Cenozoic stable isotope constraints on the Eurasian continental interior hydroclimate response to high CO2

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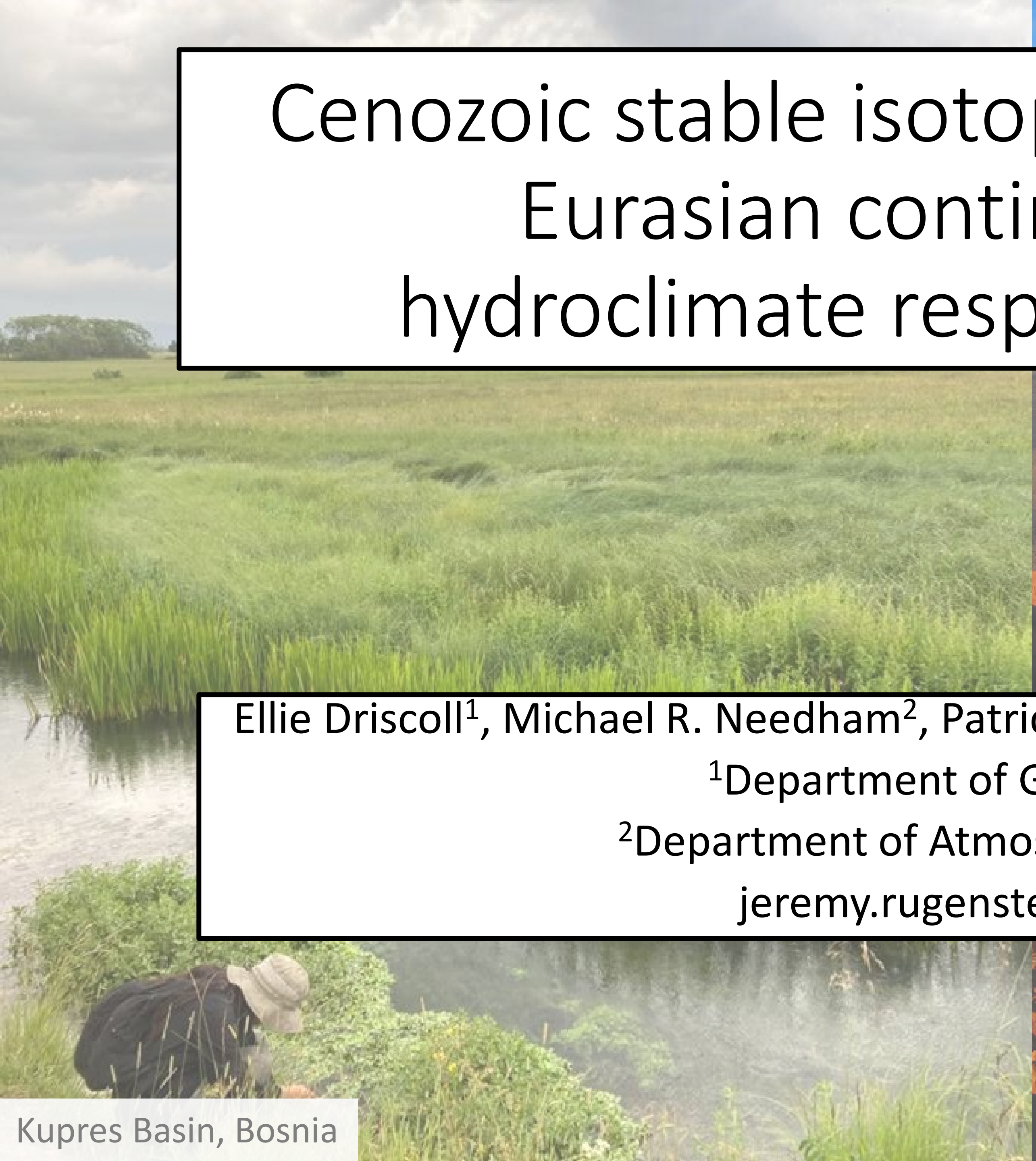
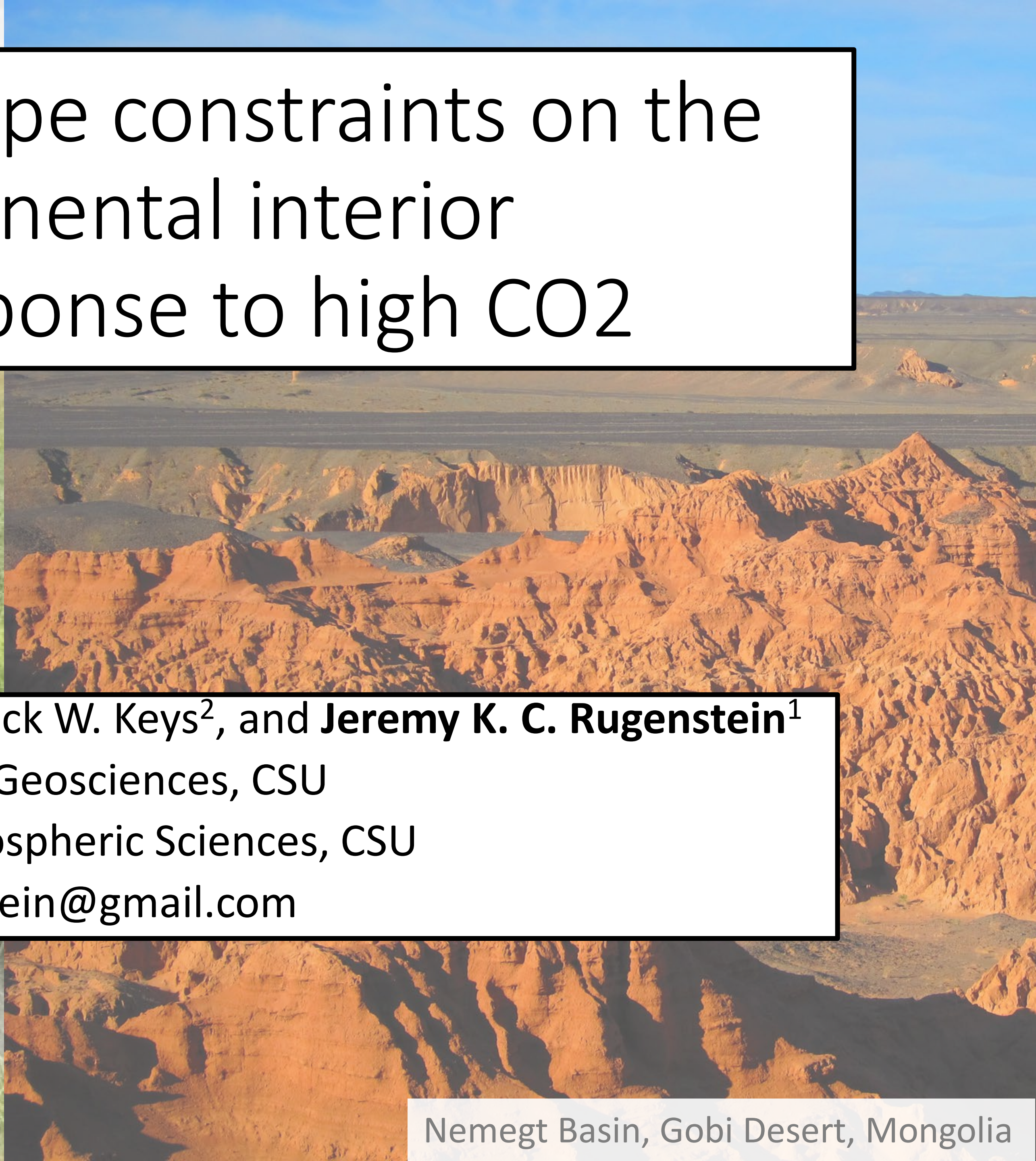


Kupres Basin, Bosnia

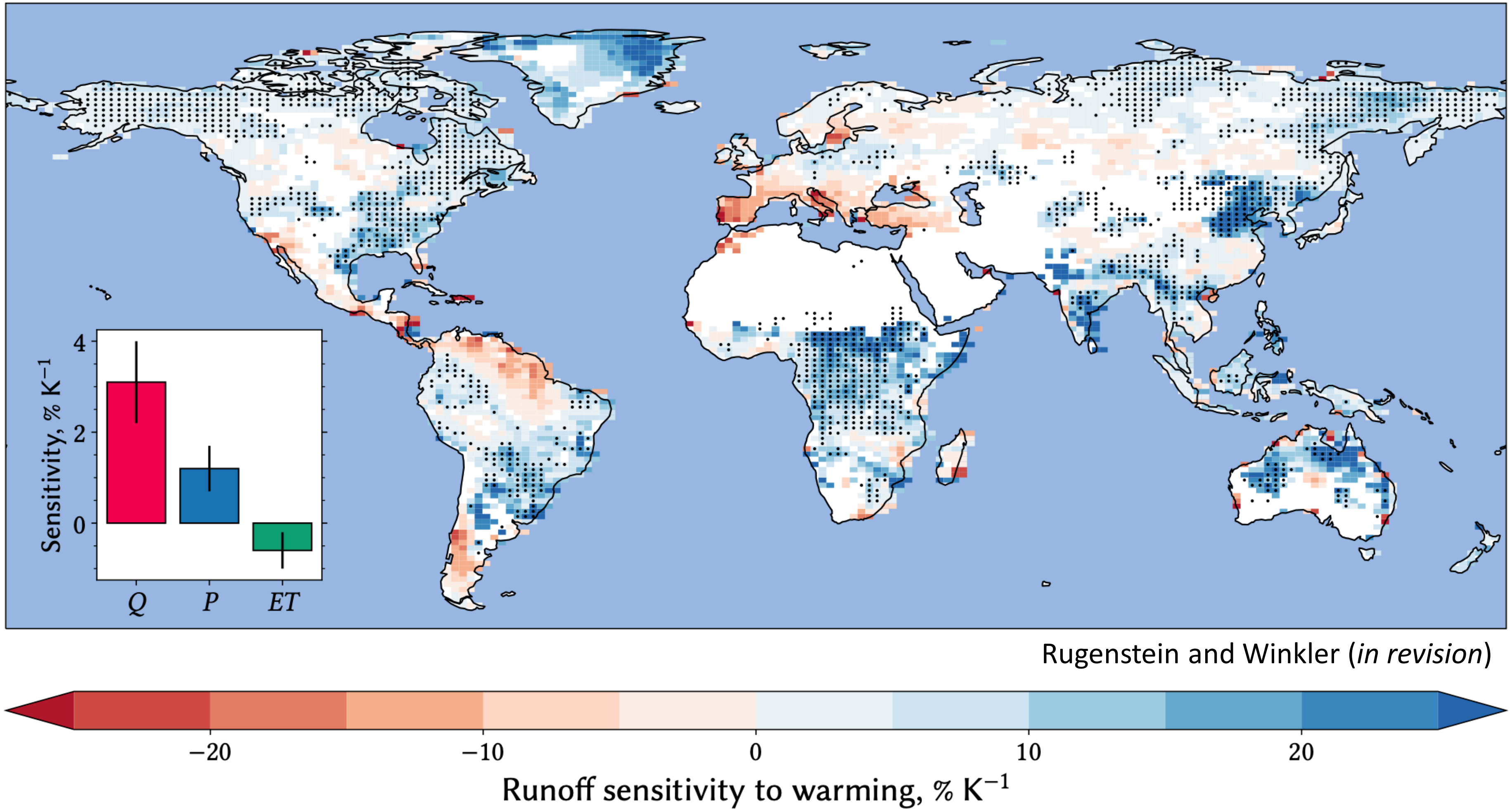


Nemegt Basin, Gobi Desert, Mongolia

Hydroclimate Uncertainty—Runoff sensitivity

Multimodel median 2070–99 (RCP 8.5) minus 1975–2004 C4MIP Models

Stippling = >75% model agree on sign of change



Rugenstein and Winkler (*in revision*)

- Land-atmosphere response to CO_2 and warming complicate predictions of terrestrial hydroclimate change

Hydroclimate Uncertainty—Runoff sensitivity

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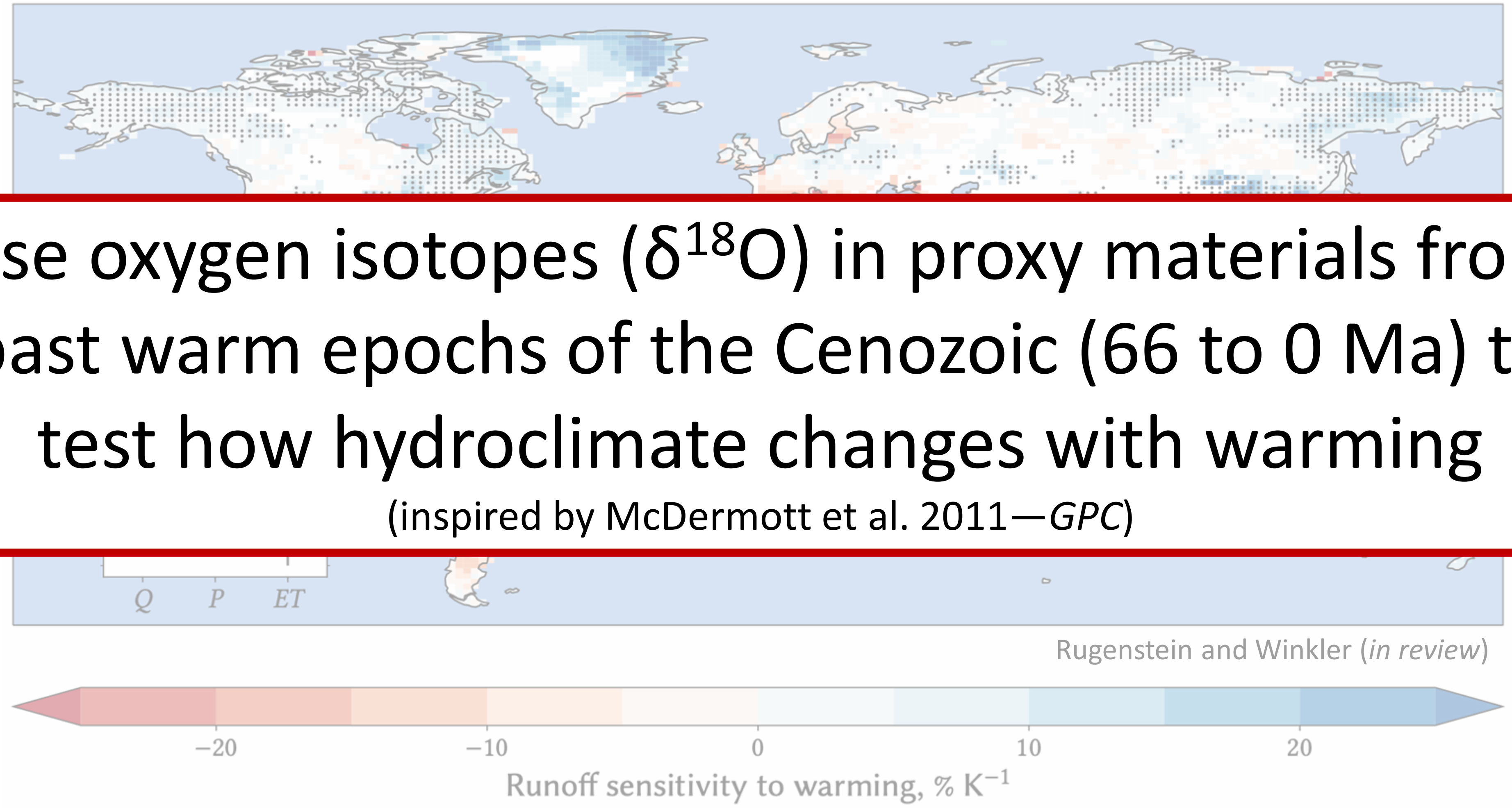
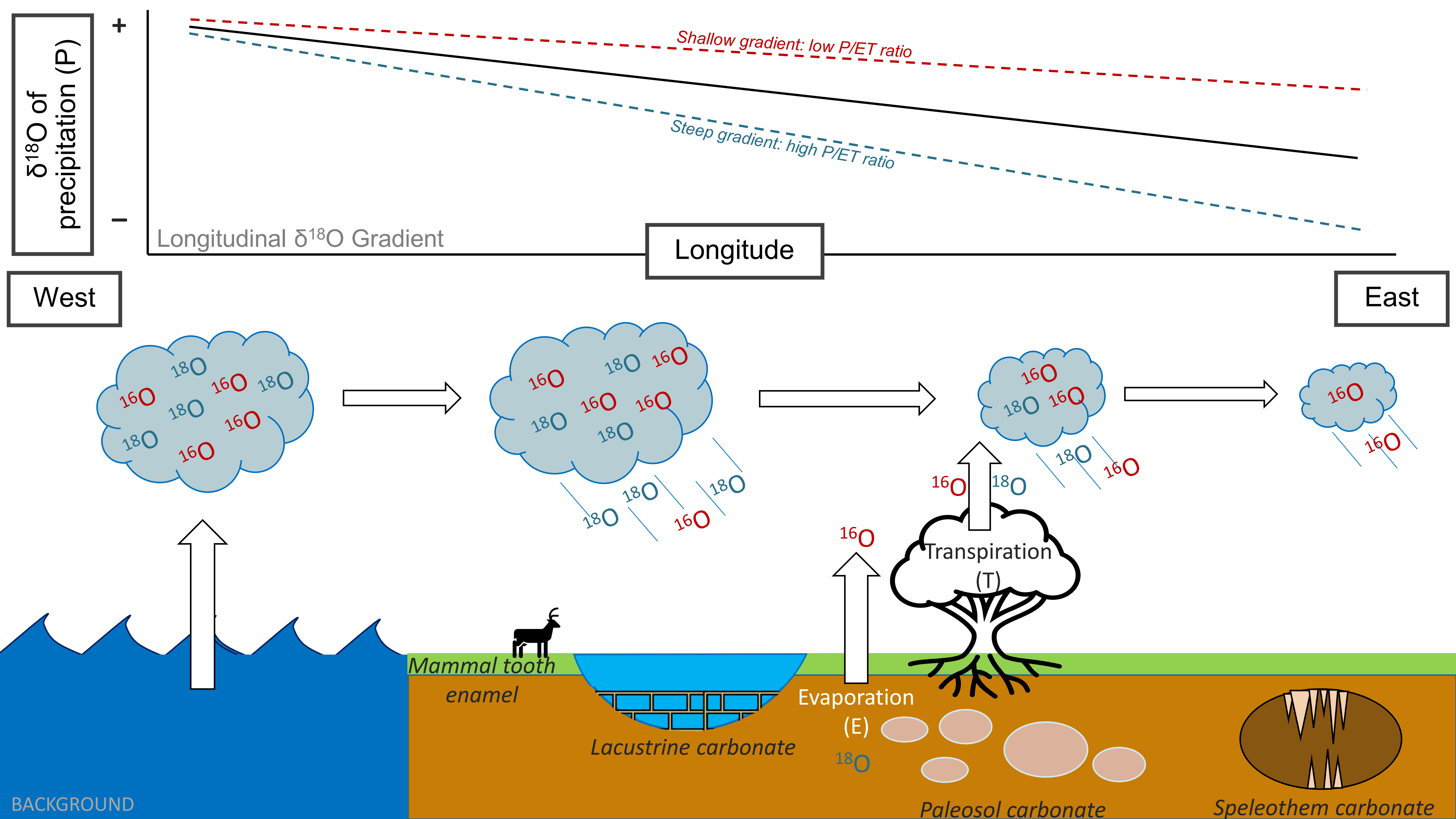


