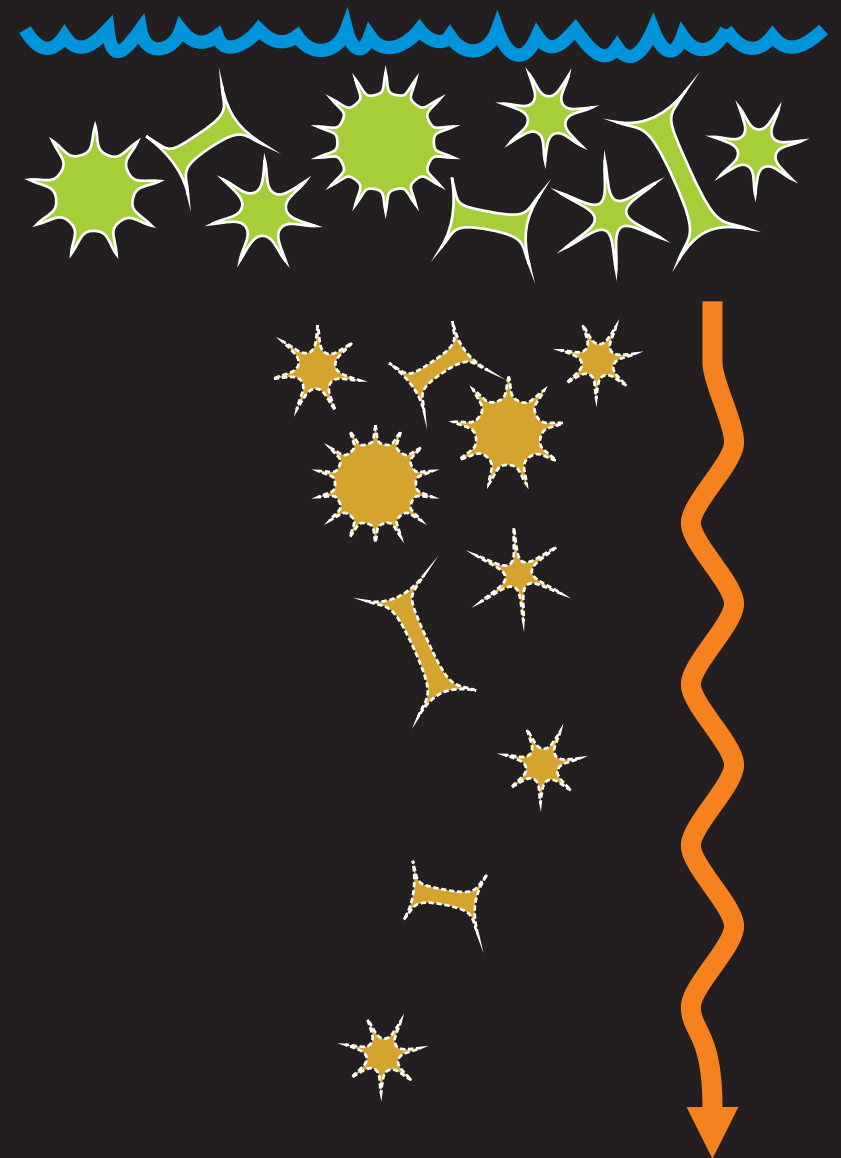
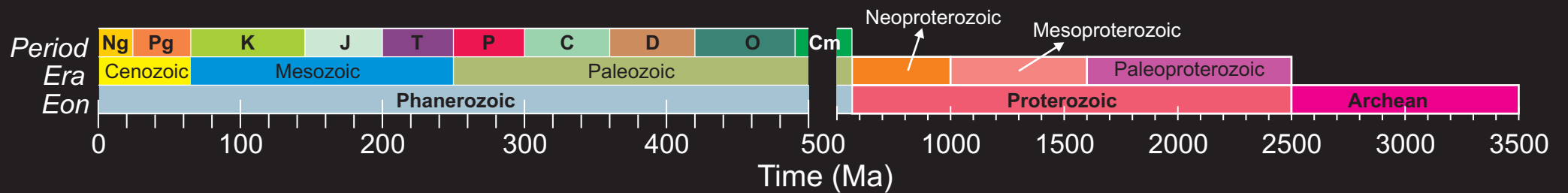


Evolution of the Ocean's Biological Pump

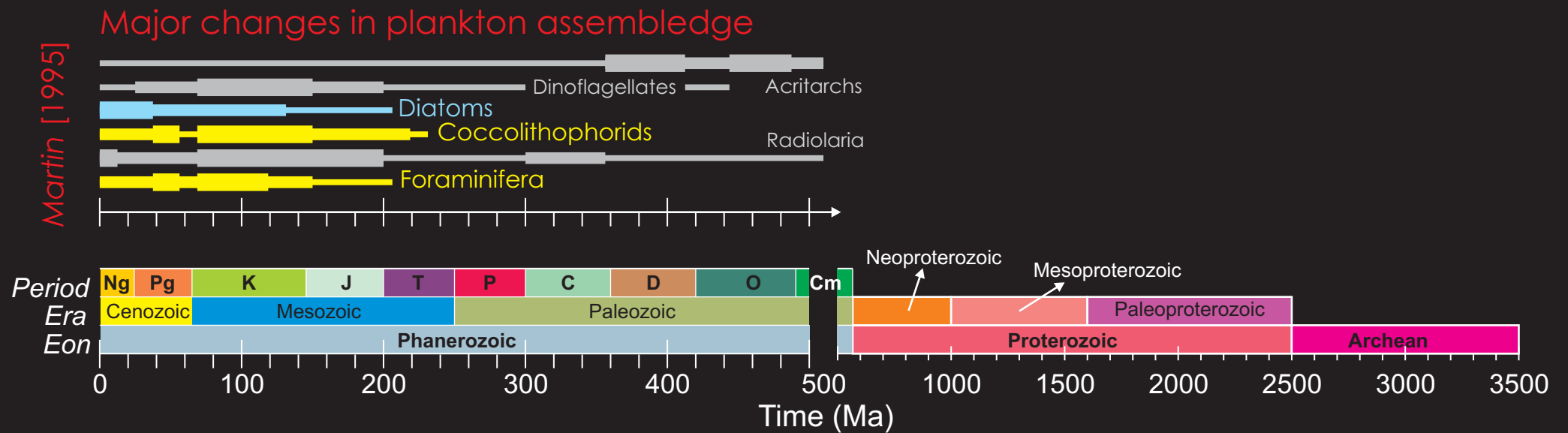
Andy Ridgwell



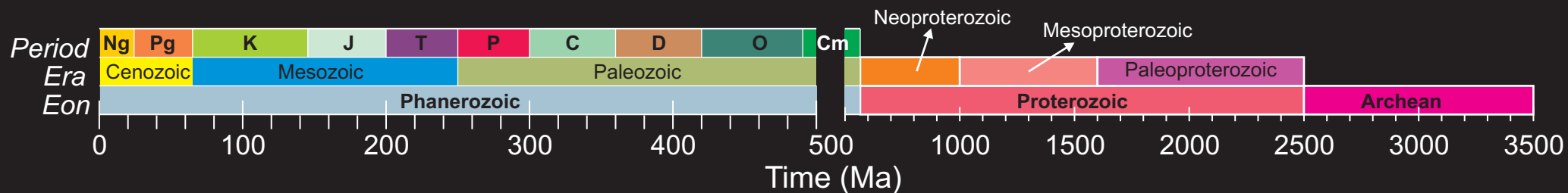
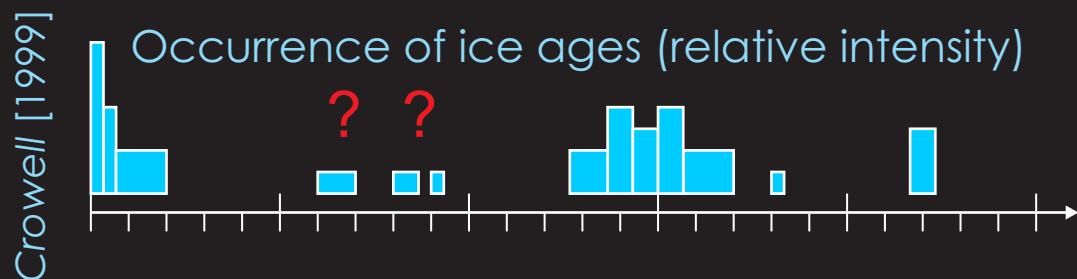
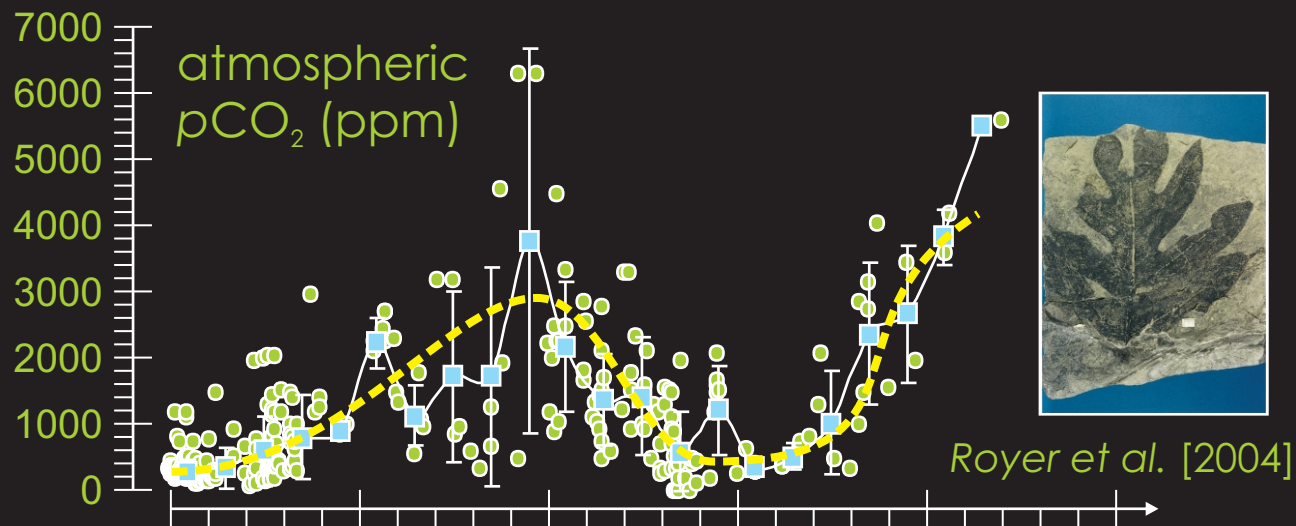
Evolution of the Biological Pump



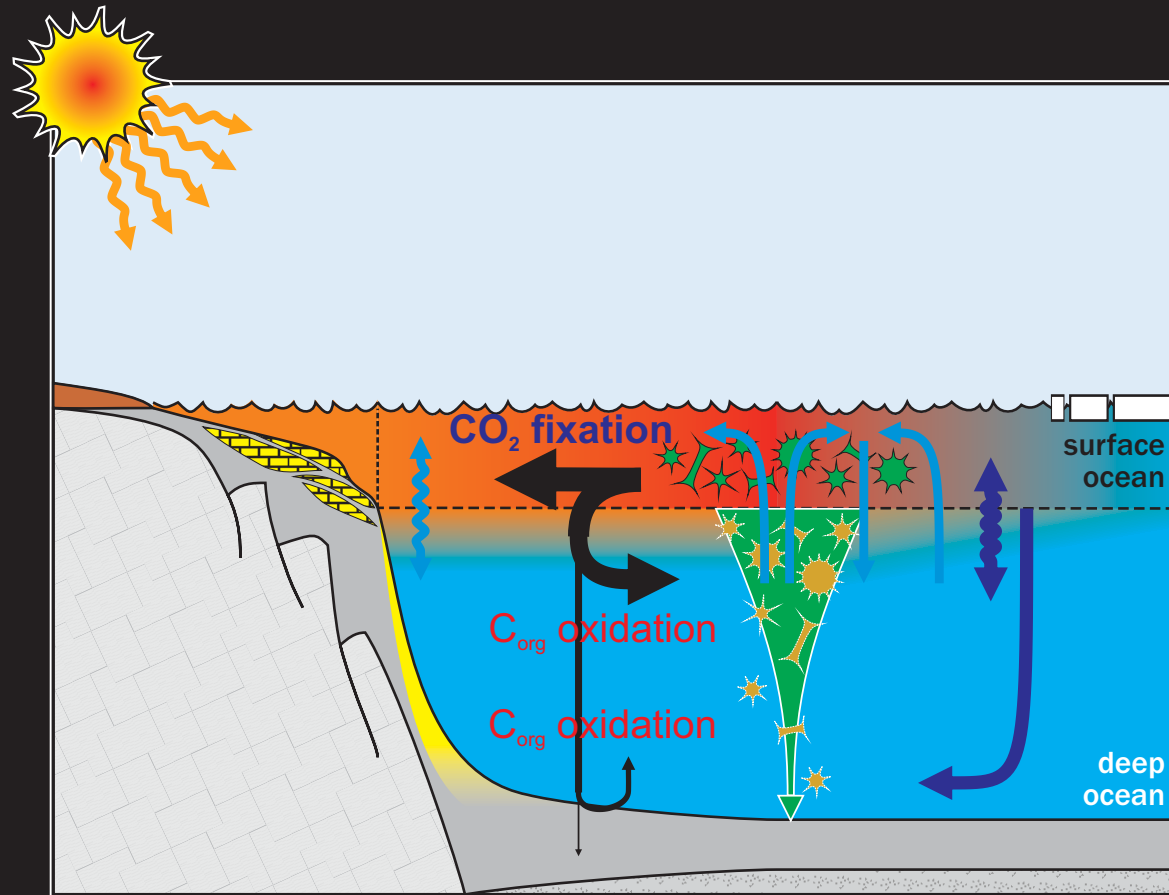
Evolution of the Biological Pump



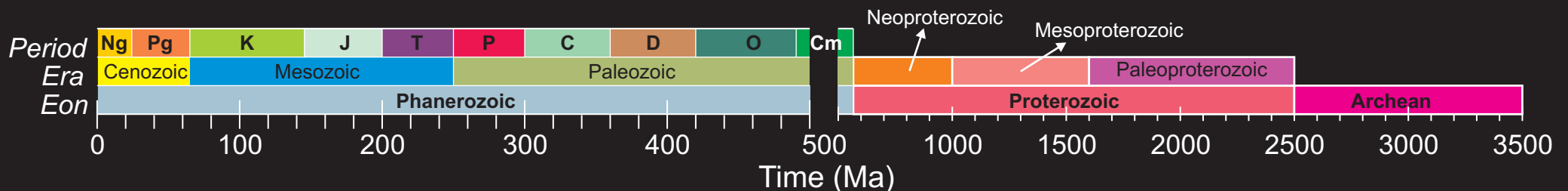
Evolution of the Biological Pump



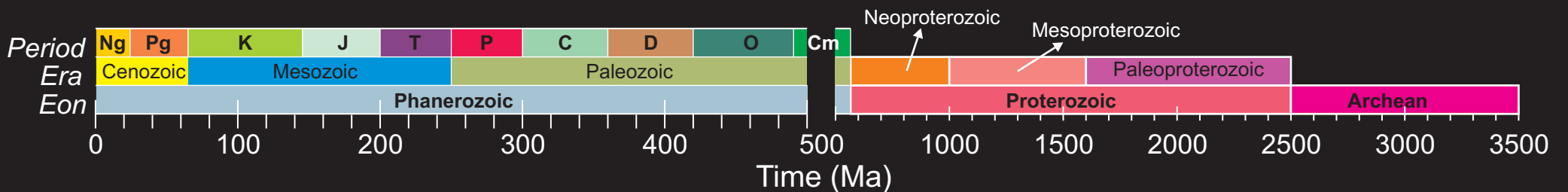
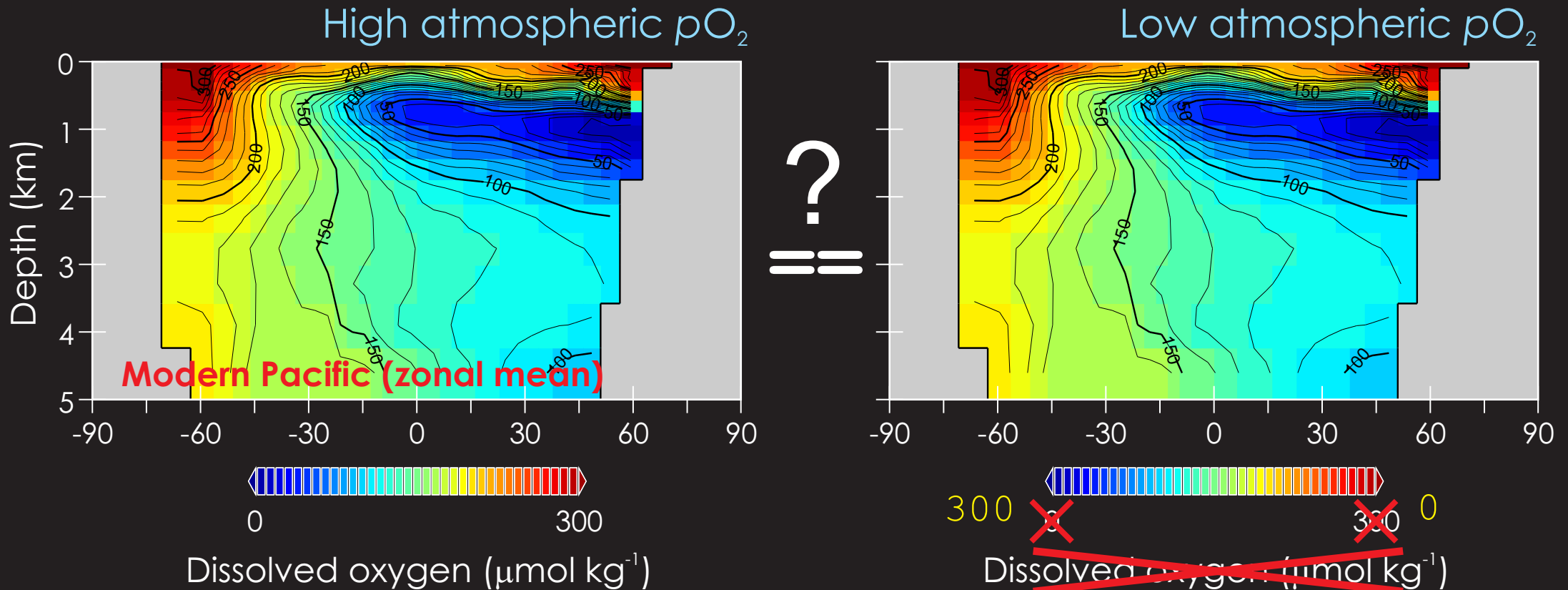
Evolution of the Biological Pump



Both physical/geochemical and biological/ecological changes occurring through Earth history will affect the processes that govern the partitioning of carbon (and alkalinity) between the surface ocean (and hence atmosphere) and ocean interior, and conversely, oxygen.

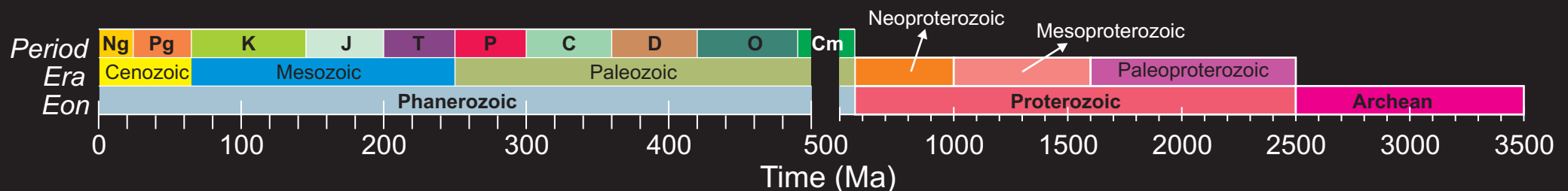
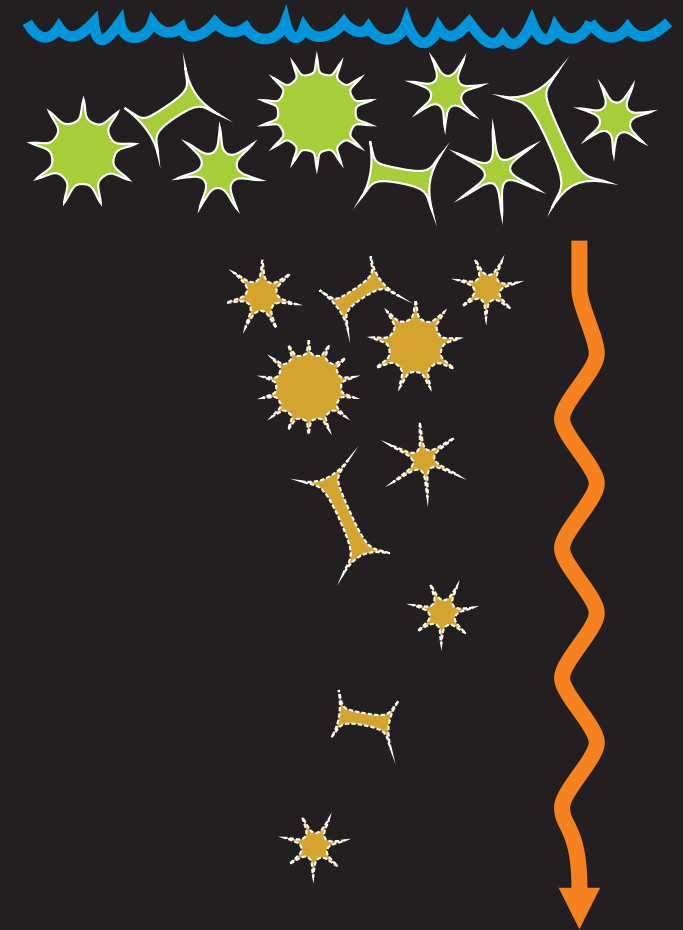


Evolution of the Biological Pump



Evolution of the Biological Pump: TALK OUTLINE

- (1) Interrogating the biological pump *in silico*.
- (2) The fundamental importance ... or not ... of the advent of pelagic calcification and mineral 'ballasting' of particulate organic matter fluxes.
- (3) Extinctions as a window onto the biological pump components.
- (4) The fundamental importance ... or not ... of physical ocean changes and particularly warming.
- (5) What came before the (vertical) particulate carbon pump?



