Mass Extinction and Ocean Anoxia: A "new" tool and a new paradigm

Kimberly V. Lau

Arizona State University, SESE Colloquium

October 20, 2021

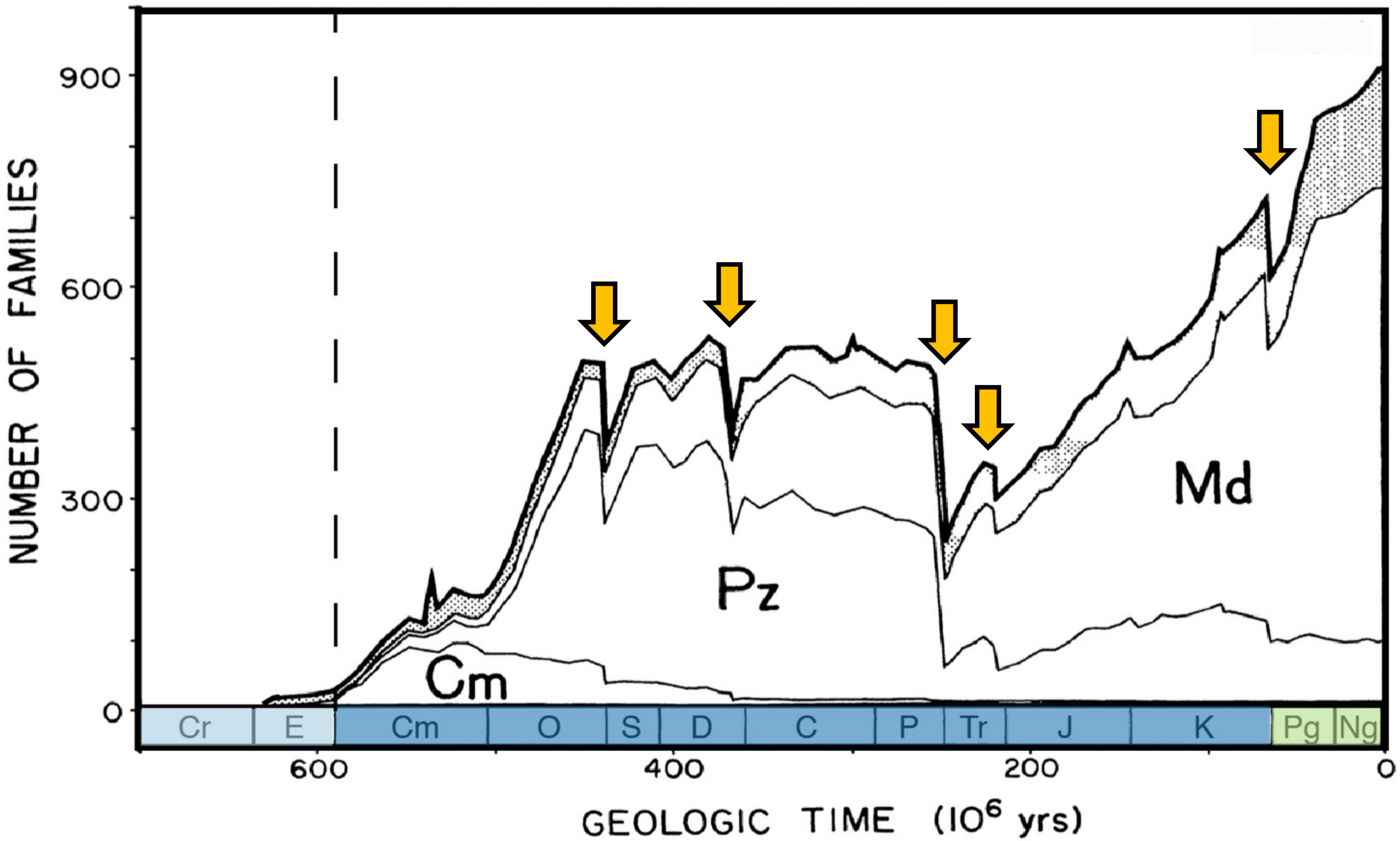
PennState

Acknowledgements

Dalton Hardisty (Michigan State), **Dominik Hülse** and **Andy Ridgwell** (UC Riverside), **Sebastiaan van de Velde** and **Sandra Arndt** (Univ. Brussels), **Katja Meyer** (Willamette University)

UC RIVERSIDE UNIVERSITY OF CALIFORNIA
NASA ASTROBIOLOGY INSTITUTE
ACS PRF
AGOURON INSTITUTE

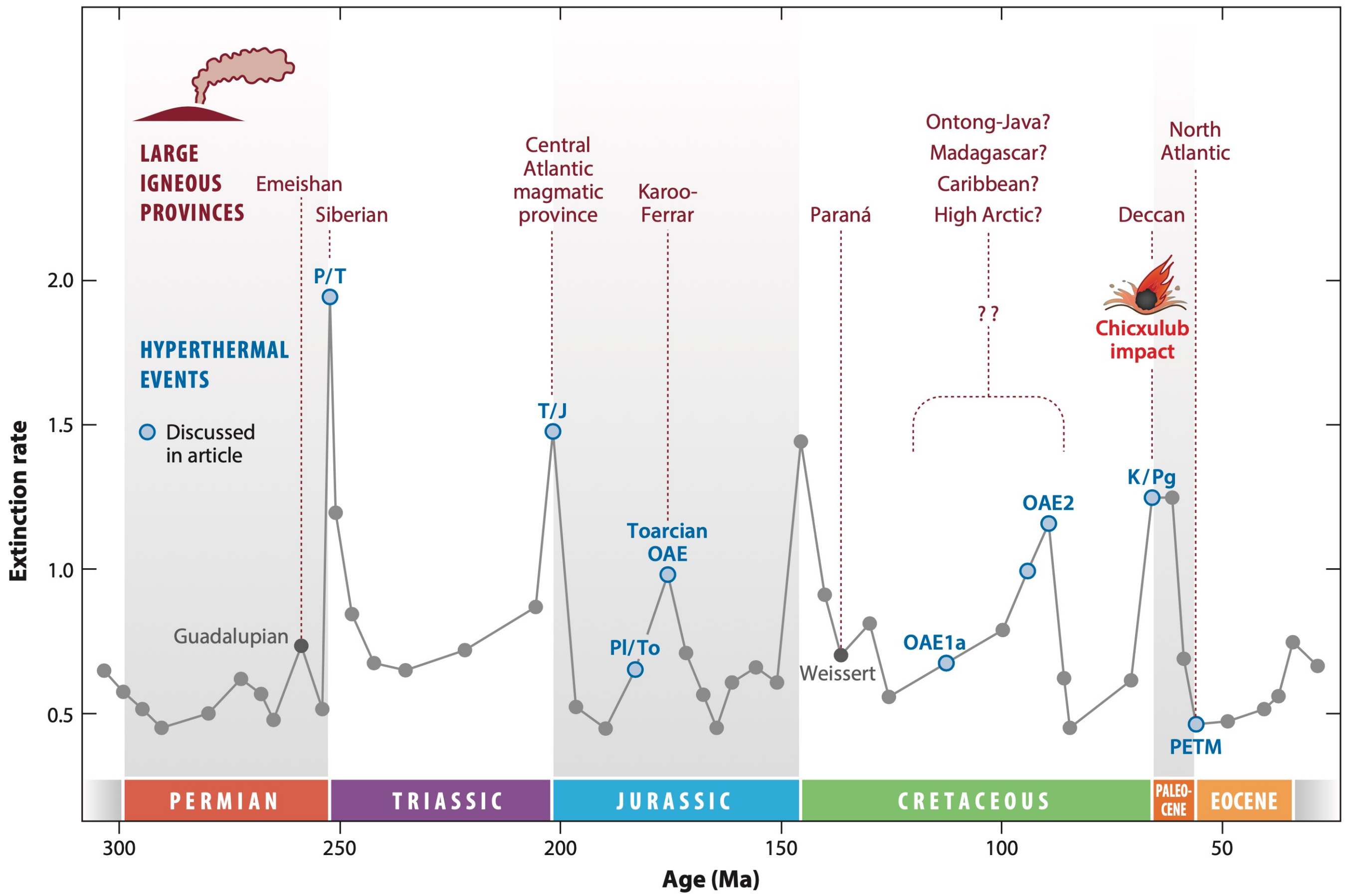
Through Earth history, the evolution of the biosphere has profoundly affected the geosphere, and vice versa.



Modified from Sepkoski, 1981

Mass extinctions are critical windows into the Earth system

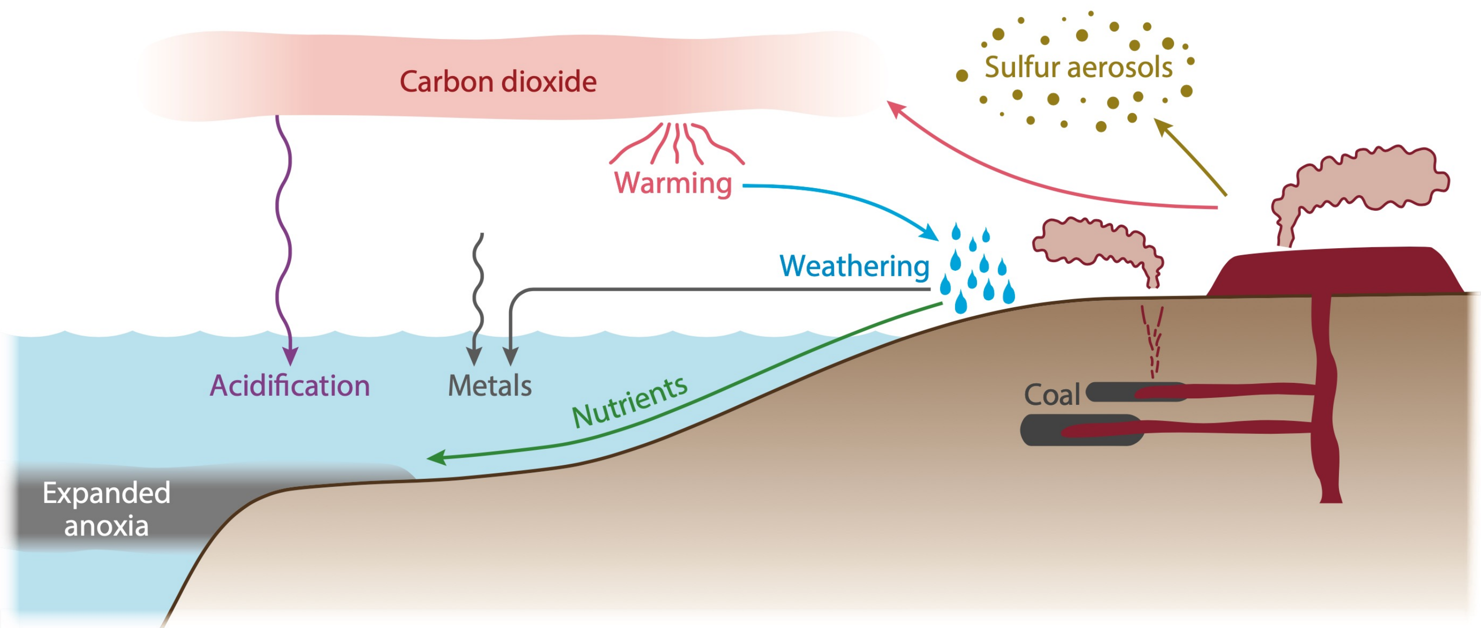
*Extinctions represent **perturbations**, usually environmentally related*

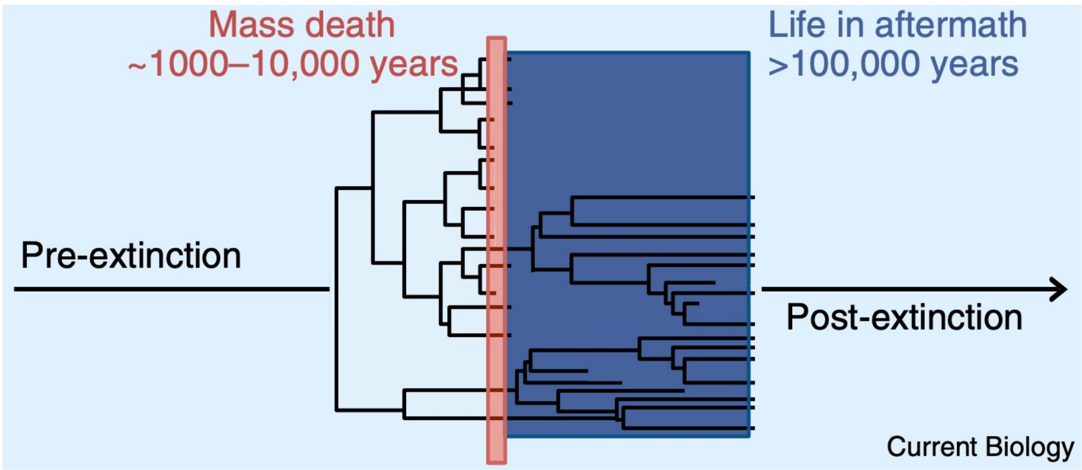


Clapham and Renne, 2019

Mass extinctions are critical windows into the Earth system

These events can reveal ***Earth system processes and feedbacks*** *and their consequences on long time scales*



