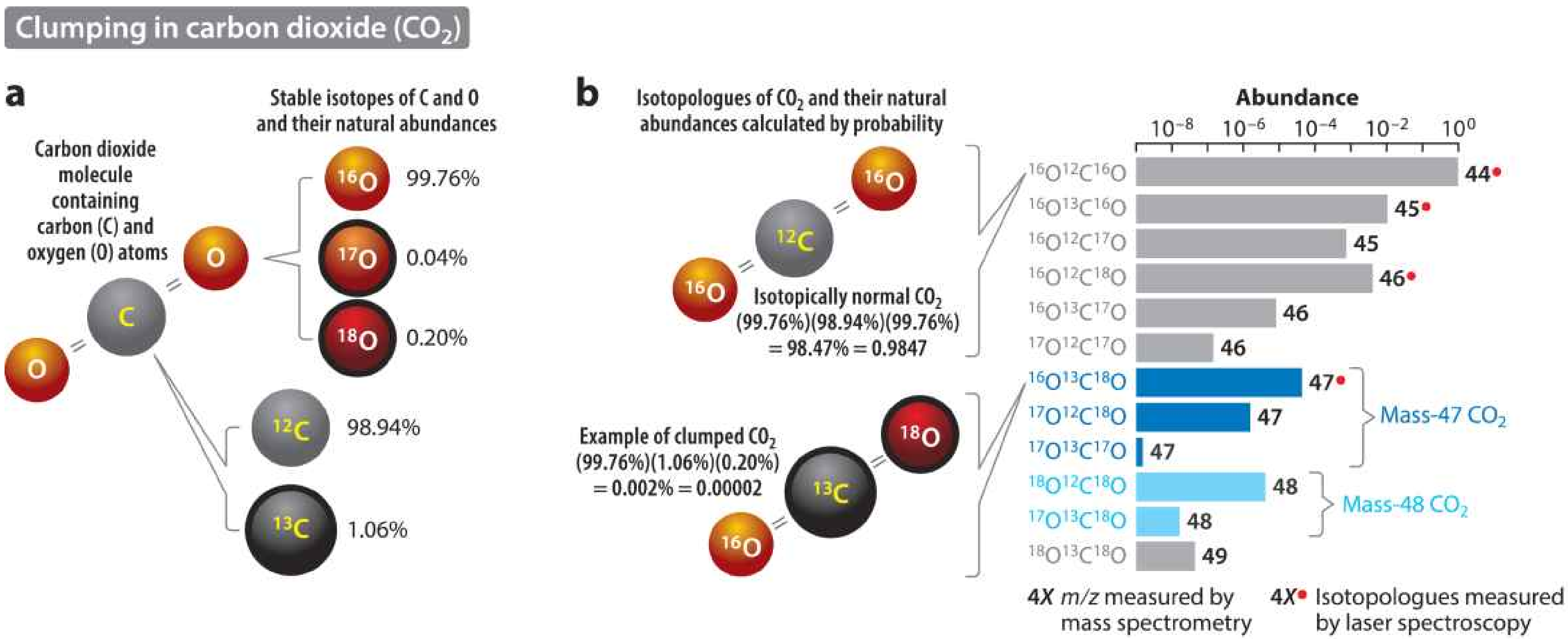


CENOGRID
Westerhold et al. (2020), Science

Clumped Isotope Thermometer

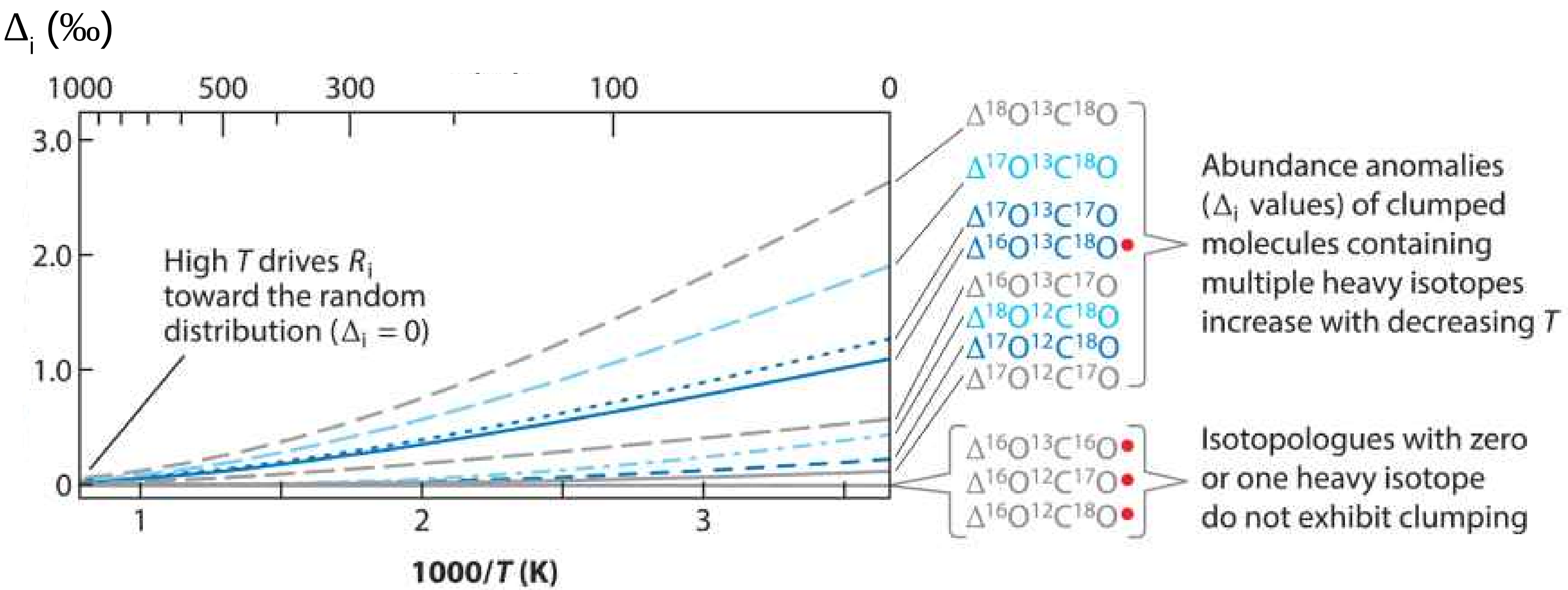
Hillaire-Marcel and De Vernal (2007),
Proxies in late cenozoic paleoceanography

Clumped Isotopes



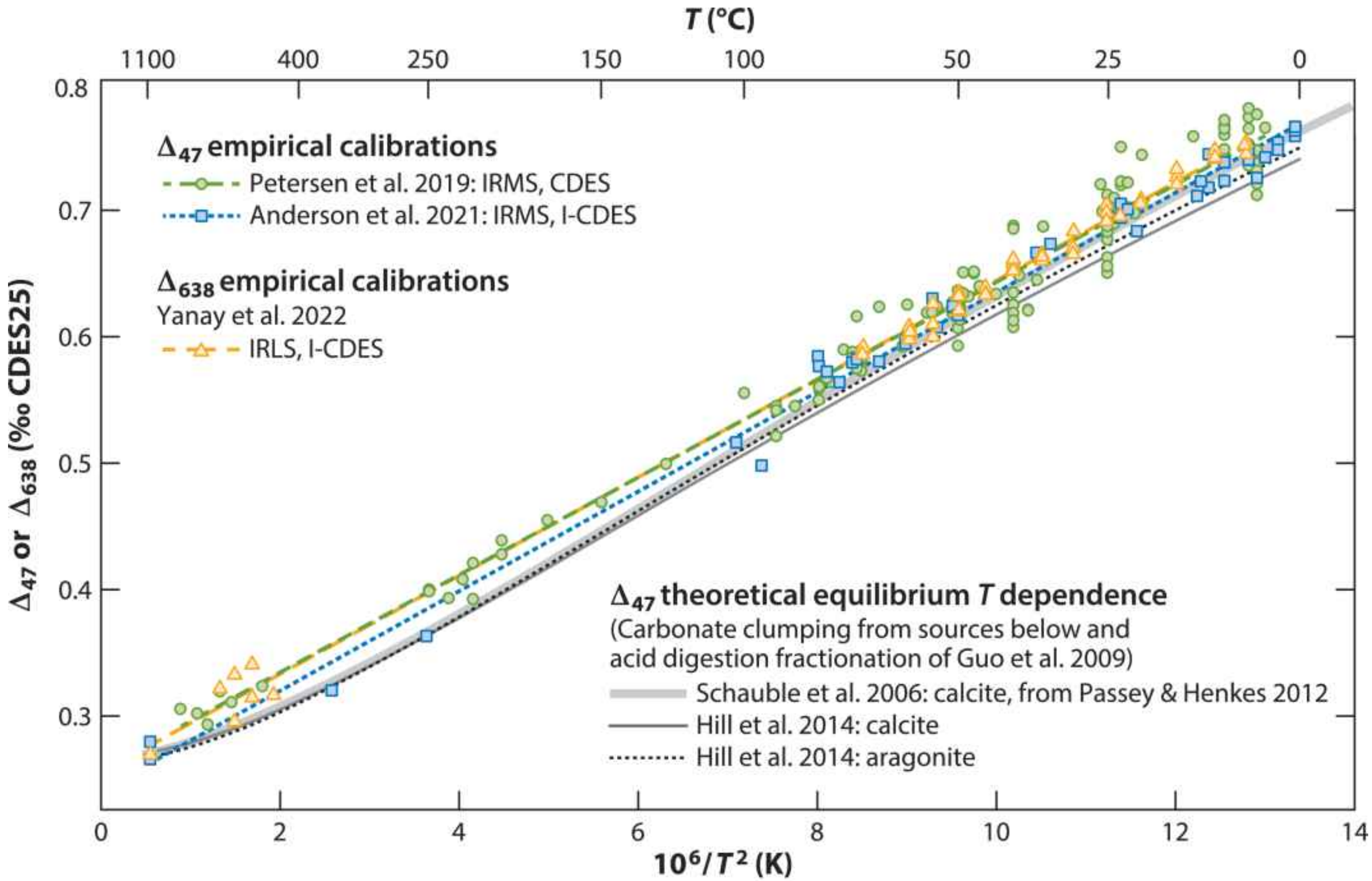
Huntington and Petersen (2023), Annual Review of Earth and Planetary Sciences

Clumped Isotopes



Huntington and Petersen (2023),
Annual Review of Earth and Planetary Sciences

Clumped Isotopes



Huntington KW, Petersen SV. 2023
Annu. Rev. Earth Planet. Sci. 51:611–41

Clumped Isotopes

- very accurate
- few secondary effects

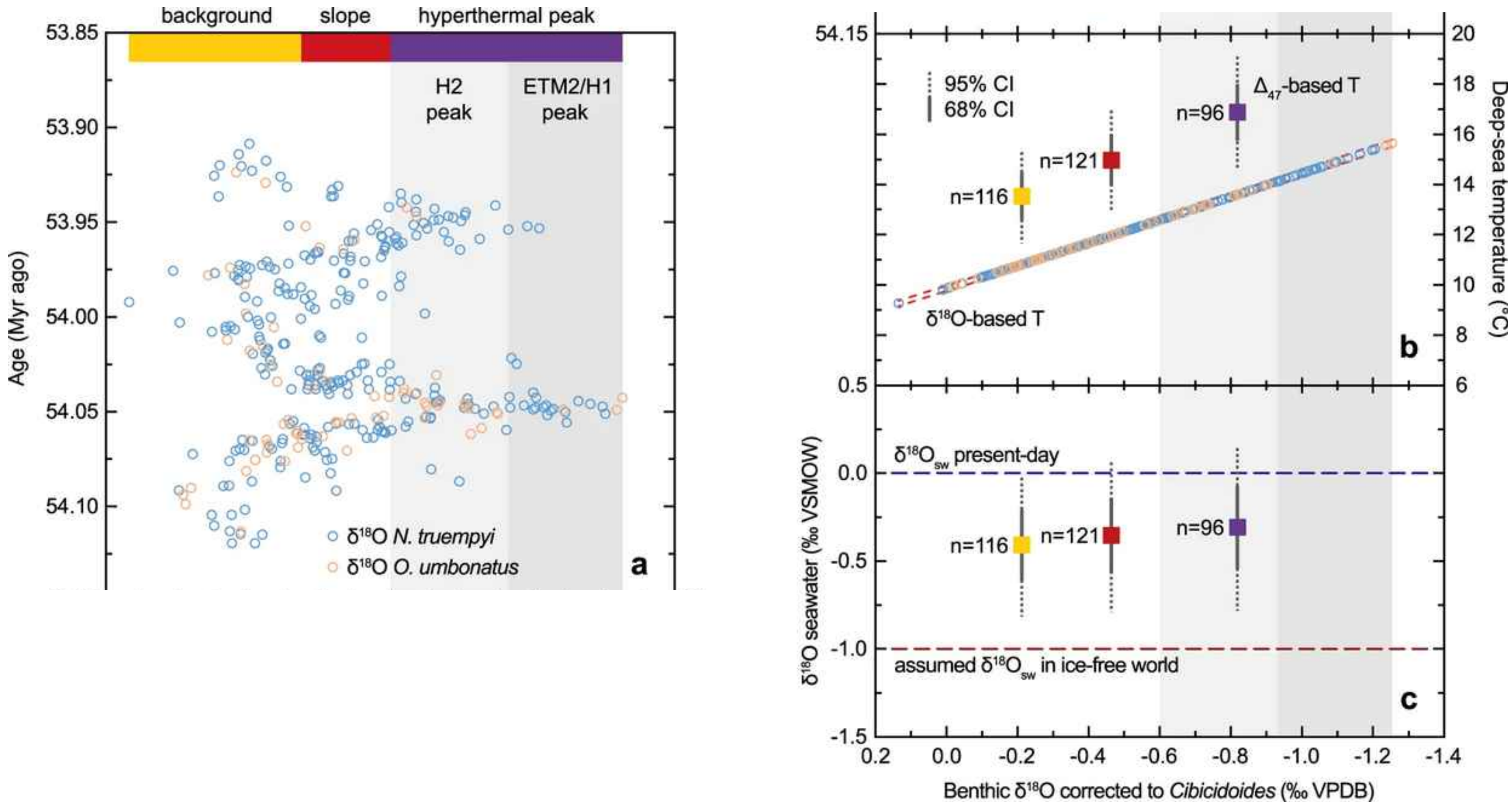
BUT

- low precision → many replicates
- large samples (few mg)

→ costly sample analysis

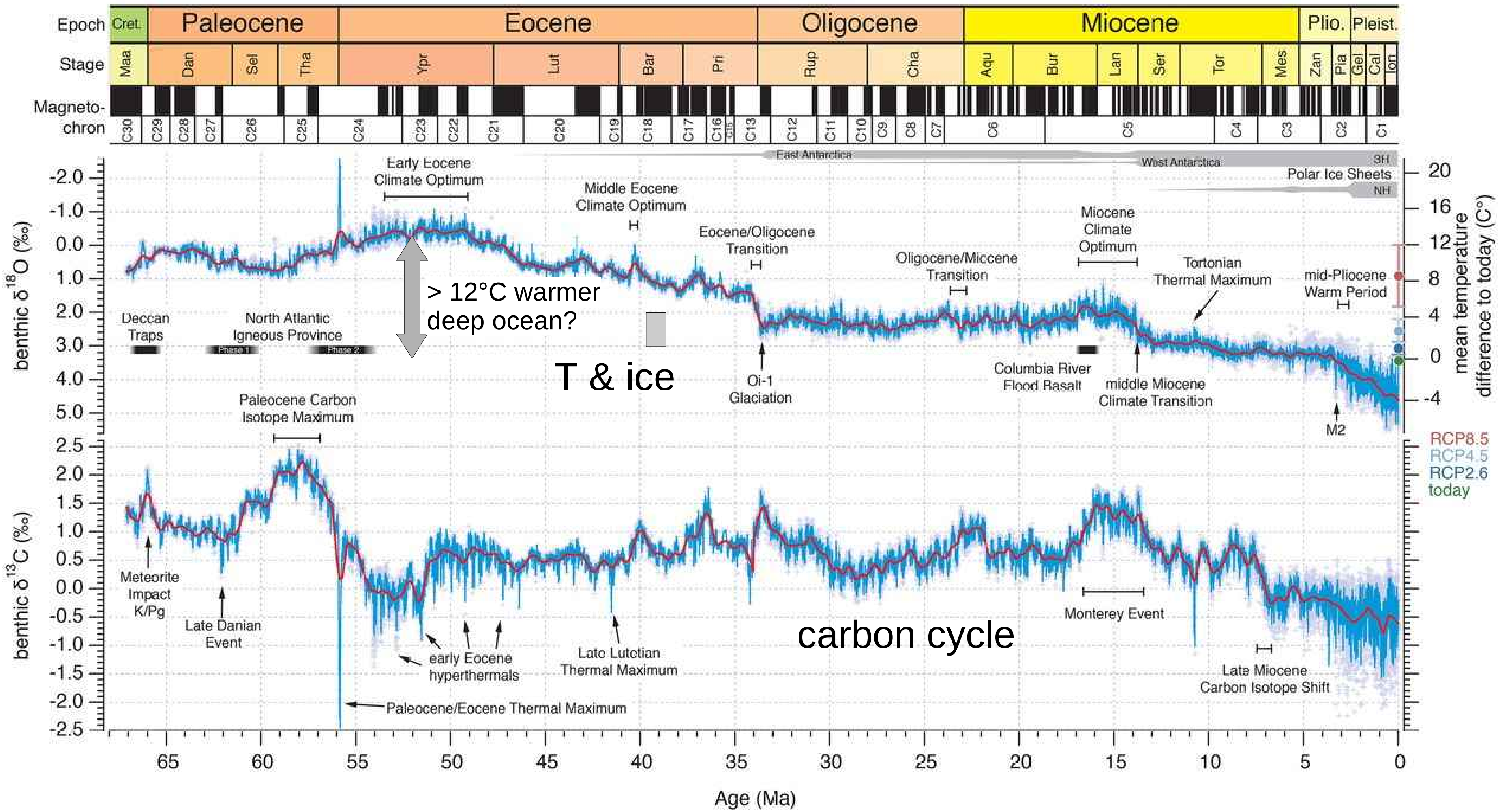
Hillaire-Marcel and De Vernal (2007), Proxies in late cenozoic paleoceanography

