

Dynamics of the Cretaceous Oceans: A Numerical Recipe

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European Research Council
Established by the European Commission



Outline

★ “Take one whole fresh super-continent and break into pieces. Pick out the rock phosphate and place to one side. Immerse the continental fragments in seawater until the shelves and interior seaways are thoroughly flooded.”

★ “Add a pinch of CO₂ and heat gently.”

★ “While the ocean is warming and de-oxygenating, gradually stir in the phosphate that was put aside earlier. Keep stirring and adding CO₂ and phosphate until a thick black carbon crust suddenly forms. Remove the crust. Repeat to create as many carbon layers as possible before the cake starts to cool and the ocean re-oxygenates.”

★ The primary question is then ...

continental
topology/
topography

temperature/
stratification

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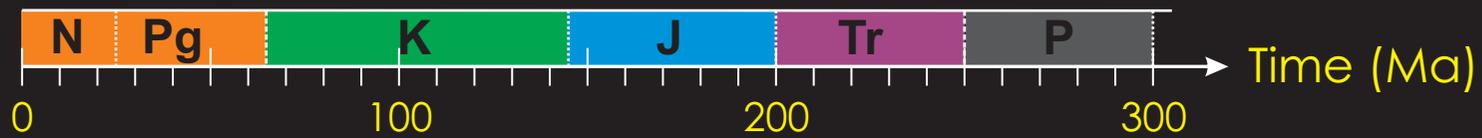
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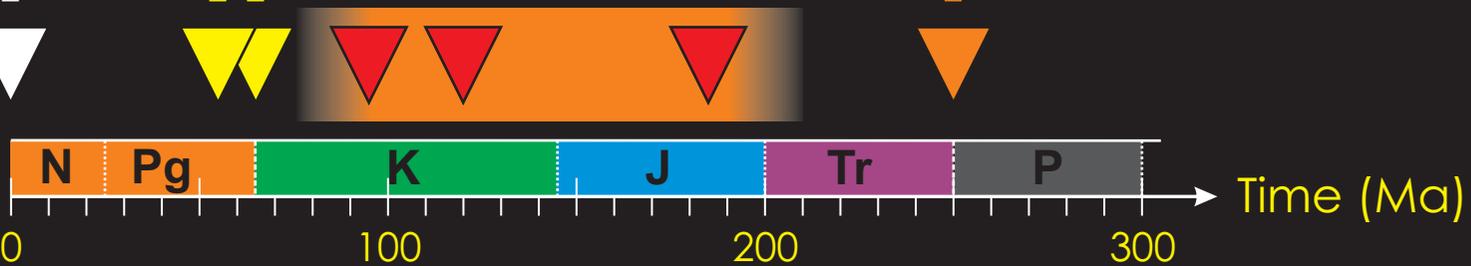
What is the 'recipe' for OAE (occurrence)?

Carbon cycle and oxygen perturbations



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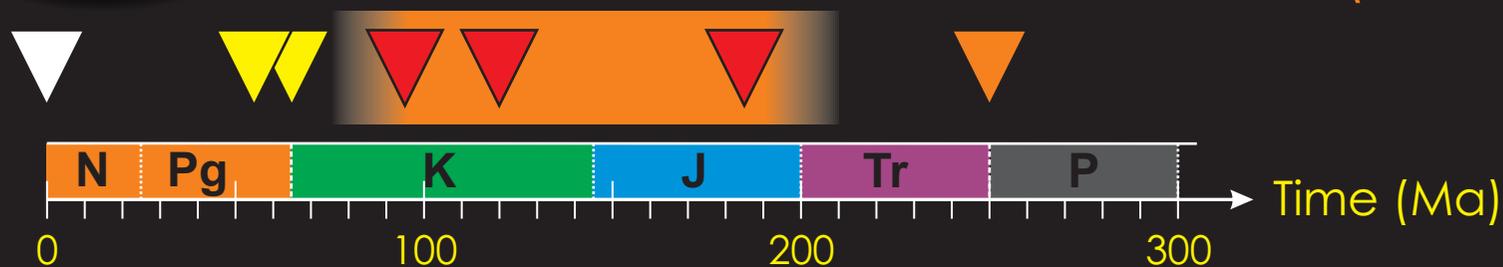
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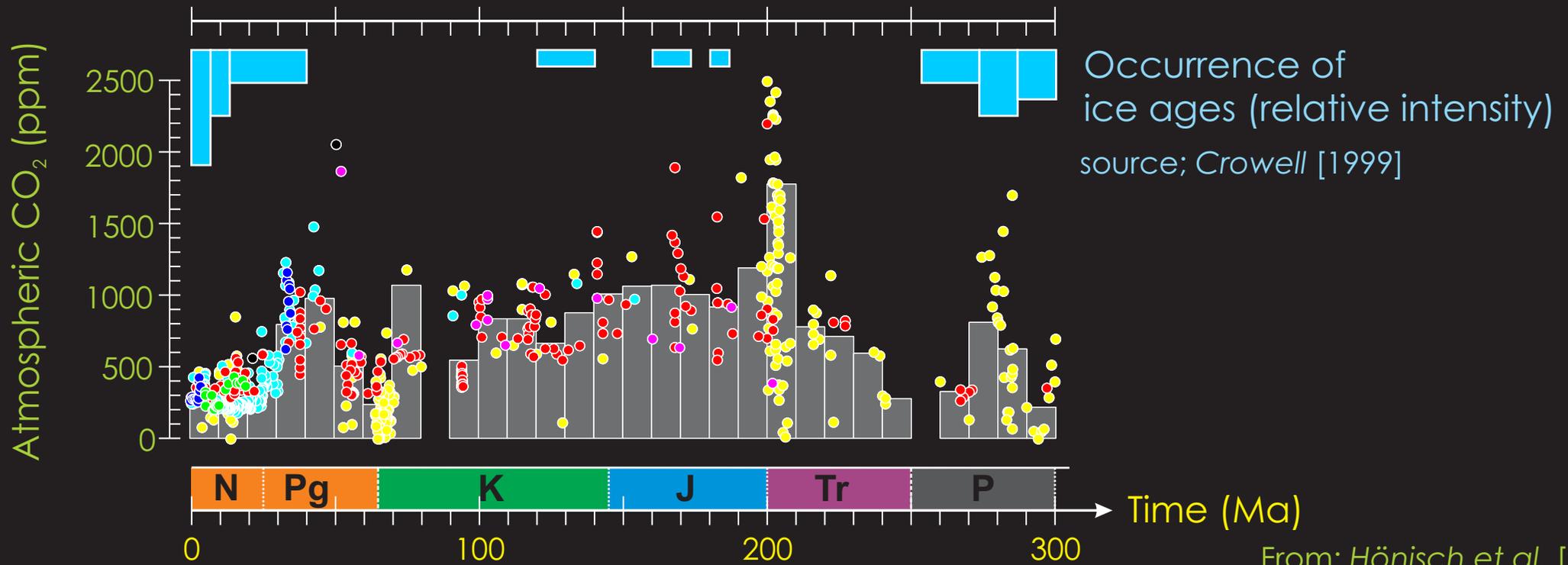
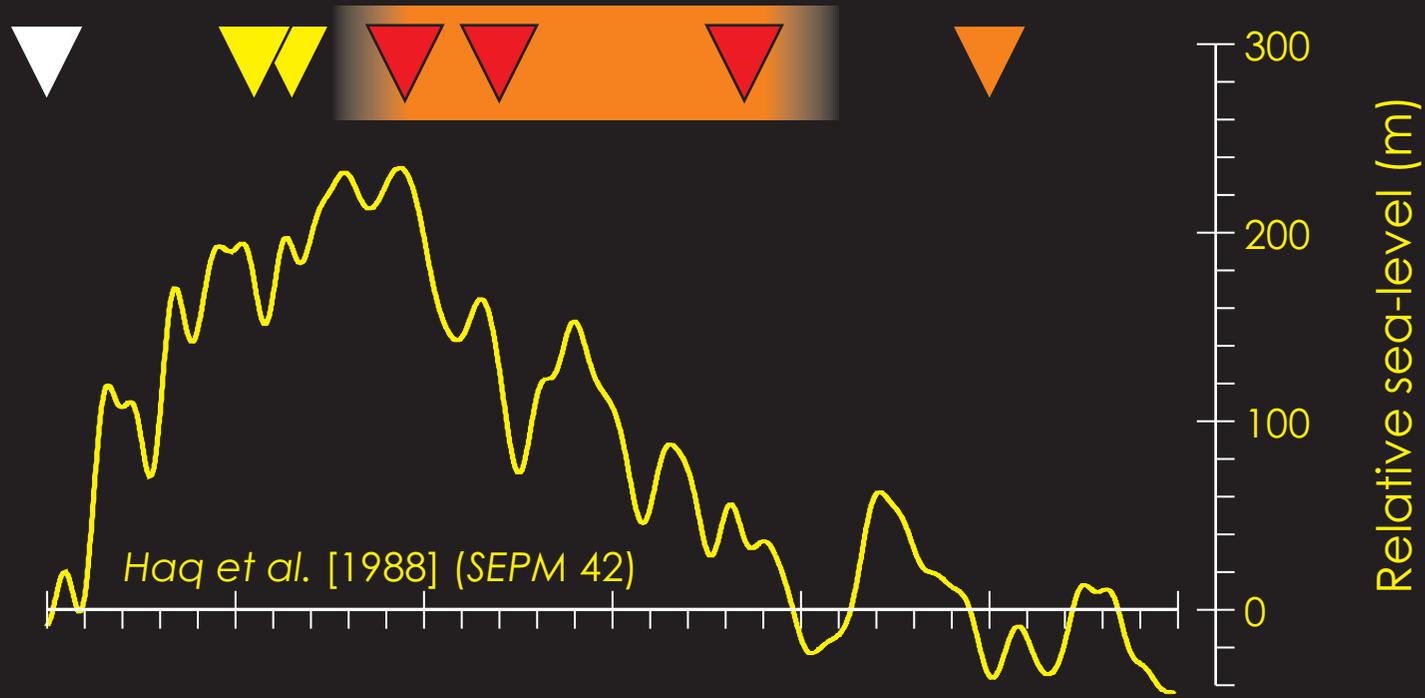
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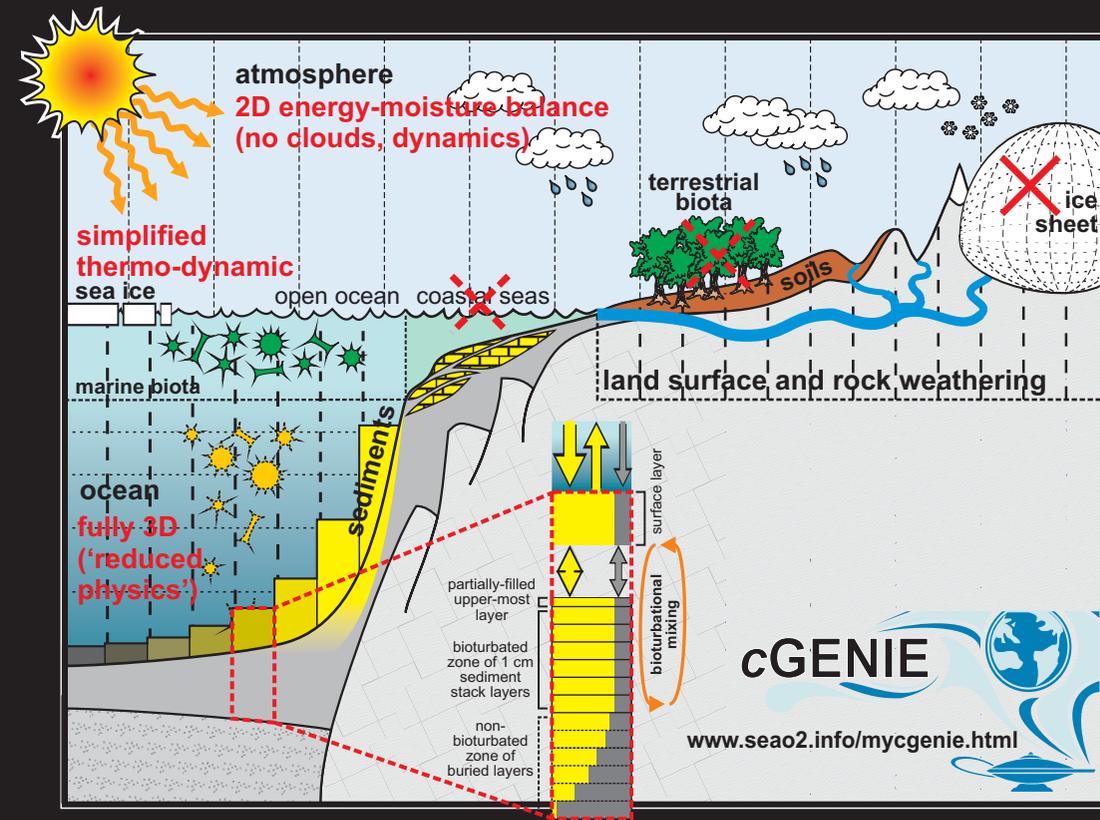


muffkie? (a-la 'cronut', 'duffin')

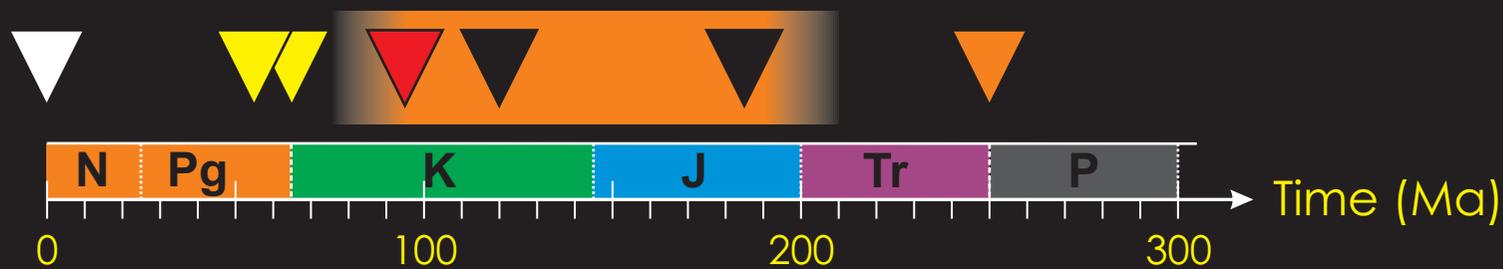


What is the 'recipe' for OAE (occurrence)?





