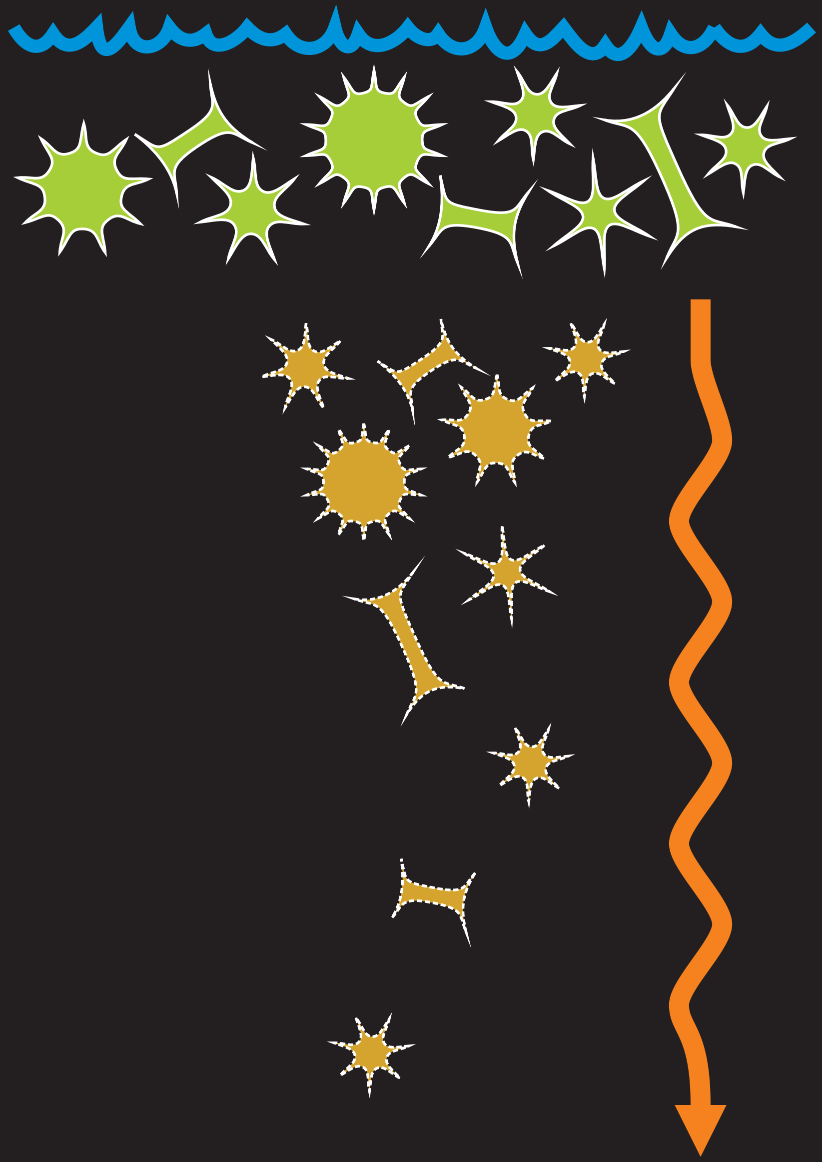
Evolution of the Ocean's Biological Pump