Rugenstein and Winkler (*in review*)

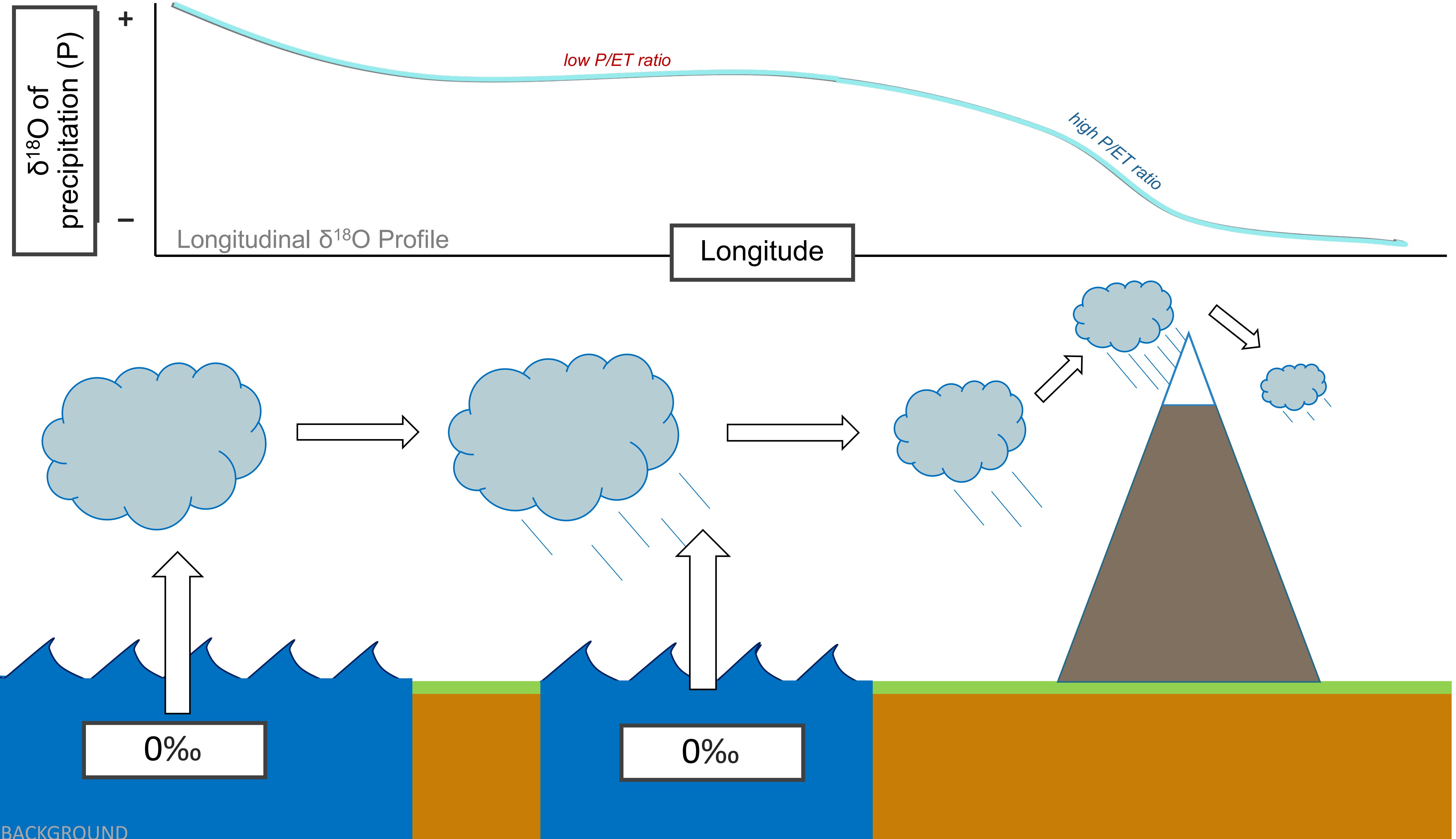
Use oxygen isotopes ($\delta^{18}O$) in proxy materials from past warm epochs of the Cenozoic (66 to 0 Ma) to test how hydroclimate changes with warming

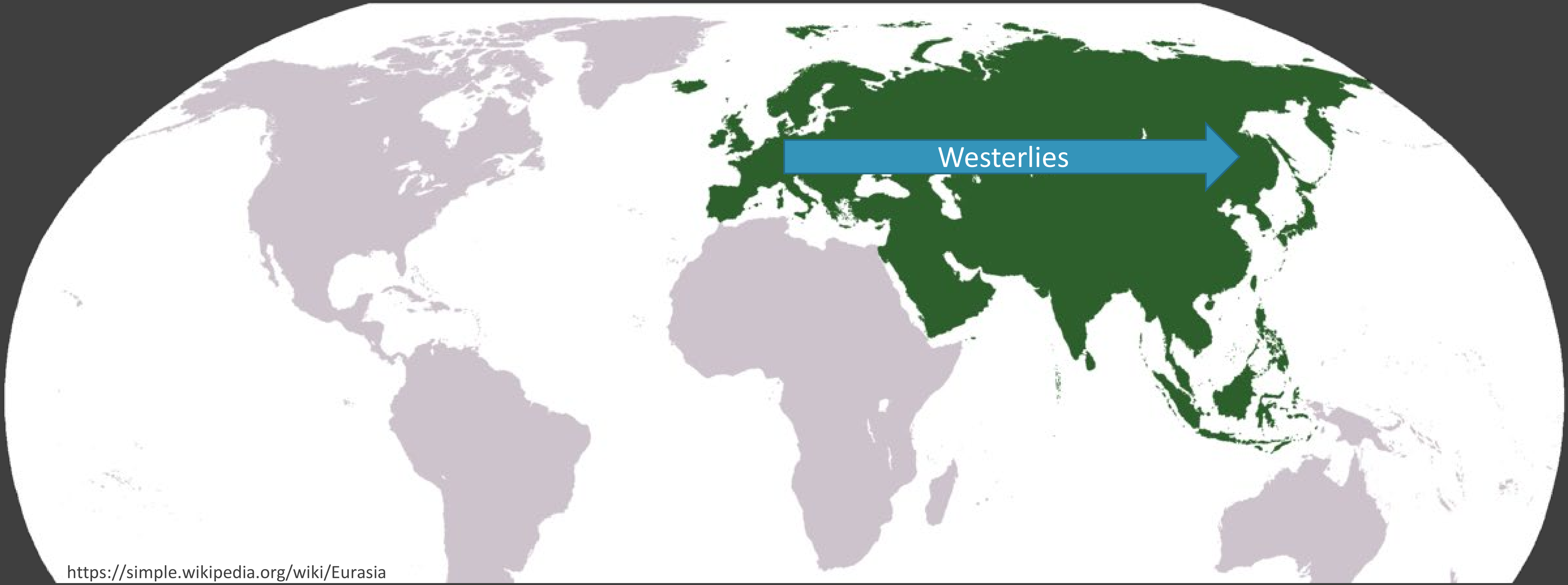
(inspired by McDermott et al. 2011—*GPC*)

- Land-atmosphere response to CO2 and warming complicate predictions of terrestrial hydroclimate change



δ18O of precipitation (P)
+
−
Shallow gradient: low P/ET ratio
Steep gradient: high P/ET ratio
Longitudinal δ18O Gradient
Longitude
West
East
18O
16O
Transpiration (T)
Evaporation (E)
Mammal tooth enamel
Lacustrine carbonate
Paleosol carbonate
Speleothem carbonate
BACKGROUND

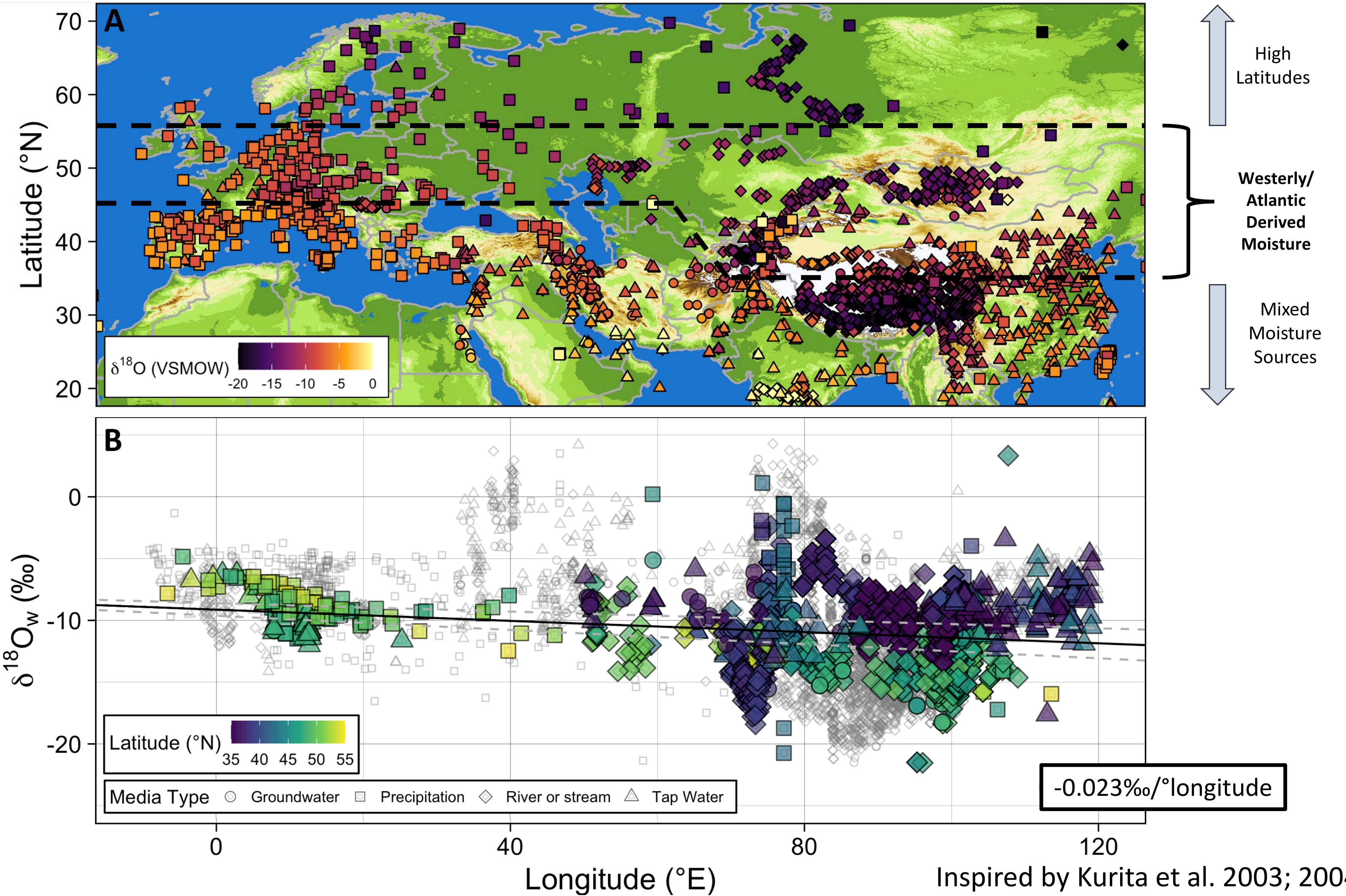

δ18O of precipitation (P)
+
−
low P/ET ratio
high P/ET ratio
Longitudinal δ18O Profile
Longitude
0‰
0‰
BACKGROUND



Why Eurasia?

- Largest continental area on earth
- Dominated by a single air mass, with moisture flux from Europe to Asia driven by the westerlies
- Much of the precipitation that falls over Asia is sourced from evaporated or transpired continental moisture from Europe

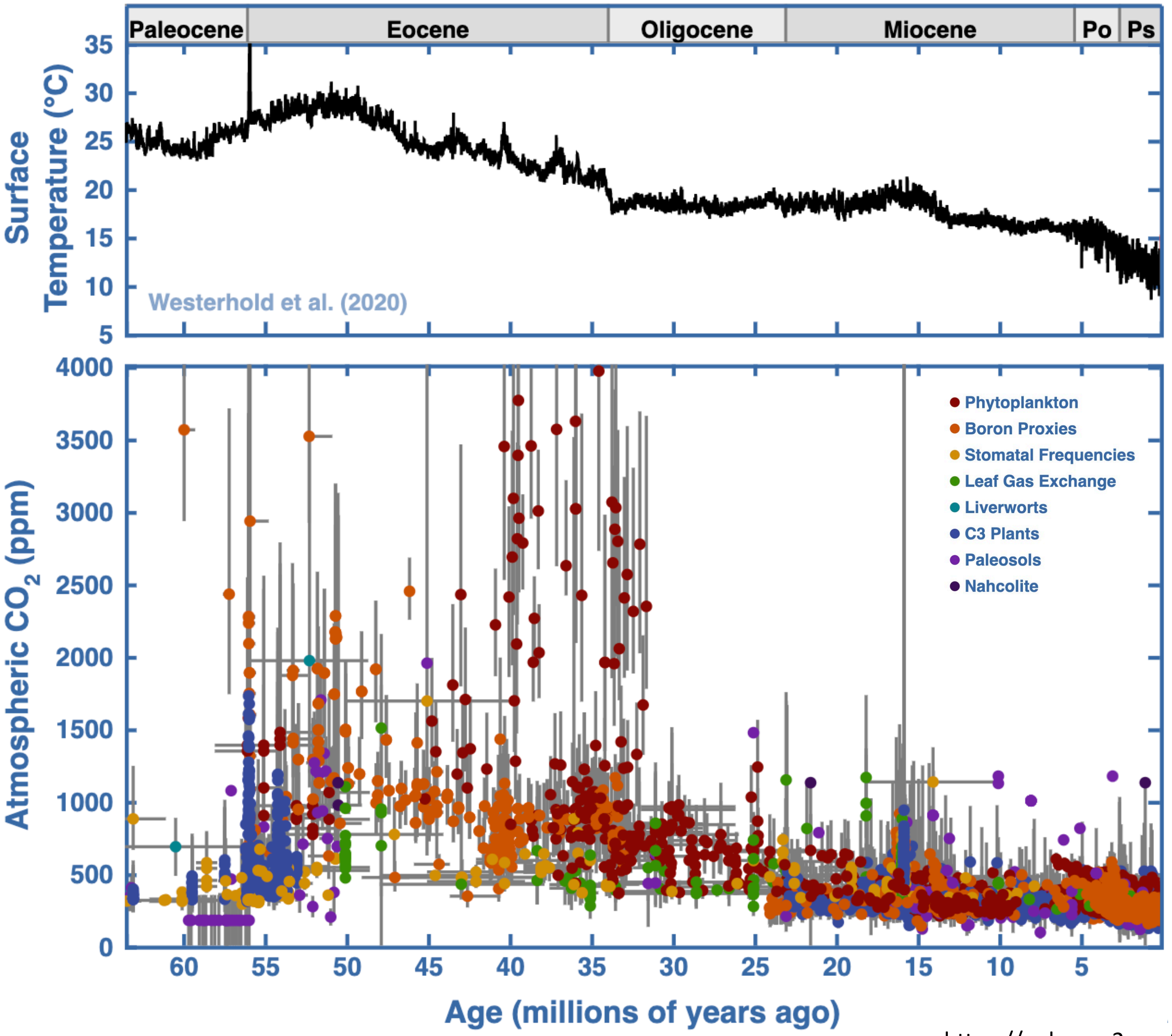
Modern δ18O Distribution & Longitudinal Profile



Inspired by Kurita et al. 2003; 2004

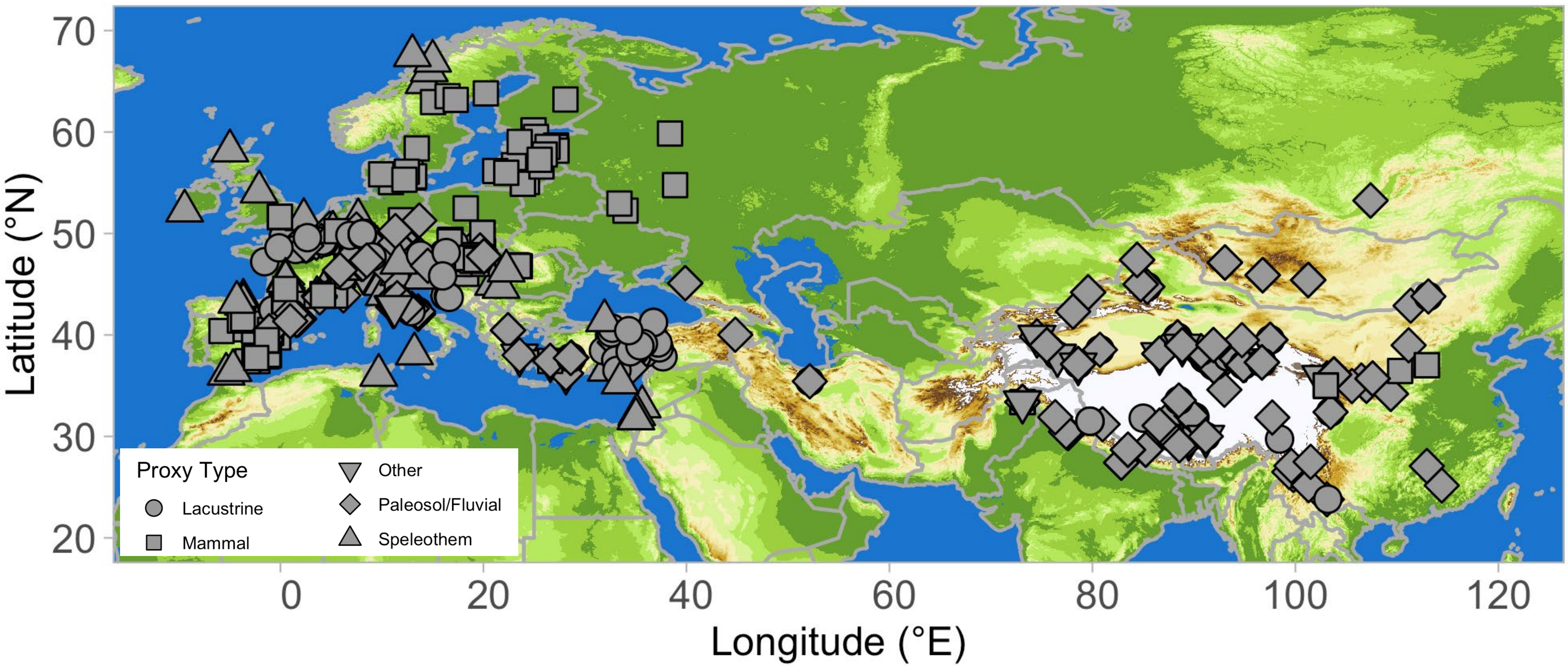
Why the Cenozoic Era?