'cGENIE' Earth system model ('of Intermediate Complexity')



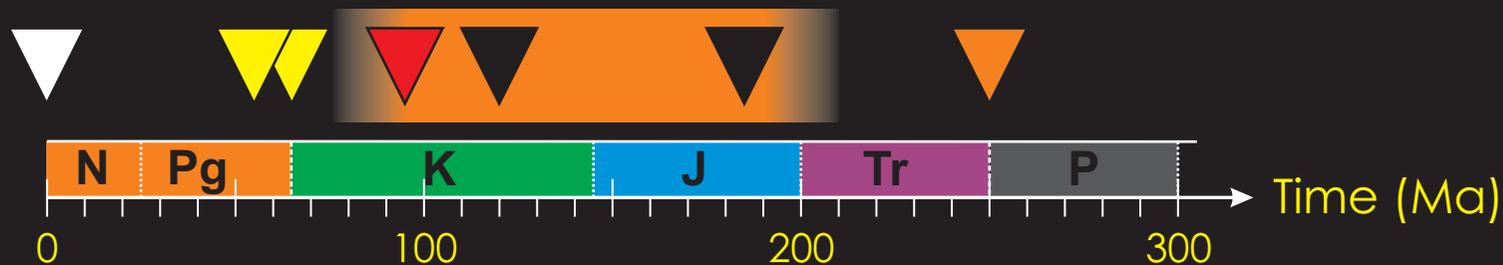
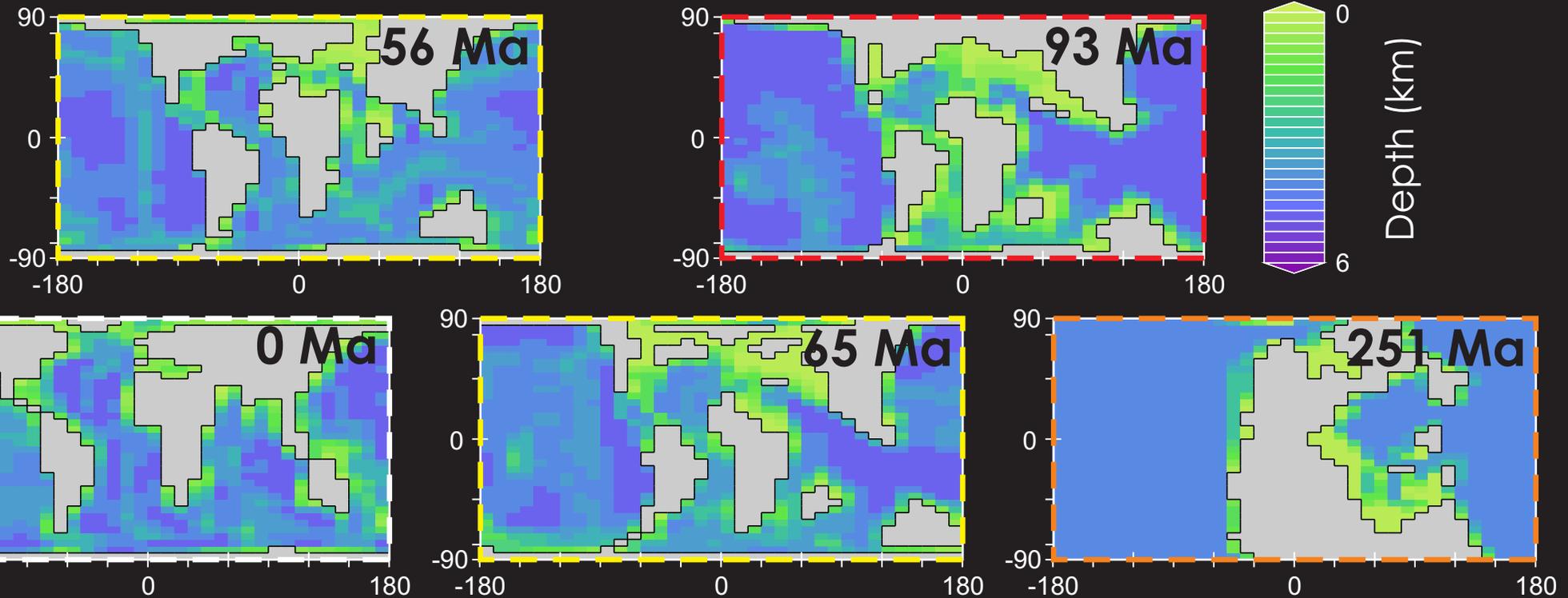
Importance of baking tin topology/topography

Carbon cycle and oxygen perturbations

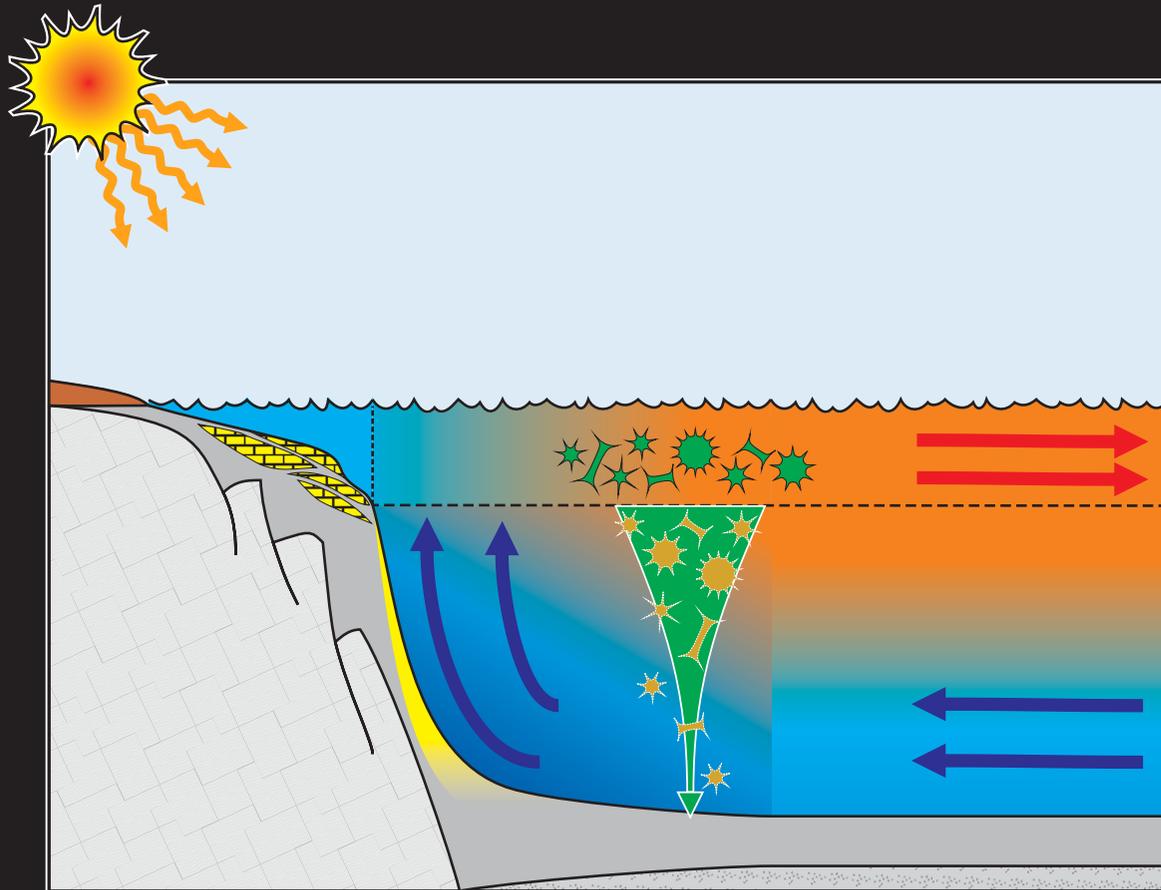
ocean bathymetry & continental configuration

<http://www.climate-lab-book.ac.uk/2014/end-of-the-rainbow/>

#endrainbow



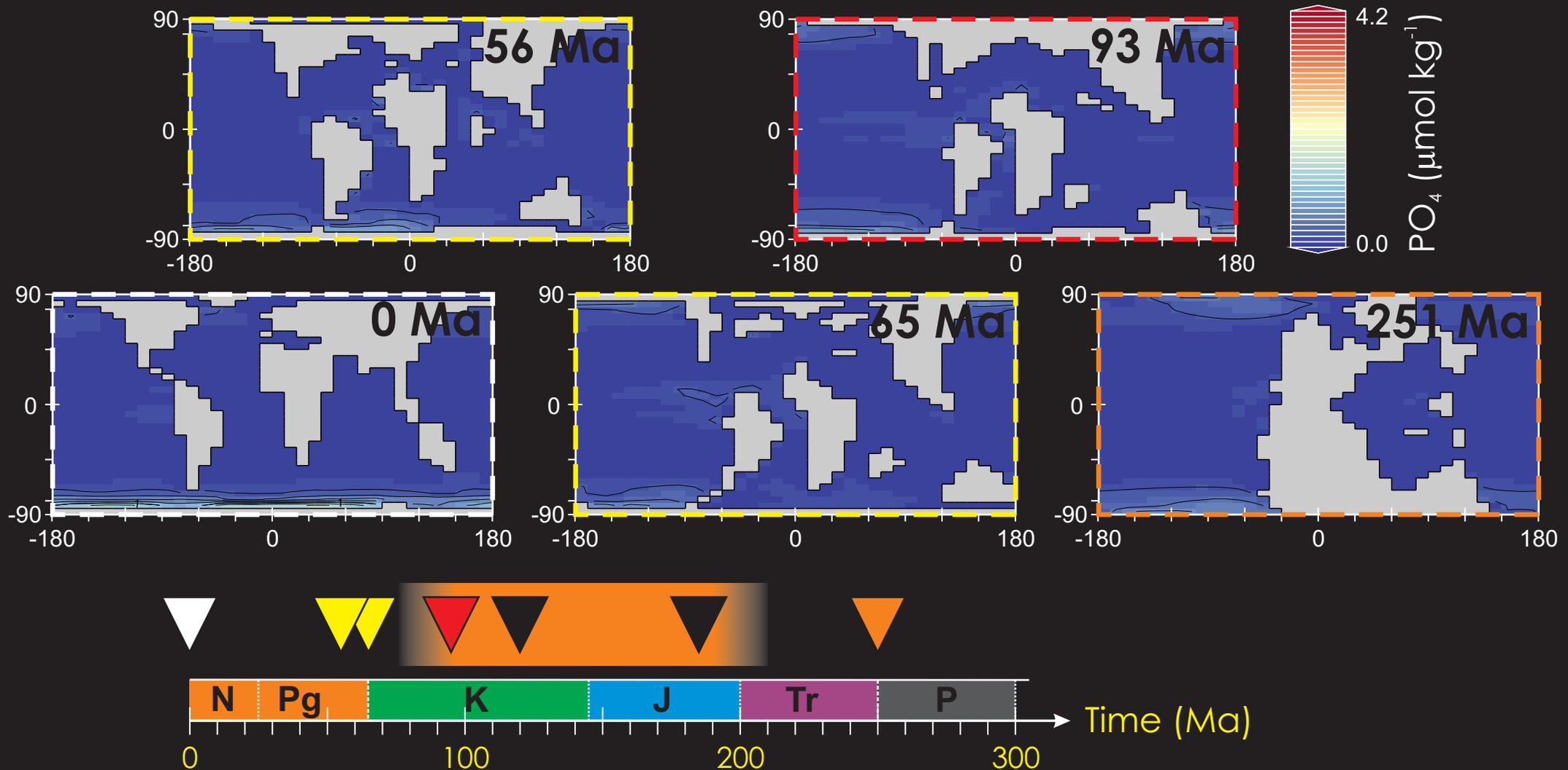
'estuarine circulation'



ocean surface [PO₄]

Biological export calculated by restoring nutrient concentrations to zero.

No 'spices' or 'flavourings' (e.g. iron) considered.

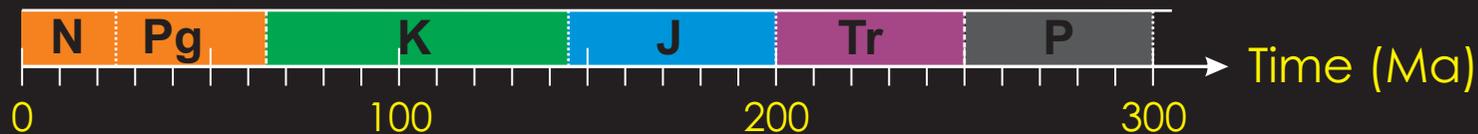
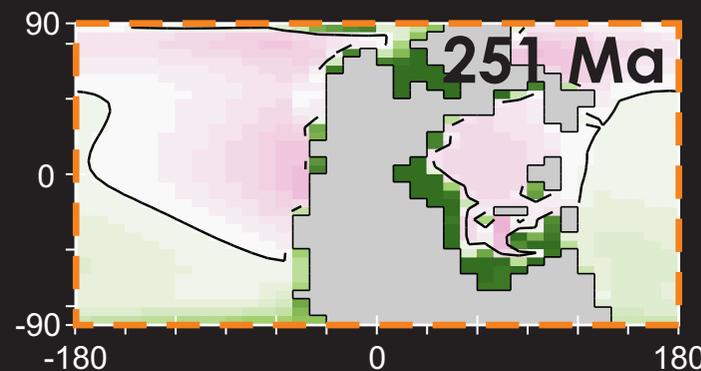
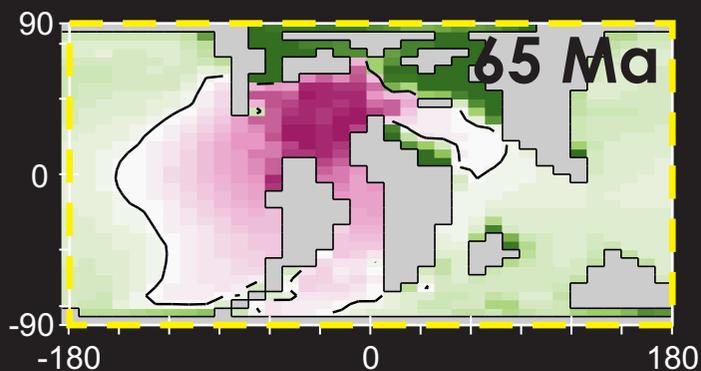
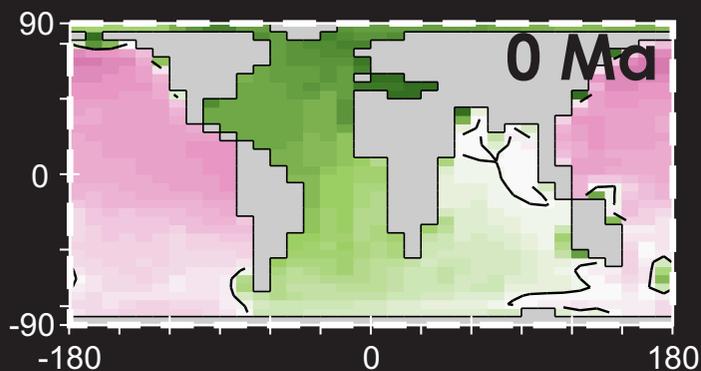
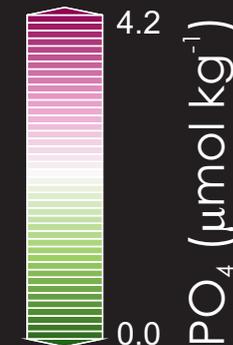
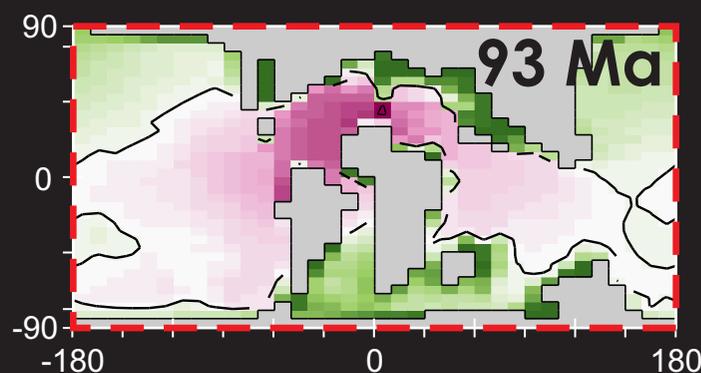
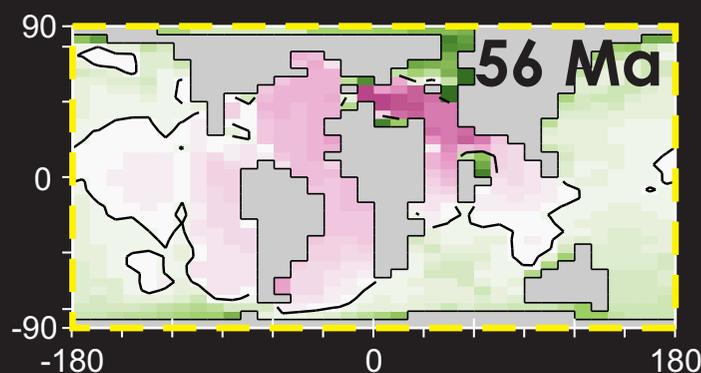