Evolution of the Biological Pump: in silico

```

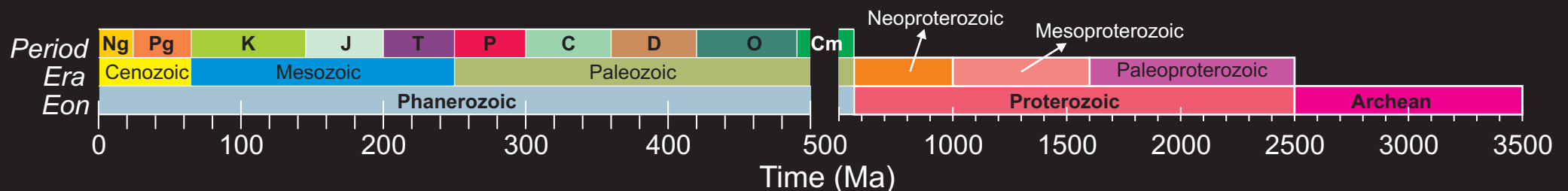
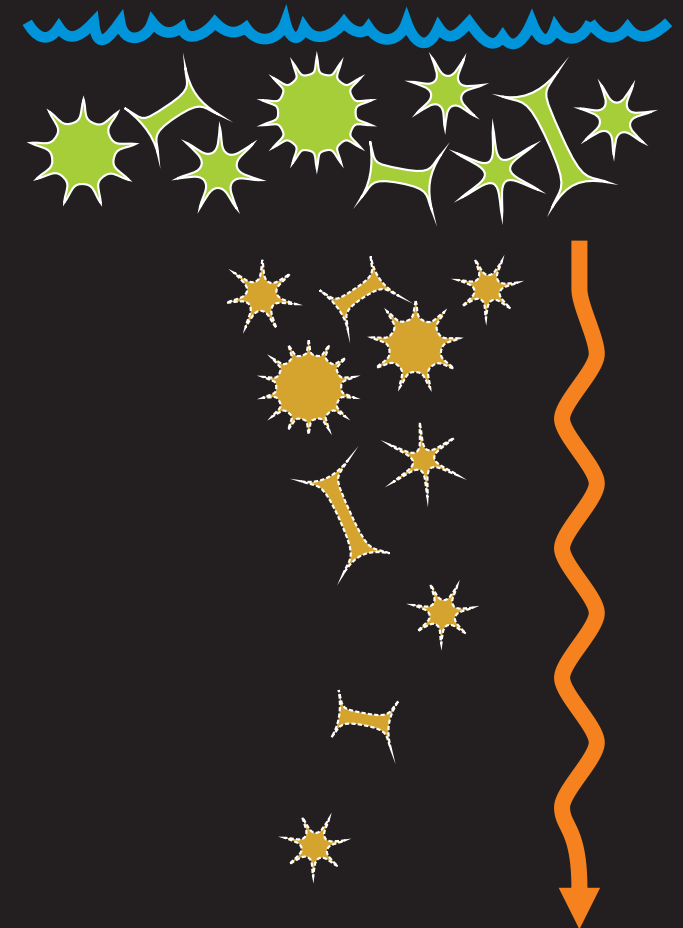
! calculate carbonate alkalinity
loc_ALK_DIC = dum_ALK &
& - loc_H4BO4 - loc_OH - loc_HPO4 - 2.0*loc_PO4 - loc_H3SiO4 - loc_NH3 - loc_HS &
& + loc_H + loc_HSO4 + loc_HF + loc_H3PO4

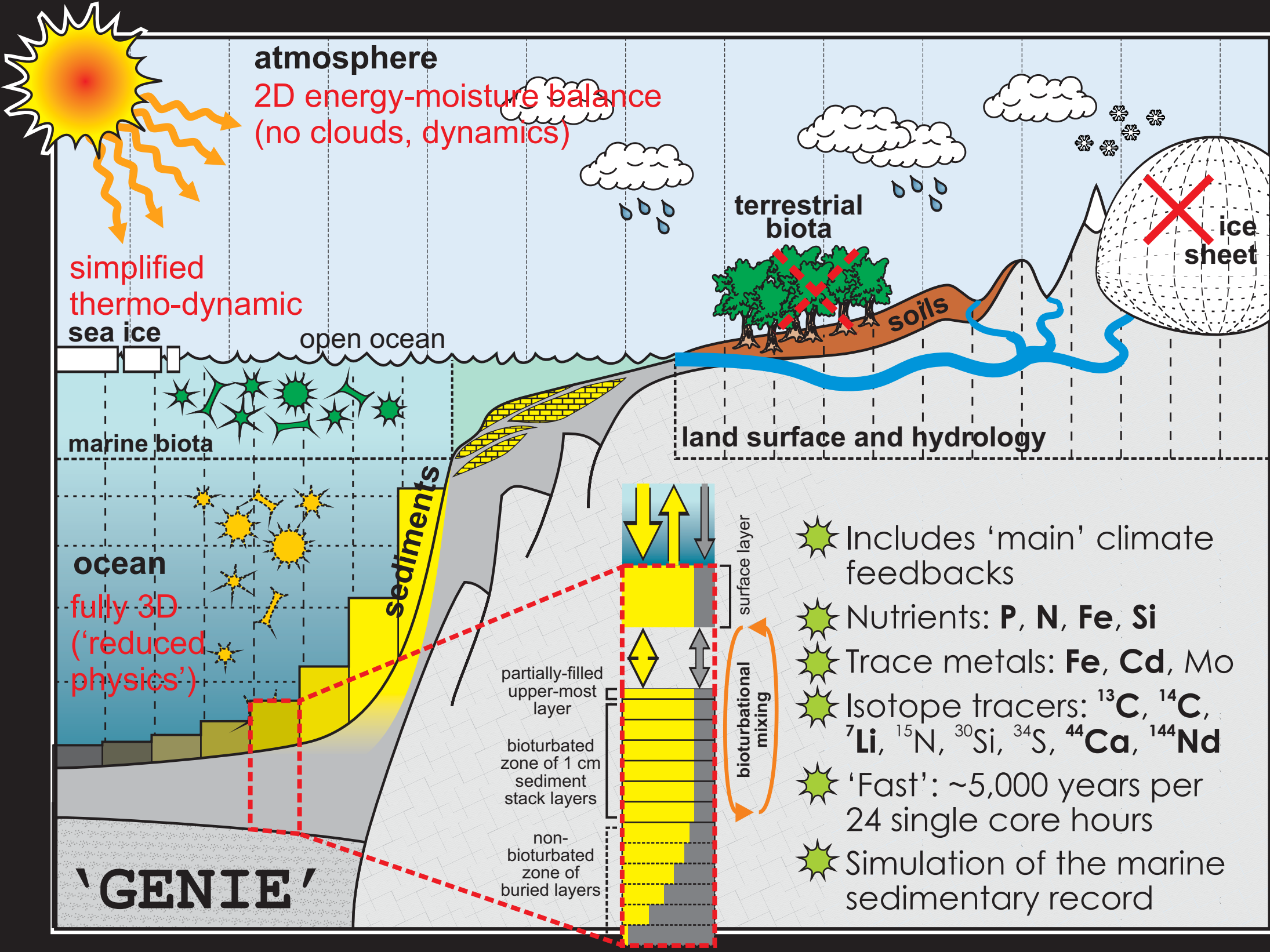
! estimate the partitioning between the aqueous carbonate species
loc_zed = ( &
& (4.0*loc_ALK_DIC + dum_DIC*dum_carbconst(icc_k) -
loc_ALK_DIC*dum_carbconst(icc_k)**2 + &
& 4.0*(dum_carbconst(icc_k) - 4.0)*loc_ALK_DIC**2 &
& )**0.5      loc_conc_HCO3 = (dum_DIC*dum_carbconst(icc_k) -
loc_zed)/(dum_carbconst(icc_k) - 4.0)

loc_conc_CO3 = &
& ( &
& loc_ALK_DIC*dum_carbconst(icc_k) - dum_DIC*dum_carbconst(icc_k) - &
& 4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))

loc_conc_CO2 = dum_DIC - loc_ALK_DIC + &
& ( &
& loc_ALK_DIC*dum_carbconst(icc_k) - dum_DIC*dum_carbconst(icc_k) - &
& 4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))

loc_H1 = dum_carbconst(icc_k1)*loc_conc_CO2/loc_conc_HCO3
loc_H2 = dum_carbconst(icc_k2)*loc_conc_HCO3/loc_conc_CO3
    
```





atmosphere
 2D energy-moisture balance
 (no clouds, dynamics)

simplified
 thermo-dynamic

sea ice

open ocean

terrestrial
 biota

soils

~~ice
 sheet~~

marine biota

land surface and hydrology

ocean

fully 3D
 ('reduced
 physics')

sediments

partially-filled
 upper-most
 layer

bioturbated
 zone of 1 cm
 sediment
 stack layers

non-
 bioturbated
 zone of
 buried layers

surface layer

bioturbational
 mixing

- Includes 'main' climate feedbacks
- Nutrients: **P, N, Fe, Si**
- Trace metals: **Fe, Cd, Mo**
- Isotope tracers: ^{13}C , ^{14}C , ^7Li , ^{15}N , ^{30}Si , ^{34}S , ^{44}Ca , ^{144}Nd
- 'Fast': ~5,000 years per 24 single core hours
- Simulation of the marine sedimentary record

'GENIE'

cGENIE UCR 2014 version: README



Andy Ridgwell

March 5, 2014

1. To get an exact (read-only) copy of the ('mu□n' development branch)cGENIE source code used for the UCR presentation – in linux, (ideally from your home directory) type:
svn co https://svn.ggy.bris.ac.uk/subversion/genie/tags/cgenie.UCR2014
--username=genie-user cgenie.muffin

NOTE: All this must be typed continuously on ONE LINE, with a S P A C E before '--username', and before 'cgenie'. You will be asked for a password – it isg3n1e-user.

2. You need to set a couple of environment variables – the compiler name, netCDF library name, and netCDF path. These are specified in the fileuser.mak (genie-main directory). If the cgenie code tree (cgenie.muffin) and output directory (cgenie output) are installed anywhere other than in your account HOME directory, paths specifying this will have to be edited in: user.mak anduser.sh (genie-main directory). Installing the model code under the default directory name (cgenie.mu□n) in your HOME directory is hence by far the simplest and avoids incurring additional/unnecessary pain (configuration complexity) ...

You will also need to have installed or linked to an appropriate FORTRAN compiler and netCDF library (built with the same FORTRAN compiler). The GNU FORTRAN compiler (gfort) version 4.4.4 or later is recommended. The netCDF version needs to be 4.0 (more recent versions require a little work-around, not documented here ...).

3. To test the code installation – change directory tocgenie.muffin/genie-main and type:

```
make testbiogem
```

This compiles a carbon cycle enabled configuration ofcGENIE and runs a short test, comparing the results against those of a pre-run experiment (also downloaded alongside the model source code). It serves to check that you have the software environment correctly configured. If you are unsuccessful here ... double-check the software and directory environment settings in user.mak (or user.sh) and for a netCDF error, check the value of theNETCDIRenvironment variable. (Refer to the User Manual for addition fault-finding tips.) If environment variables are changed: before re-trying the test, you will need to type:

```
make cleanall
```

That is is for the basic installation. To run the model it is a simple matter of calling the 'runmuffin.sh ' shell script fromgenie-main and supplying a couple of parameter values, e.g.:

```
./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.ANTH / EXAMPLE.worjh2.Caoetal2009.SPIN 10000
```

Refer to thecGENIE User manualfor more information regarding installing, running, and analyzing model output, and cGENIE Examplesfor more information on this specific example.¹ Also read the cGENIE README

Highly recommended ... is in order to have a working appreciation of the structure of the model and output, plus the format of the model output and how to visualize it – to read through:

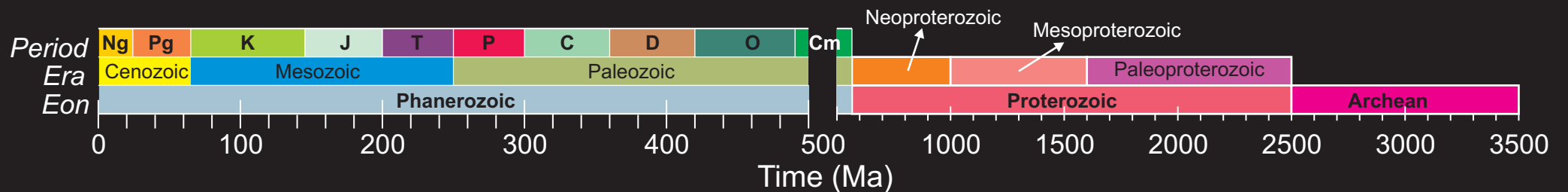
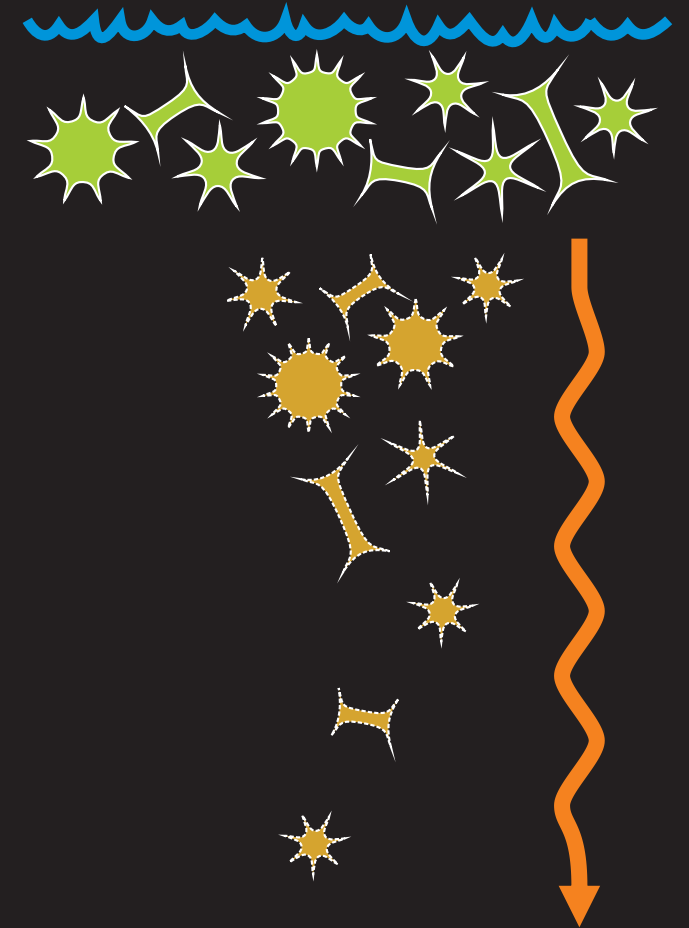
http://www.seao2.info/cgenie/labs/EC4.2013/GEOGM1110andM1404.2013-14.cGENIE_LAB.0000.pdf

(which serves as a basic introduction to the model and how to use it).

Evolution of the Biological Pump: in silico



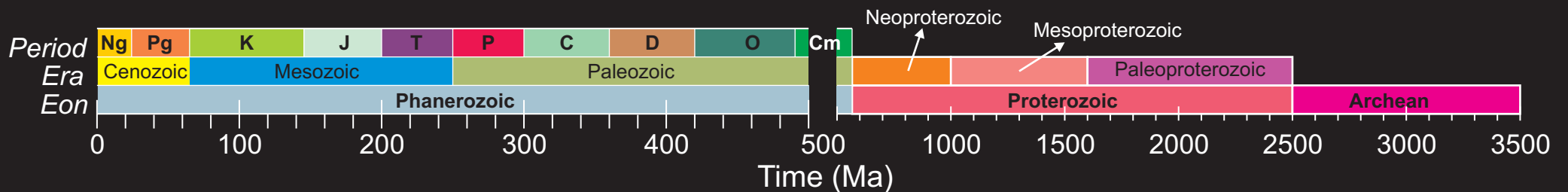
tinyurl.com/kmjhe4s



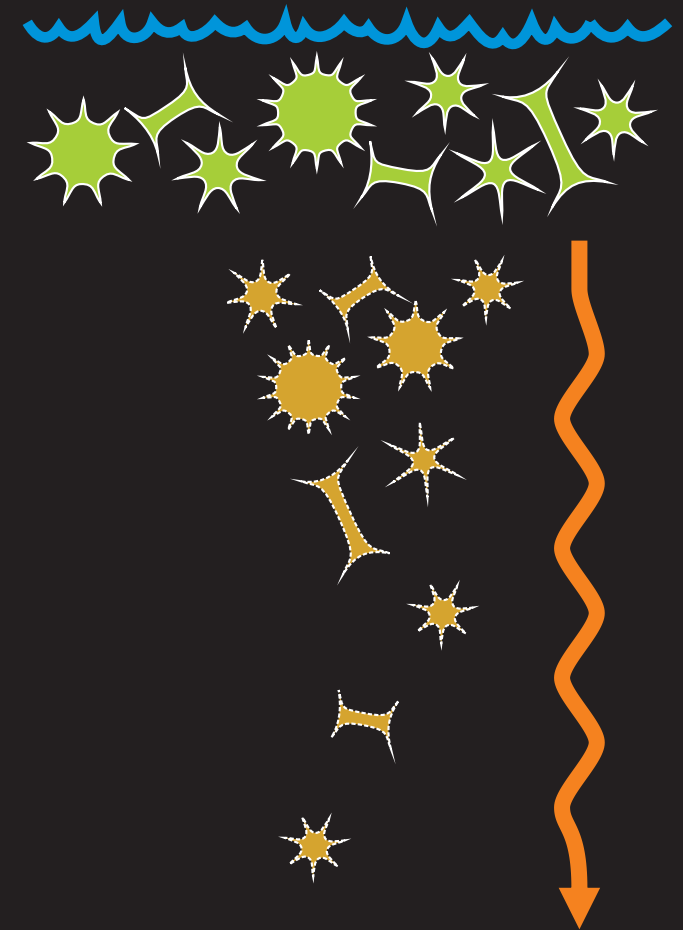
Evolution of the Biological Pump: The Mesozoic planktic calcifier revolution



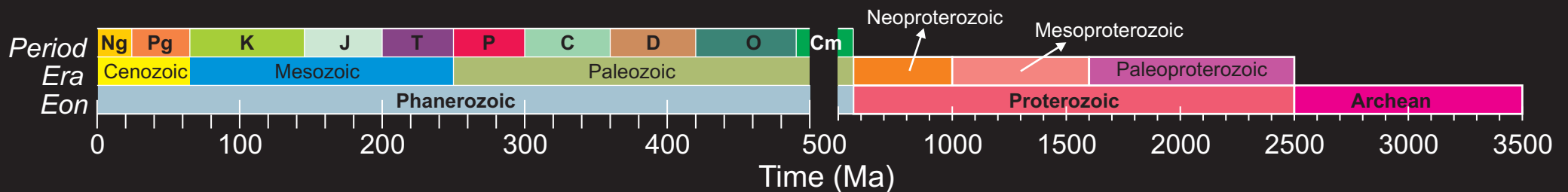
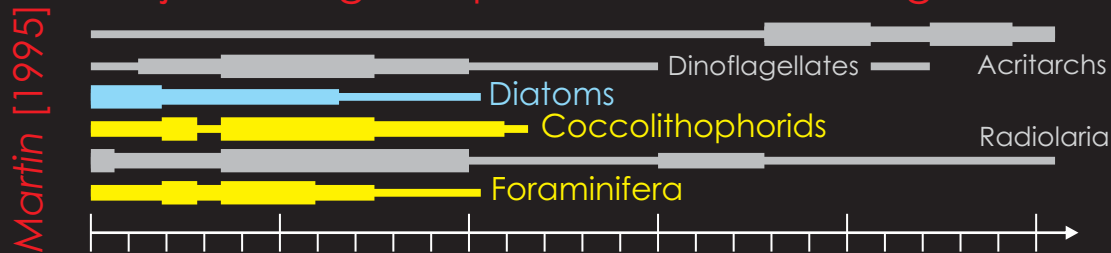
Major changes in plankton assemblage



Evolution of the Biological Pump: The Mesozoic planktic calcifier revolution



Major changes in plankton assemblage



Evolution of the Biological Pump:

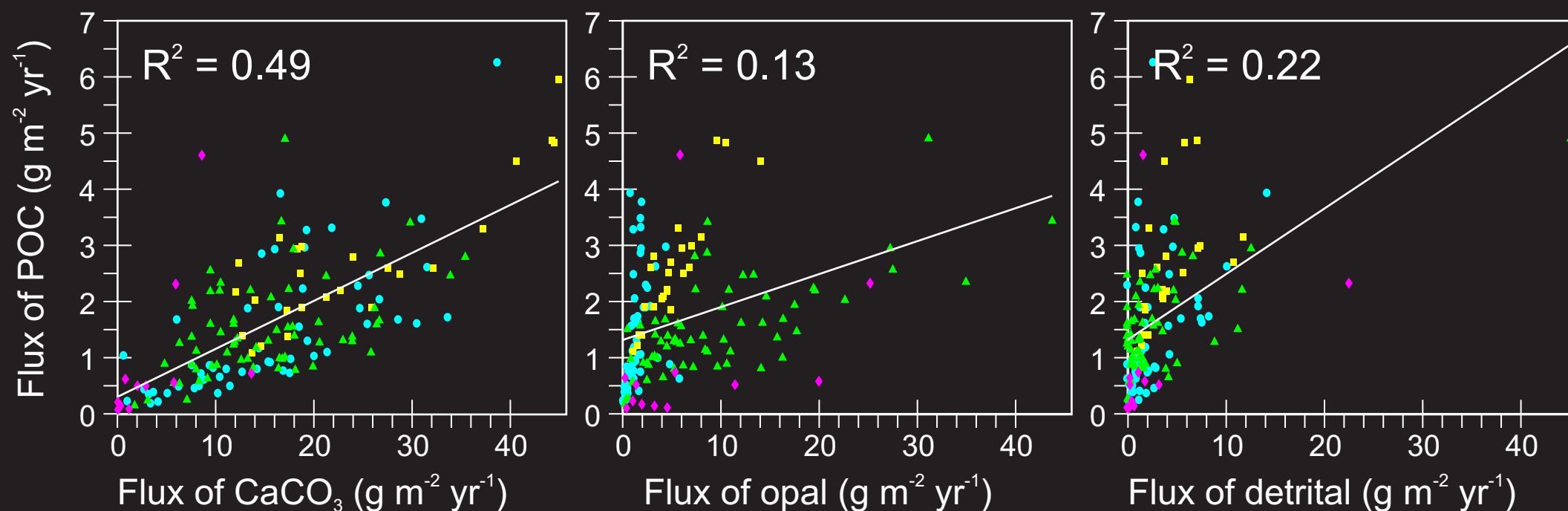
Planktic carbonate production and 'ballasting'

Compilation of sediment trap observations:

depths ≥ 2000 m (to exclude hydrodynamically distorted fluxes and relationships) and differentiated by basin:

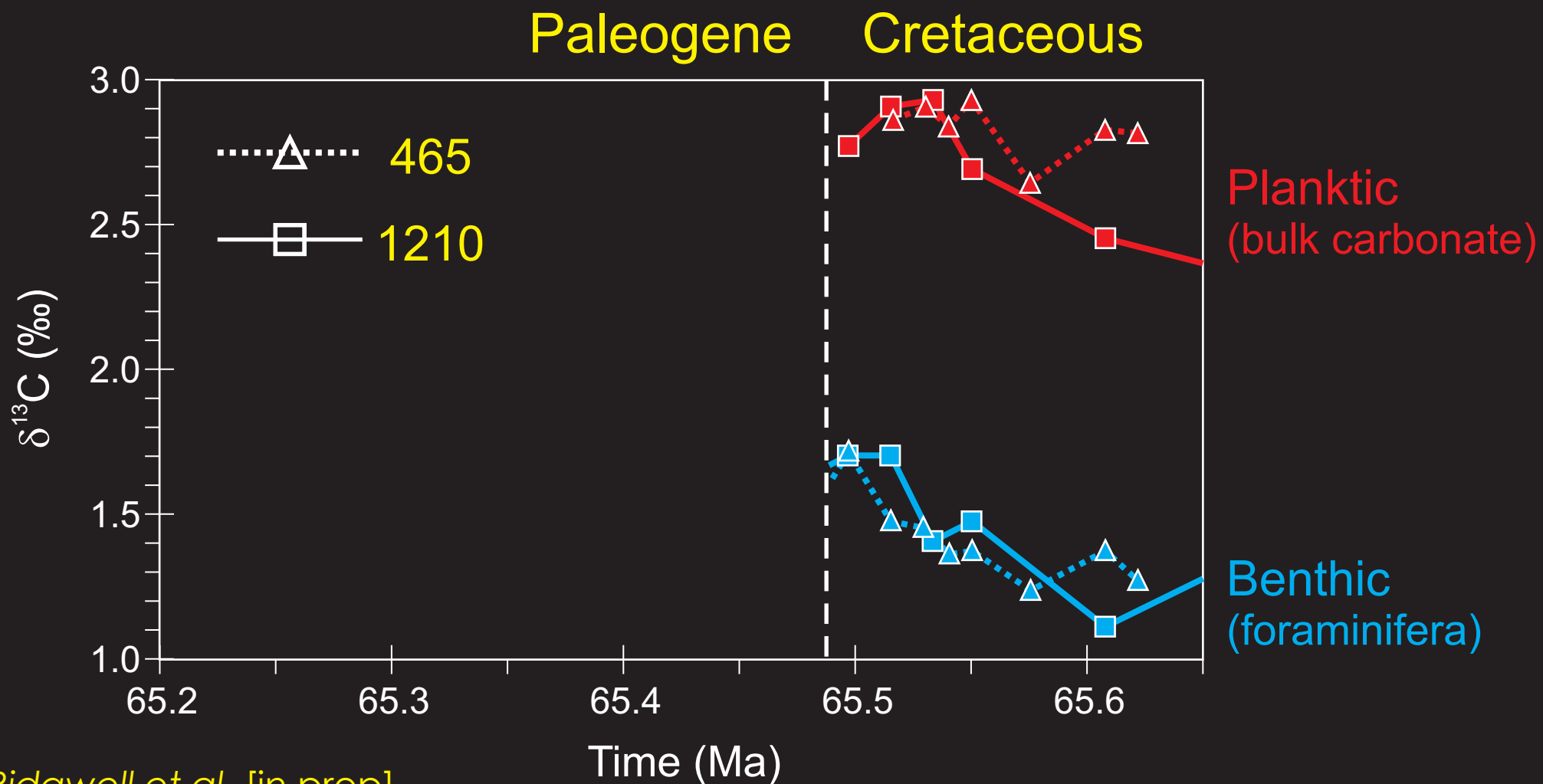
cyan == Atl, yellow == Ind, green == Pac, magenta == SO.