Cenozoic Era (66 Ma – 0 Ma)

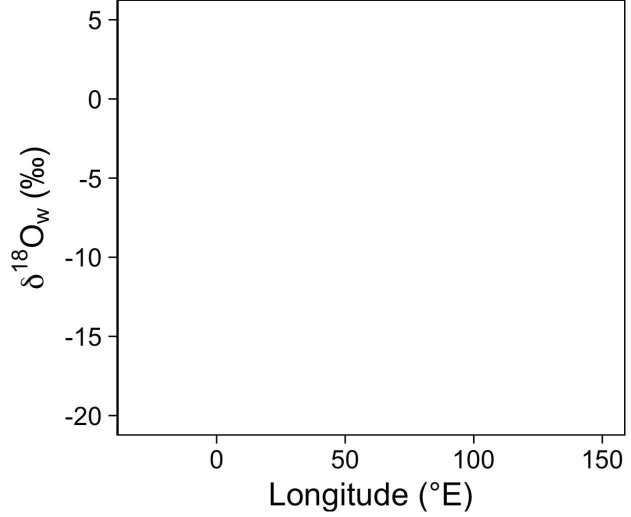


https://paleo-co2.org/

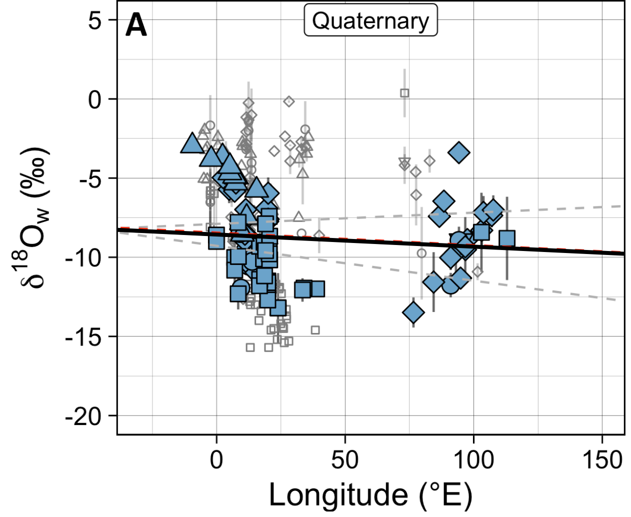
Proxy Data Compilation



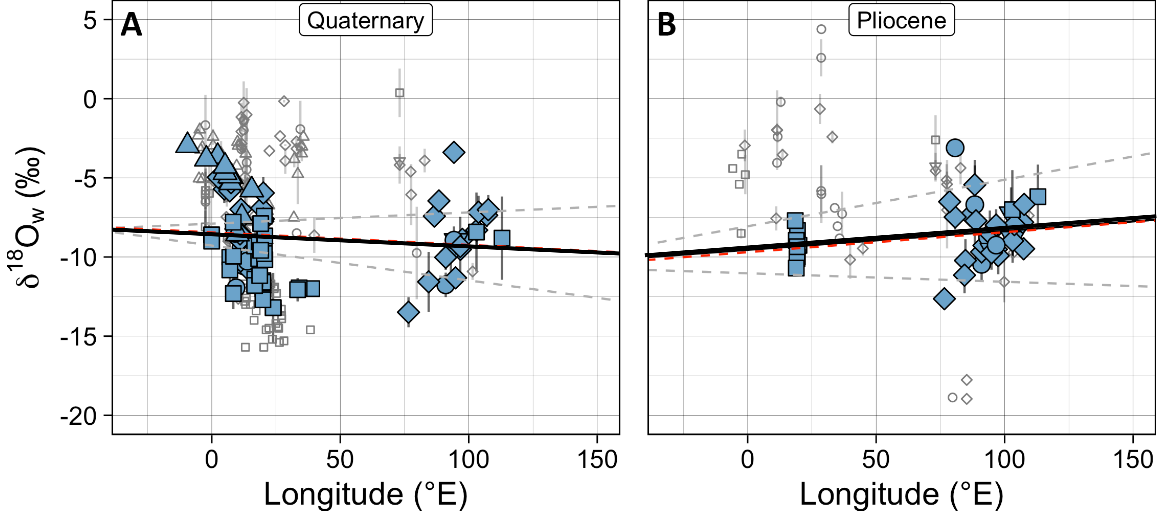
- Compiled paleo-$\delta^{18}O$ from mammal teeth, paleosol carbonates, lacustrine carbonates, and speleothems
  - ~15,000 samples at 440 sites from 66 Ma to 0 Ma (from 143 total publications)
- All data now available online for querying at the PATCH Lab (Kukla et al. 2022—*AJS*)



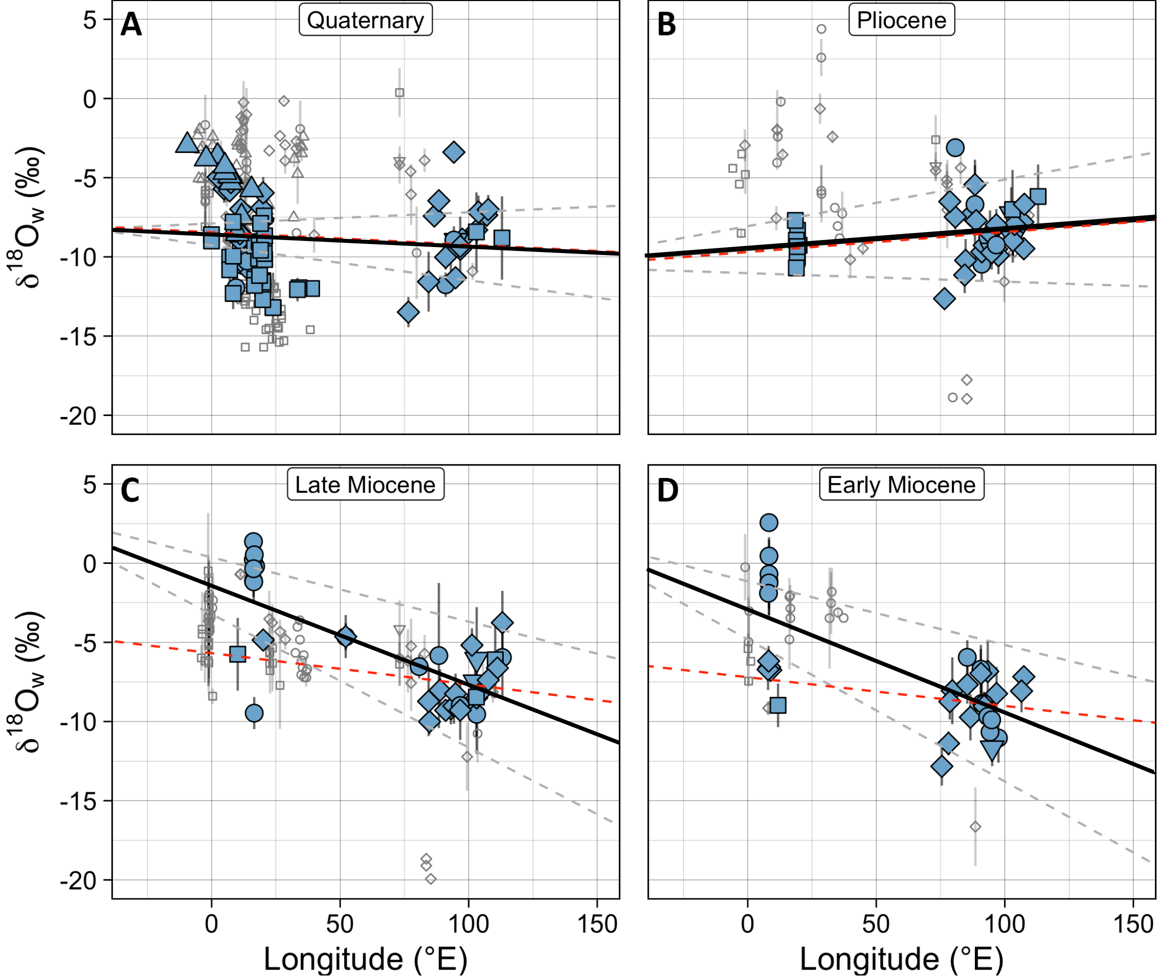
Proxy $\delta^{18}O$ Longitudinal Profiles



Proxy δ^{18}O Longitudinal Profiles

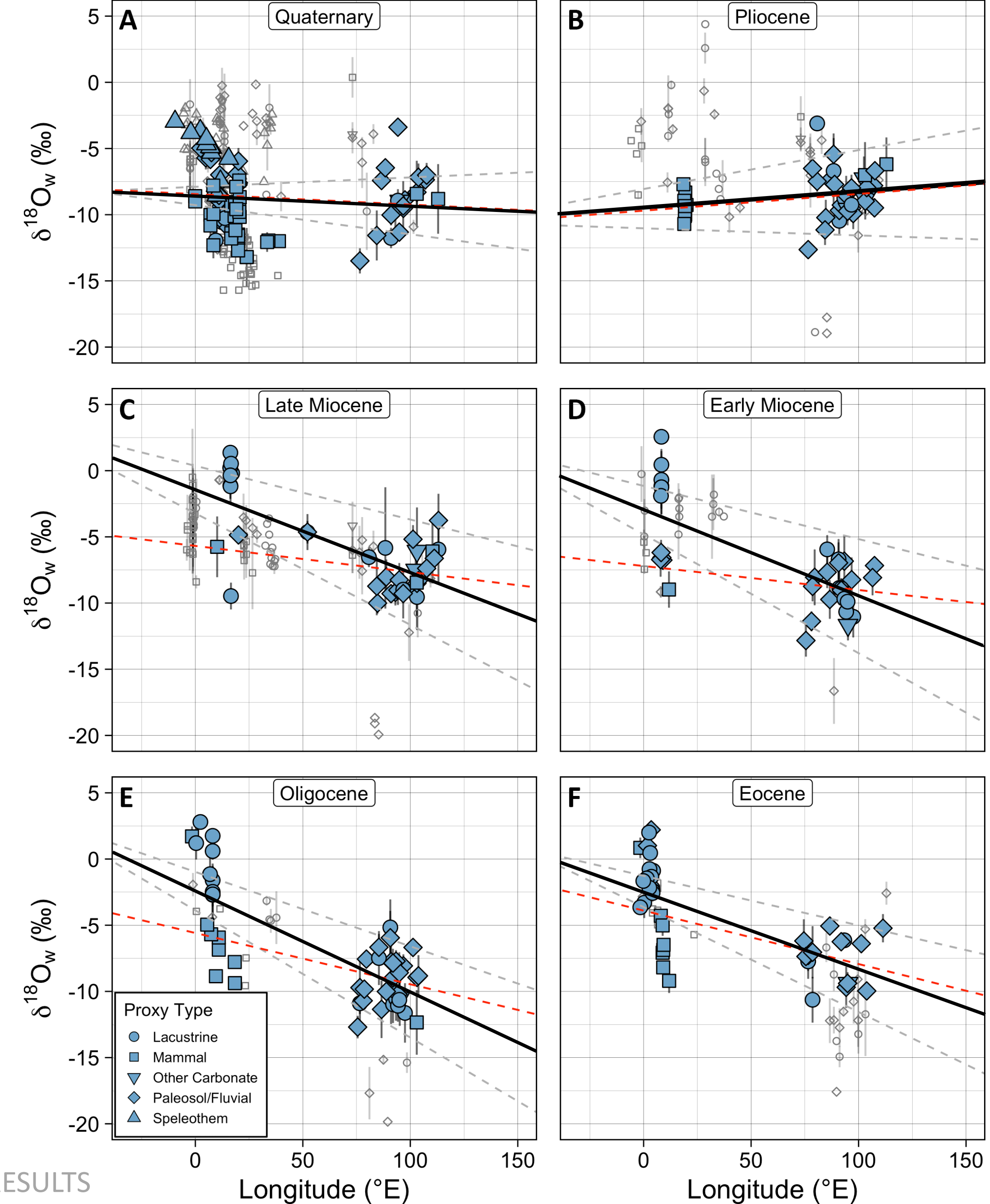


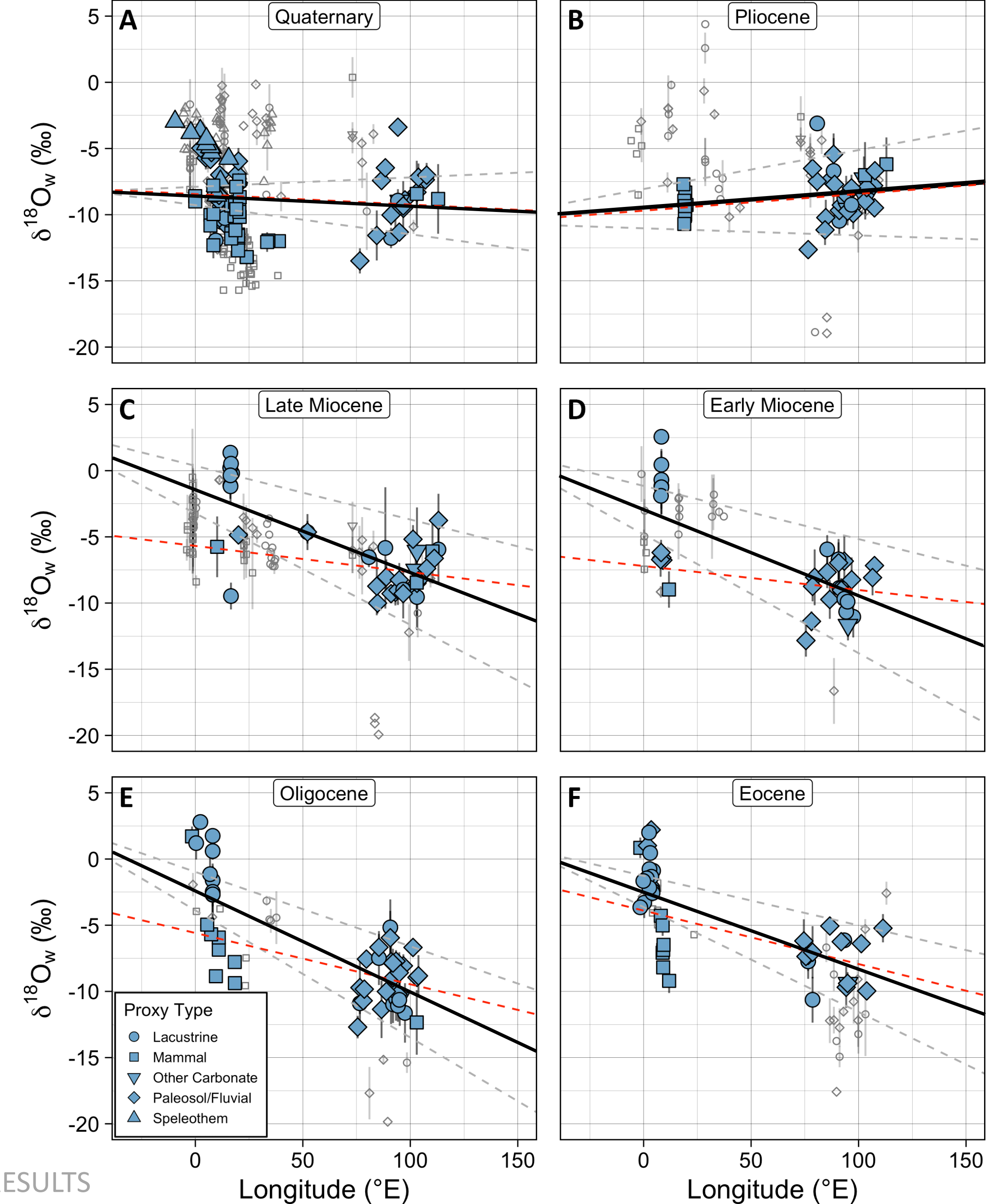
Proxy δ18O Longitudinal Profiles



Proxy $\delta^{18}O$ Longitudinal Profiles

Proxy δ^{18}O Longitudinal Profiles

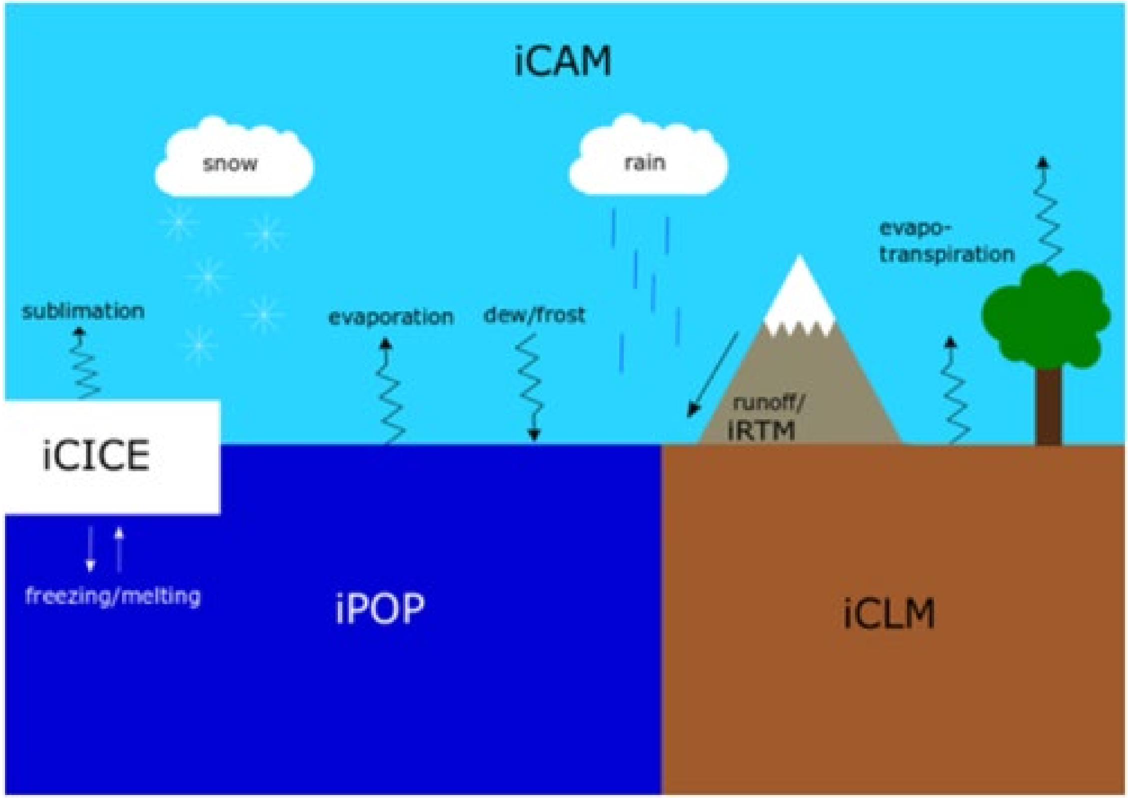




Proxy $\delta^{18}O$ Longitudinal Profiles

- Large increase in gradient between Pliocene and Miocene
- Partly caused by higher $\delta^{18}O$ in Europe during past warm intervals