Importance of baking tin topology/topography

mean water column $[\text{PO}_4]$

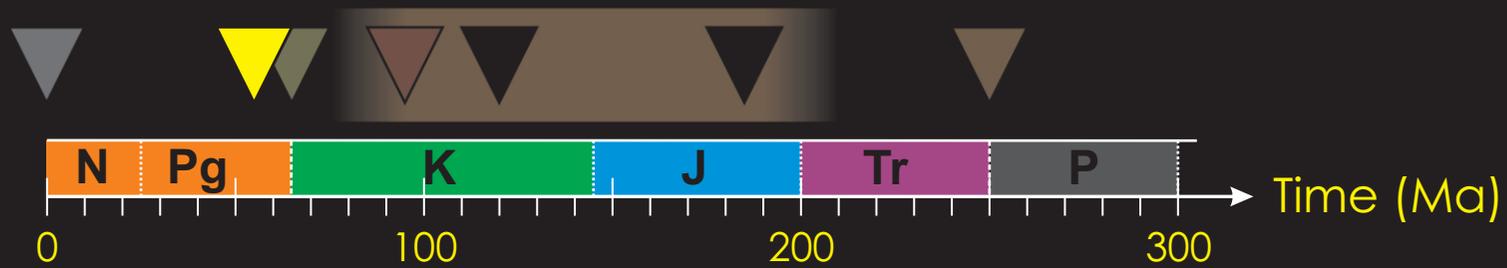
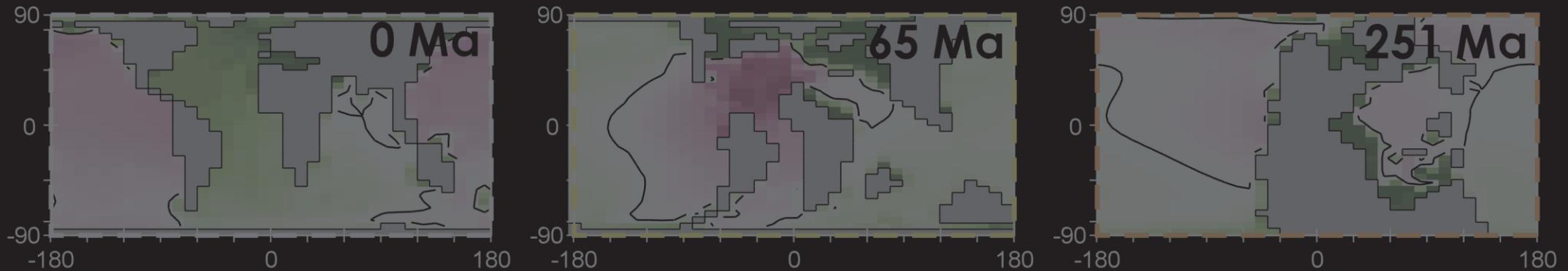
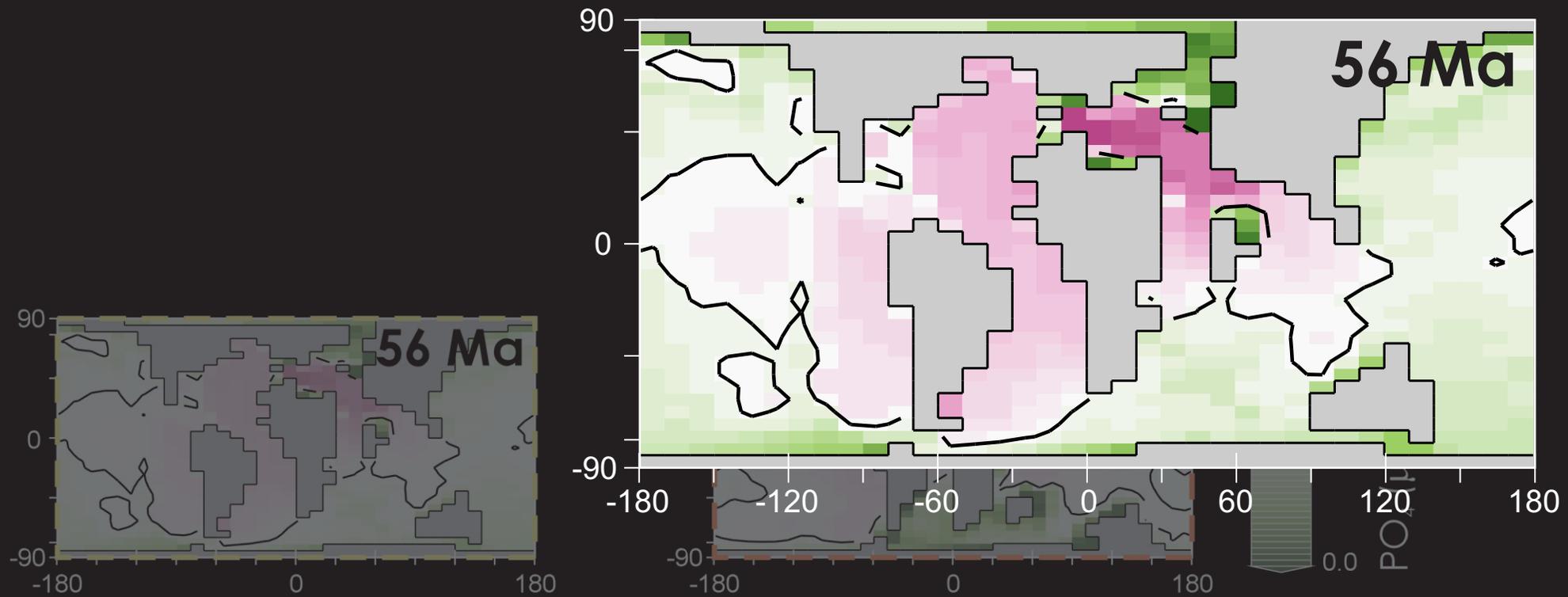
A measure of nutrient-trapping.

Contour represents concentrations equal to the prescribed whole ocean mean ($2.1 \mu\text{mol kg}^{-1}$).



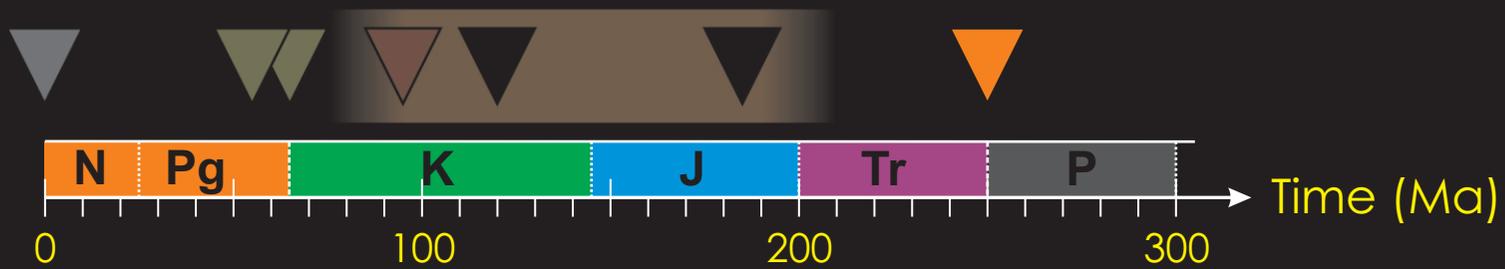
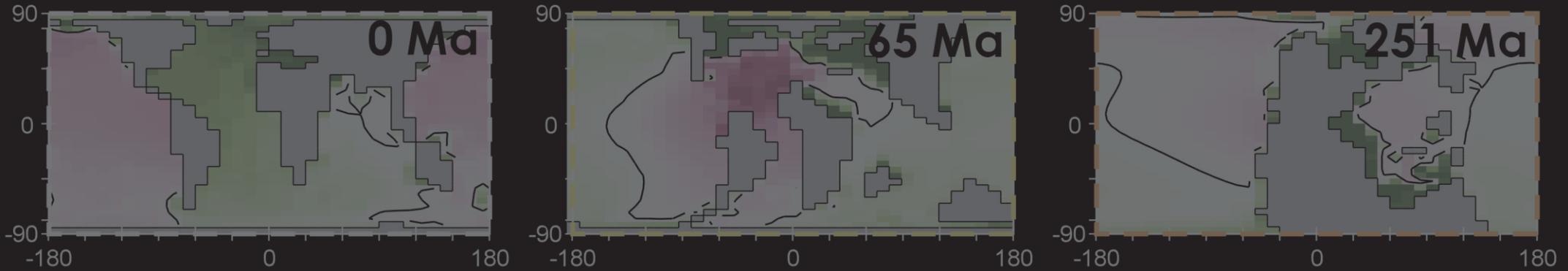
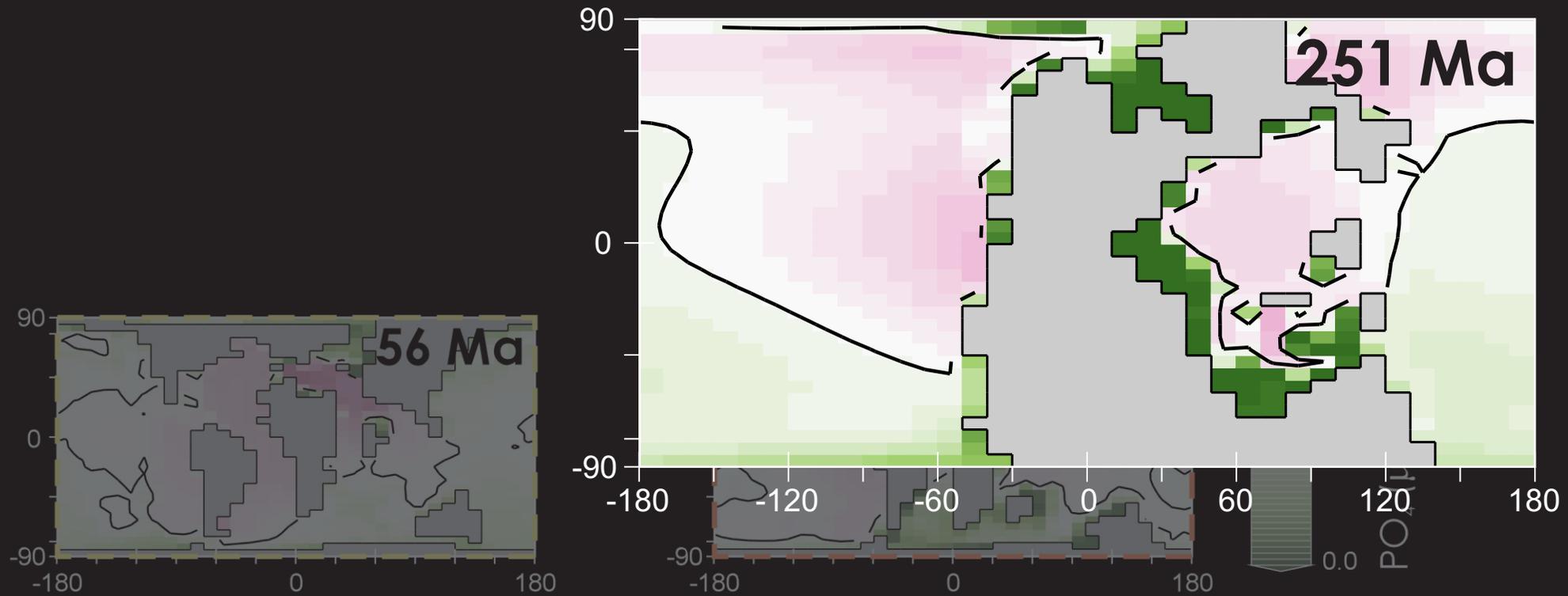
Importance of baking tin topology/topography