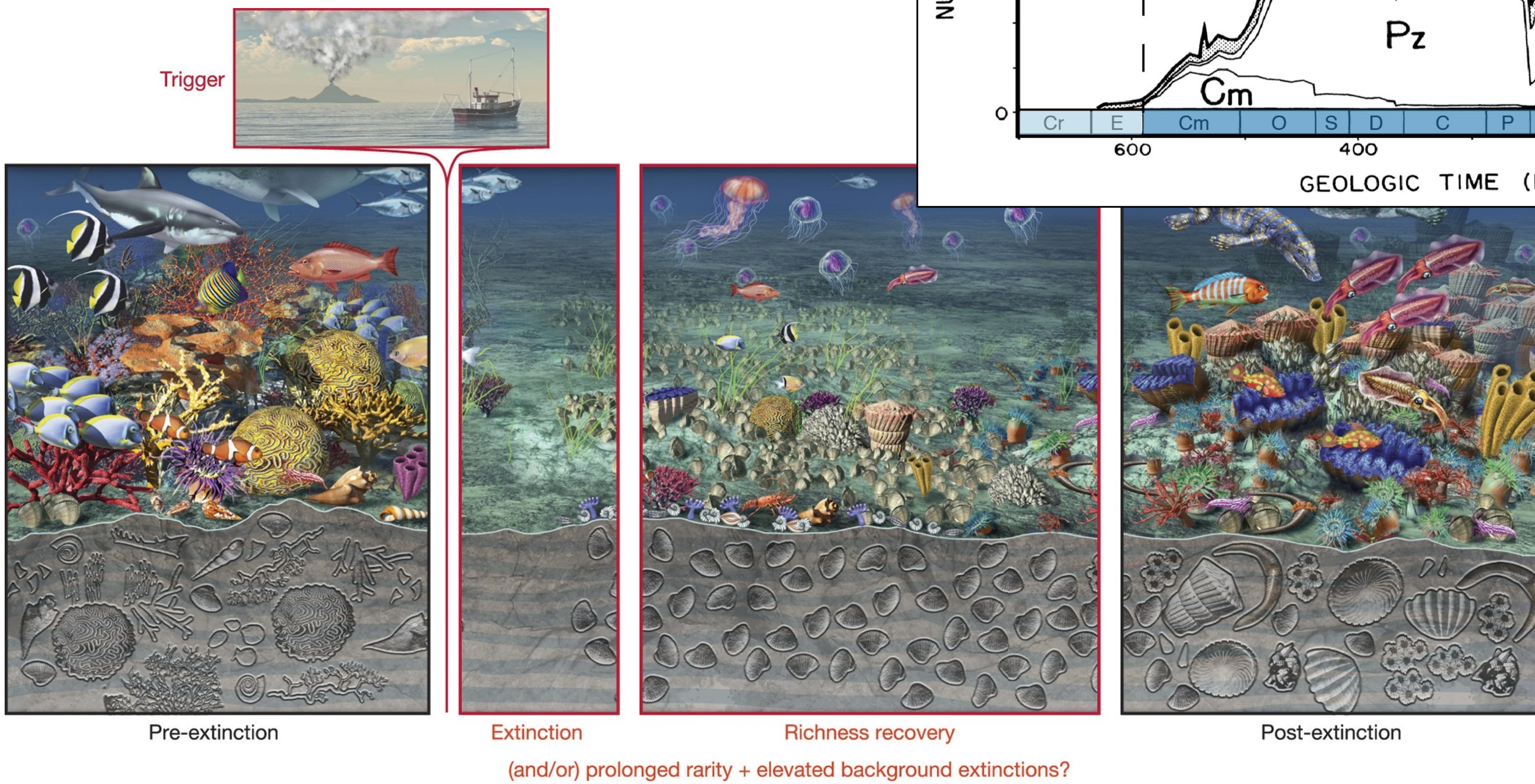


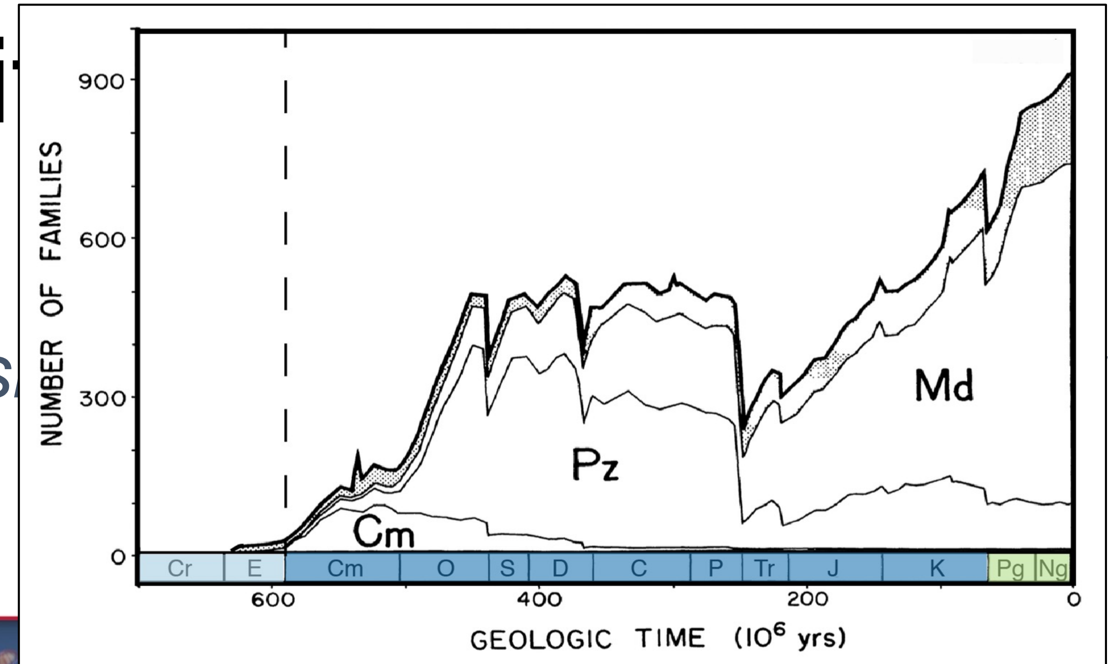
Clapham and Renne, 2019

Hull, 2019

Mass extinctions are cri
into the Earth system

Extinctions are important drivers of divers

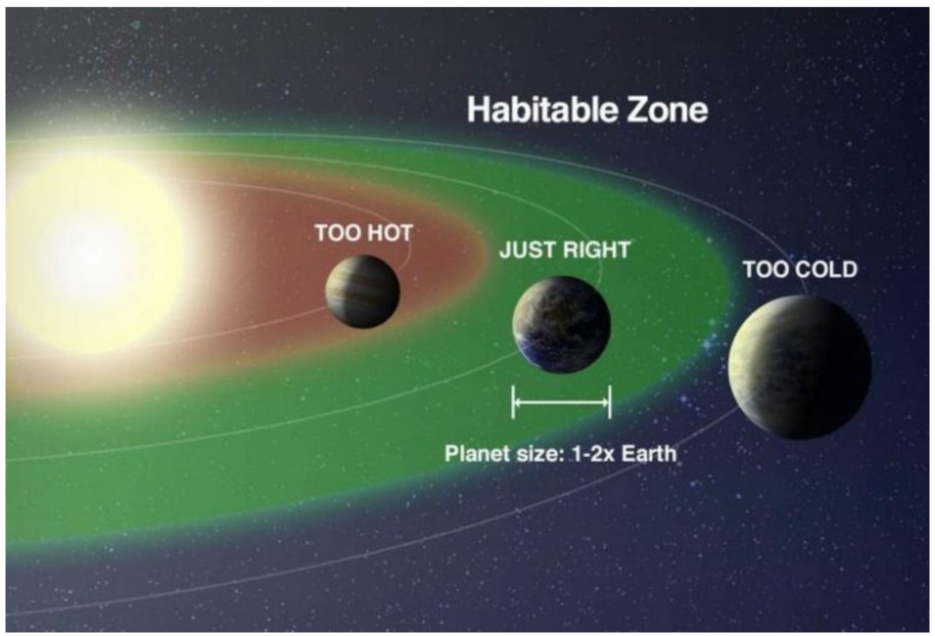


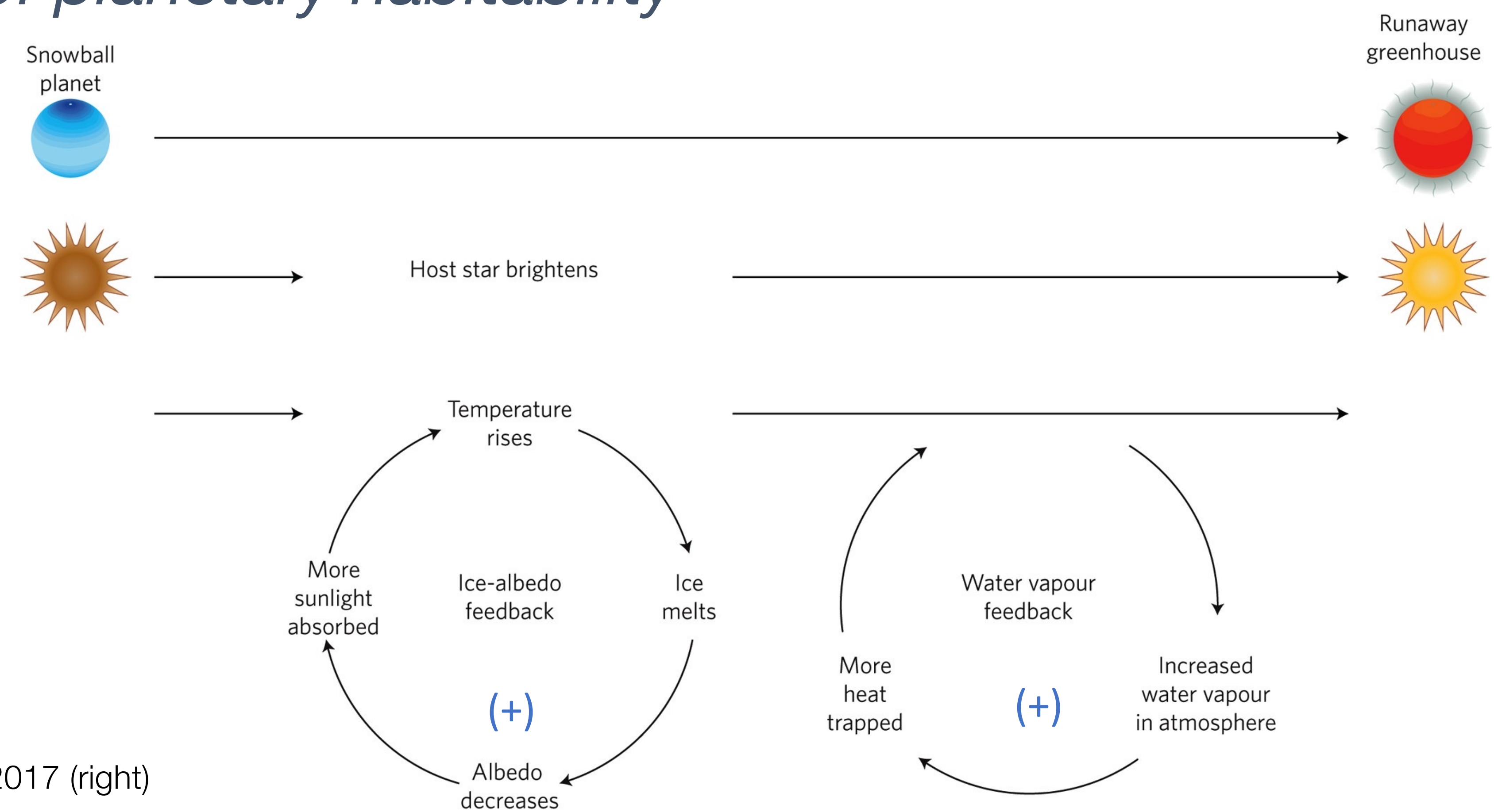


Hull et al., 2015

Mass extinctions are critical windows into the Earth system

These feedbacks are important for understanding the parameters of planetary habitability

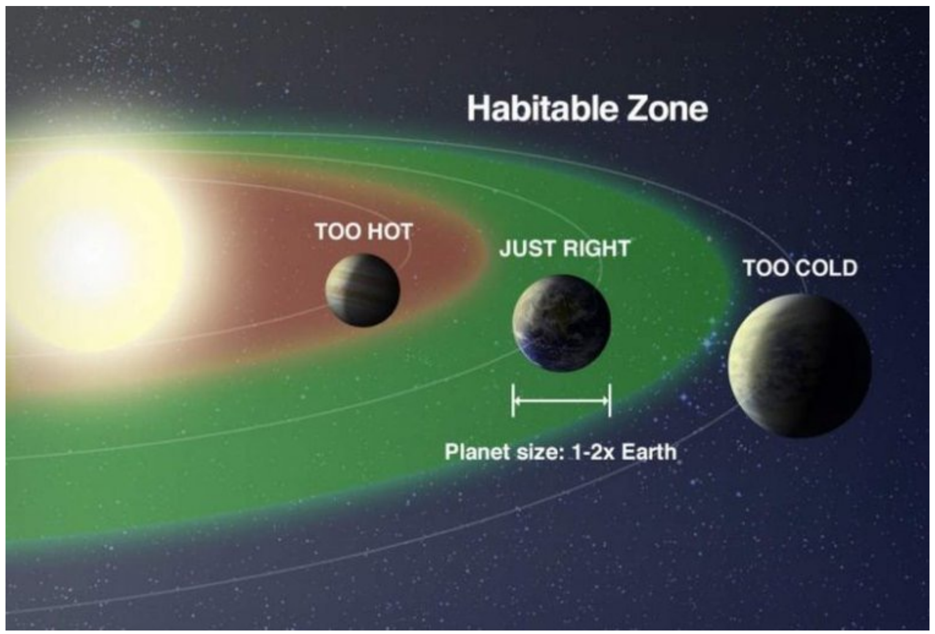


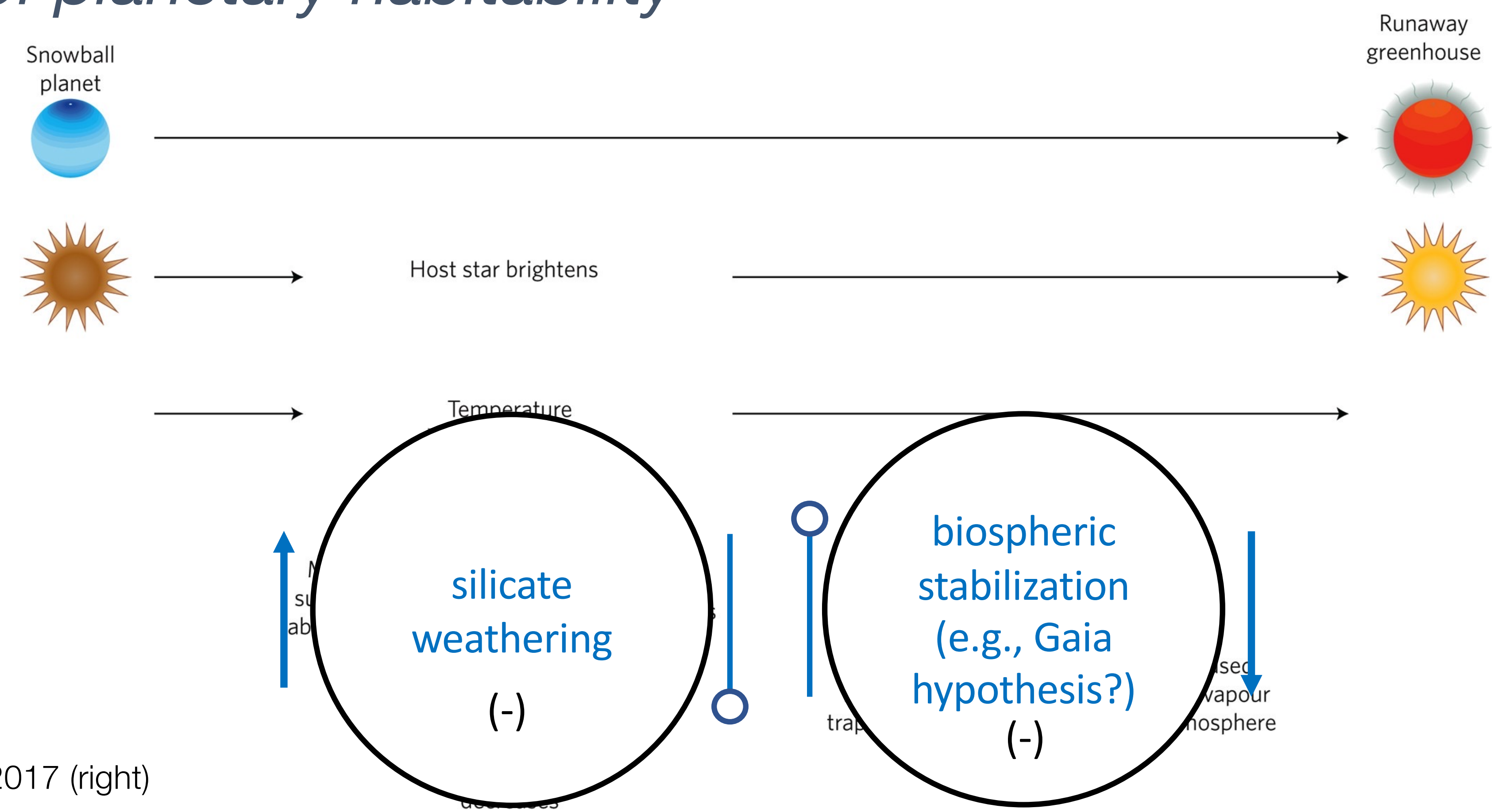


NASA (above); Ingersoll, 2017 (right)

Mass extinctions are critical windows into the Earth system

These feedbacks are important for understanding the parameters of planetary habitability

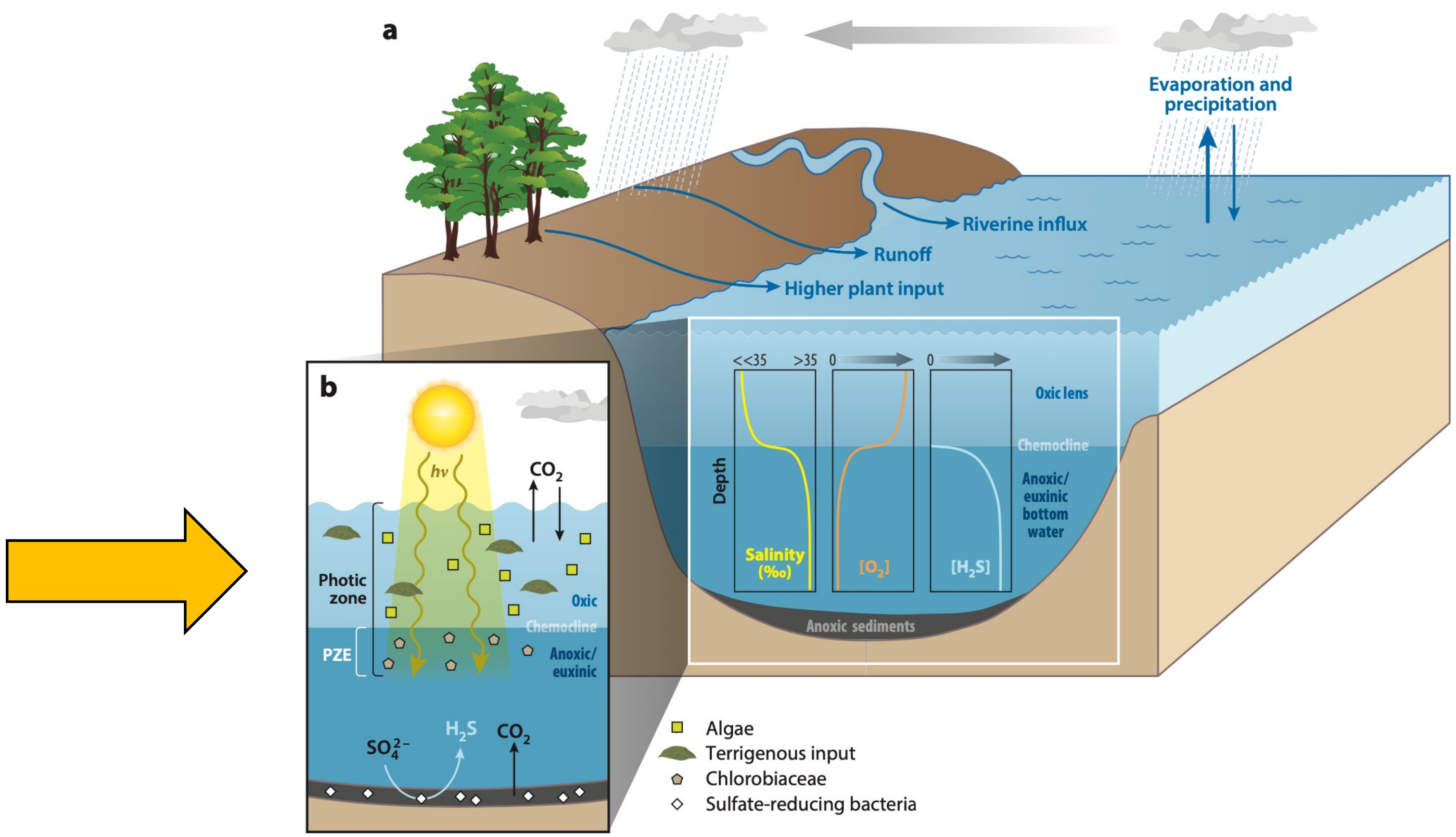




NASA (above); Ingersoll, 2017 (right)

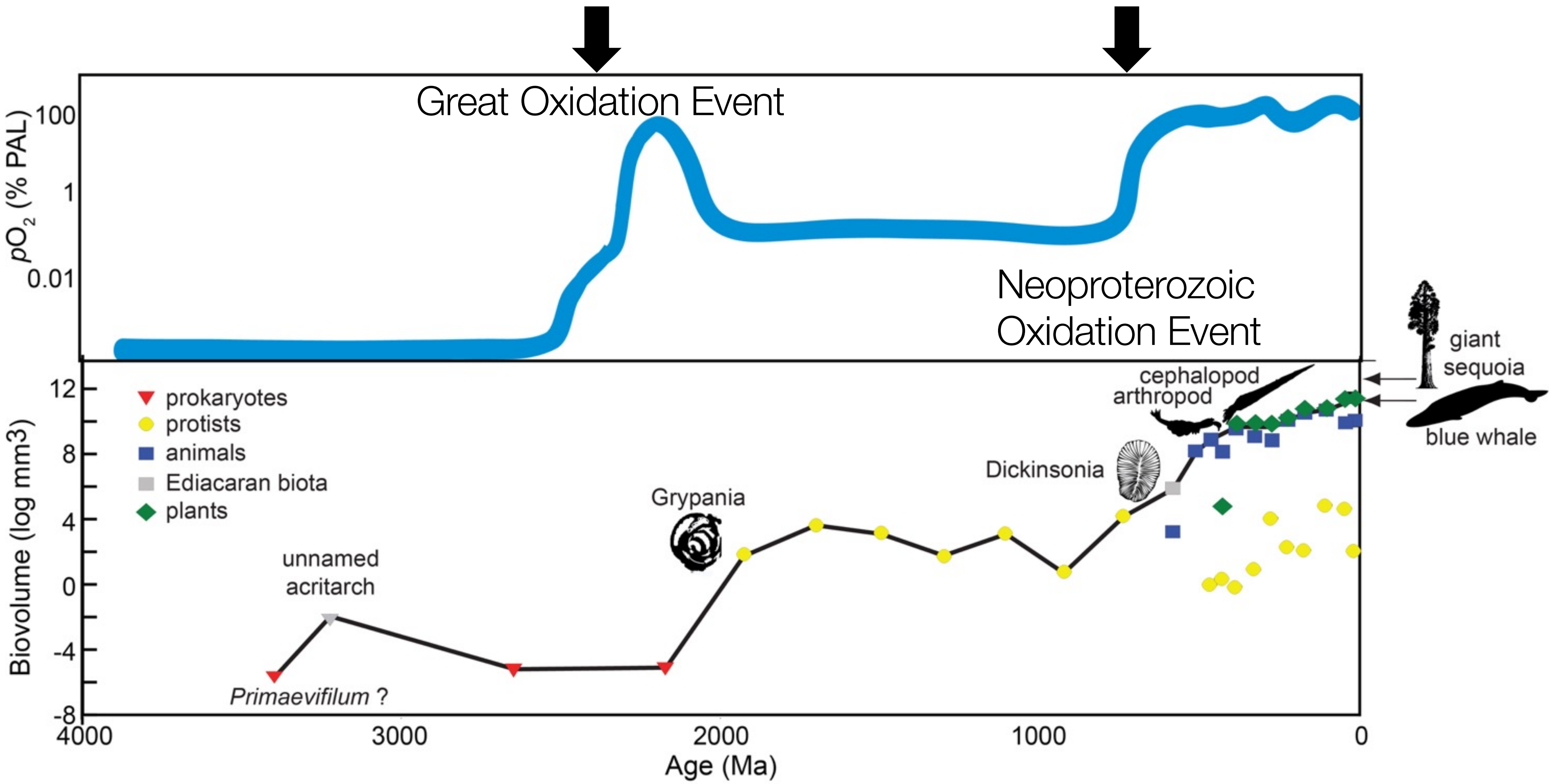
Mass extinctions are critical windows into the Earth system

*Major shifts in the biosphere include not only macroscopic complex life, but **microbial biogeochemistry** that is not well preserved in the fossil record*



Whiteside and Grice, 2016

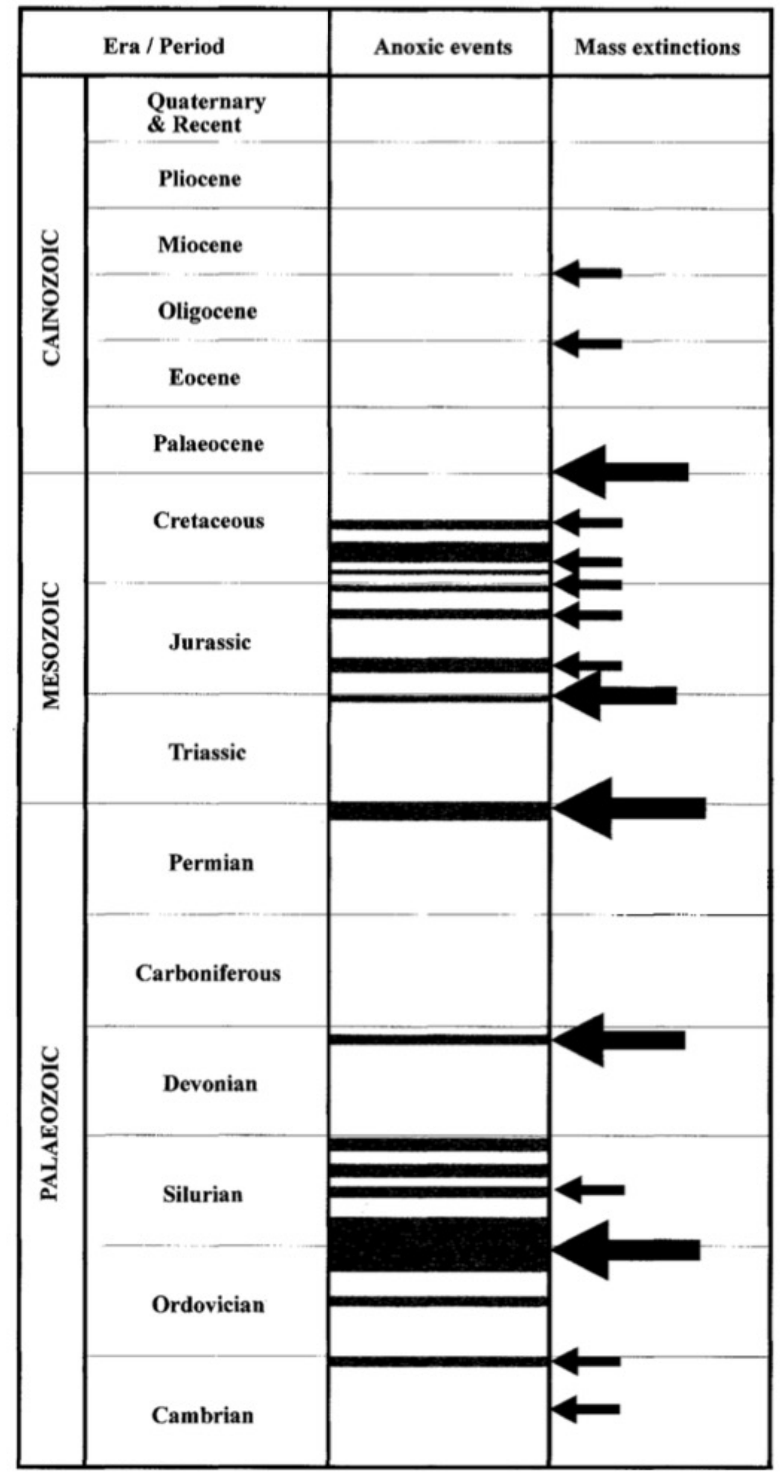
Periods of evolutionary innovation coincide with oxygenation