Clumped isotope temperatures



Agterhuis et al. (2022)
Communications Earth & Environment

Cenozoic Climate

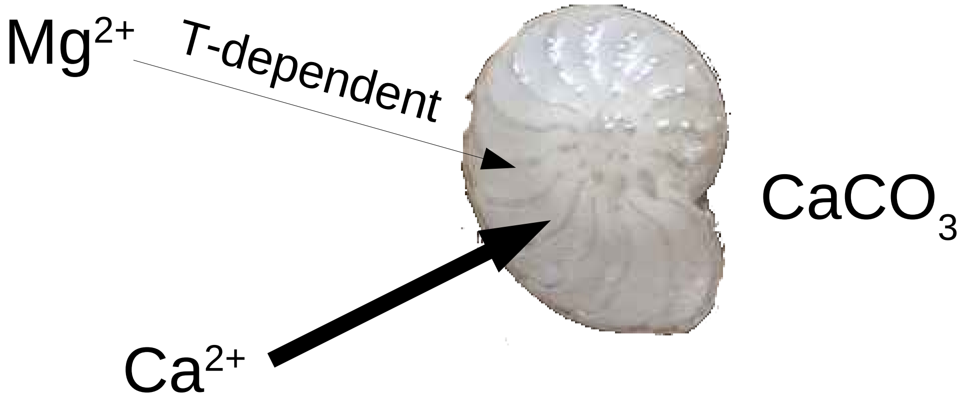


CENOGRID
Westerhold et al. (2020), Science

Mg/Ca paleothermometer

Mg/Ca paleothermometer

Mg/Ca in foraminifera



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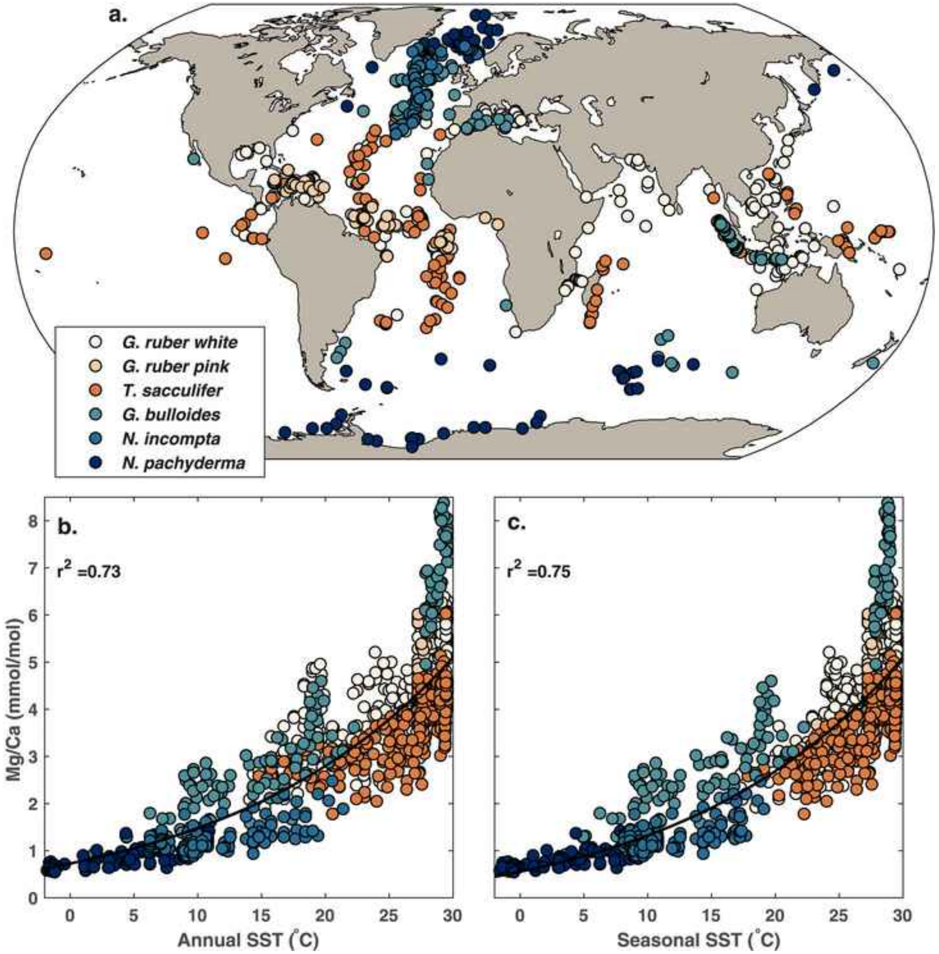
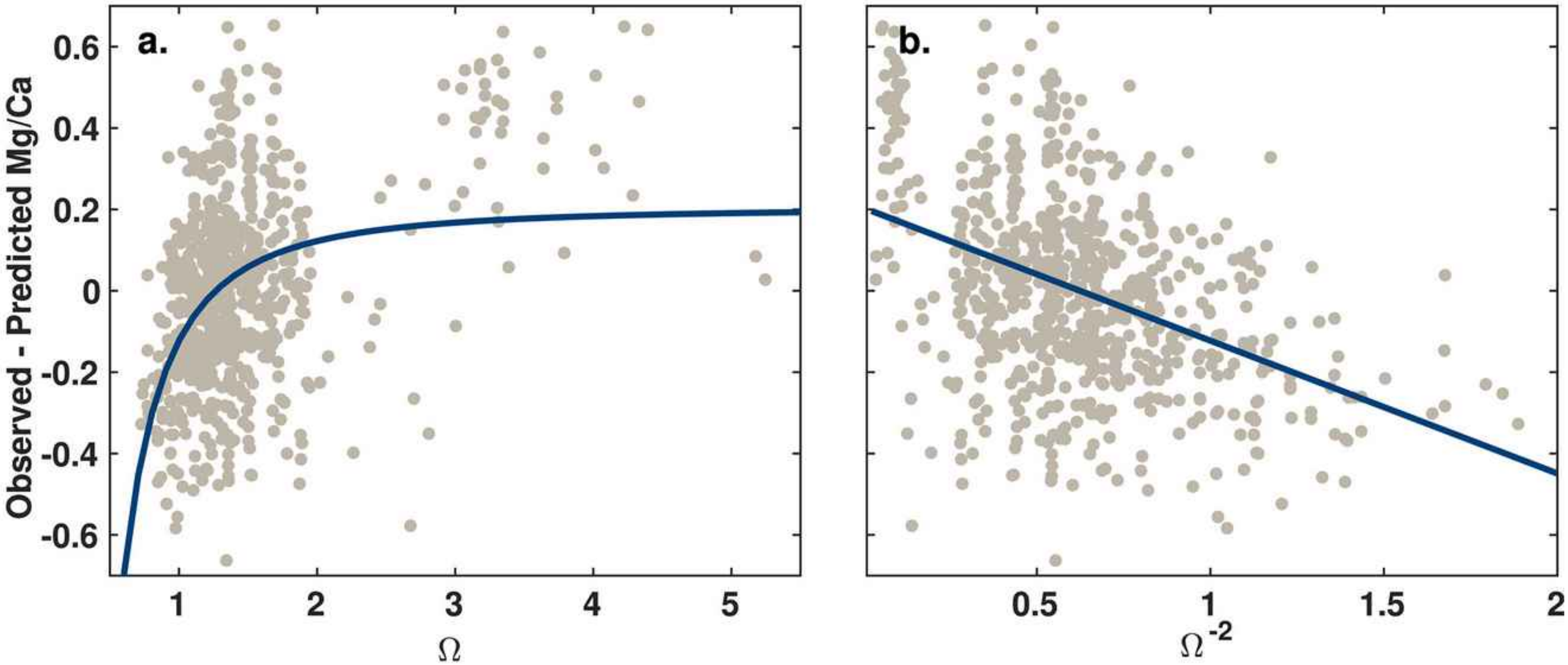


Tierney et al. (2019)
Paleoceanography and
Paleoclimatology

Mg/Ca paleothermometer

Mg/Ca in foraminifera



Tierney et al. (2019)
Paleoceanography and
Paleoclimatology

Mg/Ca paleothermometer

Mg/Ca in foraminifera

- records past water temperature
- species-specific calibrations
- Mg/Ca in seawater – dependent
- Ω – dependent
- precision typically ~ 1°C

TEX86 paleothermometer

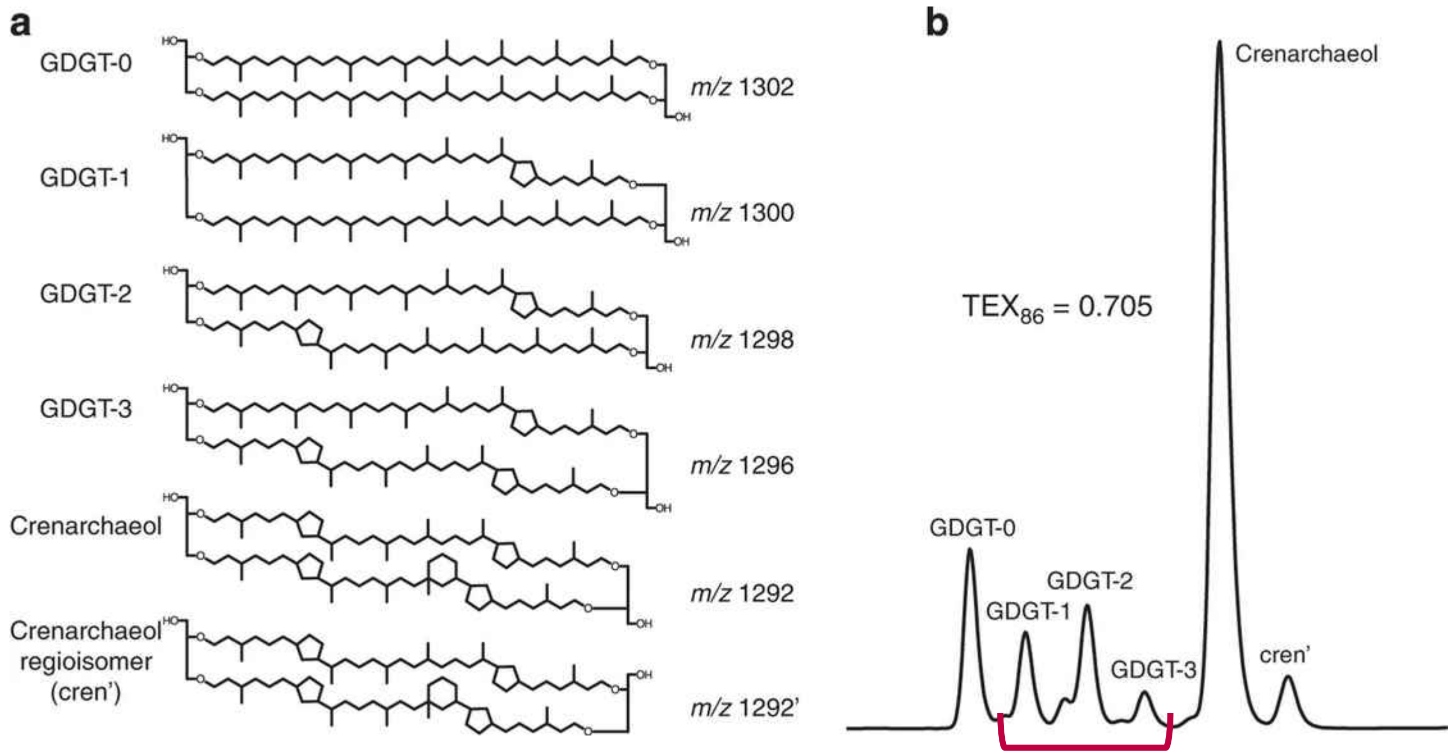
TEX86 paleothermometer

TEX86 proxy for SST

- based on specific organic molecules from sediments formed by archaea (similar to bacteria)
- the abundance ratio of certain molecules depends on ambient seawater temperatures
- mainly records near-sea surface T

TEX86 paleothermometer

TEX86 proxy for SST

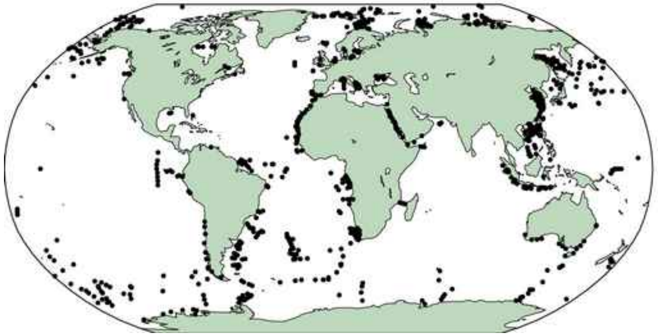


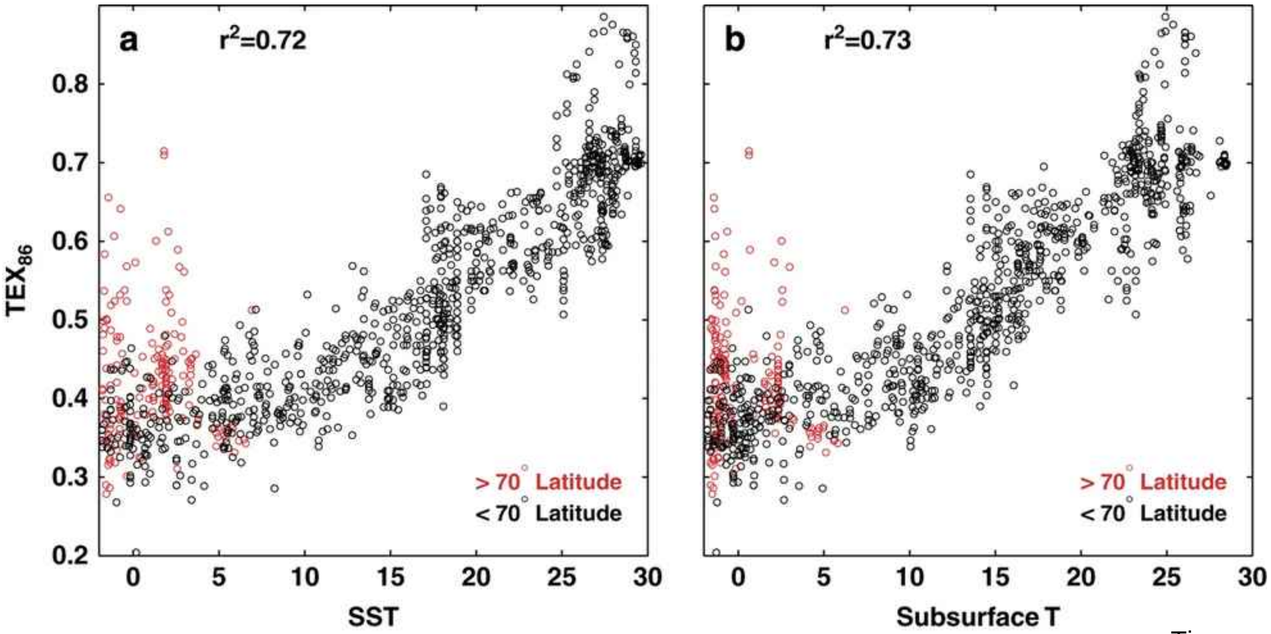
Tierney & Tingley (2015)
Nature Scientific data

GDGT = Glycerol dialkyl glycerol tetraether (lipids)