Andy Ridgwell

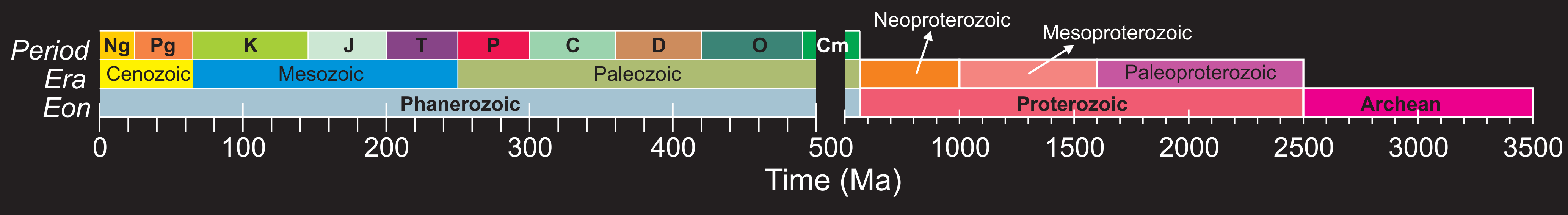


THE ROYAL SOCIETY
CELEBRATING 350 YEARS

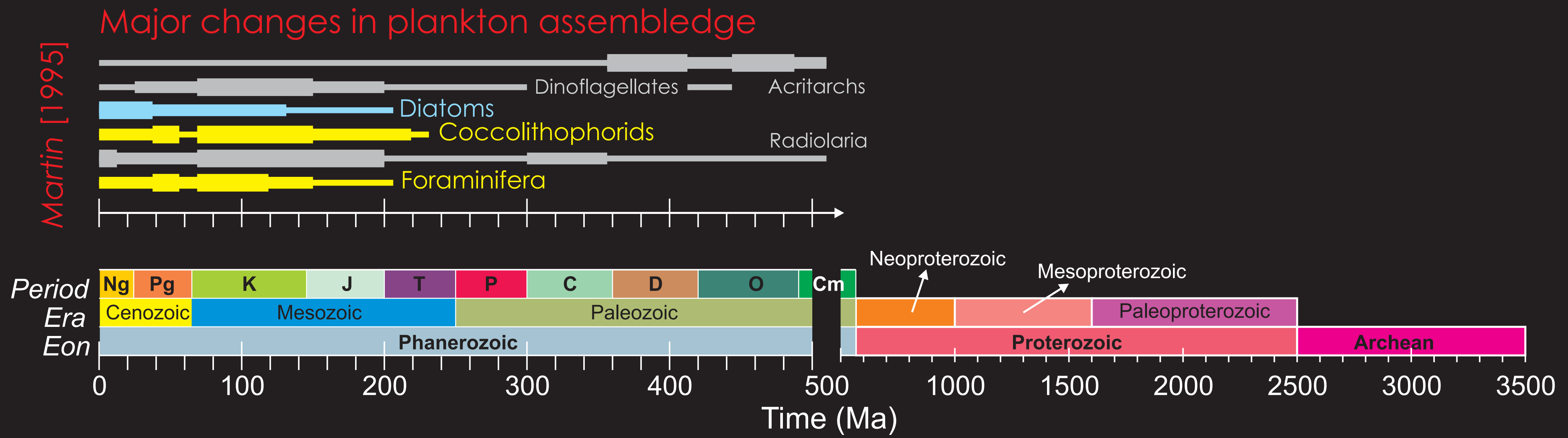
University of BRISTOL

BRIDGE

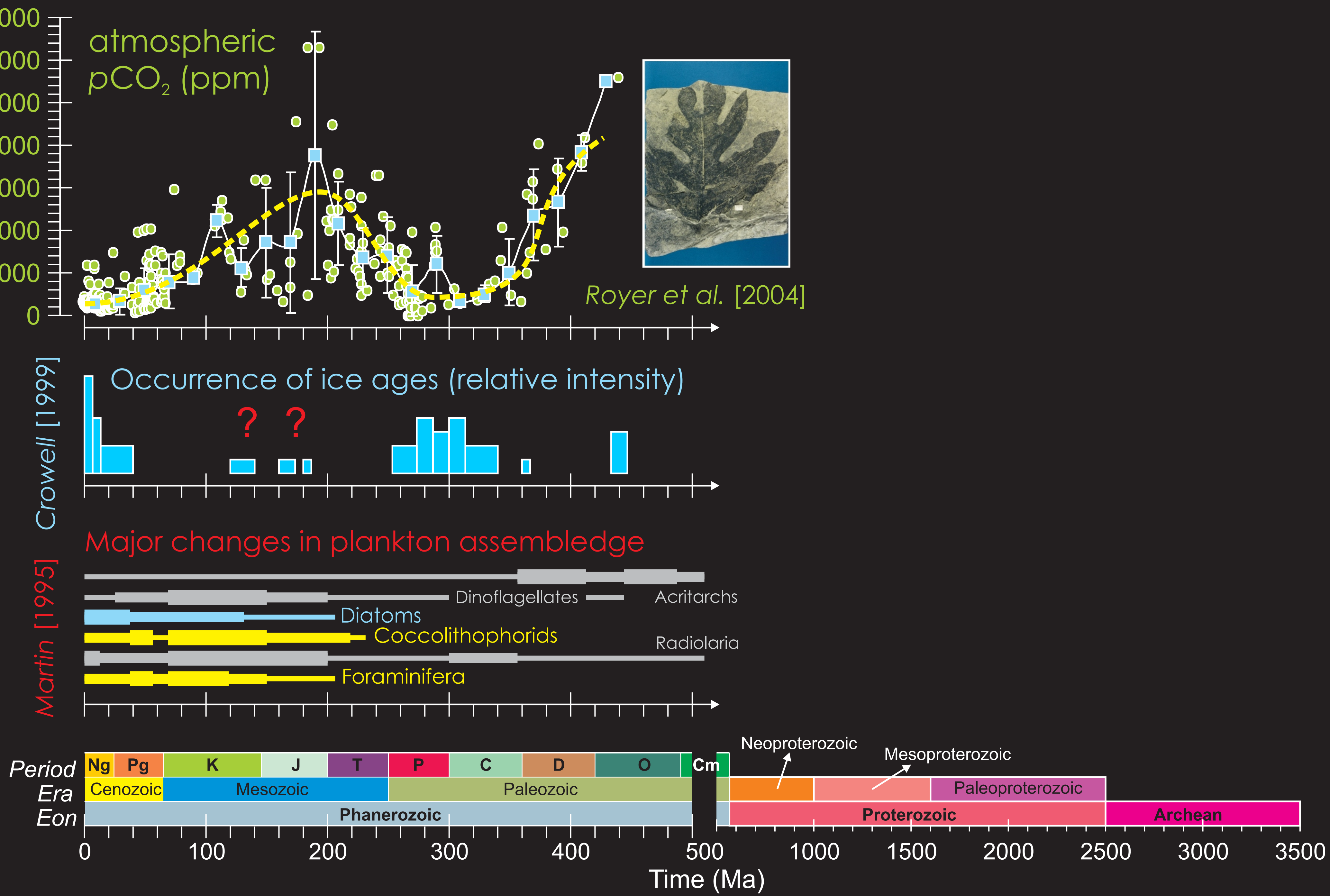
Evolution of the Biological Pump



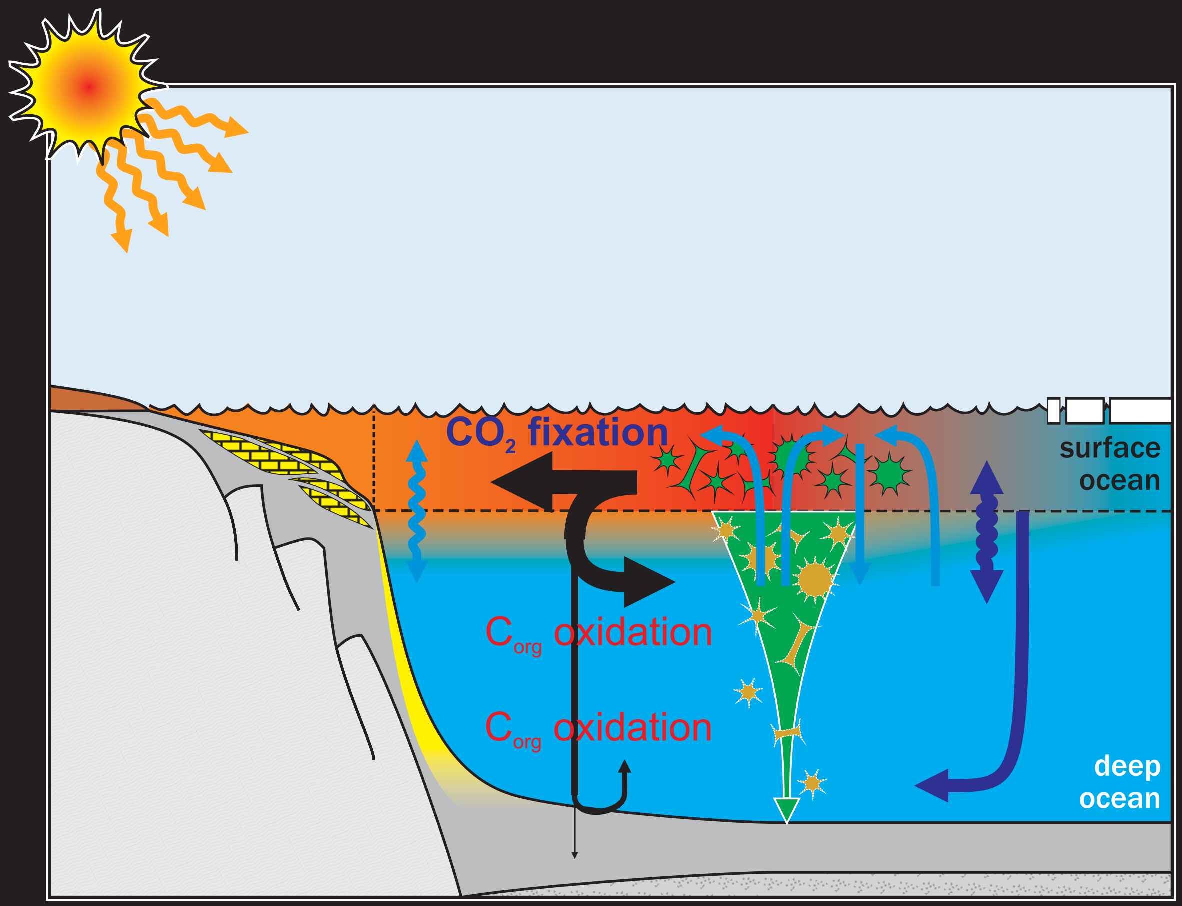
Evolution of the Biological Pump



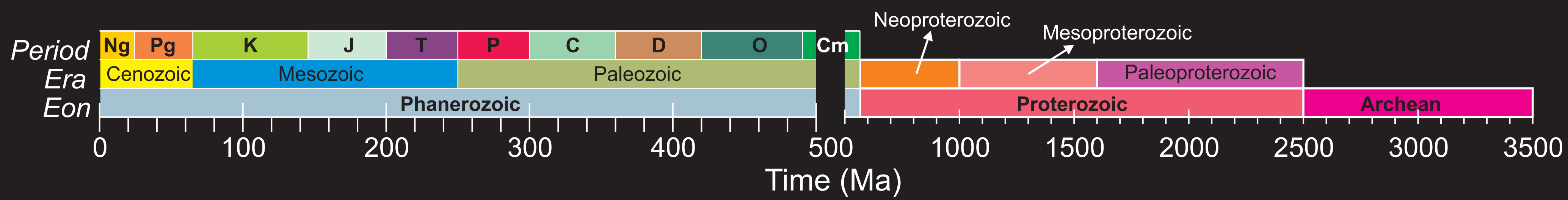
Evolution of the Biological Pump



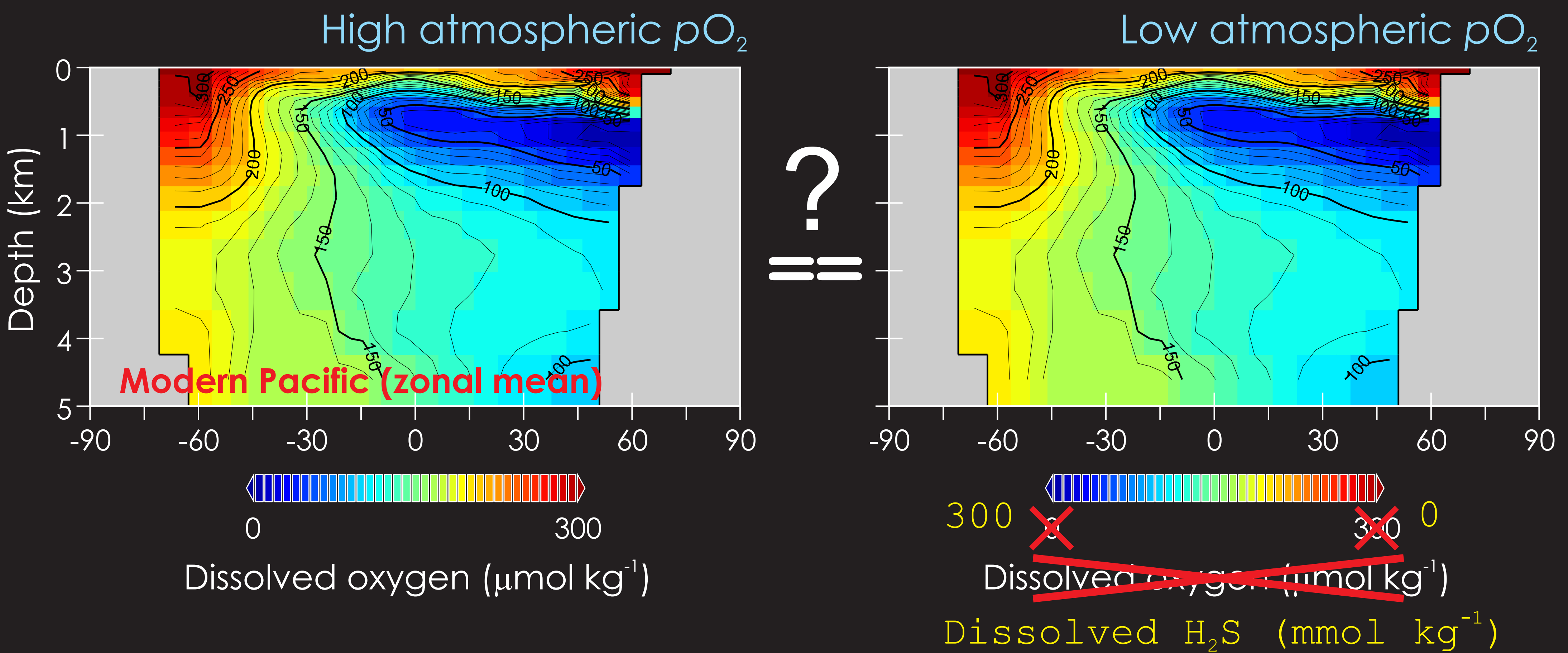
Evolution of the Biological Pump

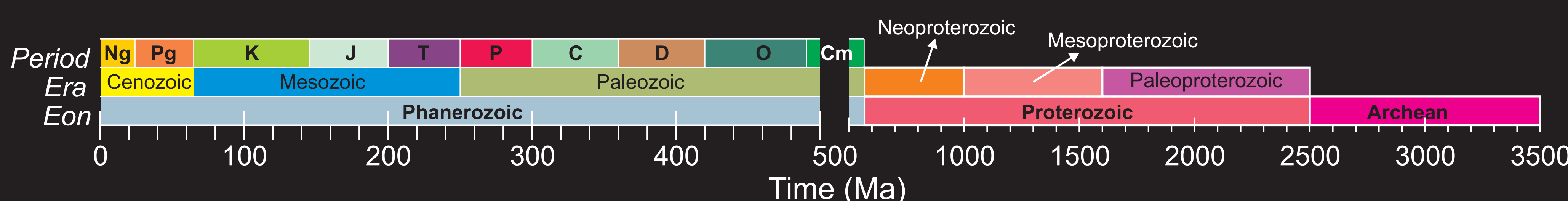


Both physical/geochemical and biological/ecological changes occurring through Earth history will affect the processes that govern the partitioning of carbon (and alkalinity) between the surface ocean (and hence atmosphere) and ocean interior, and conversely, oxygen.



Evolution of the Biological Pump





Evolution of the Biological Pump: TALK OUTLINE

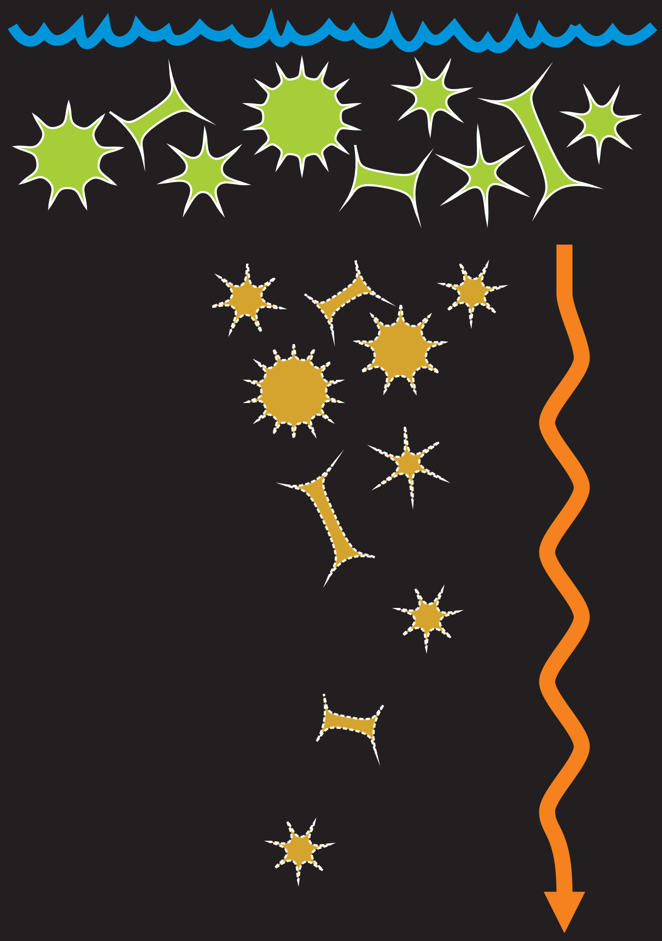
(1) Interrogating the biological pump *in silico*.