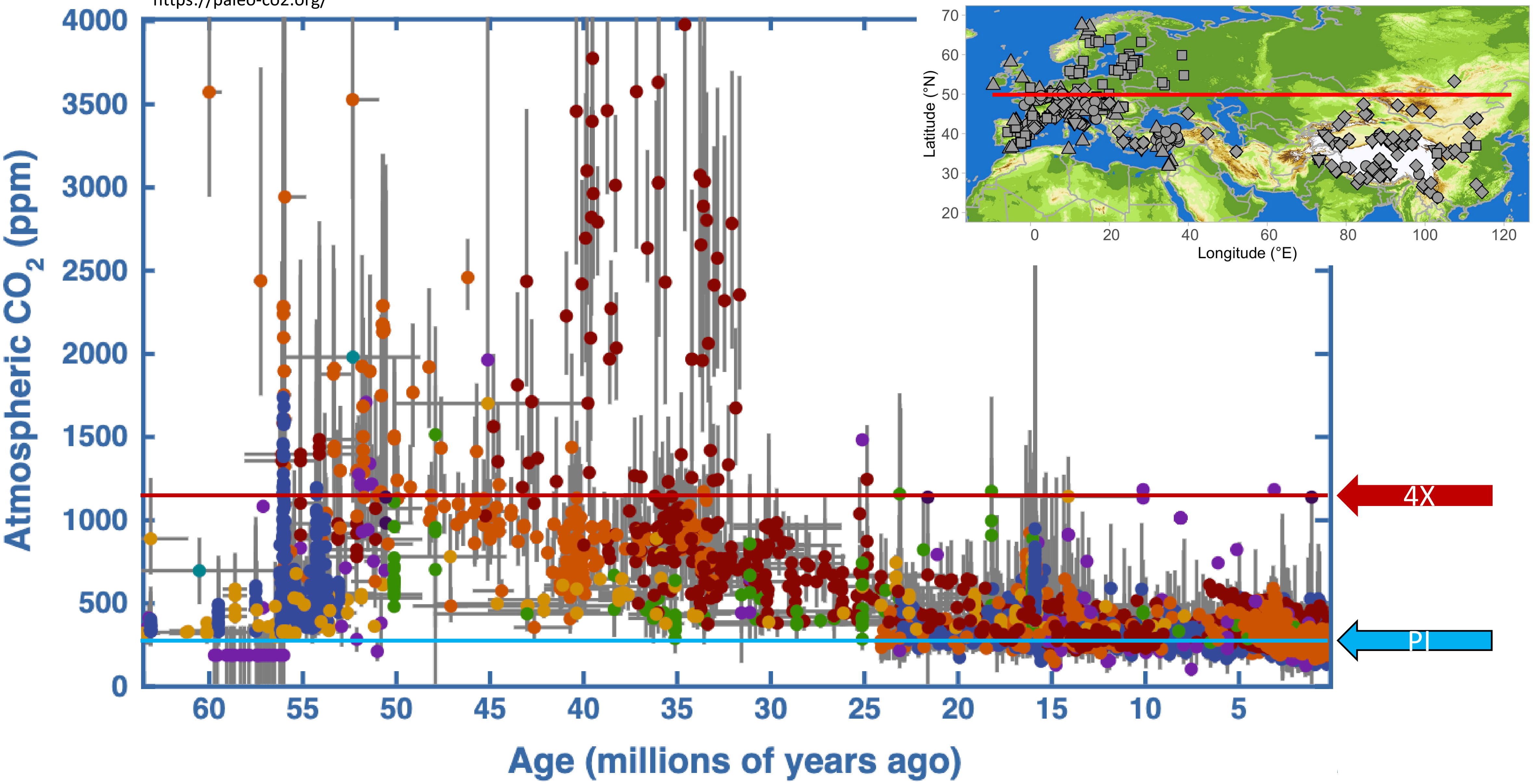
Modeled δ^{18}O Zonal Profile with higher CO_2



3-D Isotope-enabled Community Earth System Model (iCESM1.2)

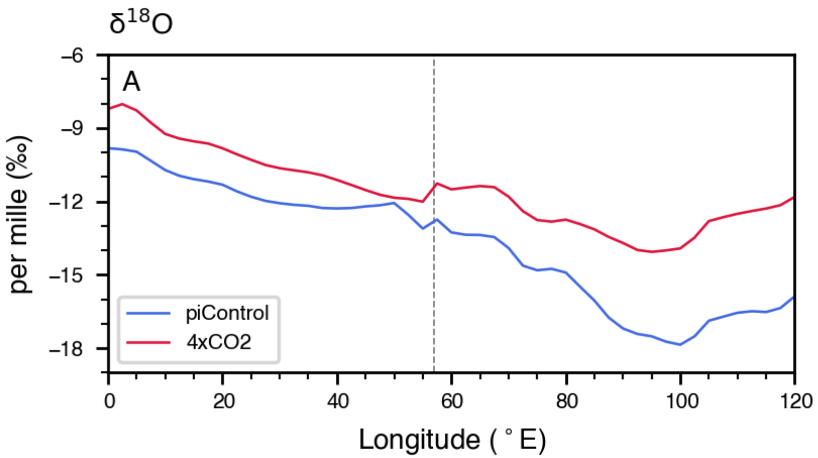
- 2 simulations—pre-industrial (284.7 ppm) and 4x CO_2 (1138.8 ppm)
- Forced by prescribed SSTs and sea ice concentrations from CESM2 simulations in the CMIP6 archive
- Prescribed pre-industrial phenology
- 5 year spin-up to permit 1 m soil δ^{18}O to equilibrate

https://paleo-co2.org/

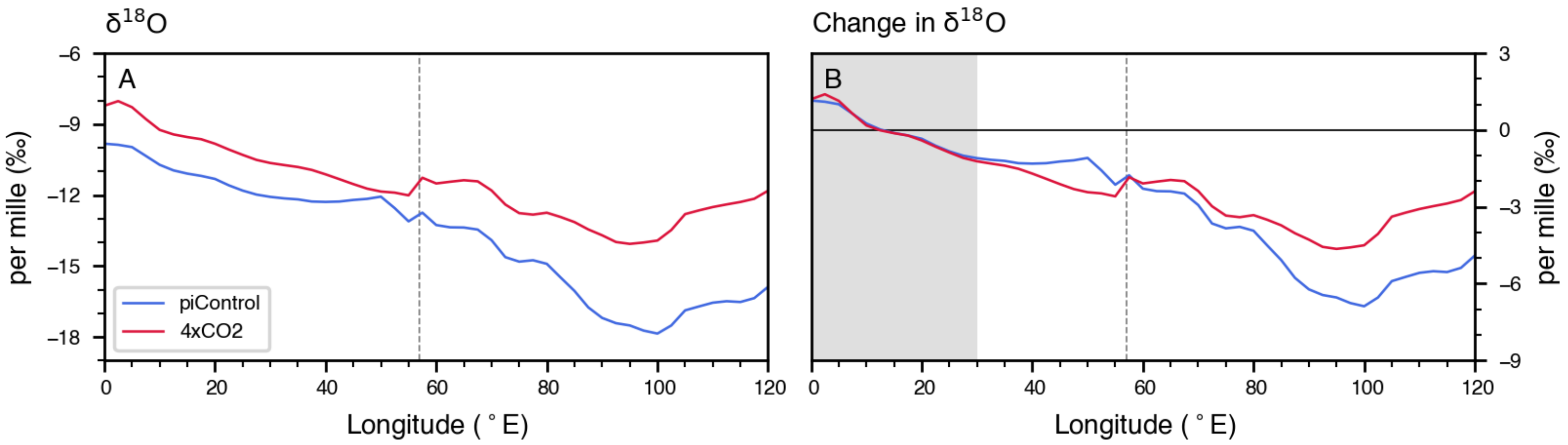


We modeled $\delta^{18}O$ in precipitation along 50°N from -10°E to 120°E at
Pre-Industrial *p*CO_2 and **4X-Pre-Industrial *p*CO_2**

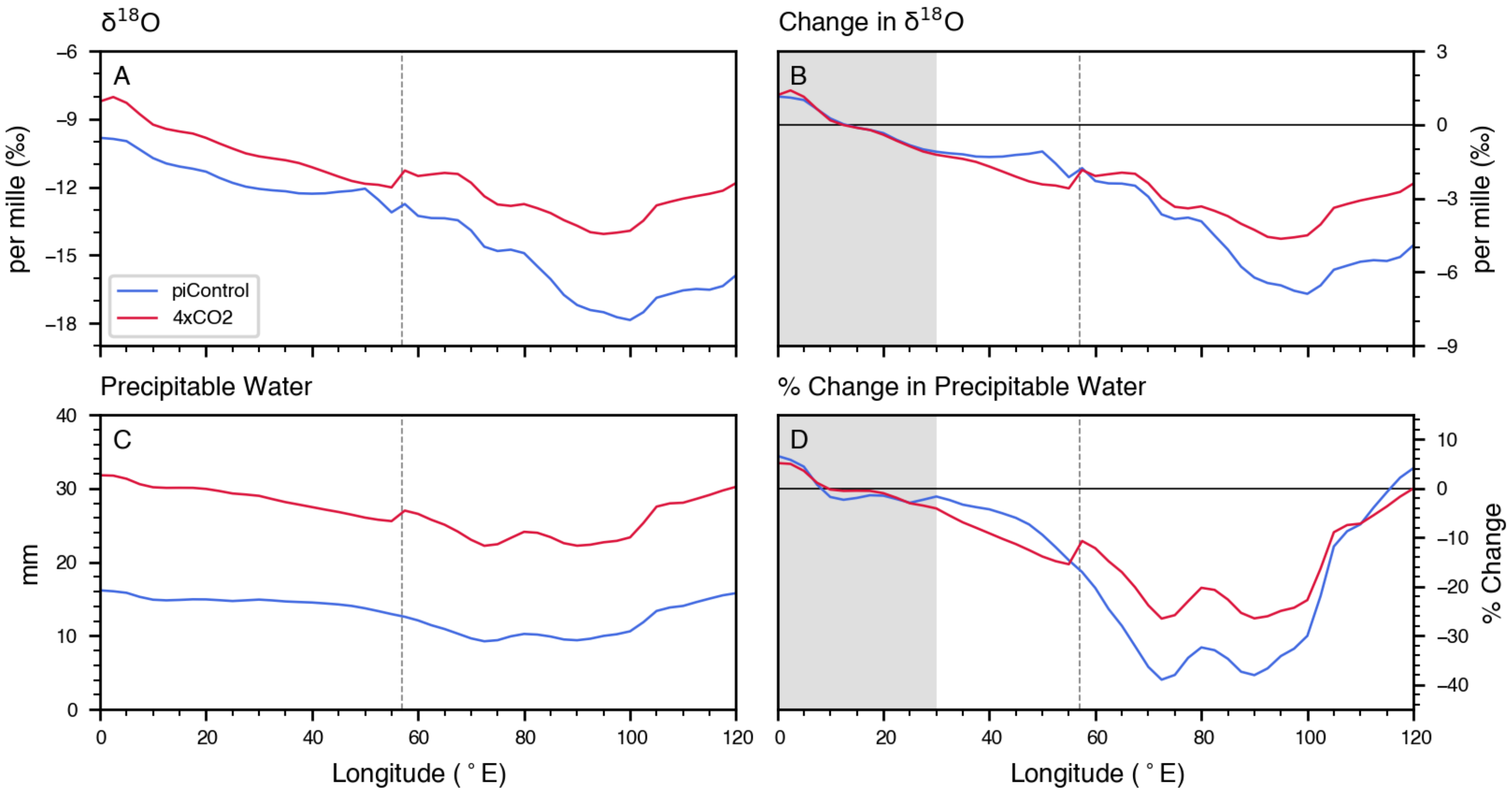
Modeled Isotopic Gradients



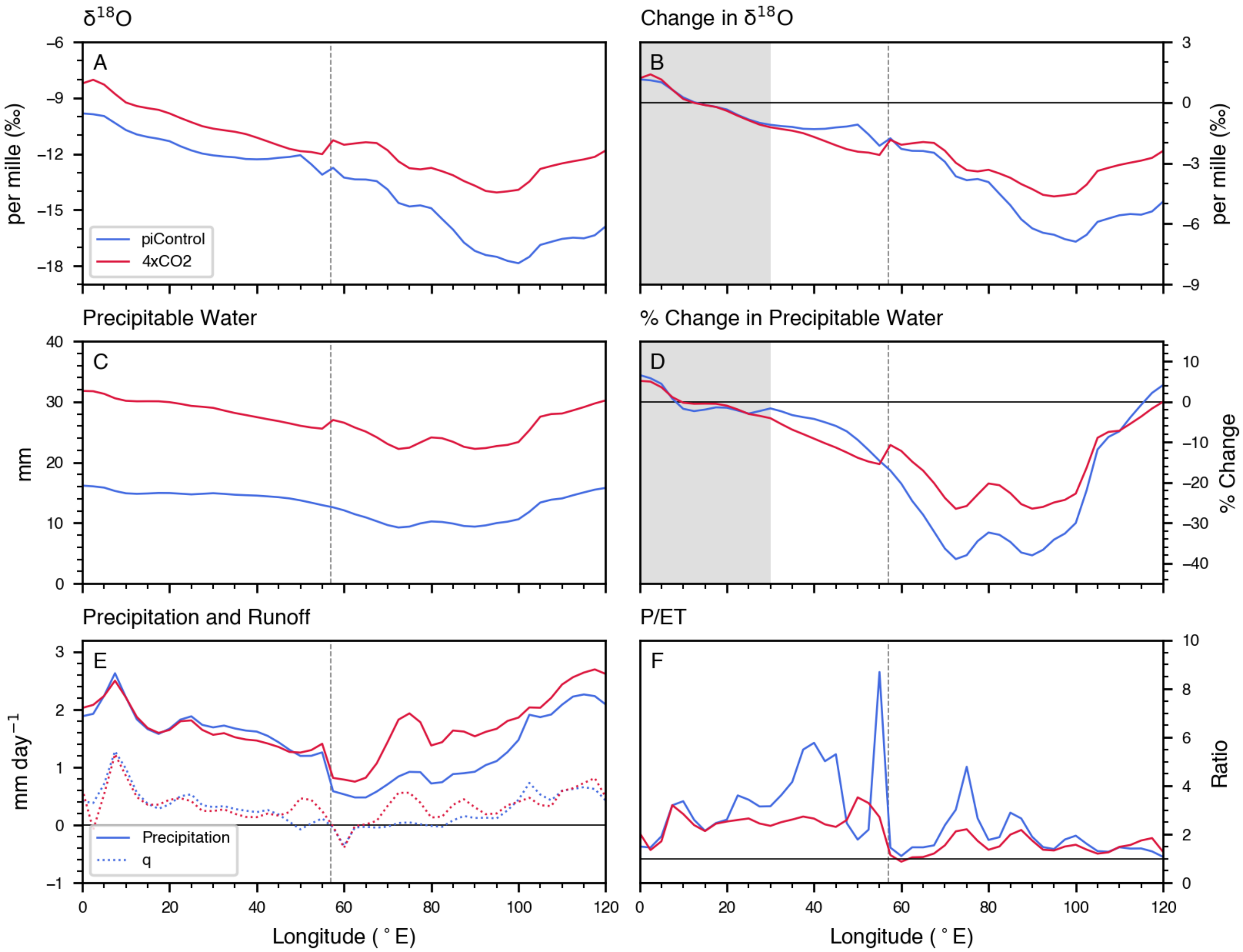
Modeled Isotopic Gradients



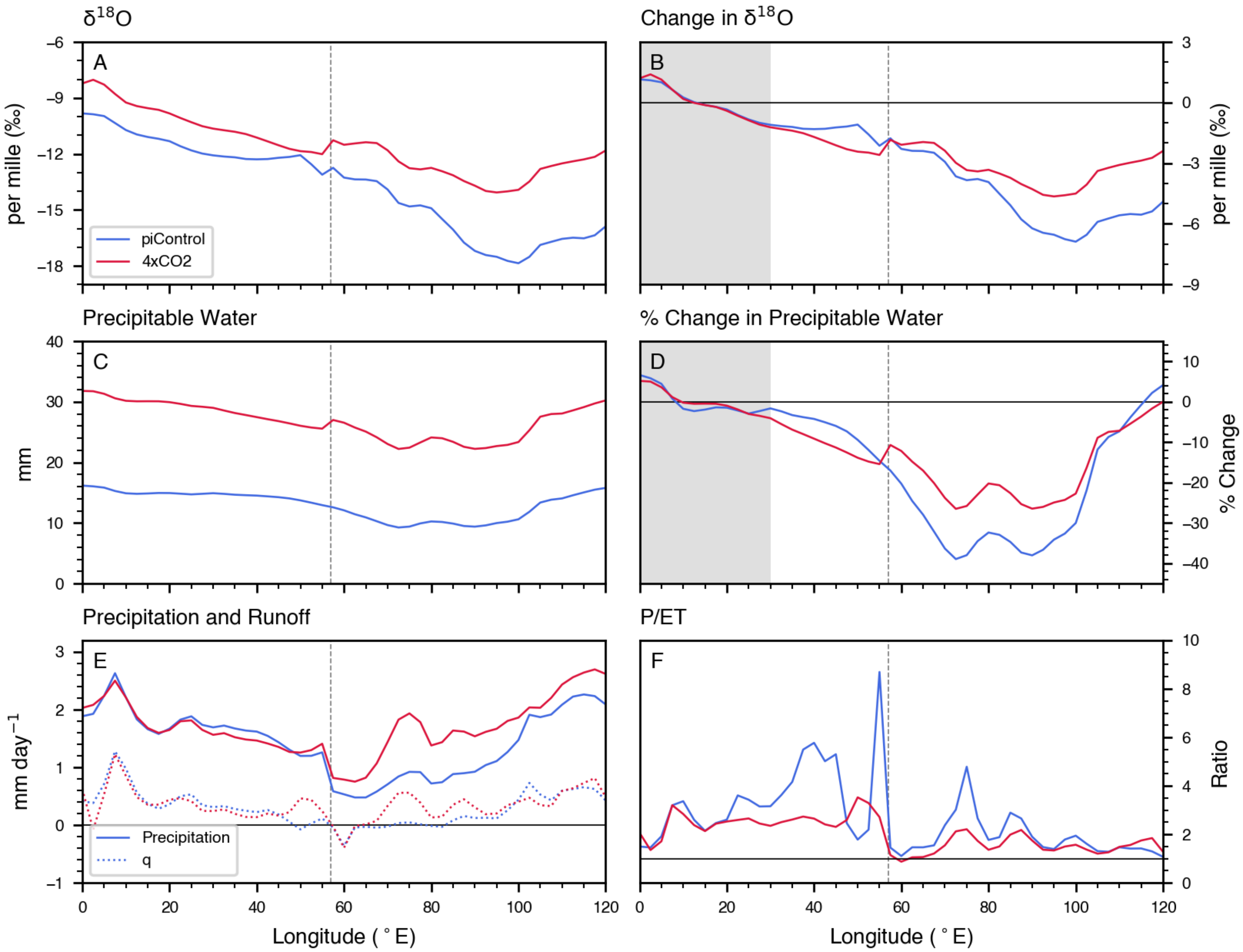
Modeled Isotopic Gradients



Modeled Isotopic Gradients



Modeled Isotopic Gradients

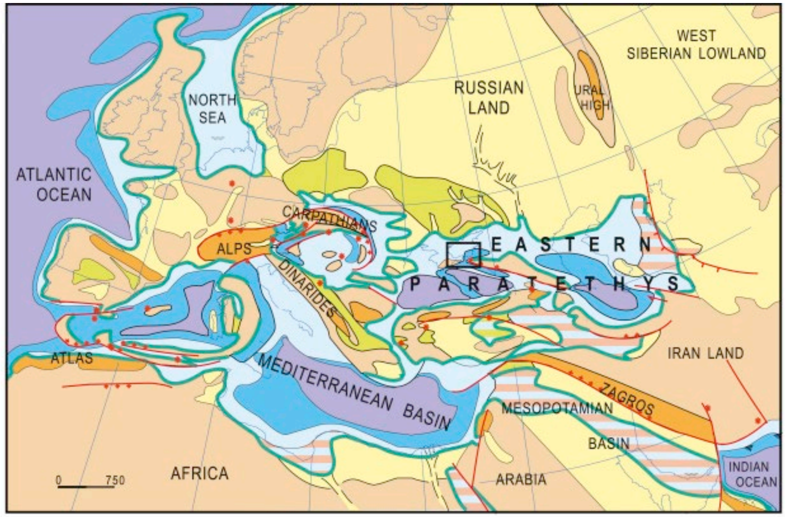


- Shallower gradients produced under high pCO_2
- Divergent response at ~90°E due to lack of topography in the reactive transport model
- **Models predict a shallower gradient with rising CO_2; data suggests the opposite!**