Carbon cycle and oxygen perturbations



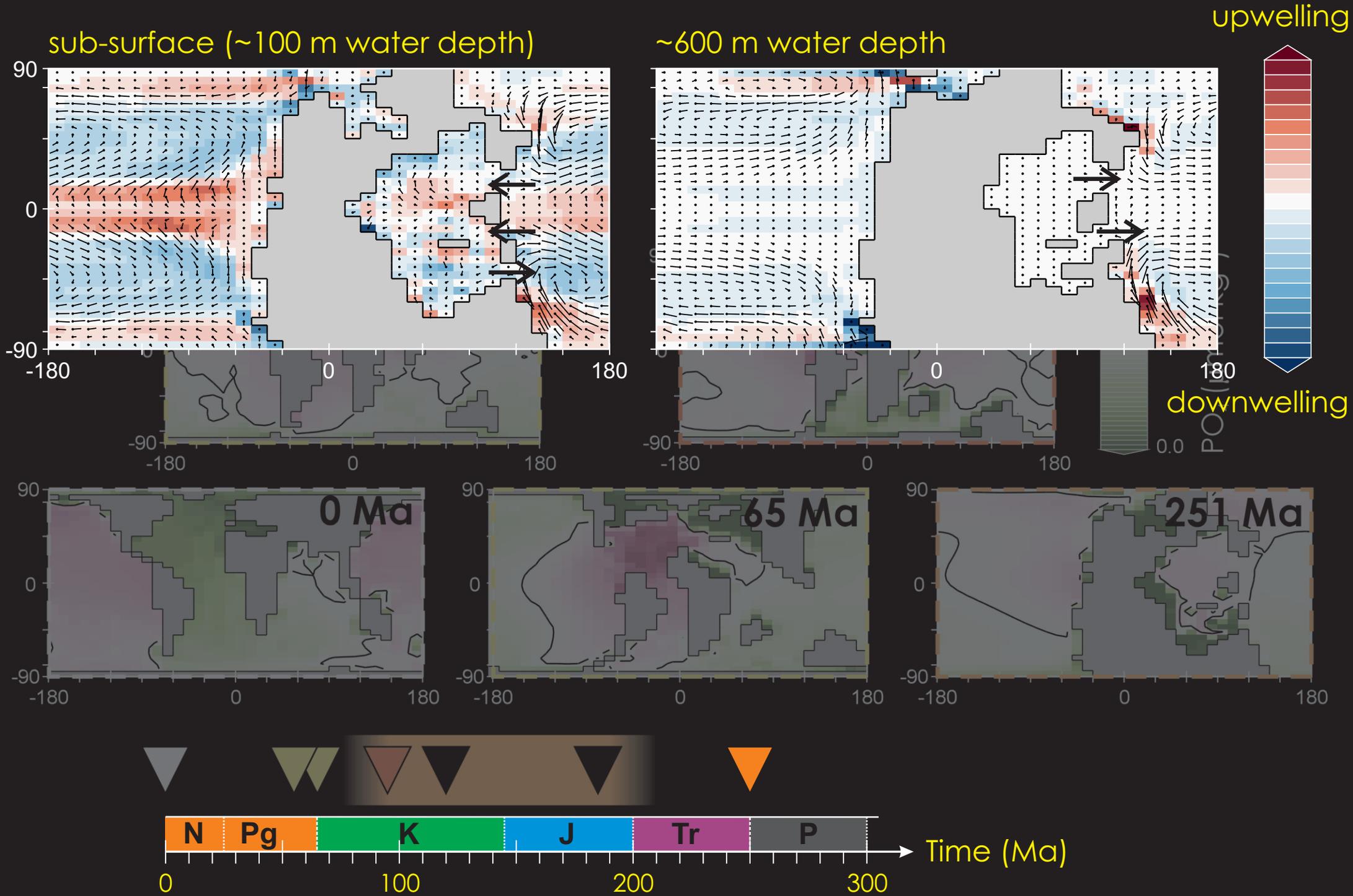
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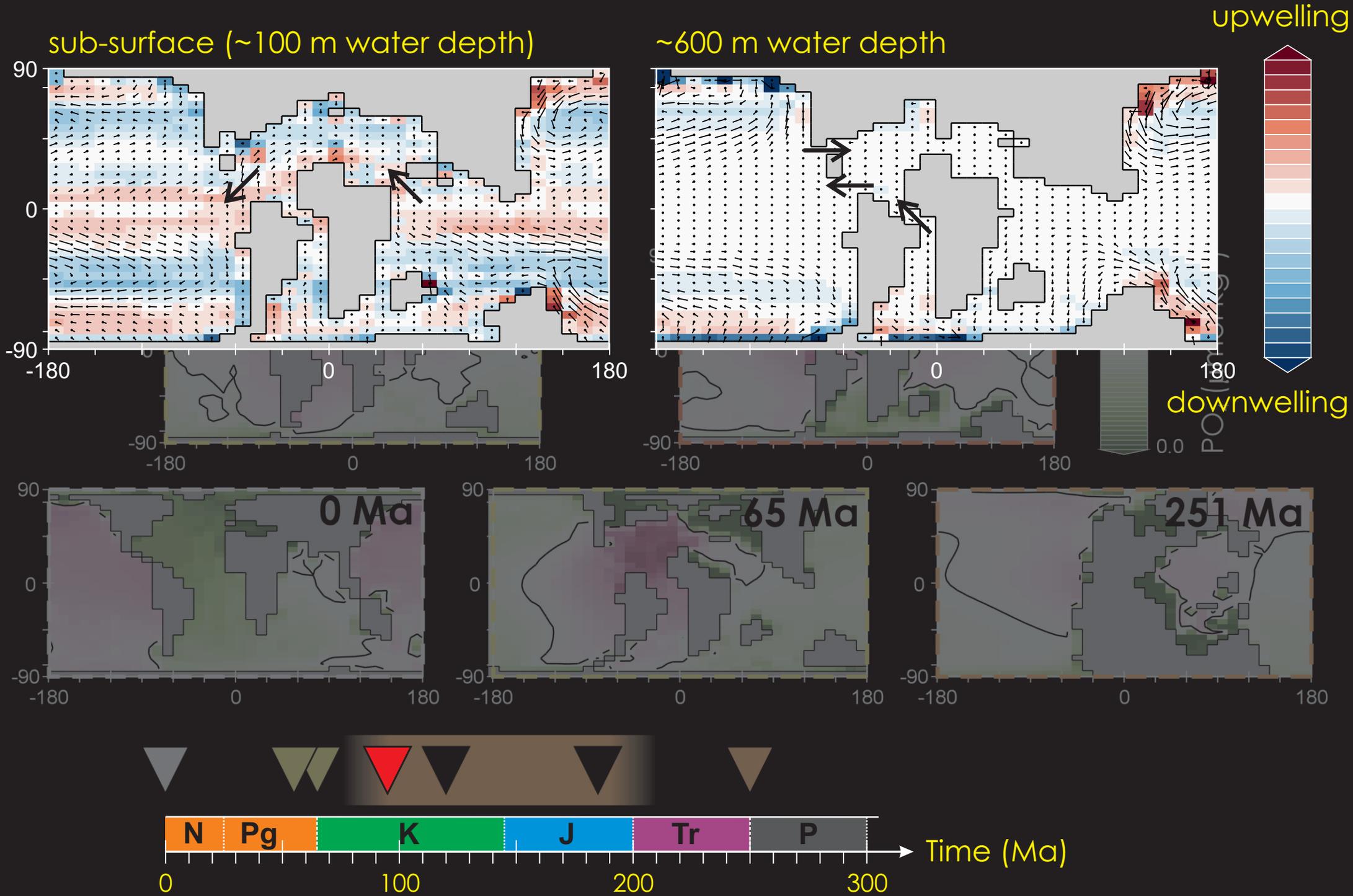
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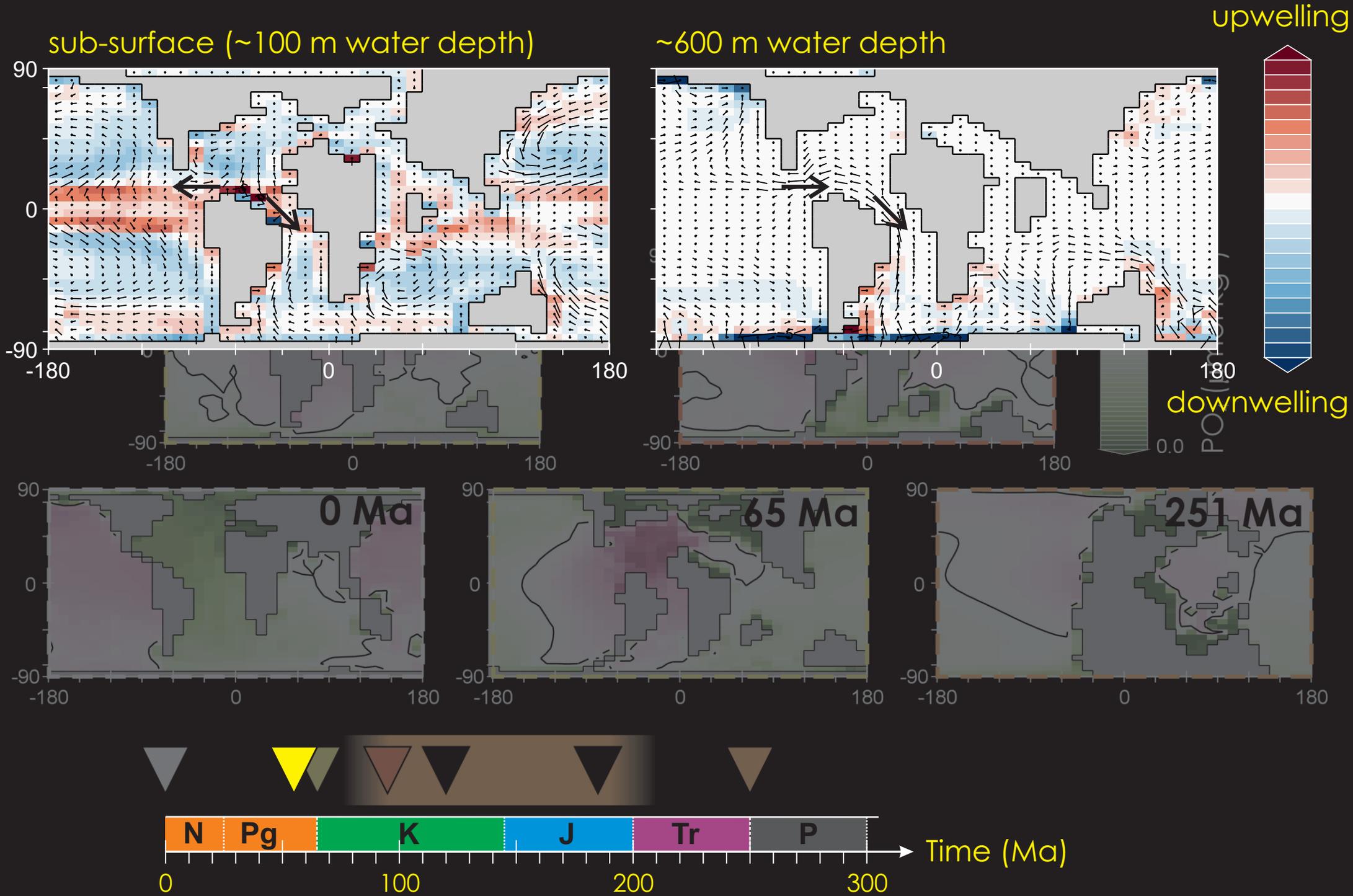
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Importance of baking tin topology/topography

Carbon cycle and oxygen perturbations



What is the 'recipe' for OAE (occurrence)?

- ★ An 'estuarine-like' circulation, bringing in relatively nutrient-rich water at depth and removing relatively nutrient-depleted waters at the surface, will tend to lead to the trapping of nutrients and hence regional anoxia.
- ★ Conversely, a circulation pattern in which water is net exported at depth will tend to act against the occurrence of regional OAE-like conditions.
- ★ However, the late Permian Tethys appears to have had an anti-estuarine circulation.

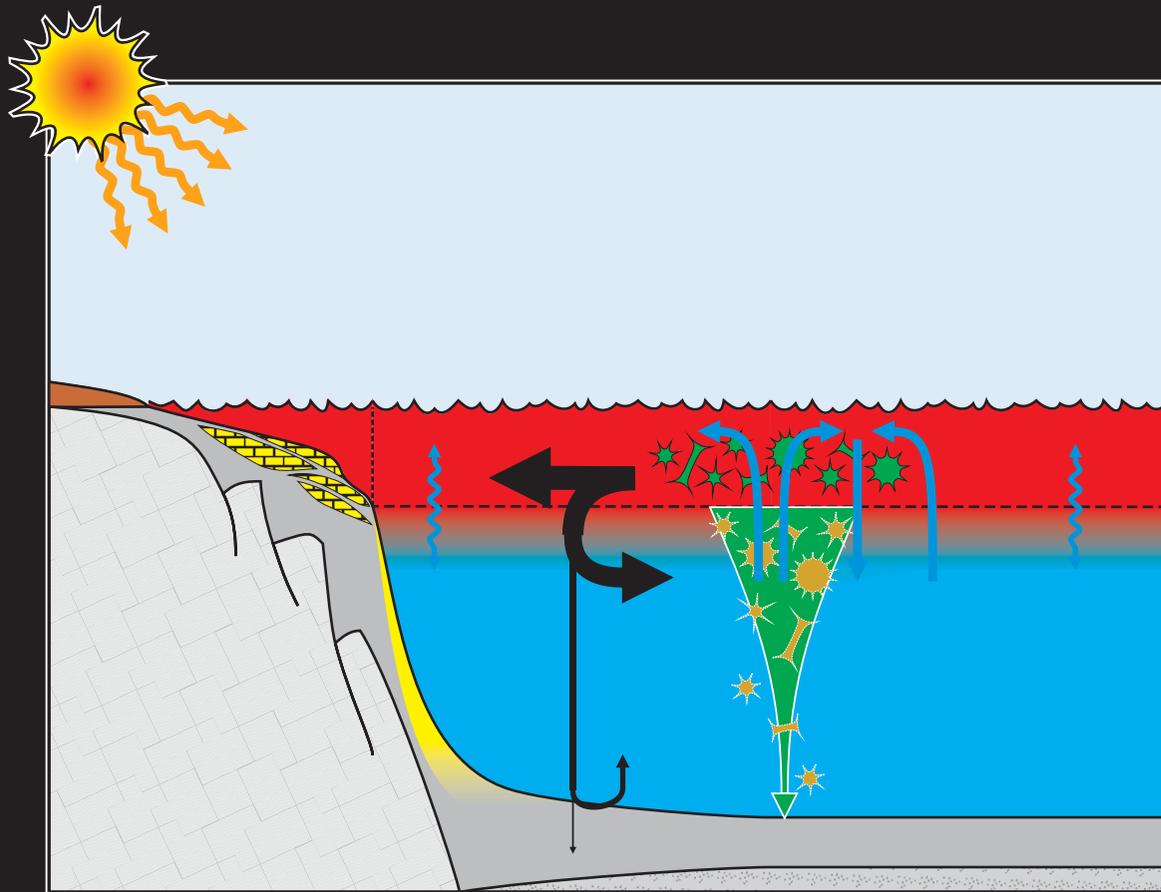


muffkie?

(warm == stratified) && (stratified == anoxic) == .true.

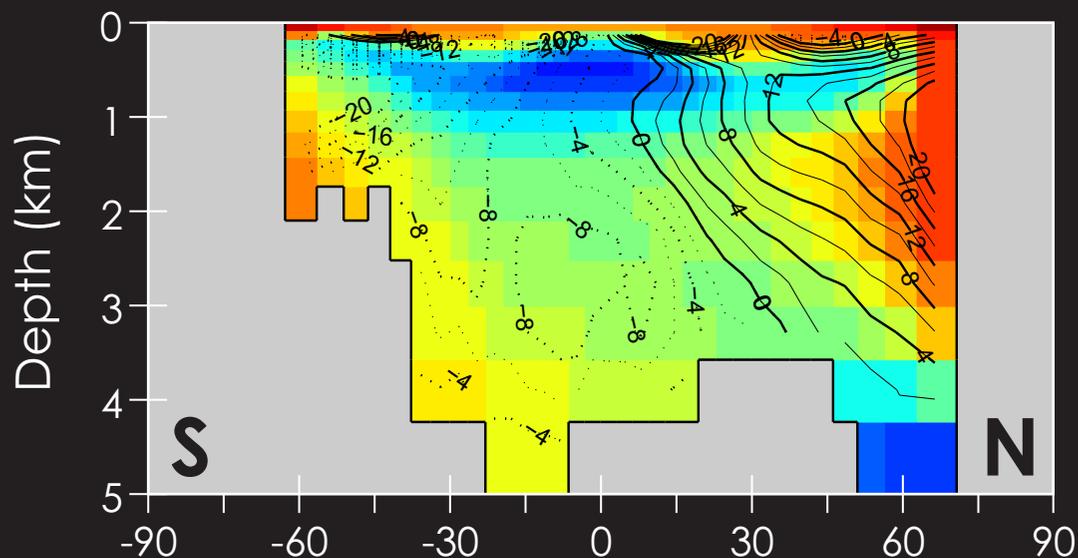
???

('stratified' || 'sluggish' || 'stagnant')

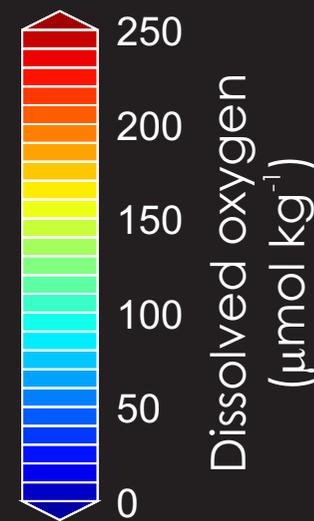
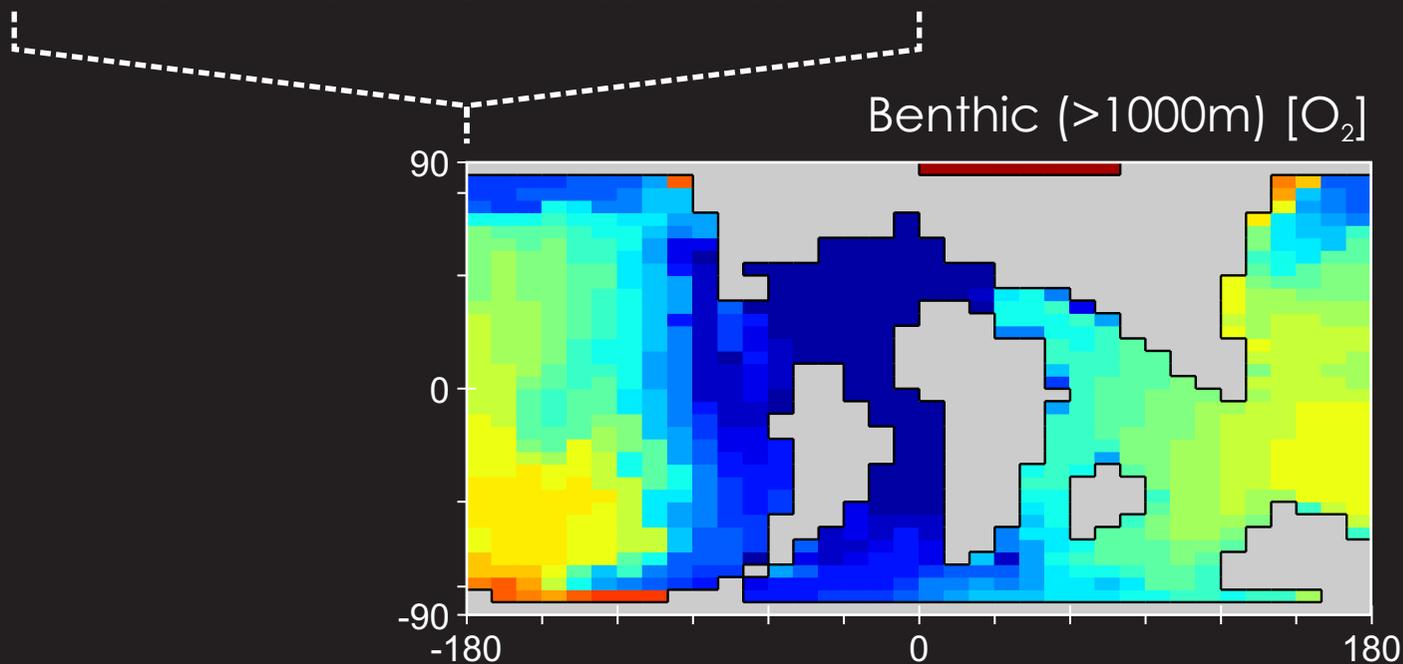




color-scale

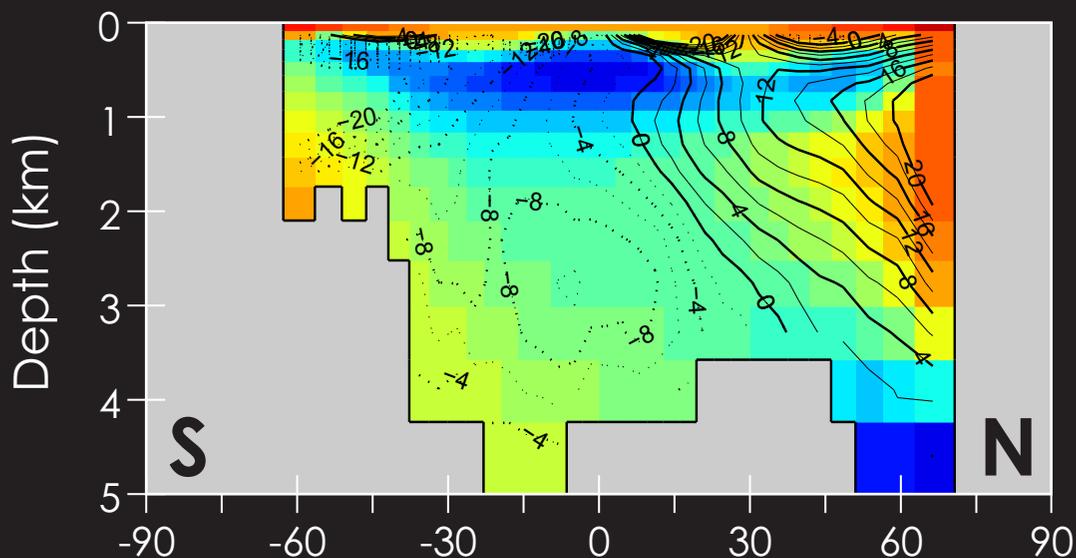


x4 CO₂ reference simulation
(65 Ma)