[Wilson et al., 2012; GBC 26, doi:10.1029/2012GB004398]



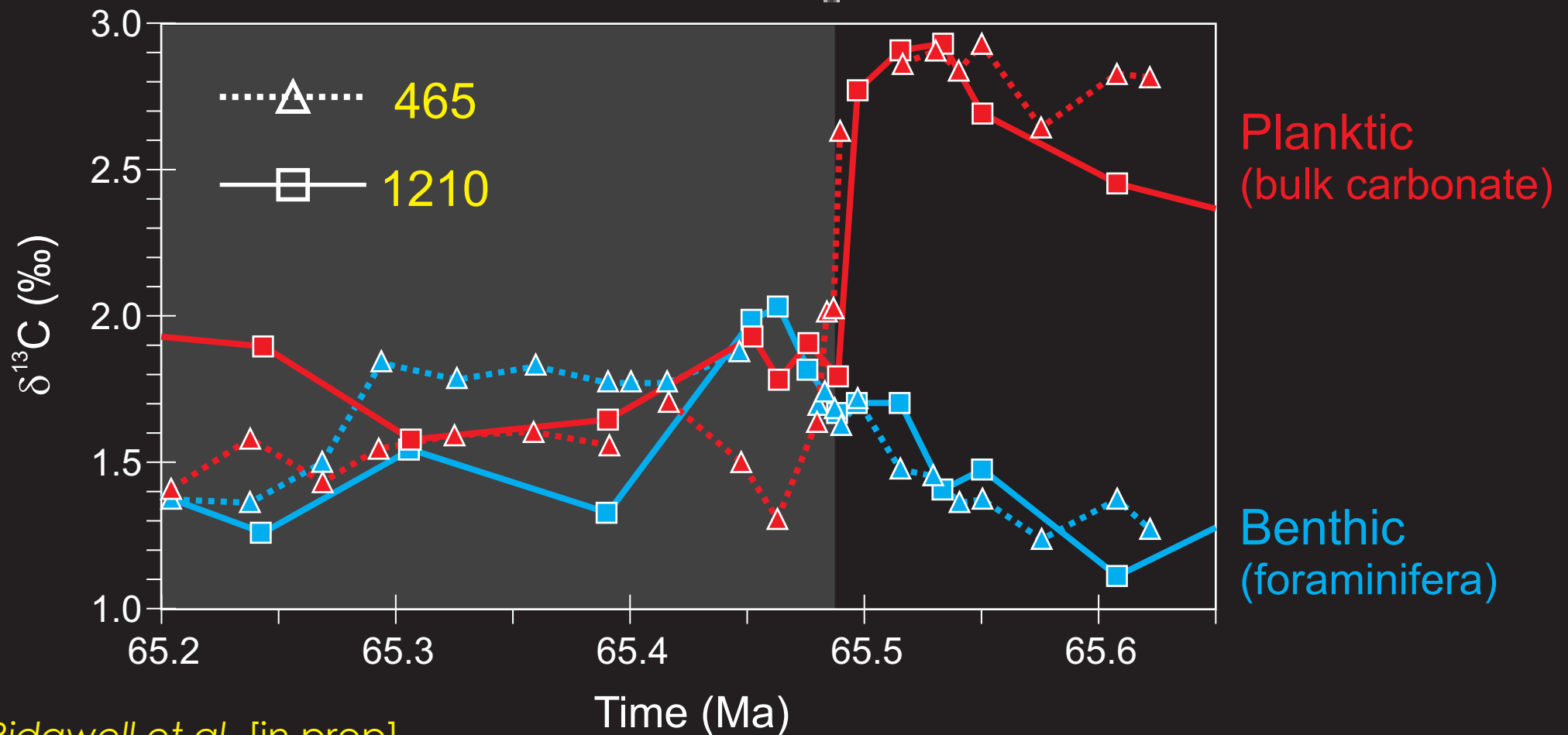
Evolution of the Biological Pump: 'Hiccups'

(temporary disruption or removal of one or more processes)

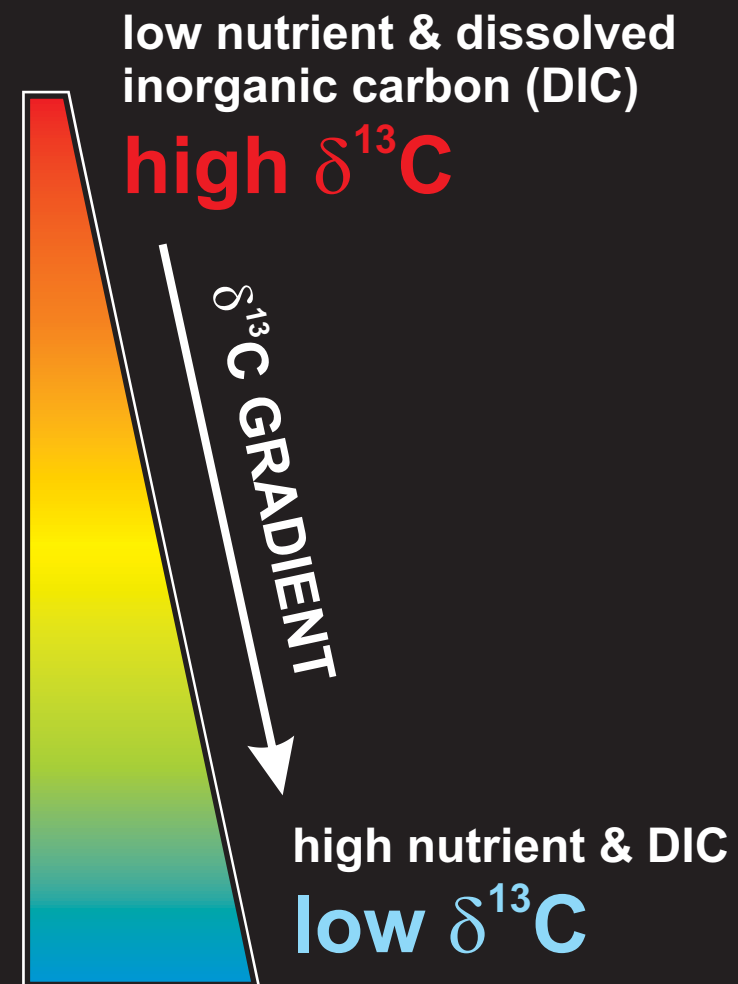
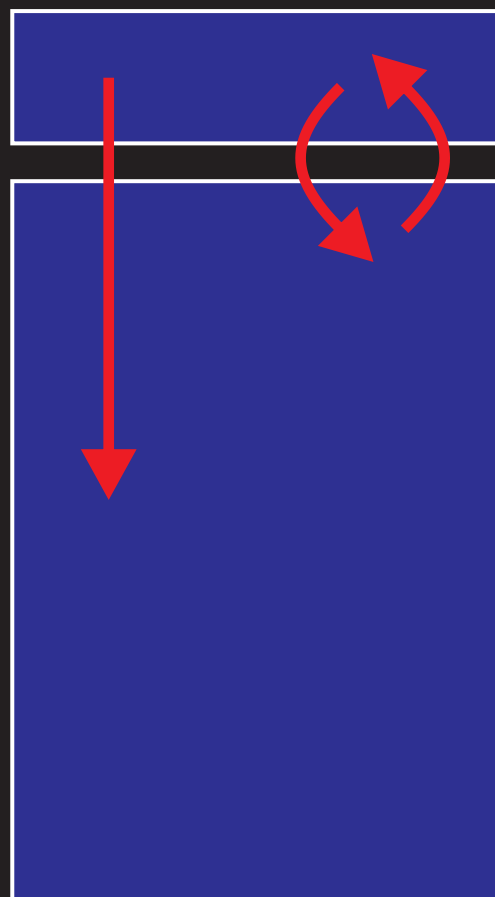
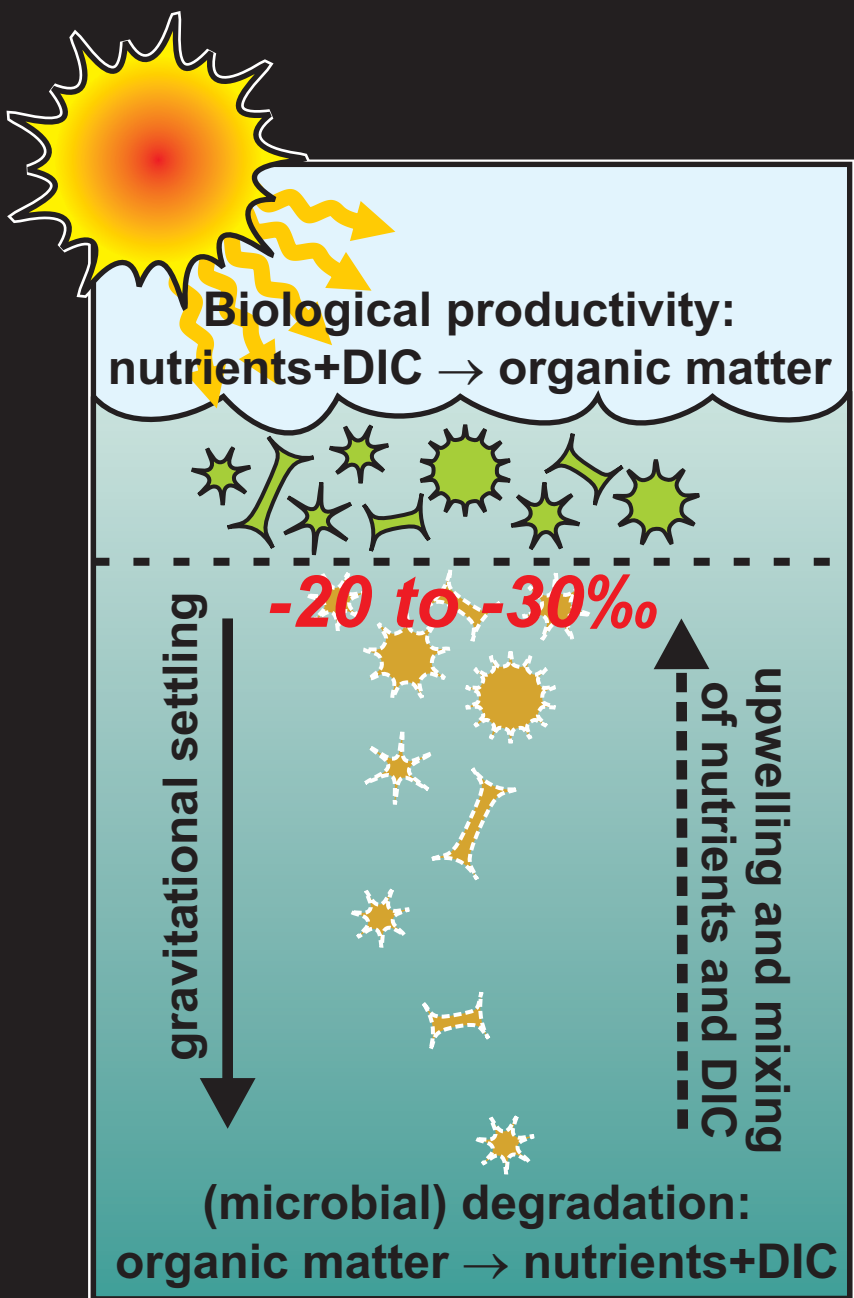


Evolution of the Biological Pump: 'Hiccups'

(temporary disruption or removal of one or more processes)



Evolution of the Biological Pump: 'Hiccups'

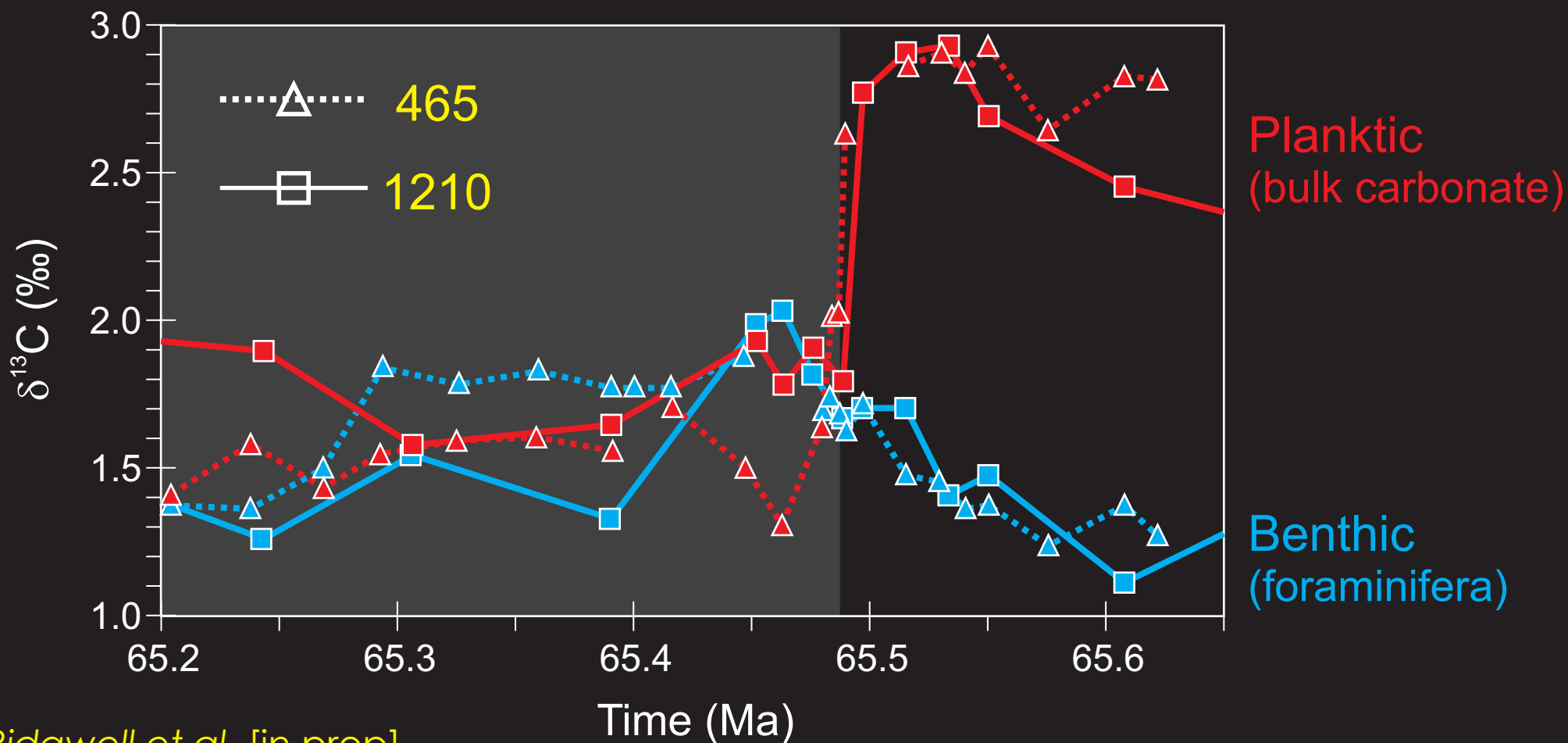


Evolution of the Biological Pump: 'Hiccups'

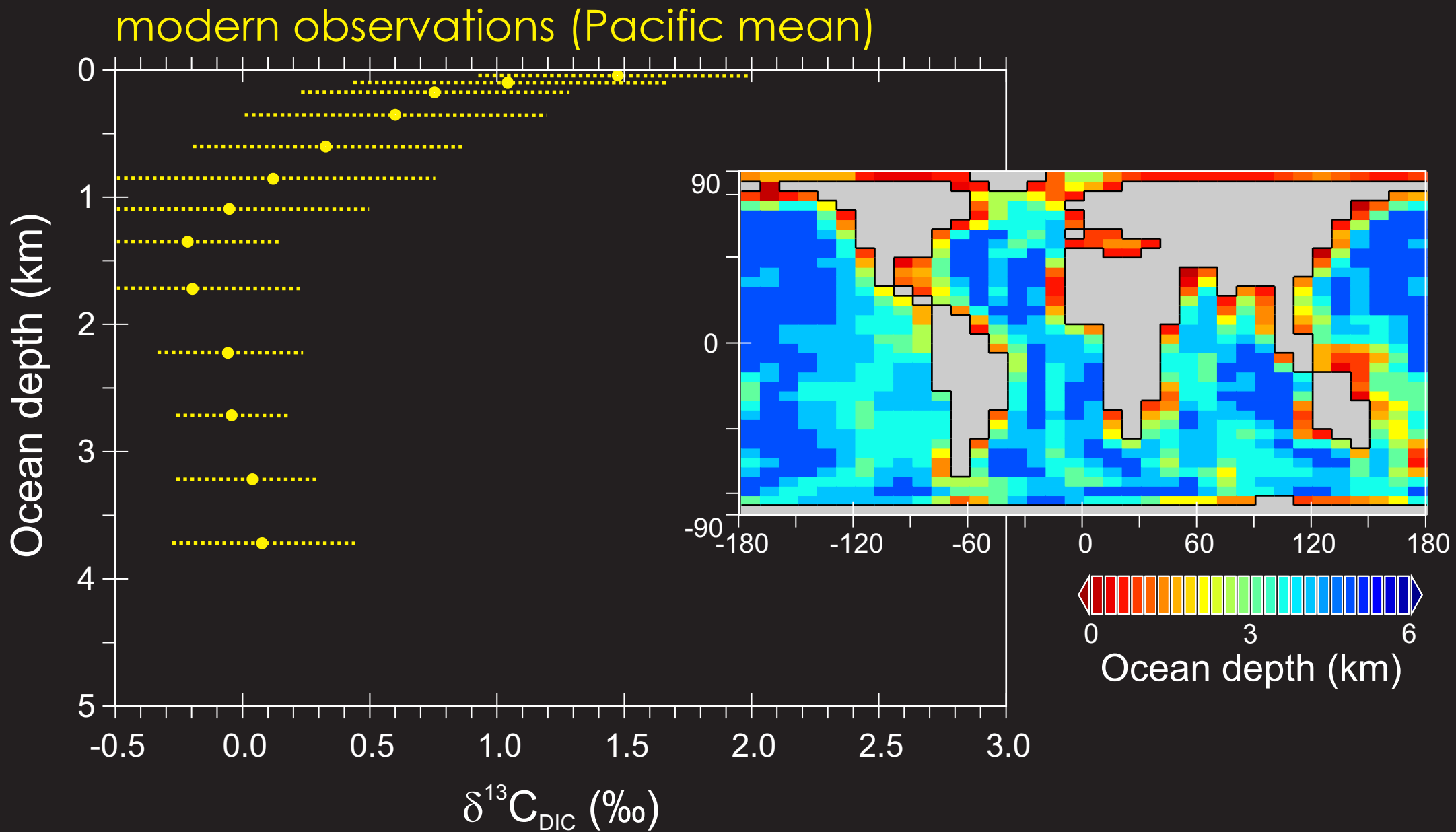
Severe extinction amongst
calcifying plankton
(and less interesting creatures
such as dinosaurs etc.)



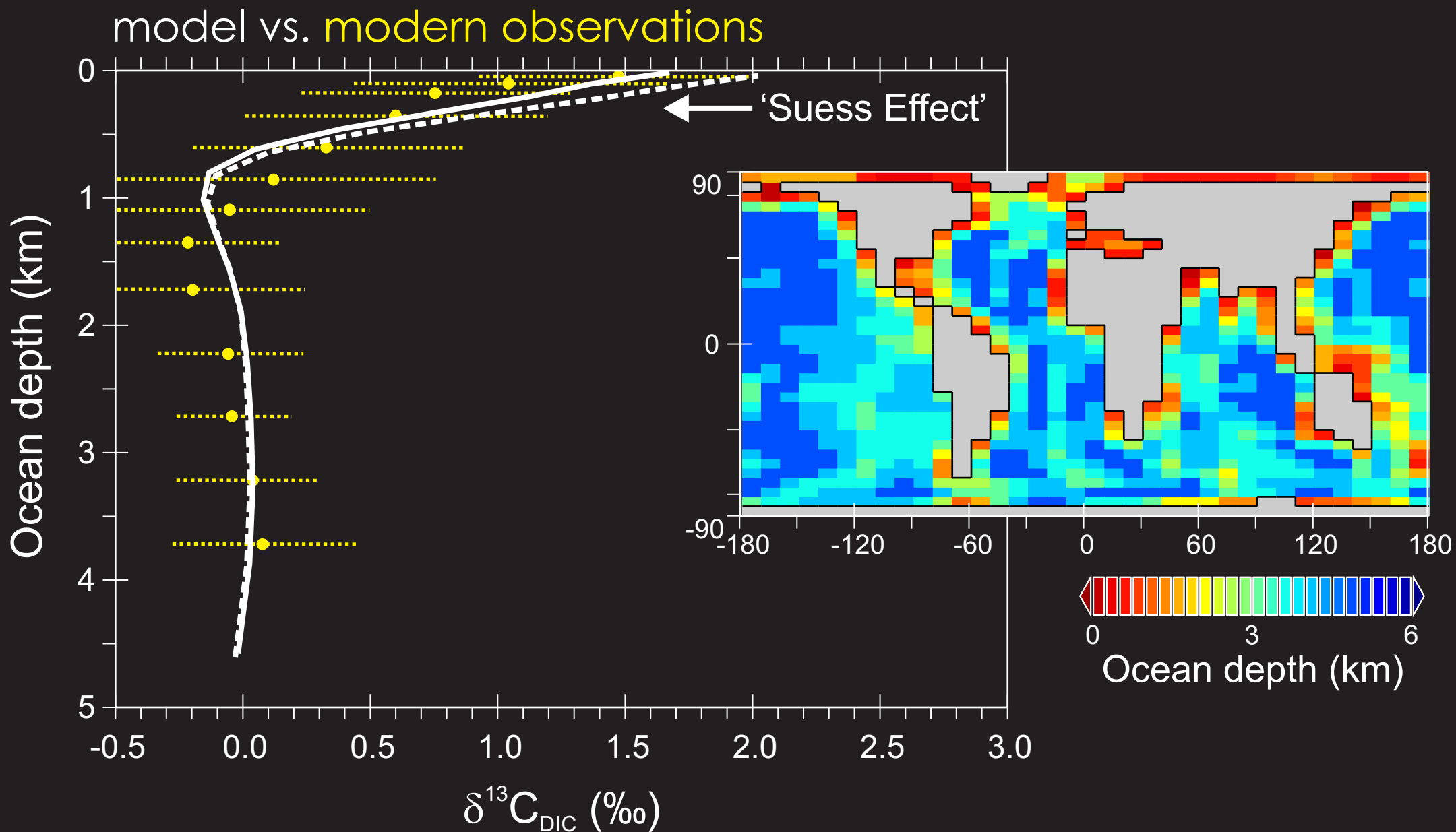
(biogenic mineral flux == 0)
&&
(organic carbon flux == 0)
=> ballasting == .true.