Proxy biases and seasonality

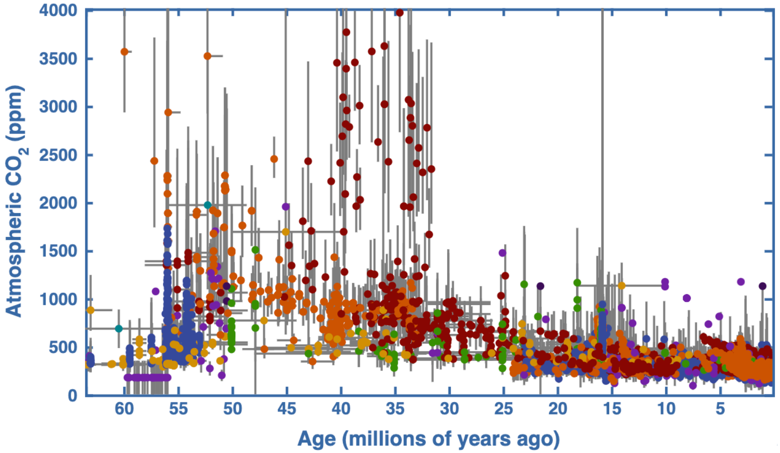
Caves et al. 2017

Changes in paleogeography



Popov et al., 2019

Cenozoic cooling and pCO_2 reduction

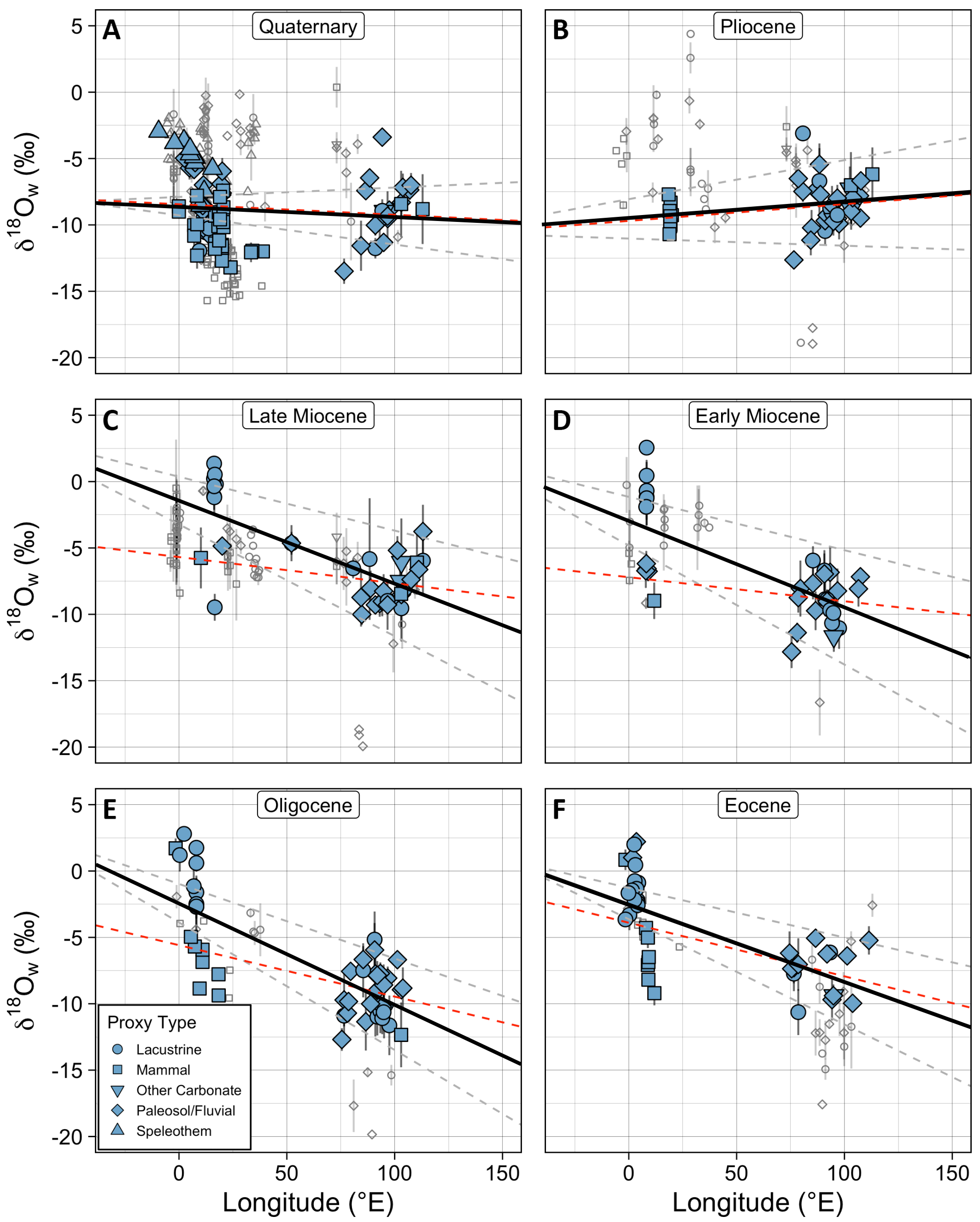


https://paleo-co2.org/

What drives changes in the proxy $\delta^{18}O$ profile over the Cenozoic?

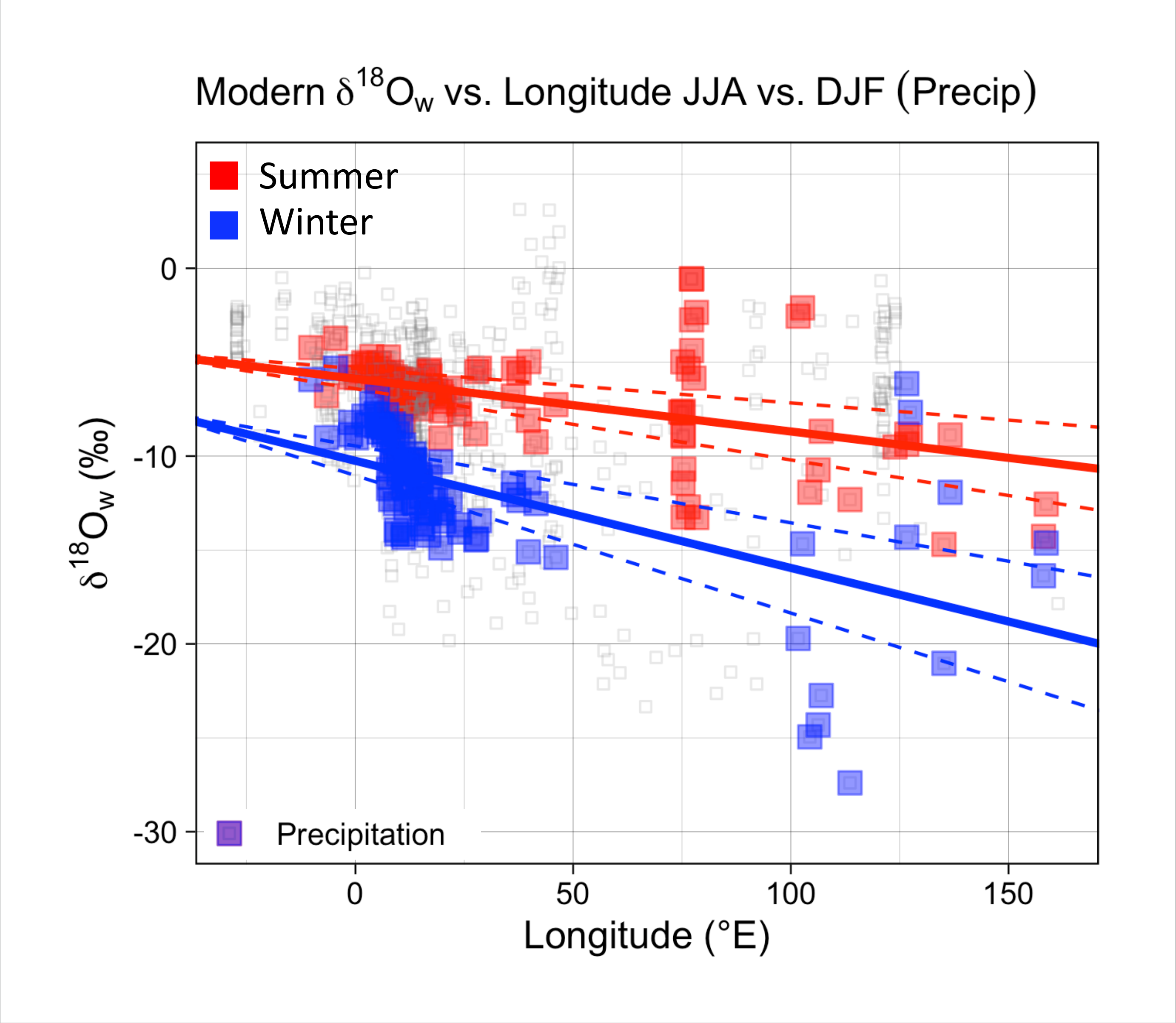
Proxy Biases: Evaporation

- Lacustrine samples most prone to evaporative enrichment; raises $\delta^{18}O$ of carbonate
- Screened for evaporation by plotting O vs. C
  - Use only the lowest 20% of lacustrine values from sites indicating evaporative enrichment (Rowley and Currie 2006)
- Excluding lacustrine samples (red dashed line):
  - We see the same trend of steeper gradient in early Cenozoic, then shallower in the Pliocene and Quaternary
- Other non-evaporatively enriched samples have similarly high $\delta^{18}O$



Seasonality of Proxy Formation

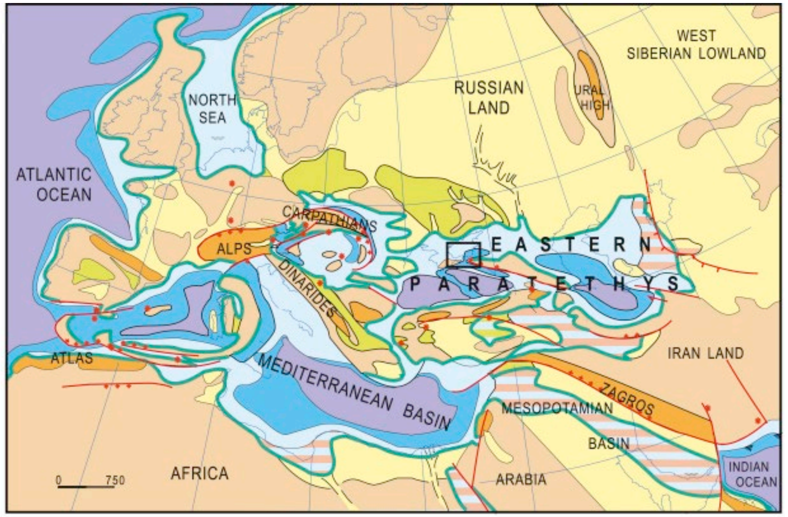
- Precipitation $\delta^{18}O$ is highly seasonally variable
  - Thus, the timing of carbonate formation influences the $\delta^{18}O$ of carbonate
- Paleosol carbonates form in warm and dry periods
  - Other proxies likely also have seasonal biases that are less well understood
- Shift in timing of carbonate formation:
  - **Eocene-Late Miocene:** Carbonates in Europe may have formed in summer months and thus record peak $\delta^{18}O$
  - **Pliocene and Quaternary:** Shift in carbonate seasonality (changes in wet season) in Europe may drive shift to lower $\delta^{18}O$ recorded in proxies



Proxy biases and seasonality

- Evaporative enrichment does not appear to drive changes in the gradient
- Decrease in Pliocene $\delta^{18}O$ in Europe is potentially due to a shift in the seasonality of proxy formation

Changes in paleogeography



Popov et al., 2019

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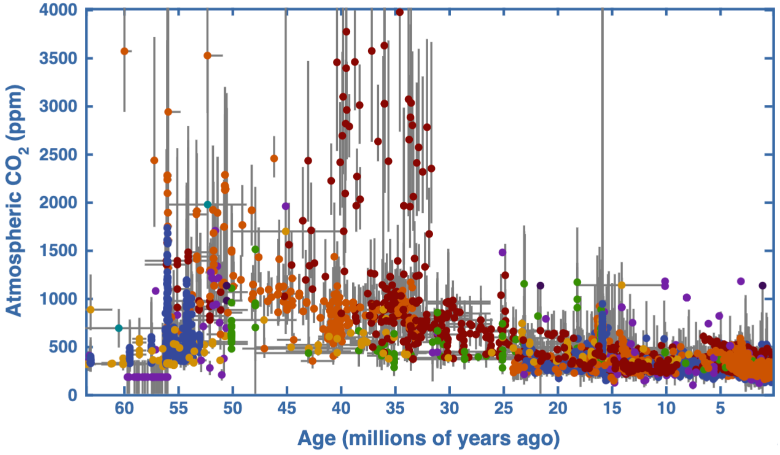
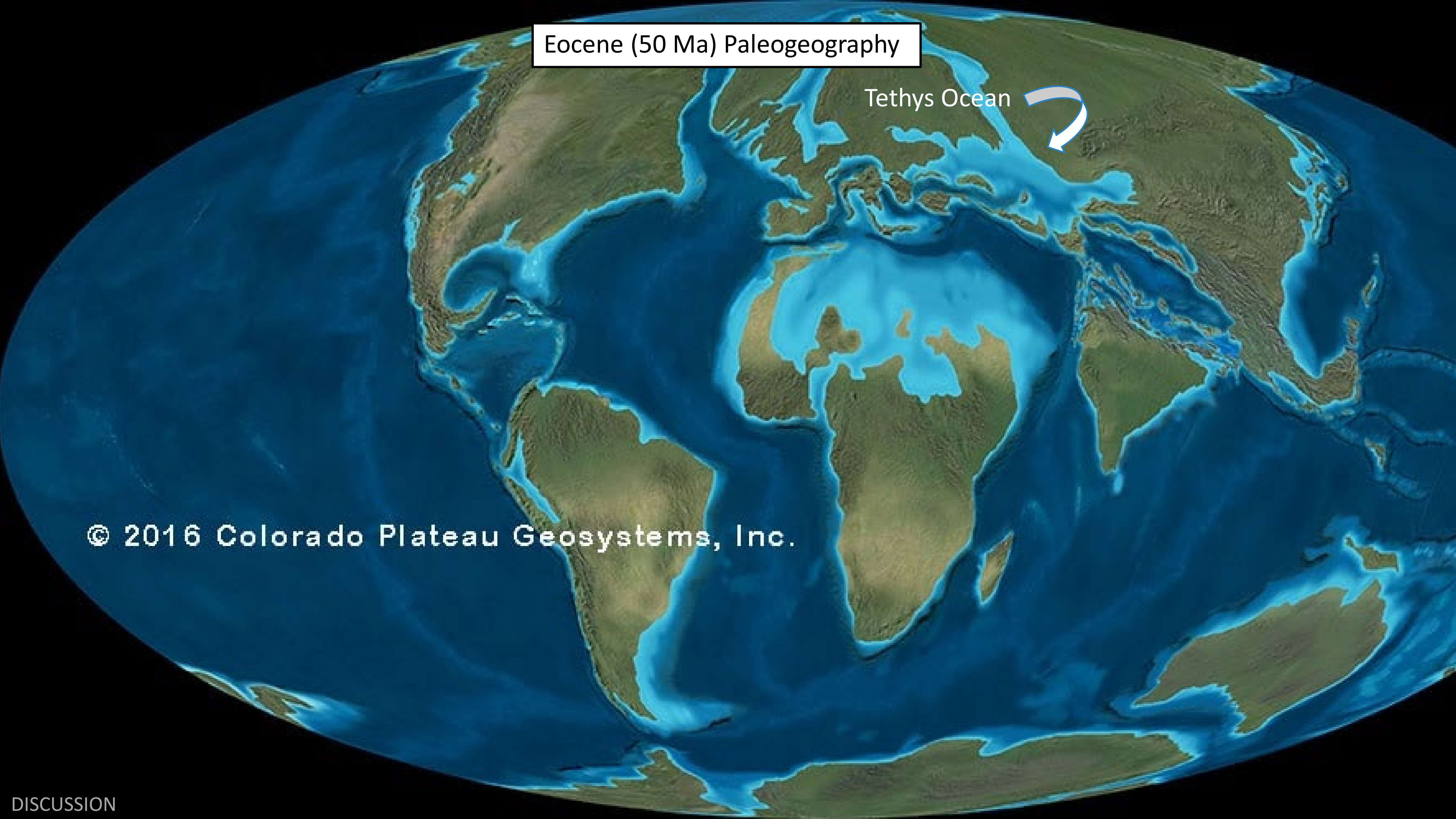


https://paleo-co2.org/

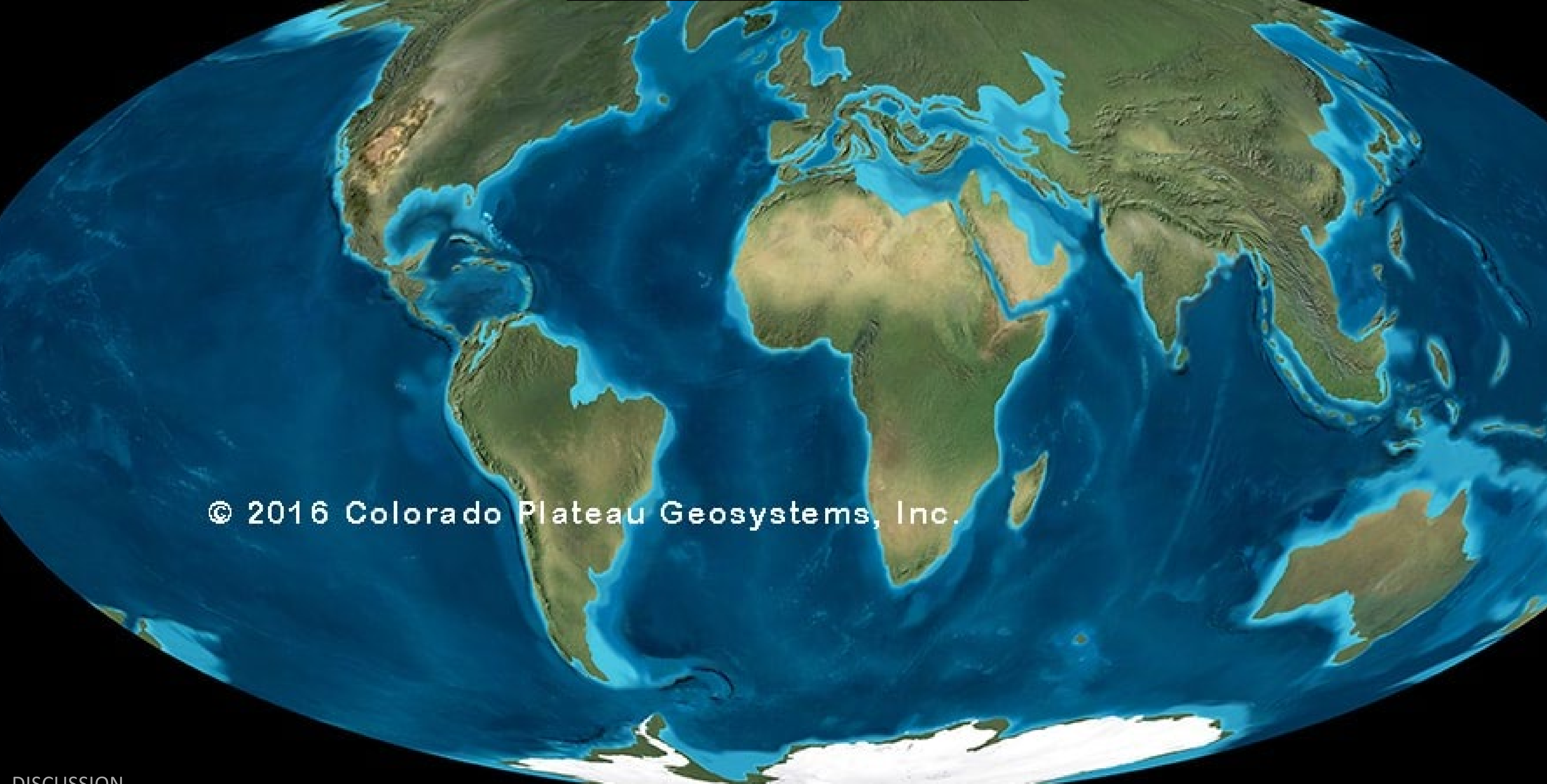
What drives changes in the proxy $\delta^{18}O$ gradient throughout the Cenozoic?