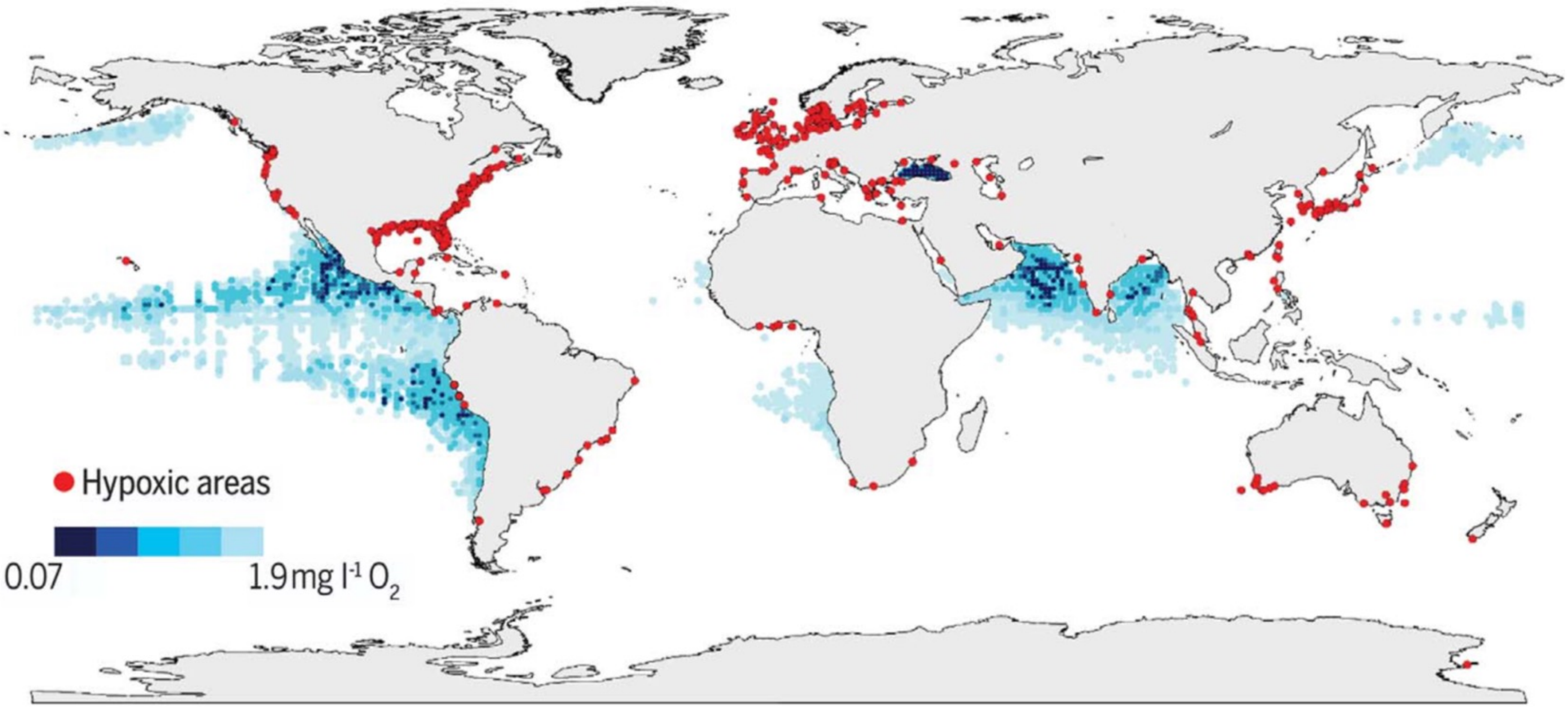
Modified from Lyons et al., 2014 and Payne et al., 2011

Mass extinctions are often accompanied by the de-oxygenation of marine environments

Horne, 1999

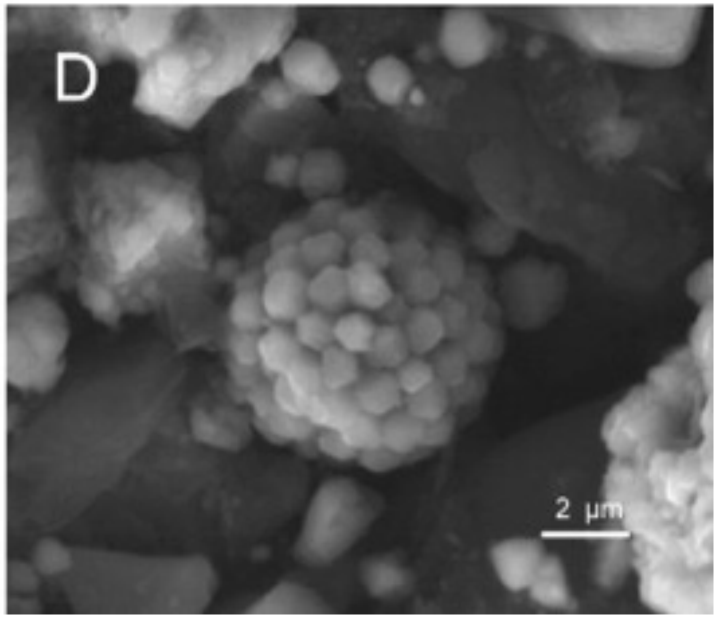


Ocean anoxia and hypoxia is a growing concern



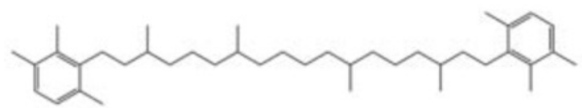
Breitburg et al., 2018

Proxies advance our understanding of the evolution of the redox landscape

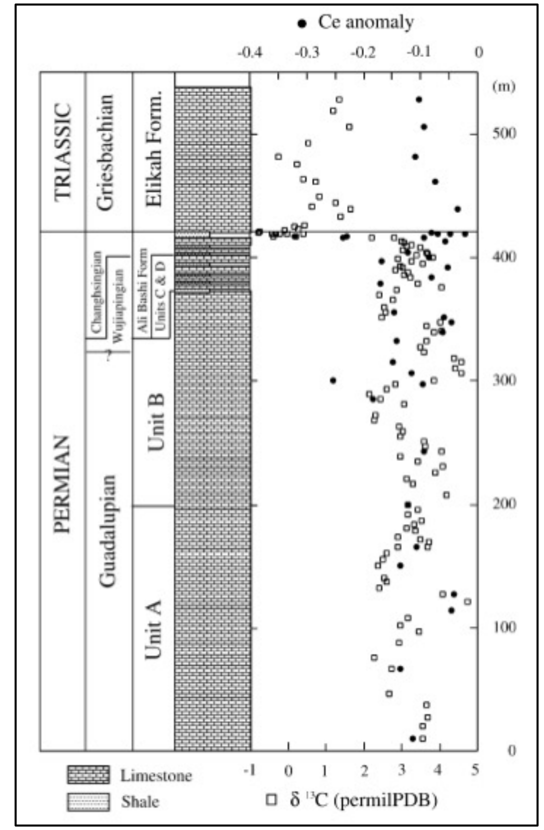


Pyrite framboids, Meishan
Shen et al., 2007

Organic-rich shale,
Great Bank of Guizhou



Grice et al., 2005 **isorenieratane**



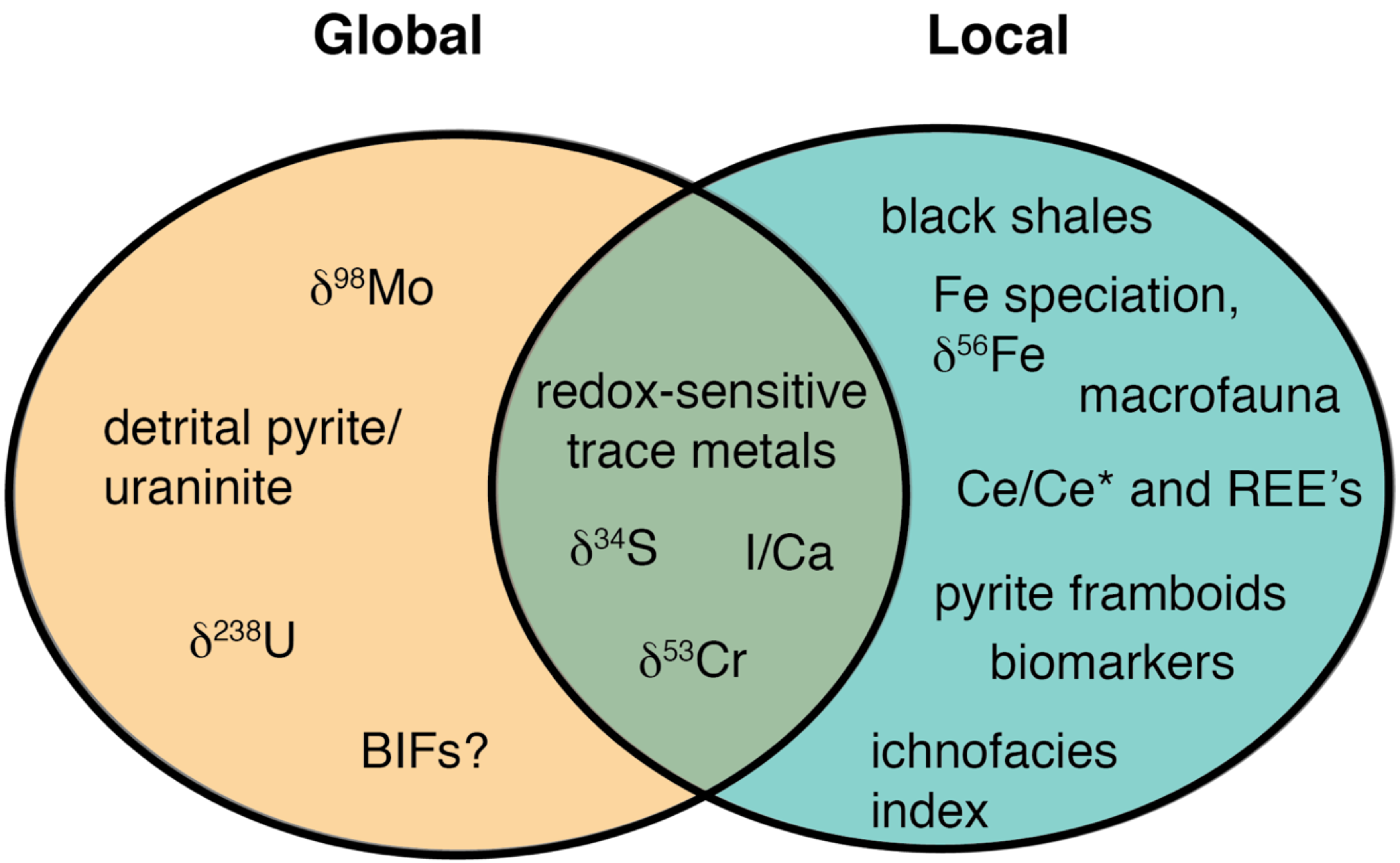
Kakuwa and Matsumoto, 2006

Inorganic geochemical proxies have the potential to

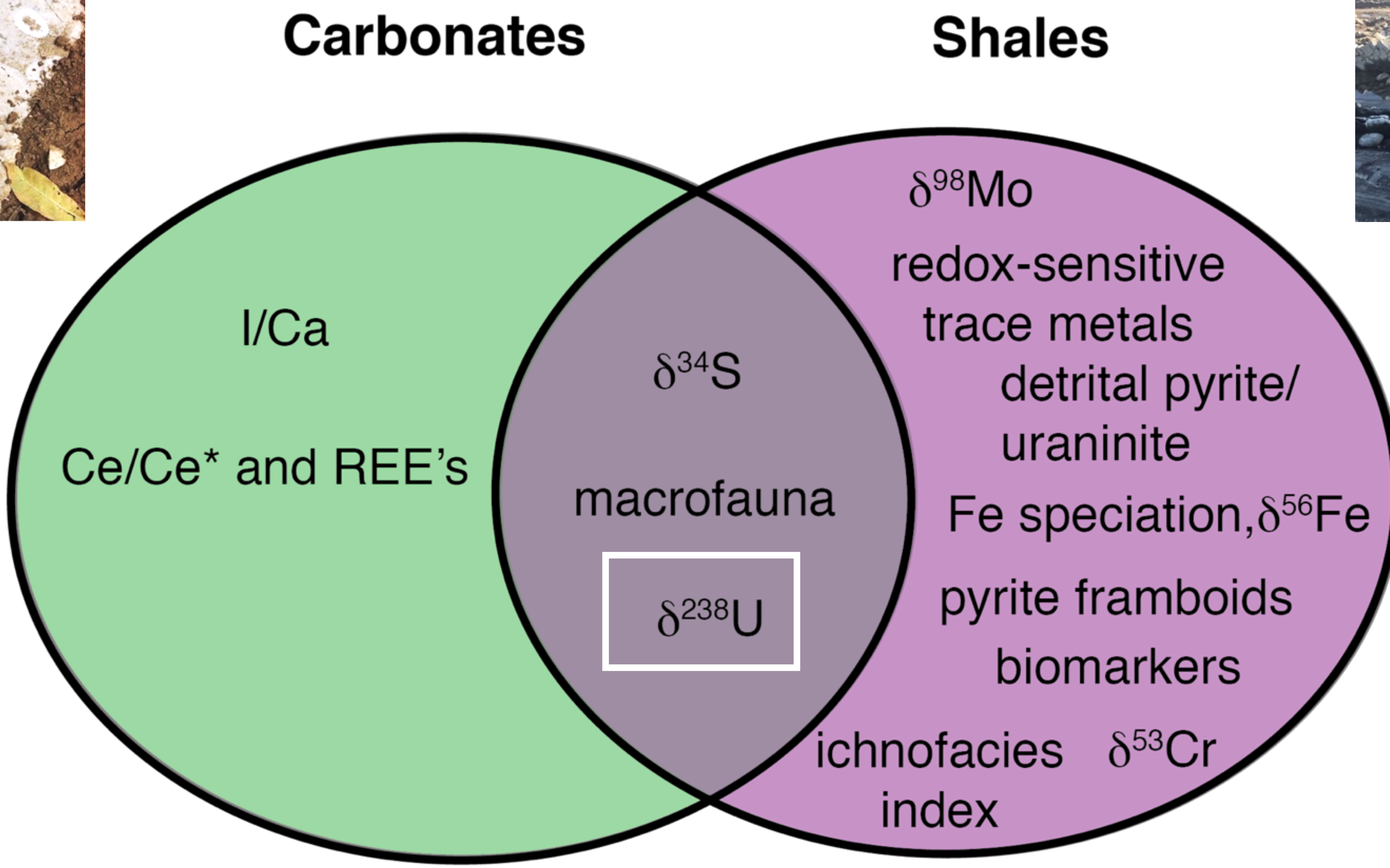
(1) track redox conditions at a broad range of spatial scales *and*

(2) be analyzed (and compared) in multiple sedimentary archives.

A diverse toolkit for paleo-redox interpretation



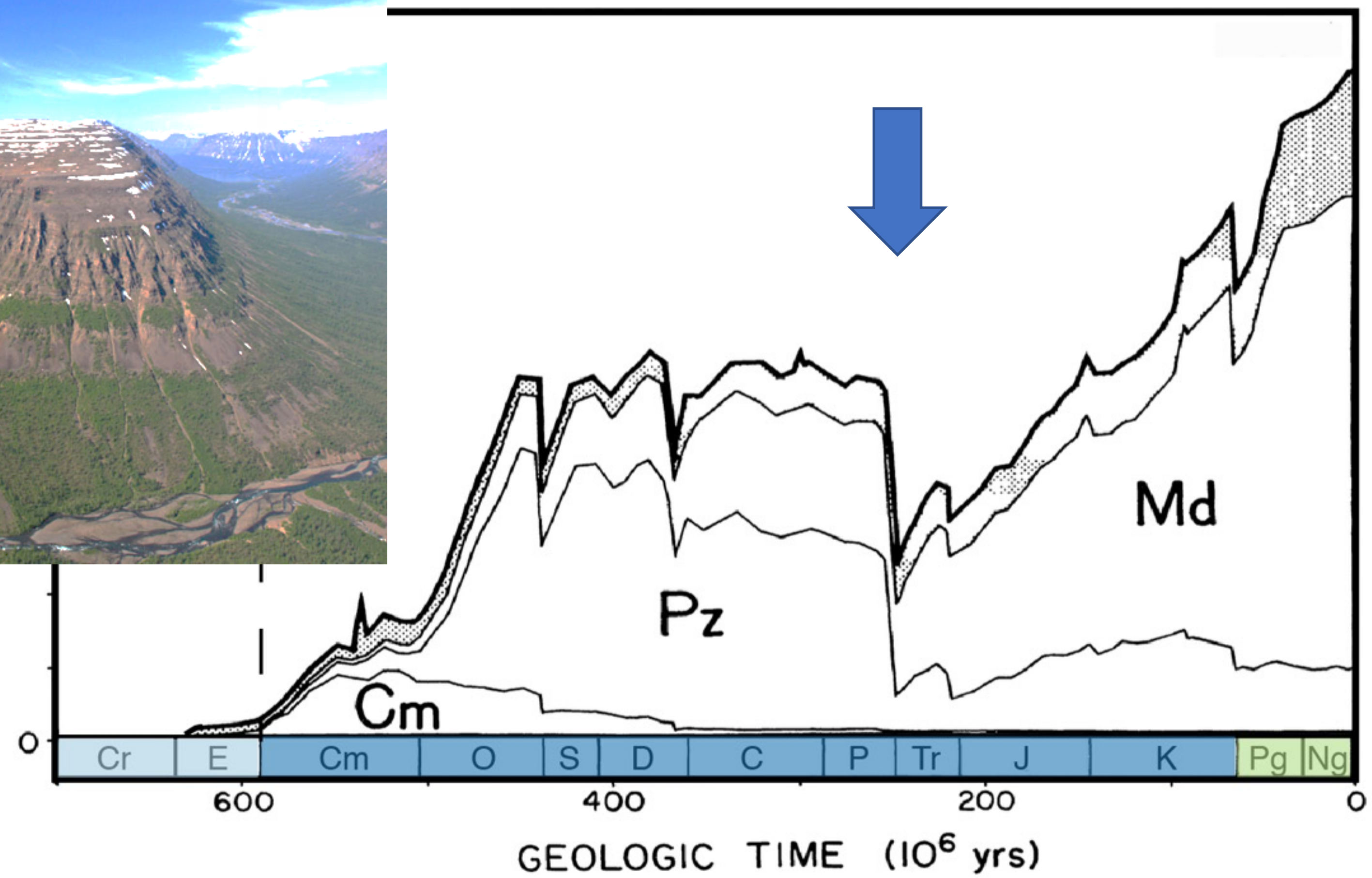
A diverse toolkit for paleo-redox interpretation