TEX86 paleothermometer

TEX86 proxy for SST



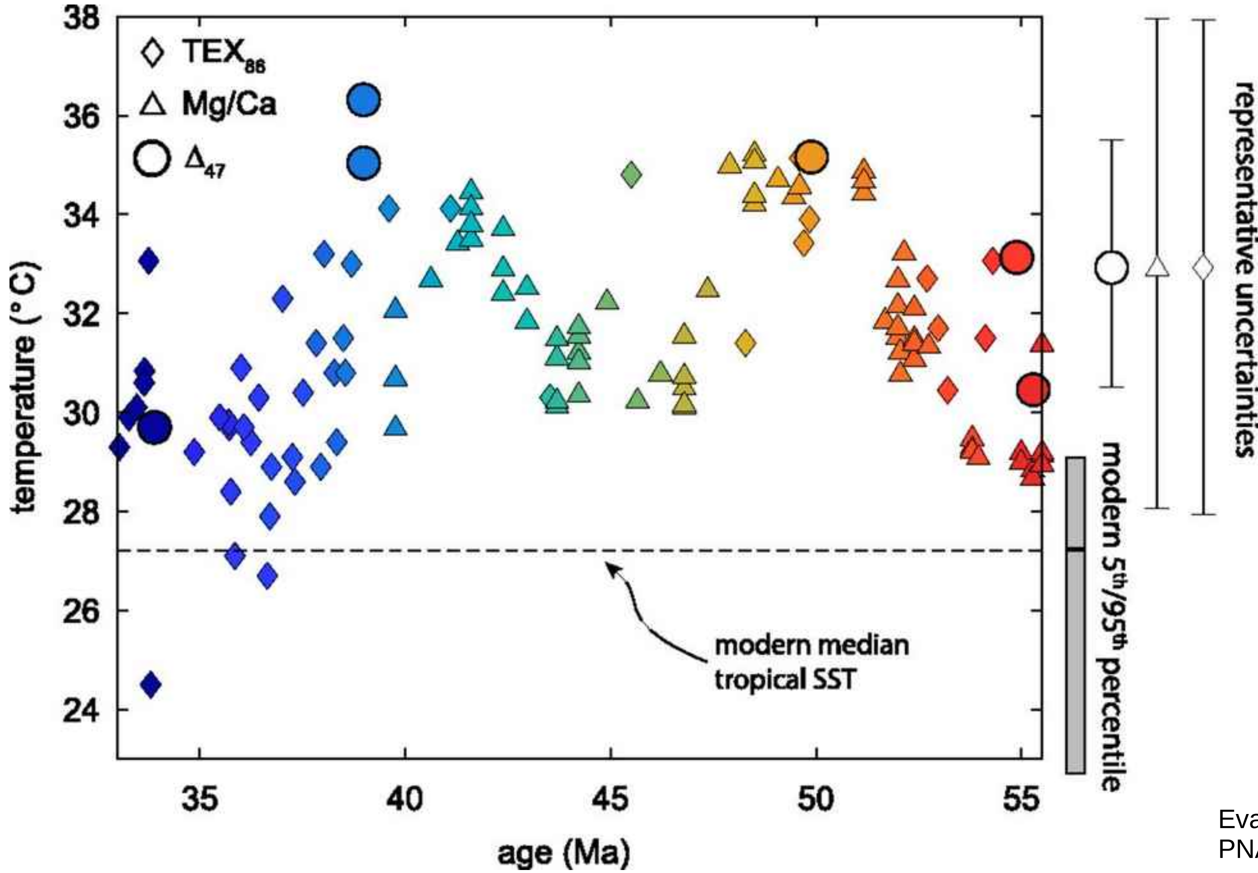


Tierney & Tingley (2015)
Nature Scientific data

Hothouse Climate

Hothouse Climate

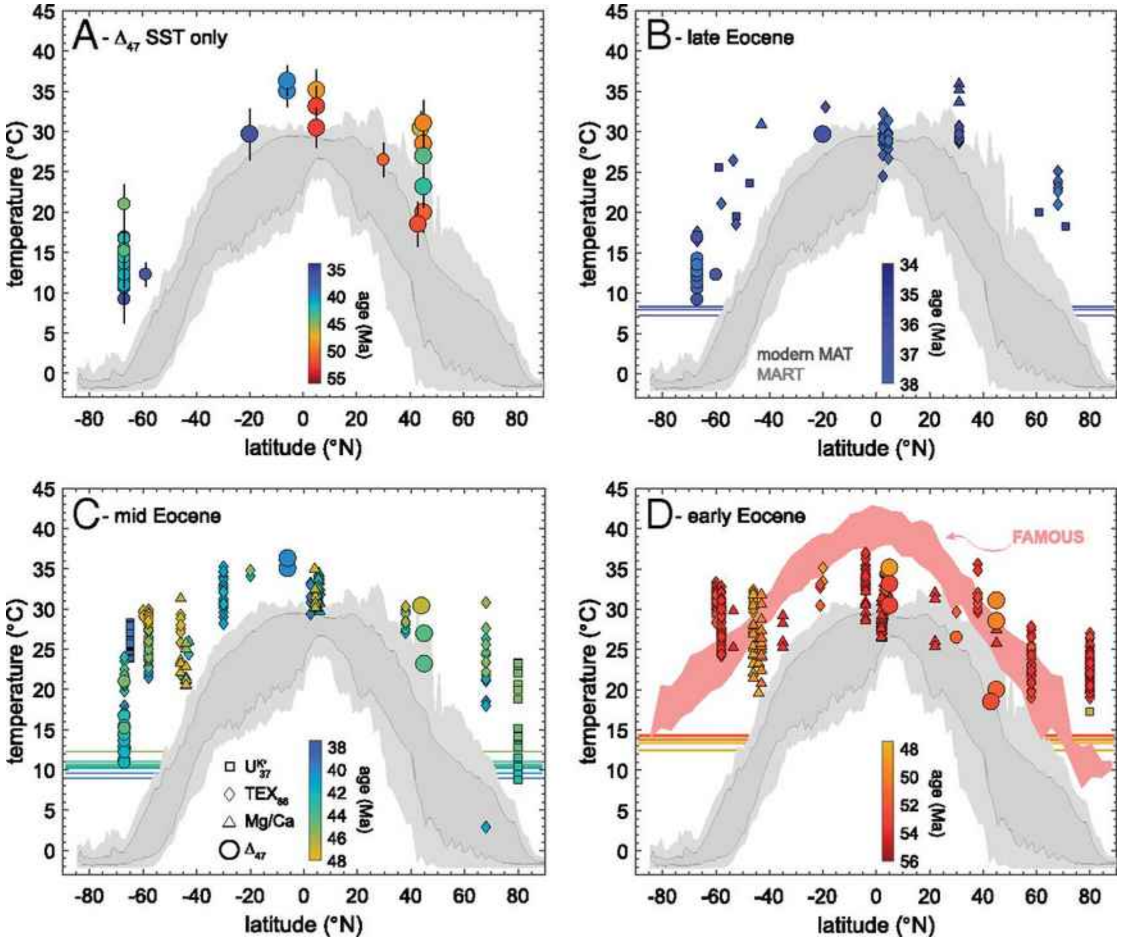
Eocene low latitude sea surface T



Evans et al. (2018)
PNAS

Equable Climate

Eocene latitudinal sea surface T



Evans et al. (2018)
PNAS

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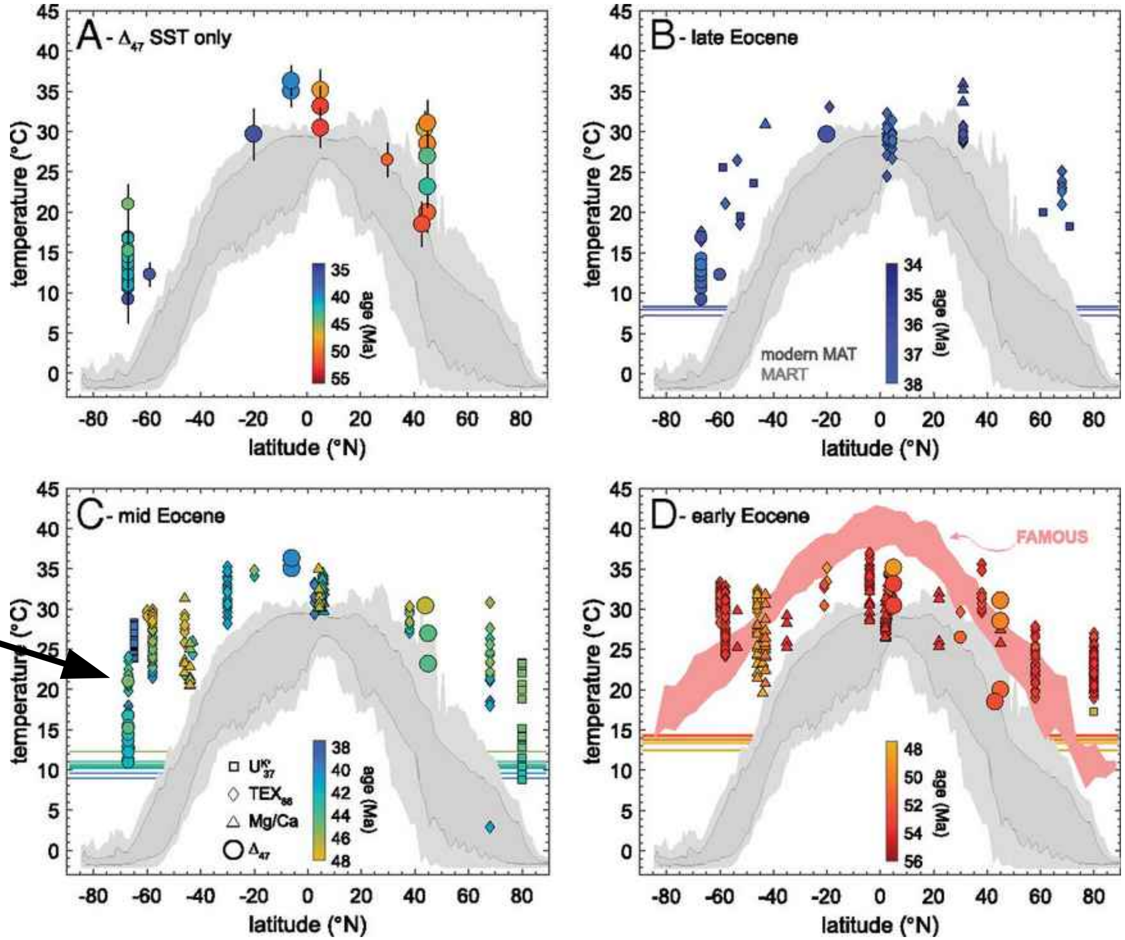
Equable Climate

Eocene latitudinal sea surface T

warm poles!

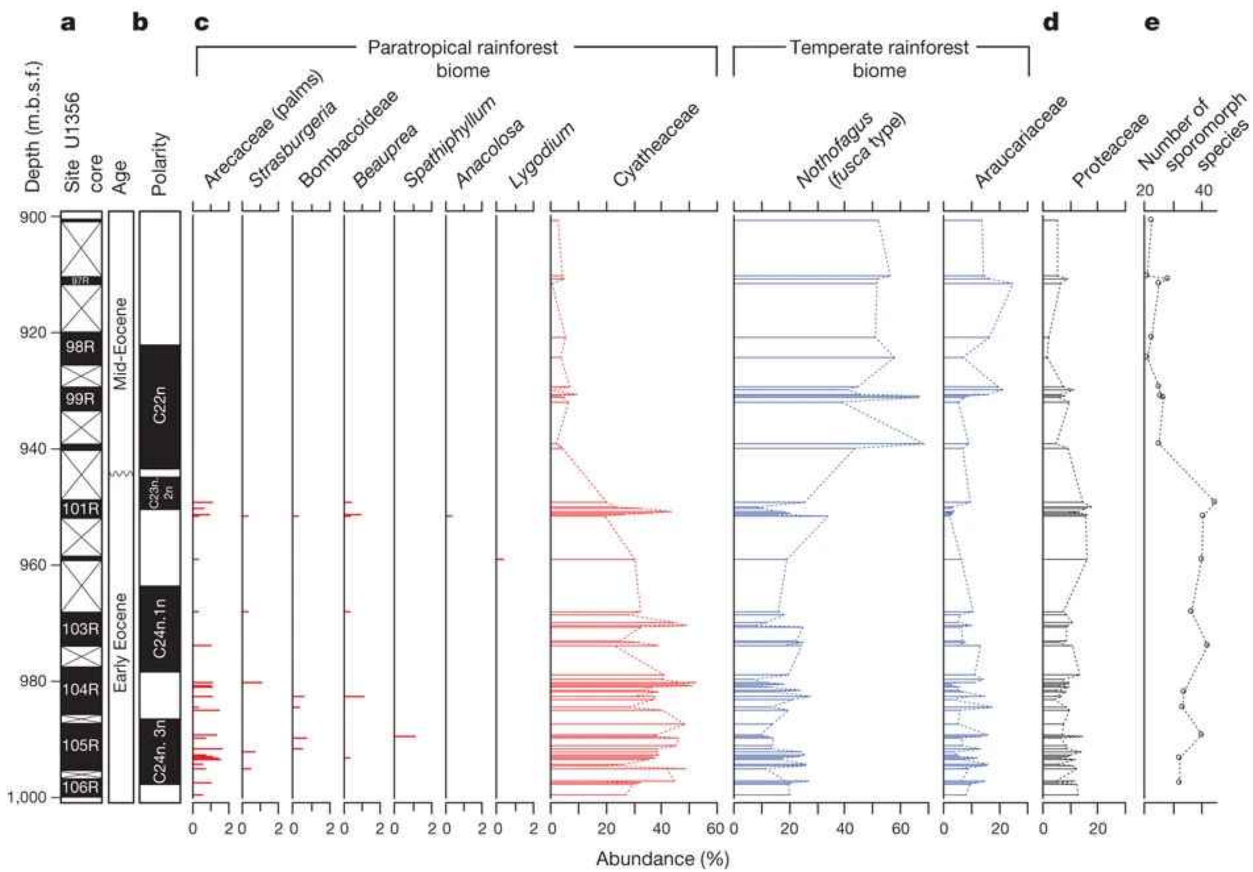
"Equable Climates"



Evans et al. (2018) PNAS

Equable Climate

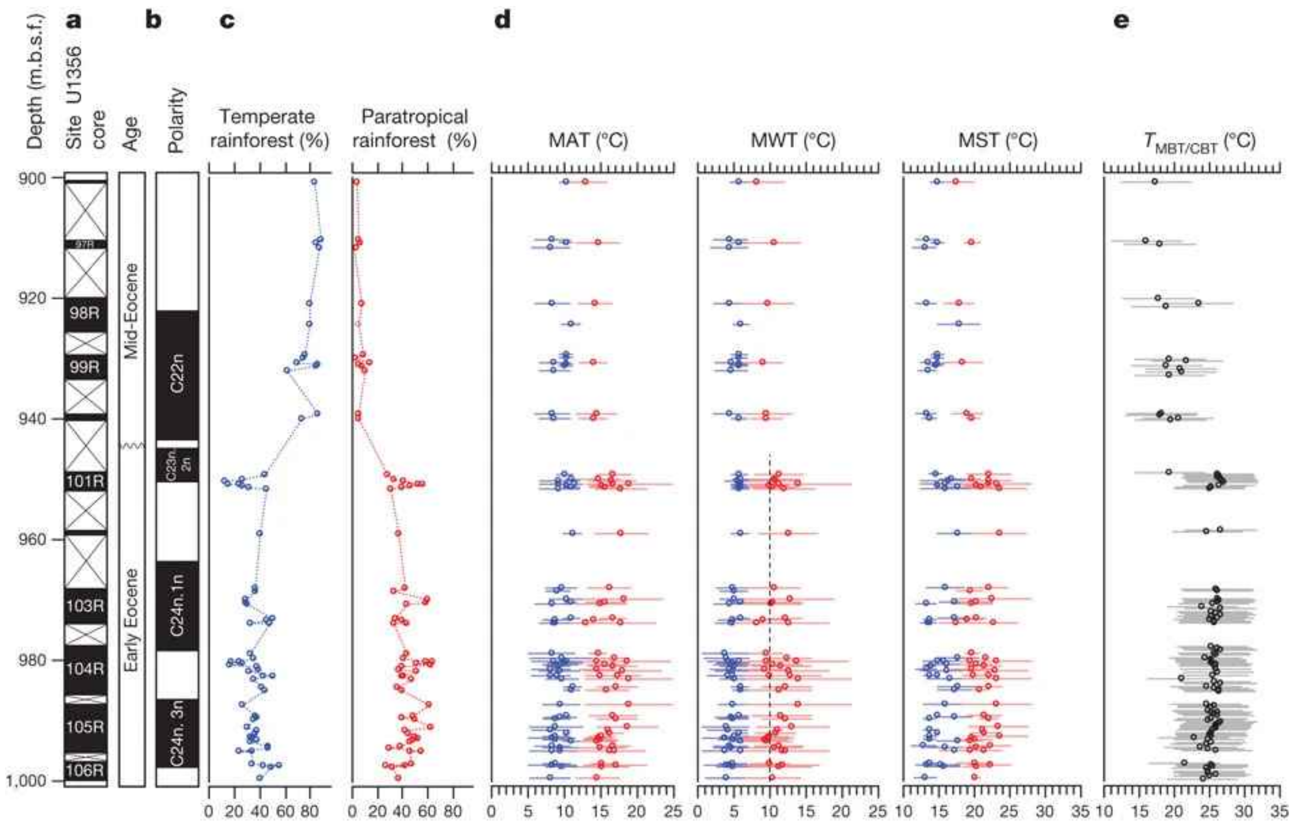
Eocene East Antarctic climate from pollen