Eocene (50 Ma) Paleogeography



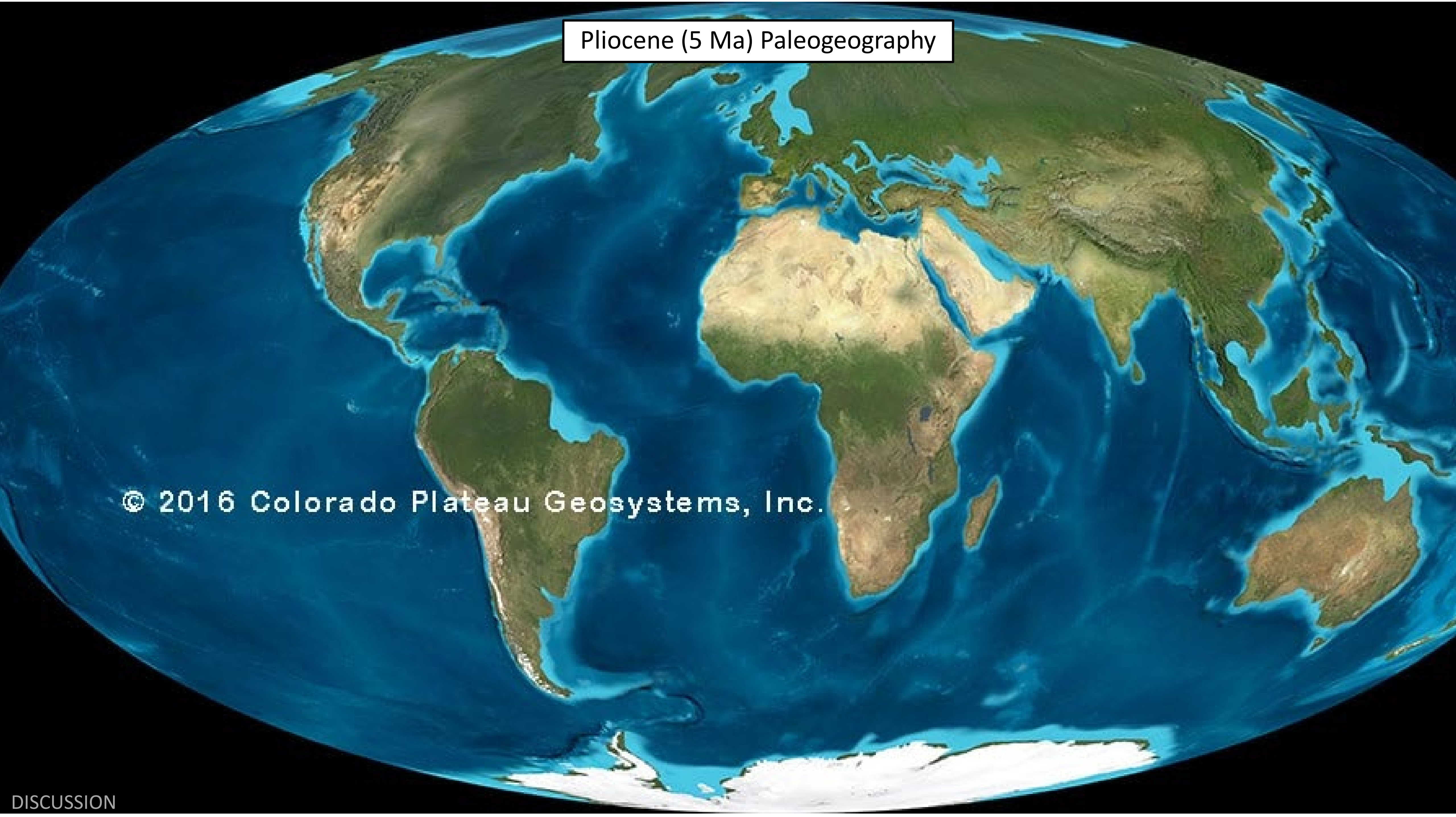
DISCUSSION

Mid-Miocene (13 Ma) Paleogeography

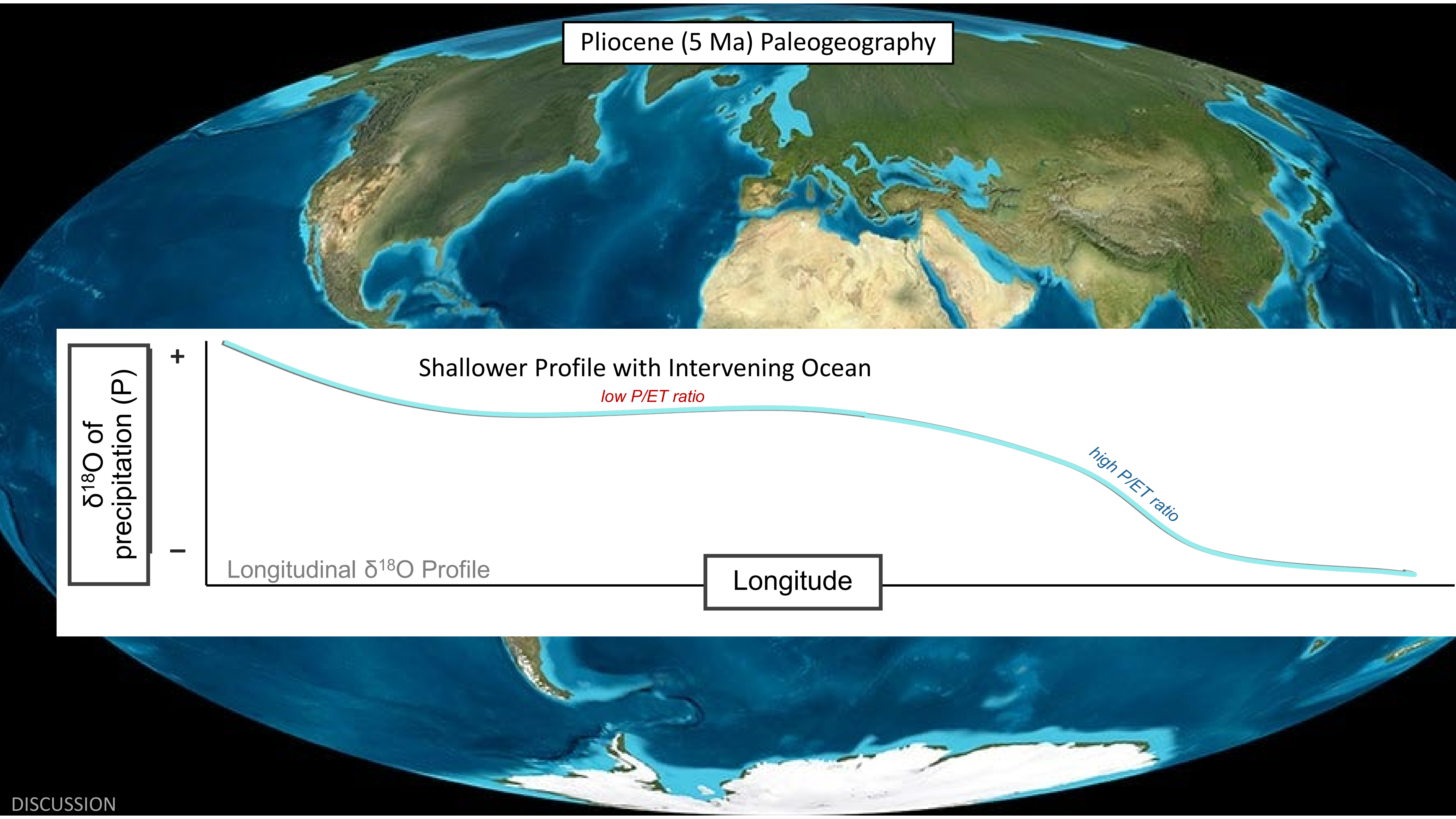


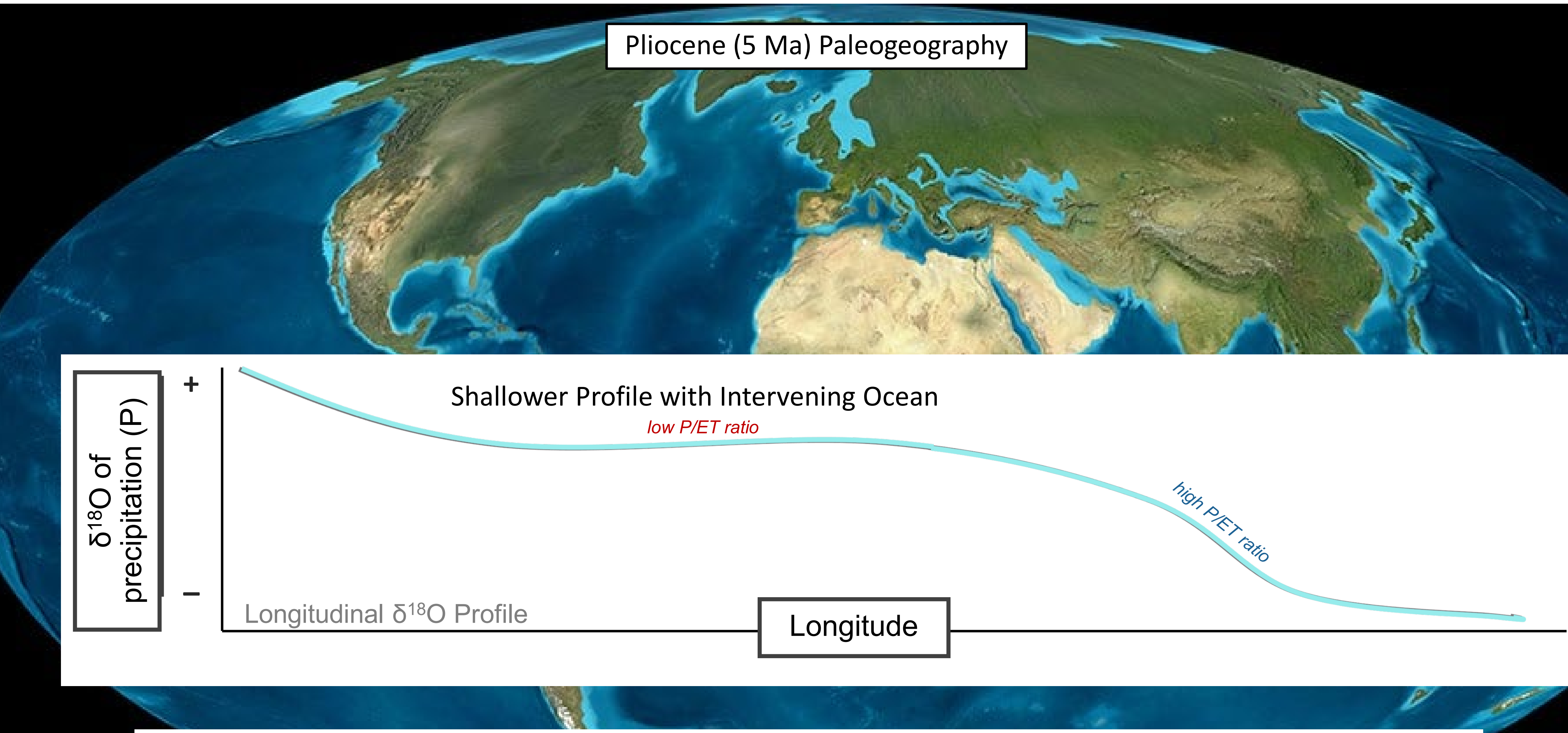
DISCUSSION

Pliocene (5 Ma) Paleogeography



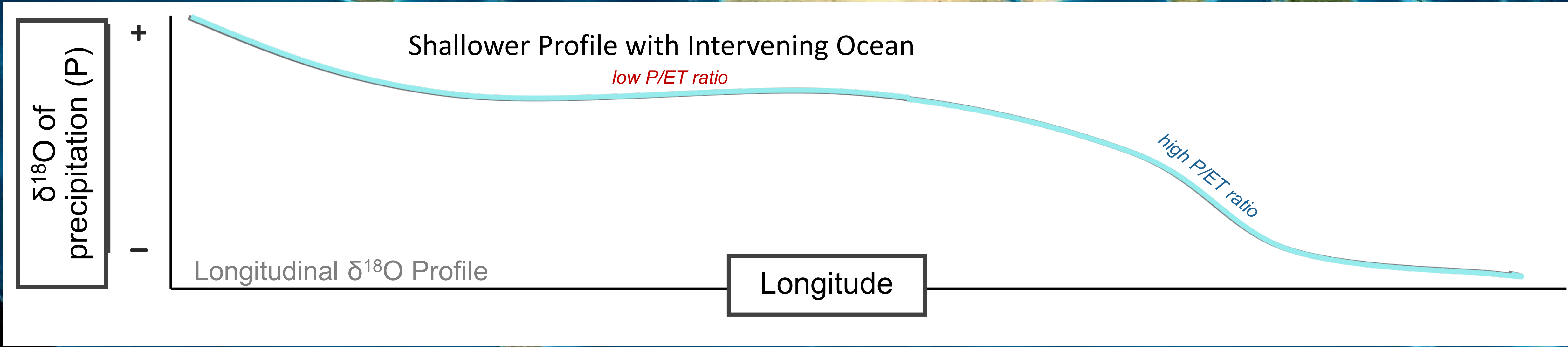
DISCUSSION


Pliocene (5 Ma) Paleogeography
Shallower Profile with Intervening Ocean
low P/ET ratio
high P/ET ratio
δ18O of precipitation (P)
+
–
Longitudinal δ18O Profile
Longitude
DISCUSSION



- Topographic changes:
  - Cenozoic ranges are oriented E-W and therefore do not block westerly moisture from inland transport
  - Instead, help to prevent mixing of moisture sources between Atlantic/westerly moisture and southerly (Mediterranean, Indian Ocean, etc.) moisture

Pliocene (5 Ma) Paleogeography



- Ice-sheet/vegetation changes:
  - Northern Hemisphere ice not present before Pliocene
  - Large changes in vegetation at high latitudes—may cause large changes in hydroclimate (Feng et al. 2022)
  - These changes are ~ coincident with shift in zonal $\delta^{18}O$ gradient

Proxy biases and seasonality

- Evaporative enrichment is filtered and does not drive changes in the gradient
- Downward shift in Pliocene $\delta^{18}O$ in Europe is potentially due to a shift in the seasonality of proxy formation

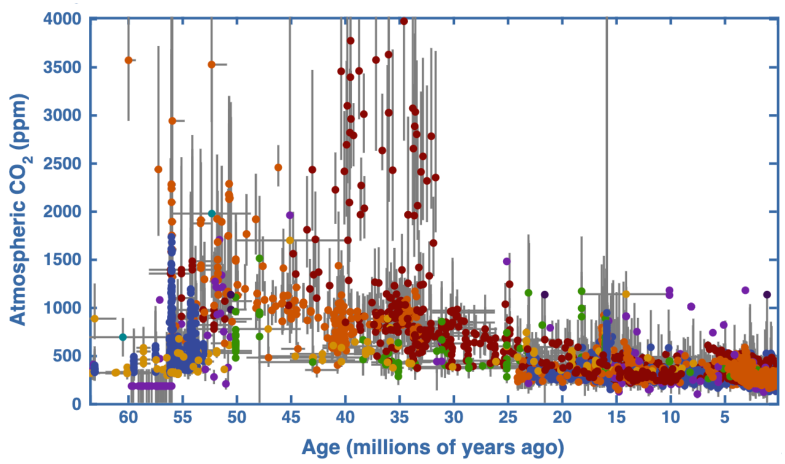
Küçükusyal and Kapur, 2014

Changes in paleogeography

- Changes in Paratethys extent or topography are not driving changes in the $\delta^{18}O$ profile
- Changes in ice sheet extent and vegetation may explain disagreement

Popov et al., 2019

Cenozoic cooling and pCO_2 reduction

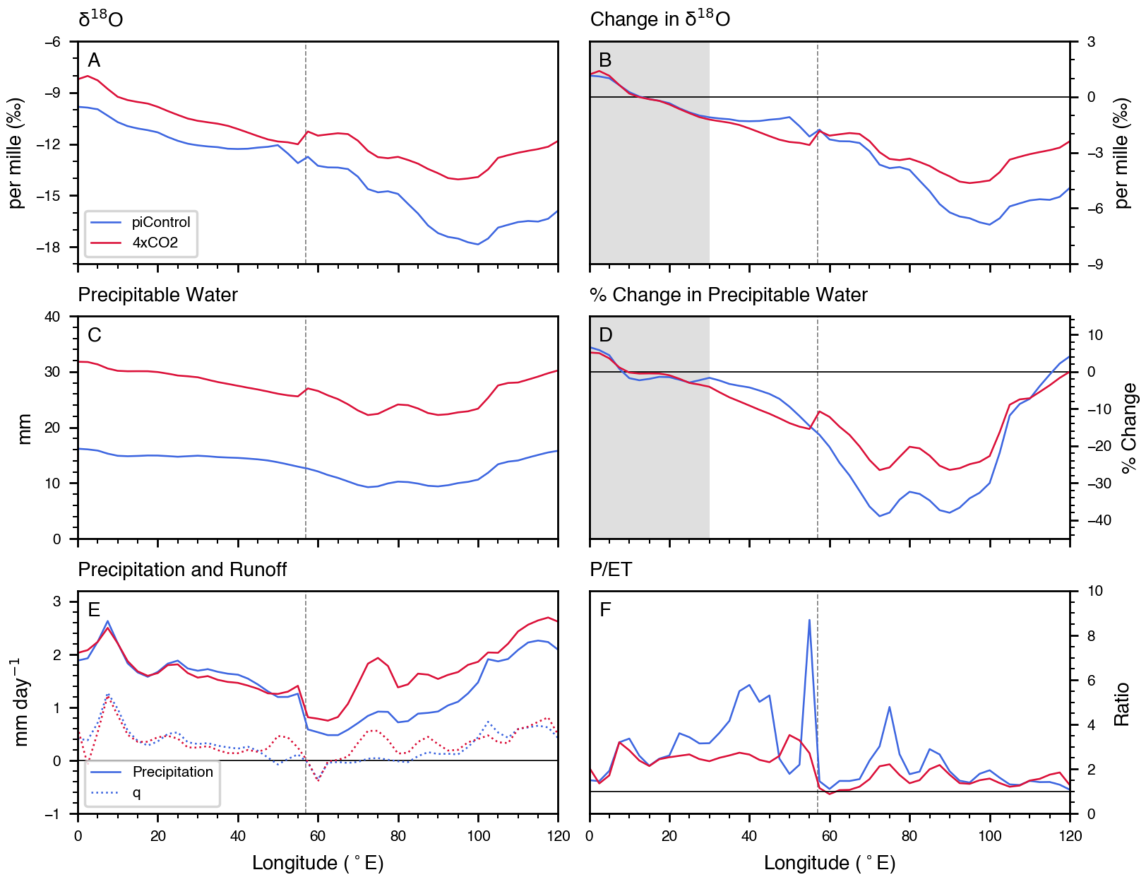


https://paleo-co2.org/

What drives changes in the proxy $\delta^{18}O$ gradient throughout the Cenozoic?