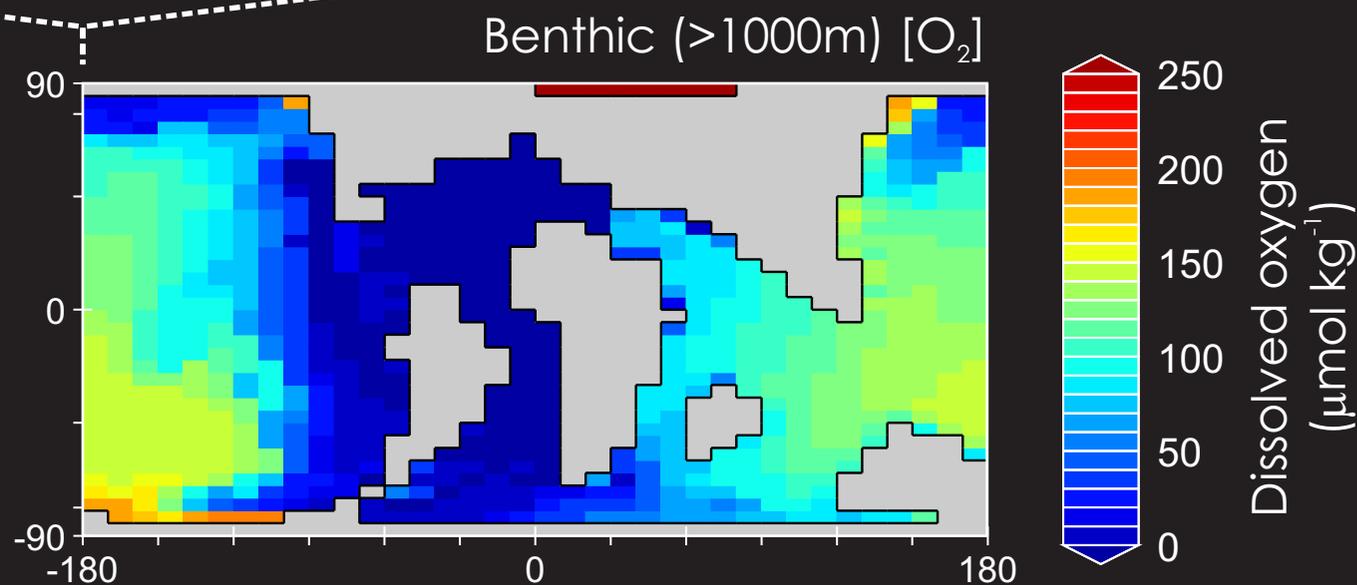


color-scale



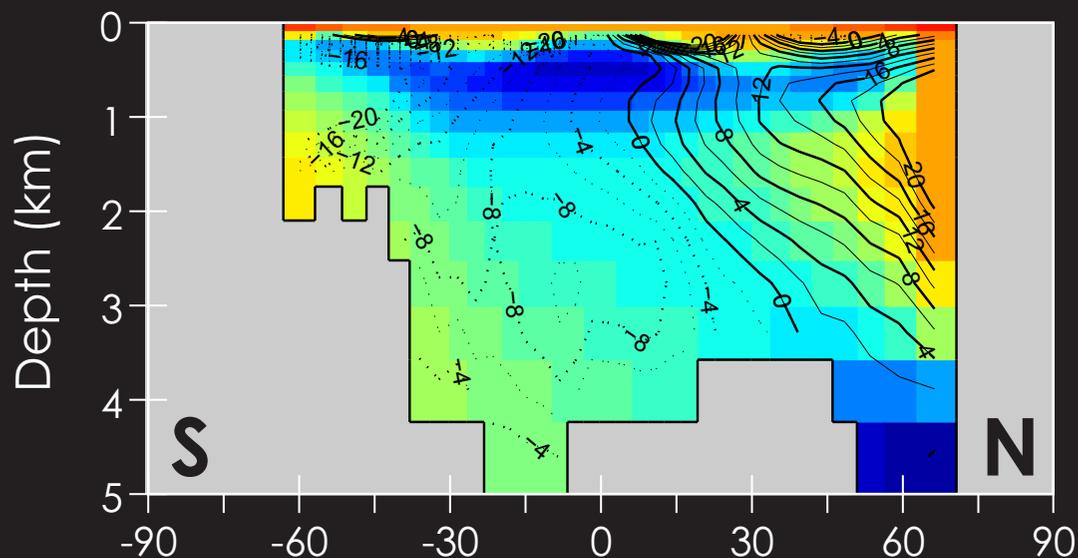
x8 CO₂ @ 10,000 yrs

(started from end of the x4 simulation)



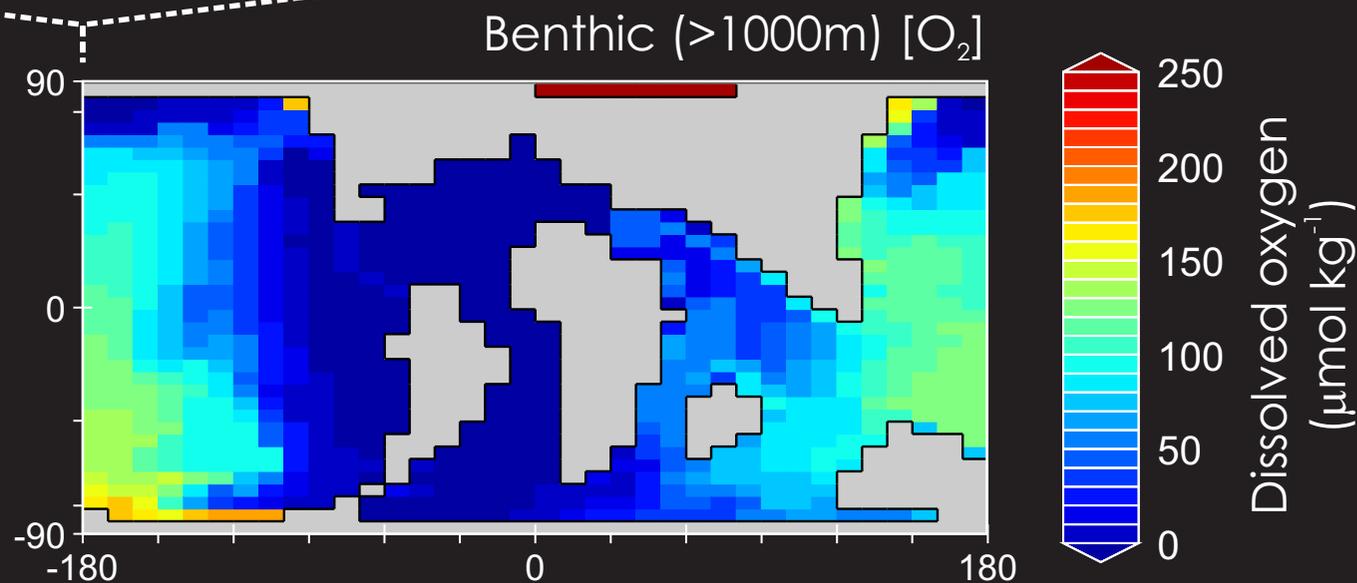


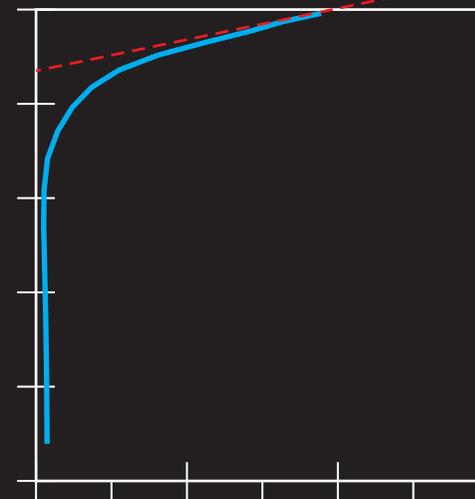
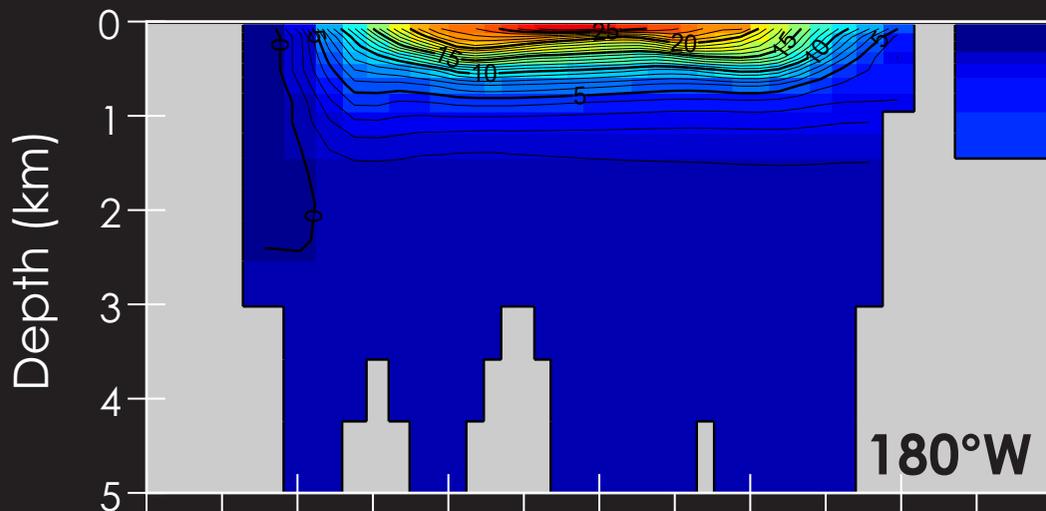
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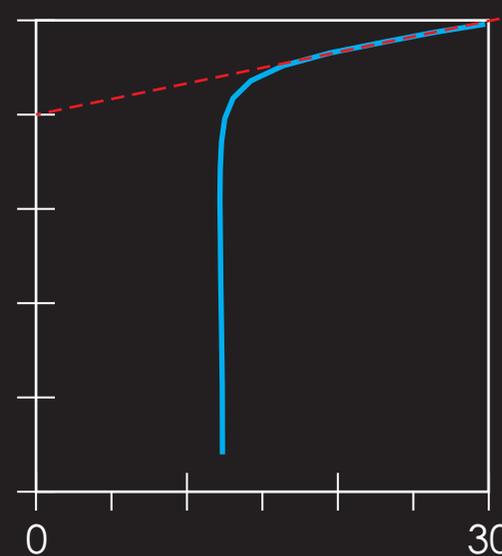
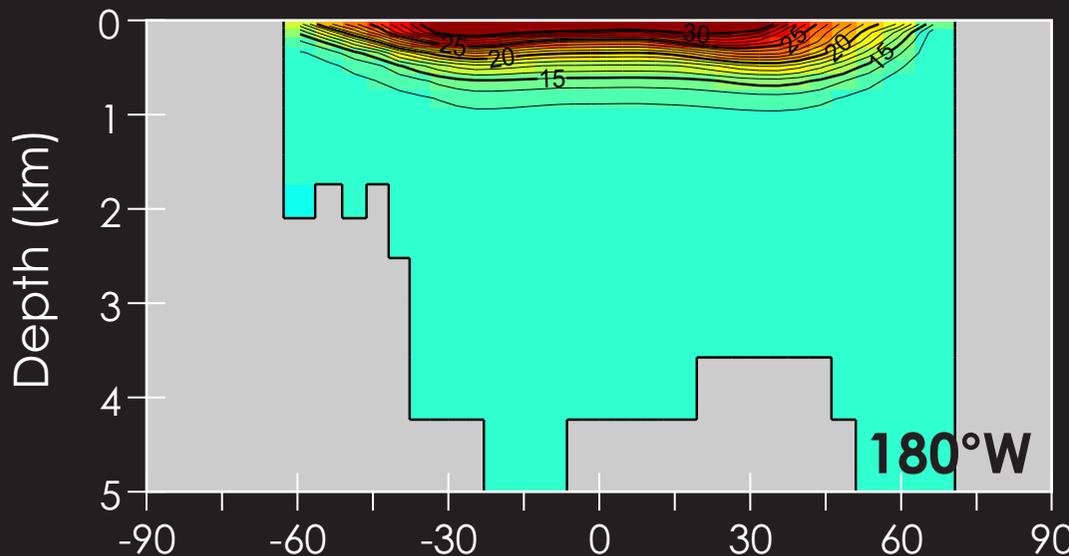
x16 CO₂ @ 10,000 yrs

(started from end of the x4 simulation)





x1 CO₂ pre-industrial reference simulation



x4 CO₂ Maastrichtian reference simulation

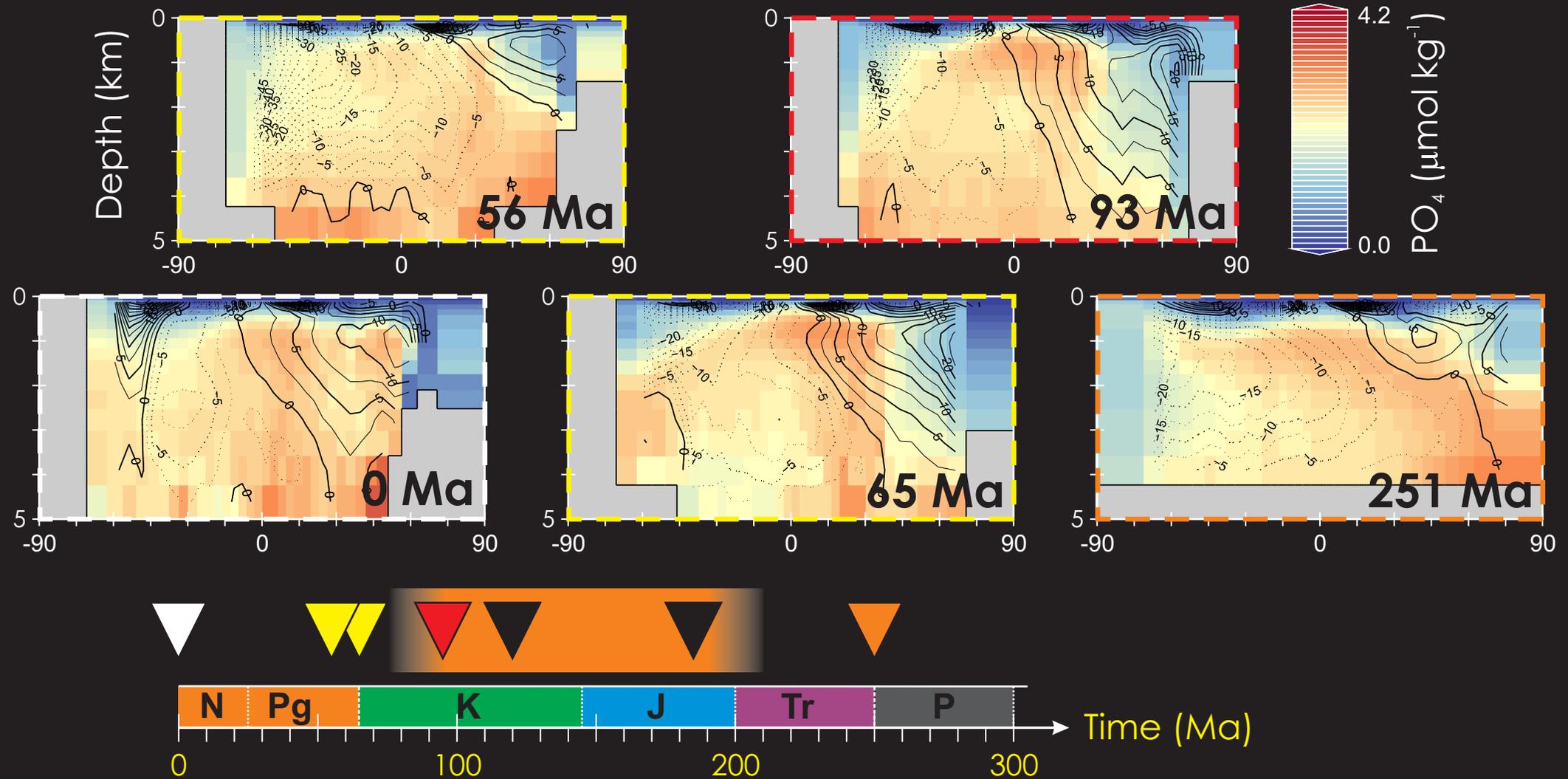
Temperature (°C)