Pross et al. (2012)
Nature

Equable Climate

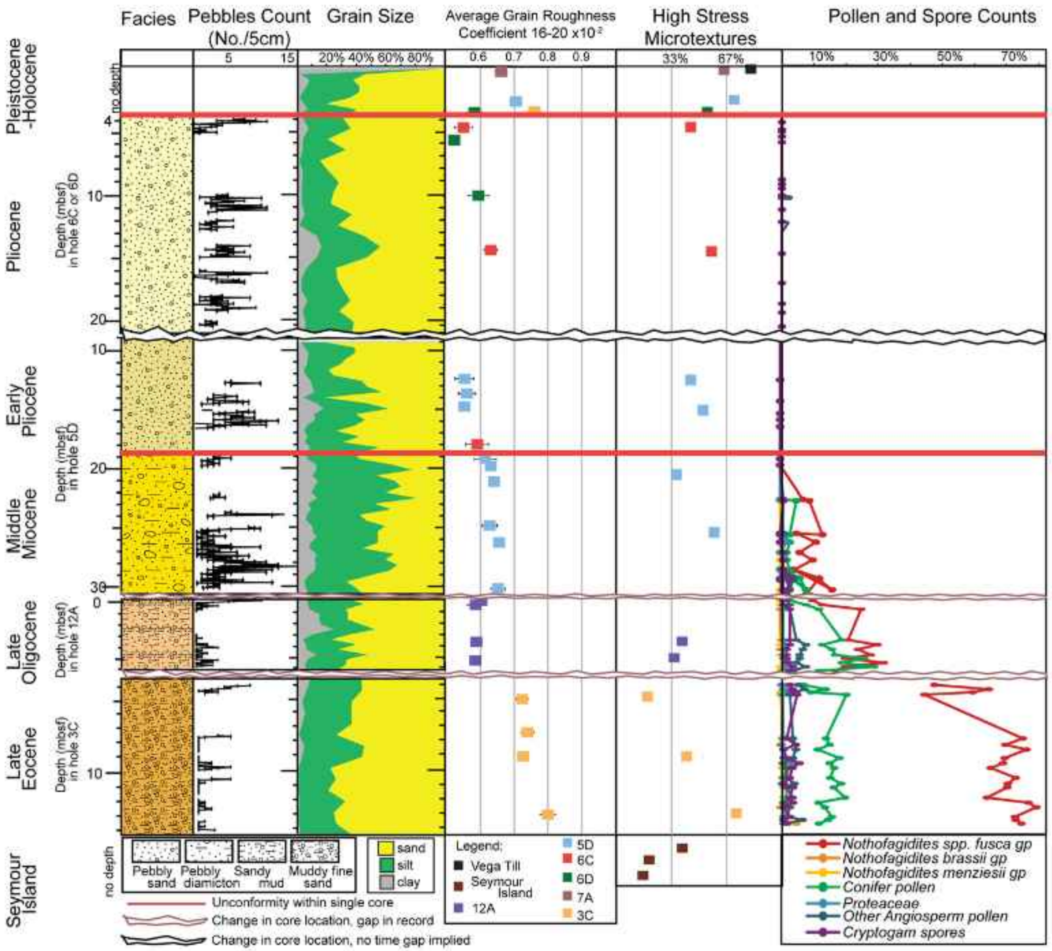
Eocene East Antarctic climate from pollen



Pross et al. (2012) Nature

Equable Climate

Cenozoic West Antarctic climate from pollen

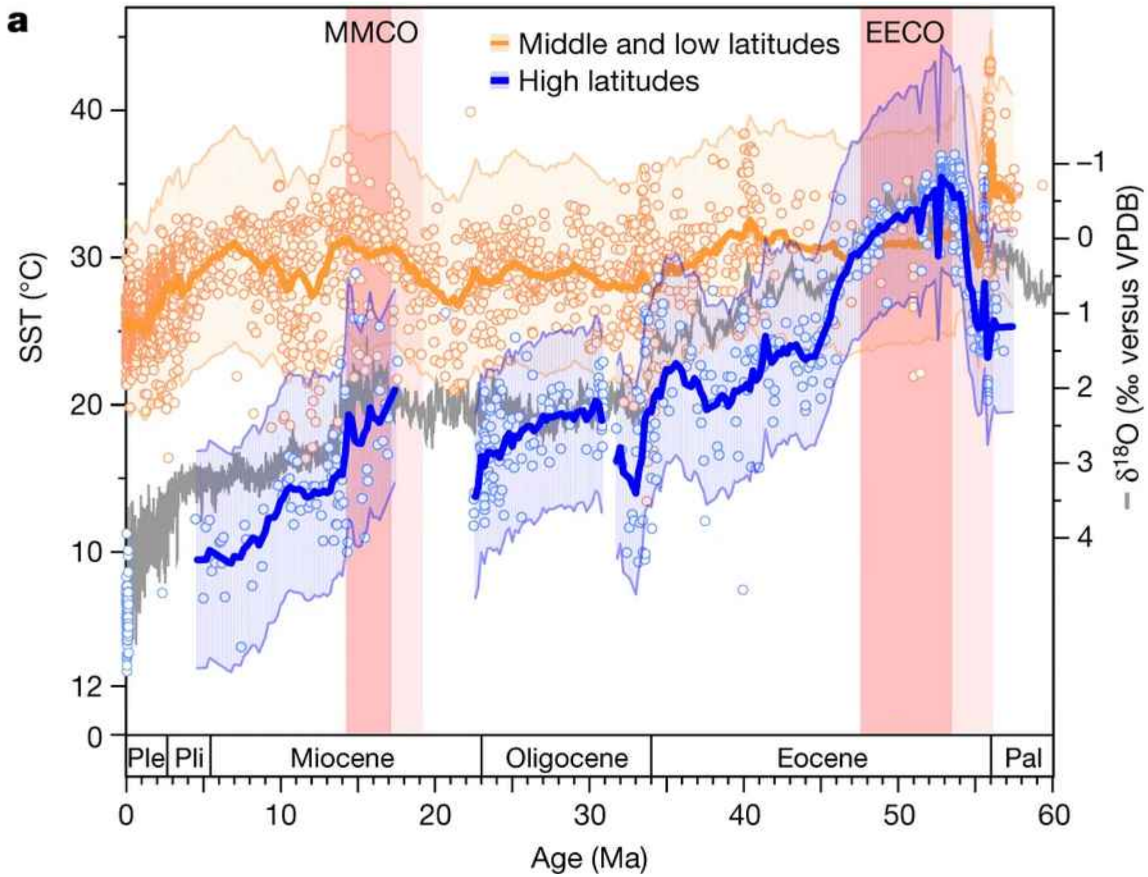


Beech

Anderson et al. (2011) PNAS

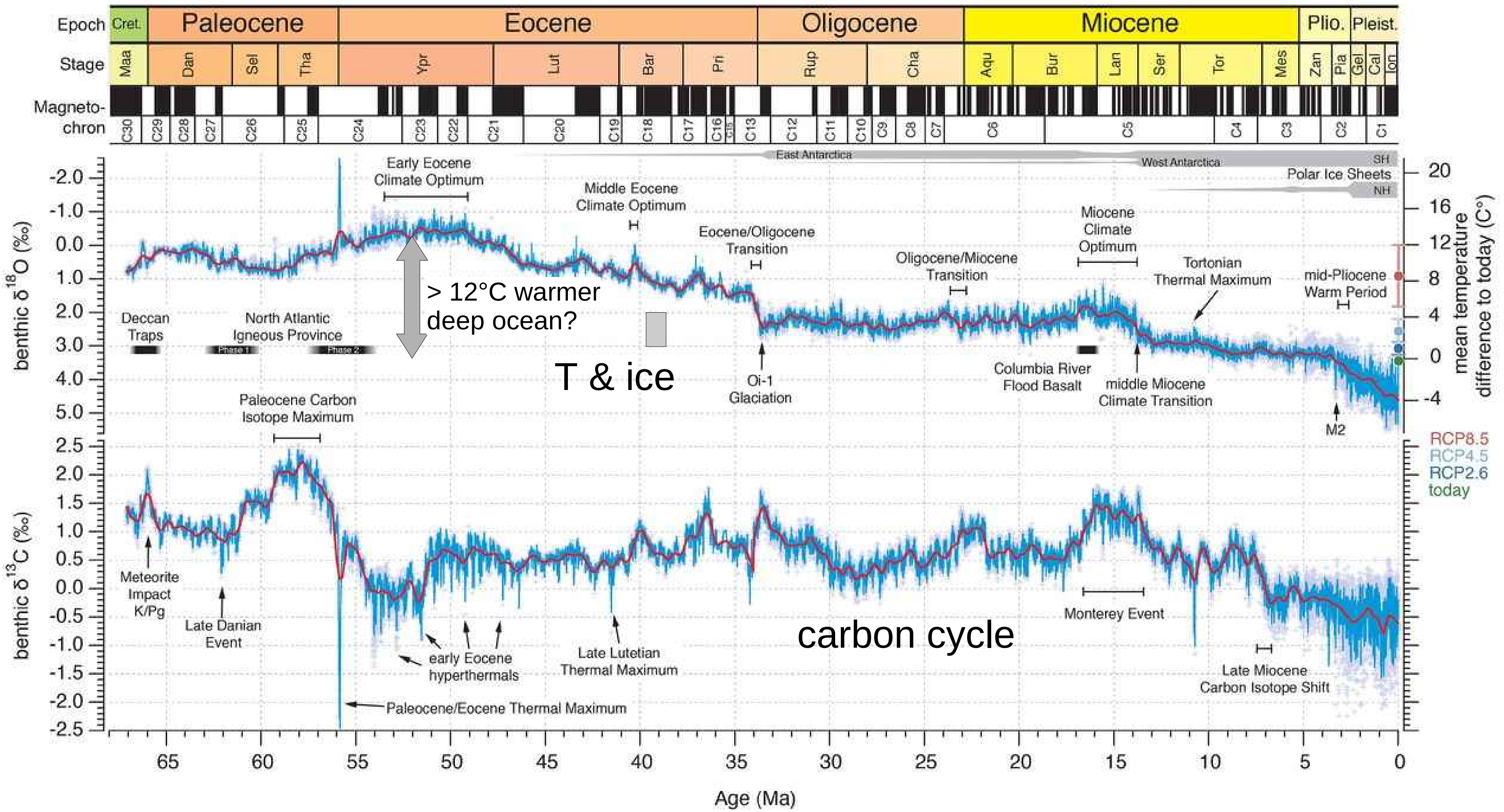
Equable Climate

Evolution of latitudinal temperature gradient



Auderset et al. (2022)
Nature

Equable Climate



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Westerhold et al. (2020), Science

Equable Climate

Causes

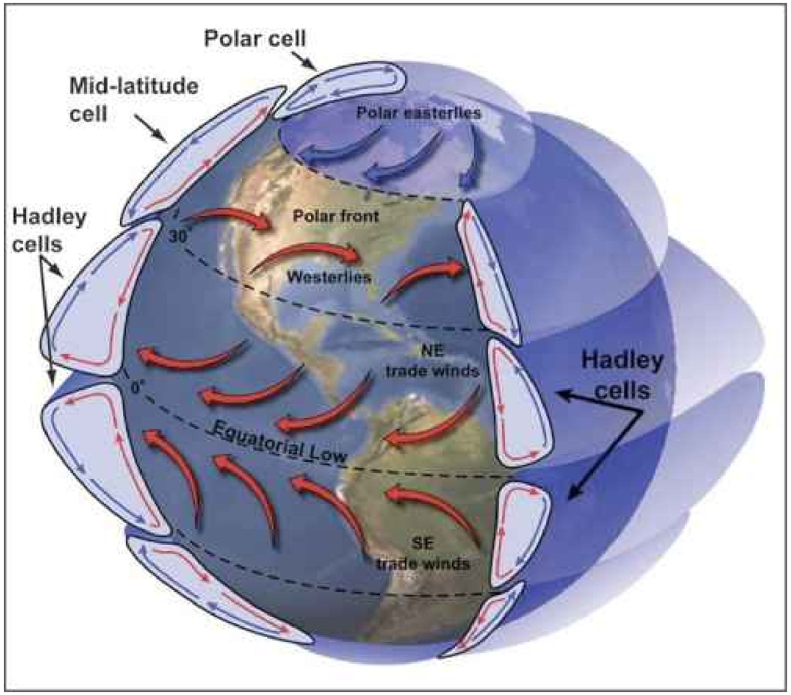
- high altitude cloud cover?

Mark Piana
Harvard University
Equable Climate Dynamics

Equable Climate

Causes

- high altitude cloud cover?
- atmospheric cell change?



Mark Piana
Harvard University
Equable Climate Dynamics

Equable Climate

Causes

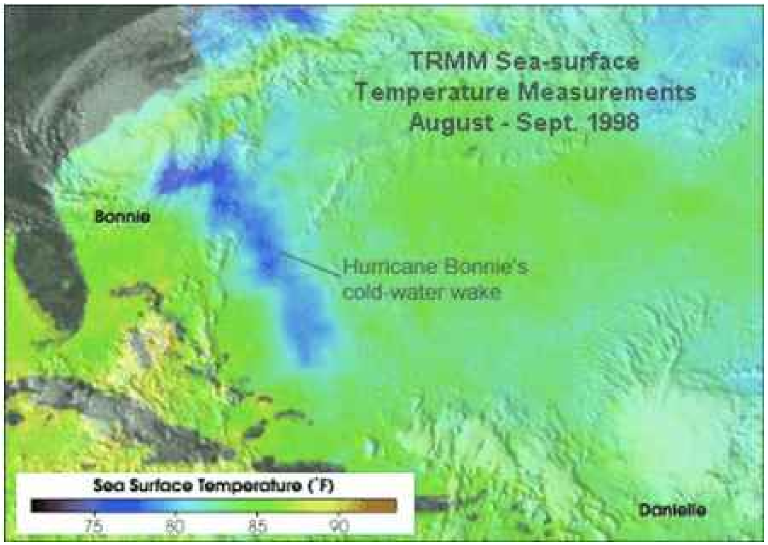
- high altitude cloud cover?
- atmospheric cell change?
- polar stratospheric clouds?

Mark Piana
Harvard University
Equable Climate Dynamics

Equable Climate

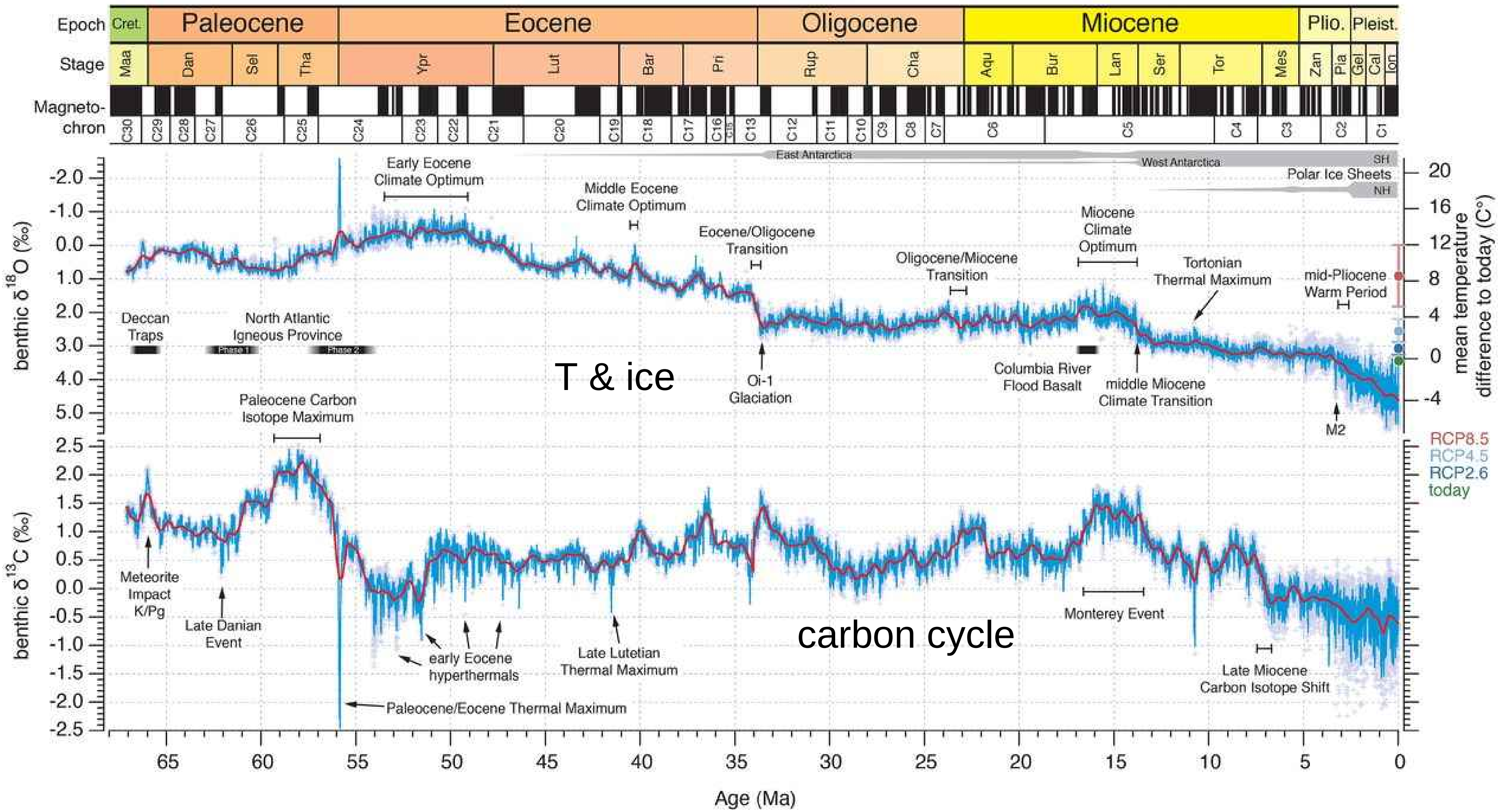
Causes

- high altitude cloud cover?
- atmospheric cell change?
- polar stratospheric clouds?
- cyclone ocean mixing?