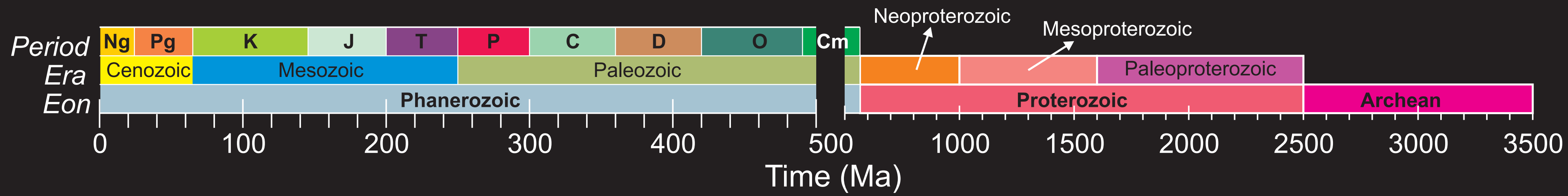
(2) The fundamental importance ...
or not ... of the advent of pelagic calcification and mineral 'ballasting' of particulate organic matter fluxes.

(3) Extinctions as a window onto the biological pump components.

(4) The fundamental importance ...
or not ... of physical ocean changes and particularly warming.

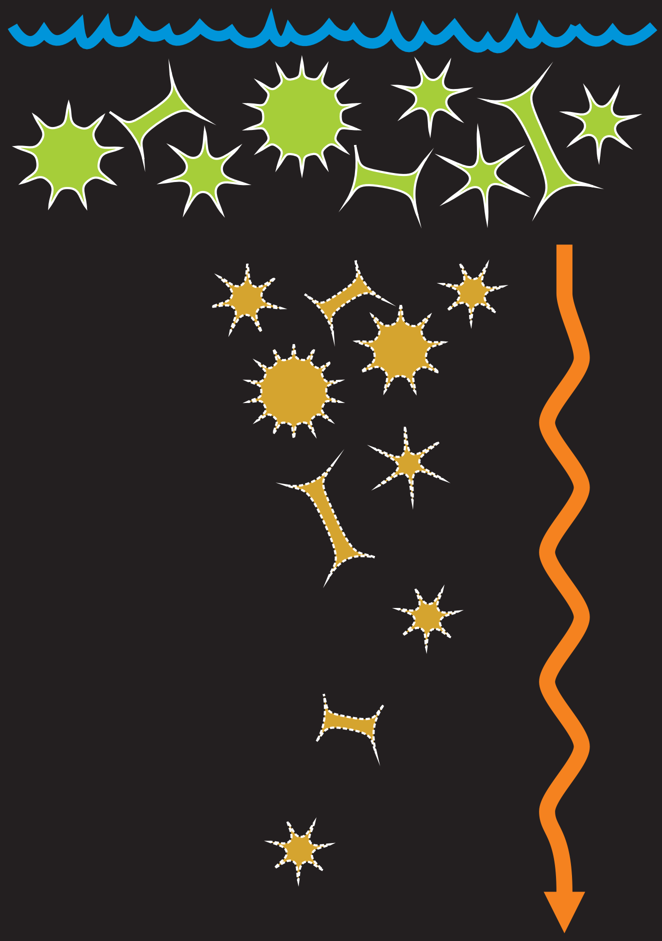
(5) What came before the (vertical) particulate carbon pump?