Importance of ocean temperature

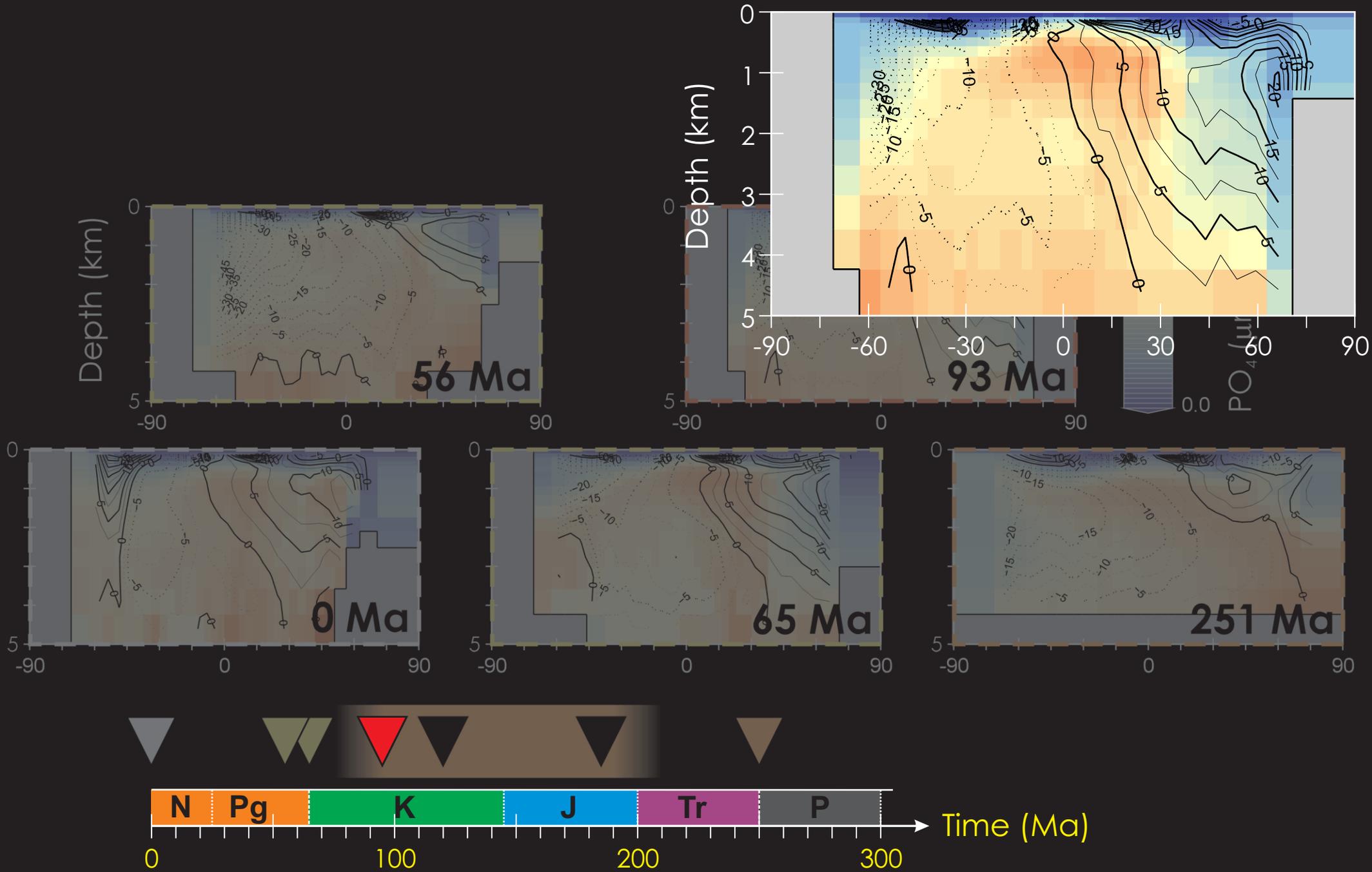
zonal mean latitude-depth $[\text{PO}_4]$ distribution

A measure of the partitioning of PO_4 and hence oxygen consumption, in the water column.

Contour overlay is the global mean overturning stream-function.

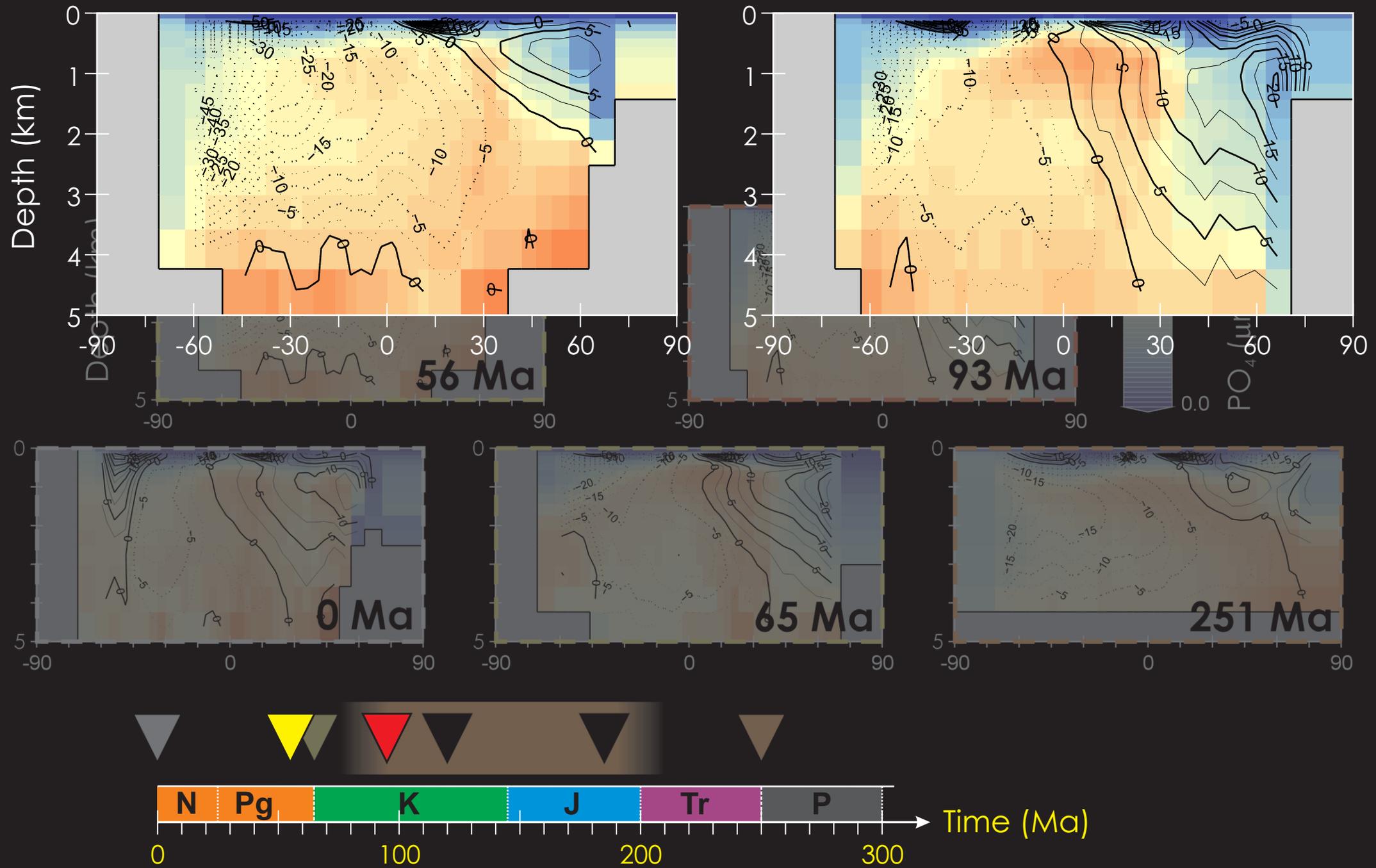


Importance of oven temperature



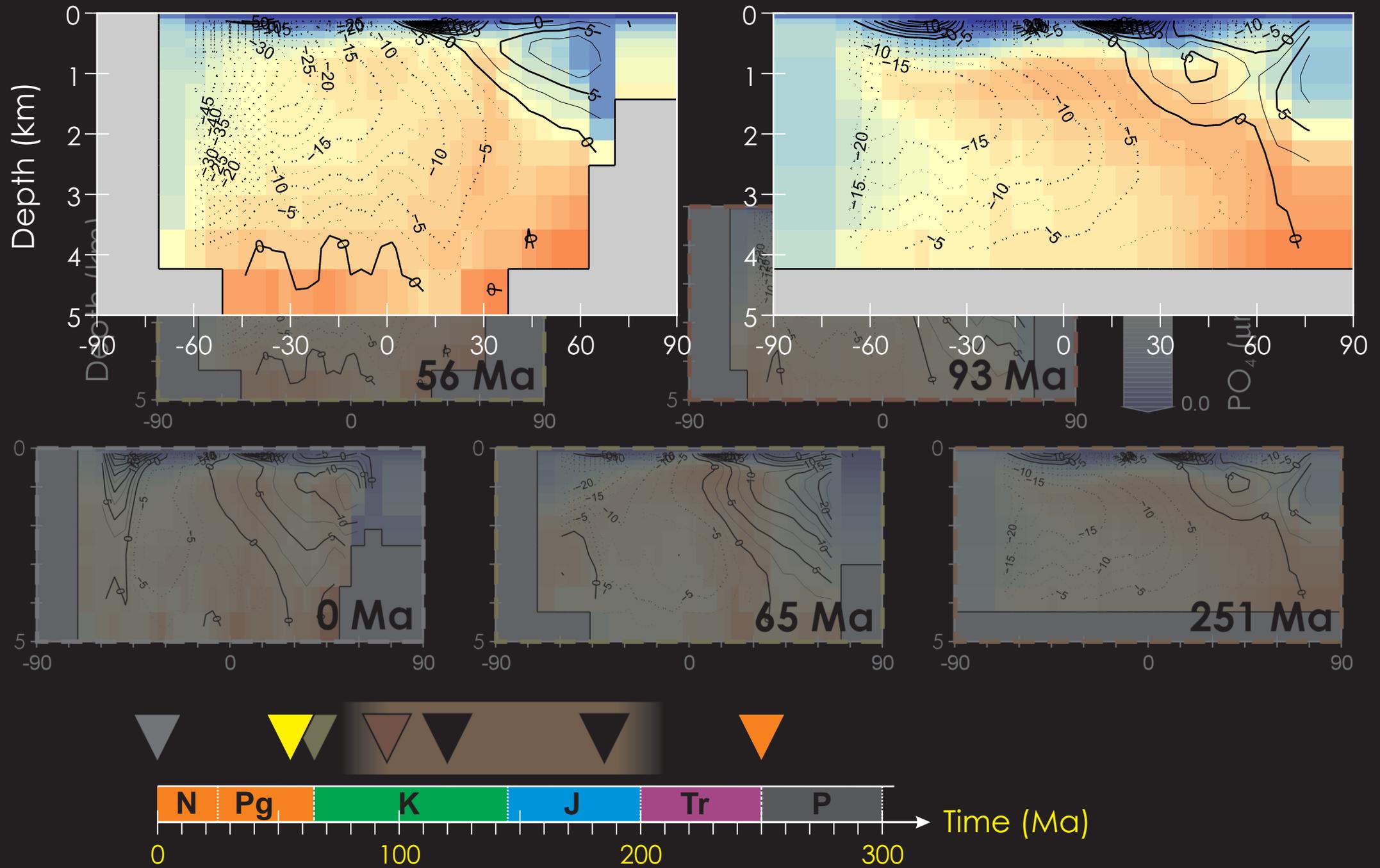
Importance of oven temperature

Carbon cycle and oxygen perturbations



Importance of ocean temperature

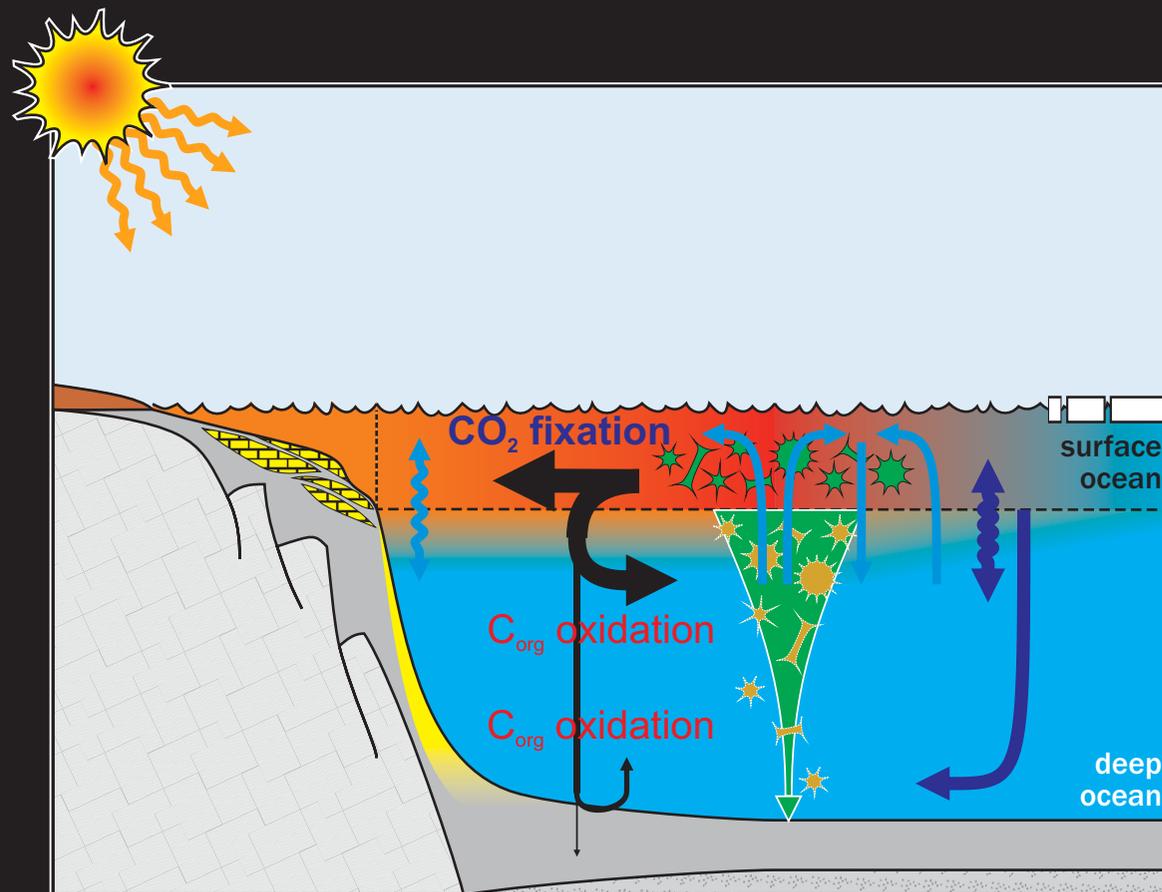
Carbon cycle and oxygen perturbations



What is the 'recipe' for OAE (occurrence)?

- ★ Strong (vigorous) ventilation of the deep ocean, rather than acting against the tendency towards OAE-like conditions, may actually be a pre-requisite as PO_4 is more rapidly returned to shallow and intermediate depths .
- ★ Conversely, weak ventilation and PO_4 trapping in the deep ocean may tend to act against the occurrence of OAE-like conditions.