Mark Piana
Harvard University
Equable Climate Dynamics

Cenozoic Climate



CENOGRID
Westerhold et al. (2020), Science

Carbon Isotopes

Hillaire-Marcel and De Vernal (2007),
Proxies in late cenozoic paleoceanography

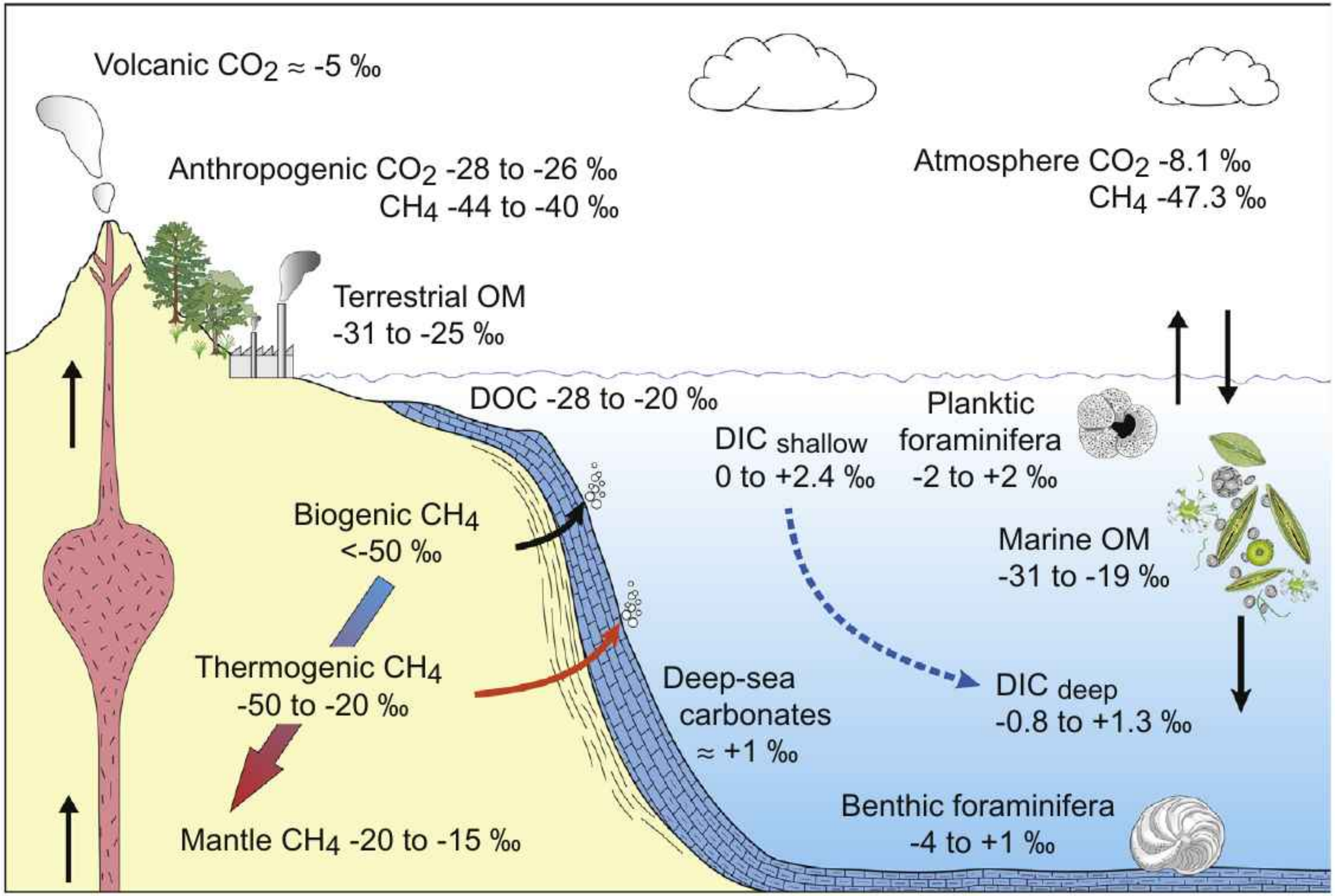
Carbon Isotopes

- C & O isotopes can be measured from $CaCO_3$
- C also in organics or gas
- ^{12}C – 98.9 %

  ^{13}C – 1.1 %
- photosynthesis discriminates against ^{13}C with $\alpha \sim 1.25$

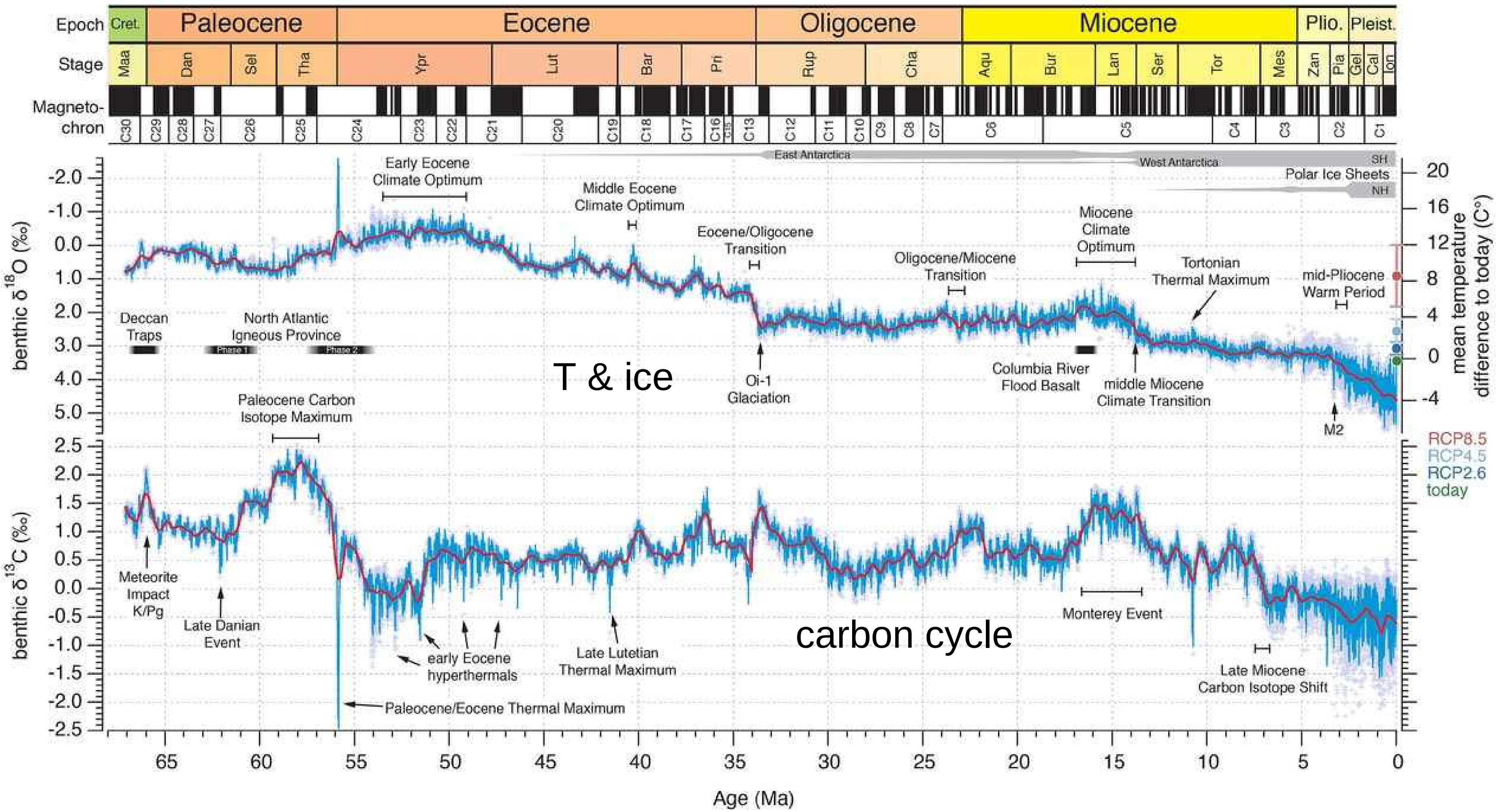
Hillaire-Marcel and De Vernal (2007),
Proxies in late cenozoic paleoceanography

Carbon Isotopes



Mackensen & Schmiedl (2019)
Earth-Science Revies

Cenozoic Climate



CENOGRID
Westerhold et al. (2020), Science

PETM

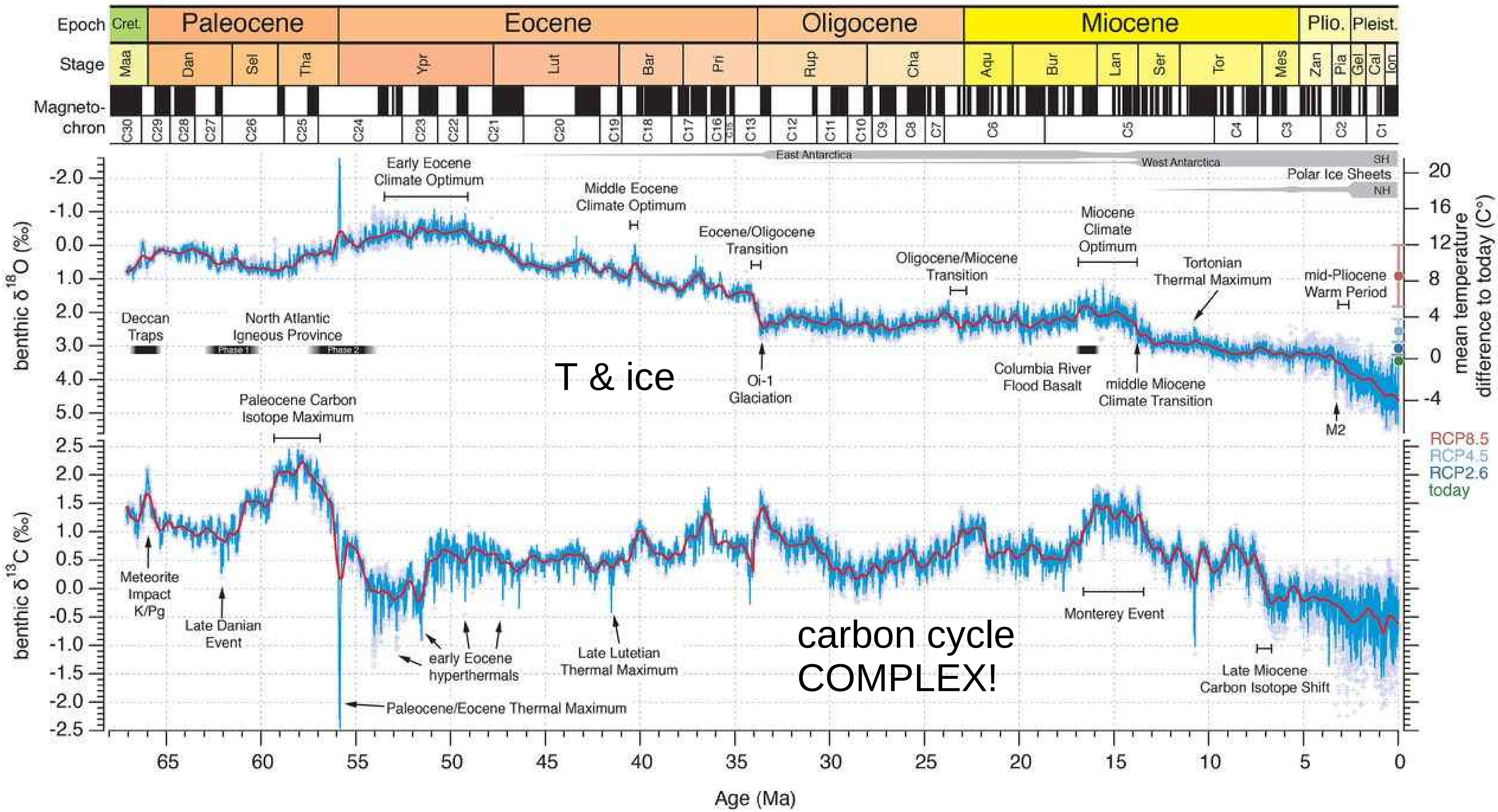
Paleocene–Eocene Thermal Maximum

caused by massive input of greenhouse gases (CO_2 and/or CH_4)

possible causes:

- submarine methane hydrates
- uplift and weathering of marine shelves
- warming-induced death of tropical plants (due to photorespiration)
- North Atlantic volcanism
- permafrost thaw

Cenozoic Climate



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CENOGRID
Westerhold et al. (2020), Science

Boron Isotopes

Boron Isotopes

boron species in seawater:

$B(OH_3)$ und $B(OH)_4^-$

^{10}B – 19.65 %

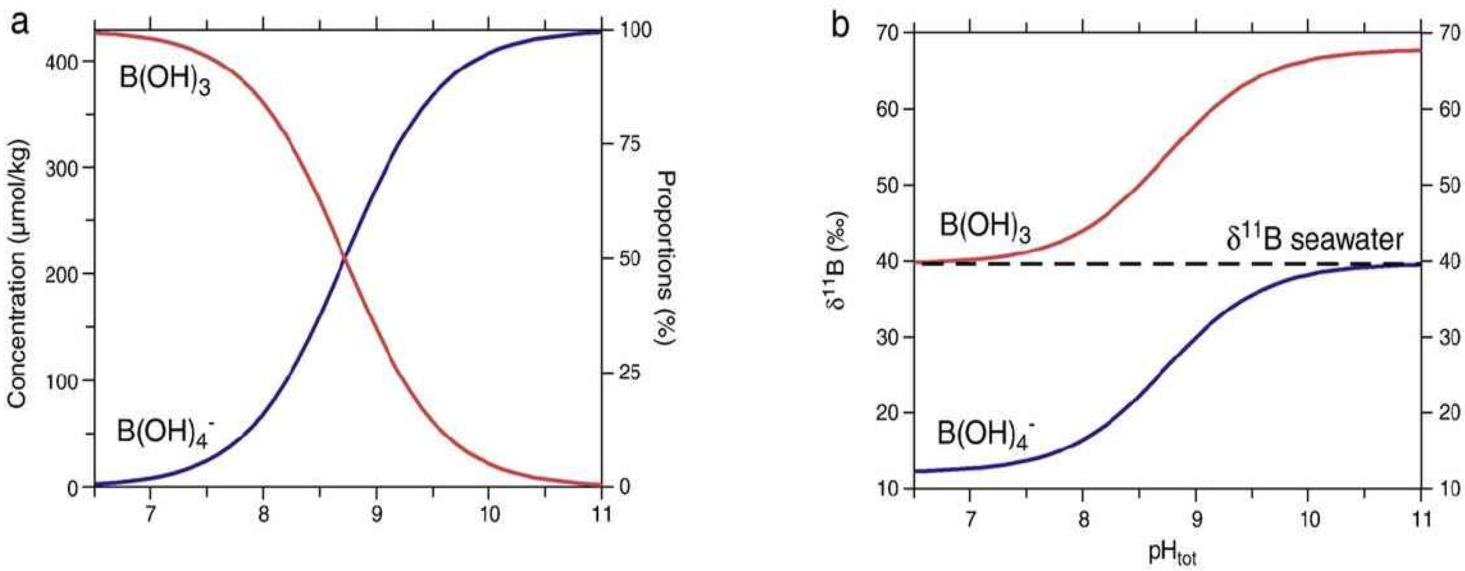
^{11}B – 80.35 %

$$\delta^{11}B(‰) = \left[\left(\frac{^{11}B/^{10}B_{sample}}{^{11}B/^{10}B_{NIST951}}\right) - 1\right] \times 1000.$$

- B is fractionated between the two species
- $B(OH)_4^-$ is built into the shells of foraminifera