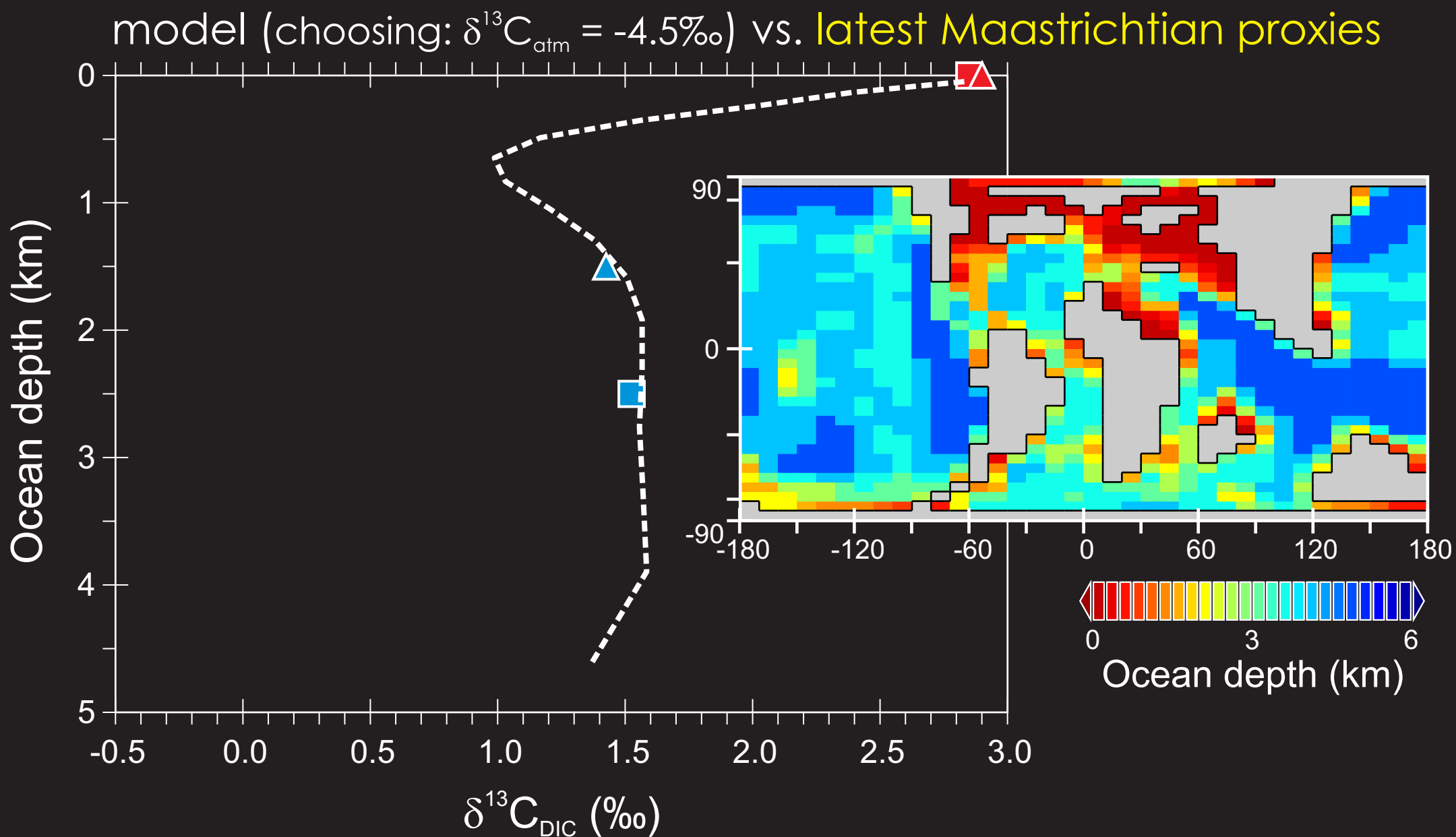
Evolution of the Biological Pump: 'Hiccups'



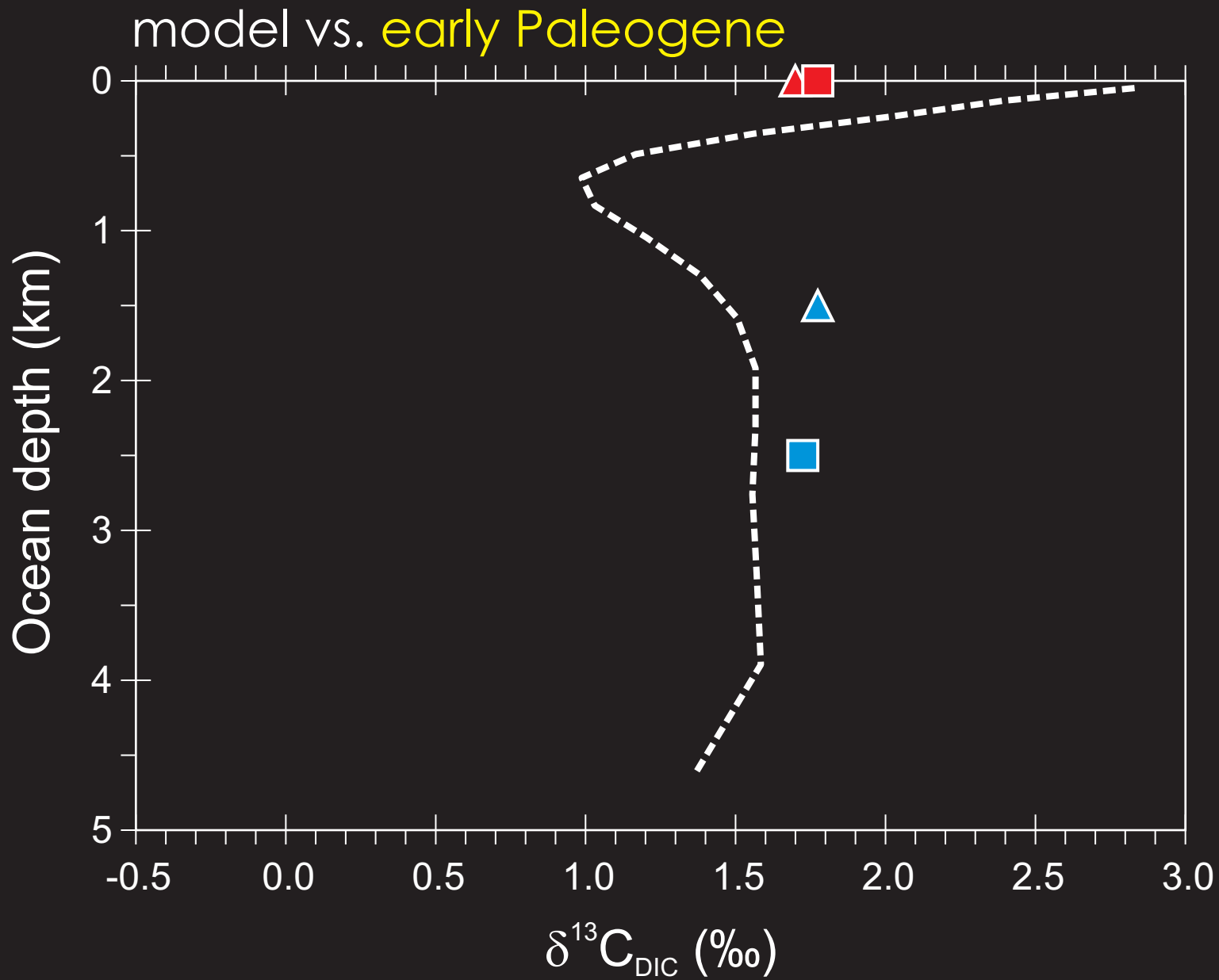
Evolution of the Biological Pump: 'Hiccups'



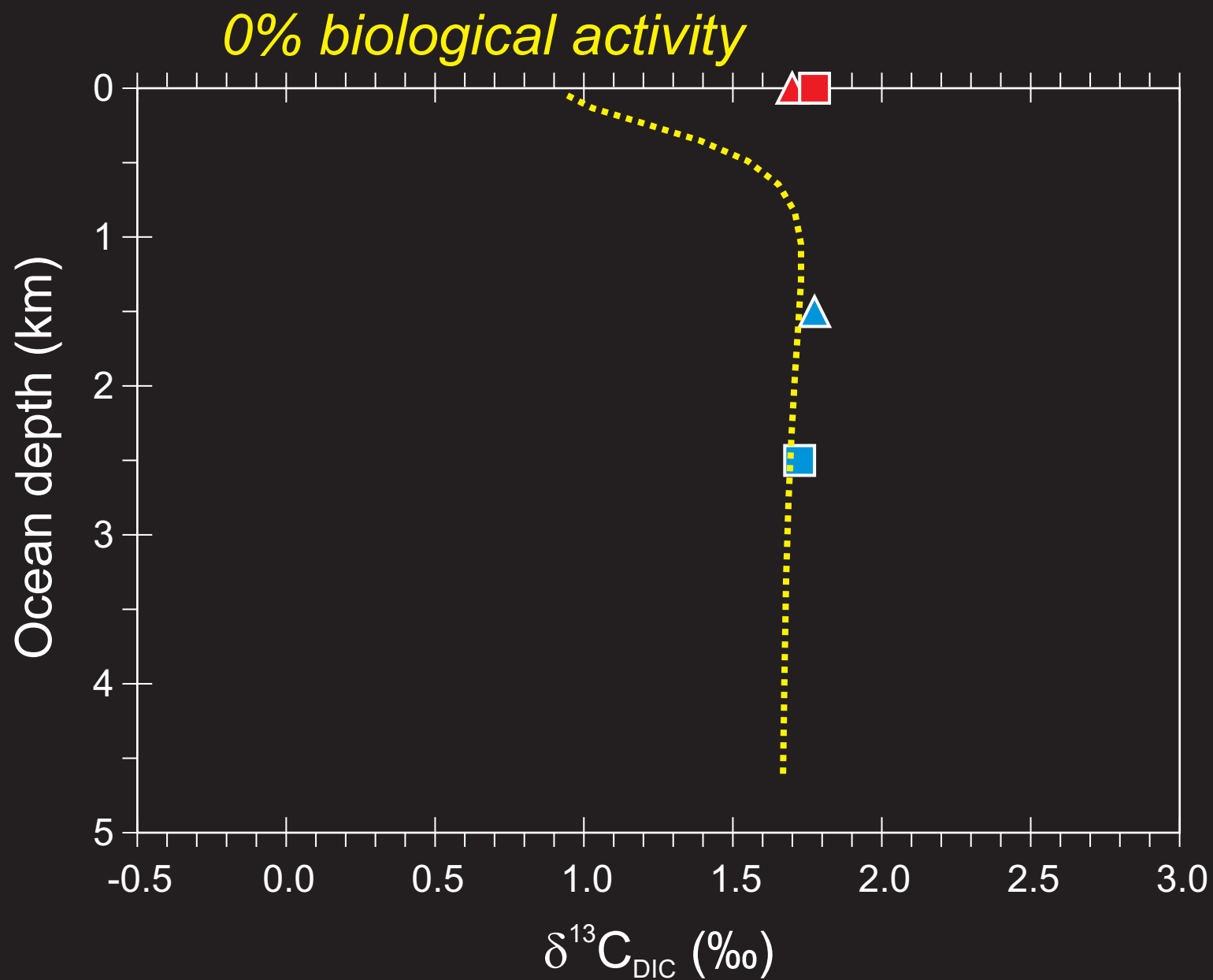
Evolution of the Biological Pump: 'Hiccups'



Evolution of the Biological Pump: 'Hiccups'



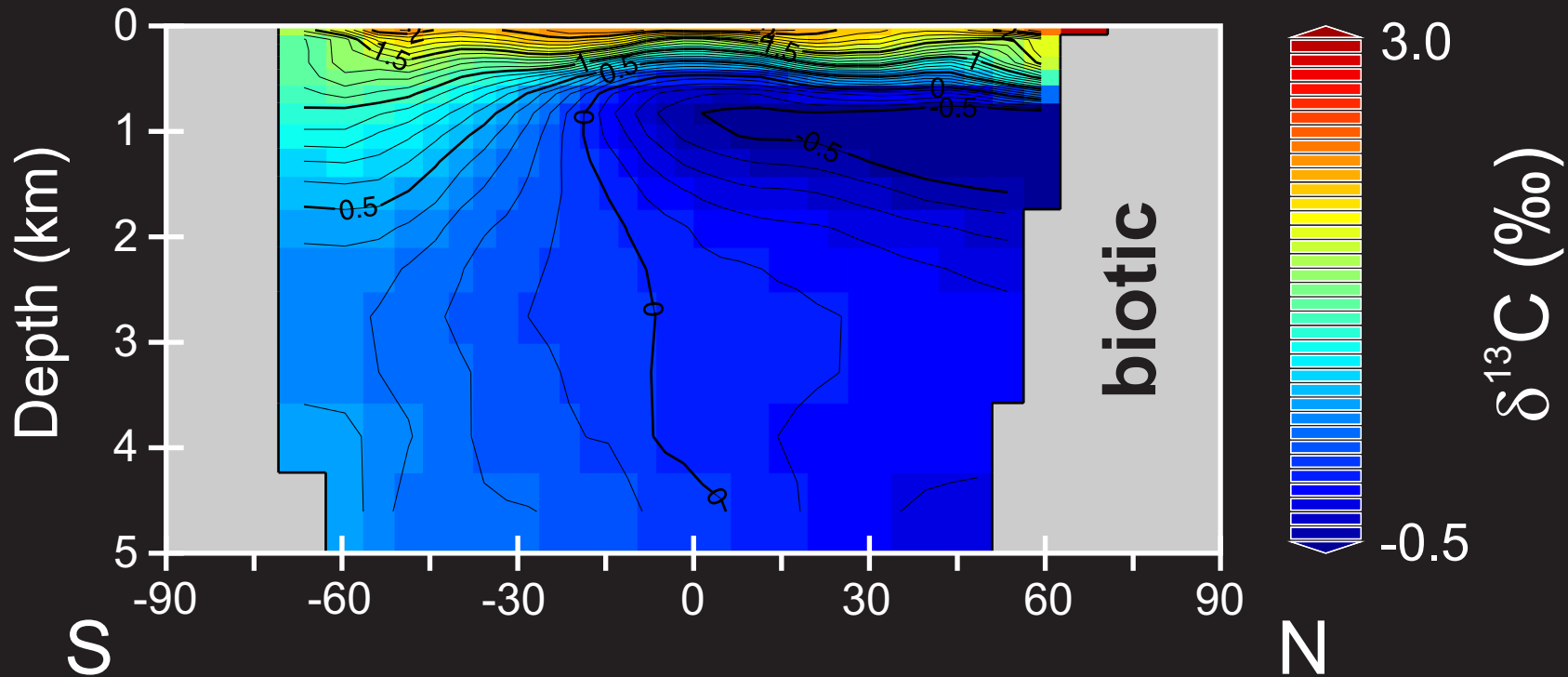
Evolution of the Biological Pump: 'Hiccups'



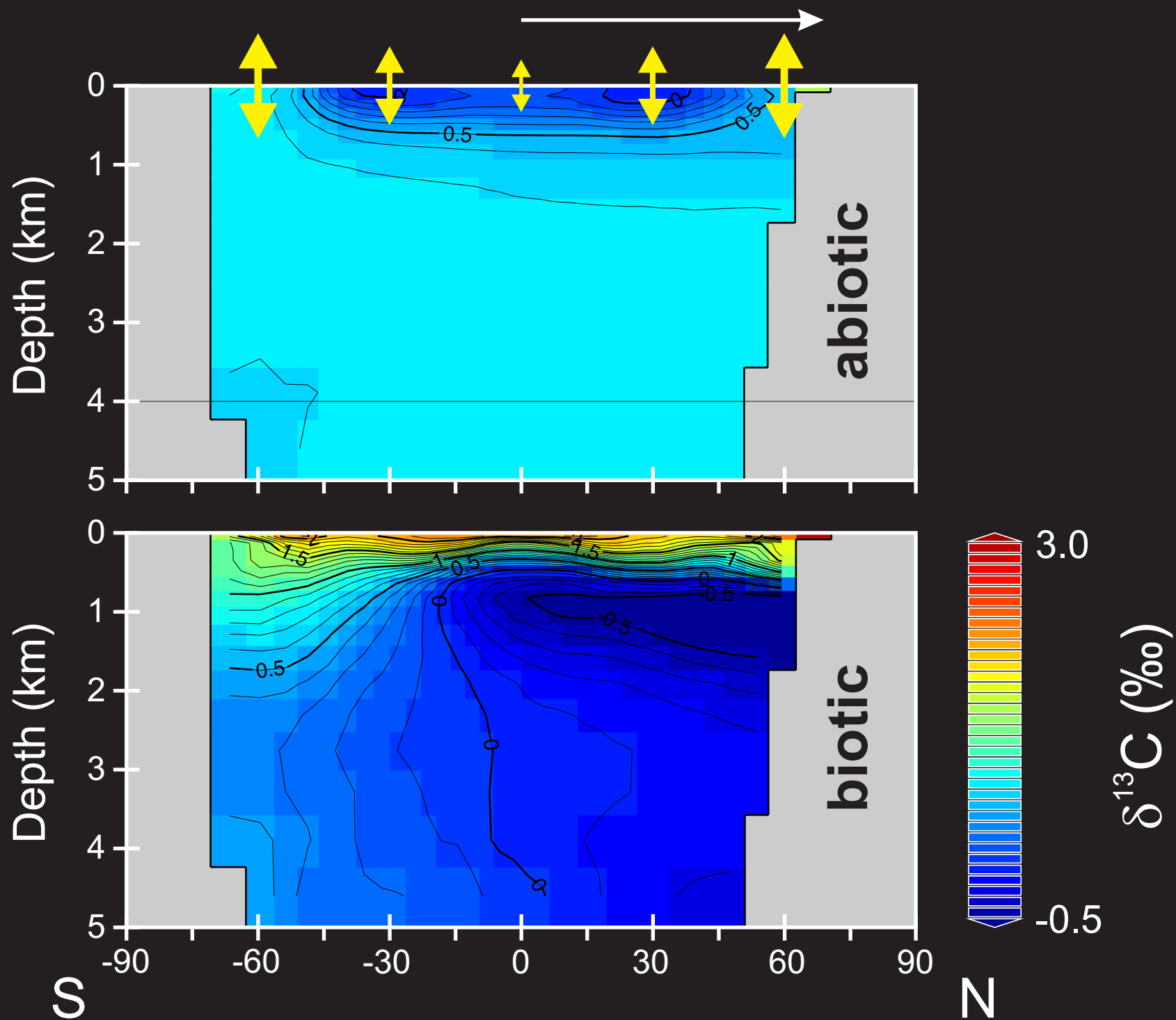
Evolution of the Biological Pump: 'Hiccups'



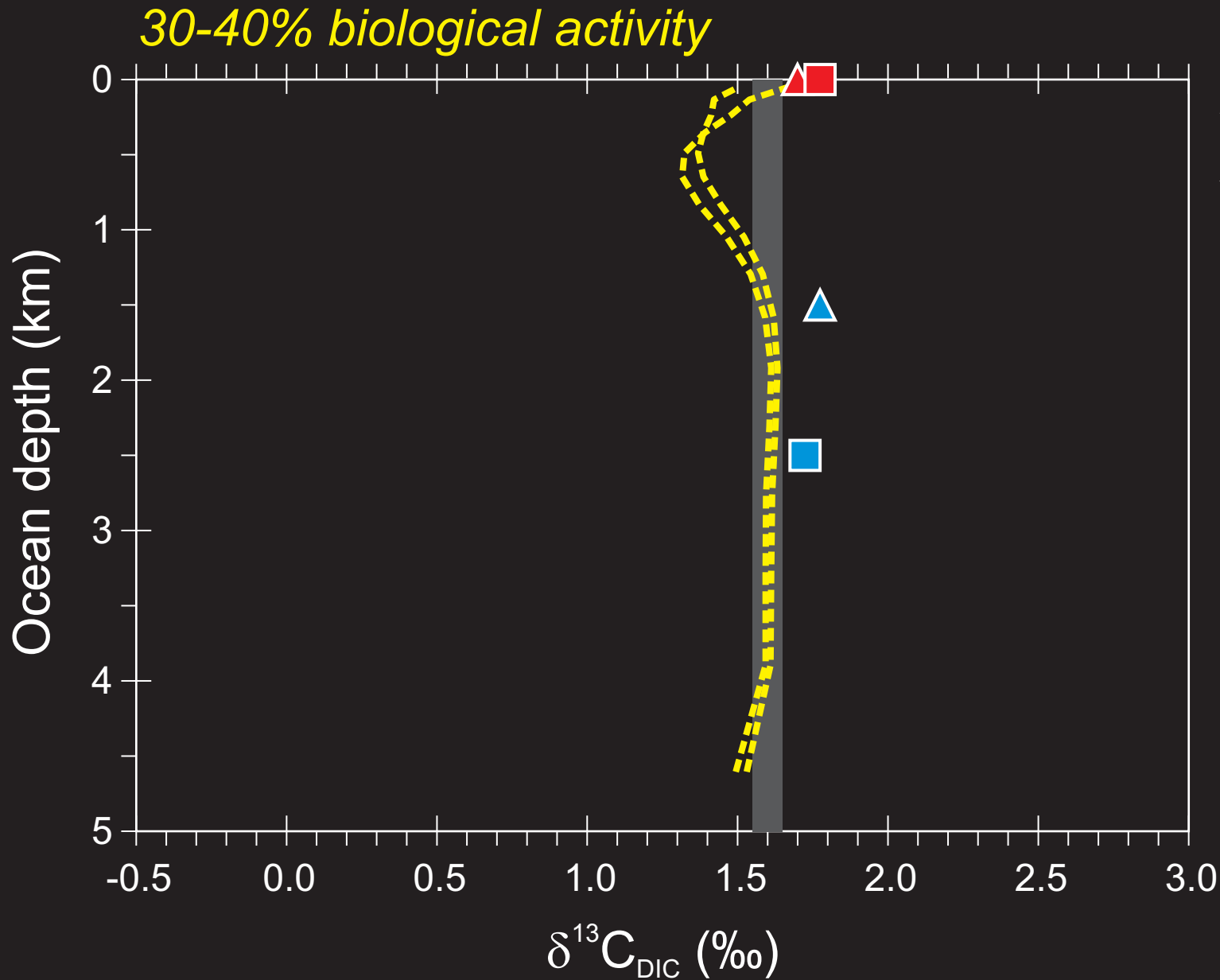
Modern Pacific zonal $\delta^{13}\text{C}_{(\text{DIC})}$ profile



increasing fractionation between $p\text{CO}_2$ and $[\text{CO}_2]$
with decreasing temperature towards to poles



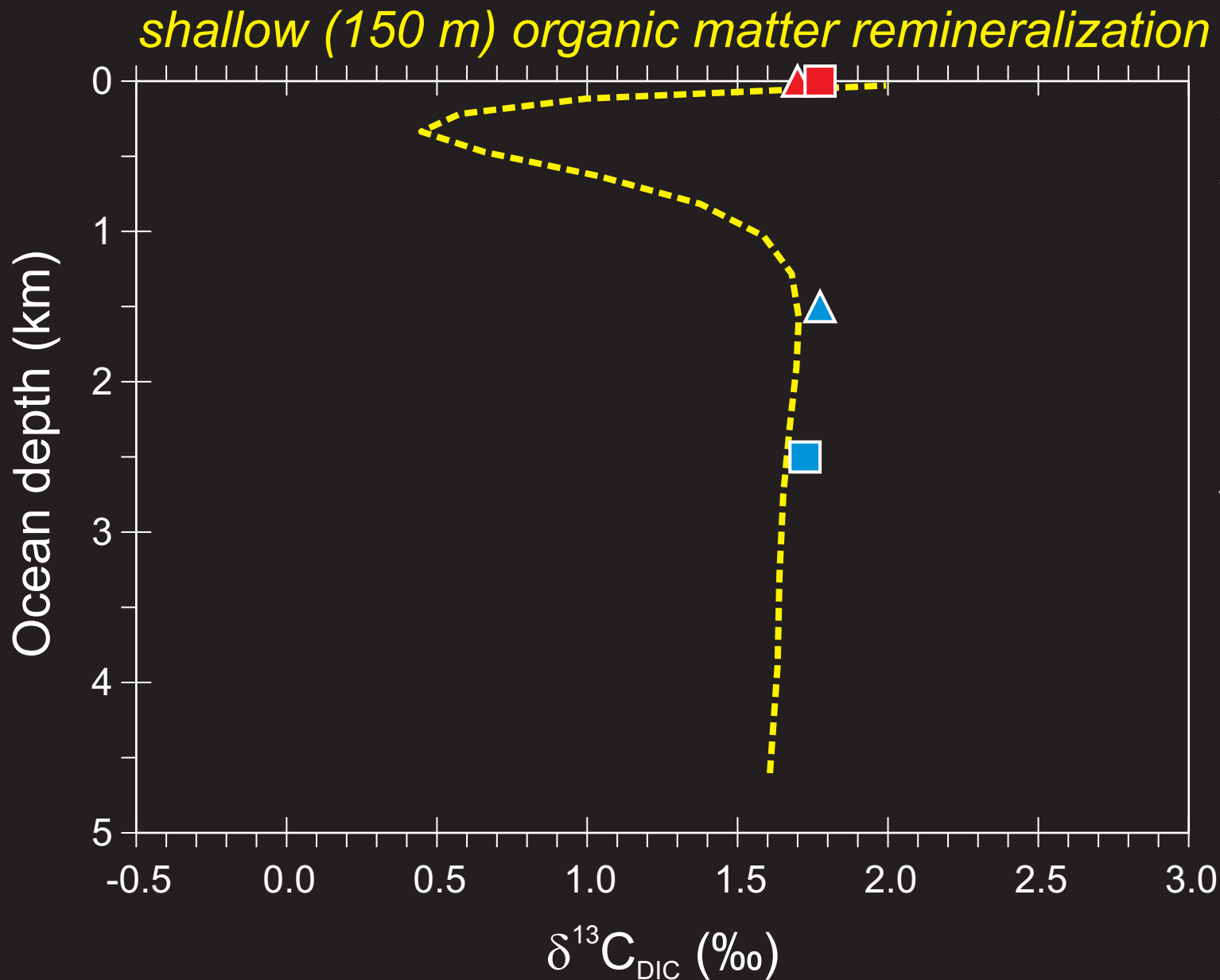
Evolution of the Biological Pump: 'Hiccups'



Answer:

A somewhat reduced biological pump ...

Evolution of the Biological Pump: 'Hiccups'



Answer:

A somewhat reduced biological pump ...

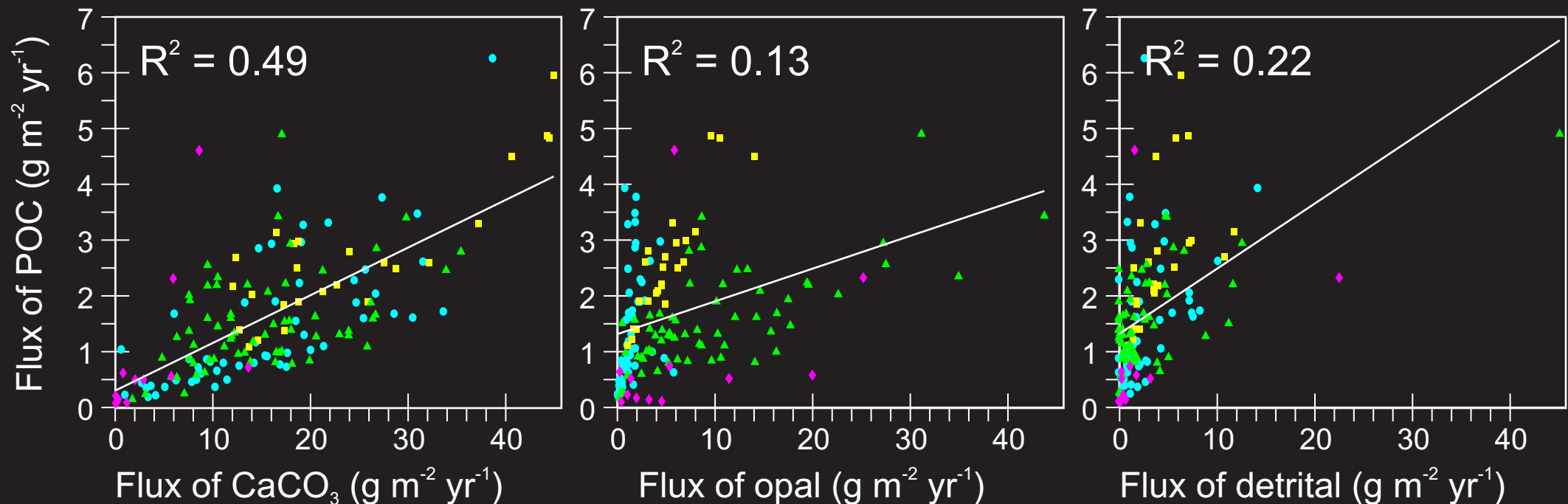
... or, a strange and different biological pump, consistent with profound ecological change post impact?