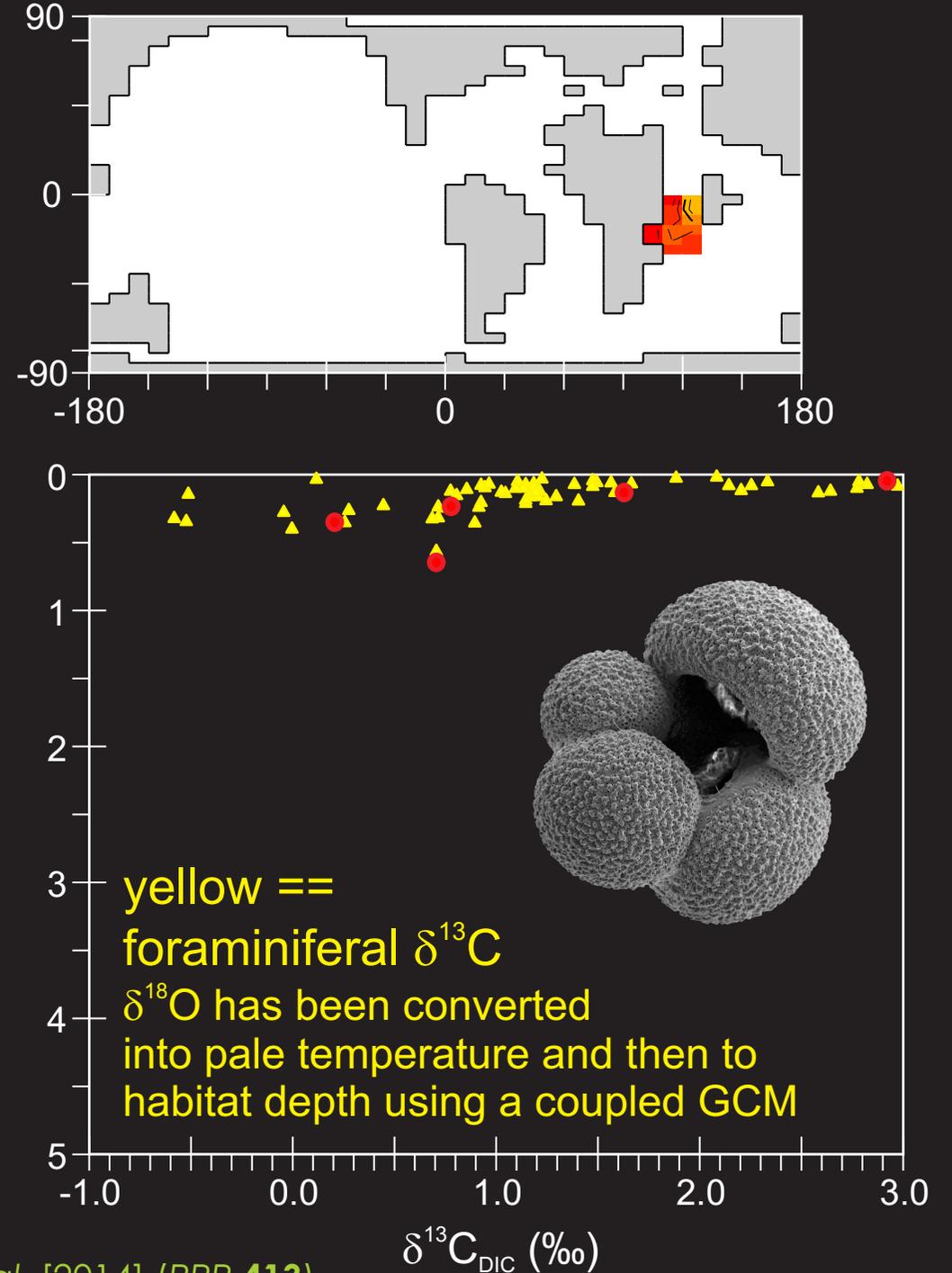


Bacterial metabolism and hence rate of degradation of settling particulate organic matter (POM) should be temperature sensitive (e.g. Q_{10} ca. ~ 2).

It is reasonable to posit that a warmer ocean interior will have an on-average shallower depth of POM remineralization and hence more rapid nutrient recycling.

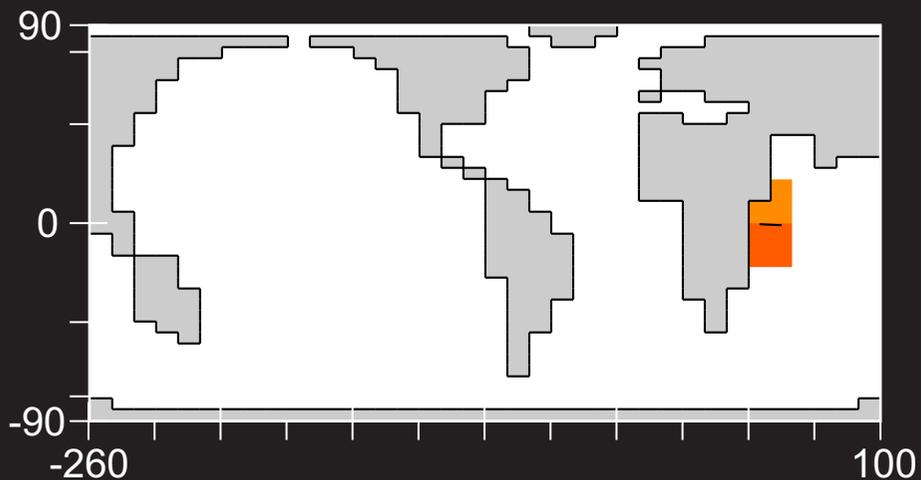
Evidence for this?

Planktic foraminiferal $\delta^{13}\text{C}$ from early Eocene Tanzania

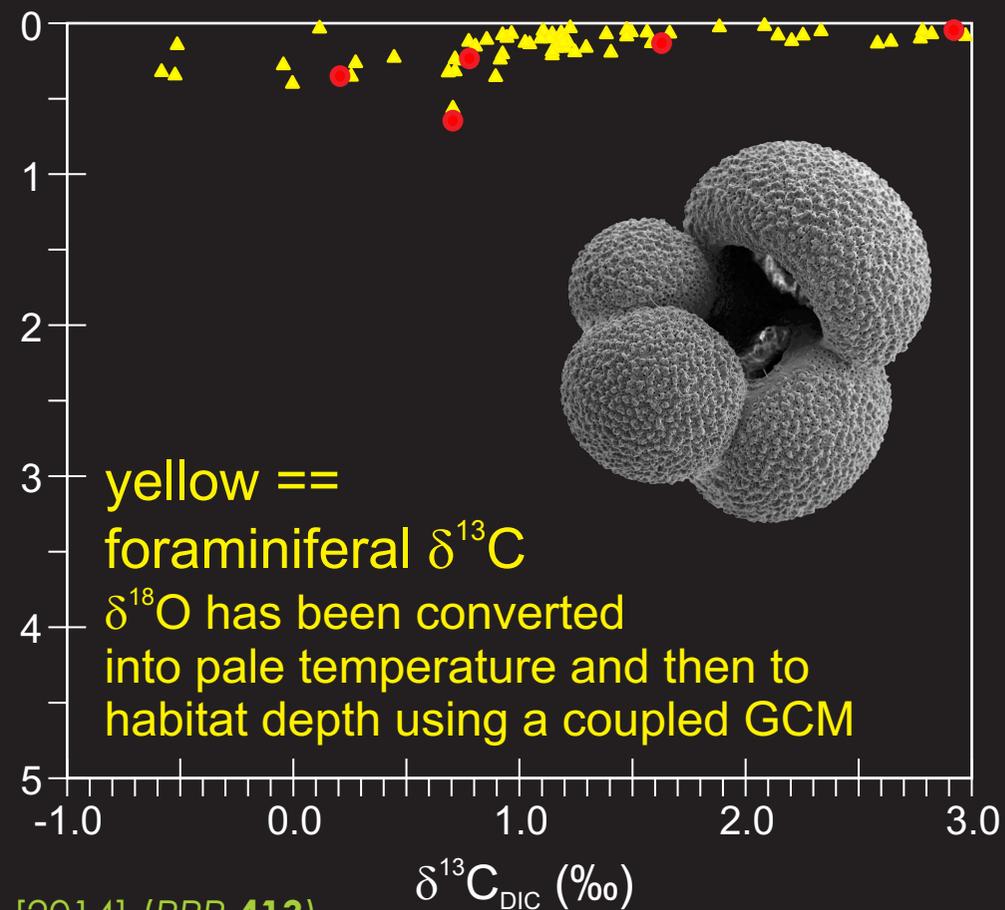
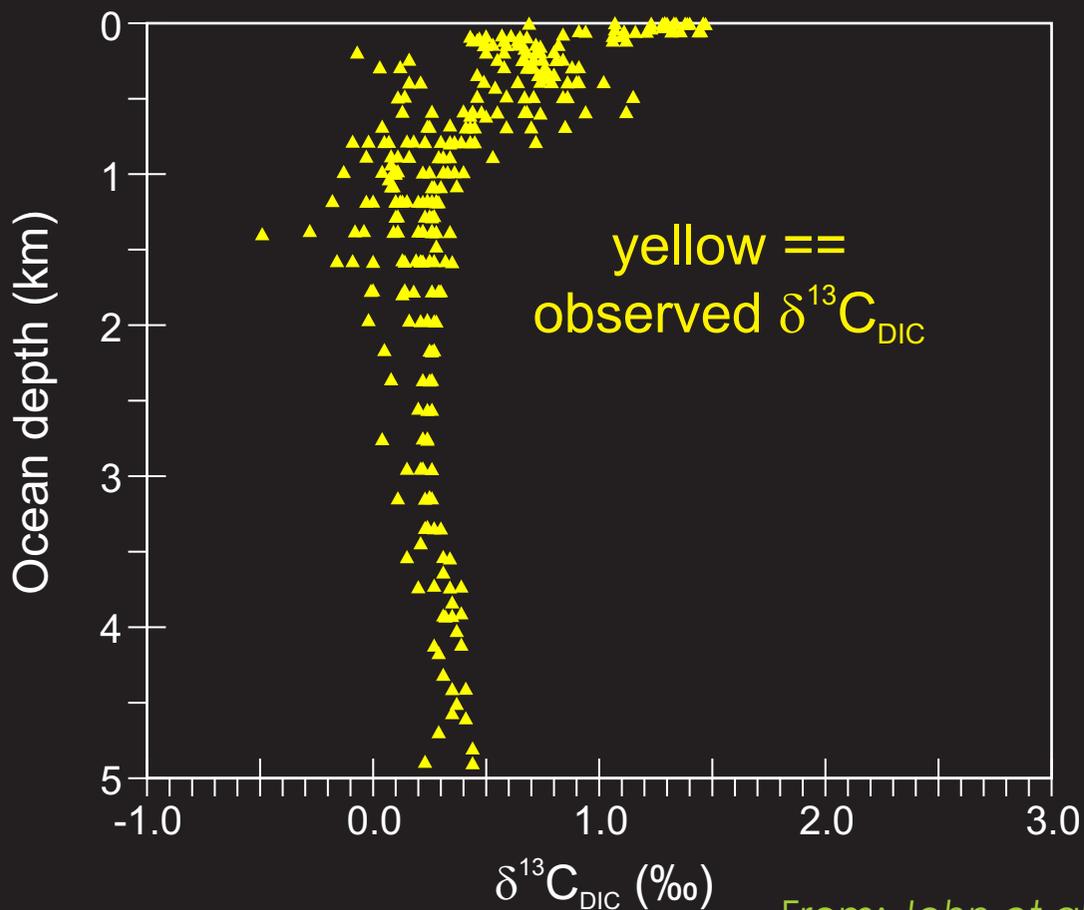
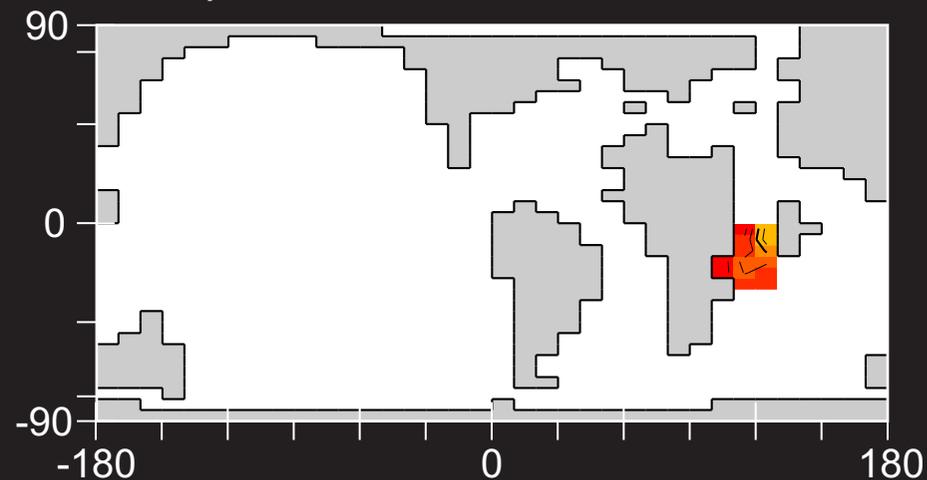


From: John et al. [2014] (PPP 413)

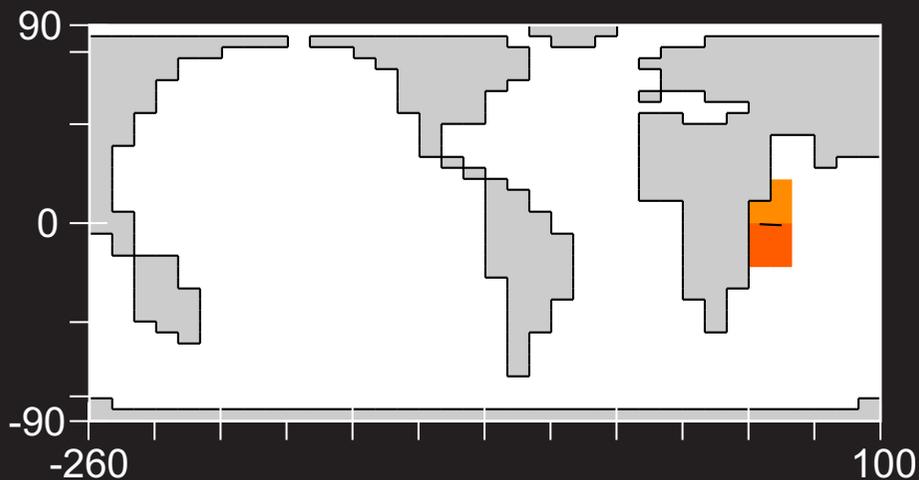
Open ocean $\delta^{13}\text{C}_{\text{DIC}}$ adjacent to modern Tanzania