Boron Isotopes

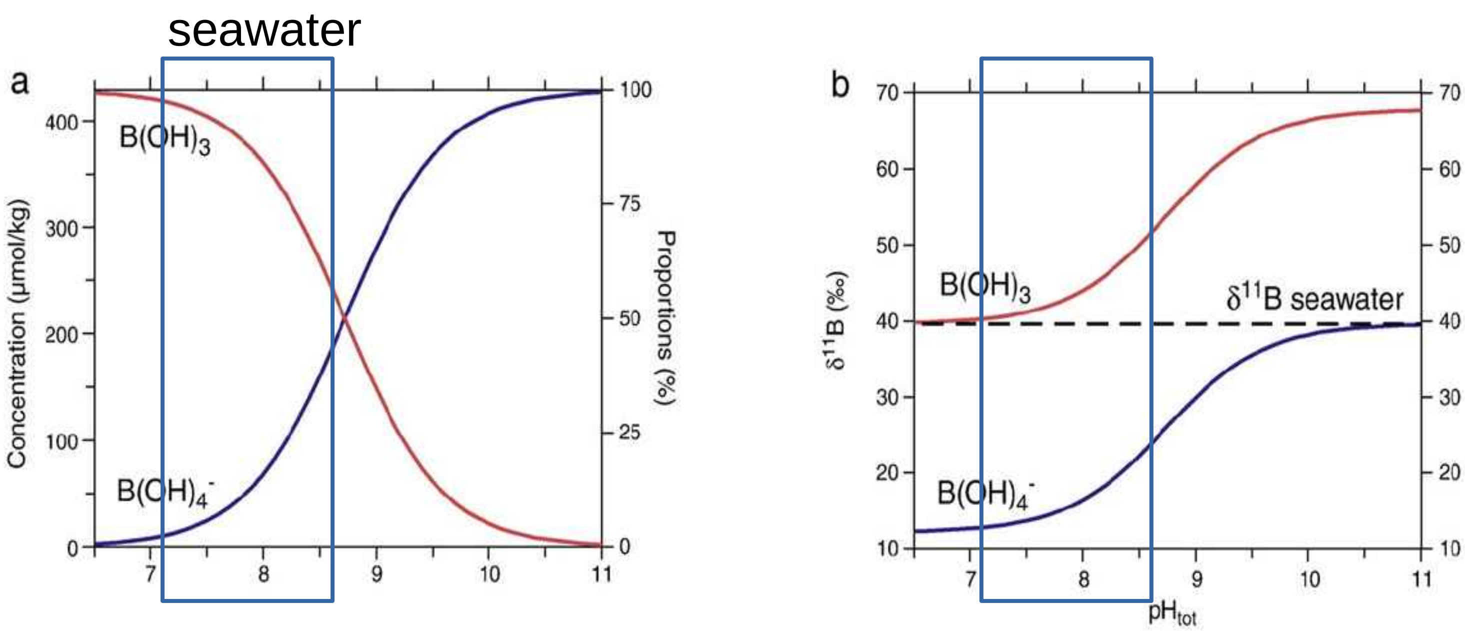
boron species in seawater:



Rae et al. (2011)
Earth and Planetary Science Letters

Boron Isotopes

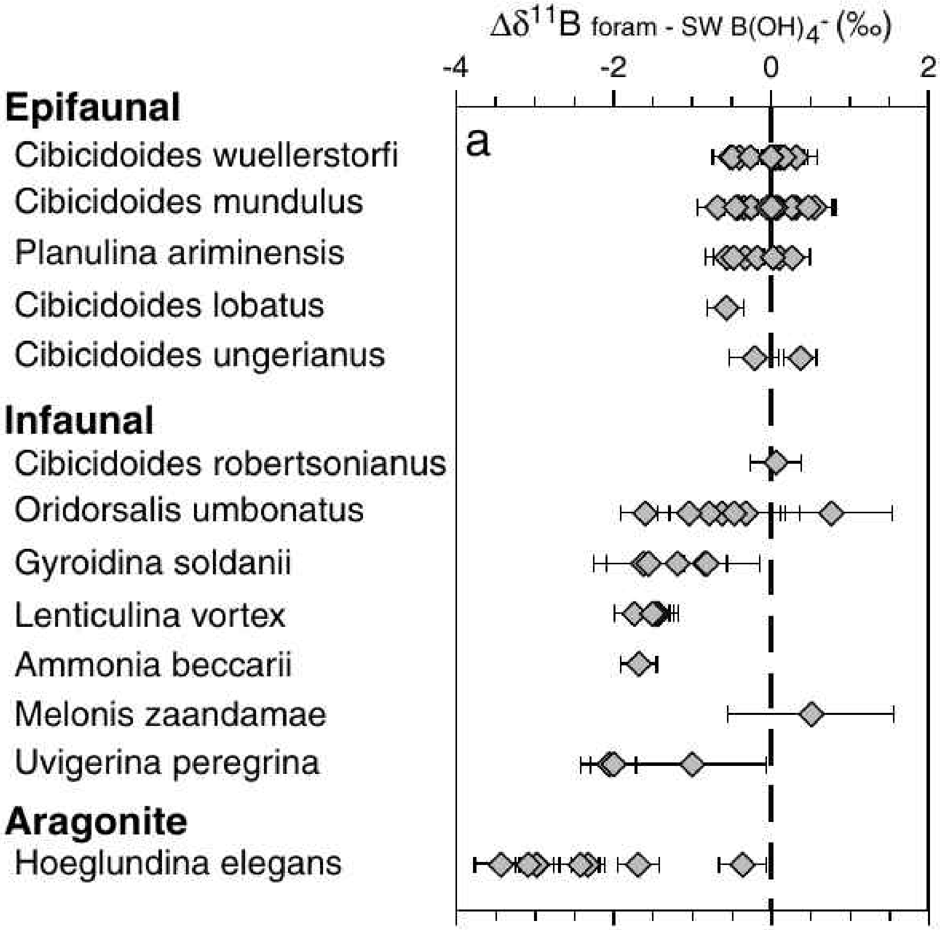
boron species in seawater:



Rae et al. (2011)
Earth and Planetary Science Letters

Boron Isotopes

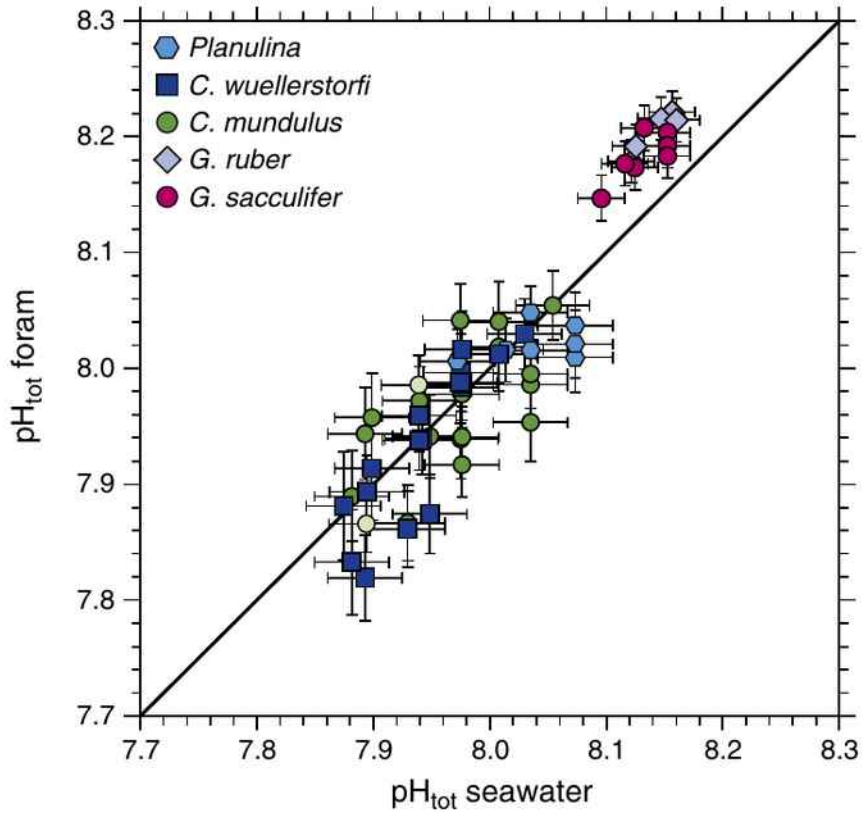
boron isotopes in benthic foraminifera



Rae et al. (2011)
Earth and Planetary Science Letters

Boron Isotopes

pH reconstructed from foraminifera



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Boron Isotopes

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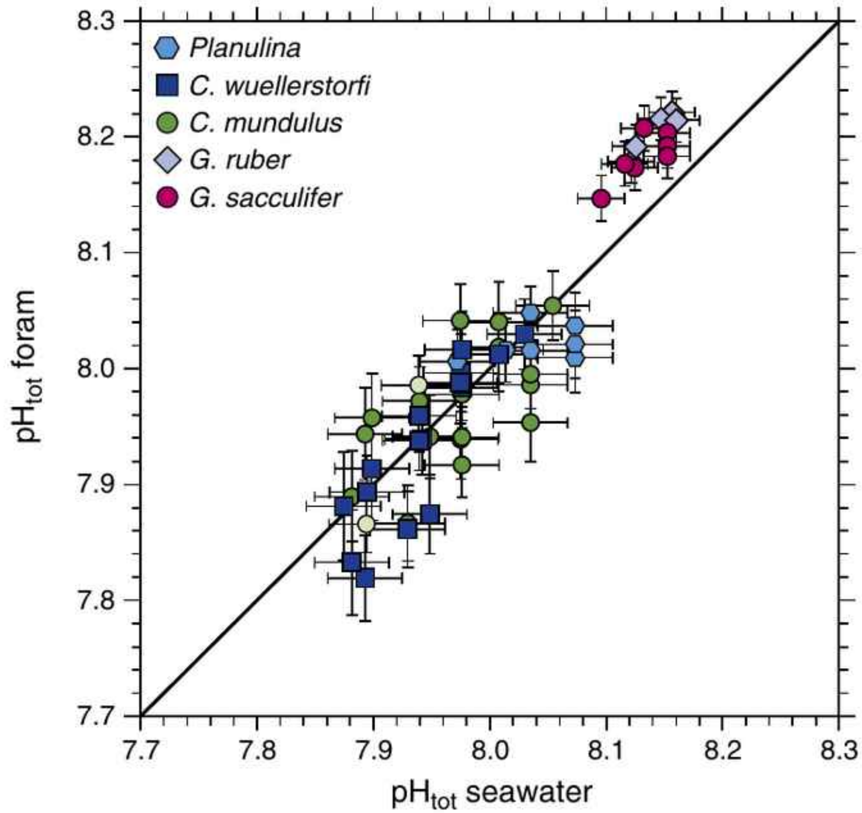
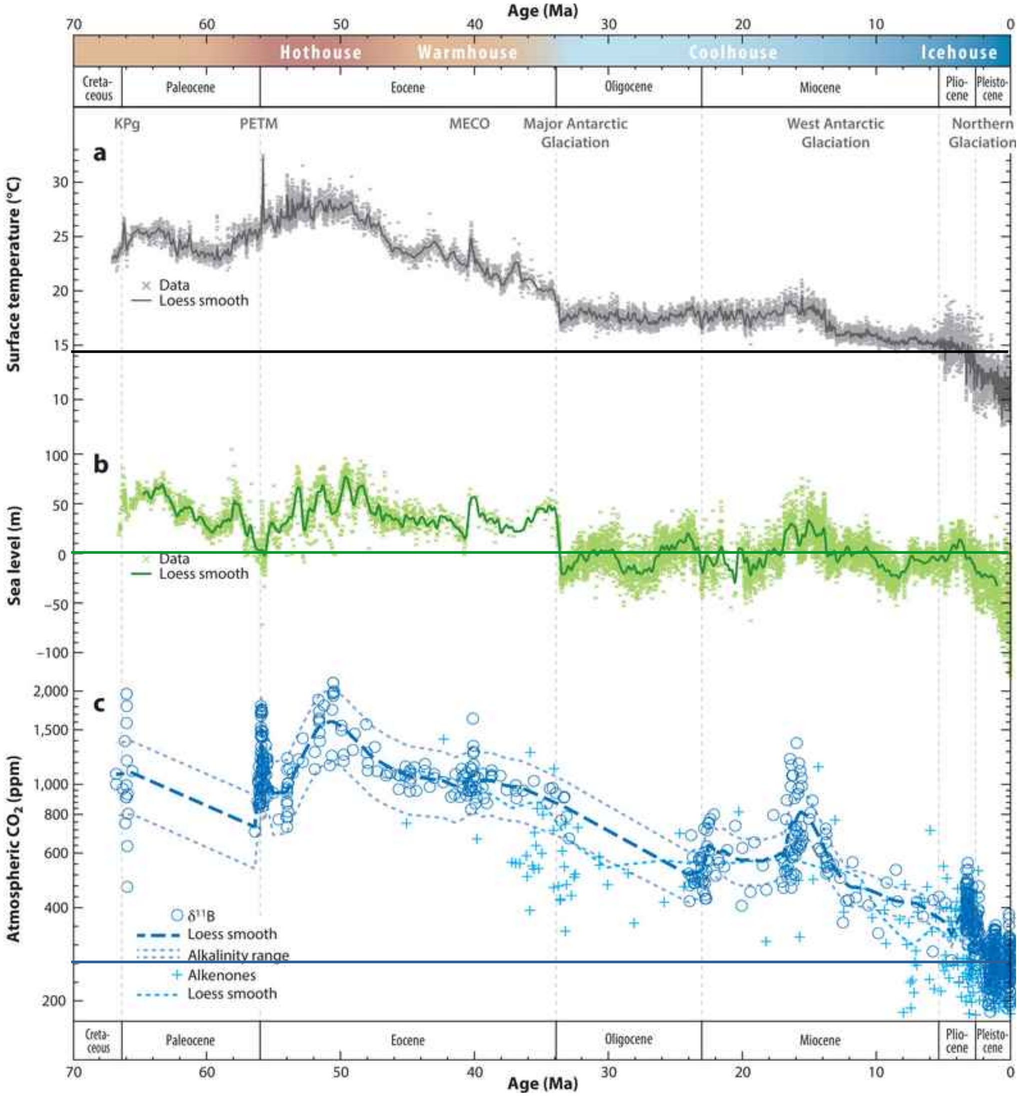


Rae et al. (2011)
Earth and Planetary Science Letters

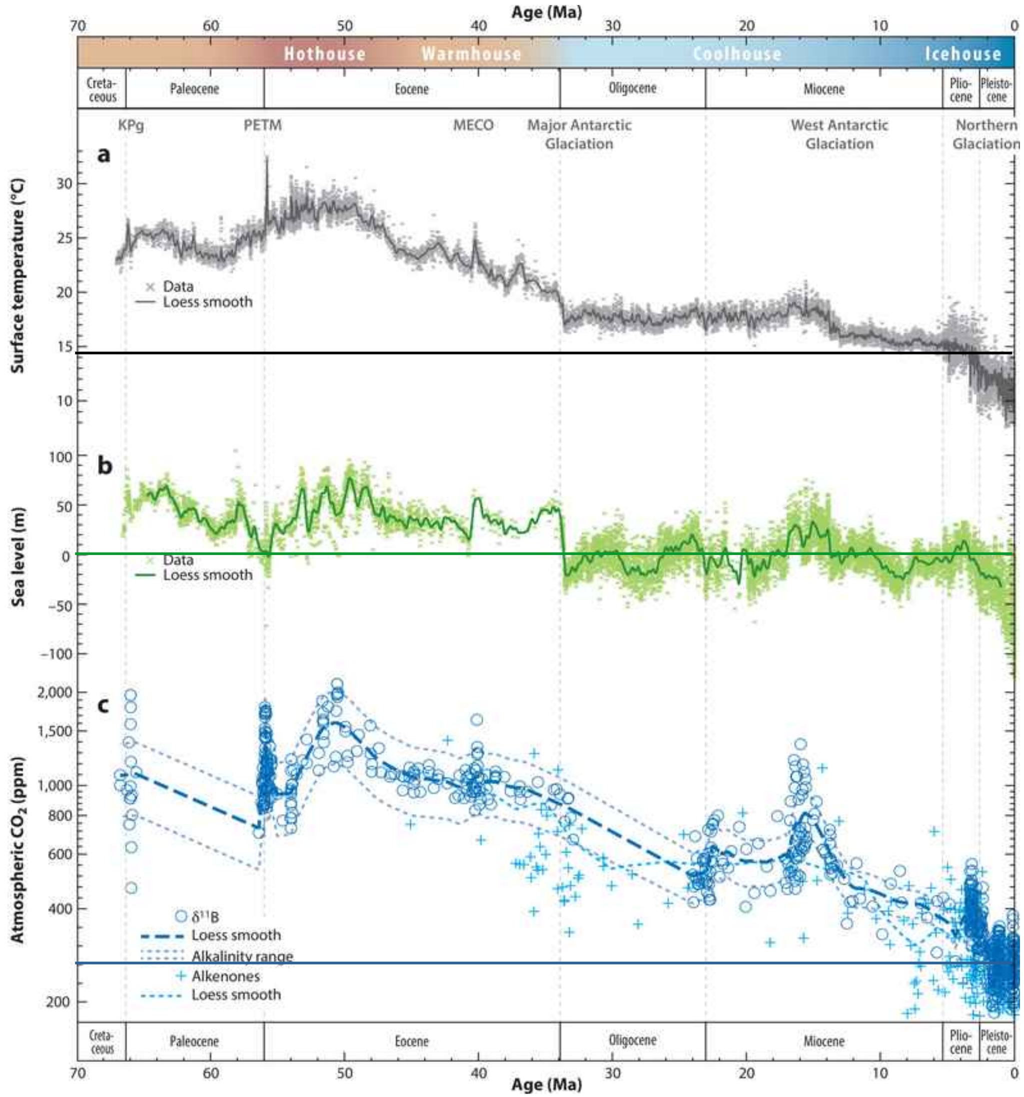
together with further assumptions, ocean pH traces (long term) atmospheric CO_2

Cenozoic Climate



Rae JWB, et al. 2021
Annu. Rev. Earth Planet. Sci. 49:609–41

Cenozoic Climate



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T and CO_2 parallel?

Climate Sensitivity

How much does Earth warm with increasing CO_2?