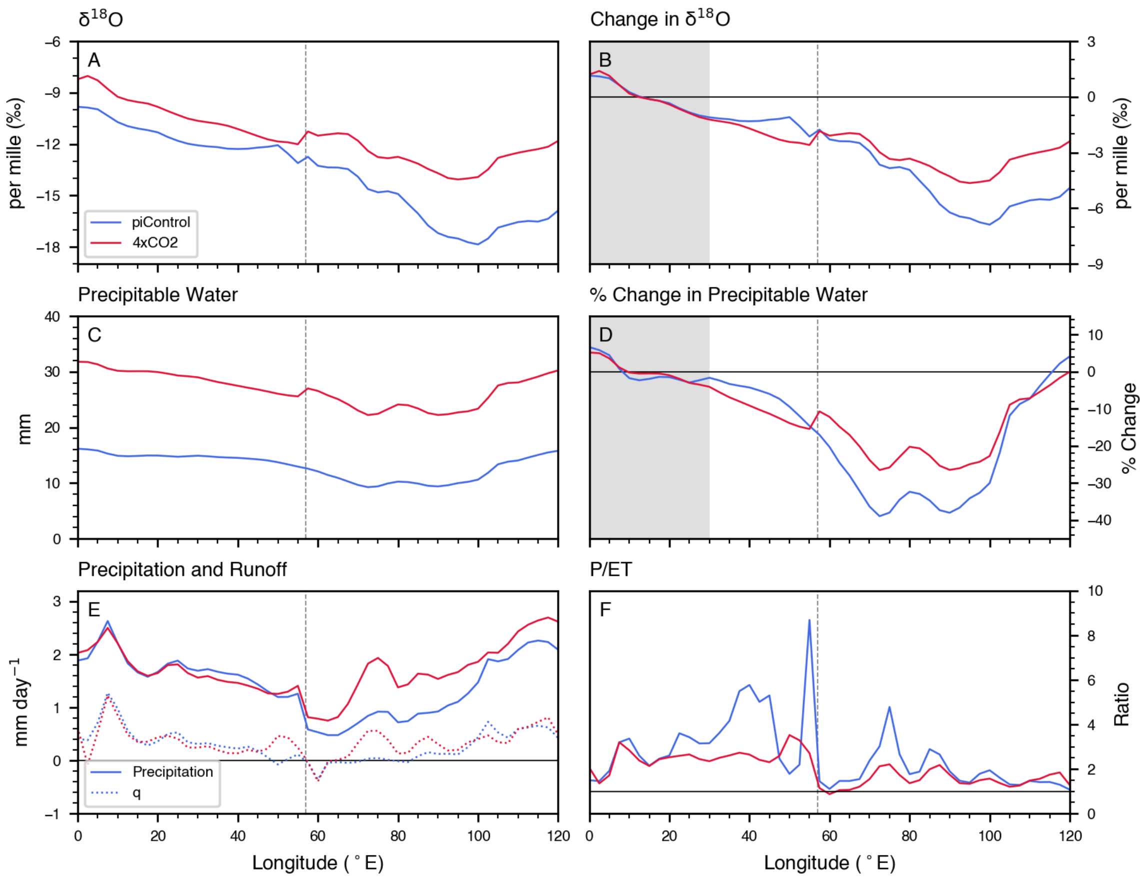
Partitioning of precipitation into runoff and ET

- Increases in specific humidity should result in shallower $\delta^{18}O$ gradients
- Increasing runoff should result in steeper $\delta^{18}O$ gradients
- P/ET decreases slightly in 4x CO_2 simulation
- Runoff change appears negligible



Partitioning of precipitation into runoff and ET

- Steeper zonal $\delta^{18}O$ gradients may indicate that runoff increases in greenhouse climates more than predicted by models
- Changes in timing of precip (seasonality or storm intensity)?
- Decreases in stomatal conductance?

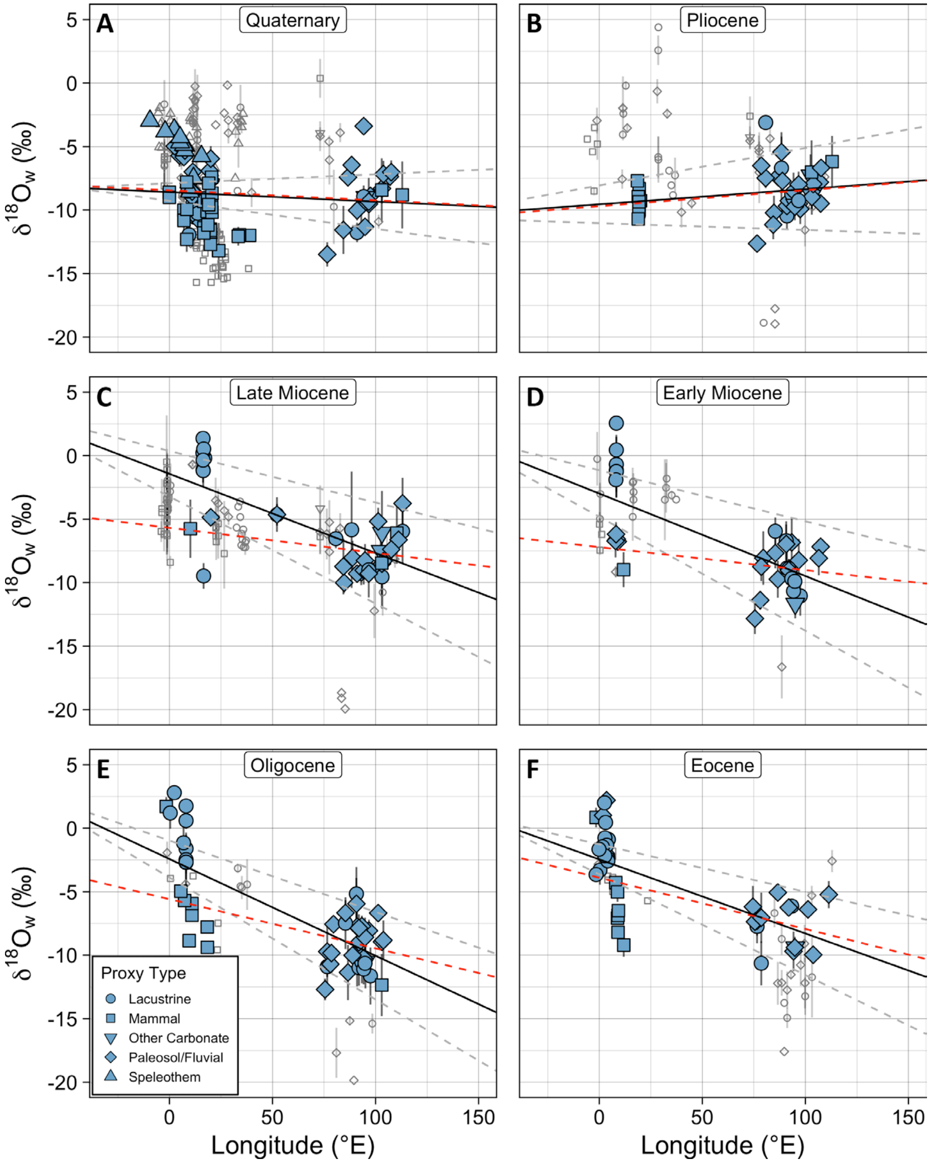


What may explain the discrepancy between the proxy and modeled $\delta^{18}O$ gradients?

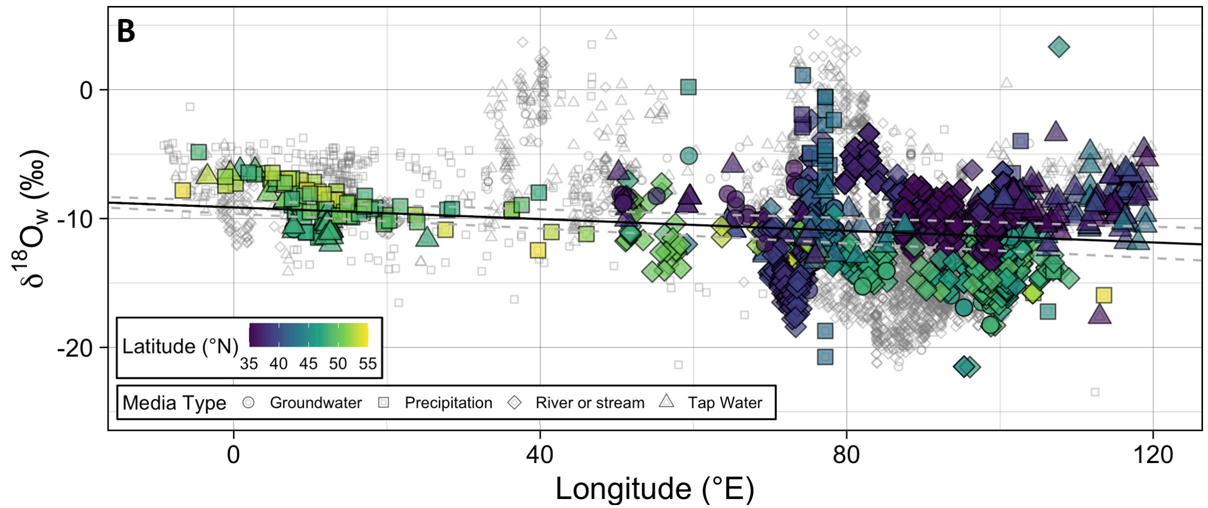
1. Seasonality
2. Changes in high-latitude albedo/land surface, including ice sheet extent and vegetation

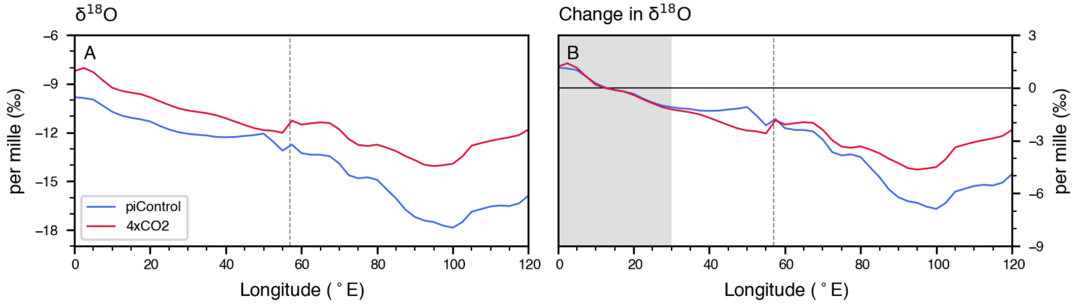
1. Under-estimated increases in runoff generation in models

Future work might try to target continental-scale patterns of $\delta^{18}O$ to understand processes that modify hydroclimate



Questions?





Now published in EPSL (Driscoll et al. 2024)

doi: 10.1016/j.epsl.2024.118623

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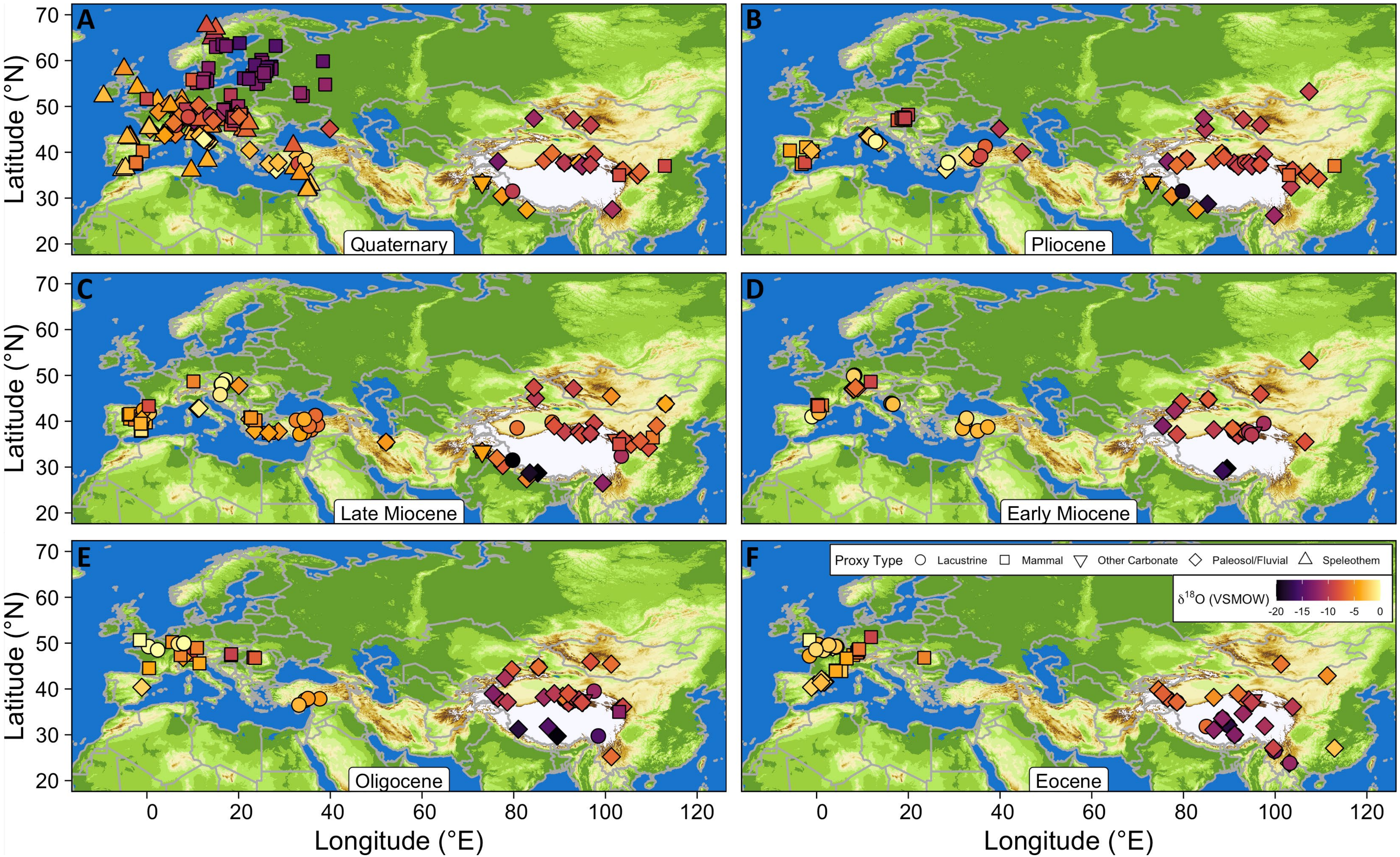
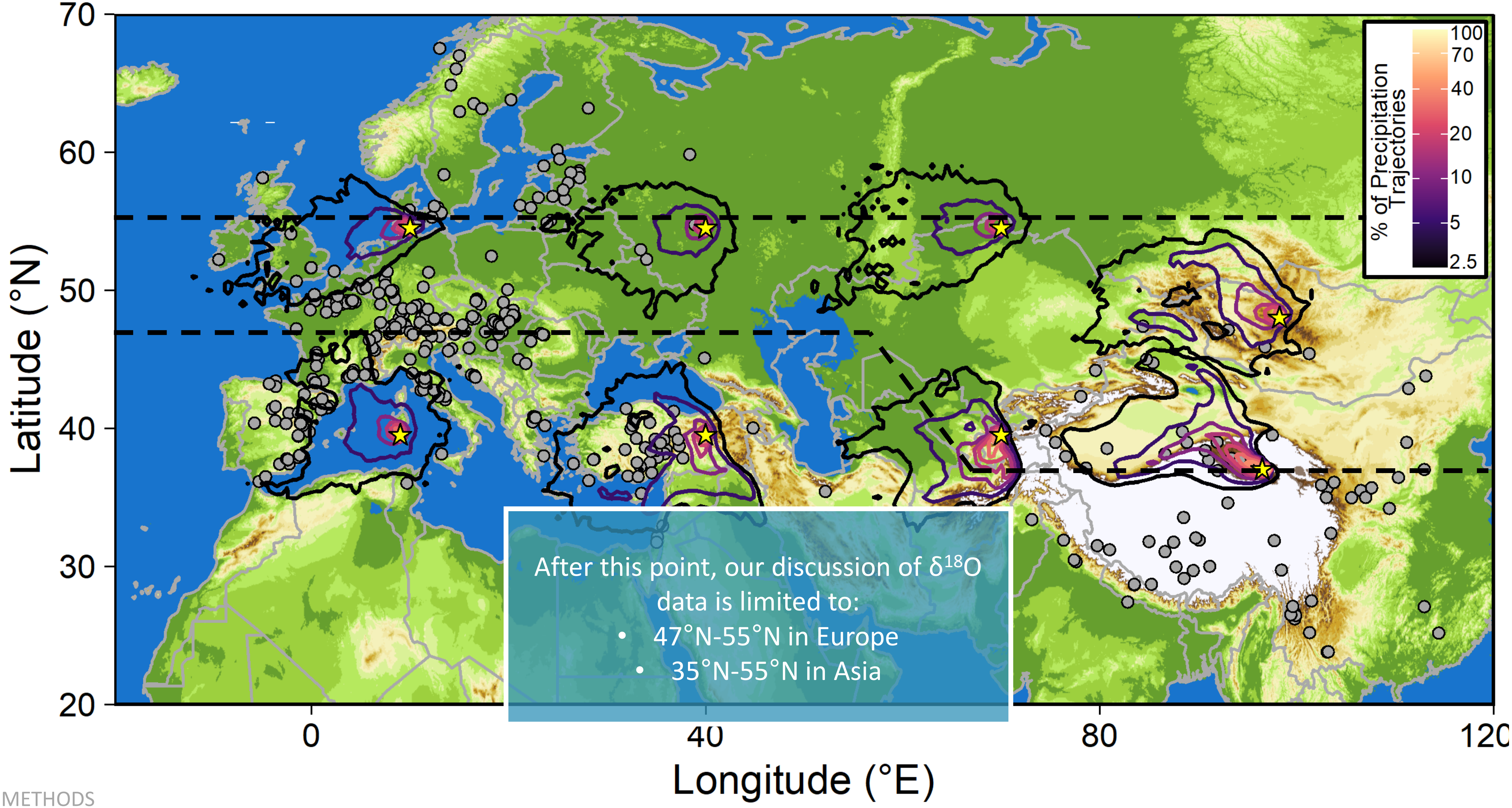
Supplemental Slides