Evolution of the Biological Pump:

Planktic carbonate production and 'ballasting'

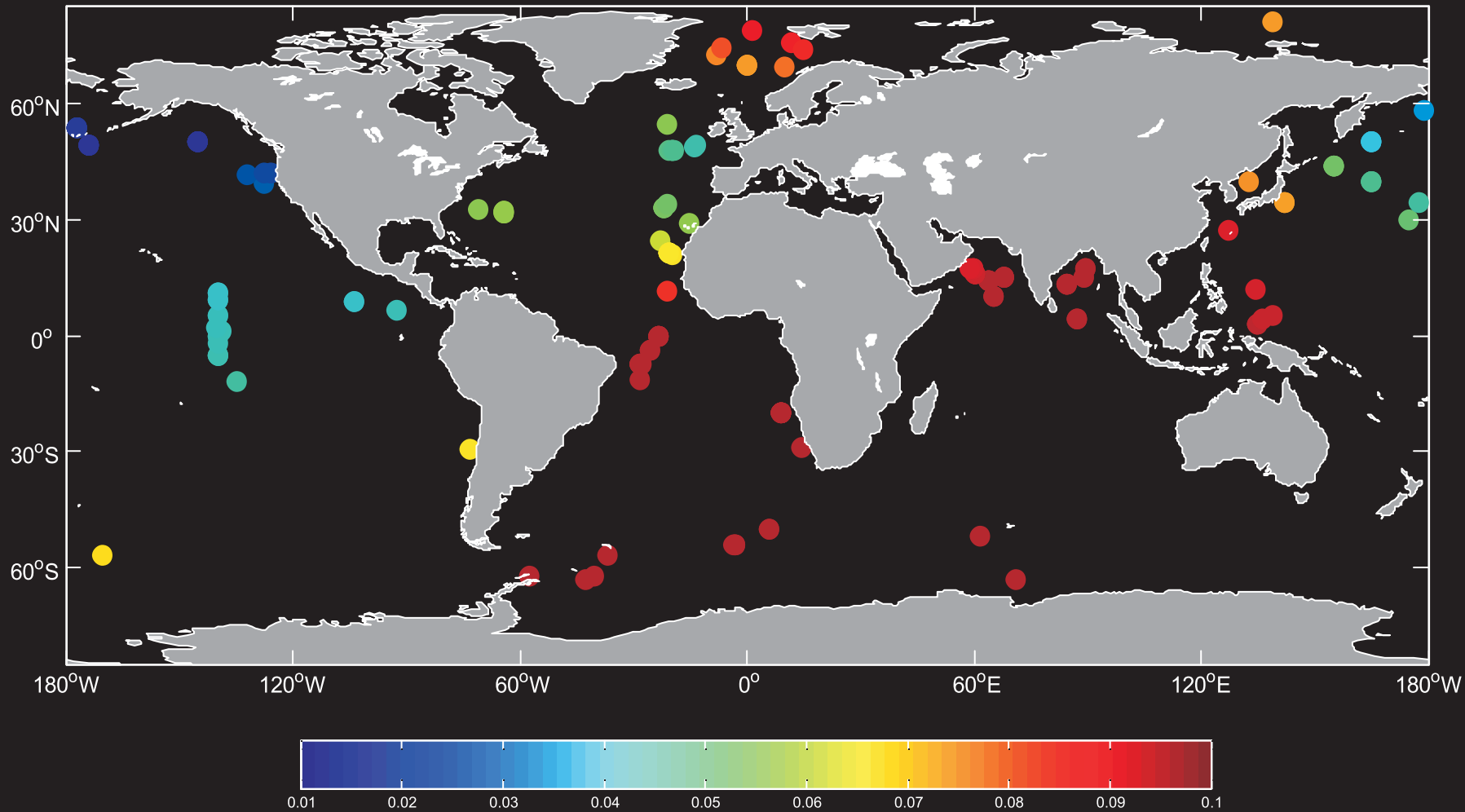
Compilation of sediment trap observations:
depths ≥ 2000 m to exclude hydrodynamically distorted
fluxes and relationships, and differentiated by basin:
cyan == Atlantic, yellow == Indian, green == Pacific,
magenta == Southern Ocean.

[Wilson et al., 2012; GBC 26, doi:10.1029/2012GB004398]



Evolution of the Biological Pump:

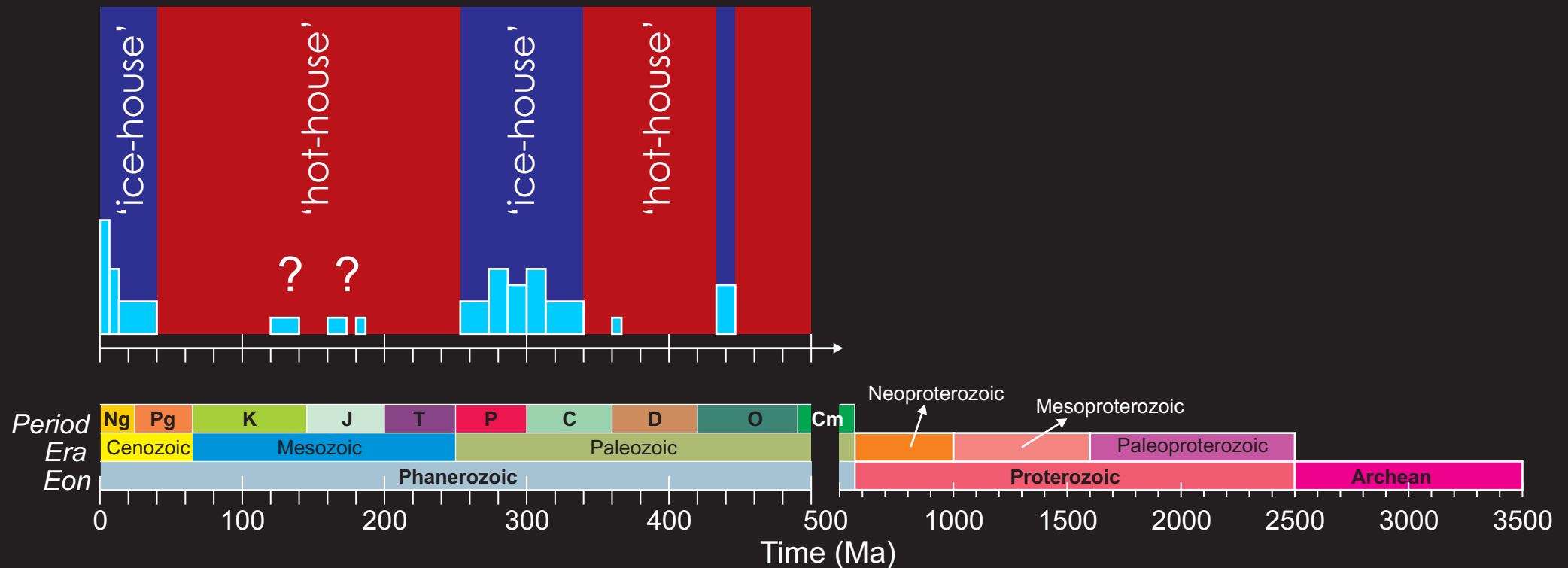
Planktic carbonate production and 'ballasting'



Spatial distribution of carrying capacity (ballasting) coefficients calculated using geographically weighted regression analysis for CaCO_3 .

Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



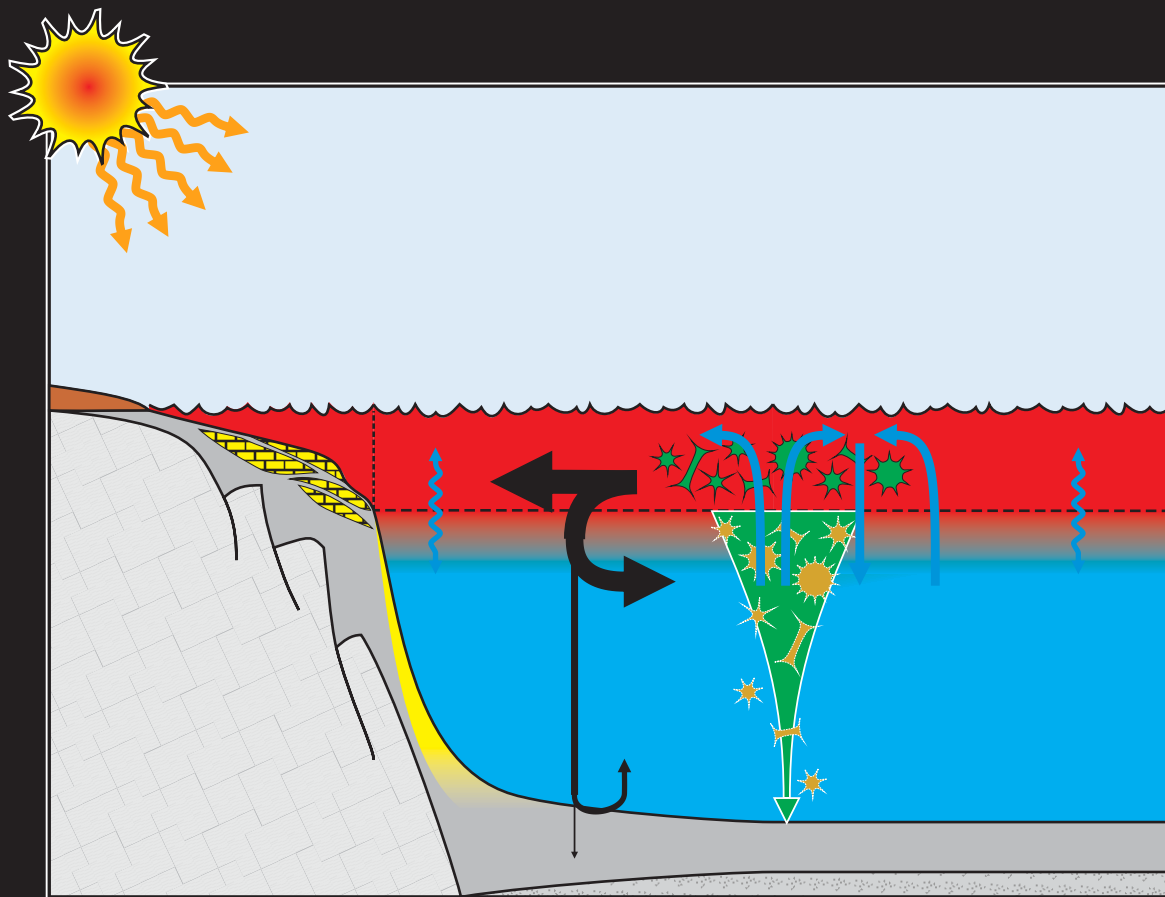
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates

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

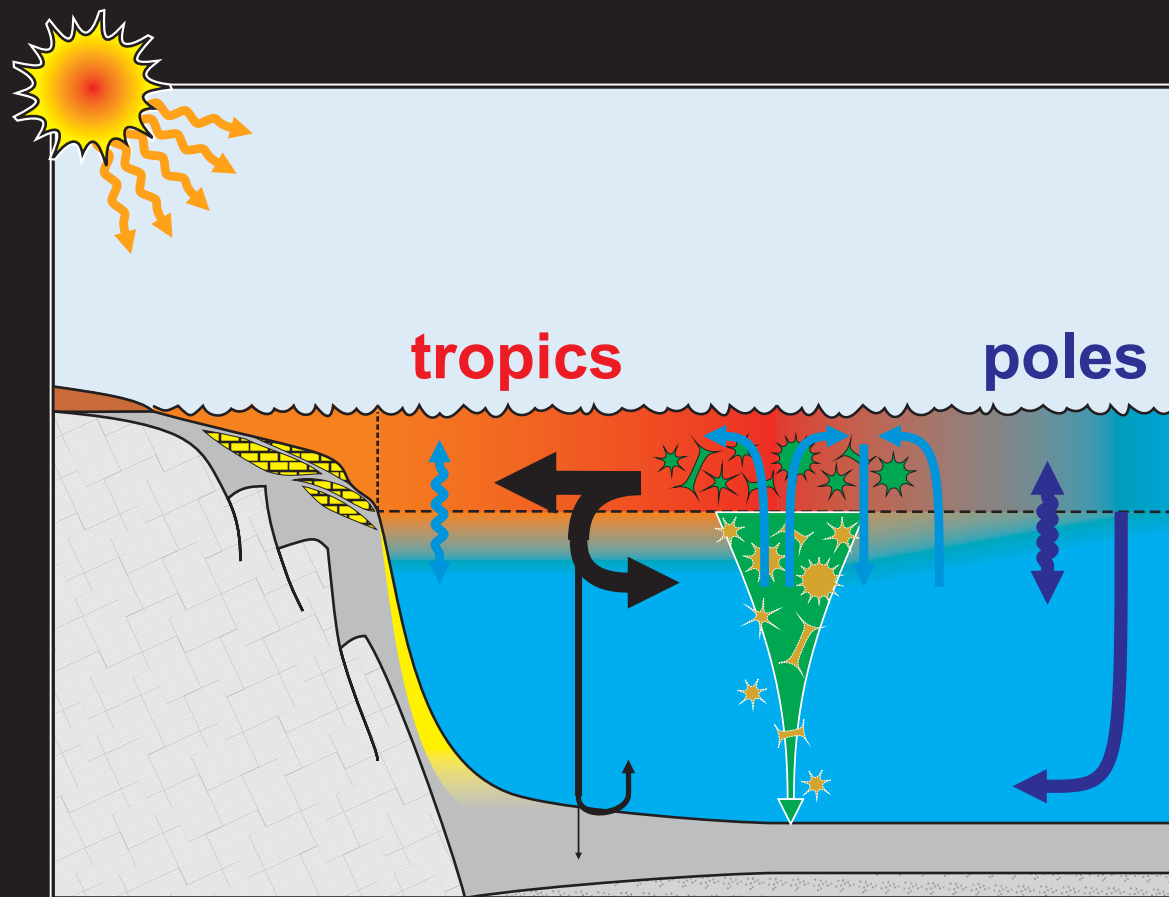
???

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



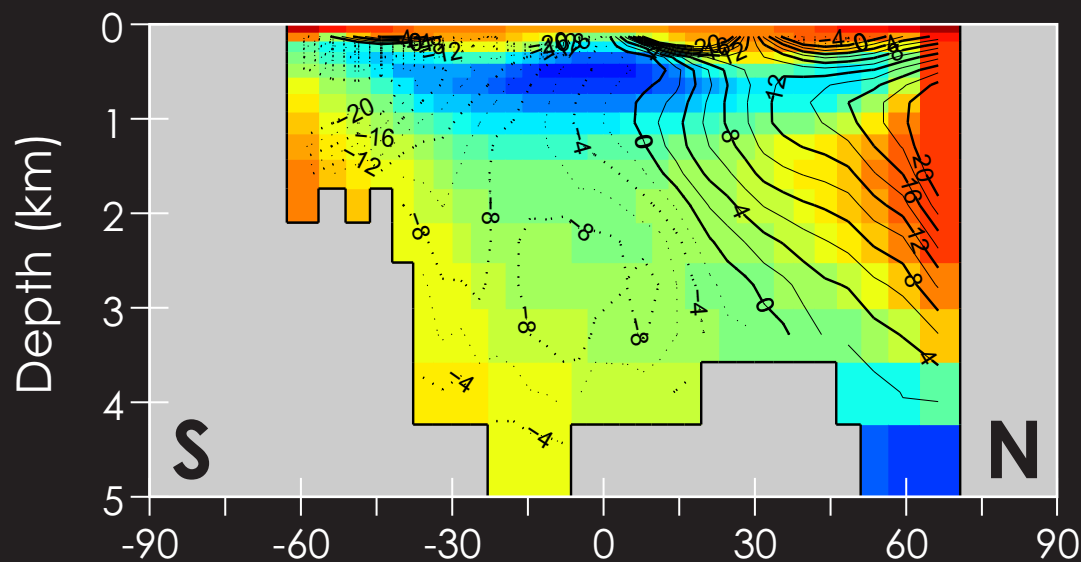
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates

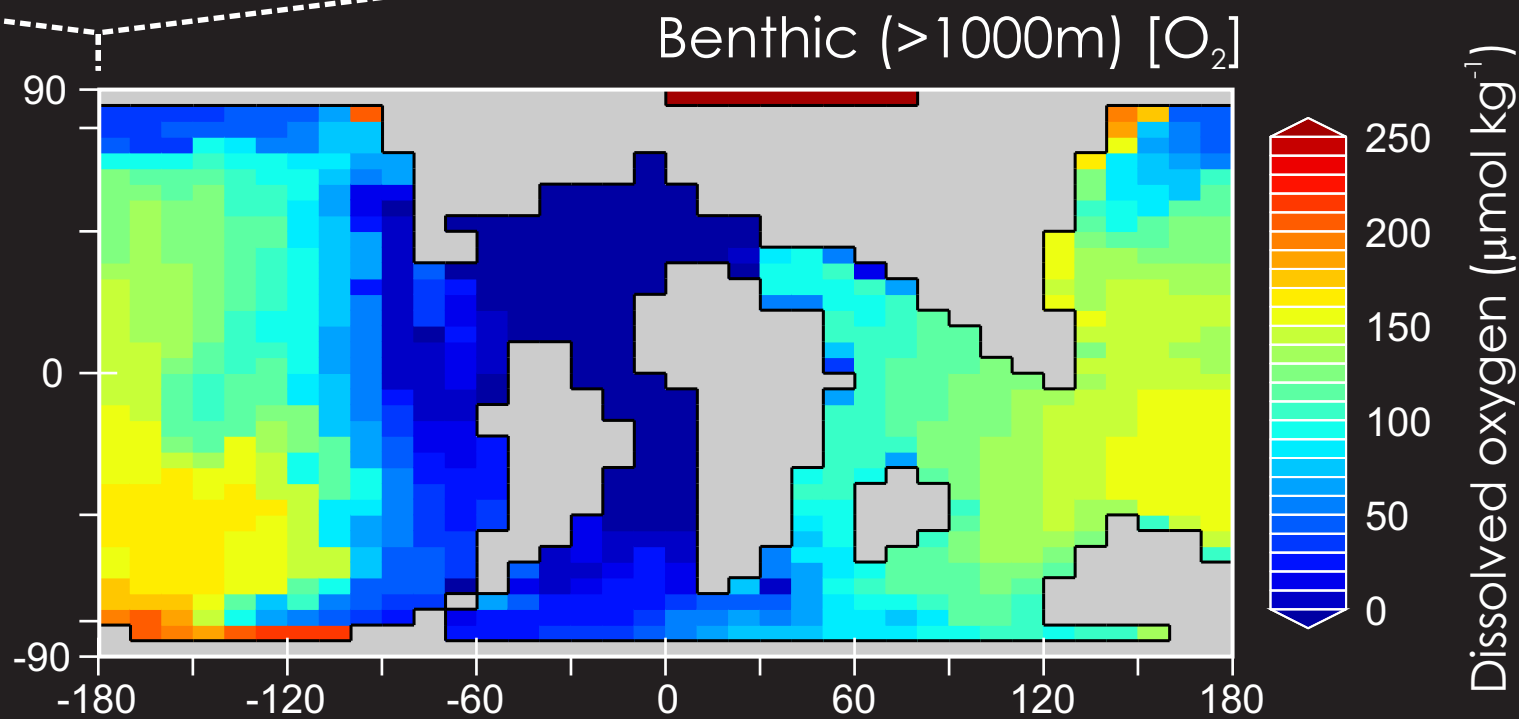


Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates

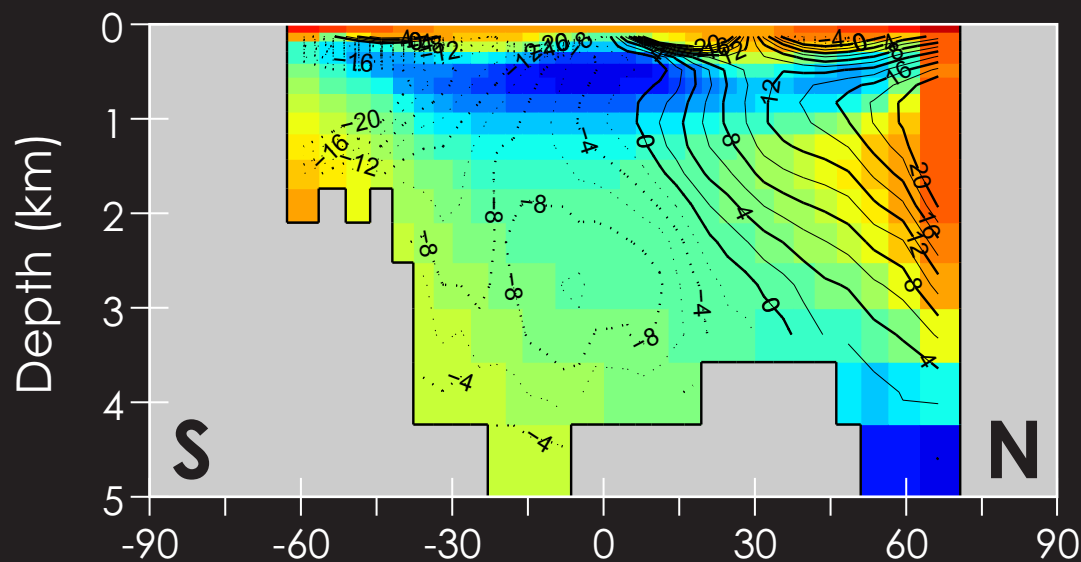


x4 CO₂ reference simulation



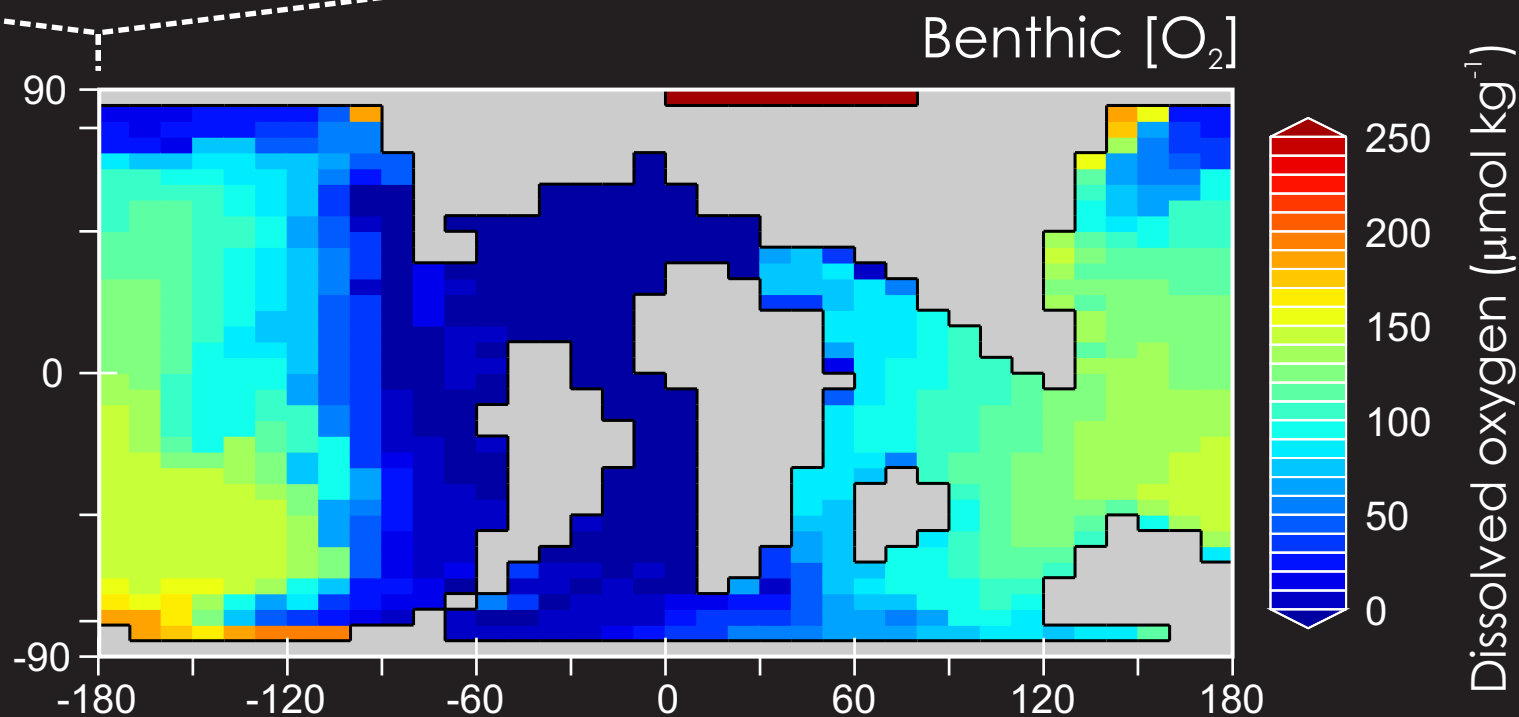
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