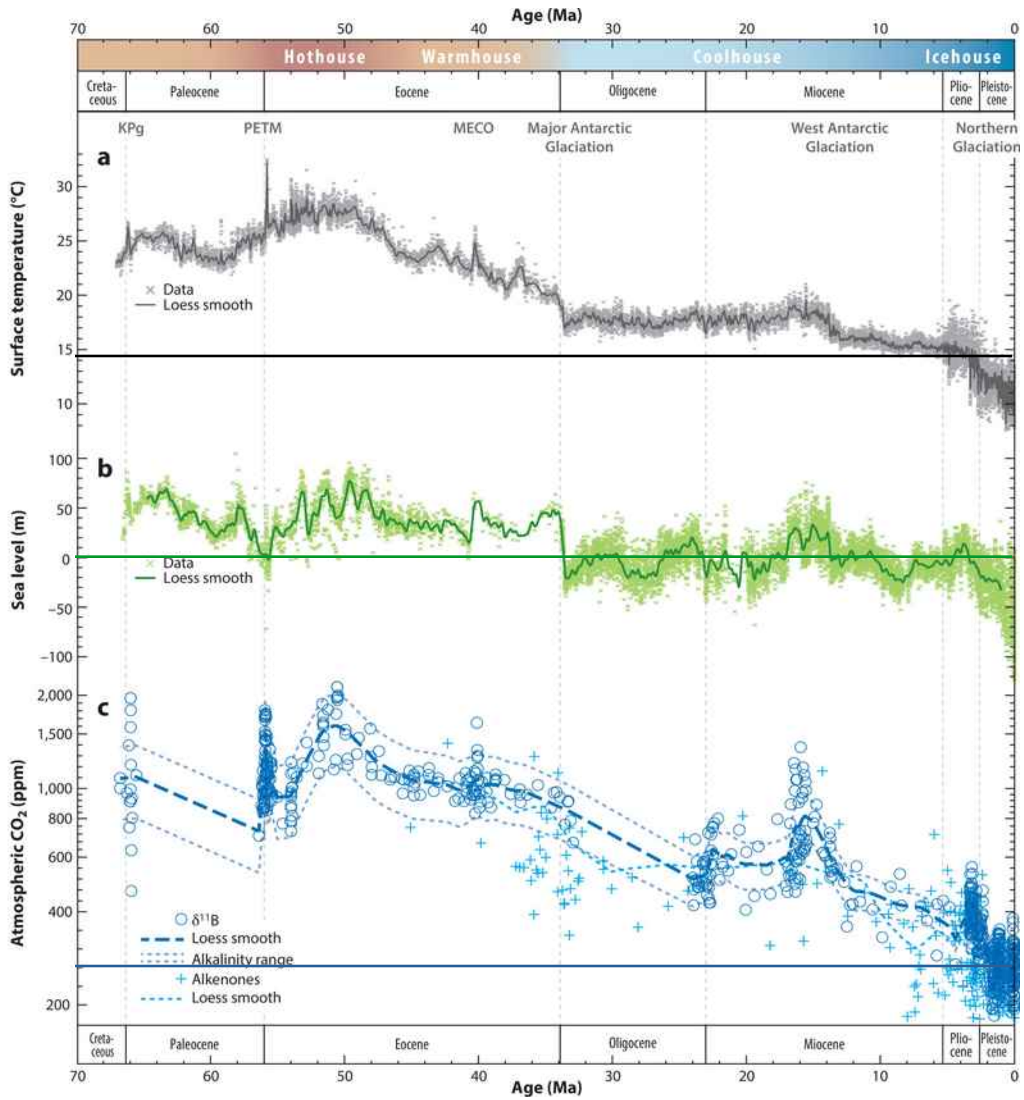
Equilibrium Climate Sensitivity (ECS)

- long-term, including geologic feedbacks
- usually referenced to doubling of CO_2

Transient Climate Response (TCR)

- short term (~ 20 years) climate response
- including fast feedbacks
- often used for models

Cenozoic Climate



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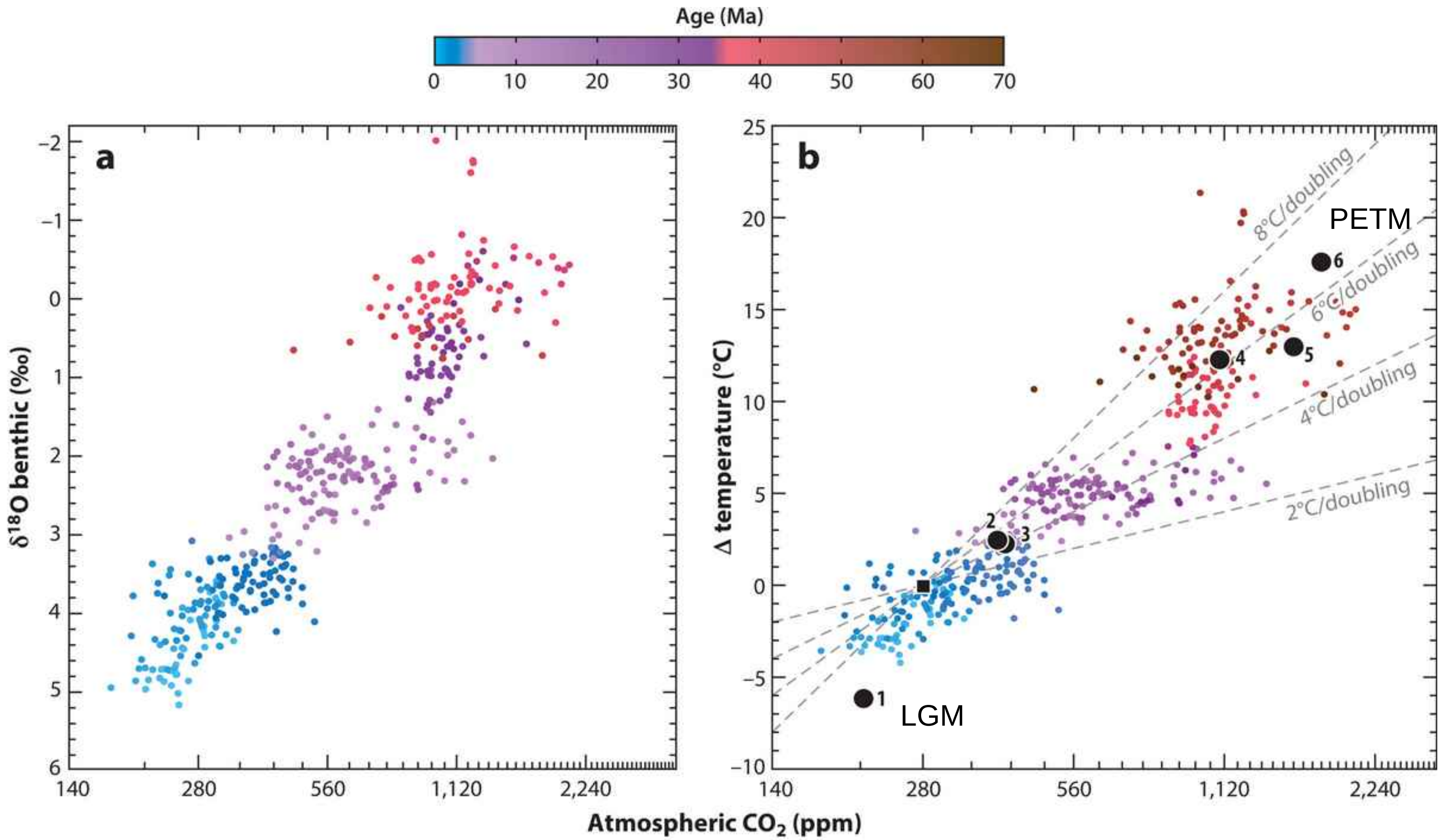
T and CO_2 parallel?

Cenozoic Climate Sensitivity



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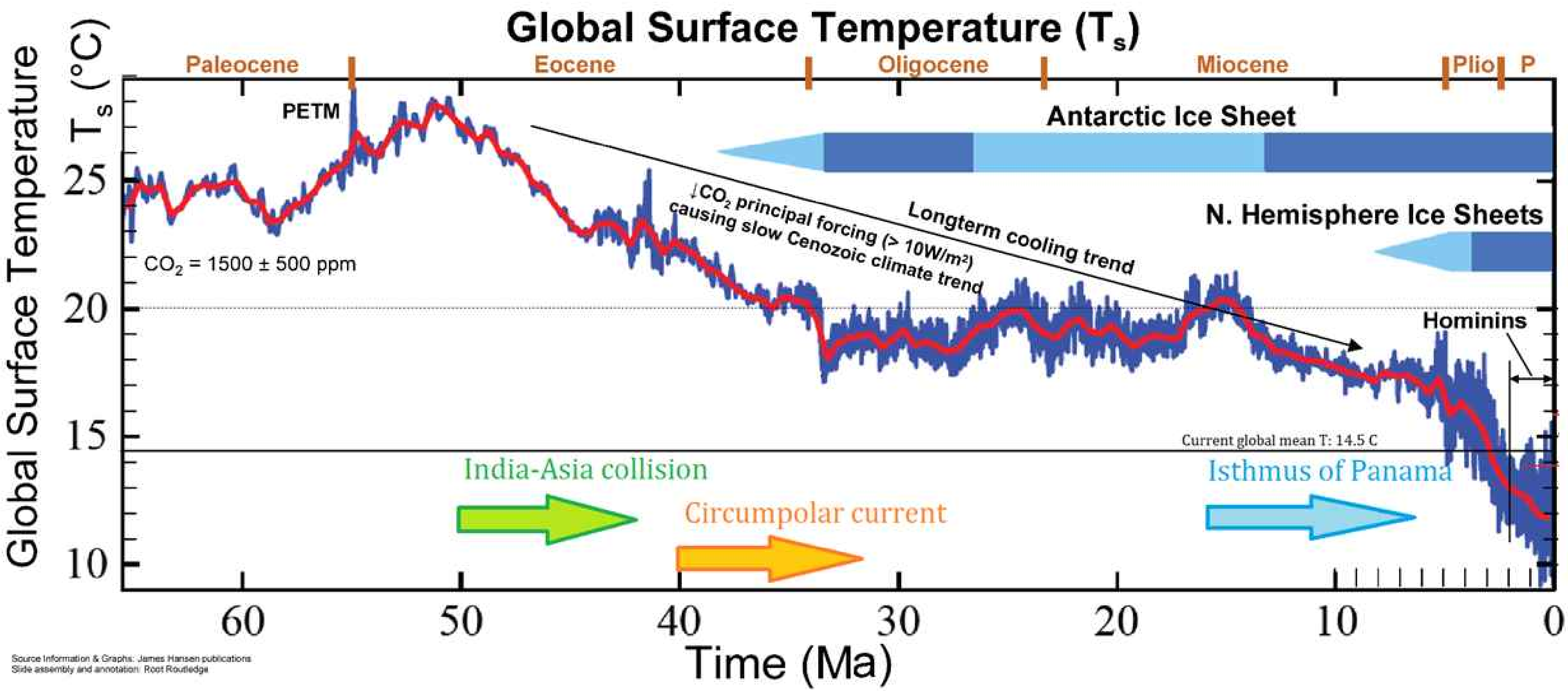
Black circles indicate independent proxy-derived estimates of surface temperature: ❶ Last Glacial Maximum (Tierney et al. 2020b), ❷ Pliocene (de la Vega et al. 2020), ❸ Pliocene (McClymont et al. 2020), ❹ late Paleocene, ❺ Early Eocene Climatic Optimum, and ❻ Paleocene–Eocene Thermal Maximum (Inglis et al. 2020). Dashed lines denote different degrees of temperature change per CO_2 doubling, providing an estimate of Earth system sensitivity.

Cenozoic Climate



Earle (2016), opentextbc.ca
after James Hansen and Root Routledge

Cenozoic cooling

Cenozoic cooling

Long term cooling trend from hot-house to ice-house

Causes debated and likely complex

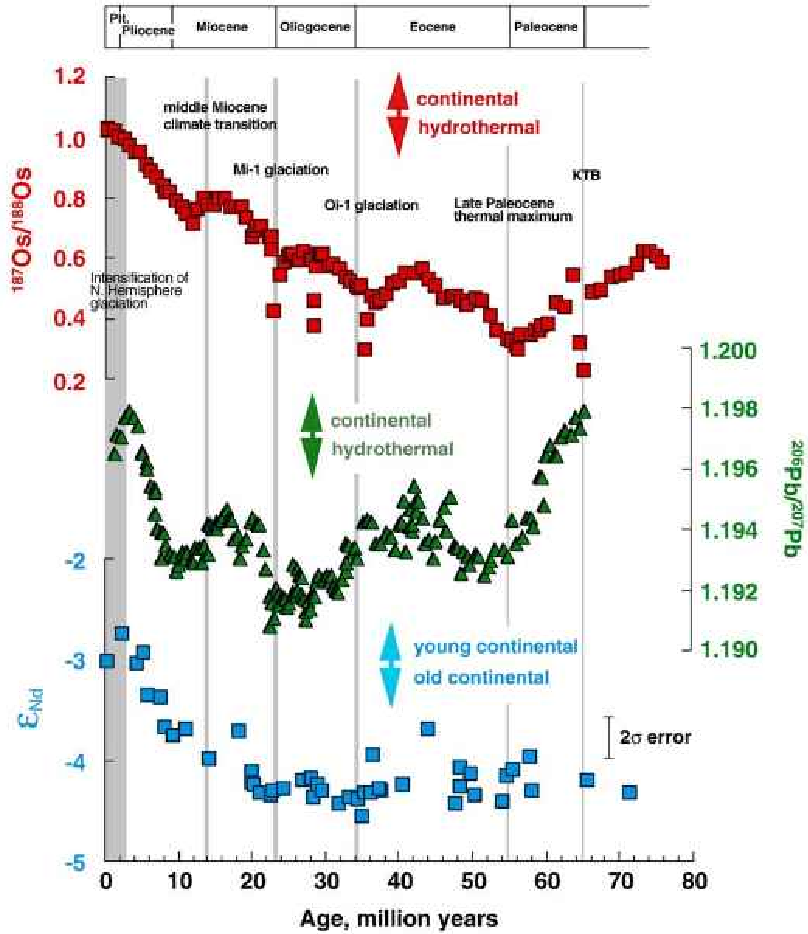
- weathering?
- isolation of Antarctica?
- faunal changes?

Cenozoic cooling

Long term cooling trend from hot-house to ice-house

Causes debatec

- weathering?



Burton (2006) Journal of Geochemical Exploration

Cenozoic cooling

spread of extensive grass lands during Miocene
favoured e.g. by seasonal aridity

development of C4 photosynthesis at ~ 10 Ma

- developed multiple times
- fixes C in molecule containing 4 C atoms
- deals better with aridity and low CO_2

Cenozoic cooling

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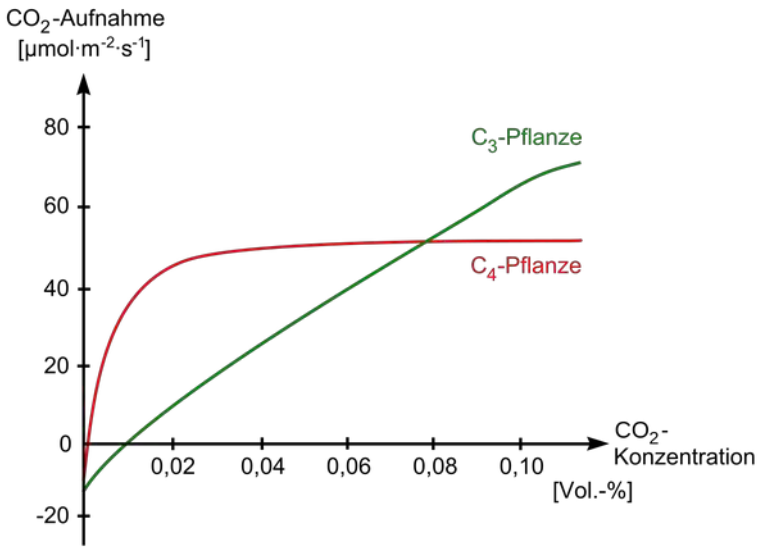


Wikipedia

Cenozoic cooling

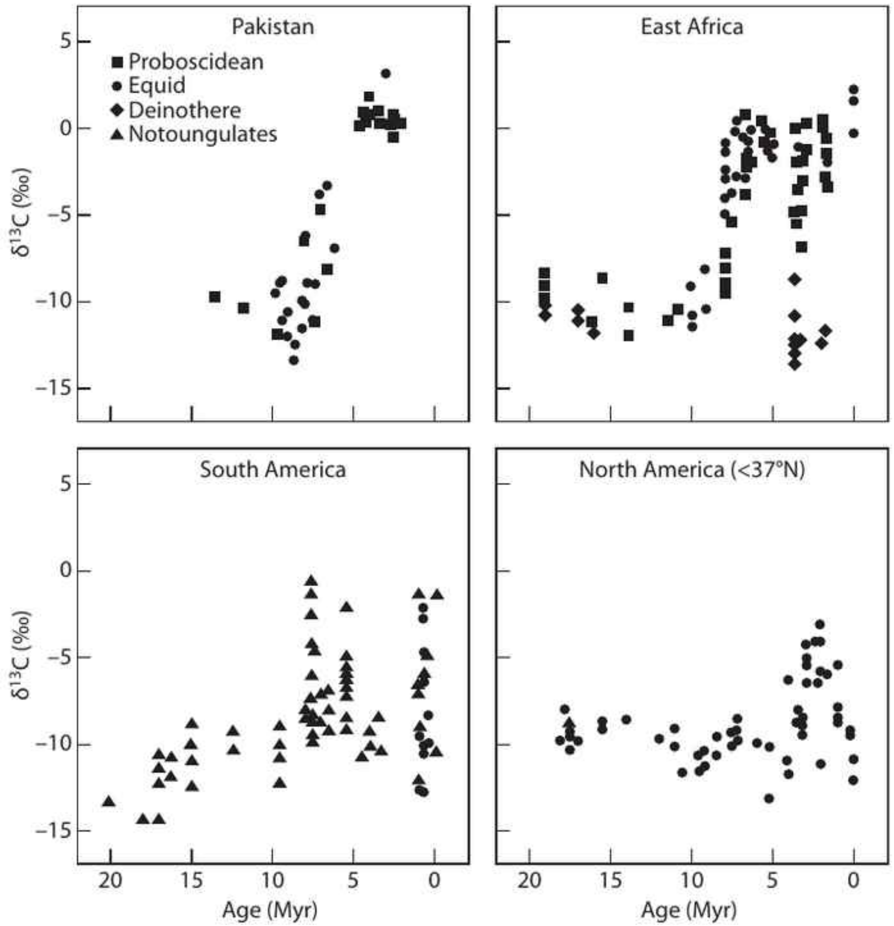
spread of extensive grass lands during Miocene favoured e.g. by seasonal aridity

development of C4 photosynthesis at ~ 10 Ma

- developed multiple times
- fixes C in molecule containing 4 C atoms
- deals better with aridity and low CO_2
- today ~ 25% of plants, mostly grasses
- global food production depends on C4 plants
- fractionates ^{13}C less than C3 plants