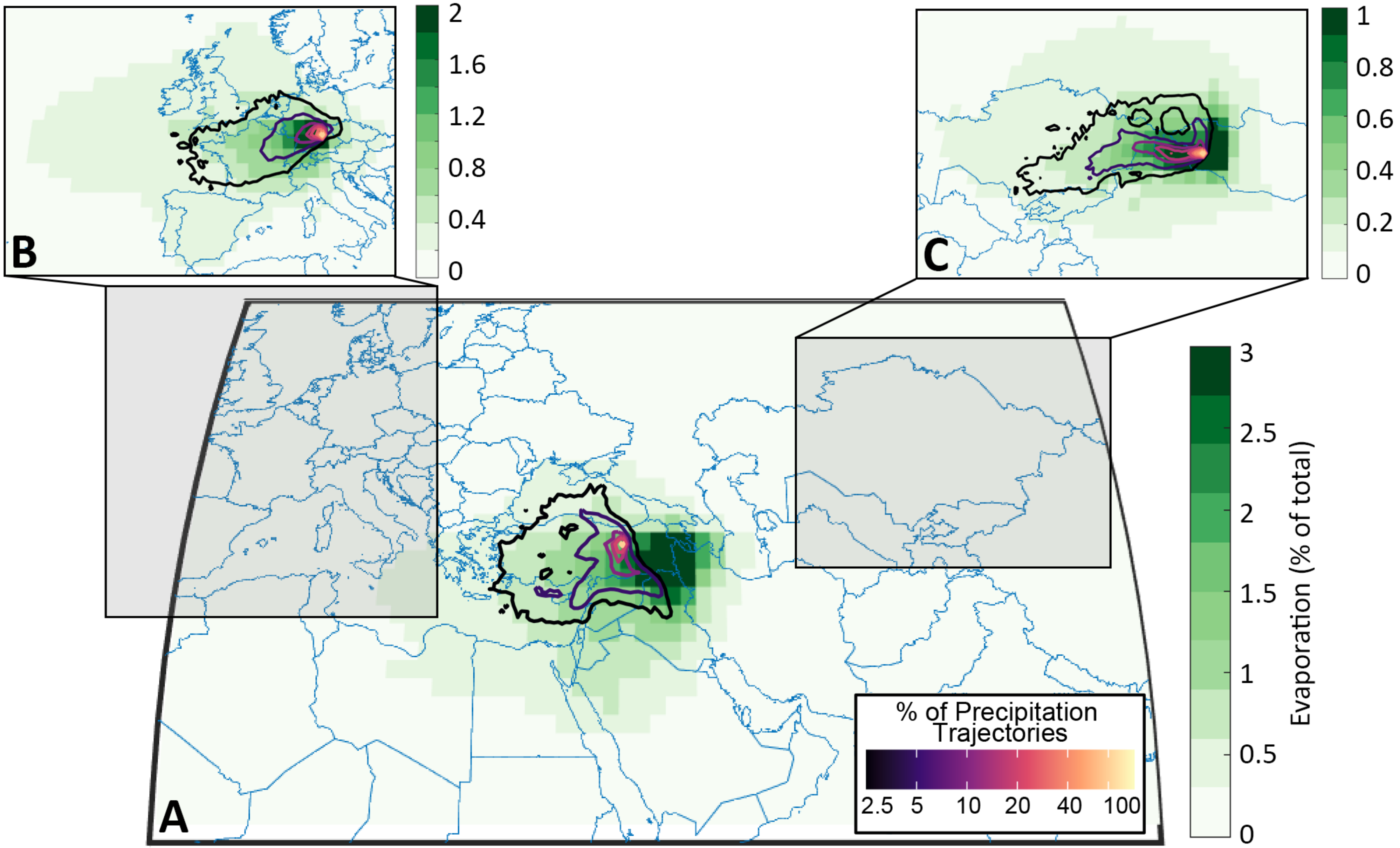

A
Quaternary
B
Pliocene
C
Late Miocene
D
Early Miocene
E
Oligocene
F
Eocene
Proxy Type
Lacustrine
Mammal
Other Carbonate
Paleosol/Fluvial
Speleothem
δ18O (VSMOW)
-20 -15 -10 -5 0
Latitude (°N)
Longitude (°E)

RESULTS

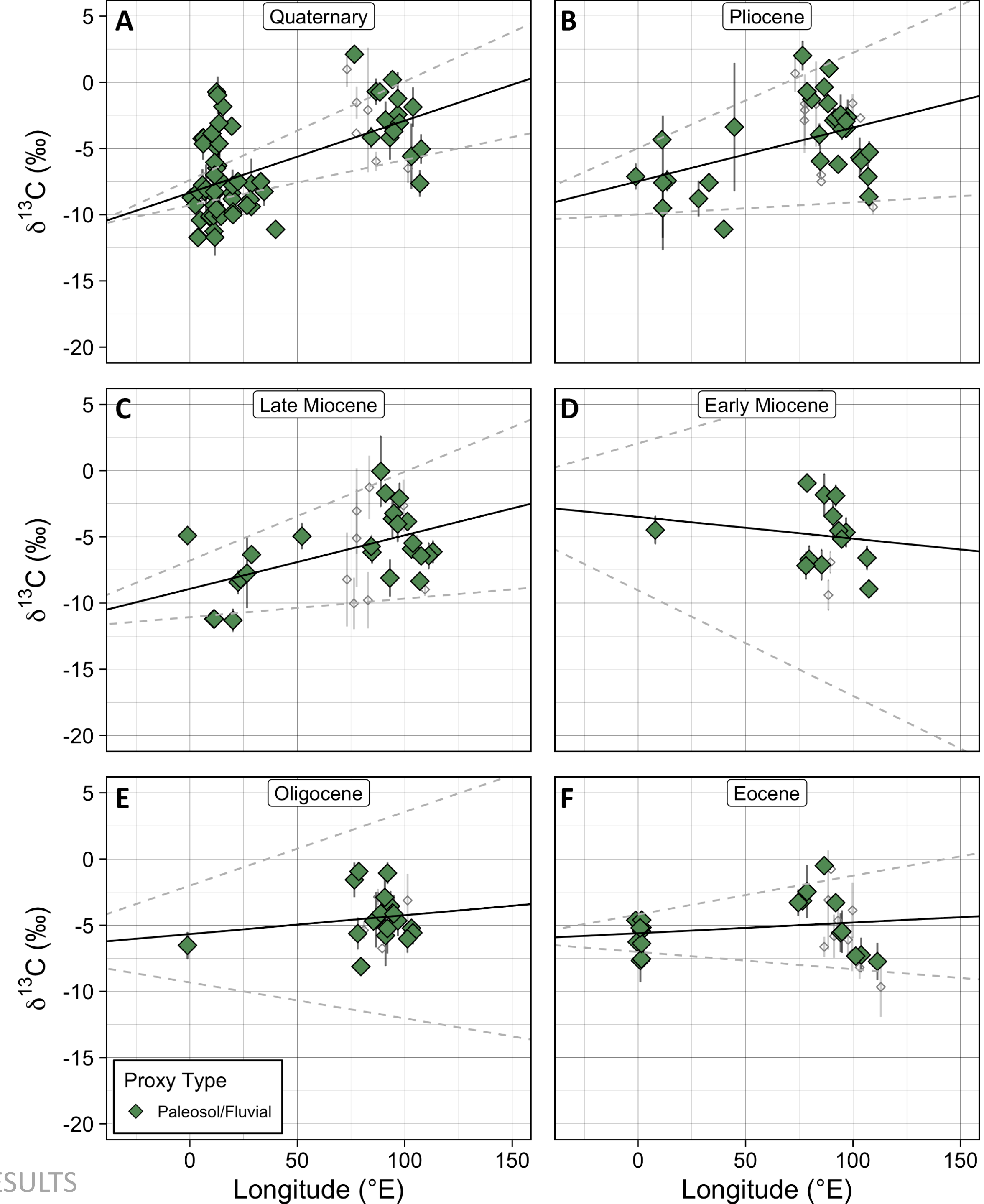


After this point, our discussion of δ¹⁸O data is limited to:

- 47°N-55°N in Europe
- 35°N-55°N in Asia



A
B
C
2
1.6
1.2
0.8
0.4
0
1
0.8
0.6
0.4
0.2
0
3
2.5
2
1.5
1
0.5
0
Evaporation (% of total)
% of Precipitation Trajectories
2.5
5
10
20
40
100



Proxy $\delta^{13}C$ Longitudinal Gradients

Geologic Epoch	Europe Mean $\delta^{13}C$	Asia Mean$\delta^{13}C$	P-value	Gradient
Quaternary	-7.68	-2.72	5.8e-07*	0.054
Pliocene	-7.42	-3.16	4.8e-04*	0.041
Late Miocene	-8.66	-4.60	0.0015*	0.041
Early Miocene	-4.49	-5.18	-	-0.016
Oligocene	-6.52	-4.52	0.17	0.014
Eocene	-5.87	-4.51	-	0.0081

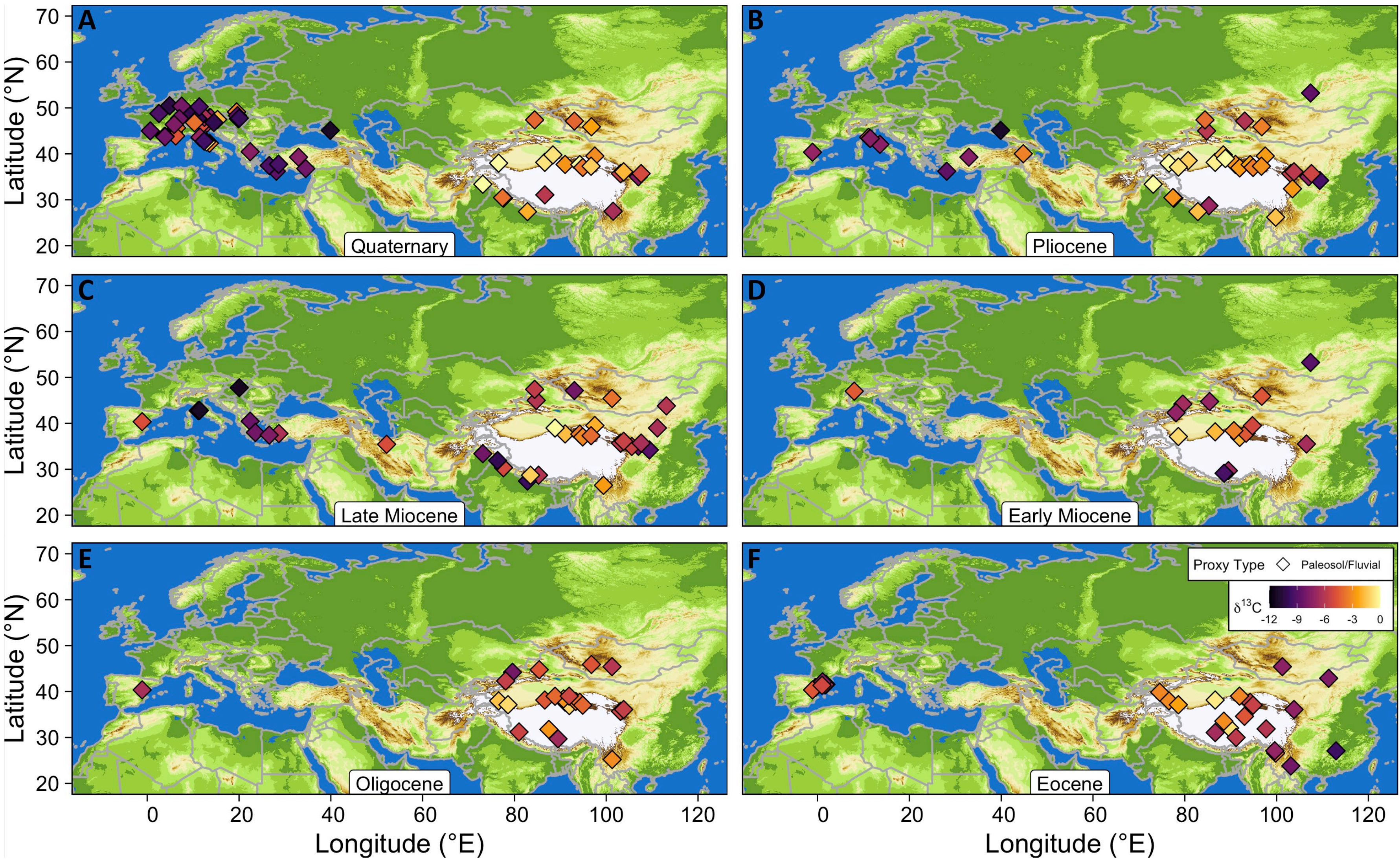
Paleosol $\delta^{13}C$ typically used as a proxy for…

- More C4 vegetation = higher $\delta^{13}C$
- C4 vegetation only widespread in Miocene
- No evidence for extensive spread of C4 in Europe or northern Asia since Miocene

- Lower pCO_2 = lower $\delta^{13}C$
- Asia $\delta^{13}C$ increases through Cenozoic -> not recording change in pCO_2
- Europe $\delta^{13}C$ decreases through Cenozoic -> may reflect change in pCO_2

Paleosol δ^{13}C as a paleo-productivity proxy

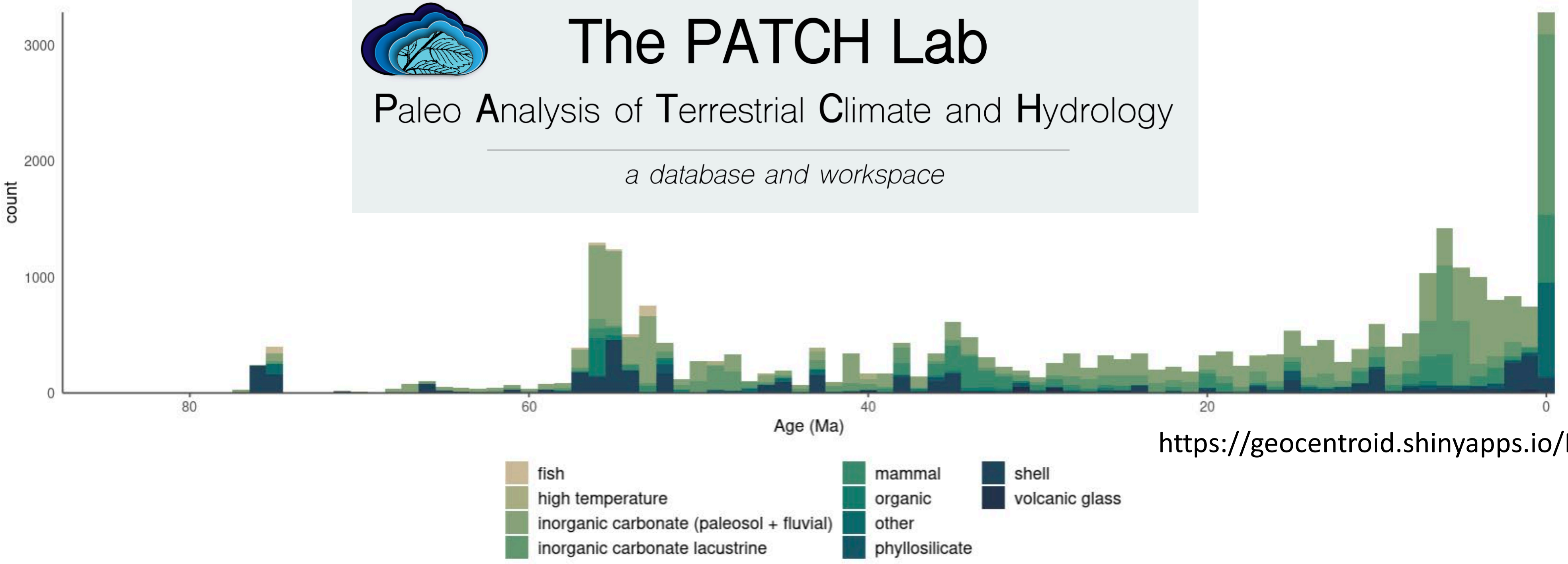
- The δ^{13}C of C3 vegetation affected by aridity
  - Field studies show increased aridity is linked to higher δ^{13}C
- Asia:
  - Increase in δ^{13}C throughout the Cenozoic indicates reduction in plant productivity
- Europe
  - Decrease in δ^{13}C suggests increase in plant productivity
  - Could also be a result of lower atmospheric $p\mathrm{CO_2}$
- Data-limited in Europe in early Cenozoic



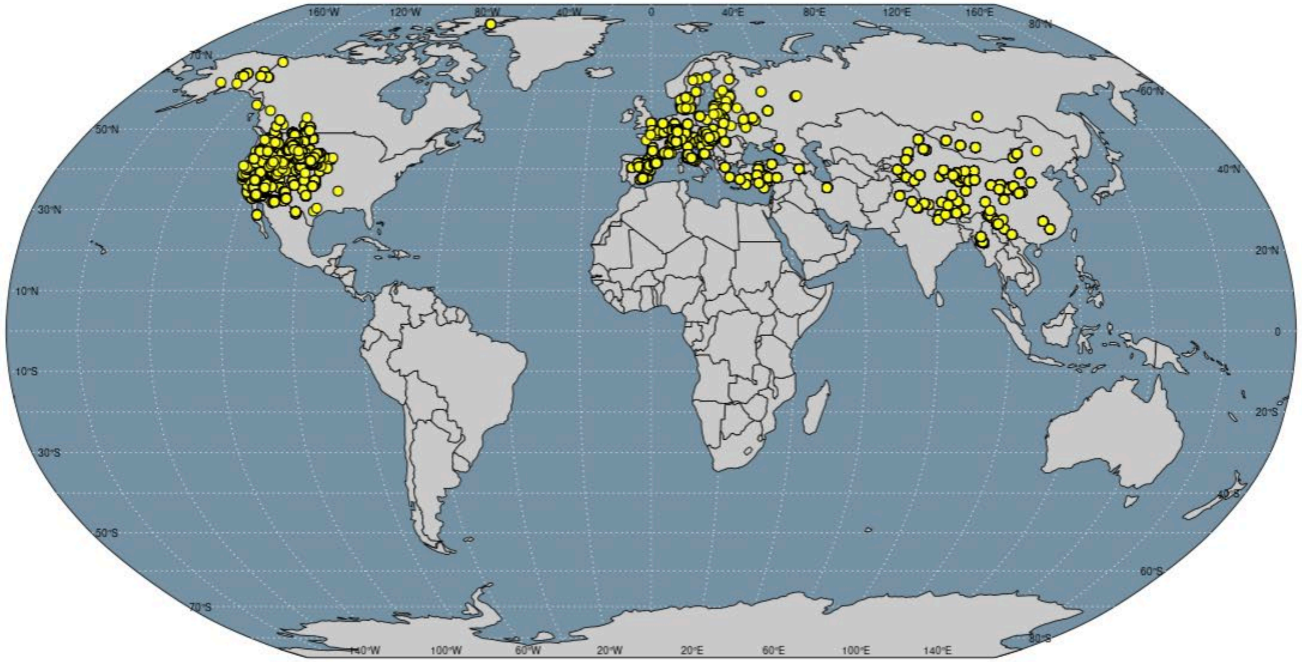
The PATCH Lab

Paleo **A**nalysis of **T**errestrial **C**limate and **H**ydrology

a database and workspace



https://geocentroid.shinyapps.io/PATCH-Lab/



Tyler Kukla
Lead curator

Jeremy Rugenstein
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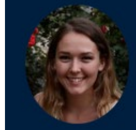

Ellie Driscoll
Curator