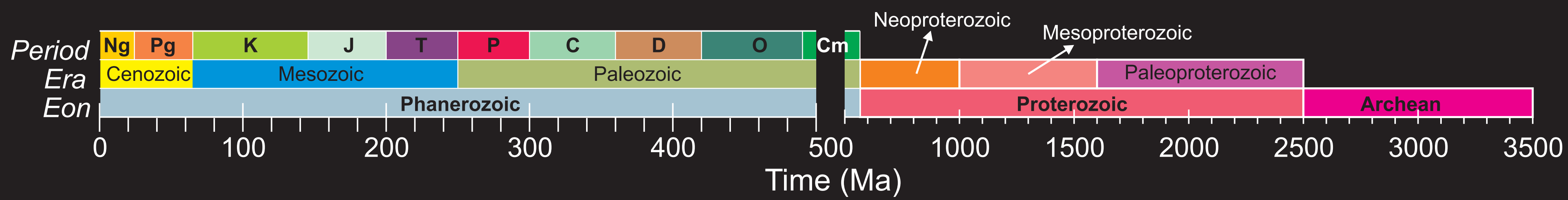


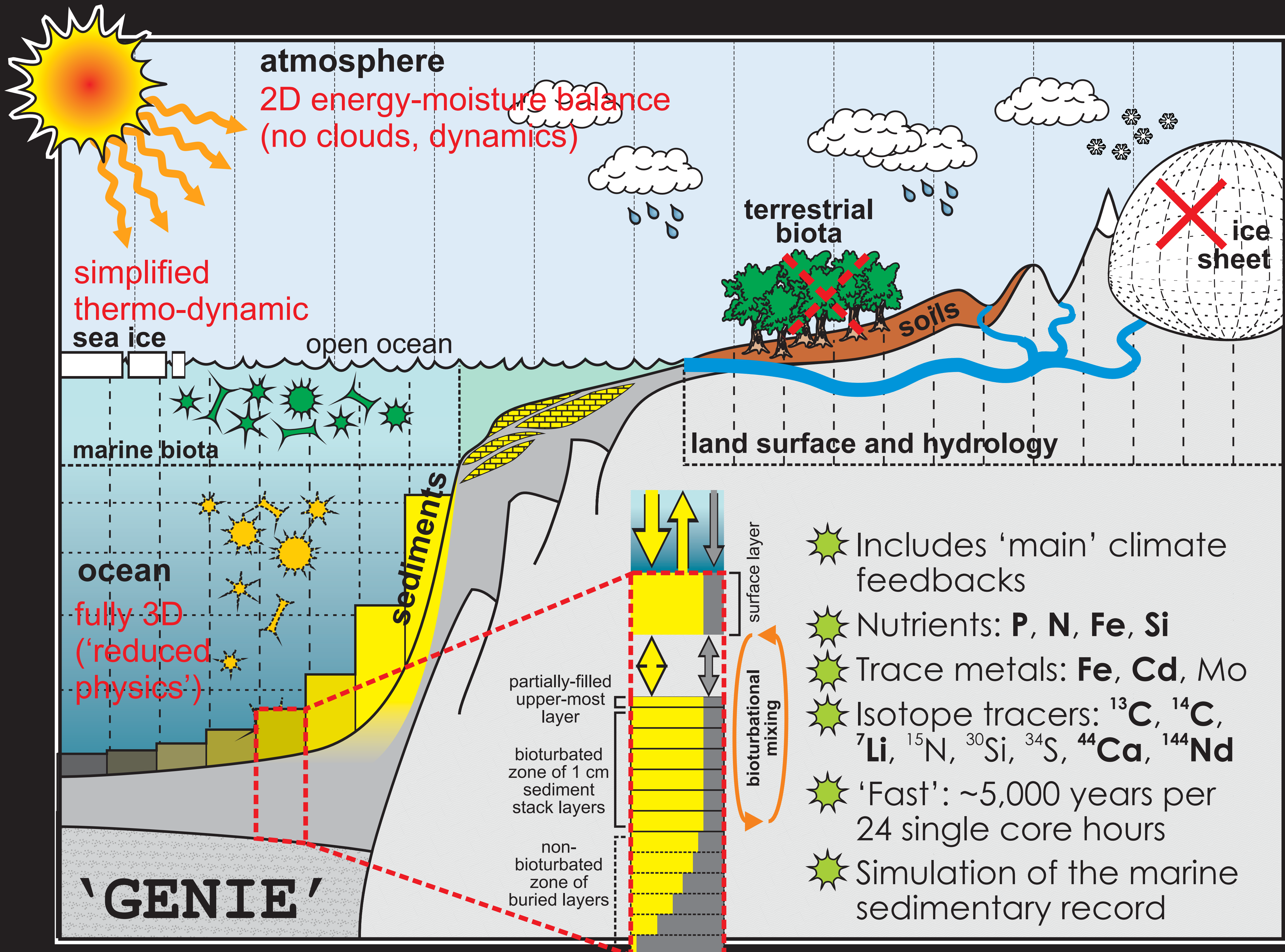


Evolution of the Biological Pump: in silico

```
! 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
ice
sheet
soils
marine biota
land surface and hydrology
sediments
ocean
fully 3D
('reduced
physics')
surface layer
bioturbational
mixing
partially-filled
upper-most
layer
bioturbated
zone of 1 cm
sediment
stack layers
non-
bioturbated
zone of
buried layers
'GENIE'
Includes 'main' climate feedbacks
Nutrients: P, N, Fe, Si
Trace metals: Fe, Cd, Mo
Isotope tracers: ^{13}C, ^{14}C, ^{7}Li, ^{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

cGENIE UCR 2014 version: README

Andy Ridgwell

March 5, 2014

1. To get an exact (read-only) copy of the ('muffin' 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 is g3n1e-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 file user.