Cenozoic cooling

spread of extensive grass lands during Miocene



$\delta^{13}C$ in fossil teeth documents global spread of C4 grasses

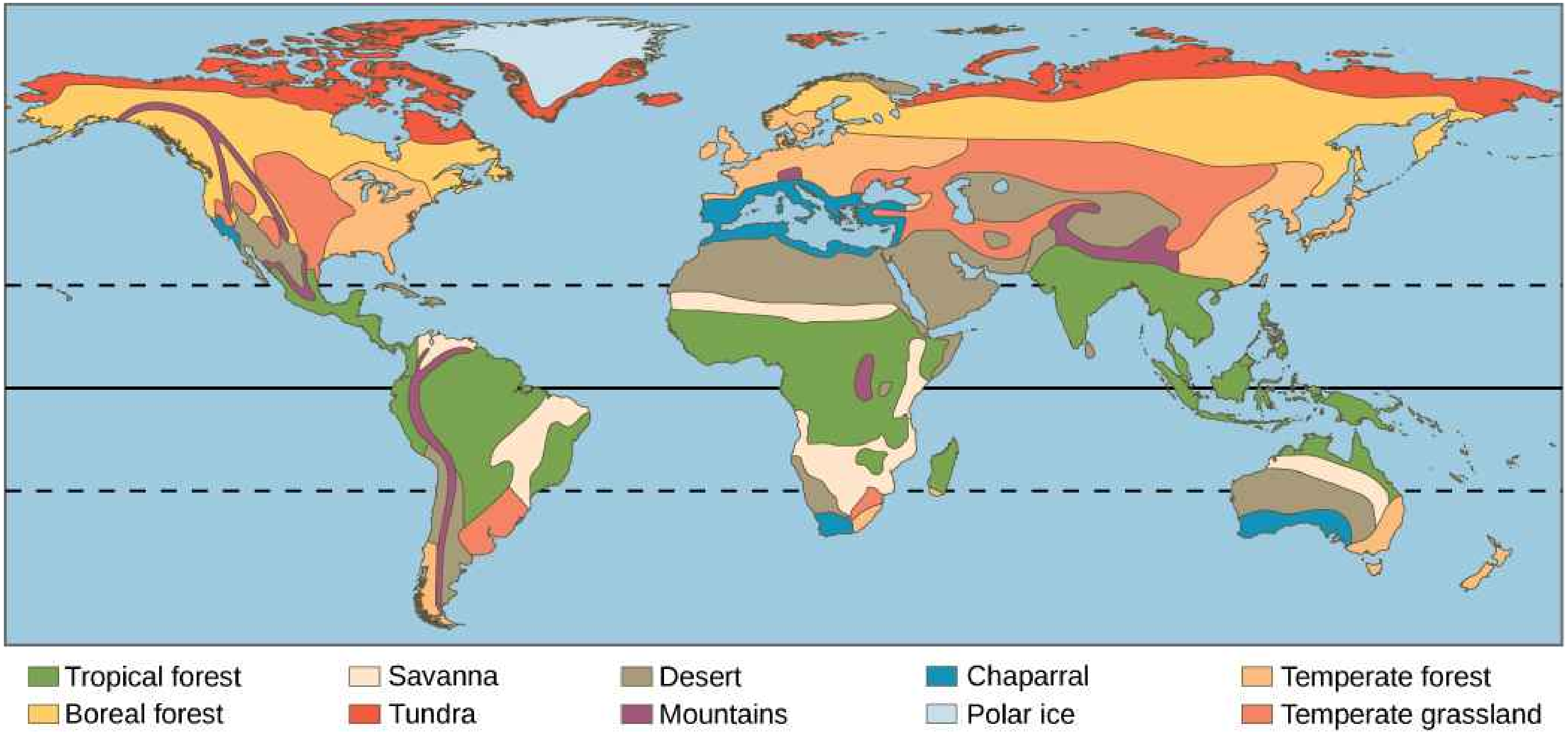
Michael Bender
Paleoclimate

Cenozoic cooling

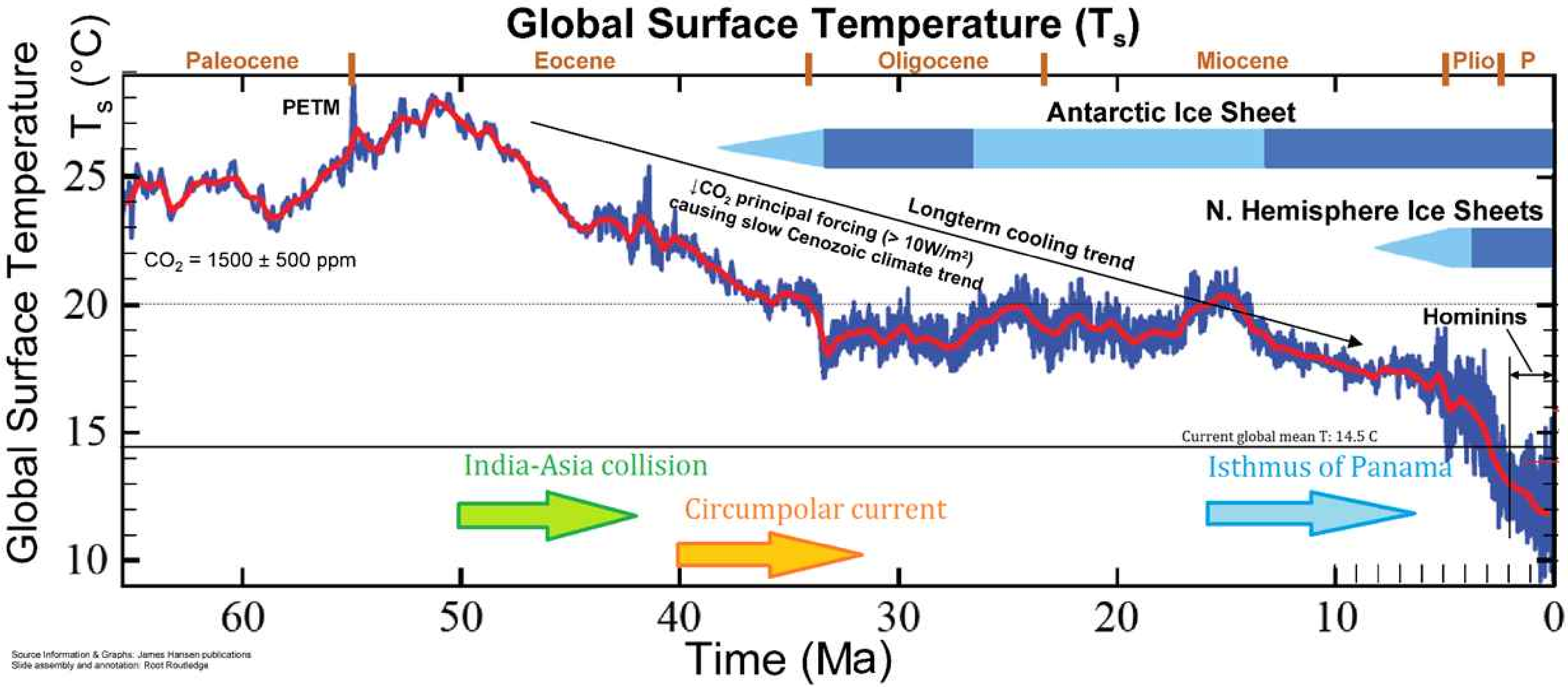
lumenlearning.com
Environmental Biology

spread of extensive grass lands during Miocene

modern biomes

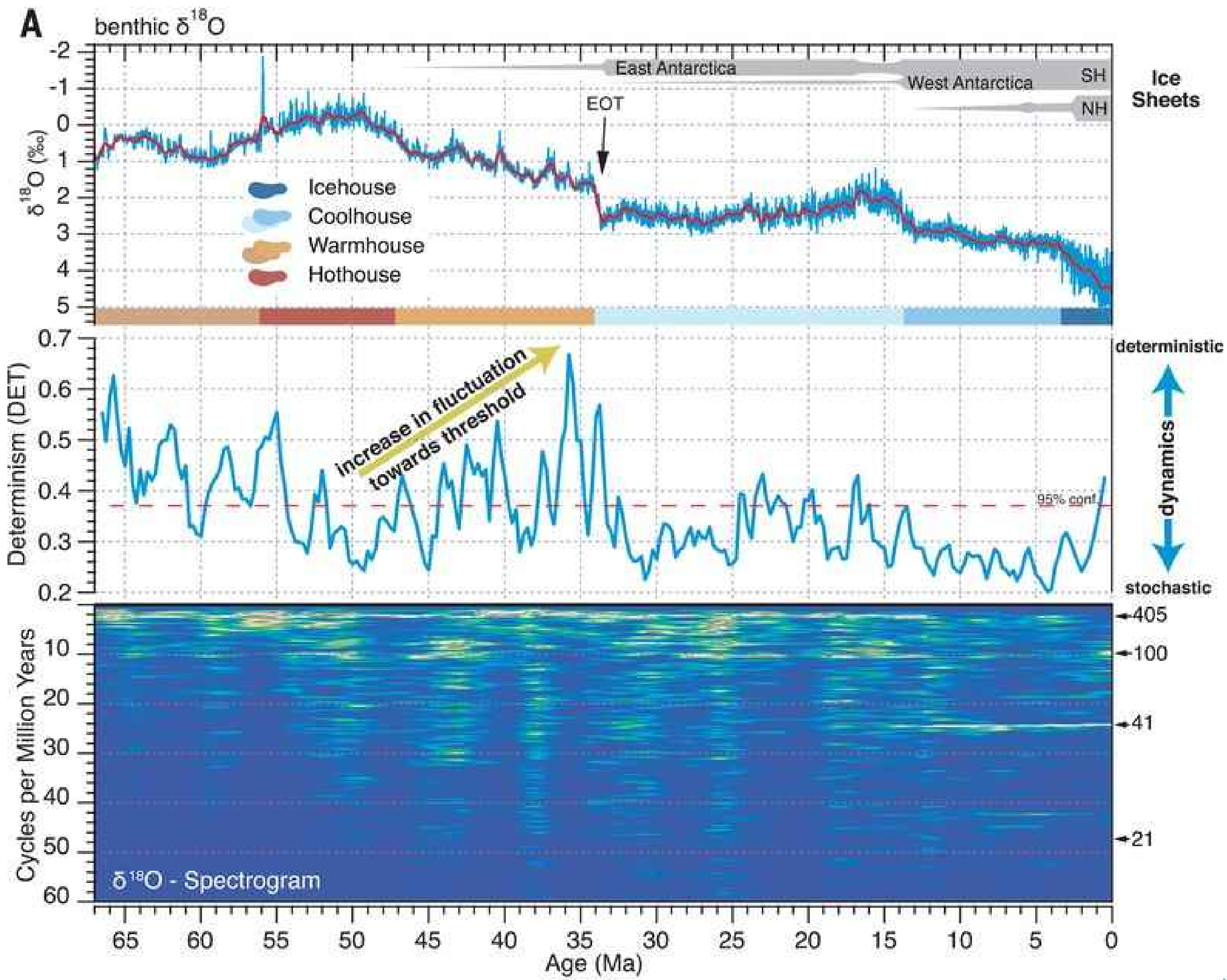


Cenozoic Climate



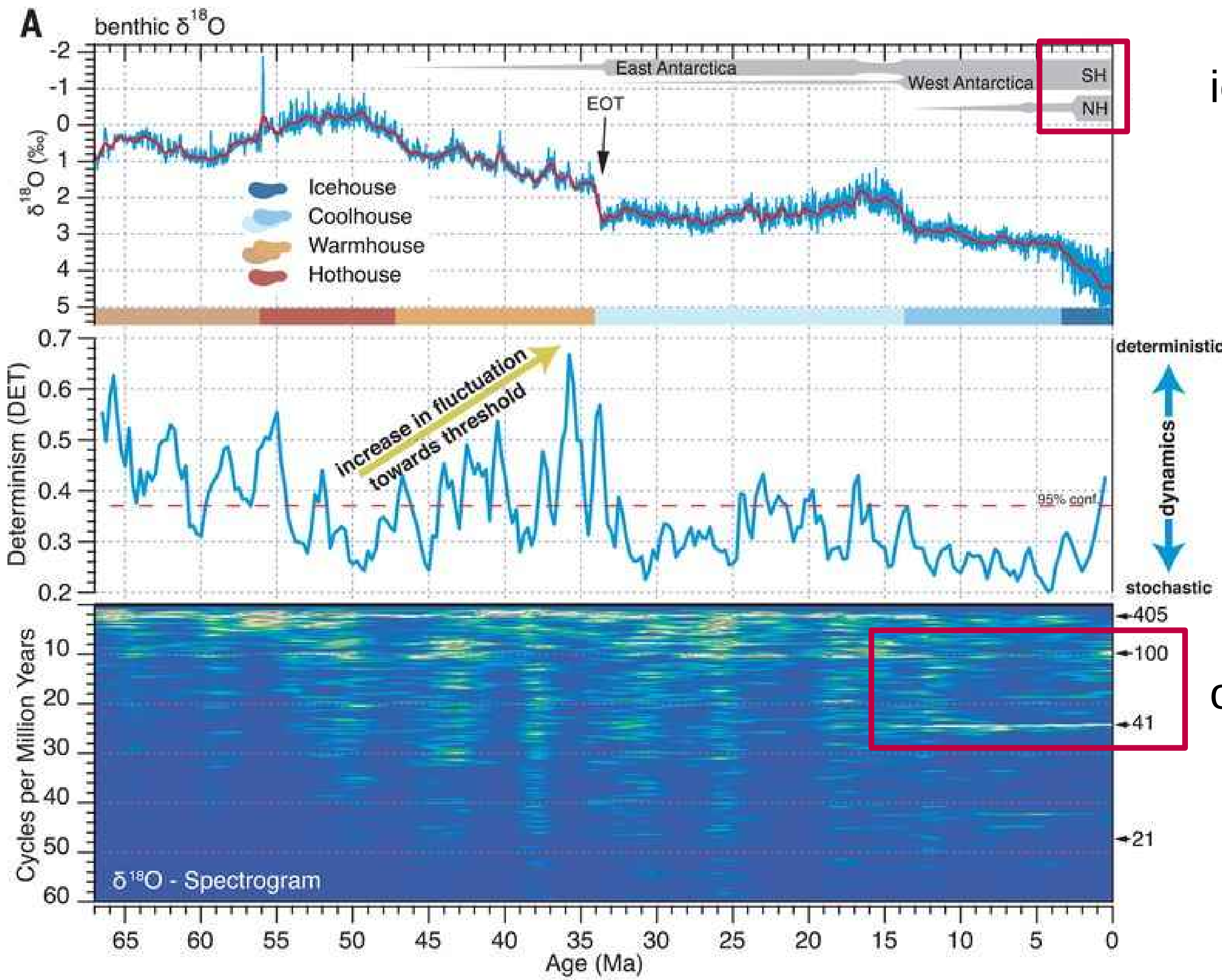
Earle (2016), opentextbc.ca
after James Hansen and Root Routledge

Cenozoic Climate



Westerhold et al. (2020)
Science

Cenozoic Climate



ice sheets

orbital forcing

Westerhold et al. (2020)
Science

Today's Summary

- Eocene Hothouse was very hot
- Equable climate led to warm poles
- PETM was extreme warm event caused by GHG

- Cenozoic climate dominated by CO_2

- Cooling was accompanied by CO2 reduction and changes in weathering and fauna

- Temperature proxies: $\delta^{18}O$, $\Delta47$, Mg/Ca, TEX86
- Carbon proxies: $\delta^{13}C$ & $\delta^{11}B$

Outlook

Today we finish 15 min early!

Monday	Introduction	Earth History
Tuesday	Proxies I	Cenozoic Hot & Warm House
Wednesday	Specific Climate System components	Pleistocene G-IG climate
Thursday	Proxies II & Climate System Interactions	Abrupt Climate Change
Friday	Current Climate Change	Future & Synthesis