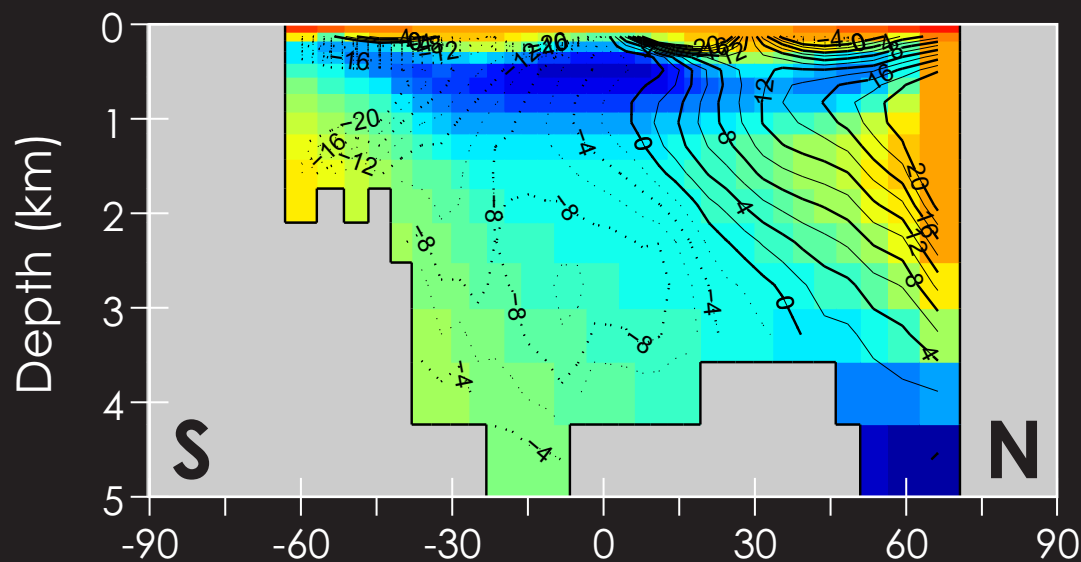
x8 CO₂ @ 10,000 yrs

(started from end of the x4 simulation)



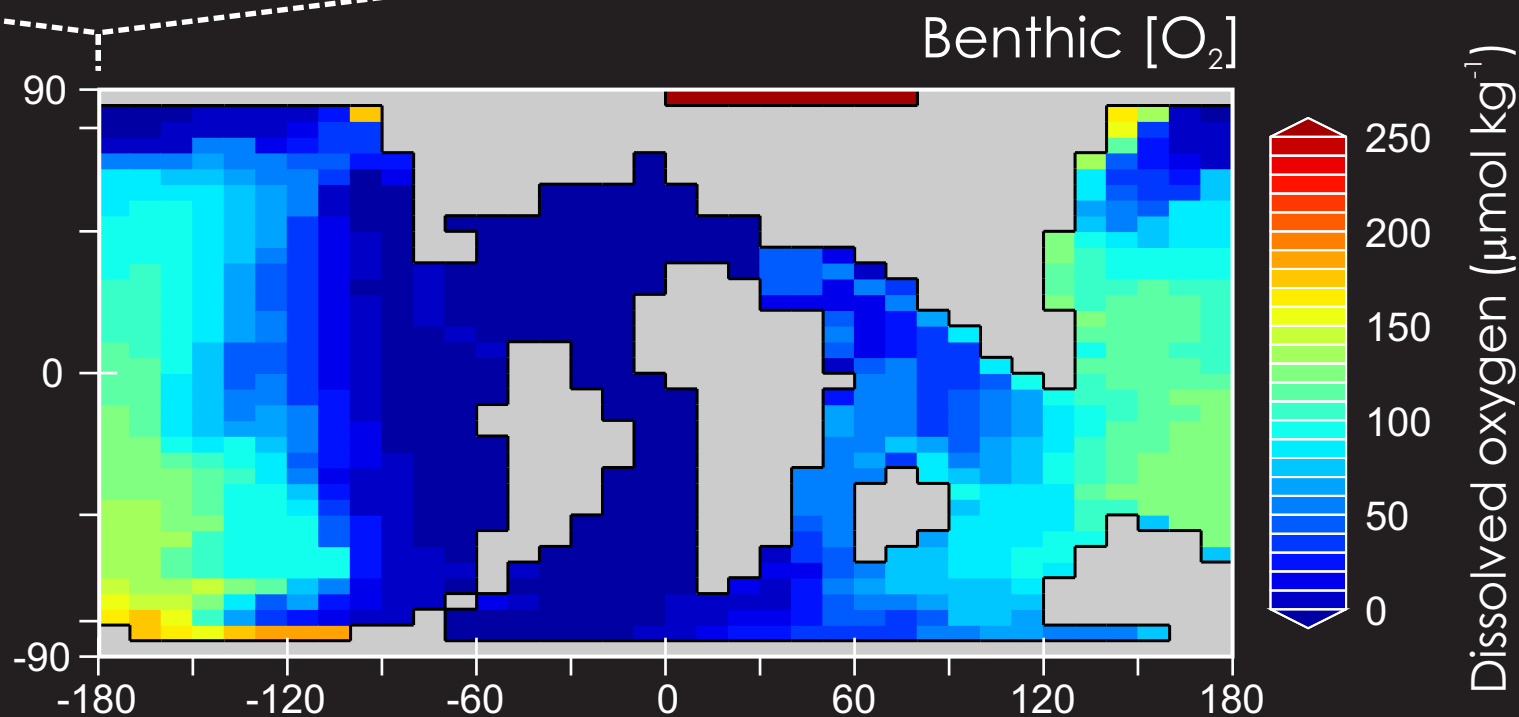
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



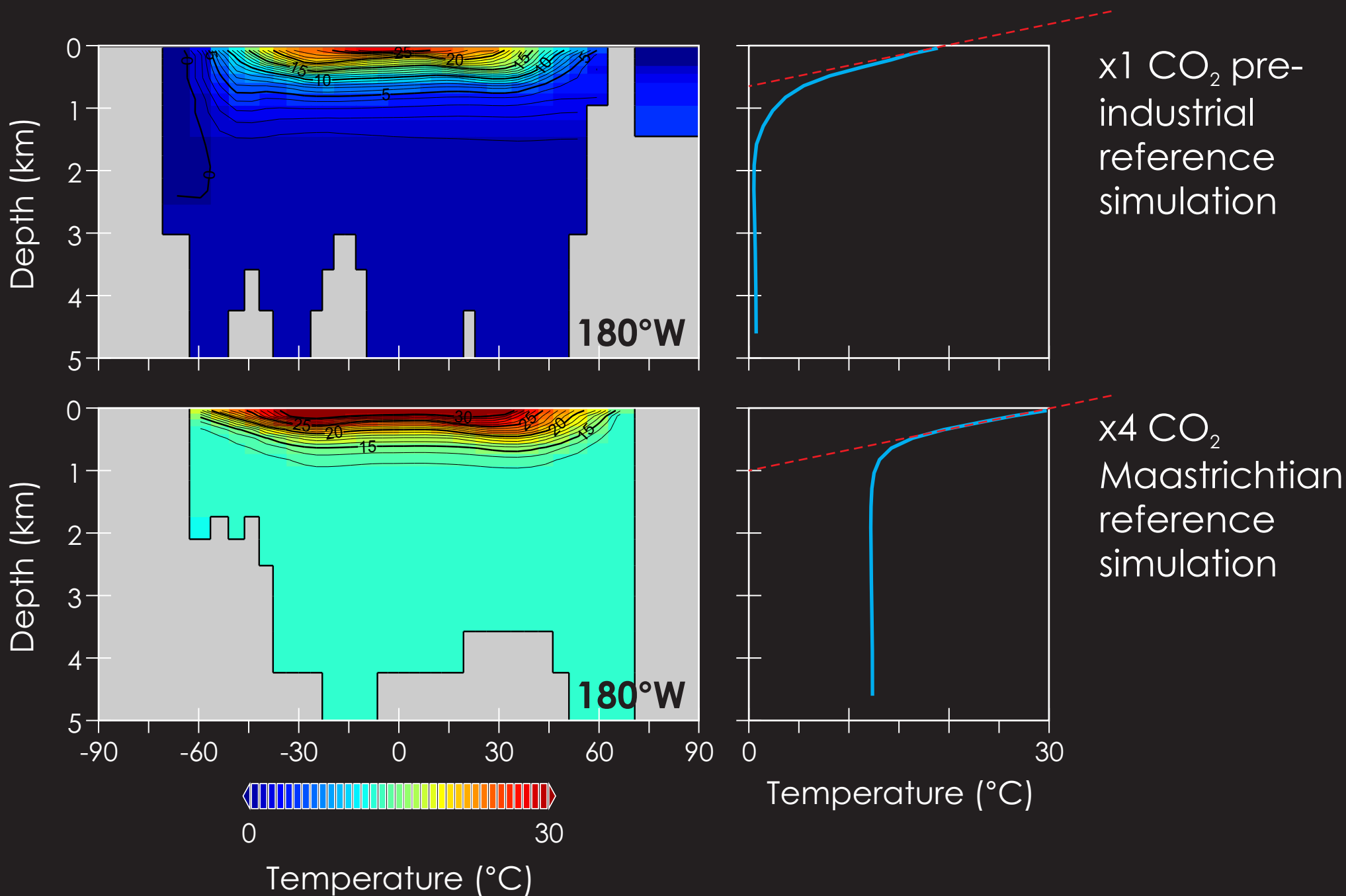
x16 CO₂ @ 10,000 yrs

(started from end of the x4 simulation)



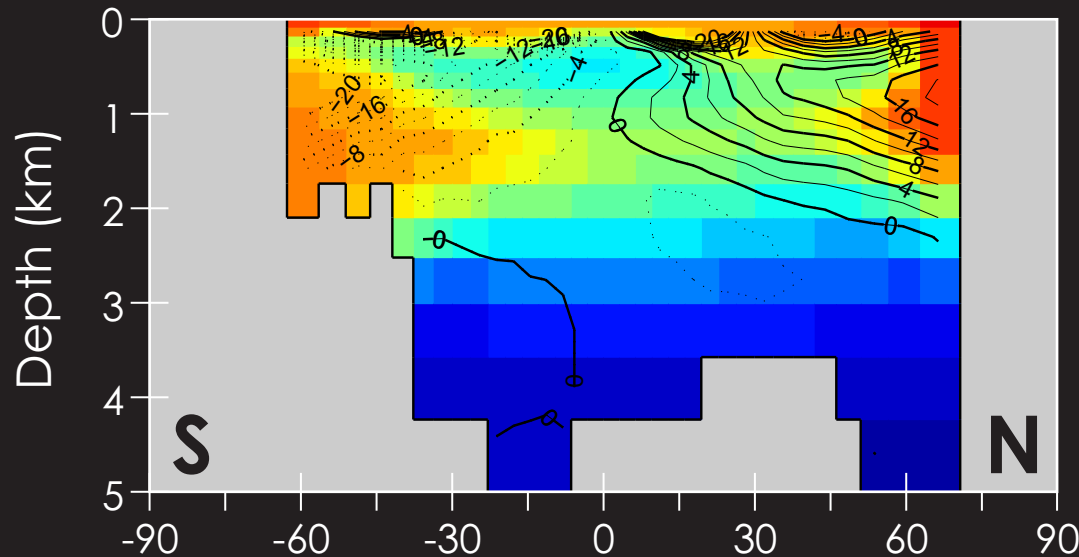
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



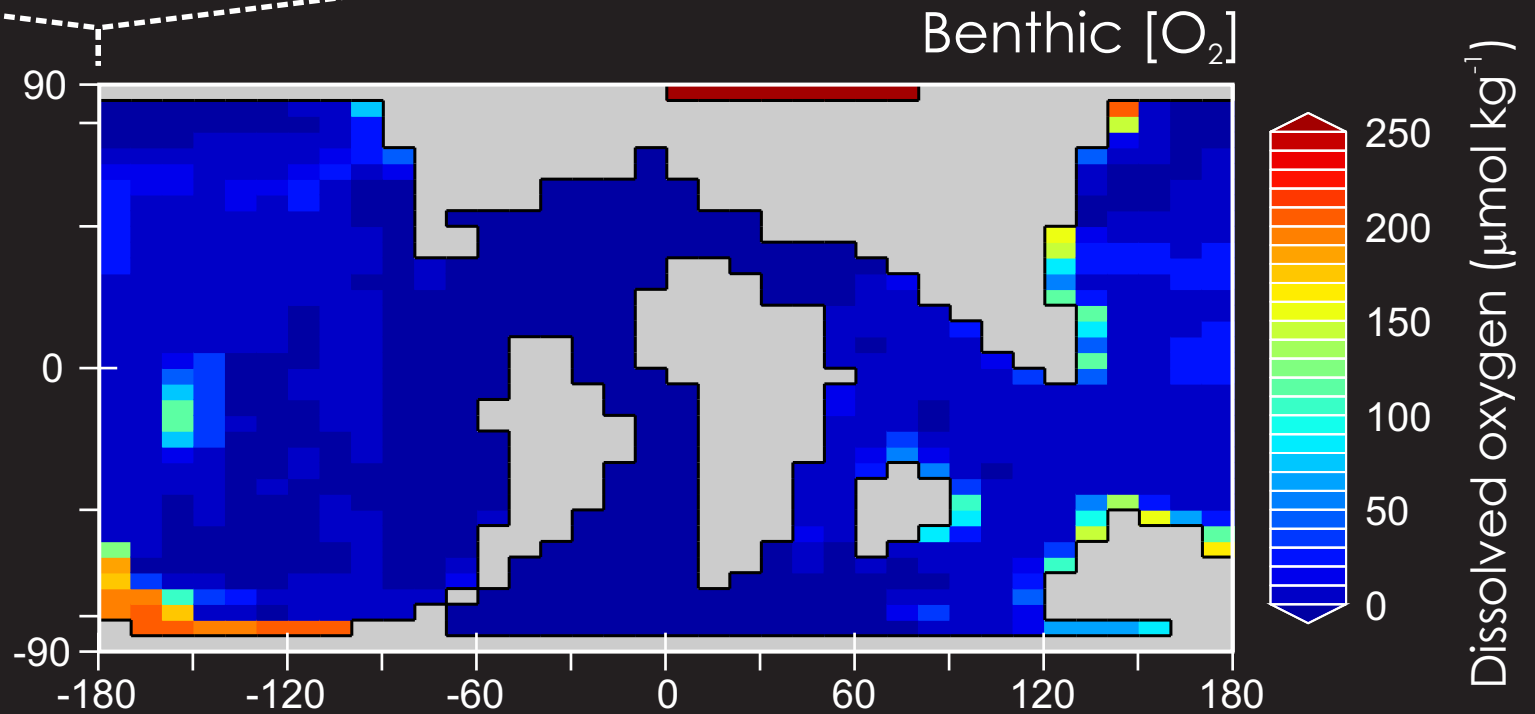
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



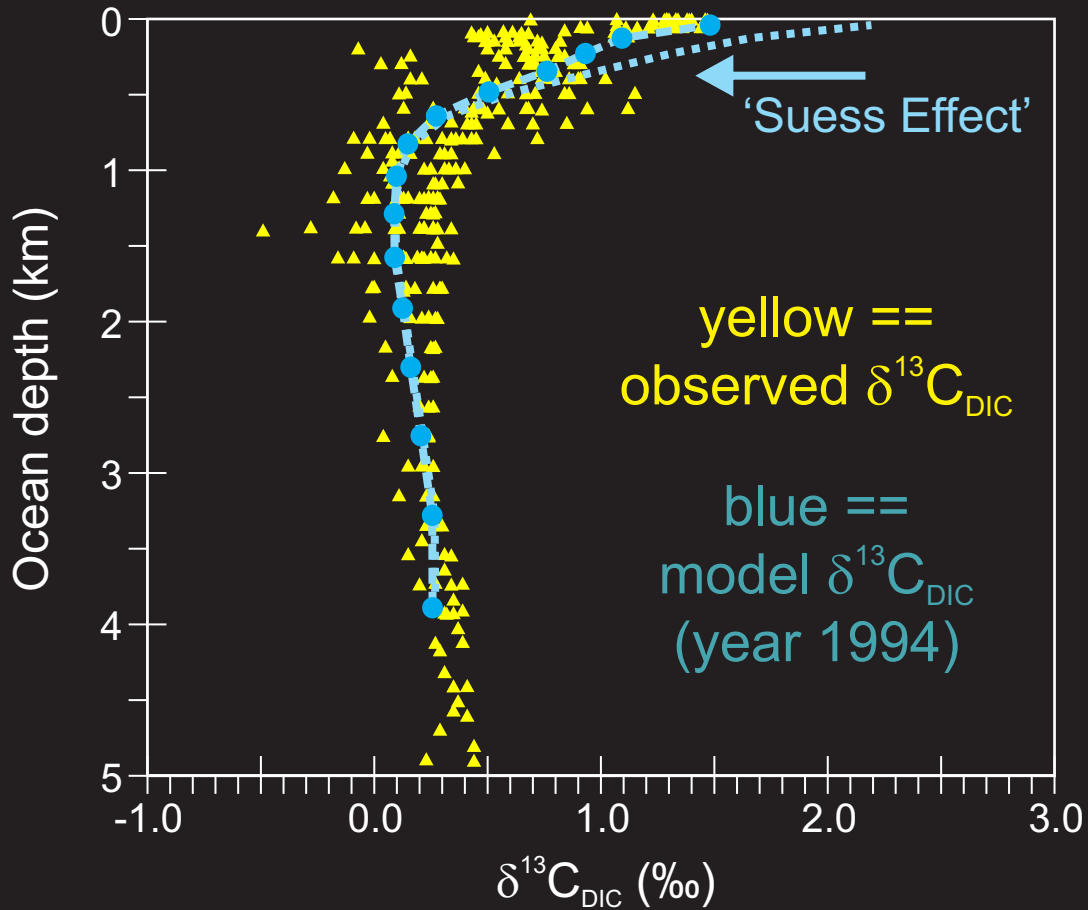
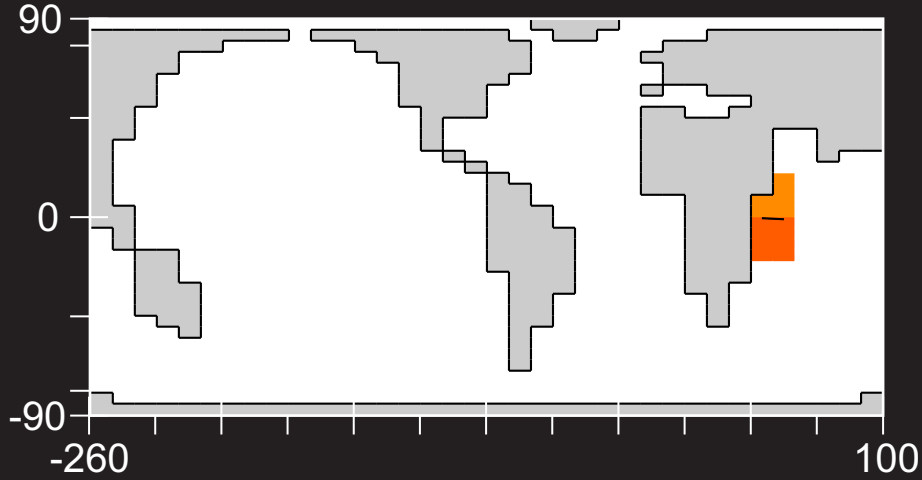
x16 CO₂ @ 2,000 yrs

transient state
(incomplete adjustment to
increased radiative forcing)

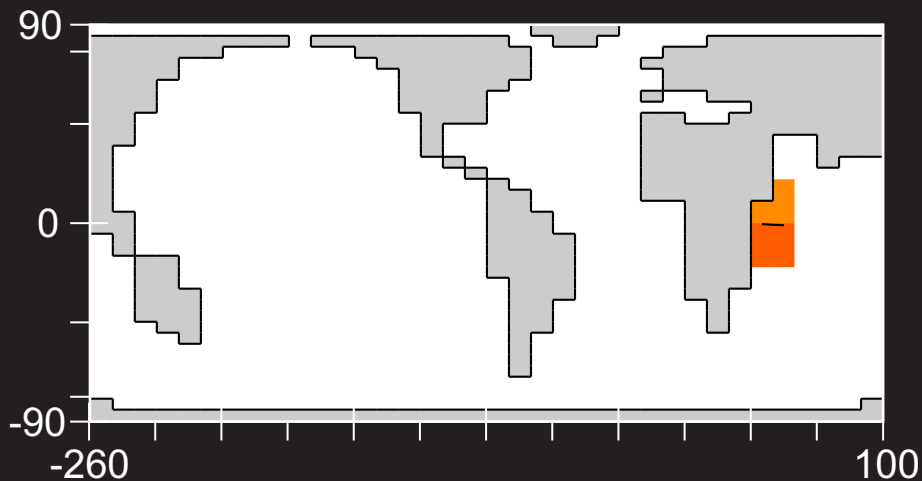




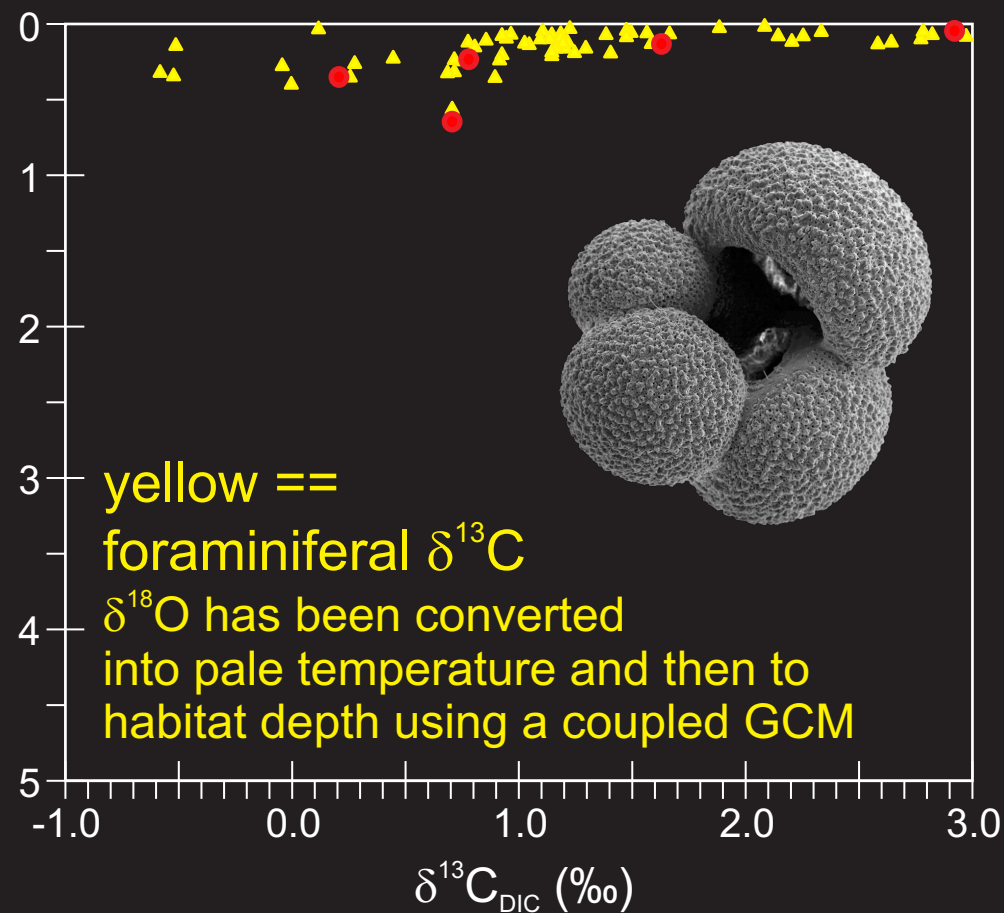
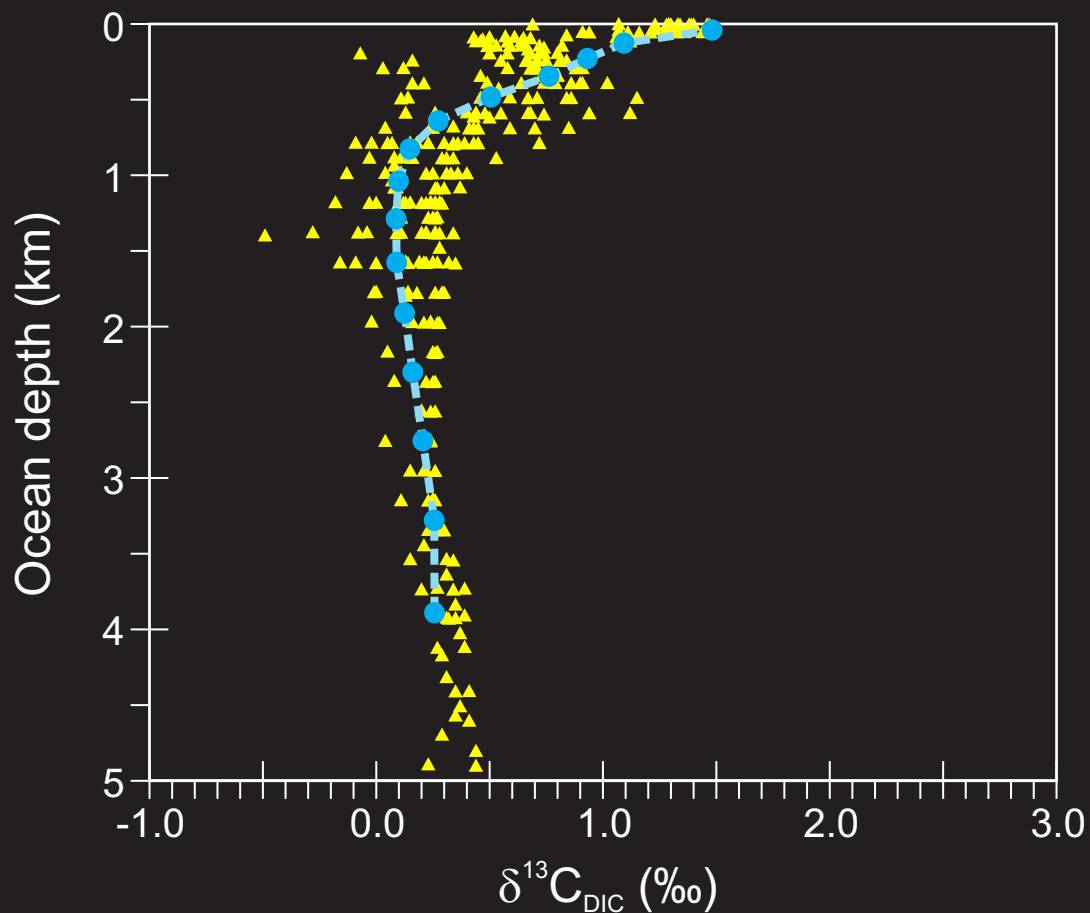
Open ocean $\delta^{13}\text{C}_{\text{DIC}}$ adjacent to modern Tanzania