A case study from the end-Permian mass extinction

An analogue for climate change in a greenhouse world

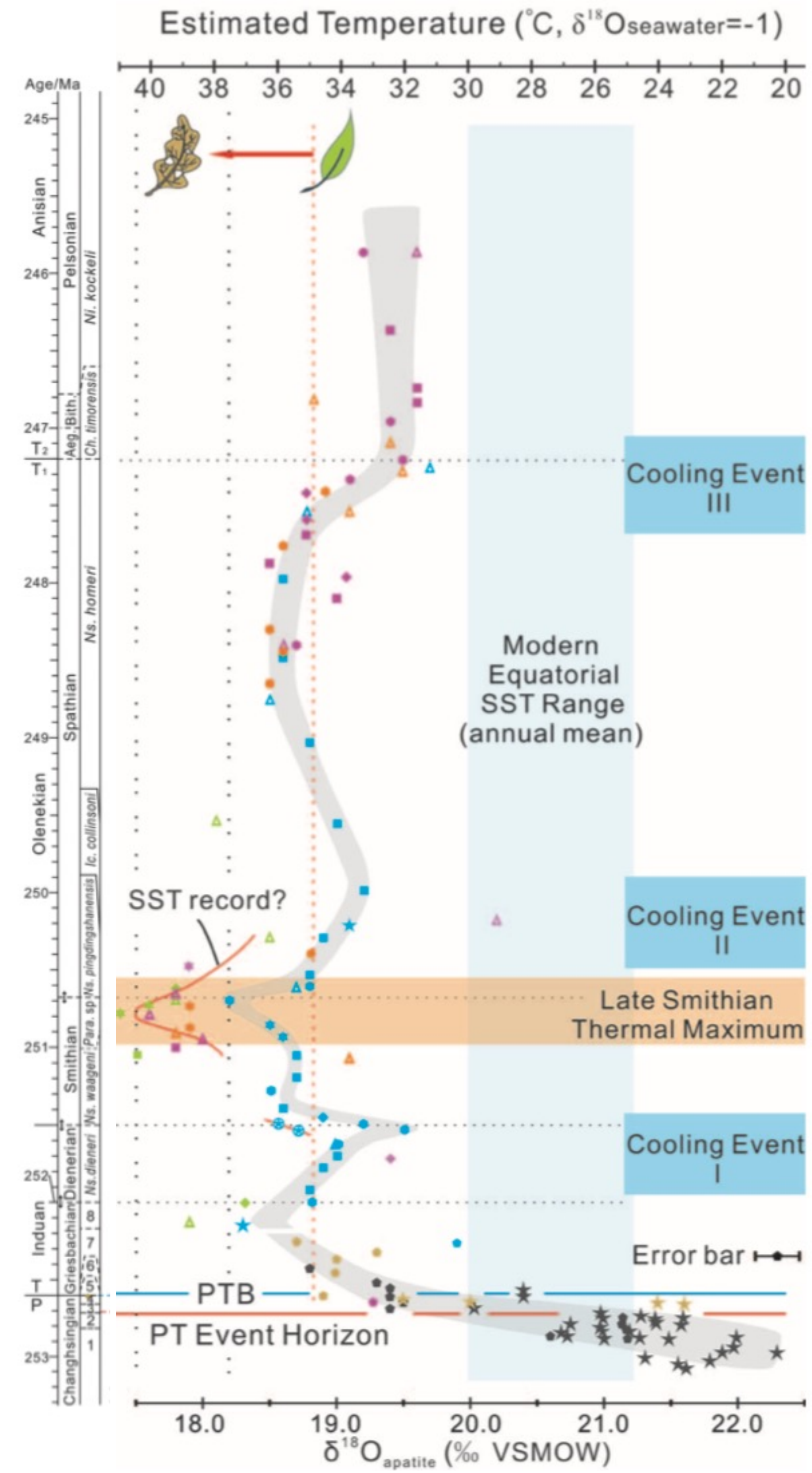
Wignall, 2011 *Nature*



Modified from Sepkoski, 1981

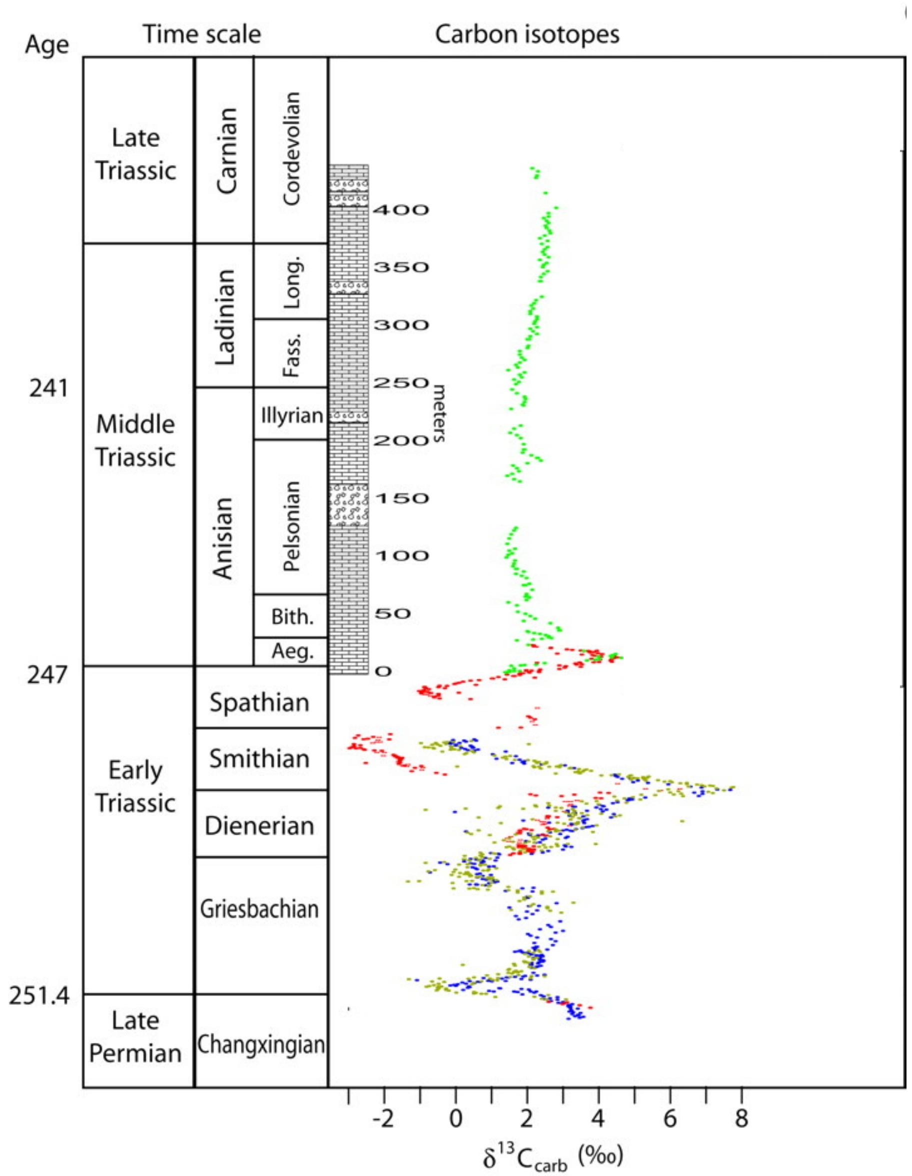
The end-Permian mass extinction is an example of ancient climate change

- <1 yr: regional warming (SO_2 greenhouse effect)
- <10 yr: cooling (sulfate aerosols), acid rain, ozone depletion
- **<10,000 yr:** ocean acidification, **global warming, and ocean stagnation** (Kiehl and Shields, 2005; Penn et al., 2018)
- **~100,000 yr: enhanced continental weathering** (2.5x to 7x, Sedlacek et al., 2004; Song et al., 2015), **potential anoxia**



Sun et al. (2012) *Science*

Evidence for carbon perturbations



Payne et al., 2004

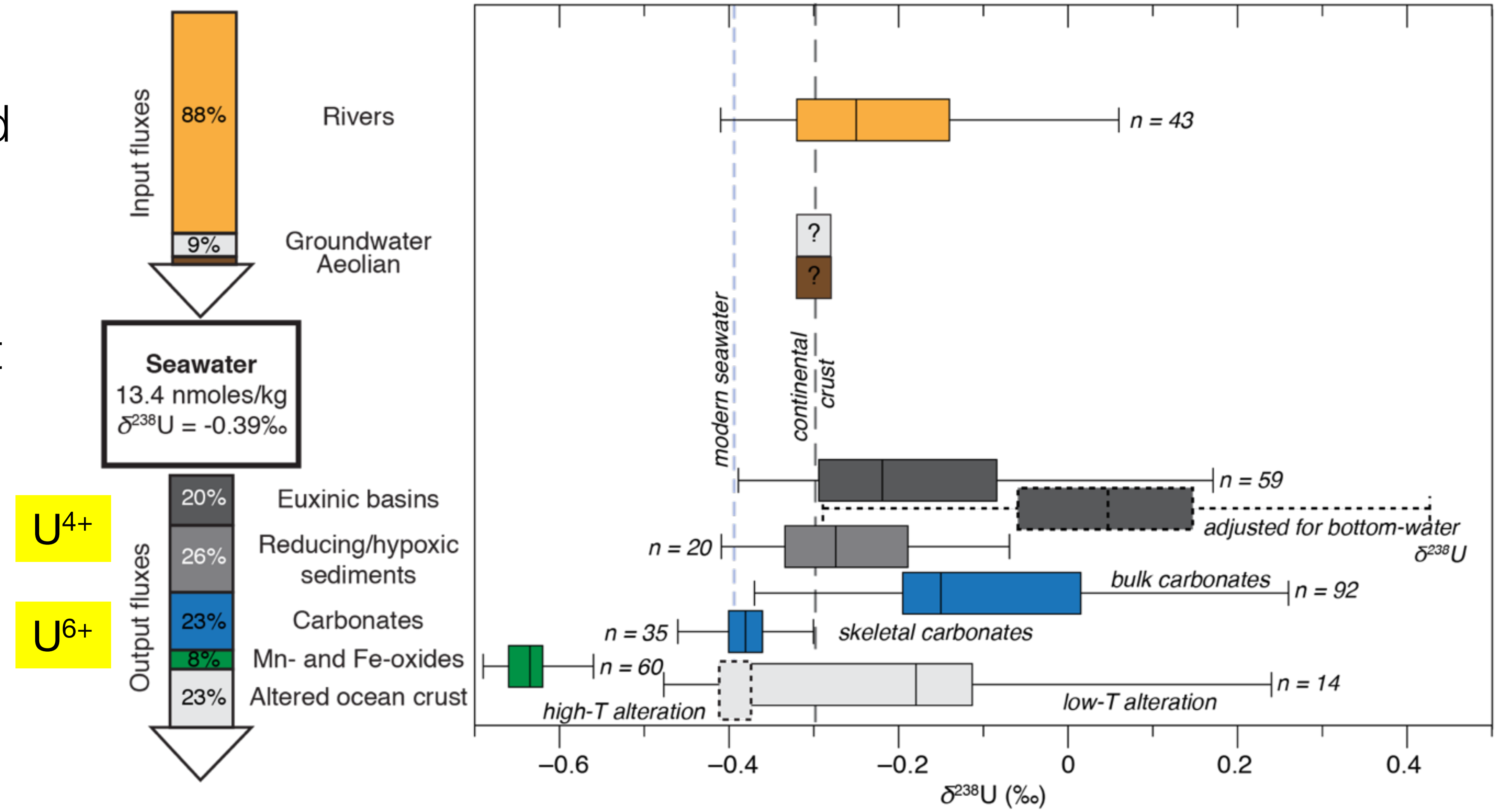
U isotopes as a proxy for marine redox conditions

Uranium occurs in two redox states:

oxidized, solube U^{6+} and reduced, insoluble U^{4+}

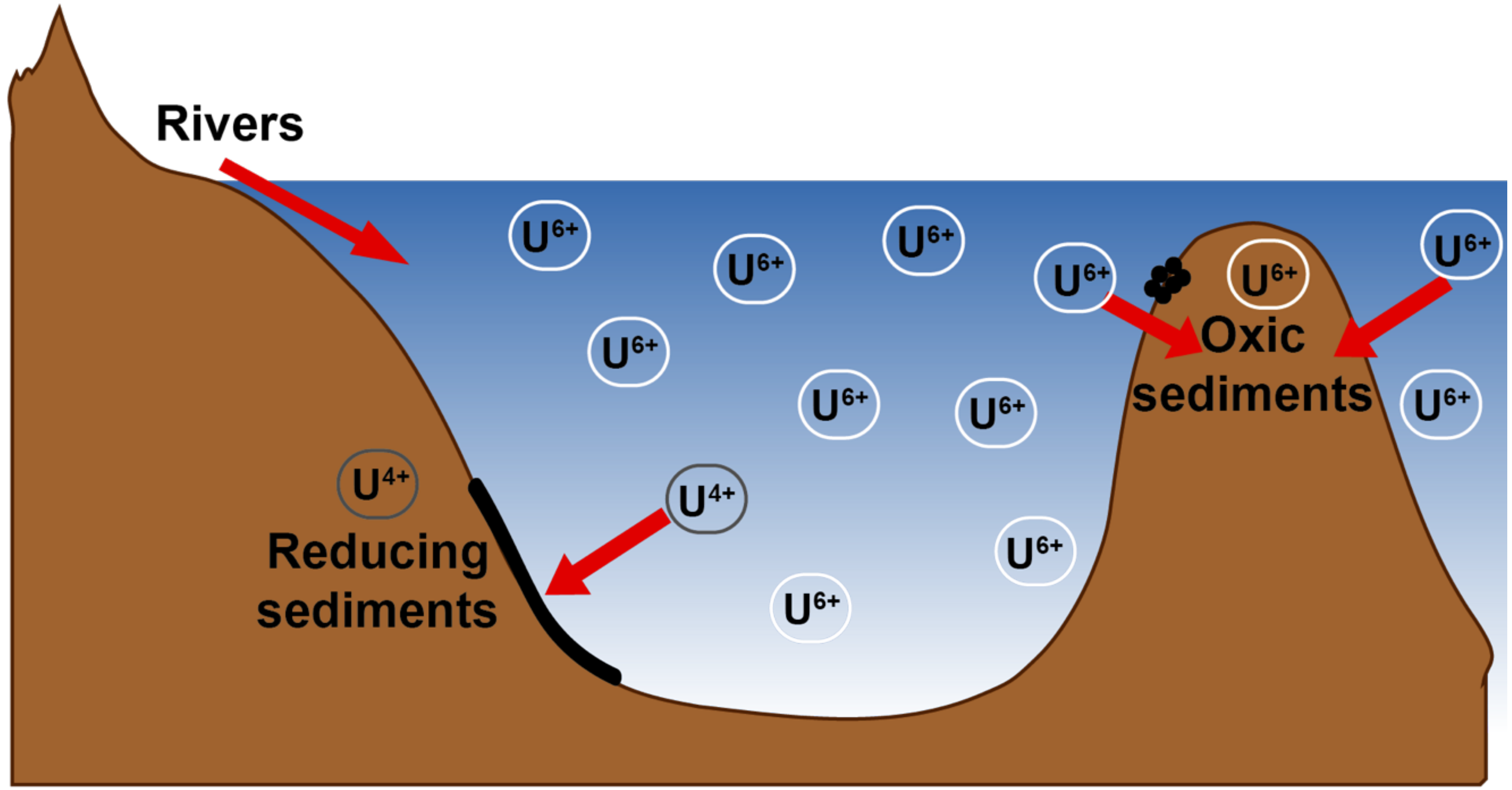
The two most abundant isotopes of uranium are ^{238}U and ^{235}U

^{238}U is preferentially partitioned to U^{4+} (*Bigeleisen, 1996*)

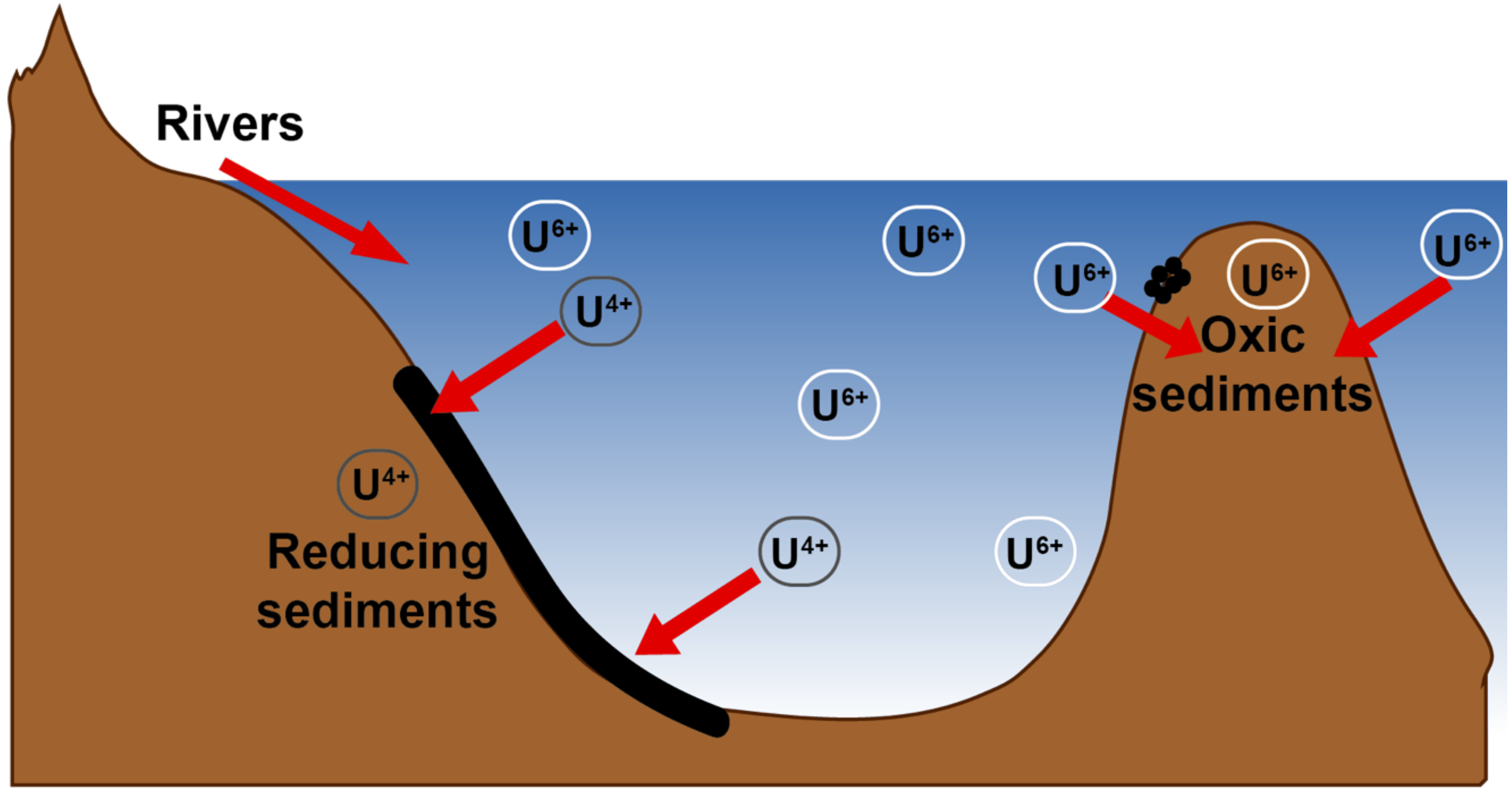


Lau et al., 2019

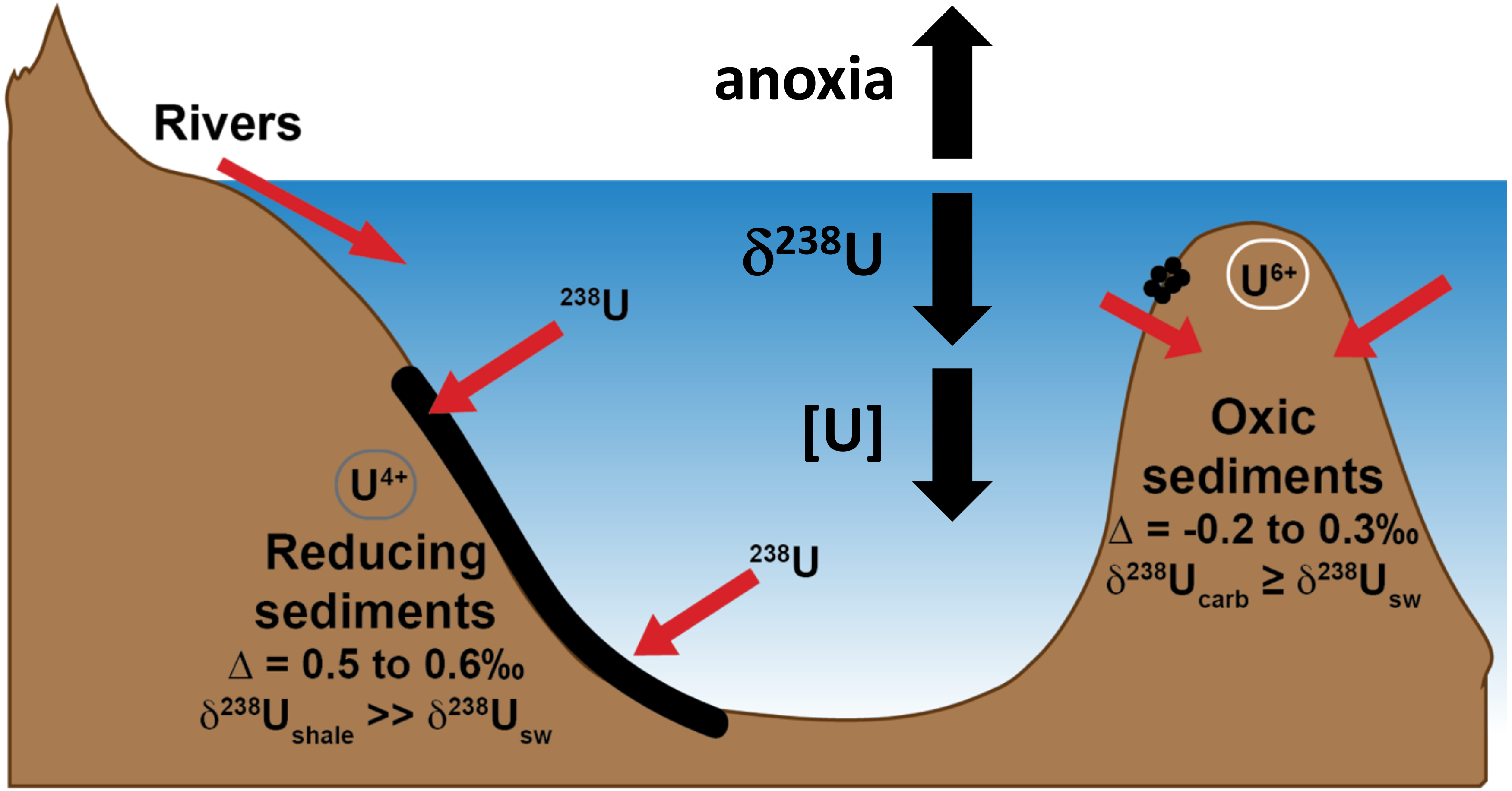
Redox conditions affect seawater [U] and $\delta^{238}U$



Redox conditions affect seawater [U] and $\delta^{238}U$



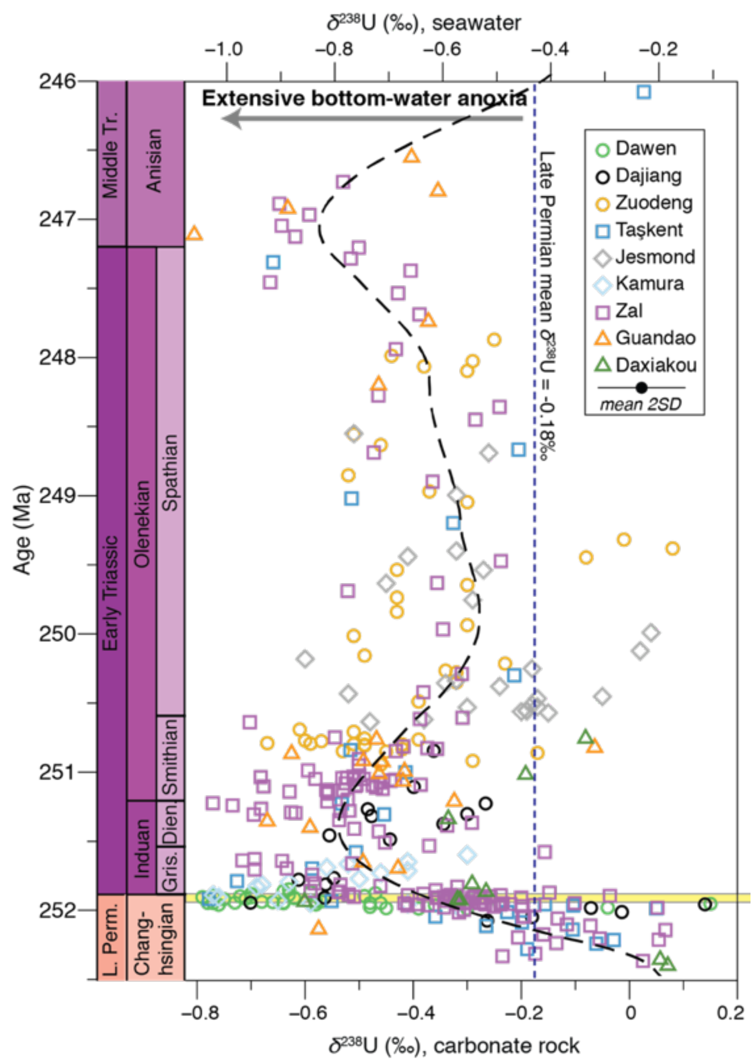
Redox conditions affect seawater [U] and $\delta^{238}U$



We can quantify the ***areal extent*** of bottom water anoxia.