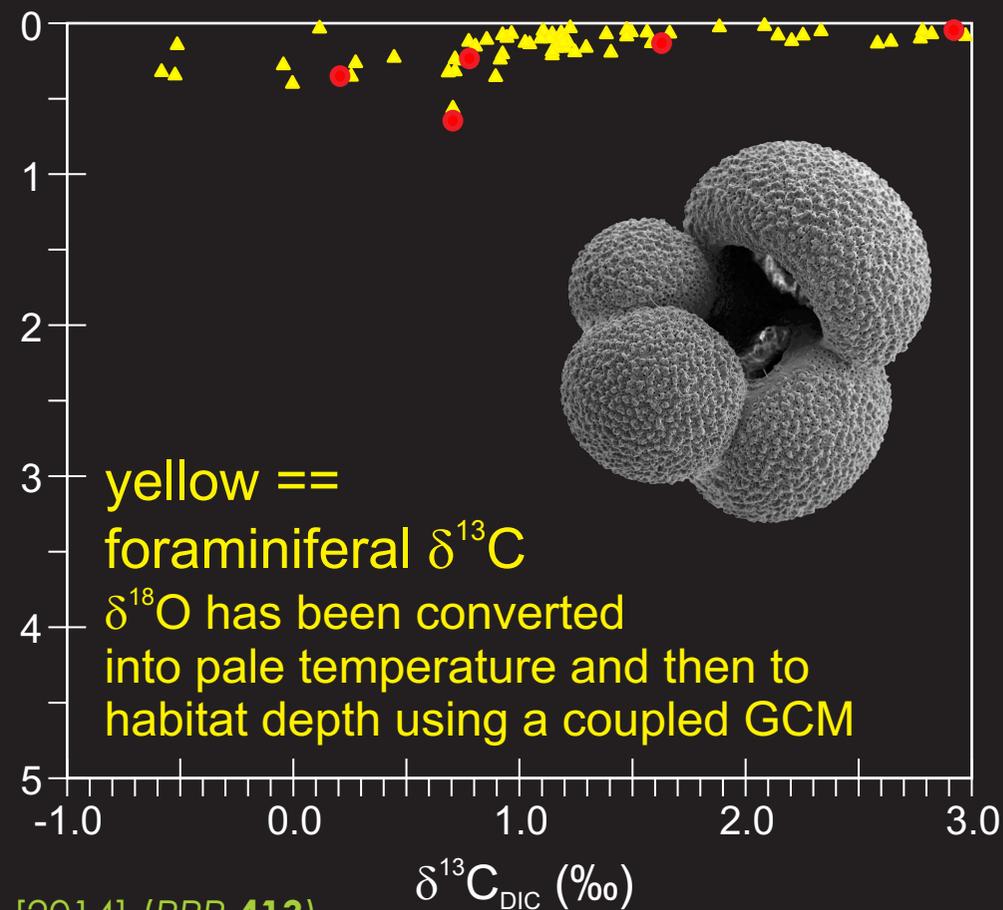
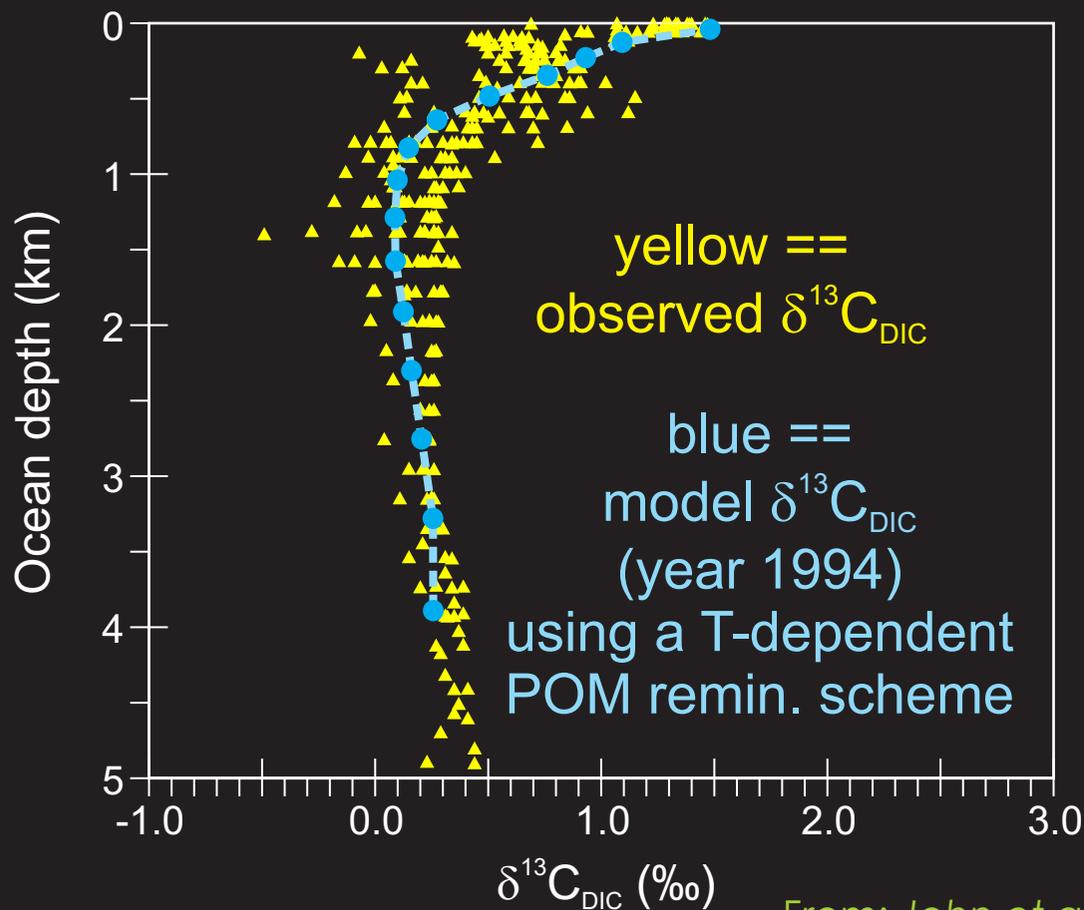
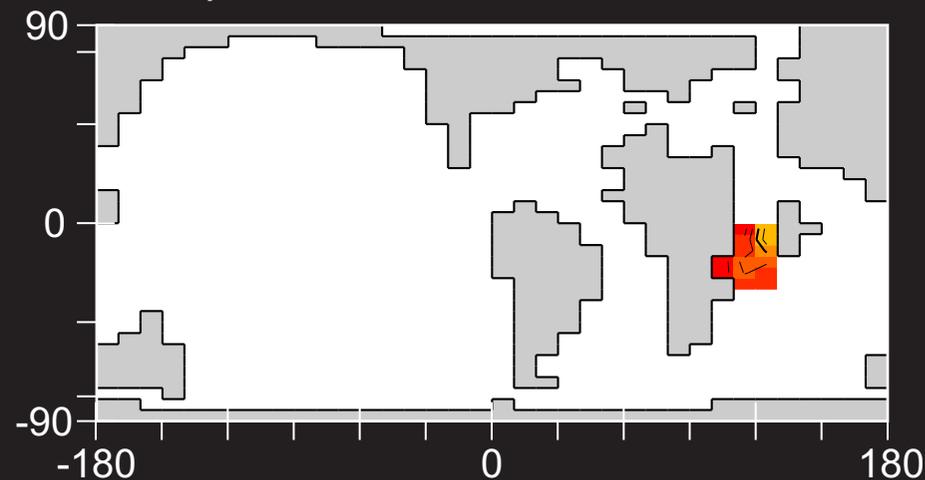
Planktic foraminiferal $\delta^{13}\text{C}$ from early Eocene Tanzania



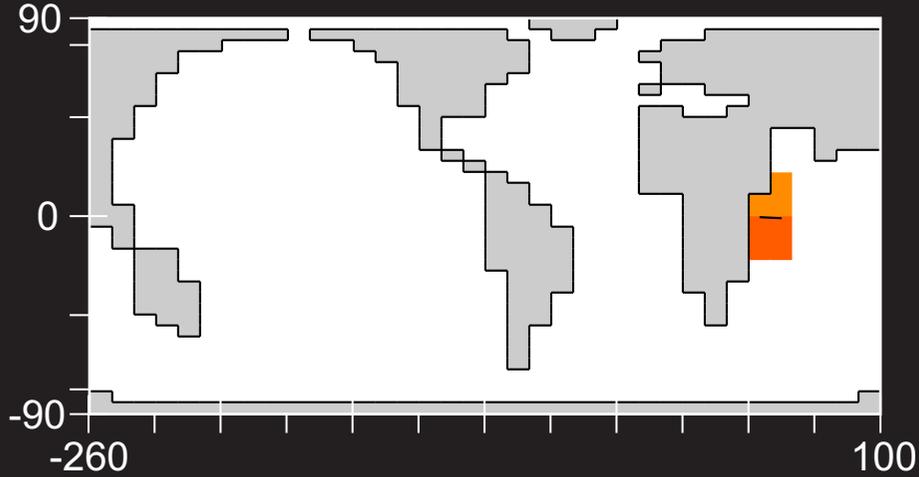
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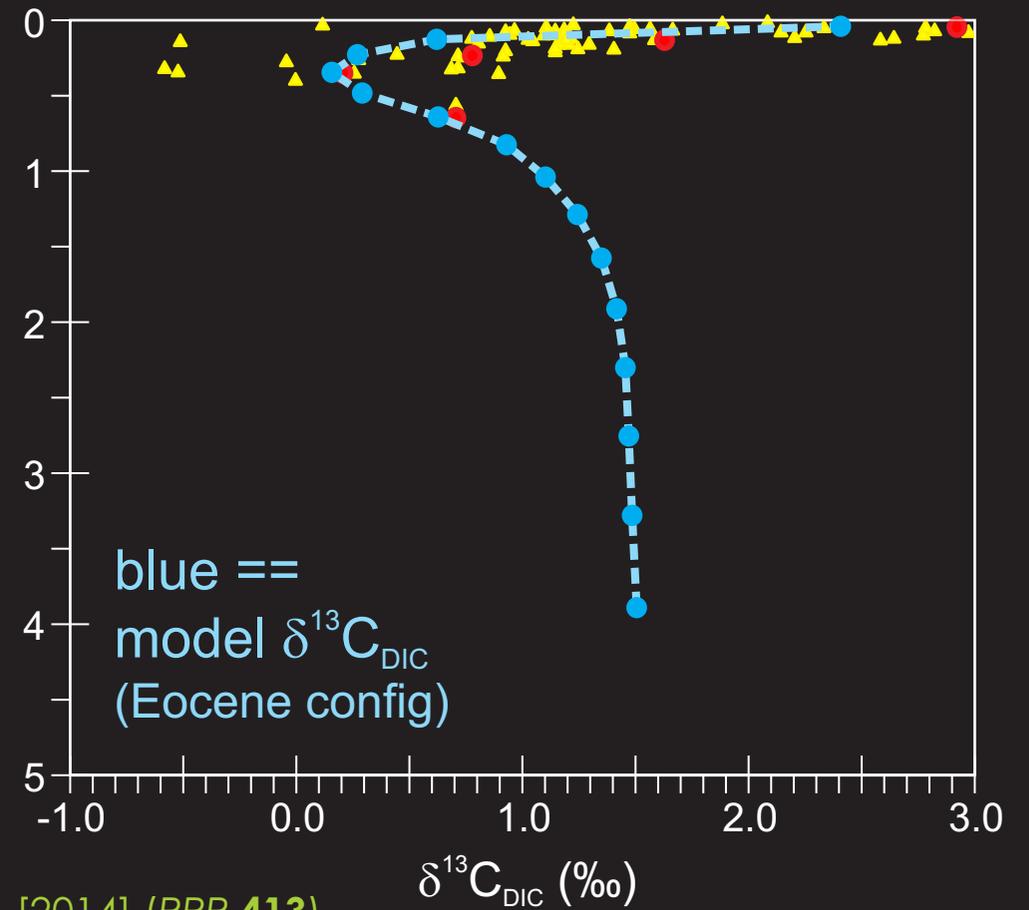
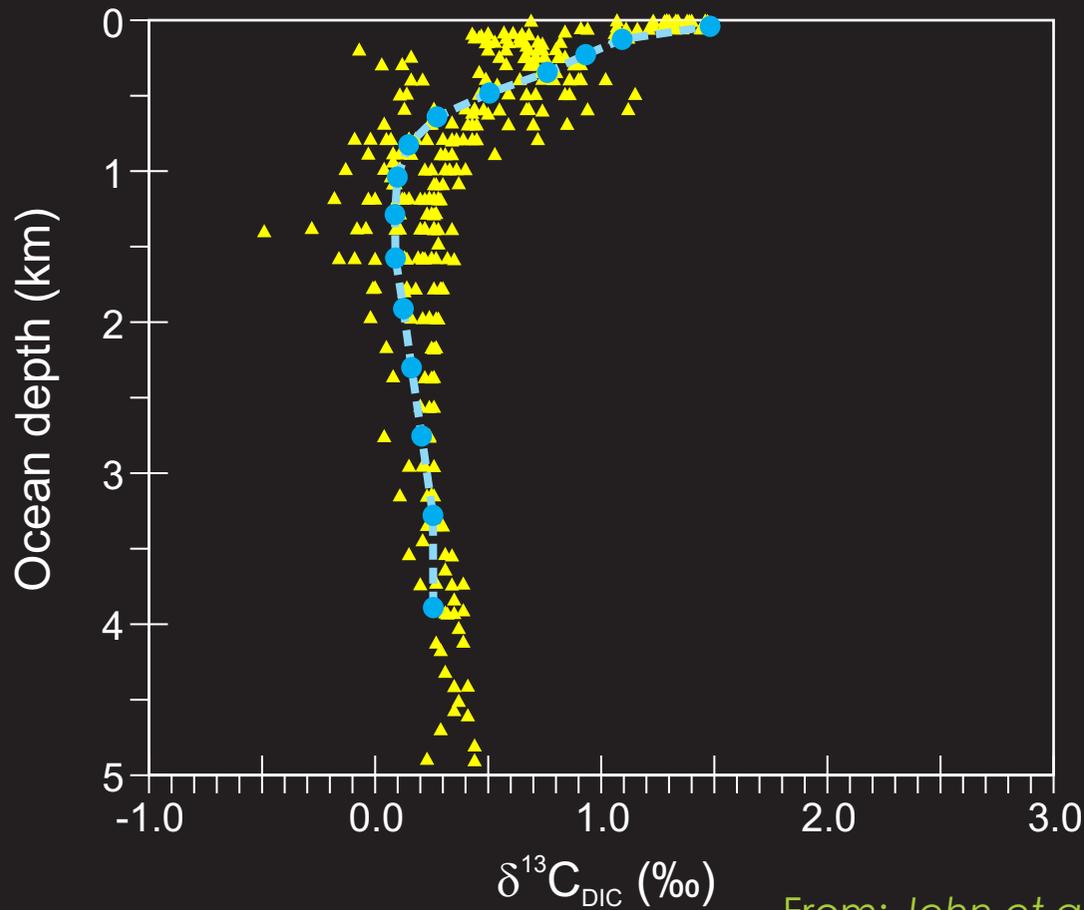
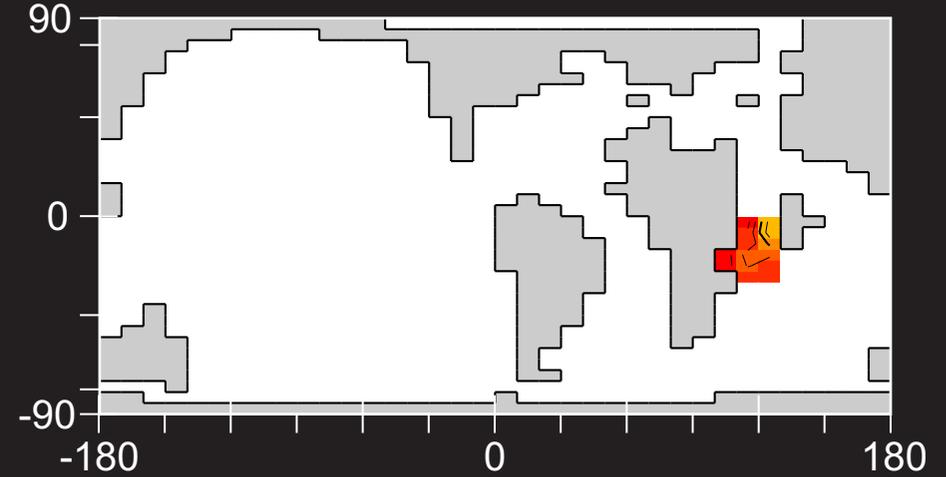
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Planktic foraminiferal $\delta^{13}\text{C}$ from early Eocene Tanzania



Conclusions

- ★ The mid Cretaceous had a tendency towards the occurrence of OAE-like conditions because of:
 - (i) nutrient trapping in the North Atlantic region,
 - (ii) vigorous ventilation of the deep ocean that helped recycle nutrients back towards the surface,
 - (iii) warm ocean temperatures and a shallow recycling depth-scale.
- ★ The Paleocene-Eocene did not experience the occurrence of OAE-like conditions because of poorer deep ocean ventilation. However, otherwise, ocean circulation and temperature were relatively favourable.
- ★ The end Permian appears anomalous in that the Tethys should have been nutrient poor. However, the Panthalassic ocean may have been well ventilated at depth with a pan-global concentration of nutrients at relatively shallow depths, then aided by progressive greenhouse warming. (i.e. not a situation of 'spreading' out from the Tethys but occurring truly globally) (analogous to the relationship of the PETM to the smaller Paleocene-Eocene hyperthermals?)
- ★ Or ... differences in atmospheric pO_2 , etc etc ... ?



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