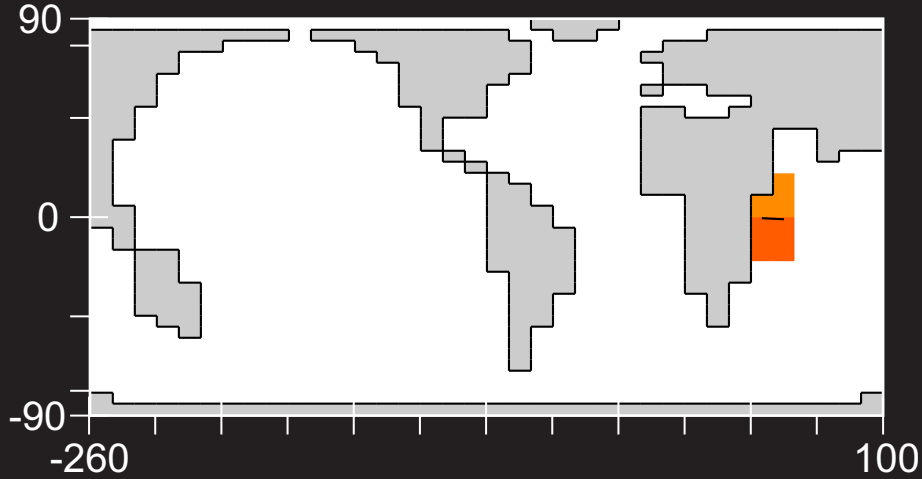
Open ocean $\delta^{13}\text{C}_{\text{DIC}}$ adjacent to modern Tanzania



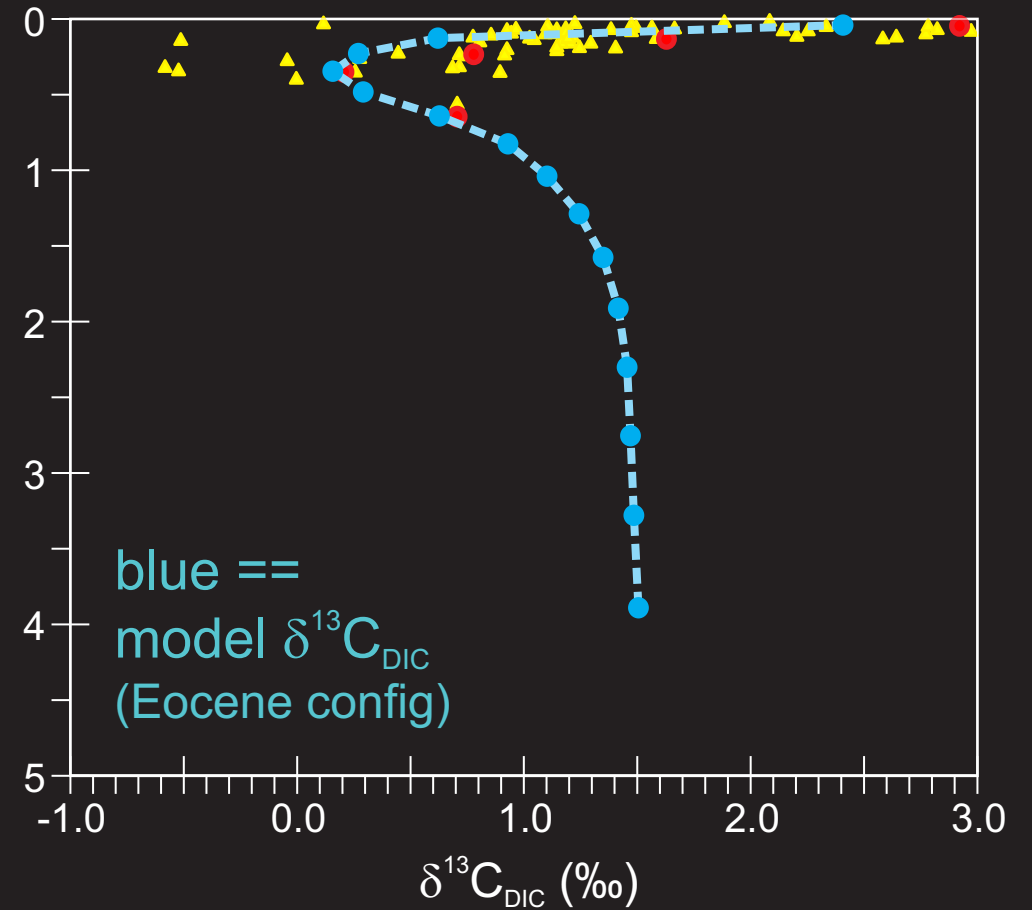
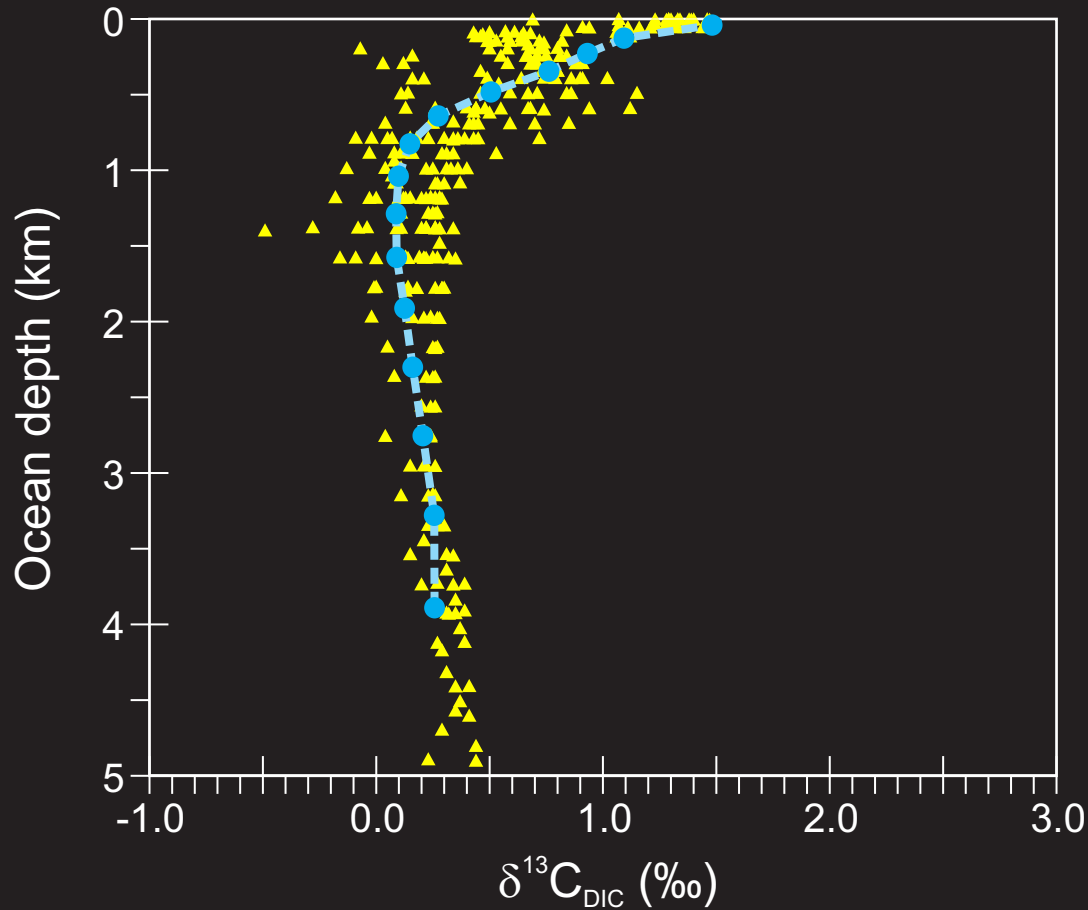
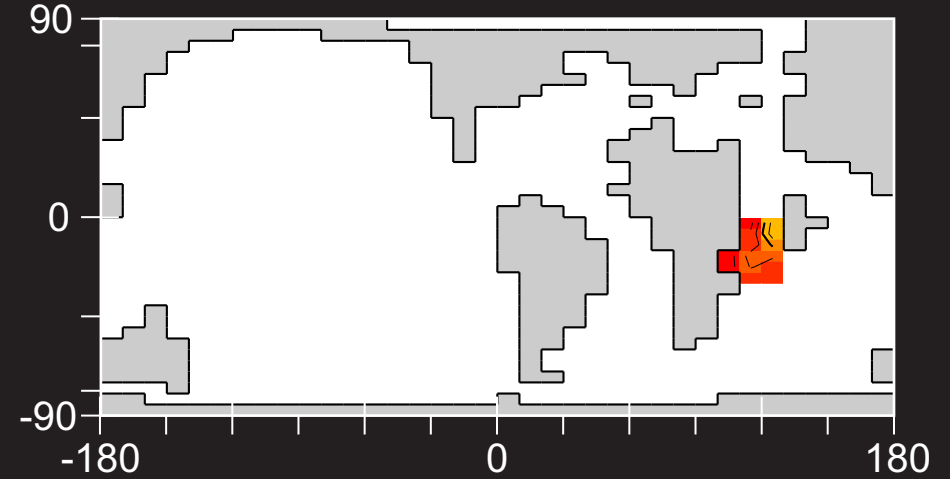
Planktic foraminiferal $\delta^{13}\text{C}$ from early Eocene Tanzania



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

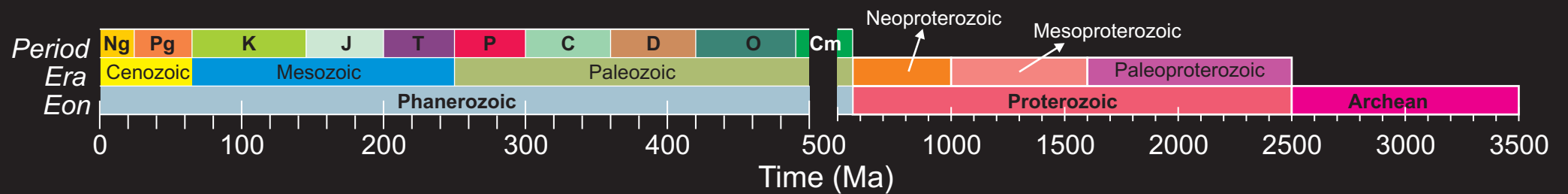


Planktic foraminiferal $\delta^{13}\text{C}$ from early Eocene Tanzania

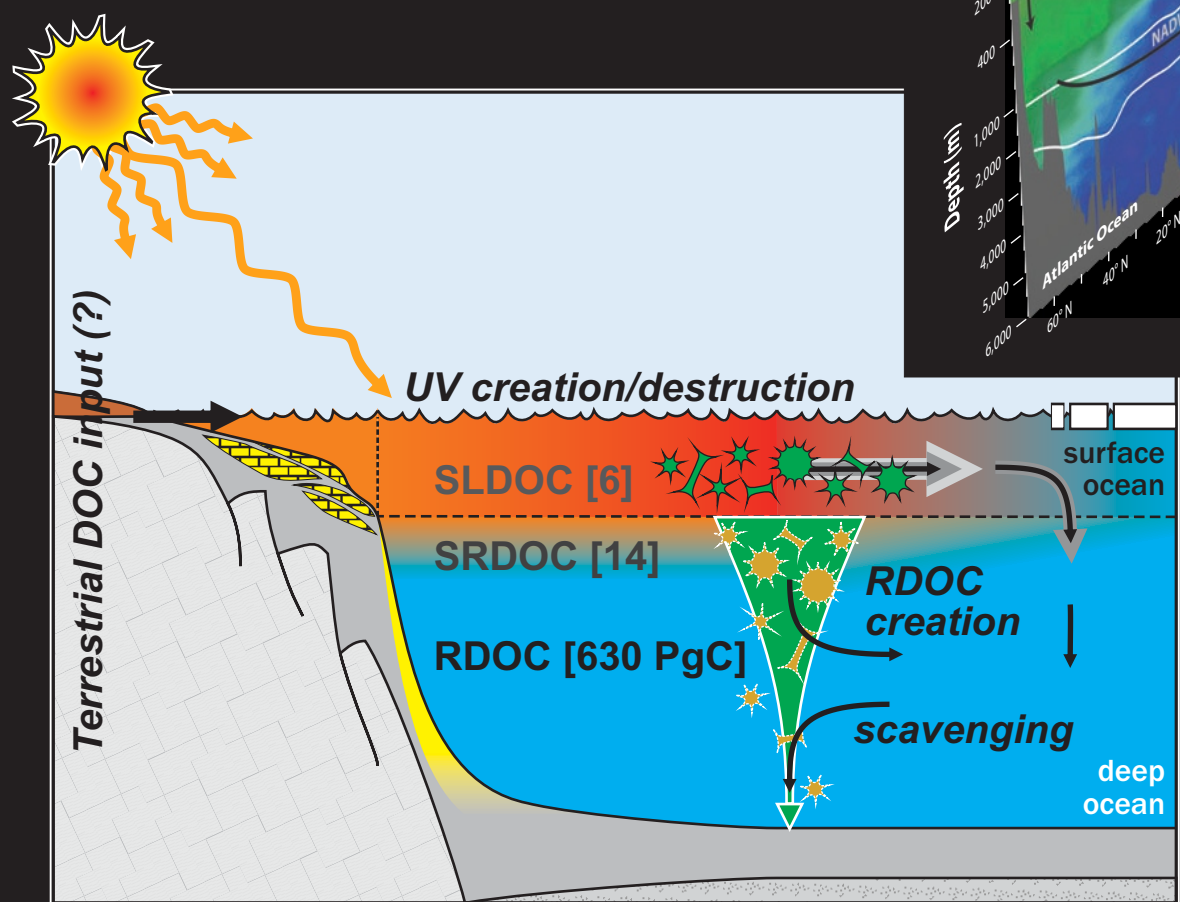
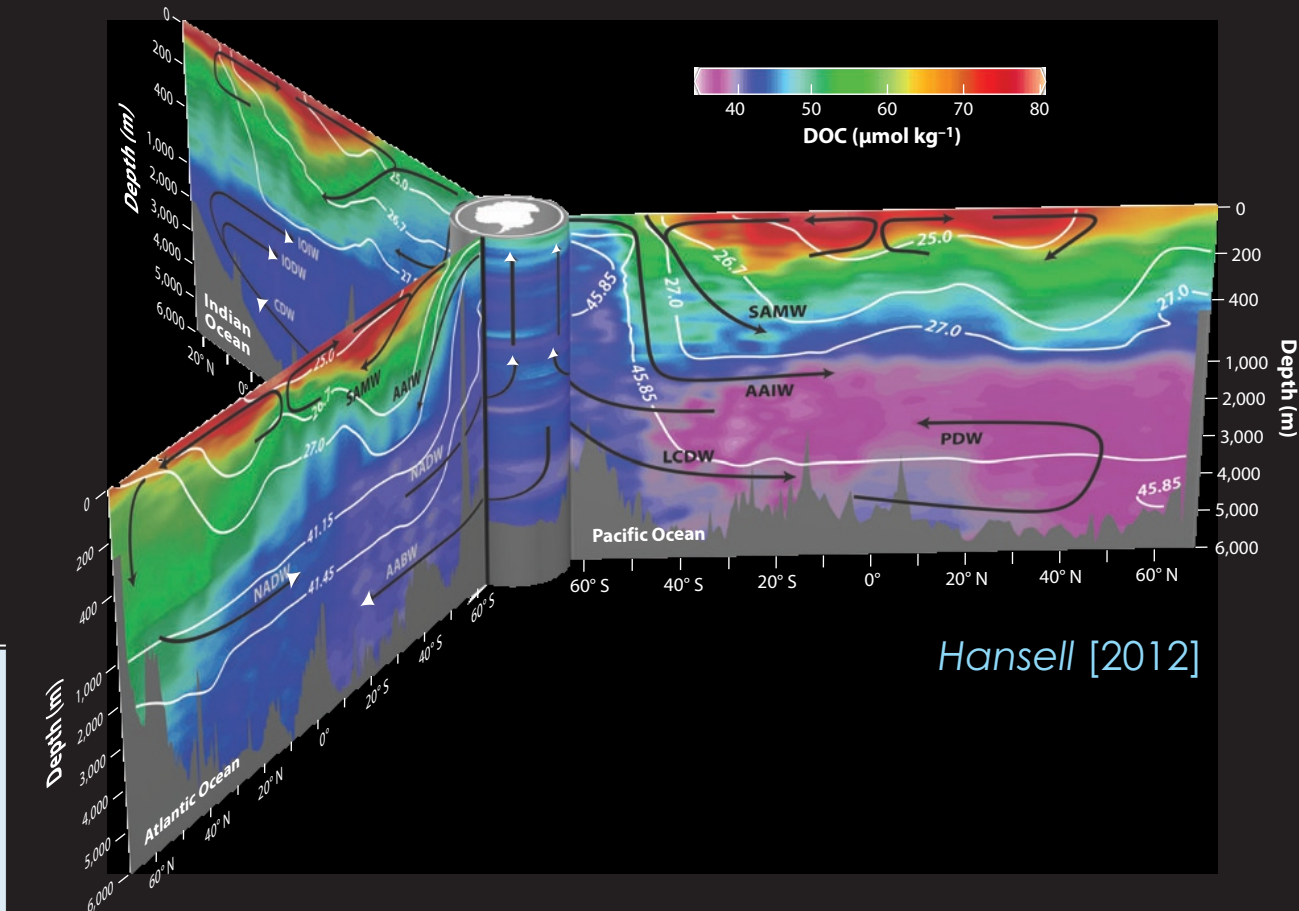


Evolution of the Biological Pump:

Dissolved organic matter

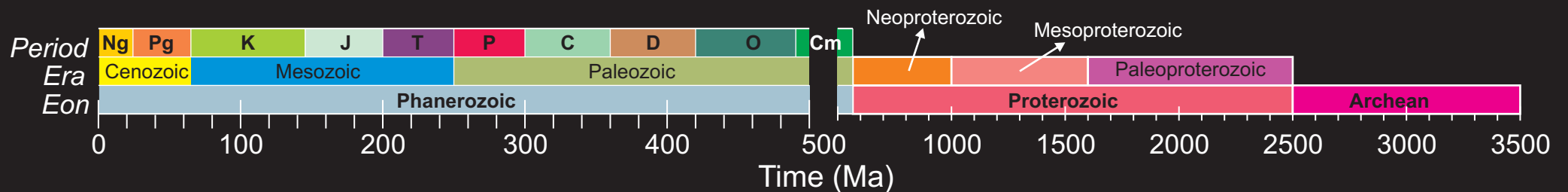
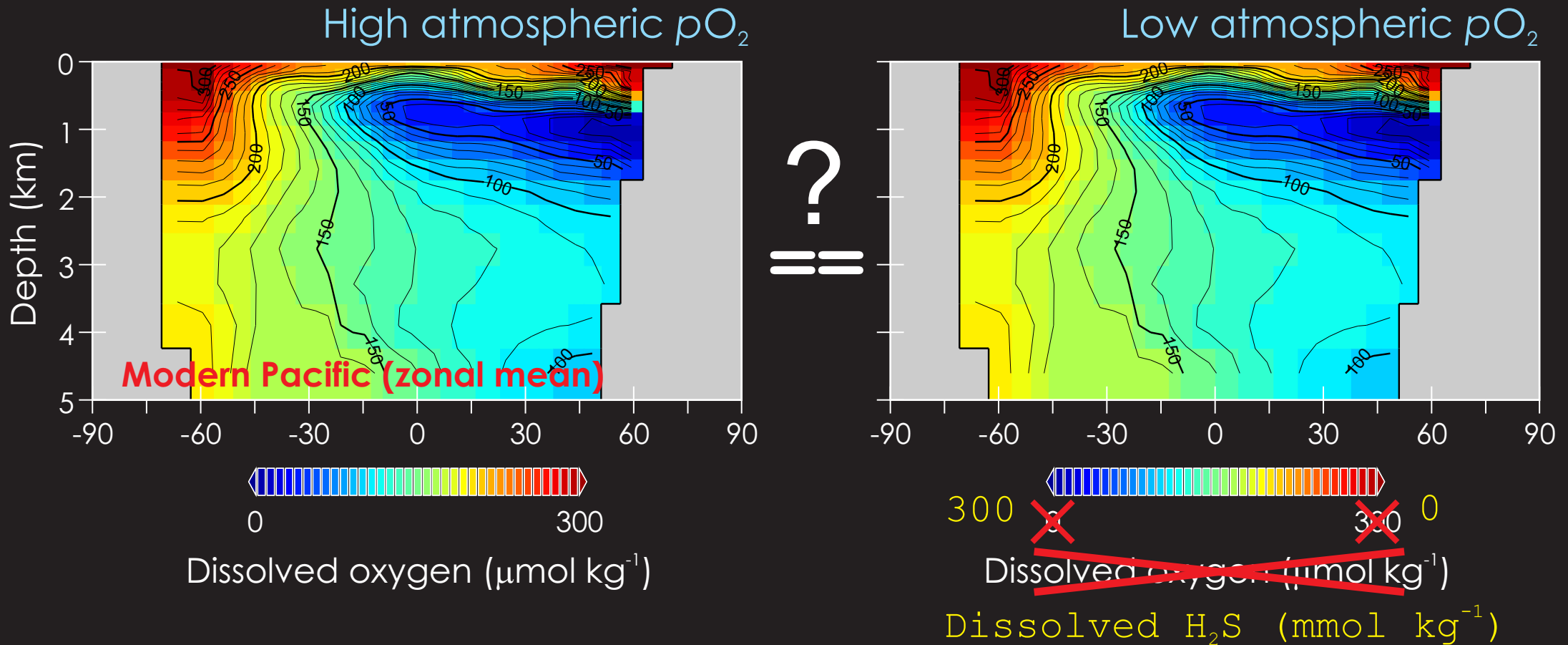