Expansion of anoxia in the Early Triassic

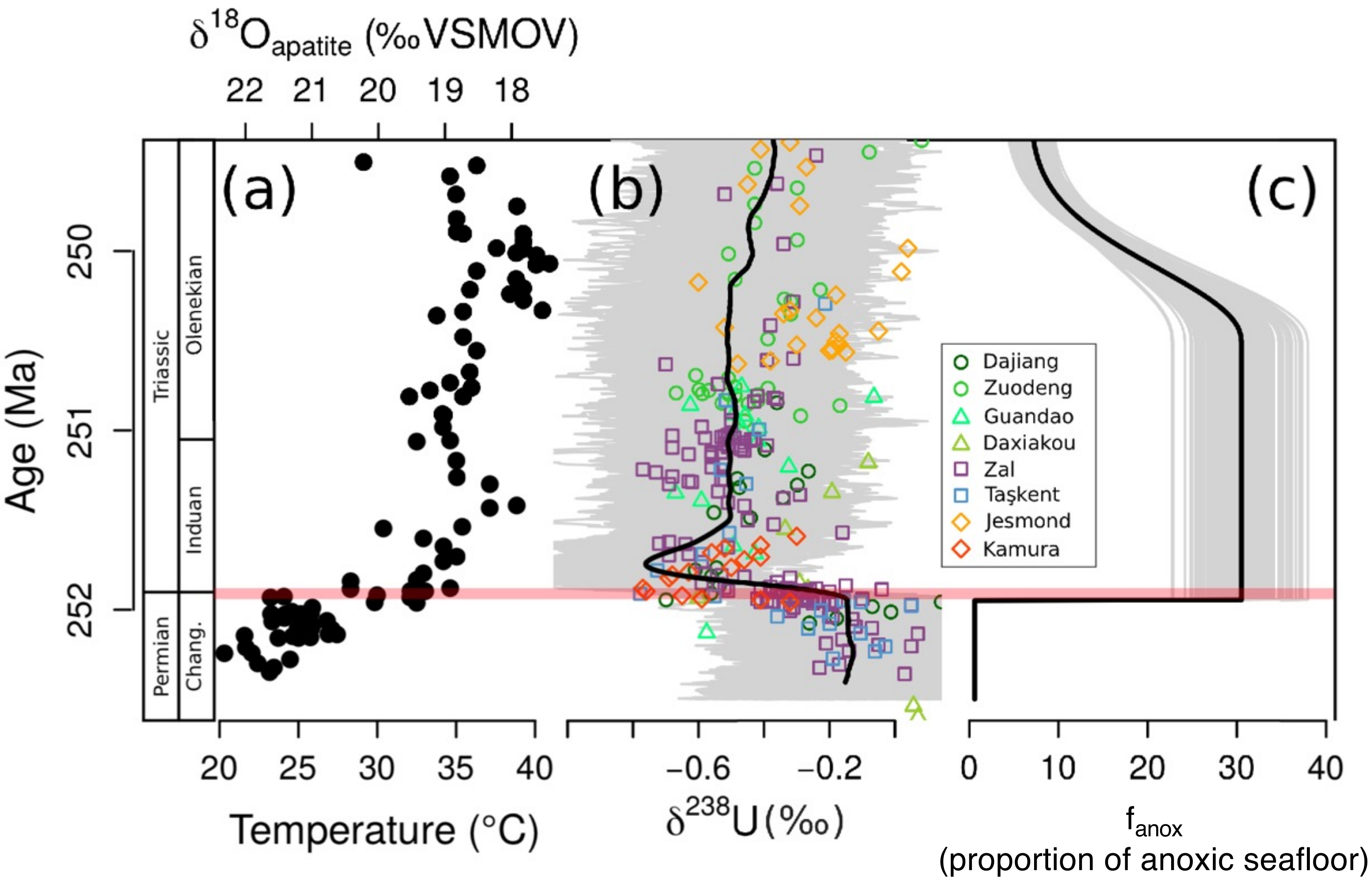
Large negative shift in $\delta^{238}U$ from multiple carbonate records = more anoxia



Lau et al., 2019
Data from: Brennecka et al., 2011; Lau et al., 2016; Elrick et al., 2017; Zhang et al., 2018 Sci Adv., Zhang et al., 2018 Geology; Zhang et al., 2018 Earth Sci Rev

Expansion of anoxia in the Early Triassic

Large negative shift in $\delta^{238}U$ from multiple carbonate records = more anoxia



Box model results account for uncertainties in:

- Diagenetic offset
- Riverine $\delta^{238}U$
- $\delta^{238}U$ isotope offset into anoxic sediments

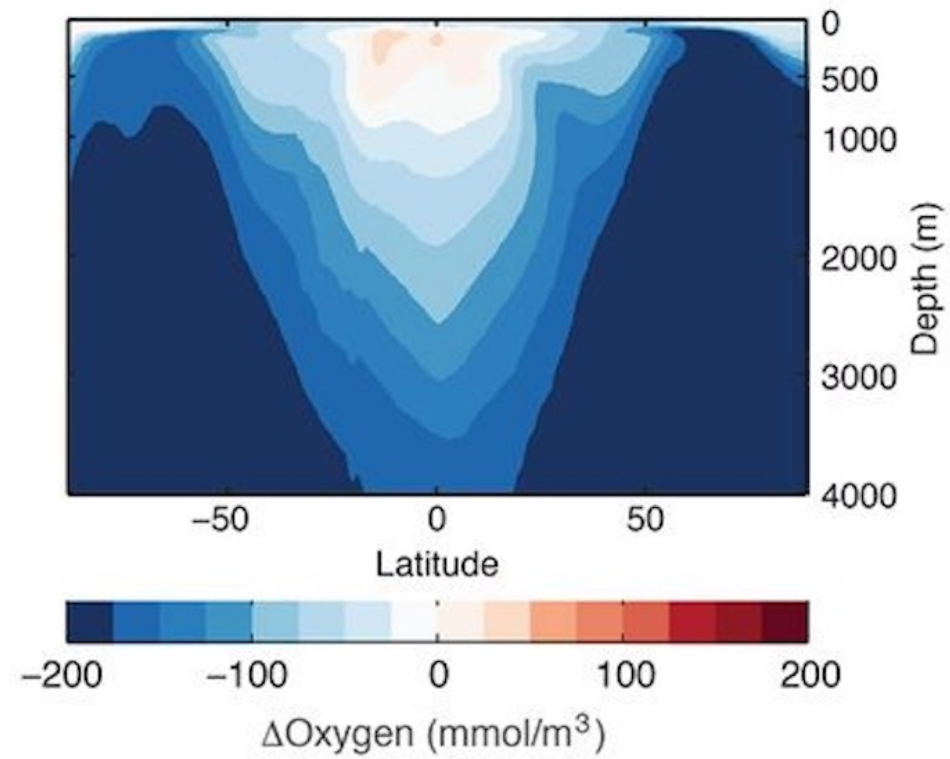
The first-order trend is a large (50 times) **but not complete** increase in anoxia in the aftermath of the extinction, followed by a longer but still elevated interval of extensive seafloor anoxia.

Model from Hülse et al., in press

Data from: Sun et al., 2012; Joachimski et al., 2012 and 2020; Lau et al., 2016; Elrick et al., 2017; Zhang et al., 2018 Sci Adv., Zhang et al., 2018 Geology; Zhang et al., 2018 ESR

How do higher temperatures impact the ocean redox state?

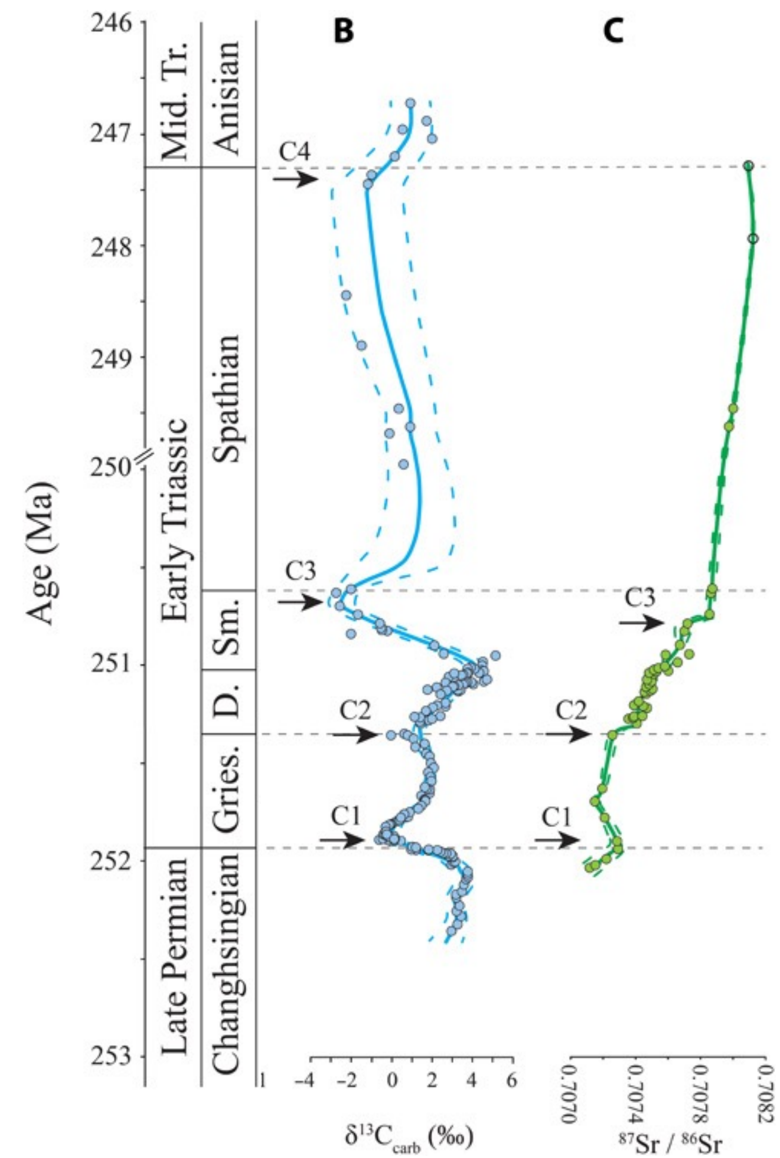
- Solubility of O_2 (g) decreases
- Global ocean circulation reorganizes due to a reduced latitudinal temperature gradient *(Winguth and Meier-Reimer, 2005; Kiehl and Shields, 2005; Montenegro et al., 2011; Winguth et al., 2012; Penn et al., 2018)*



Penn et al., 2018

How do higher temperatures impact the ocean redox state?

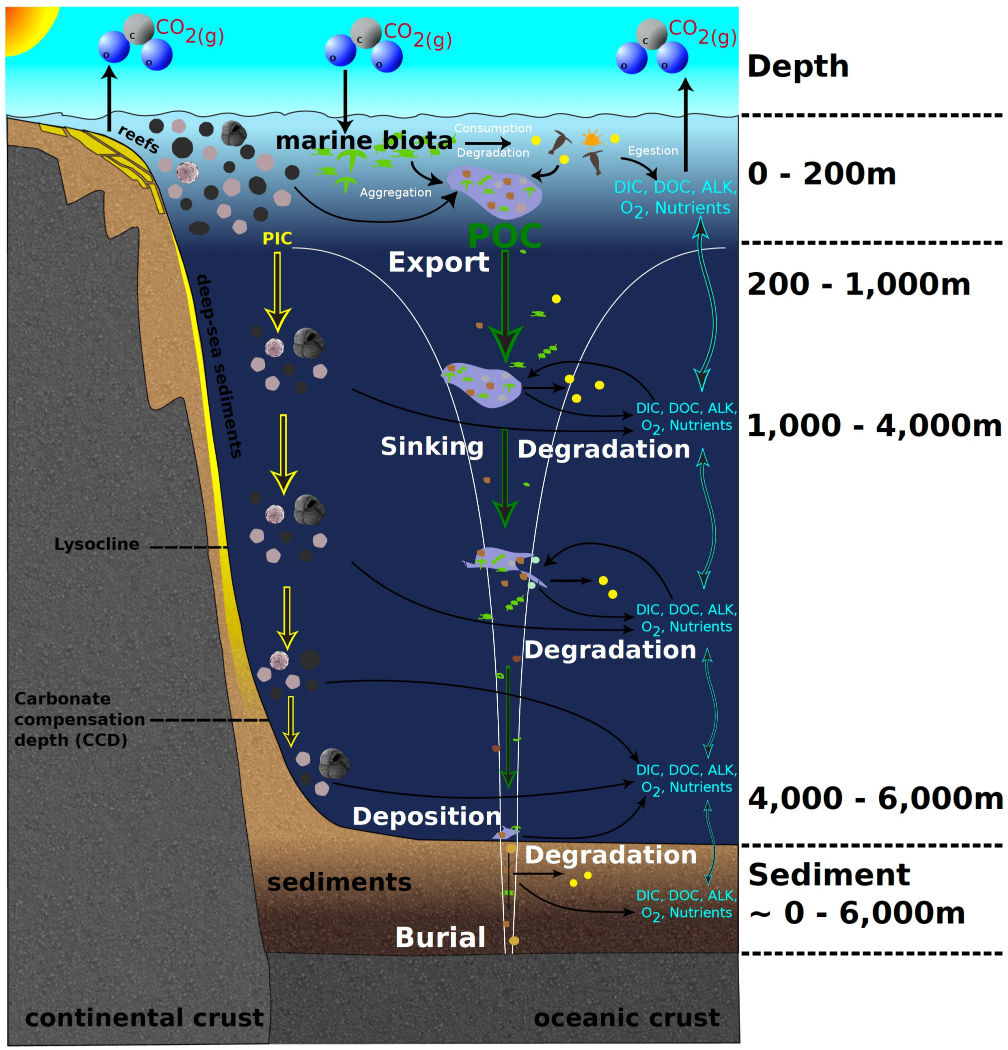
- Solubility of O_2 (g) decreases
- Global ocean circulation reorganizes due to a reduced latitudinal temperature gradient *(Winguth and Meier-Reimer, 2005; Kiehl and Shields, 2005; Montenegro et al., 2011; Winguth et al., 2012; Penn et al., 2018)*
- Continental weathering and associated nutrient delivery are enhanced *(2.5x to 7x weathering flux, Sedlacek et al., 2004; Song et al., 2015)*



Zhang et al., 2018

How do higher temperatures impact the ocean redox state?

Microbial metabolic rates increase, intensifying the biological pump



Biological productivity at the surface

Remineralization of exported organic carbon within the ocean

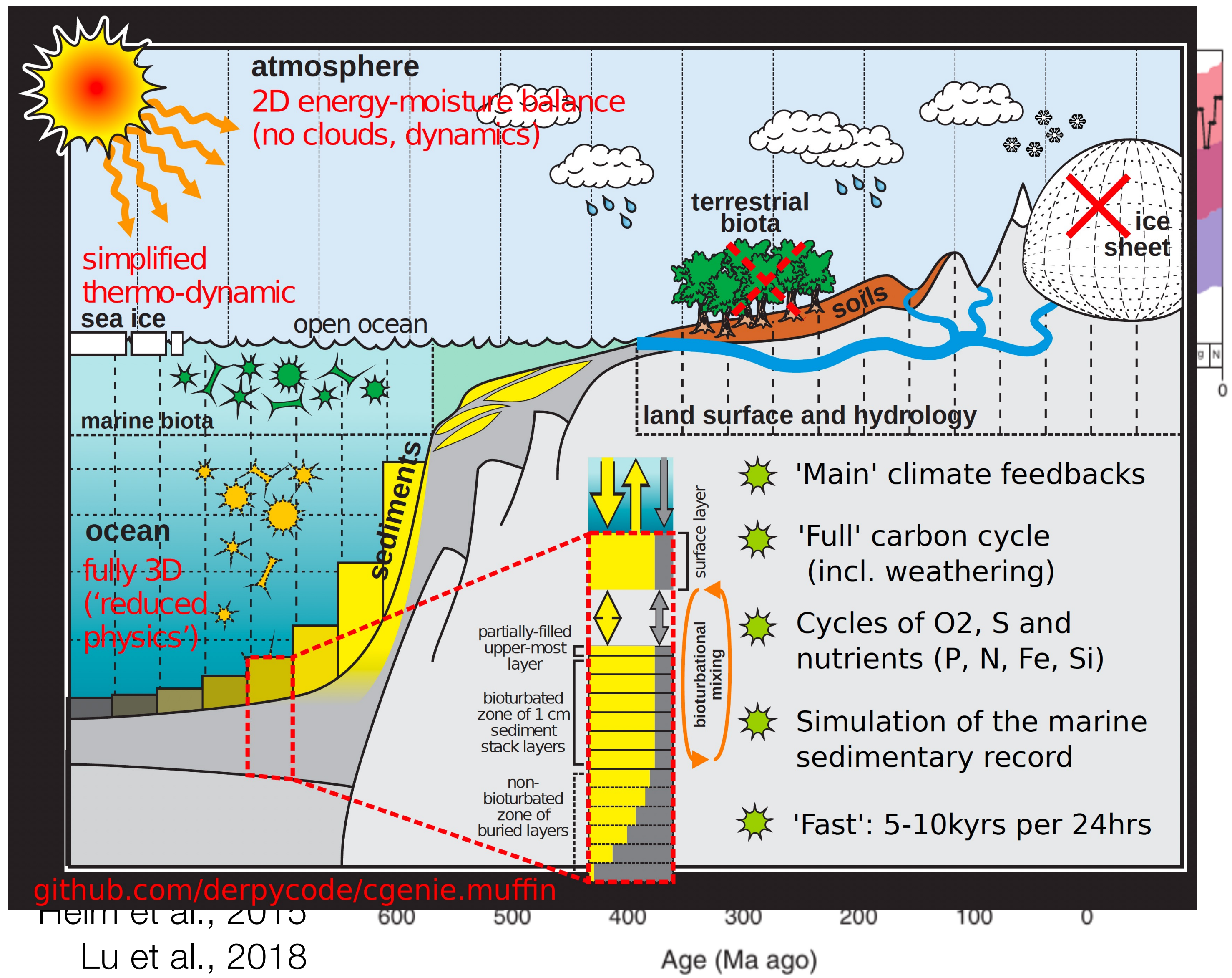
Burial of organic carbon in sediments

- At higher temperatures, higher remineralization rates result in greater release of nutrients in the shallow water column
- More efficient recycling of nutrients leads to greater export production

How do higher temperatures impact the ocean redox state?