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 and user.sh (genie-main directory). Installing the model code under the default directory name (cgenie.muffin) 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 to cgenie.muffin/genie-main and type:
   make testbiogem
   This compiles a carbon cycle enabled configuration of cGENIE 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 the NETCDF DIR environment 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 from genie-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

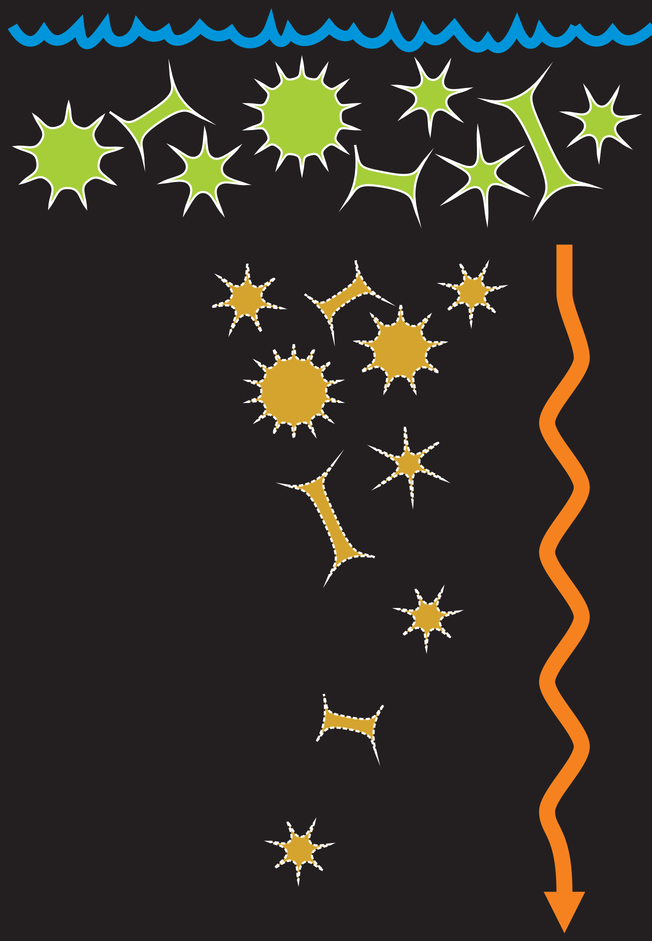
Refer to the cGENIE User manual for more information regarding installing, running, and analyzing model output, and cGENIE Examples for more information on this specific example.[1] Also read the cGENIE README
Highly recommended ... is in order to have a working appreciation of the structure of the model and output, plus the format of the model output and how to visualize it – to read through:

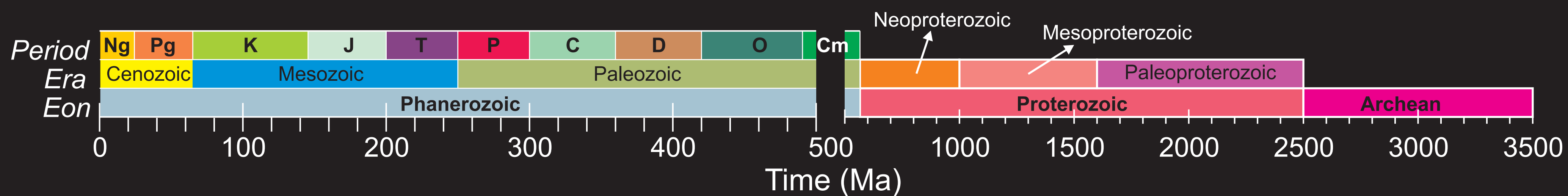