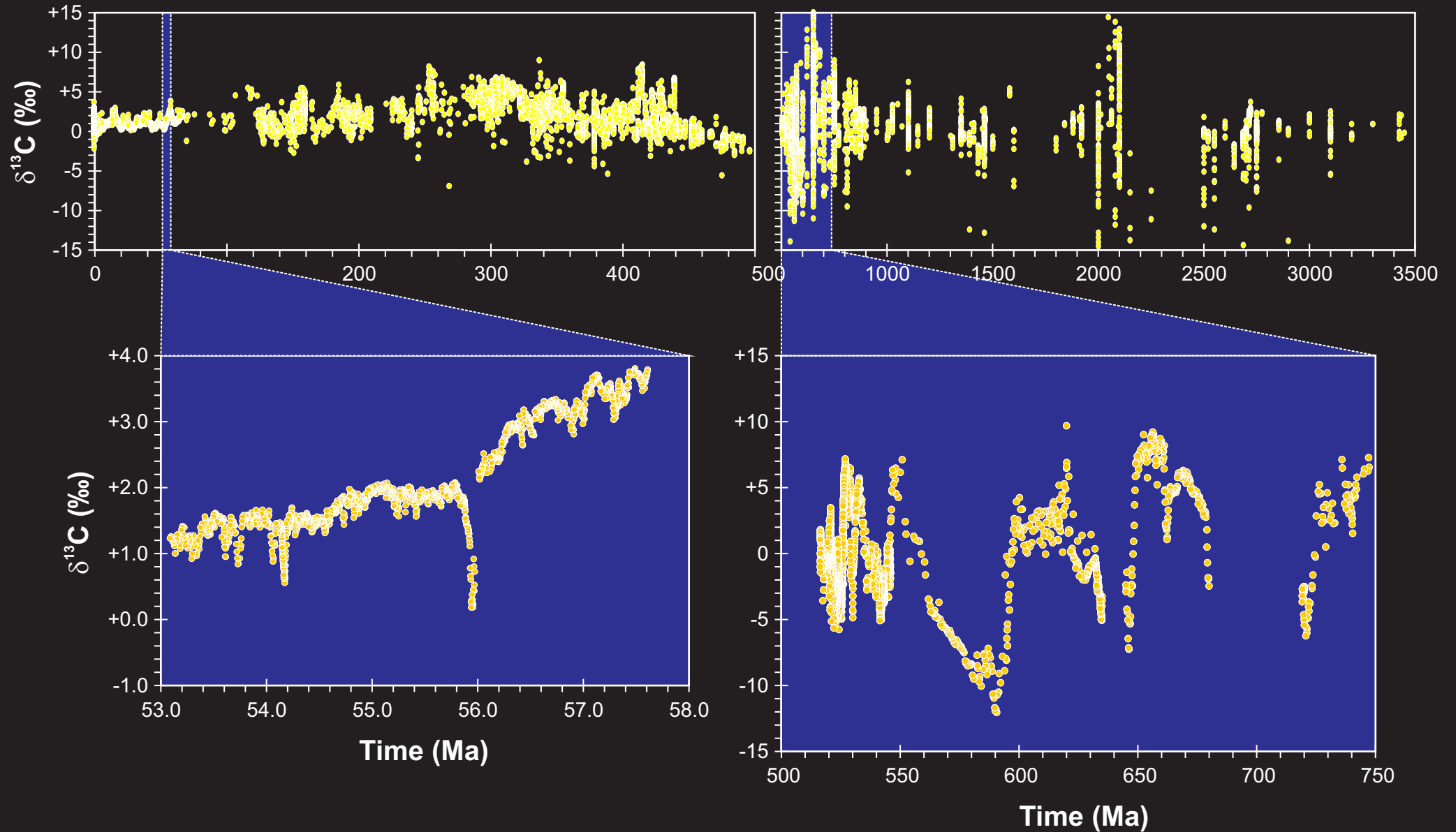
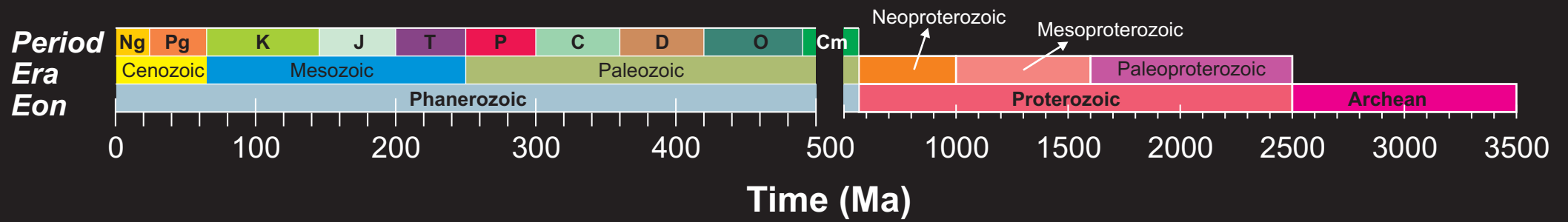
Evolution of the Biological Pump: Dissolved organic matter



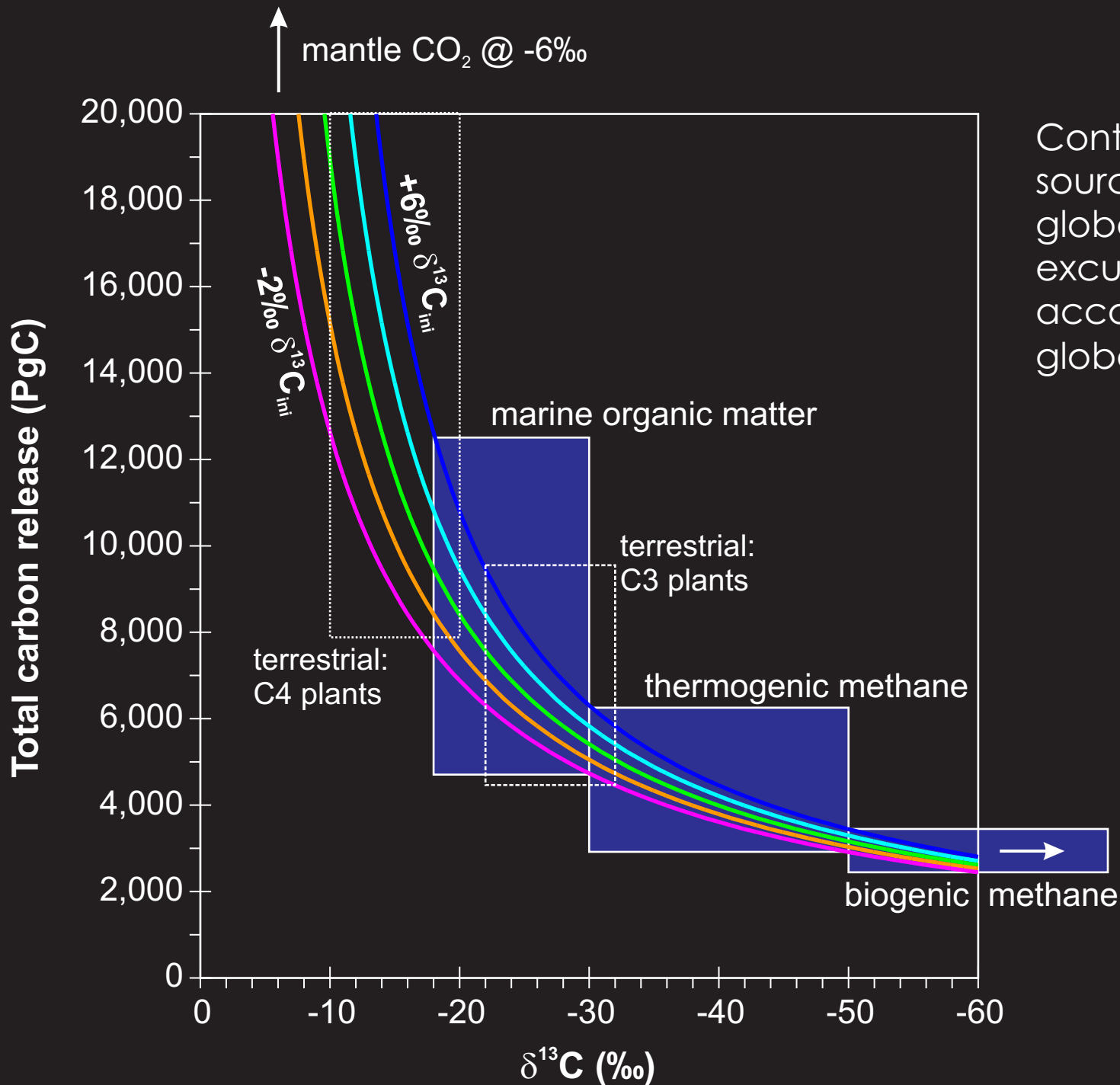
Evolution of the Biological Pump:

Dissolved organic matter



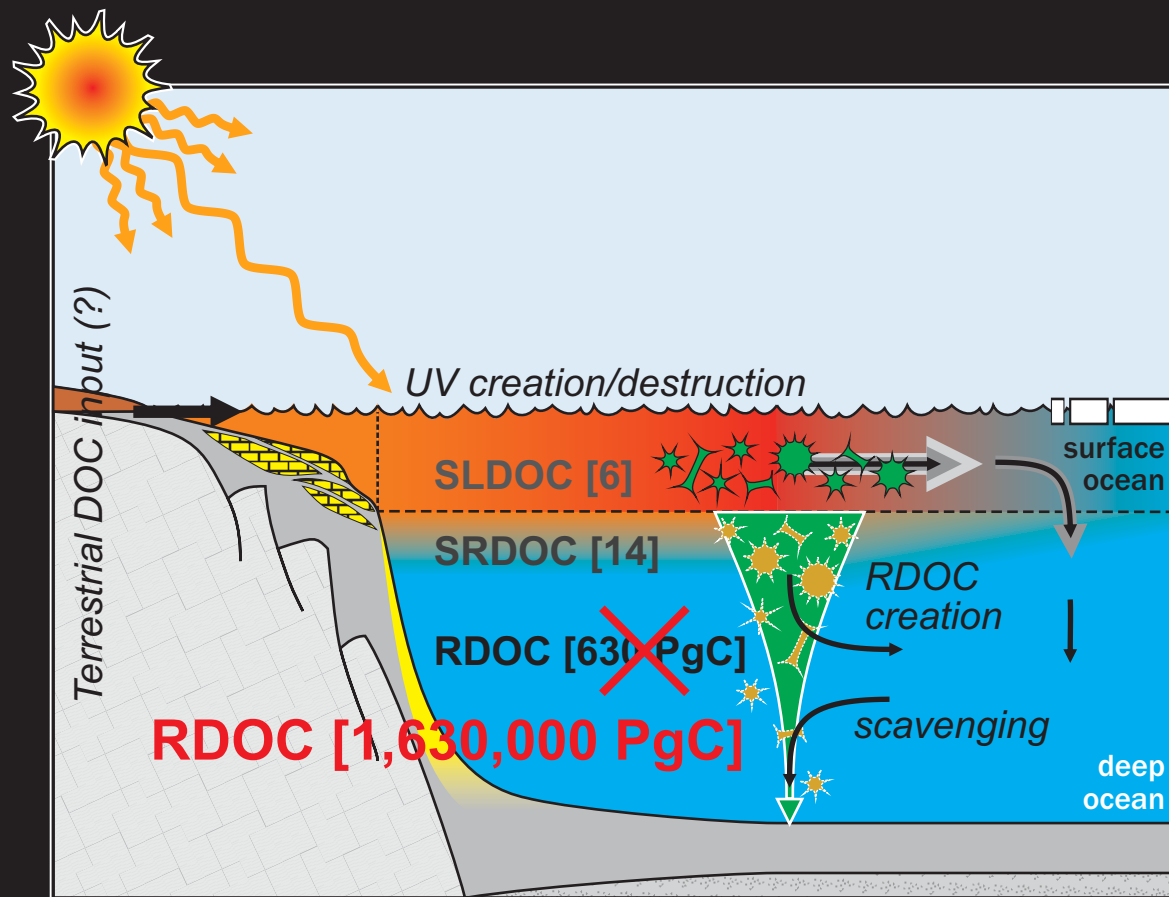
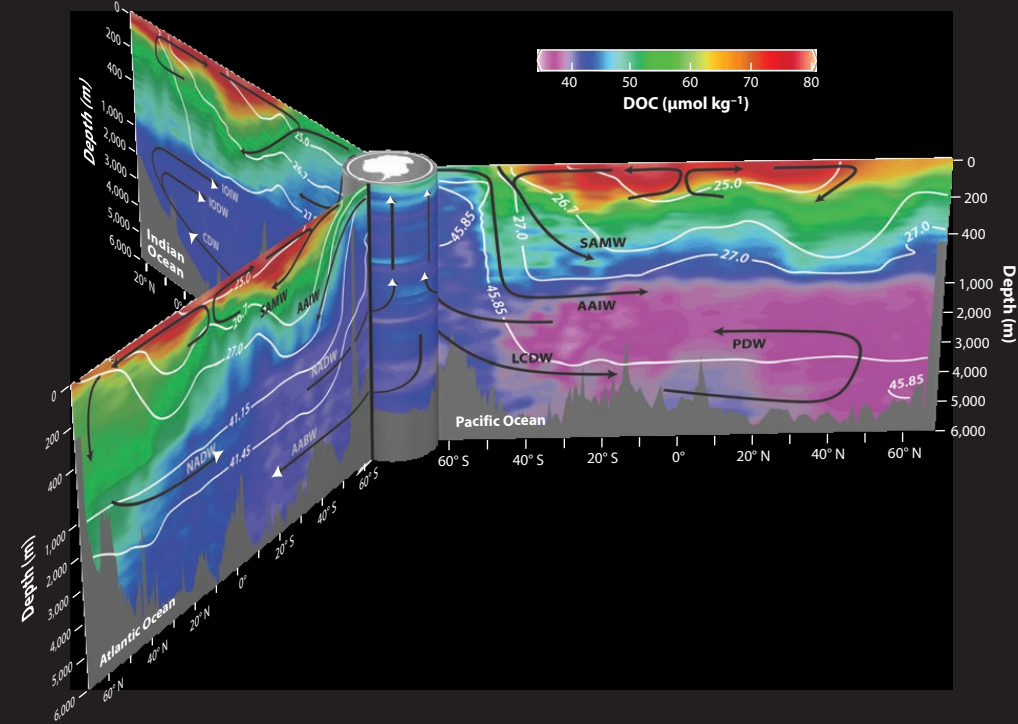


A DOC-dominated carbon cycle?

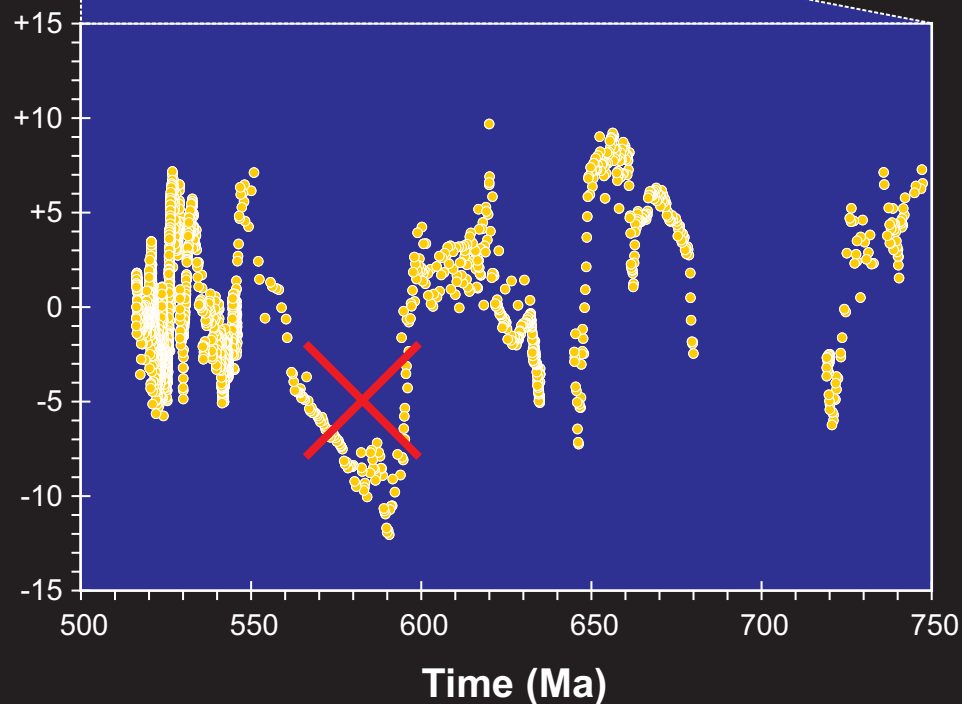
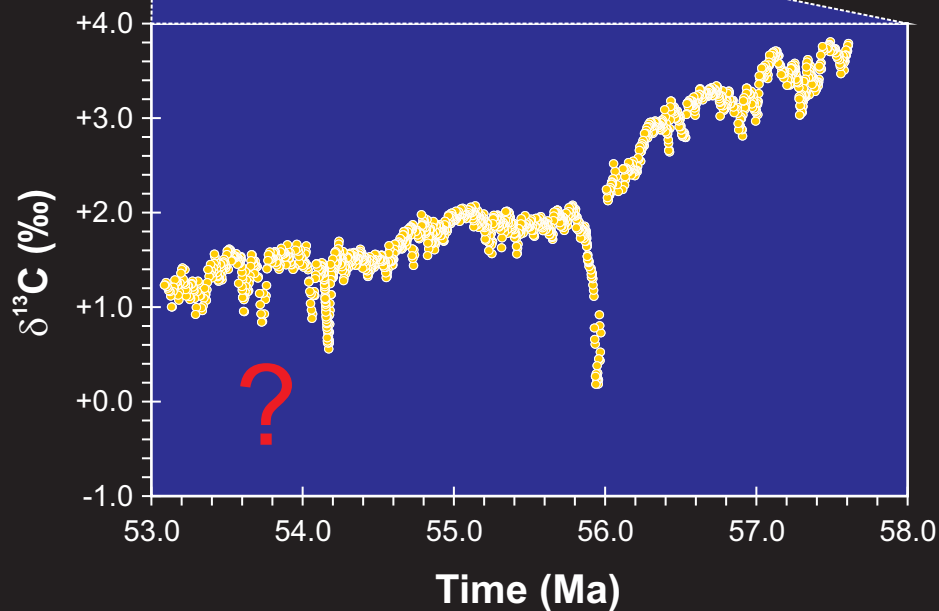
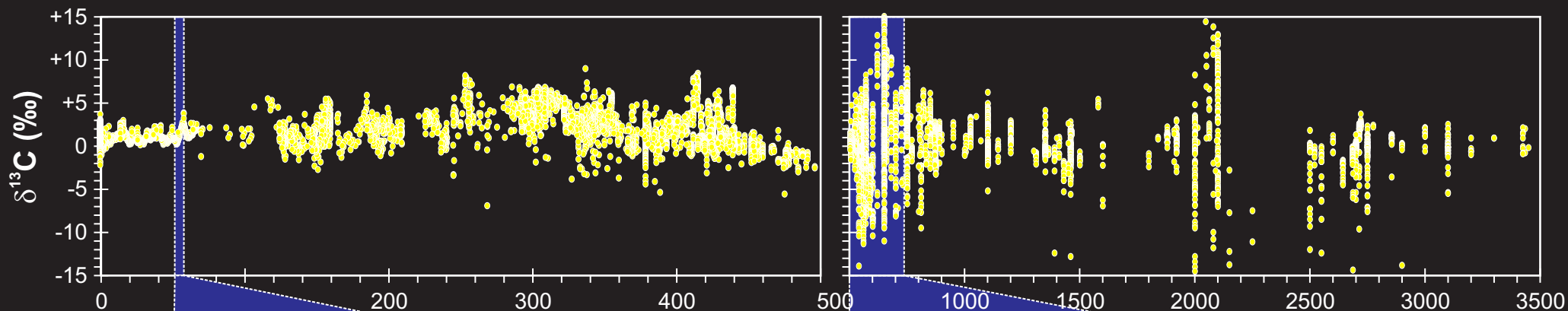
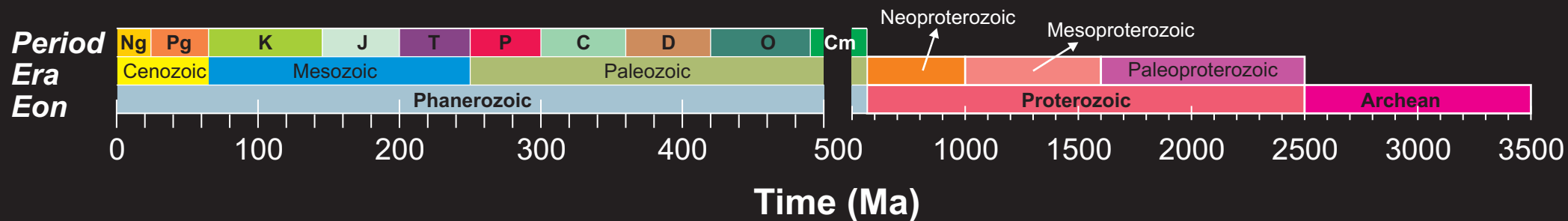


Contours of carbon release vs. source isotopic signature for a global -4‰ carbon isotopic excursion. Contours differ according to the initial mean global $\delta^{13}\text{C}$.

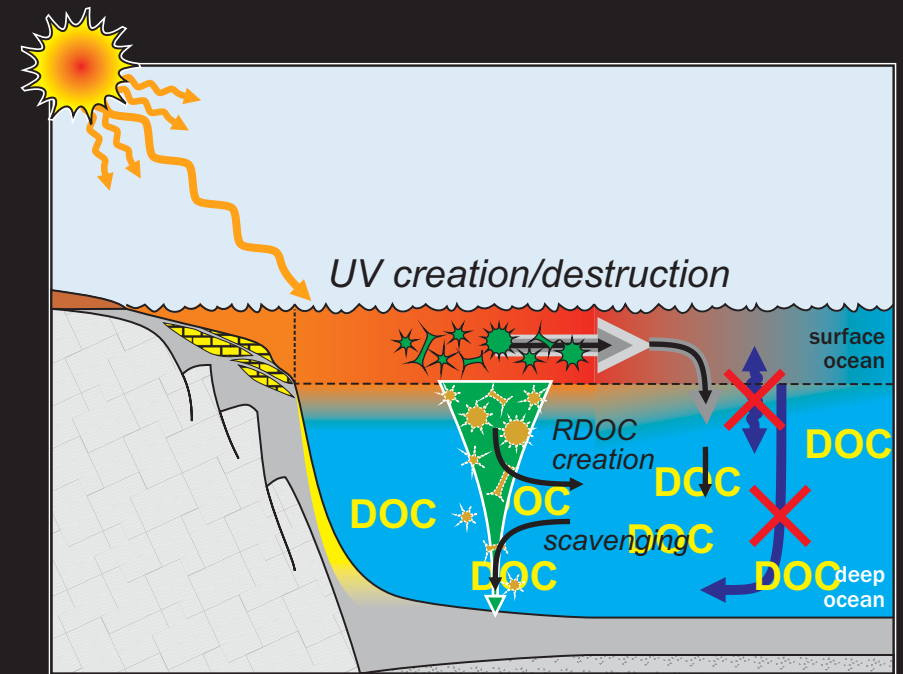
A DOC-dominated carbon cycle?



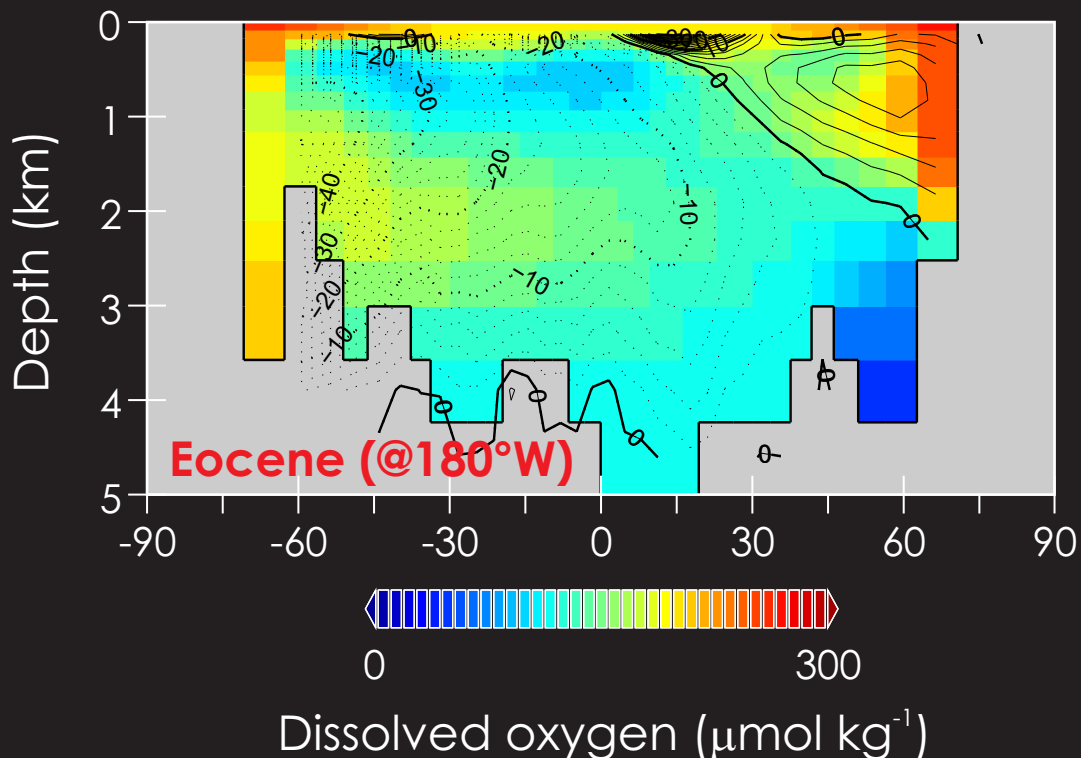
In the Rothman *et al.* [2003] model, the RDOC reservoir is assumed to have been at least 10 times the size of the inorganic (ocean DIC + atmospheric pCO_2) reservoir. For a modern DIC + pCO_2 reservoir of 39,000 PgC, this mean 390,000 PgC of DOC – more than 500 times larger than modern). For a higher late Precambrian DIC reservoir, the minimum DOC reservoir becomes 1.6×10^6 PgC, equivalent to concentration of a little over 1000 mgC per L of seawater and becoming the third most dominant dissolved species in the ocean after Cl^- .



A DOC-dominated carbon cycle?



Sexton et al. [2011]



In the Eocene hyperthermal RDOC hypothesis, difficulties include envisioning a sufficiently stratified deep ocean (even when ignoring the lack of any evidence for widespread anoxia) that could partition RDOC away from the upper ocean and destruction by oxidation/photo-degradation.

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Ellen Thomas [Yale]

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