The cGENIE intermediate complexity model

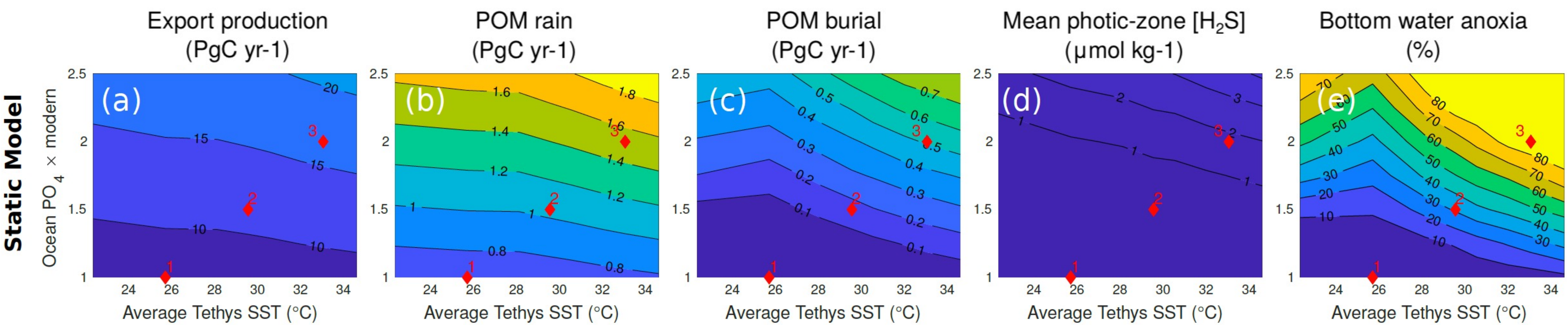
- Permian/Triassic paleogeography
- Prescribed pCO_2 to match SST estimates (Joachimski et al., 2012)
- Simulation of organic carbon reactions in sediments
- A mechanistic representation of the biological pump
  - Temperature-dependent OM remineralization
  - Sulfurization of OM
  - Slower OM sinking rate



Lu et al., 2018

How do higher temperatures impact the ocean redox state?

- A **static** model of the biological pump is not able to simulate reasonable results
  - → ***OM cycling is controlled almost entirely by nutrient concentration***
  - → ***Productivity and photic zone [H_2S] insensitive to temperature***
  - → ***Extreme sensitivity of seafloor anoxia***



Inc to > 15

Inc to > 1.4

Inc to 0.5

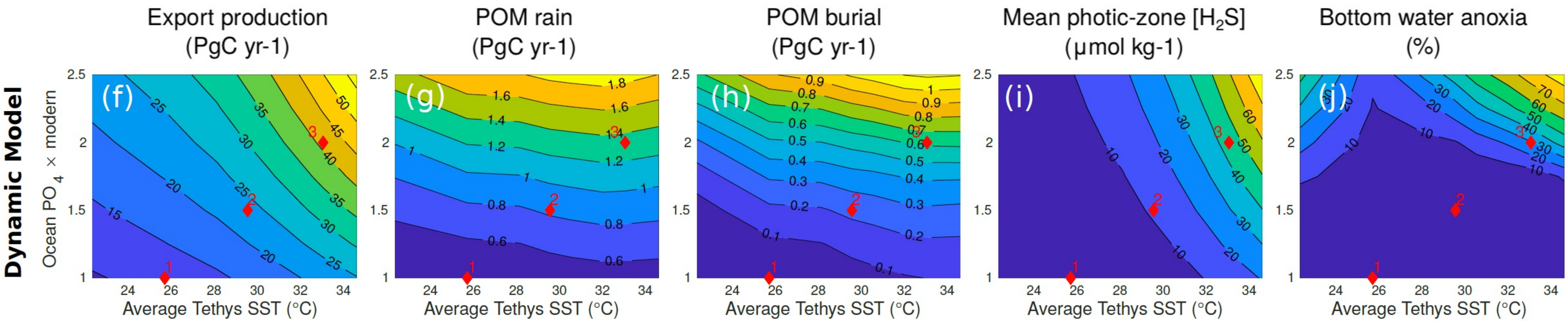
Inc to ~2

Inc to > 80%

Hülse et al., in press

How do higher temperatures impact the ocean redox state?

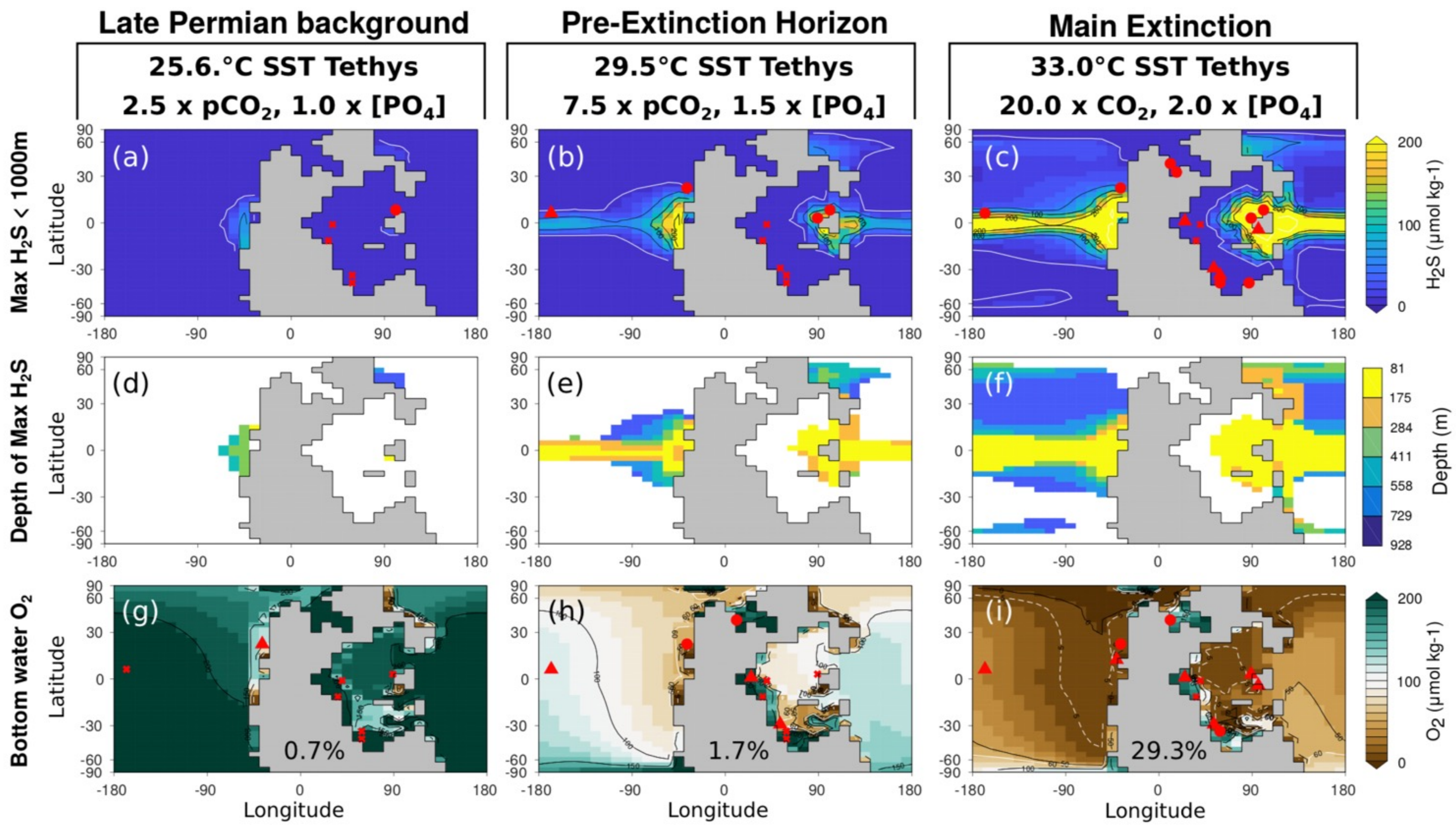
- In a **dynamic** model, microbial metabolic rates increase, intensifying the biological pump
  - → ***Nutrient recycling in the upper ocean is strengthened***
  - → ***Export production is enhanced***
  - → ***Euxinic/anoxic conditions expand upward in the water column and on the seafloor***



	Export production	POM rain	POM burial	Mean photic-zone $[H_2S]$	Bottom water anoxia
Static:	Inc to > 15	Inc to > 1.4	Inc to 0.5	Inc to ~2	Inc to > 80%
Dynamic:	Inc to > 40	Inc to > 1.3	Inc to 0.6	Inc to >40	Inc to > 30%

Hülse et al., in press

Anoxia was extensive but not global



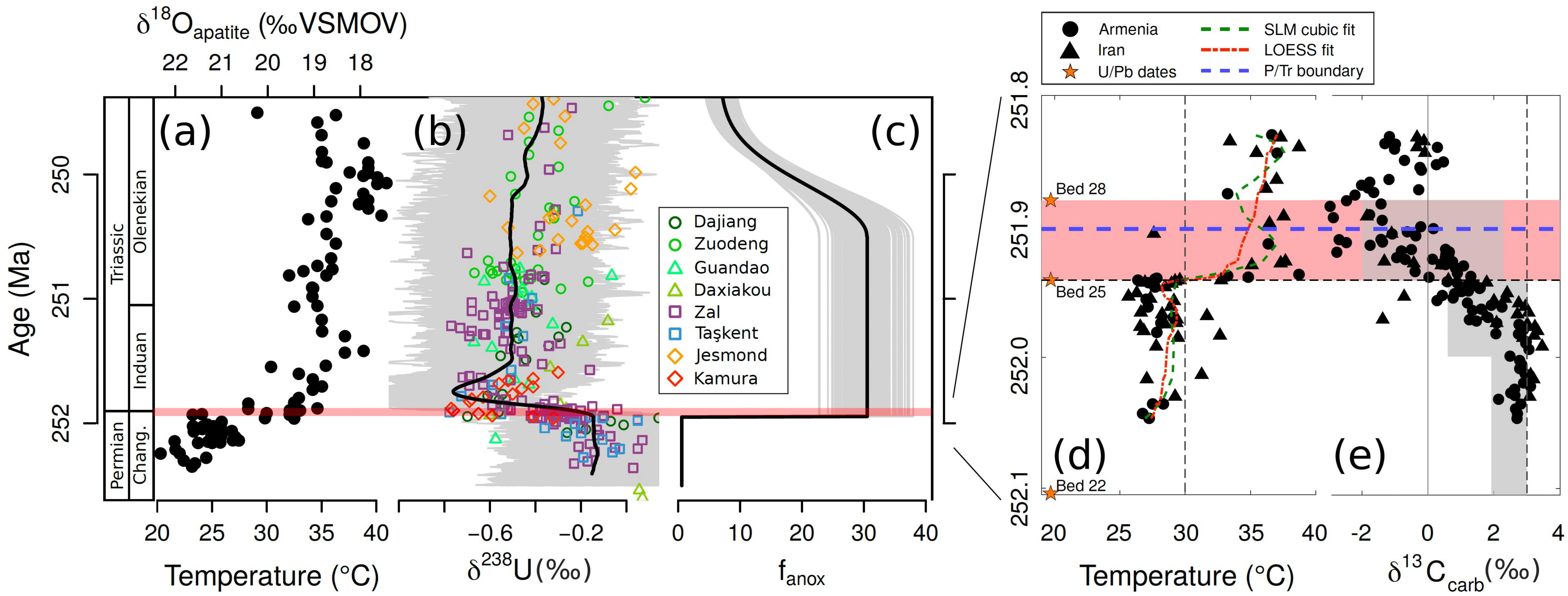
→ Red circles = *evidence for anoxia/euxinia*

→ Crosses (small points) = *no evidence for anoxia/euxinia*

→ Triangles = *ambiguous or dynamic redox conditions*

Hülse et al., in press

A more intense biological pump can impact $\delta^{13}C$ profiles

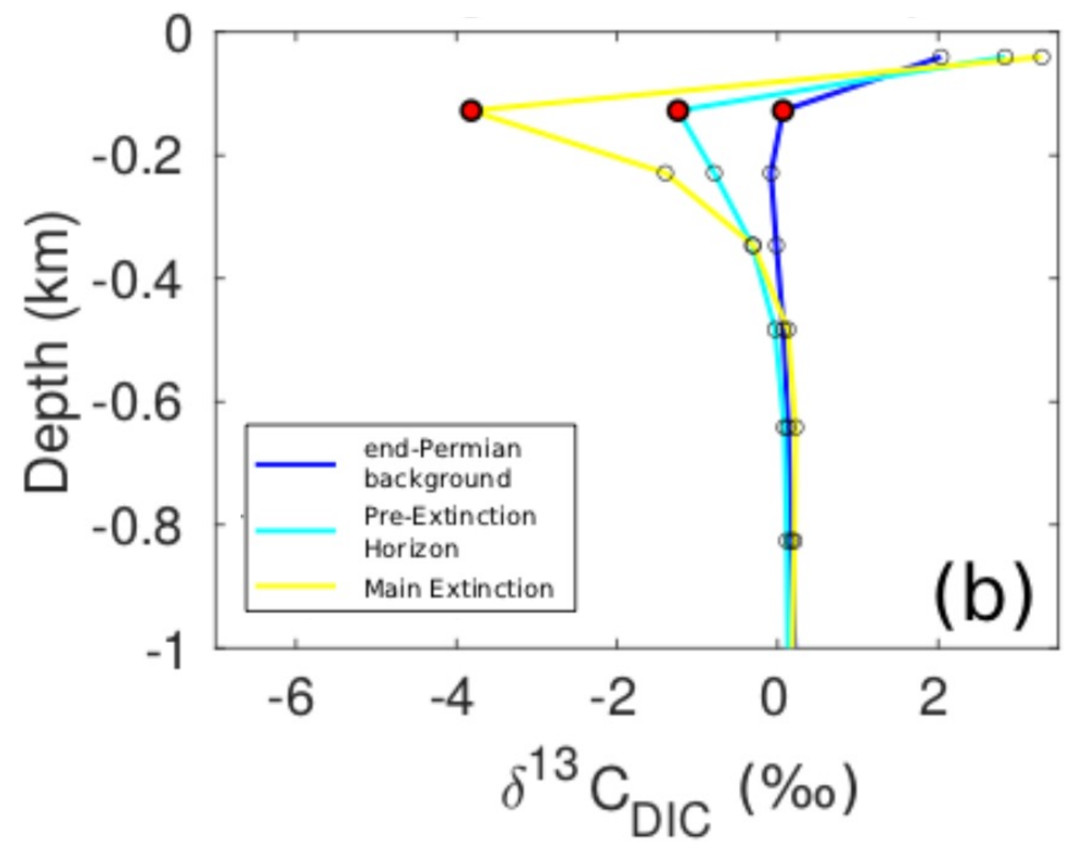


Hülse et al., in press

A more intense biological pump can impact $\delta^{13}C$ profiles

Temperature-driven increases in microbial respiration **alone** can lower seawater $\delta^{13}C$

Implications for (1) spatial variability in $\delta^{13}C$ and (2) estimating the volume and sources of C fluxes related to climate warming



Hülse et al., in press

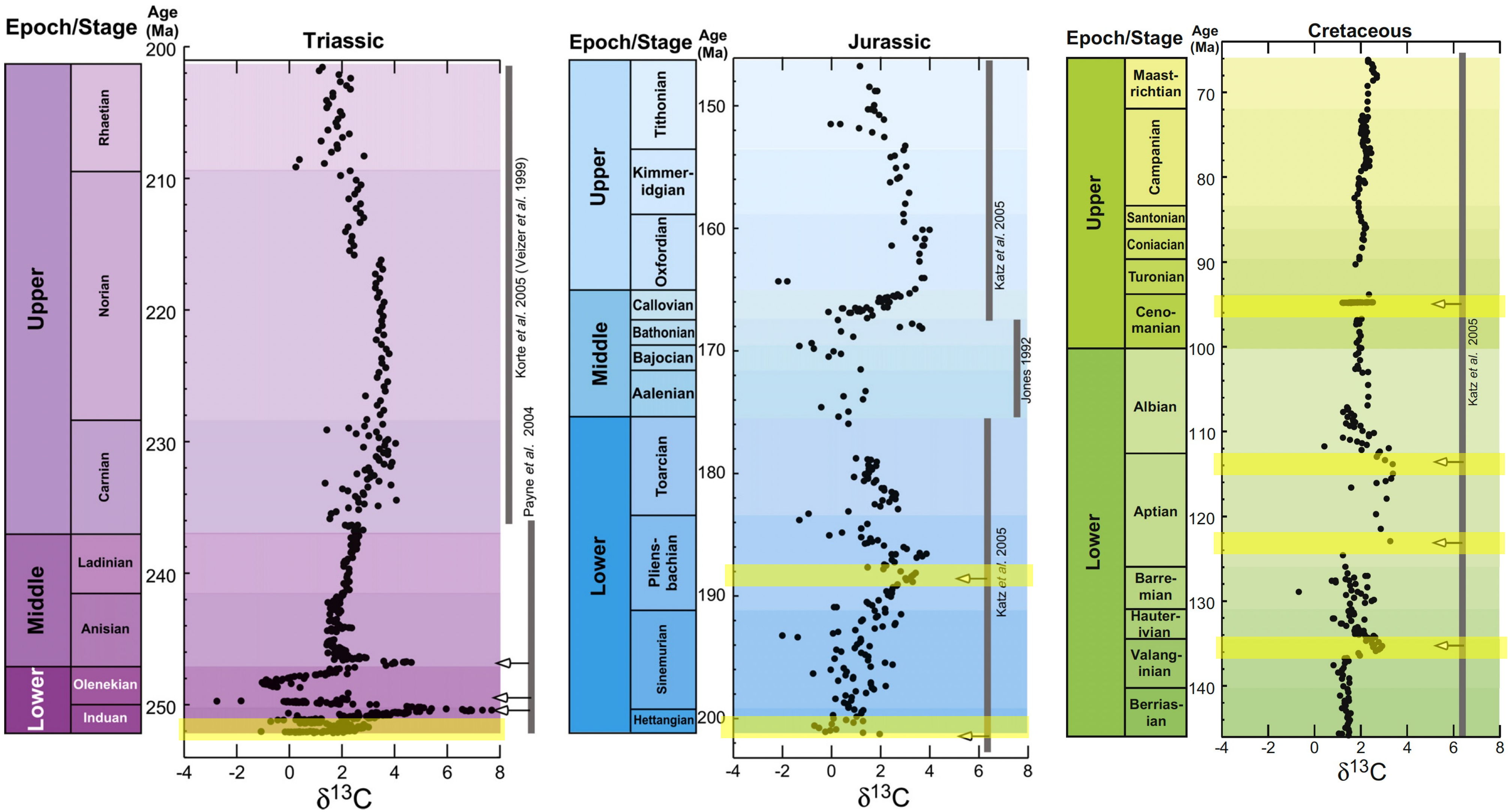
Temperature-induced changes in the biological pump can be mechanistically linked to anoxia

- Uranium isotopes can help to evaluate **how** warming temperatures are linked to the deterioration of the marine environment

- Our proposed mechanism – a strongly temperature-dependent biological pump – **does not** require extreme nutrient input or long-lasting shut-down of thermohaline circulation

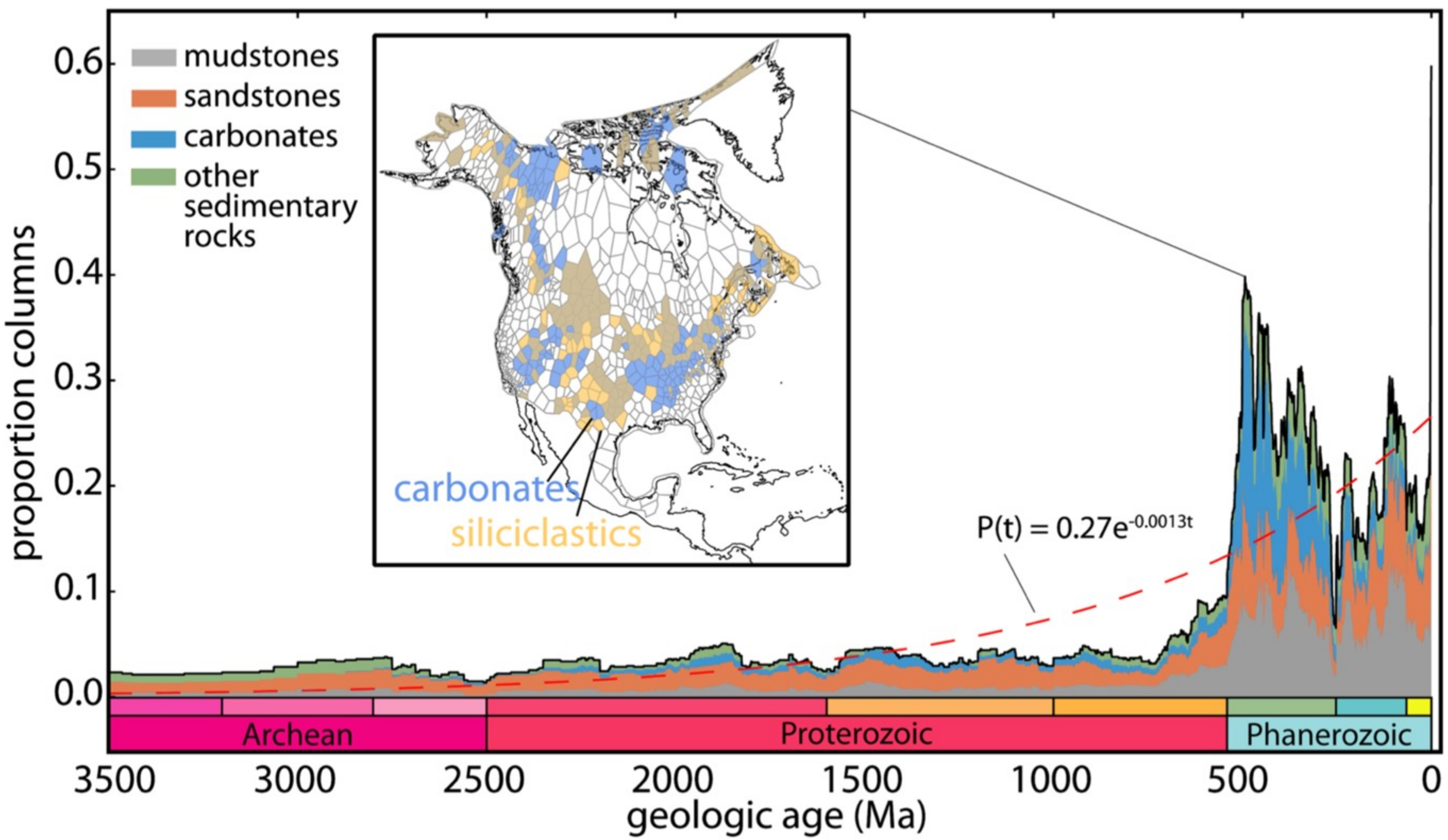
- Temperature-driven increases in microbial respiration **alone** can lower seawater $\delta^{13}C$