http://www.seao2.info/cgenie/labs/EC4.2013/GEOGM1110andM1404.2013-14.cGENIE_LAB.0000.pdf

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

Evolution of the Biological Pump: in silico

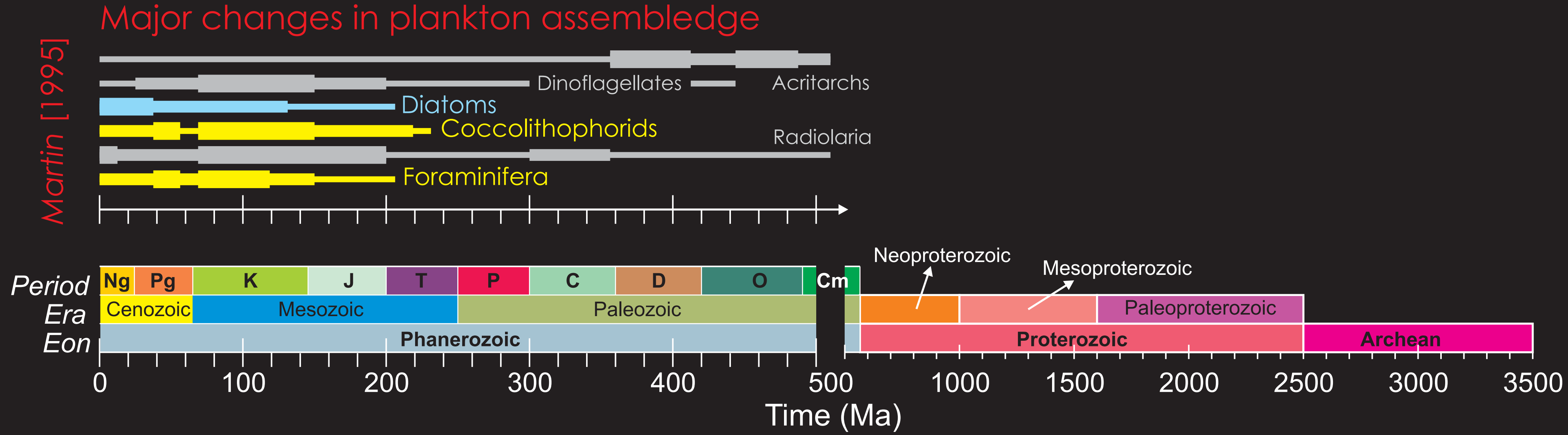
tinyurl.com/kmjhe4s



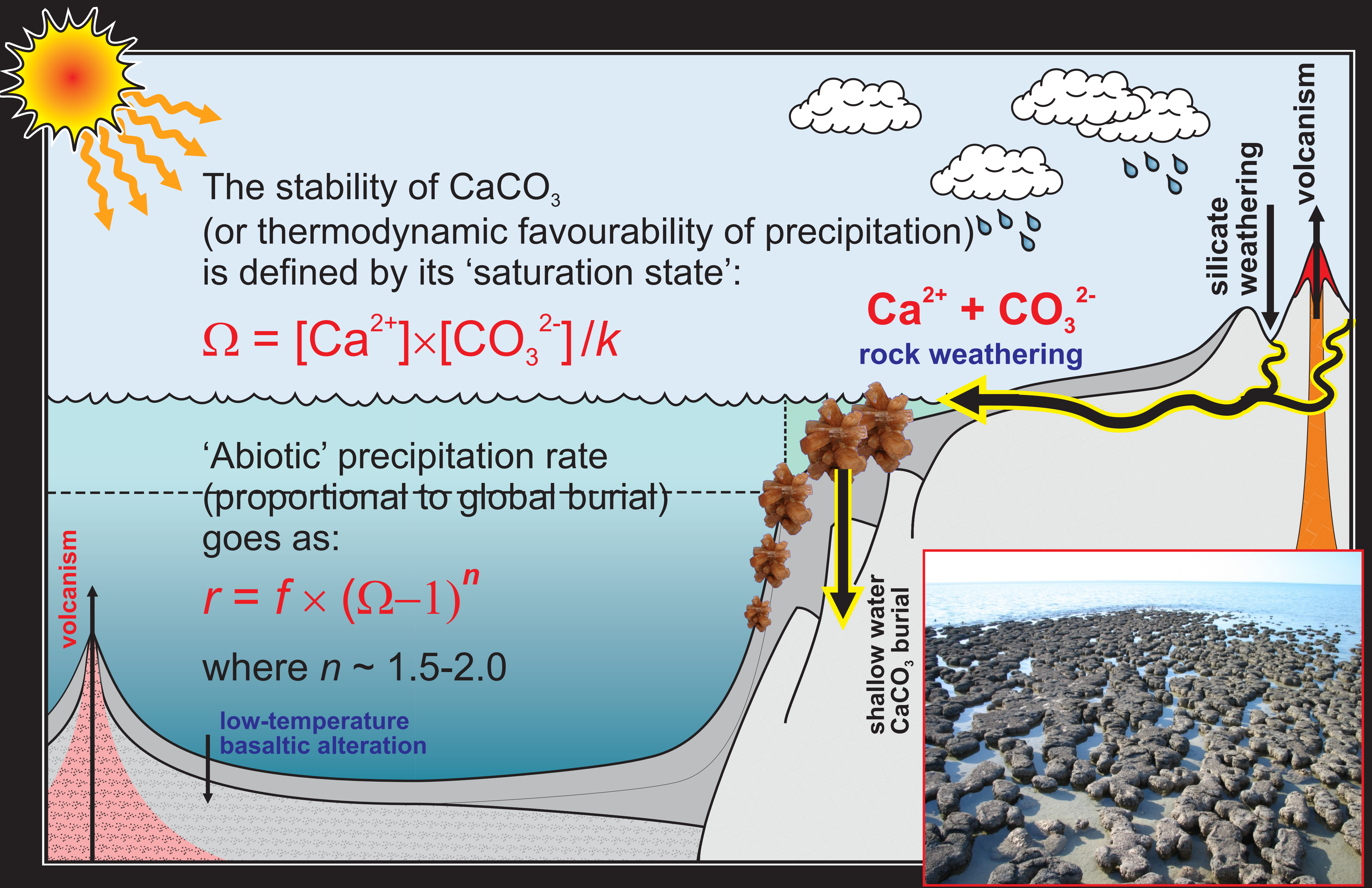


Evolution of the Biological Pump:

The Mesozoic planktic calcifier revolution



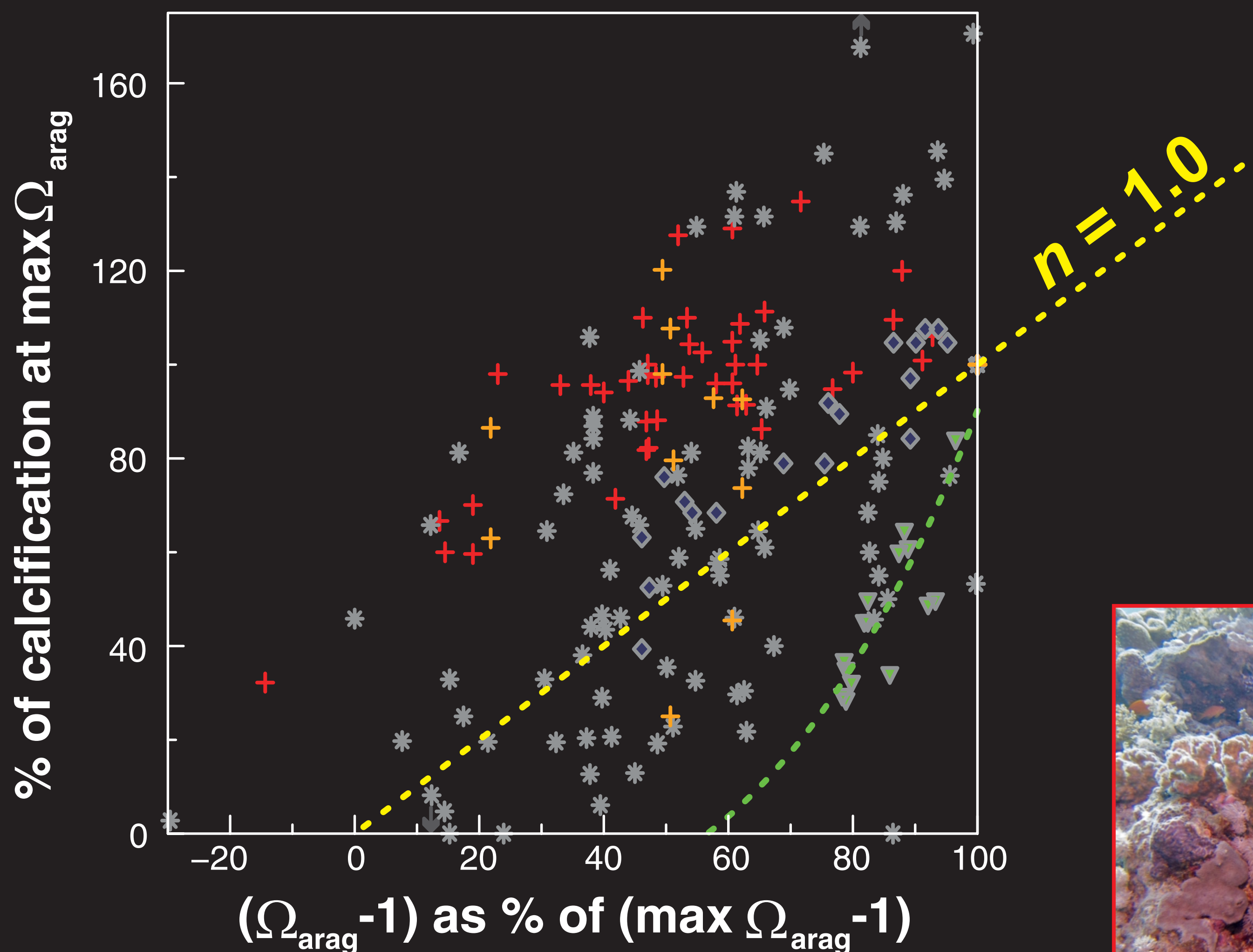
Evolution of the Biological Pump



Evolution of the Biological Pump

decreasing saturation

decreasing calcification rates
(% compared to Preindustrial conditions)

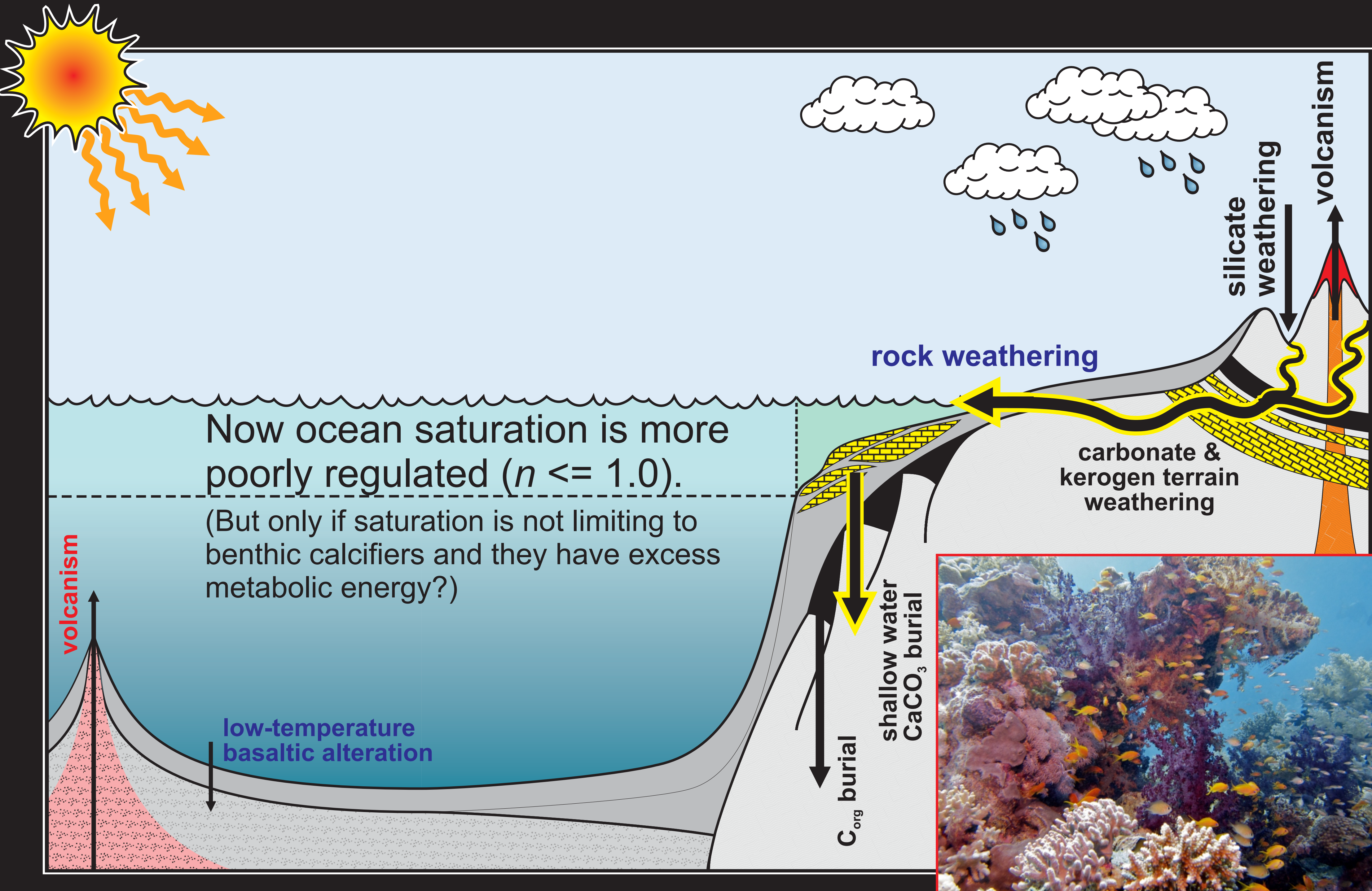


Pandolfi et al. [2011] (*Science*)

Evolution of the Biological Pump

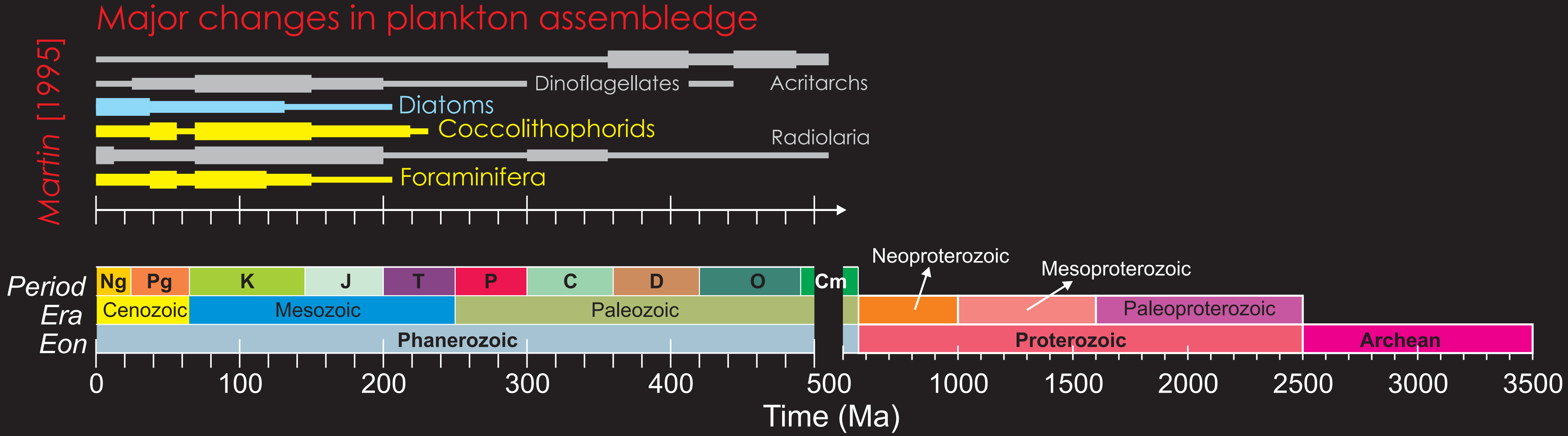
Now ocean saturation is more poorly regulated ($n <= 1.0$).

(But only if saturation is not limiting to benthic calcifiers and they have excess metabolic energy?)

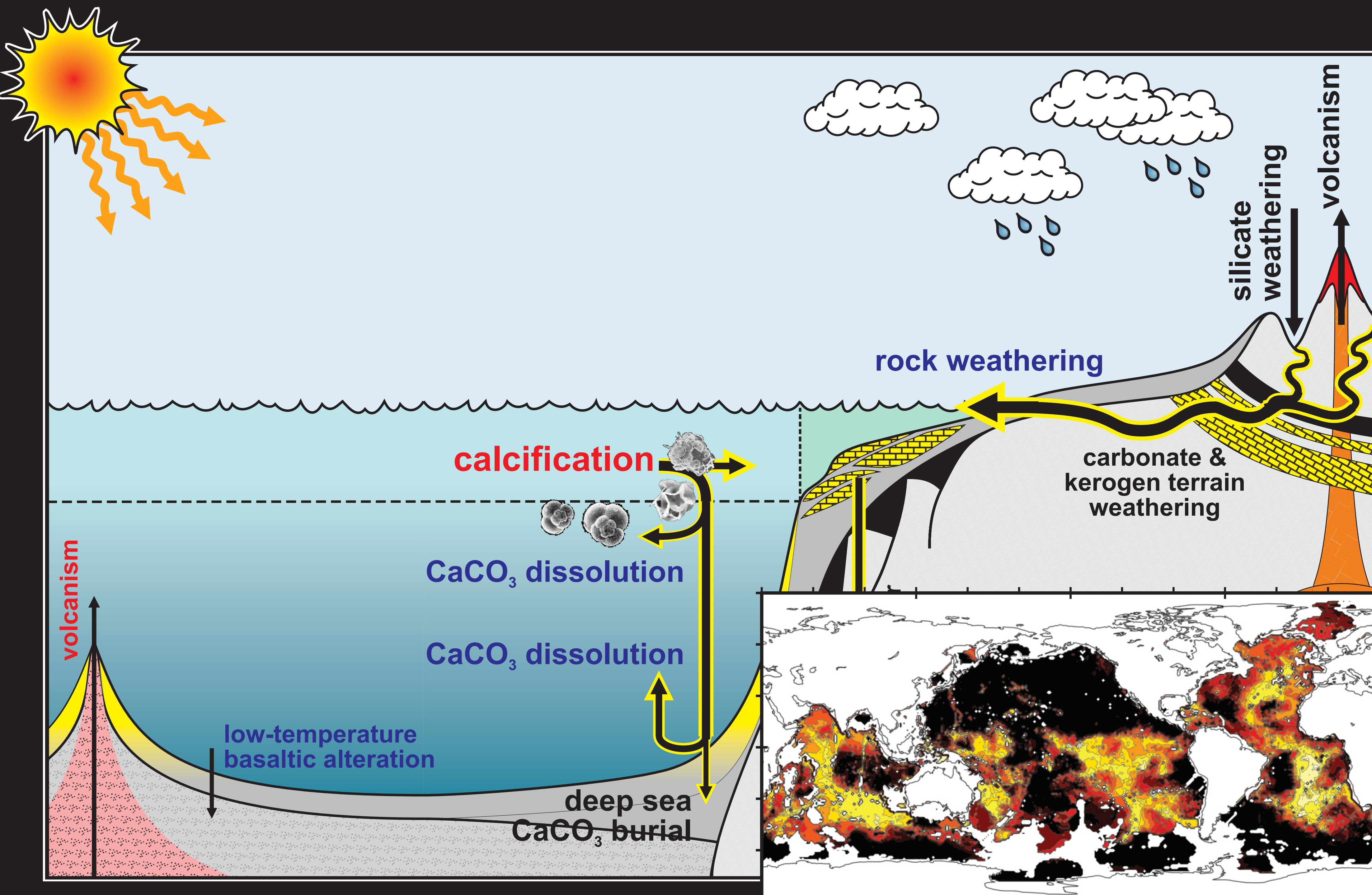


Evolution of the Biological Pump:

The Mesozoic planktic calcifier revolution

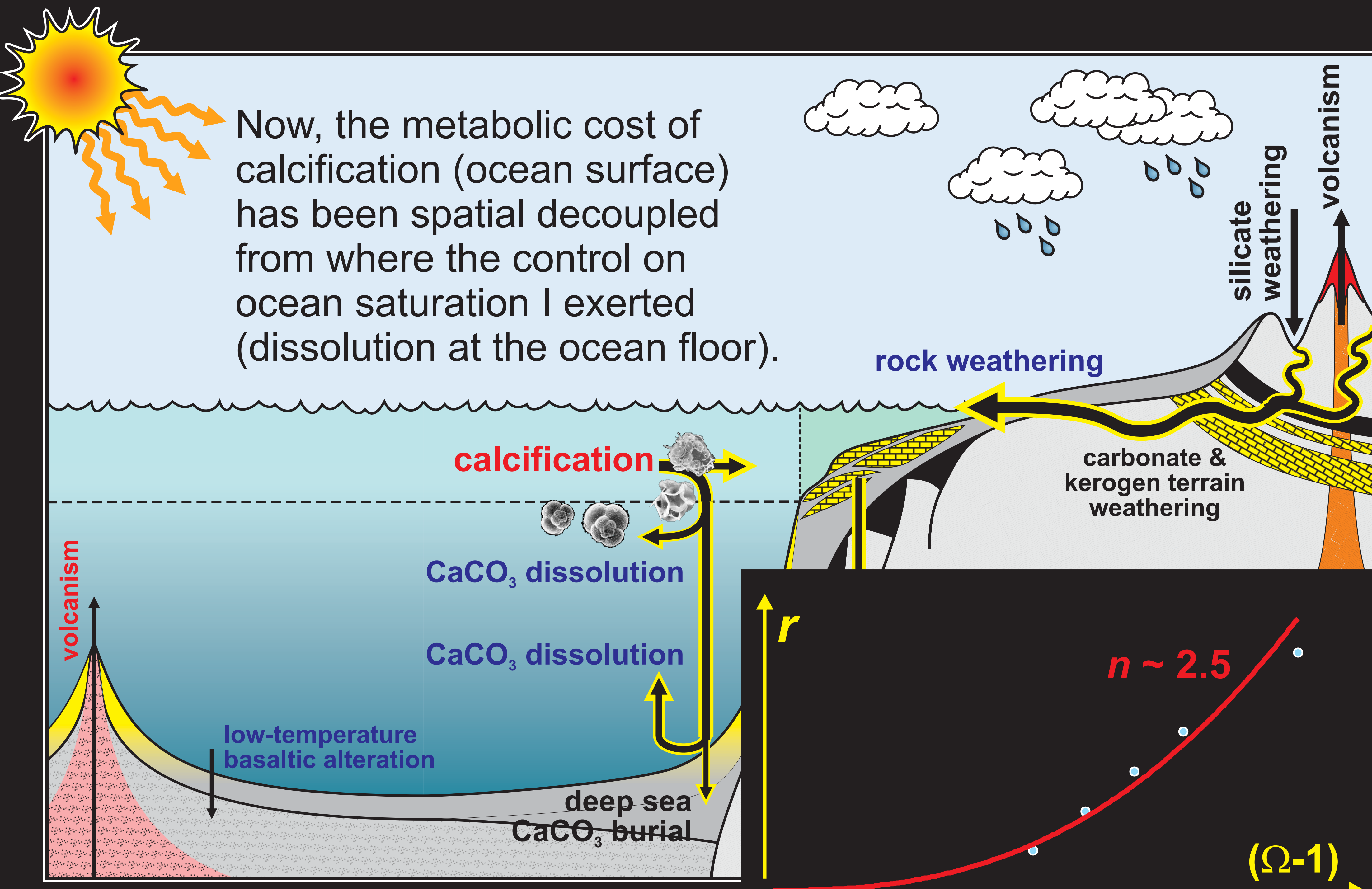


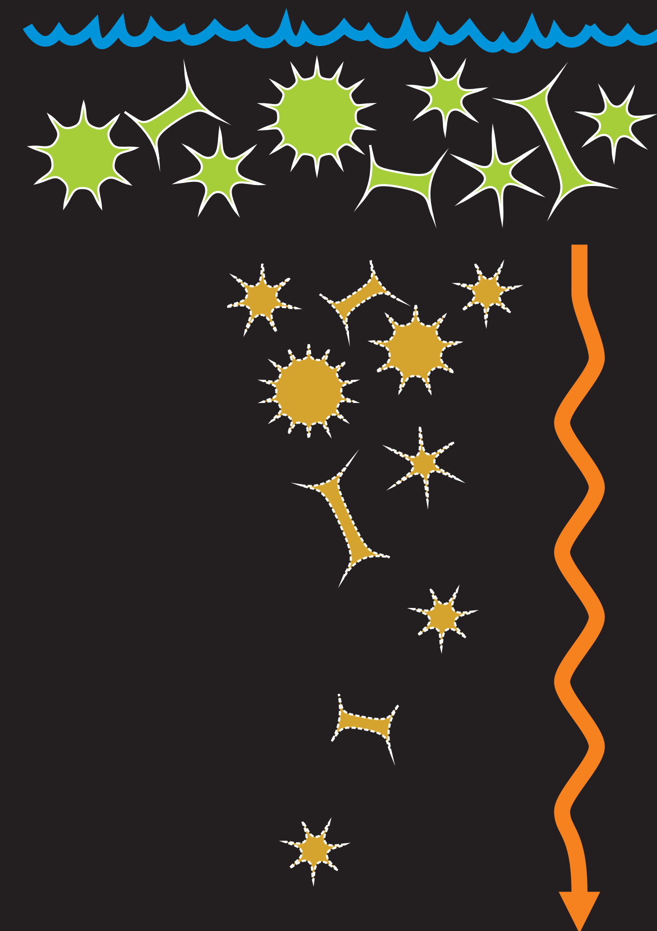
Evolution of the Biological Pump

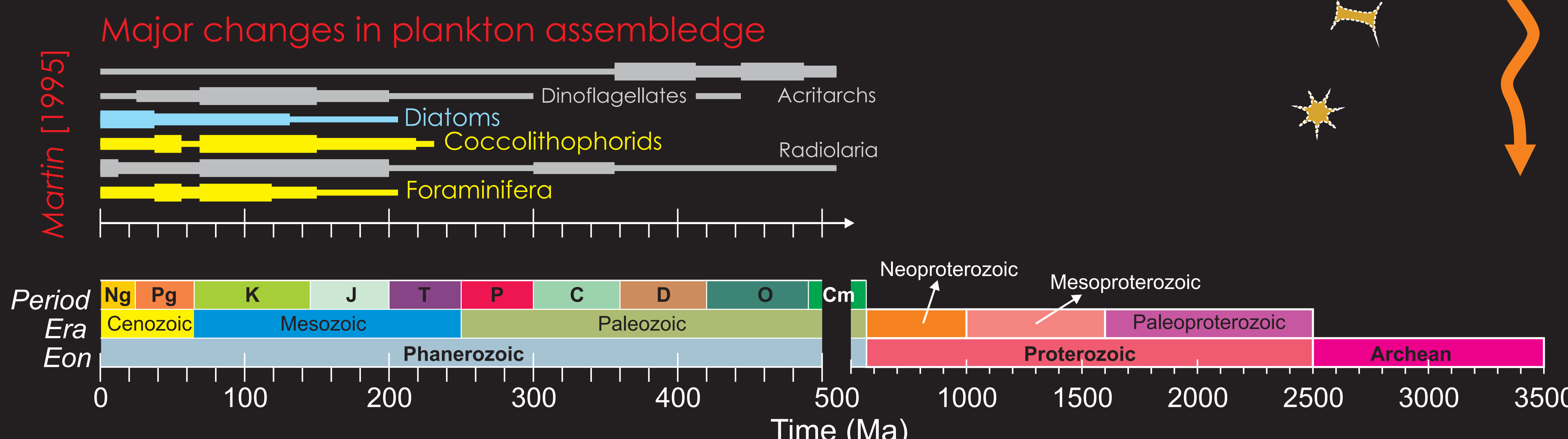


Evolution of the Biological Pump

Now, the metabolic cost of calcification (ocean surface) has been spatial decoupled from where the control on ocean saturation I exerted (dissolution at the ocean floor).






Major changes in plankton assembledge
Martin [1995]
Dinoflagellates
Acritarchs
Diatoms
Coccolithophorids
Radiolaria
Foraminifera
Period
Era
Eon
Ng
Pg
K
J
T
P
C
D
O
Cm
Cenozoic
Mesozoic
Paleozoic
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Phanerozoic
Proterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

Evolution of the Biological Pump:

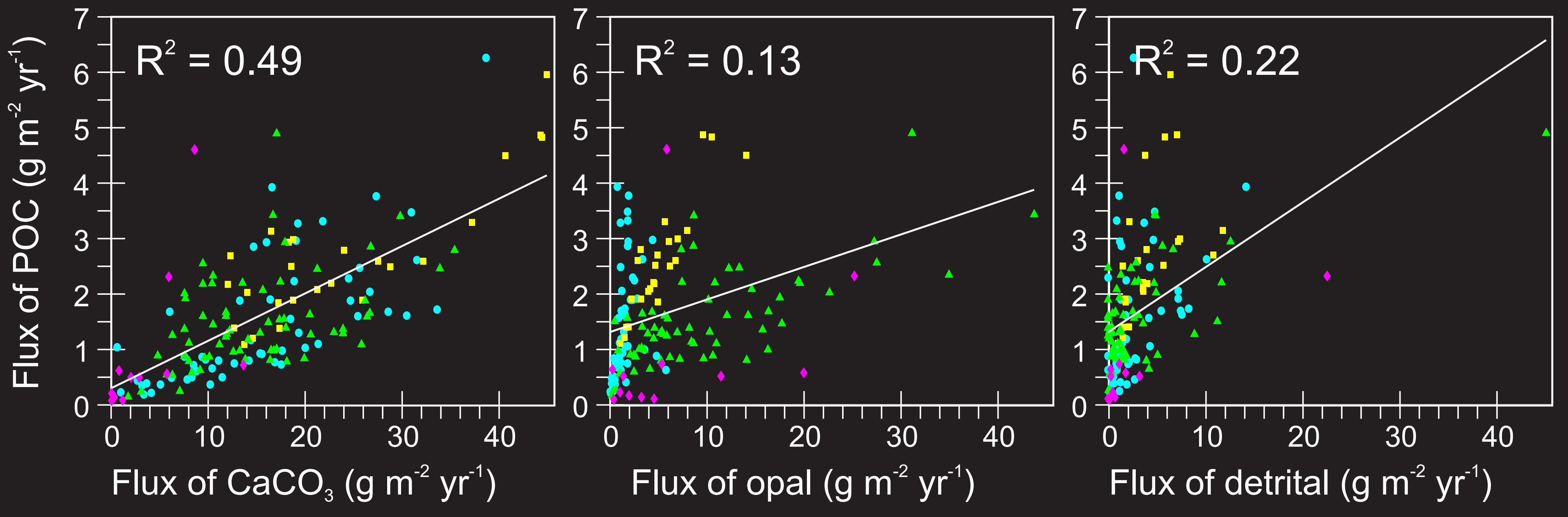
Planktic carbonate production and 'ballasting'

Compilation of sediment trap observations:

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