Temperature-induced changes in the biological pump can be mechanistically linked to anoxia



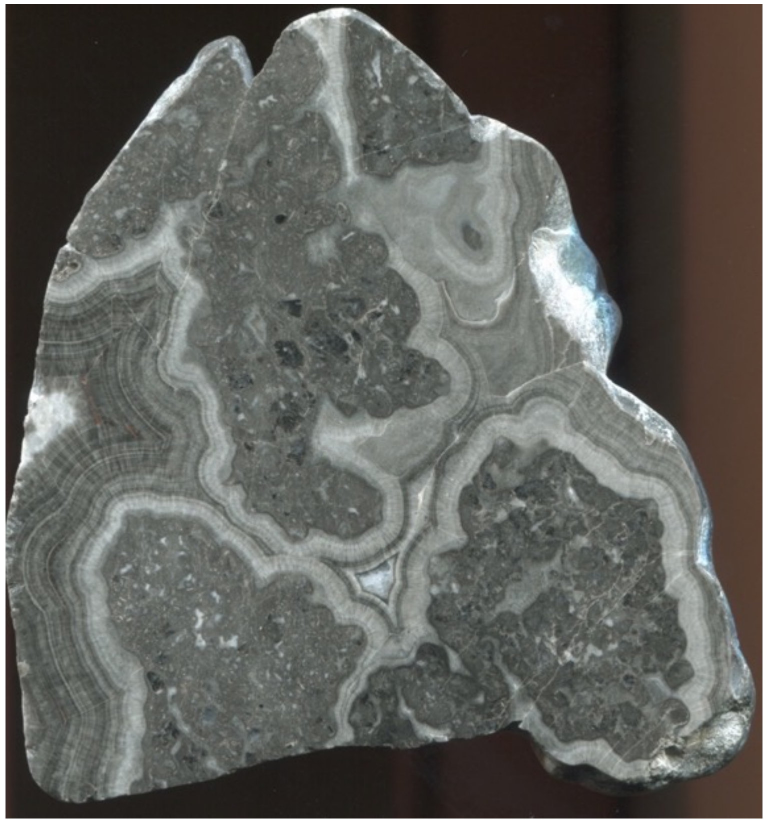
Saltzman and Thomas, 2012

Carbonate geochemical records present unique advantages …



Husson and Peters, 2018

… and challenges



Middle Triassic Microbial
Reef Boundstone, S. China

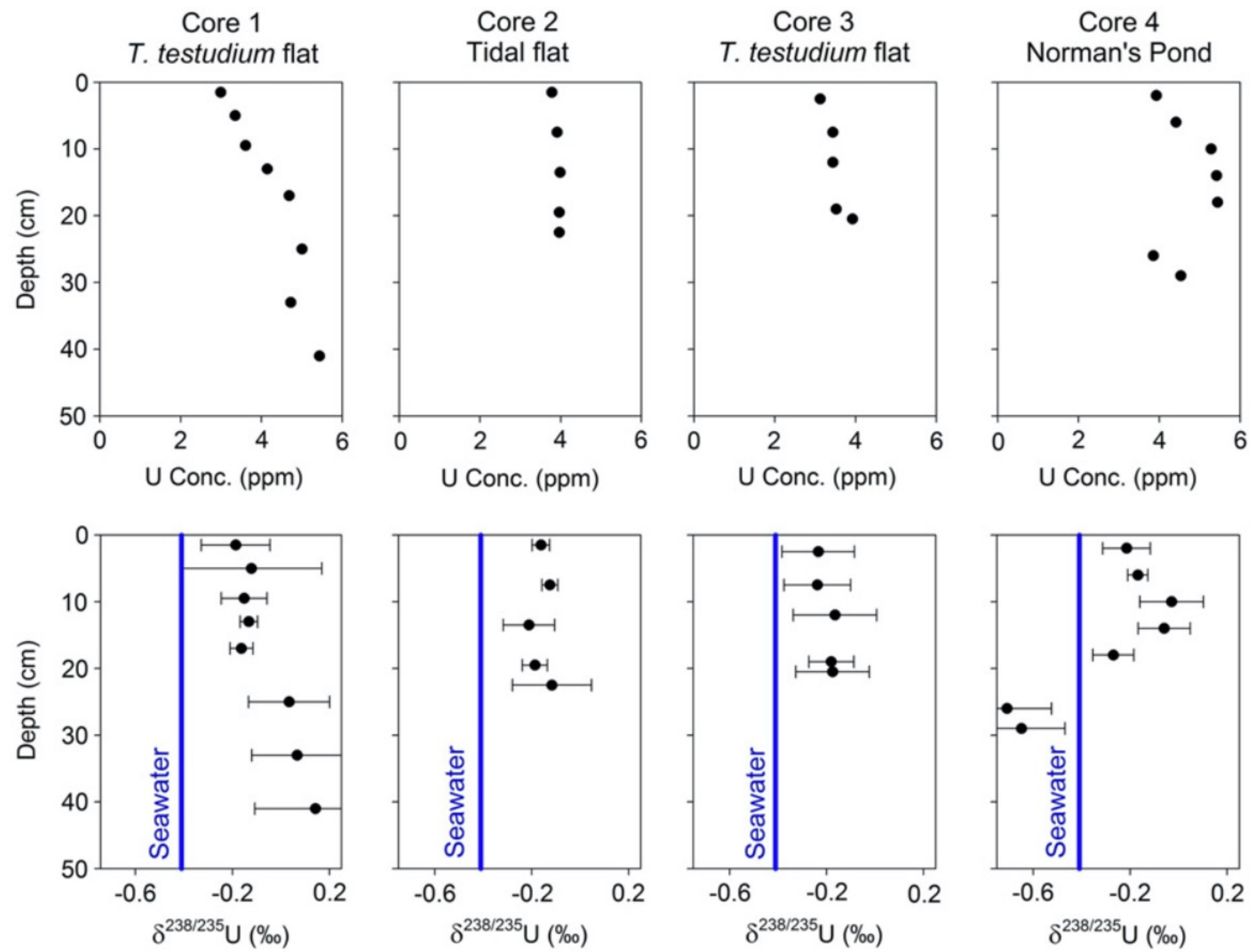
Dolomites, Italy

Challenges in interpreting carbonate geochemical records

Carbonates and diagenesis:

Are we capturing a record of seawater chemistry?

- **Romaniello et al. (2013)**, Hood et al. (2016) and (2018), Chen et al. (2018), Tissot et al. (2018)

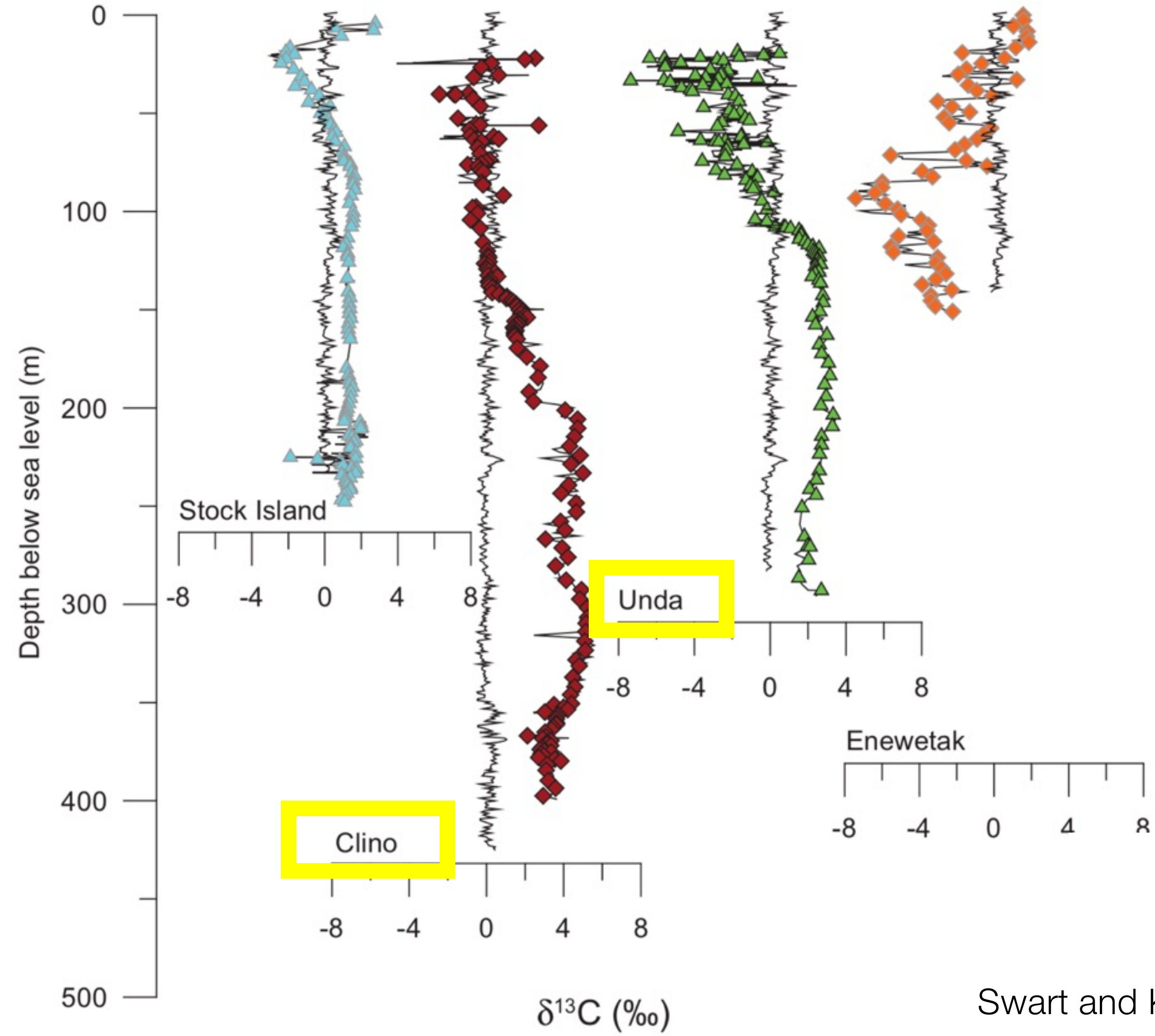


Challenges in interpreting carbonate geochemical records

Carbonates and diagenesis:

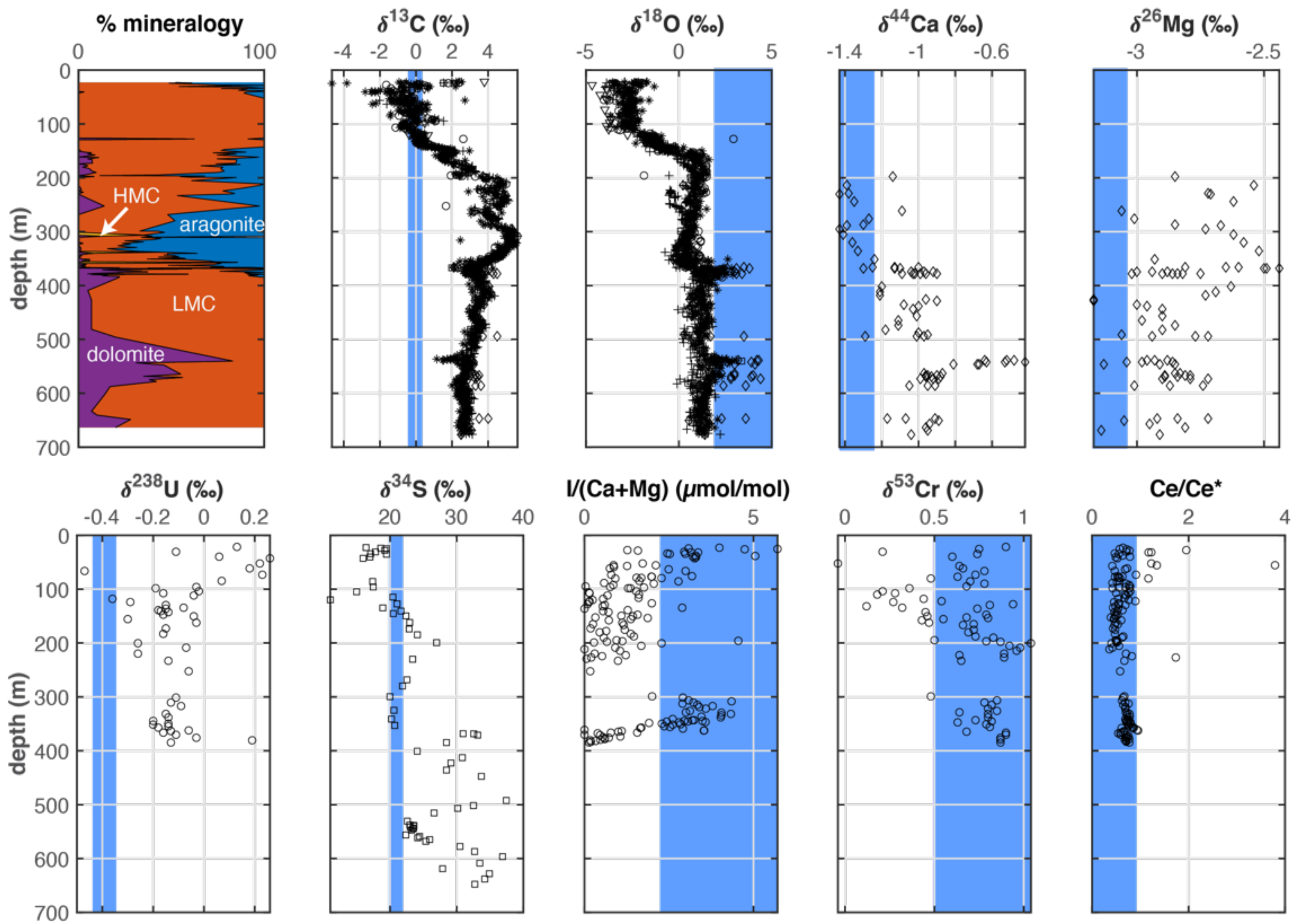
Are we capturing a record of seawater chemistry?

- Key studies performed at Clino and Unda, Late Neogene cores drilled on the Great Bahama Bank



Swart and Kennedy, 2012

Diagenetically altered recent carbonate contain the proxy ranges observed through Earth history

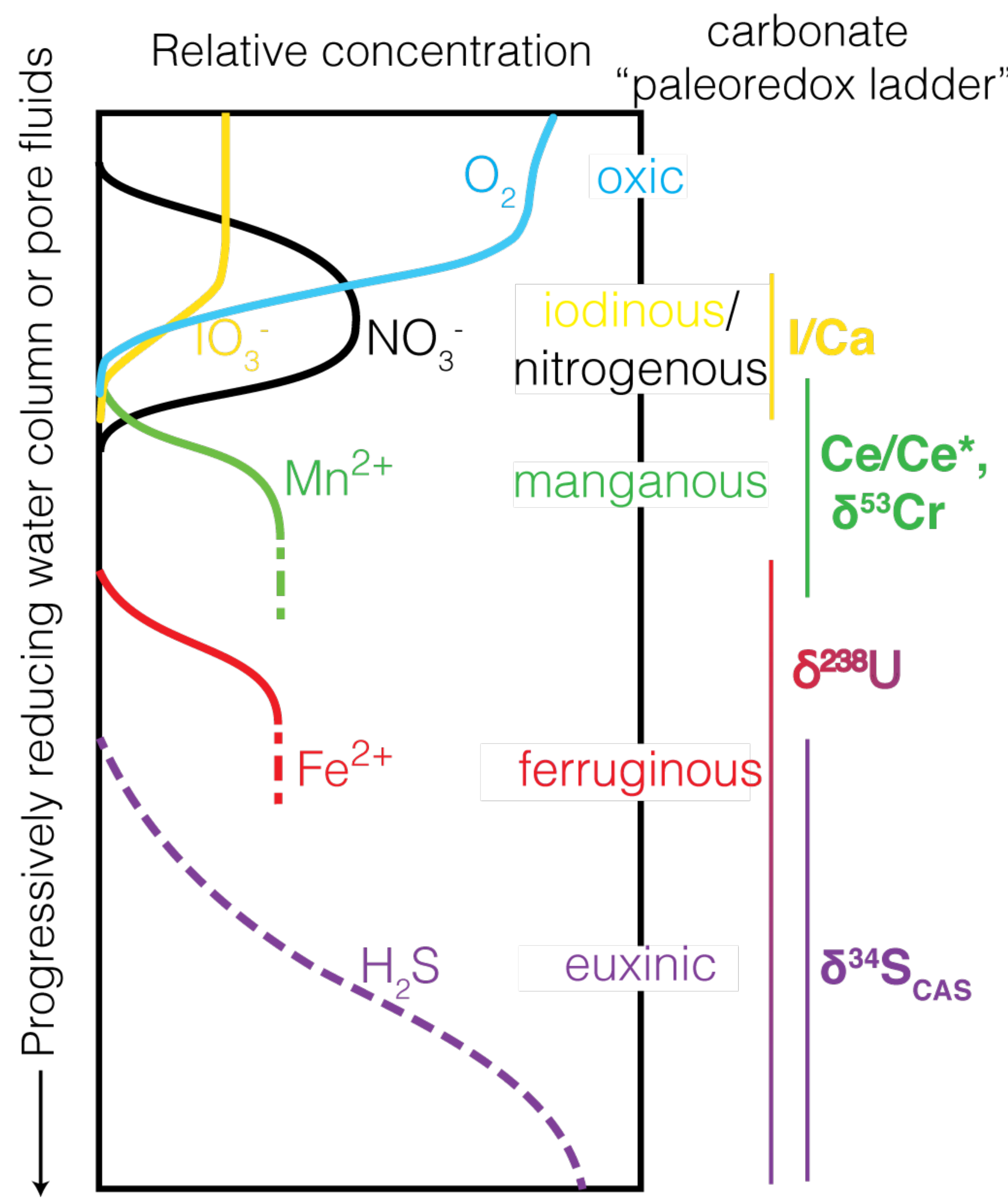


Expected values for primary carbonates reflecting oxidizing seawater geochemistry

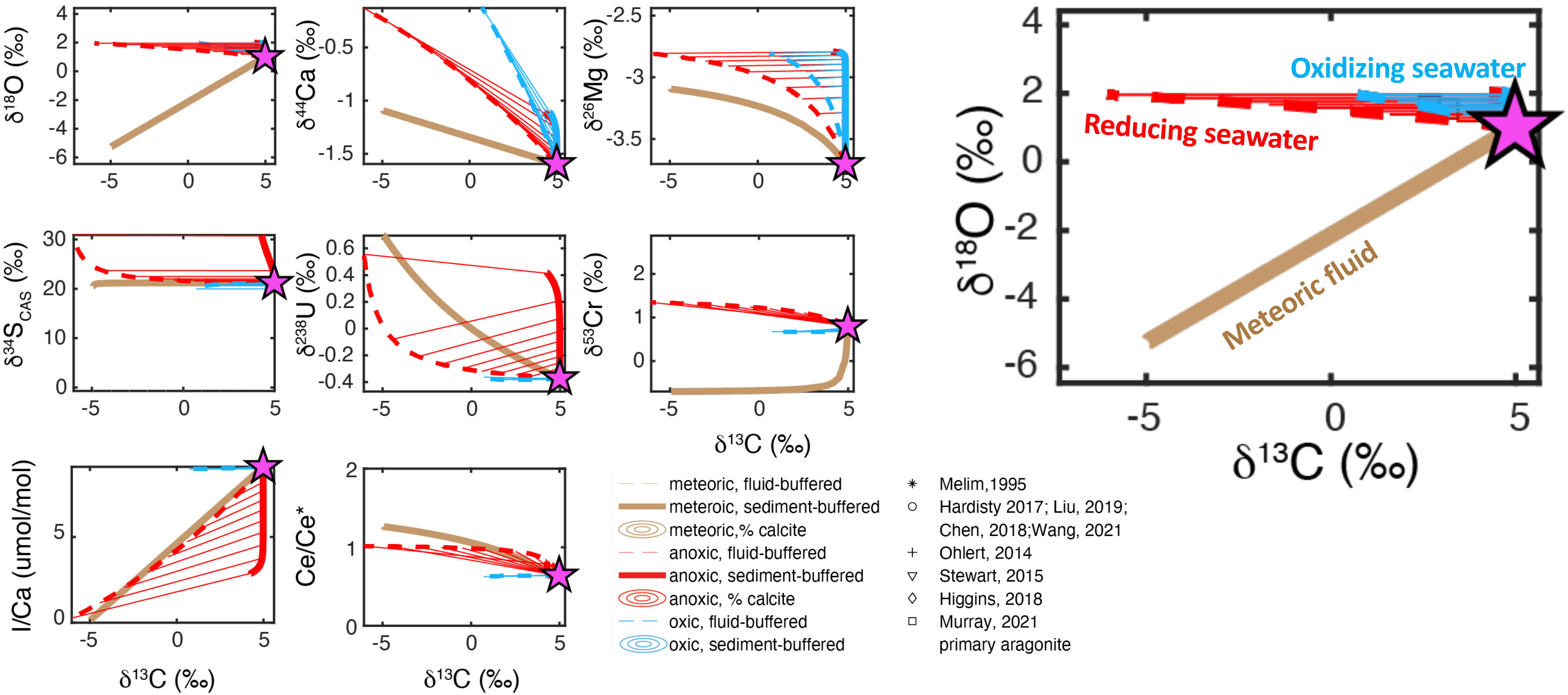
Melim et al., 2001, 2002, 2004;
Oehlert et al., 2014; Hardisty et al., 2017; Chen et al., 2018; Tissot et al., 2018; Liu et al., 2019; Dellinger et al., 2020; Murray et al., 2021

Combining proxies holds promise for fine-tuning redox thresholds

- Positioned along the paleoredox ladder
- Will respond uniquely to different diagenetic fluids



The geochemical trajectory of carbonate alteration in different diagenetic scenarios can be predicted



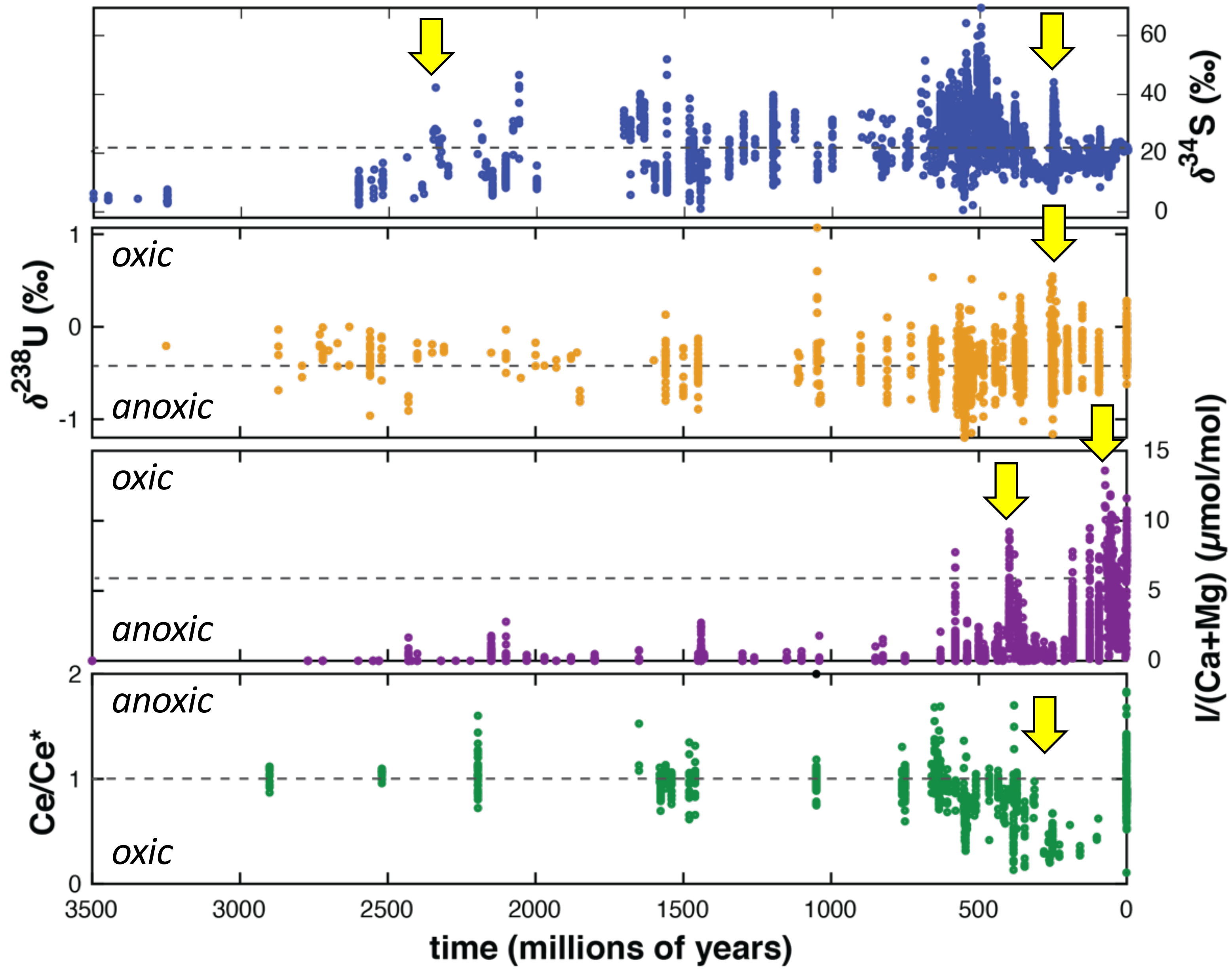
Predictive models allow us to assess multi-proxy redox studies

*δ^{34}S shifts at **2.35** Ga, change in variance at **250** Ma*

*δ^{238}U shifts at **260** Ma*

*I/(Ca+Mg) shifts at **397** and **74** Ma*

Ce/Ce shifts at **280** Ma*



Refs

Unpublished compilation courtesy of B. Gill

Chen et al., 2021

Loope et al., 2013; Hardisty et al., 2014 and 2017; Lu et al., 2017; Lu et al., 2018; Lowery et al., 2018; Wei et al., 2019; Young et al., 2019

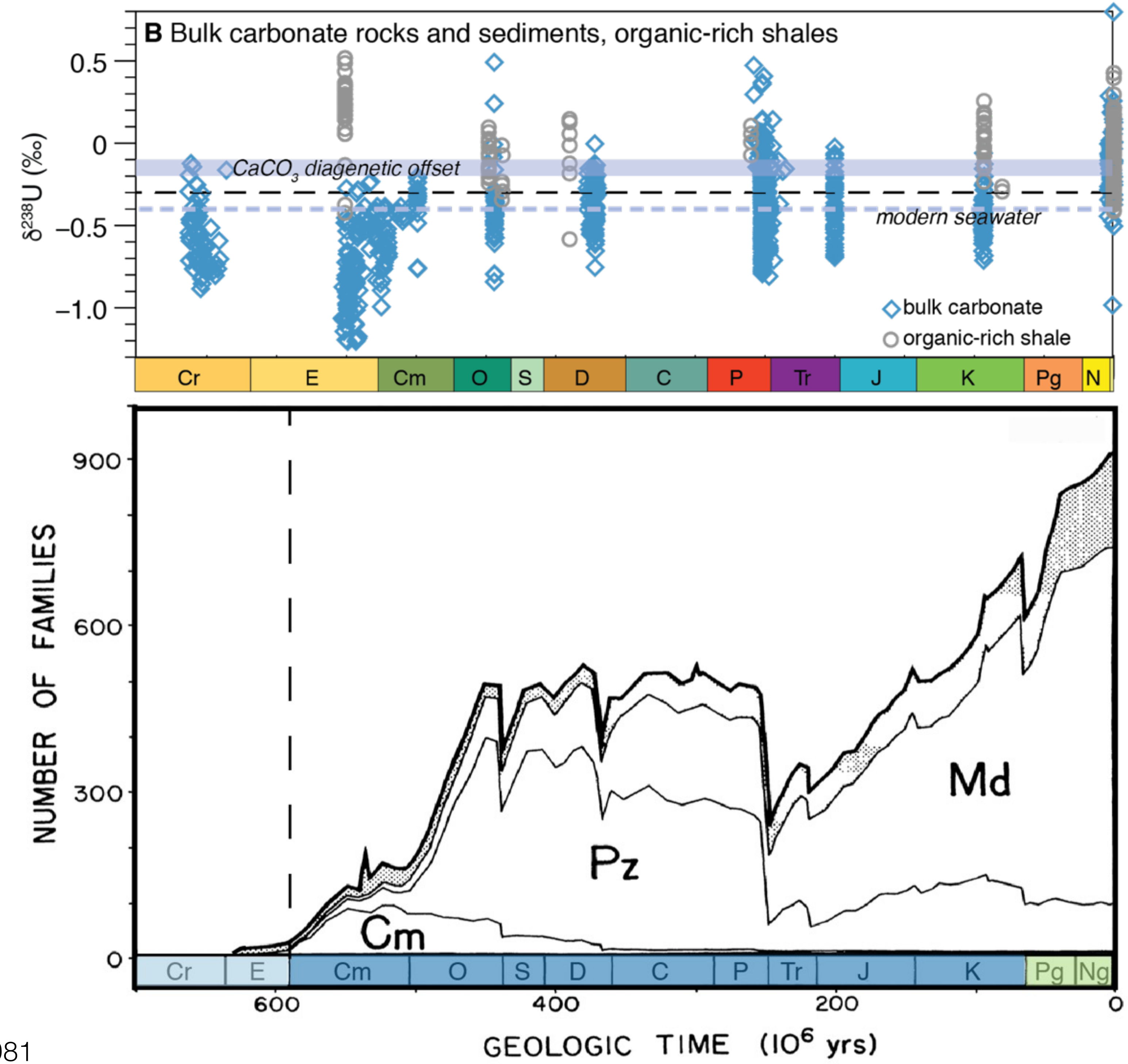
Tang et al., 2016; Wallace et al., 2017; Hood et al., 2018; Zhang et al., 2018

Summary

- The end-Permian provides a deep-time opportunity for data-model comparison to investigate the mechanistic links between climate change and biogeochemical processes.
- Carbonate U isotope records have the potential to track primary redox changes, with some variability as a result of diagenesis that can be potentially untangled with a multi-proxy approach.
- Local depositional conditions play important roles in determining the isotope signature of U in carbonate sediments.

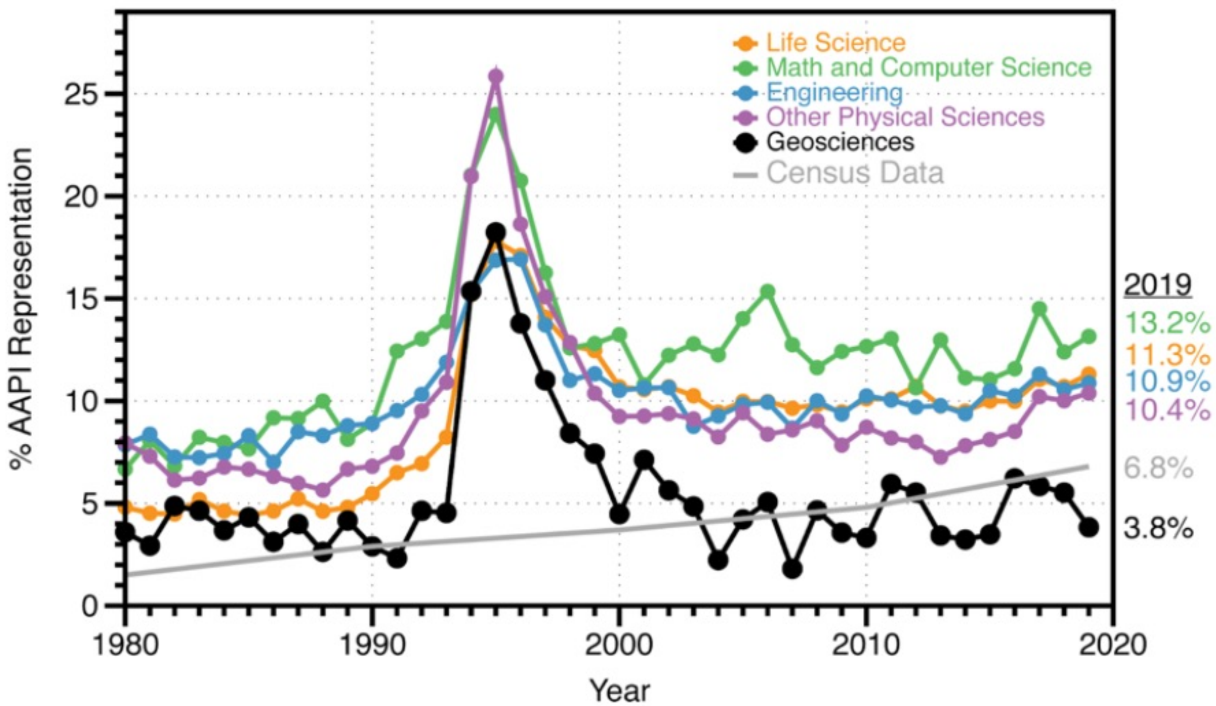
Summary

Developing and testing proxies—such as $\delta^{238}U$—can shed light on the relationship between climate and the marine redox state.



(Top) Lau et al., 2019. (Bottom) Modified from Sepkoski, 1981

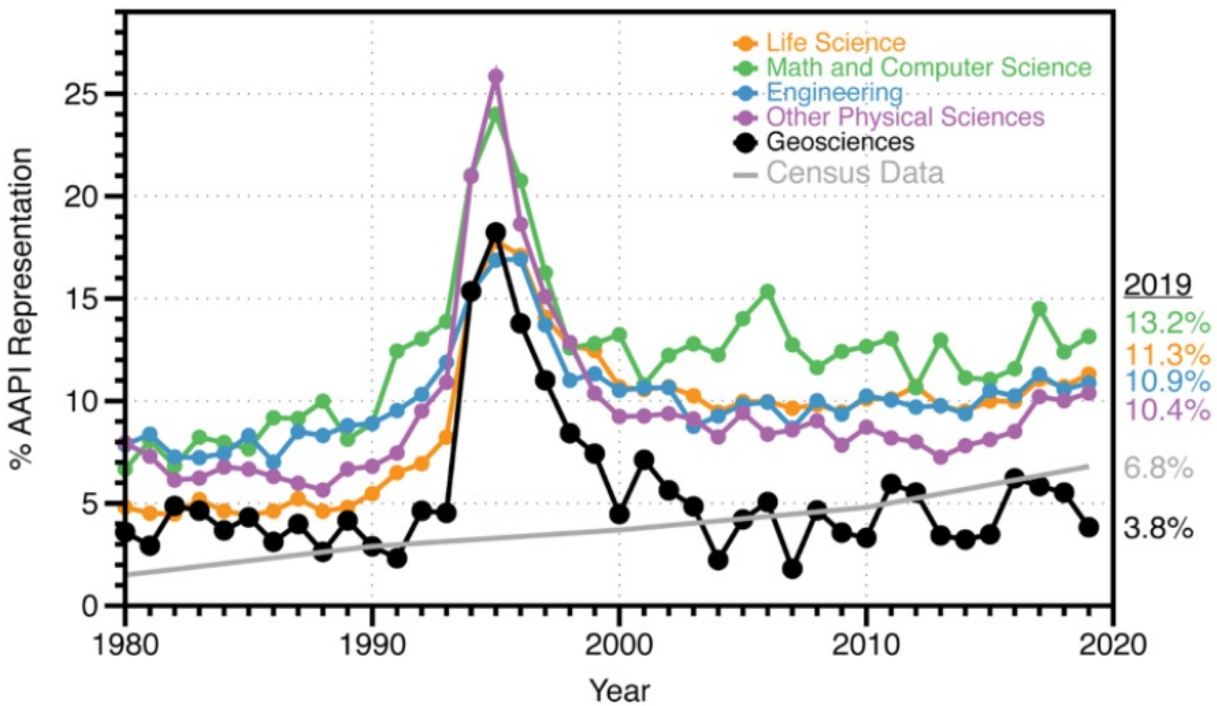
Asian Americans and Pacific Islanders in Geosciences



NSF Survey of Earned Doctorates

- The “AAPI” categorization is very broad, representing individuals with ancestry or heritage in East and Southeast Asia, the Indian subcontinent, and Oceania. It represents a huge range of social identities and backgrounds that don’t fit easily within a shared narrative.

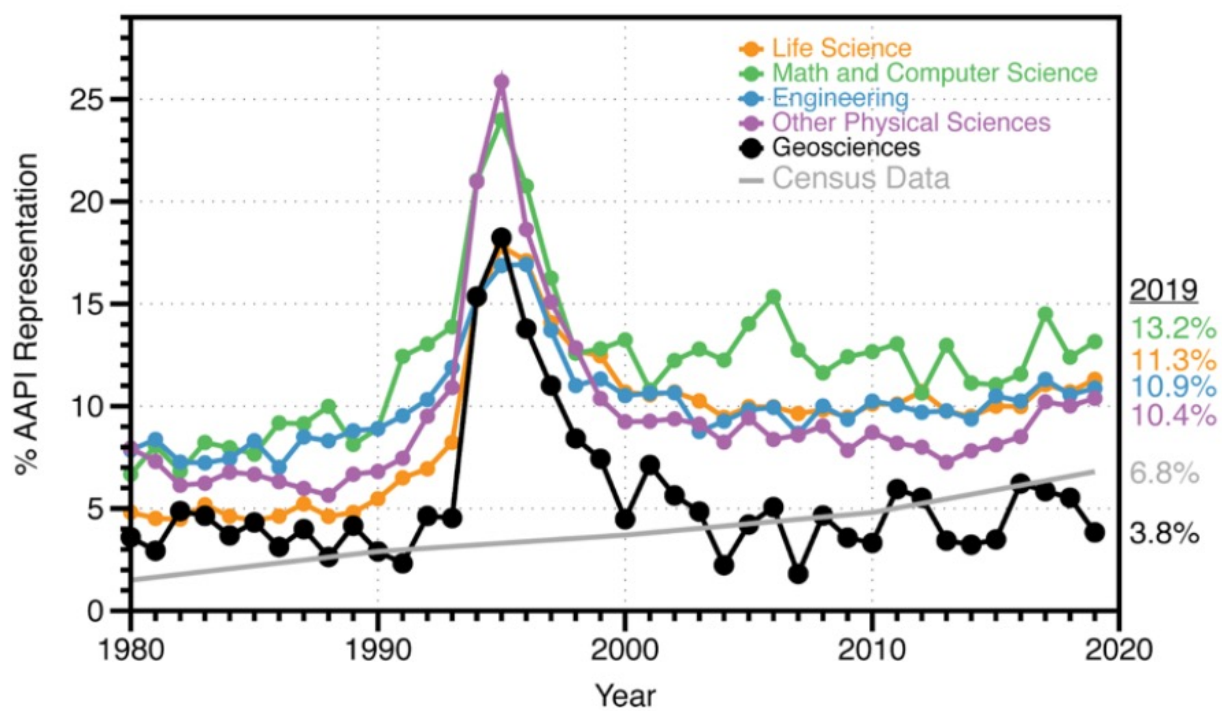
Asian Americans and Pacific Islanders in Geosciences



NSF Survey of Earned Doctorates

- The term originated in the 1960s in solidarity with the Black Power Movement and in recognition that more issues unify Asian Americans than divide them.
- “Pacific Islanders” were added to the designation in the U.S. Census in the 1980s but is now counted separately.

Asian Americans and Pacific Islanders in Geosciences



NSF Survey of Earned Doctorates

- AAPIs in Geosciences face distinct recruitment and community-building issues. A one-size fits all approach will not necessarily improve “BAJEDI”:
  - Diversity within this umbrella
  - Cultural pressures (“Model Minority”); lack of exposure to the Earth and Planetary Sciences
  - Stereotypes limit AAPI leadership (“bamboo ceiling” and “perpetual foreigner”)

“AAPIiG” community

- Co-founder with Daniel Ibarra (Brown Univ.) and Christine Y. Chen (LLNL).
- >300 people signed up so far.
- Active Slack channel and community listserv.
- Will be launching a mentoring program, research internship program, and researcher visit program this Dec./Jan.
- We are also excited to build collaborations with other communities.
- Interested? Sign up and register for events at aapigeosci.org!

Thank you