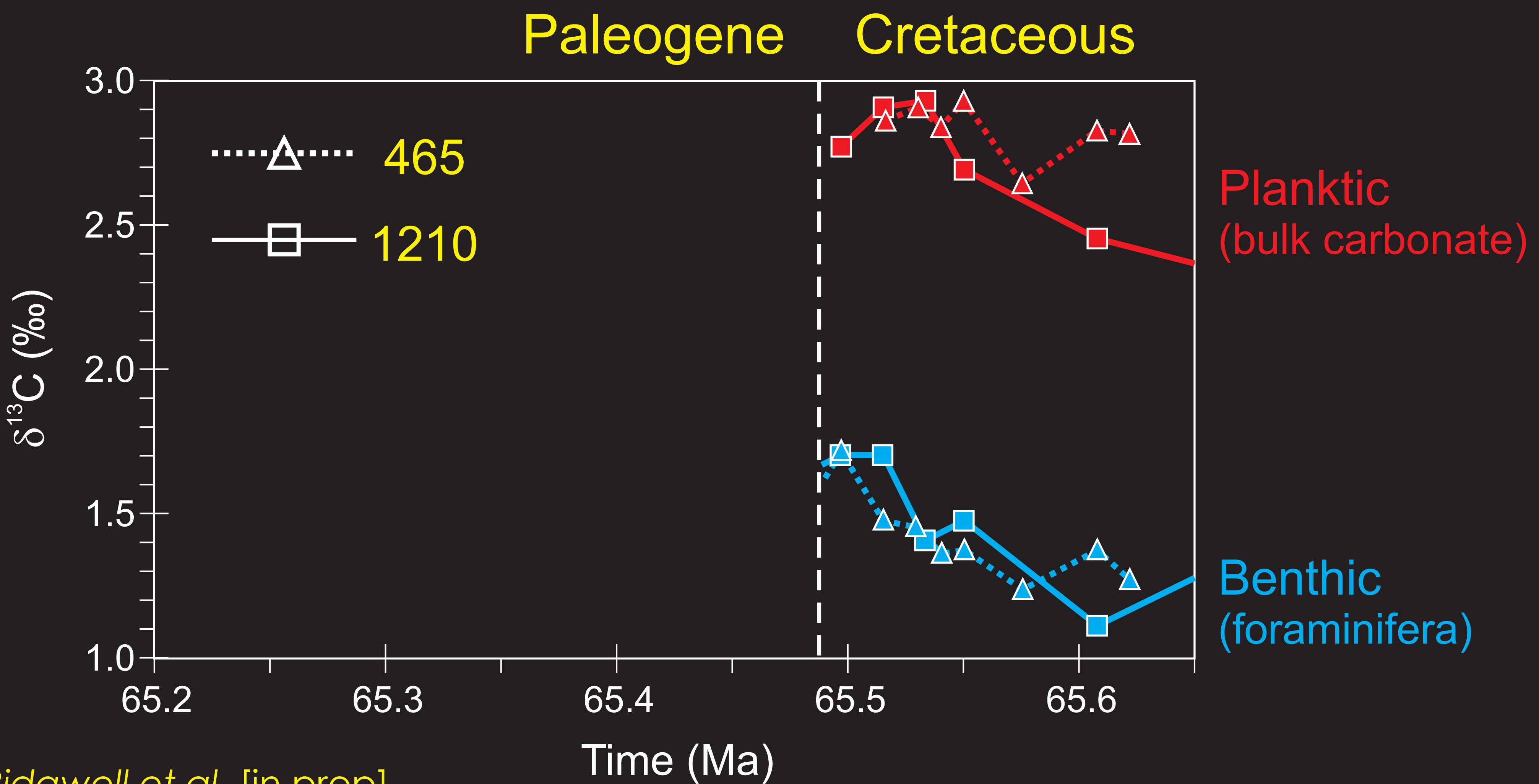
cyan == Atl, yellow == Ind, green == Pac, magenta == SO.

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



Evolution of the Biological Pump: ‘Hiccups’

(temporary disruption or removal of one or more processes)



Ridgwell et al. [in prep]

Evolution of the Biological Pump: 'Hiccups'

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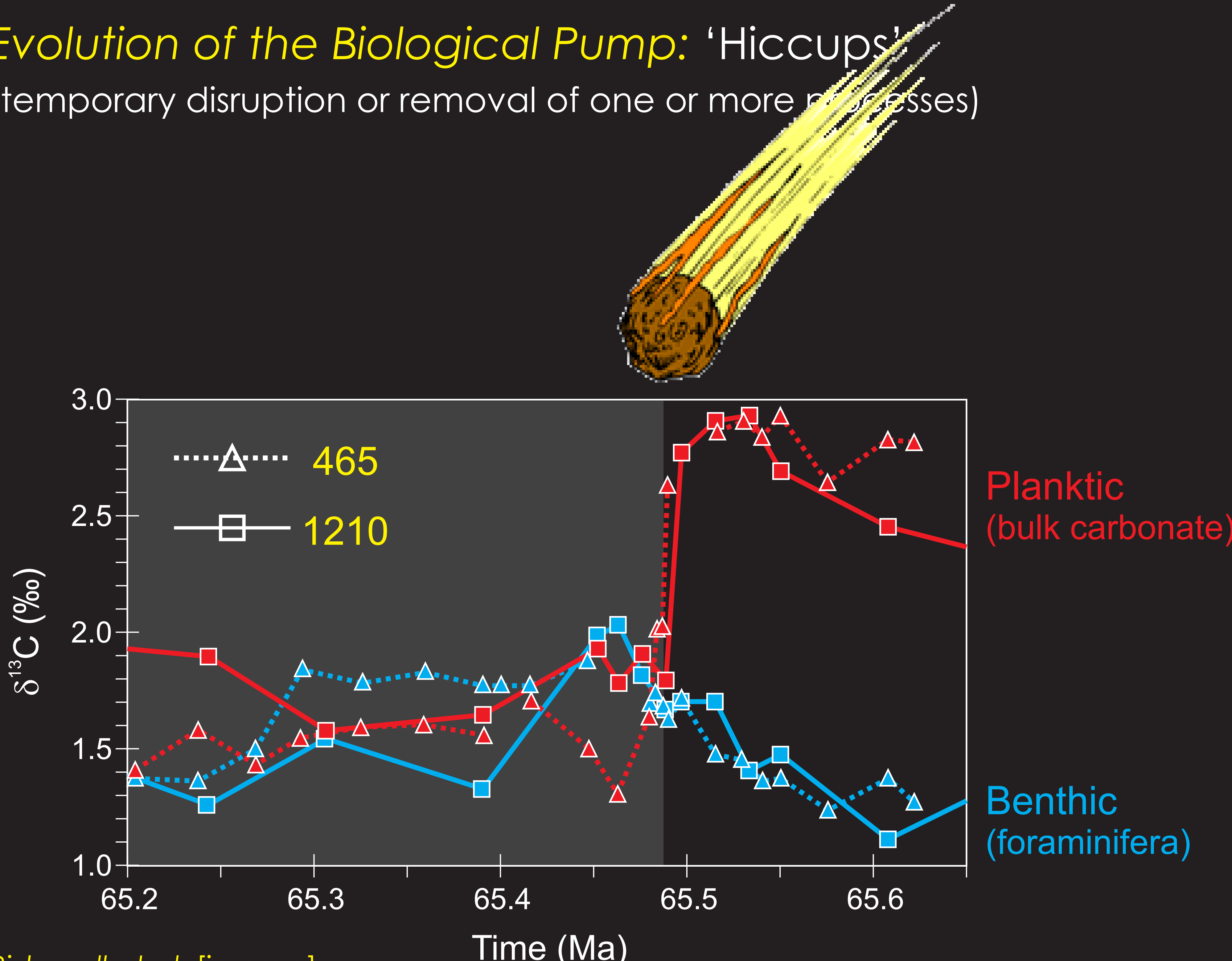
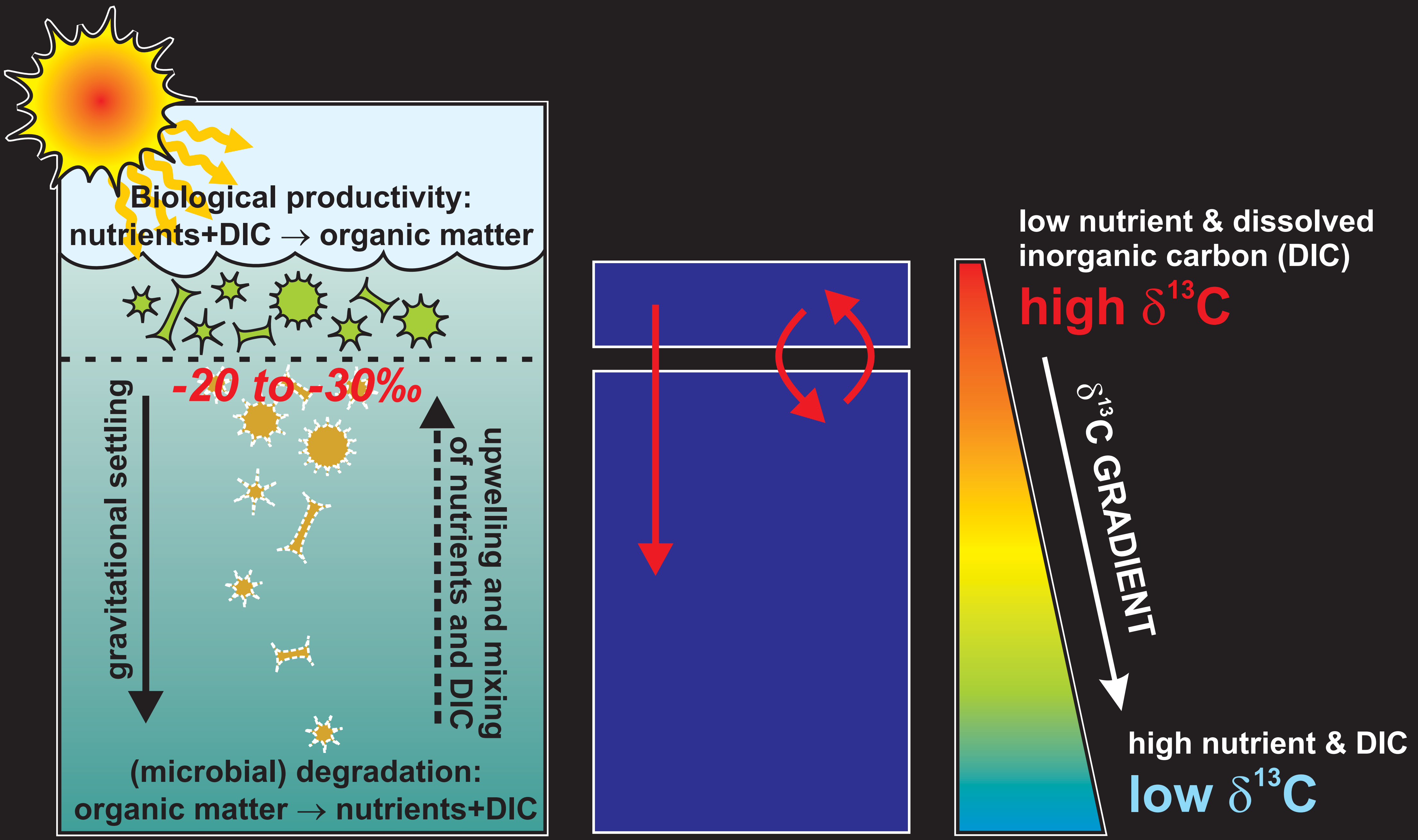


Ridgwell et al. [in prep]

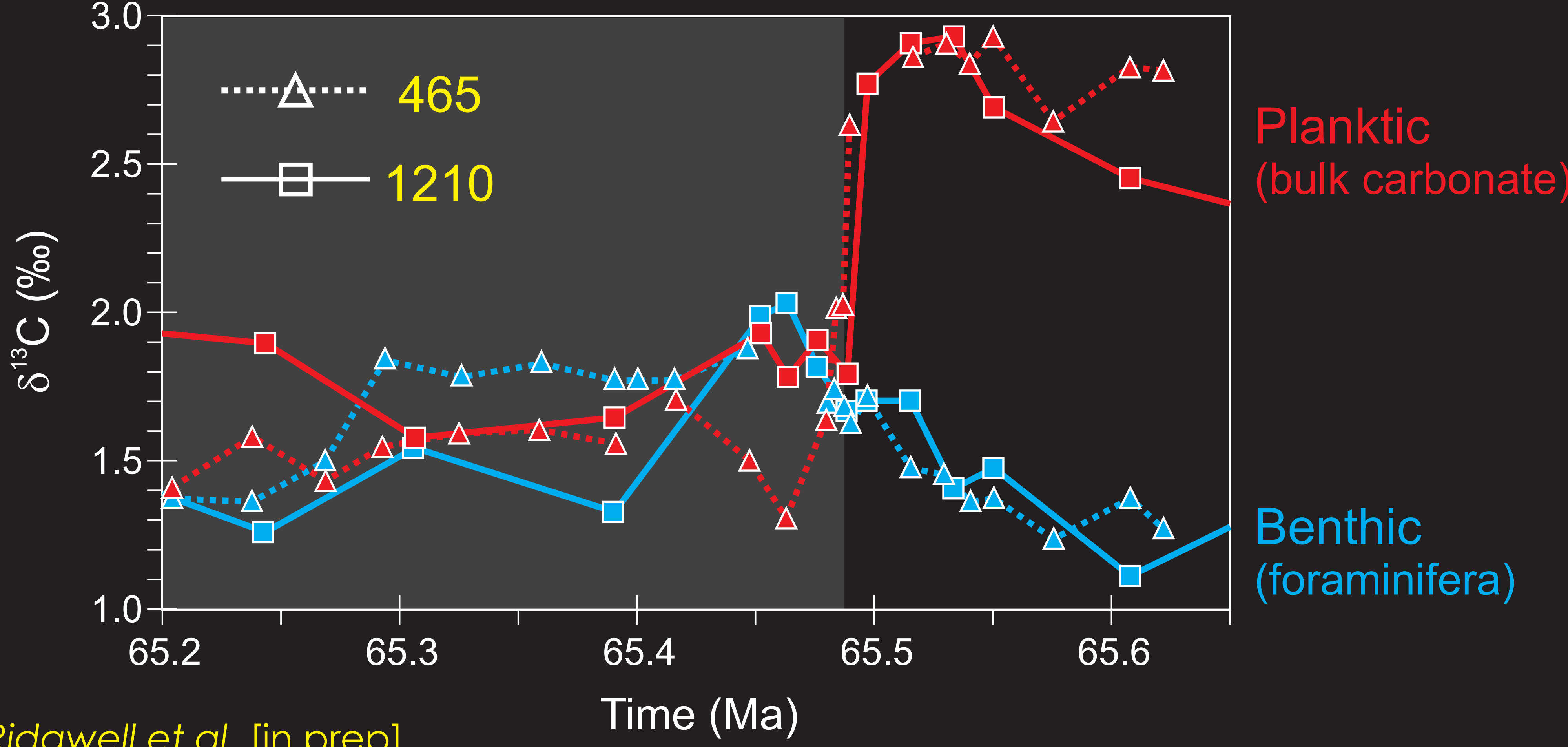
Evolution of the Biological Pump: ‘Hiccups’



Evolution of the Biological Pump: 'Hiccups'

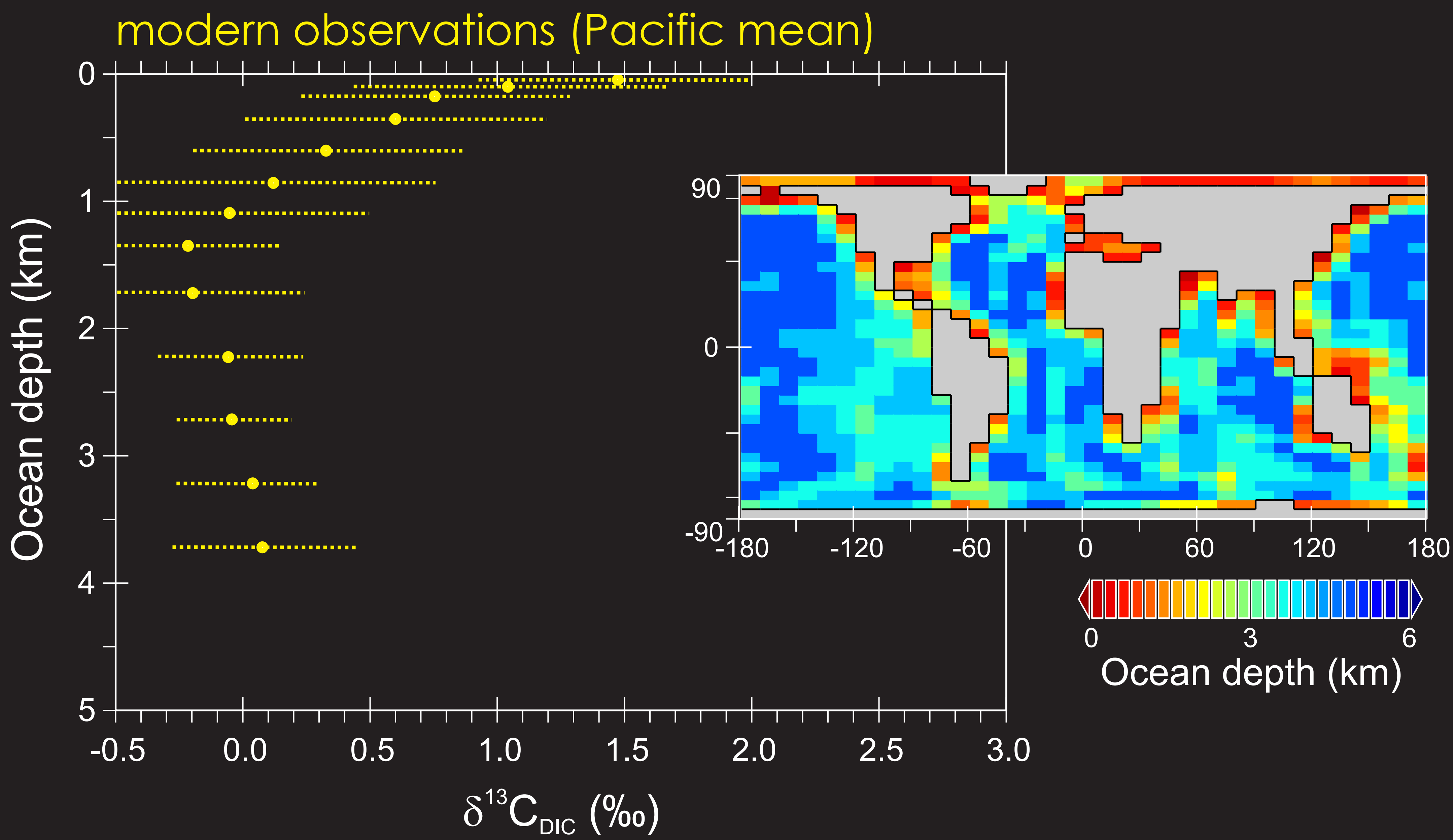
Severe extinction amongst calcifying plankton (and less interesting creatures such as dinosaurs etc.)

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



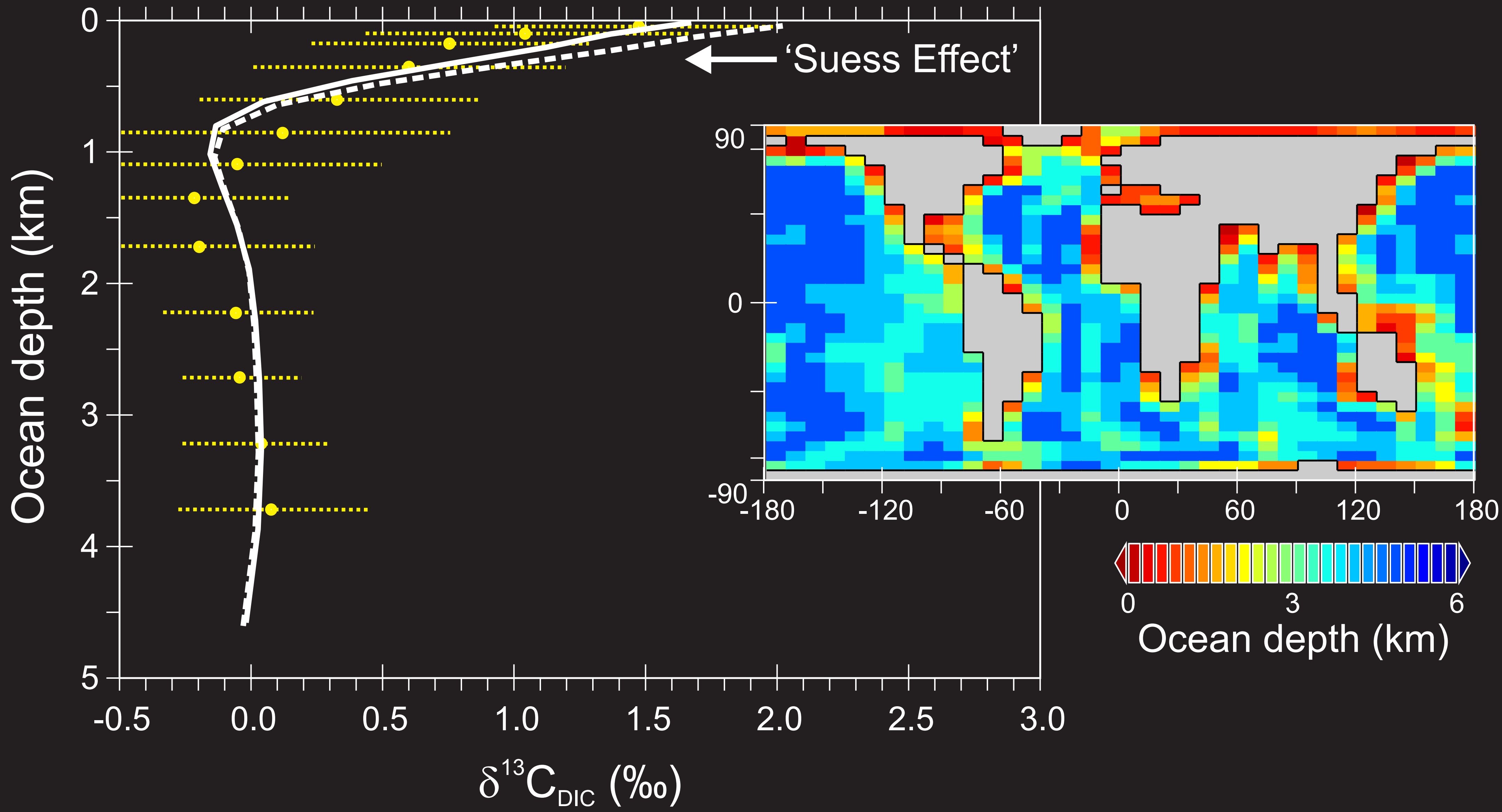
Ridgwell et al. [in prep]

Evolution of the Biological Pump: 'Hiccups'



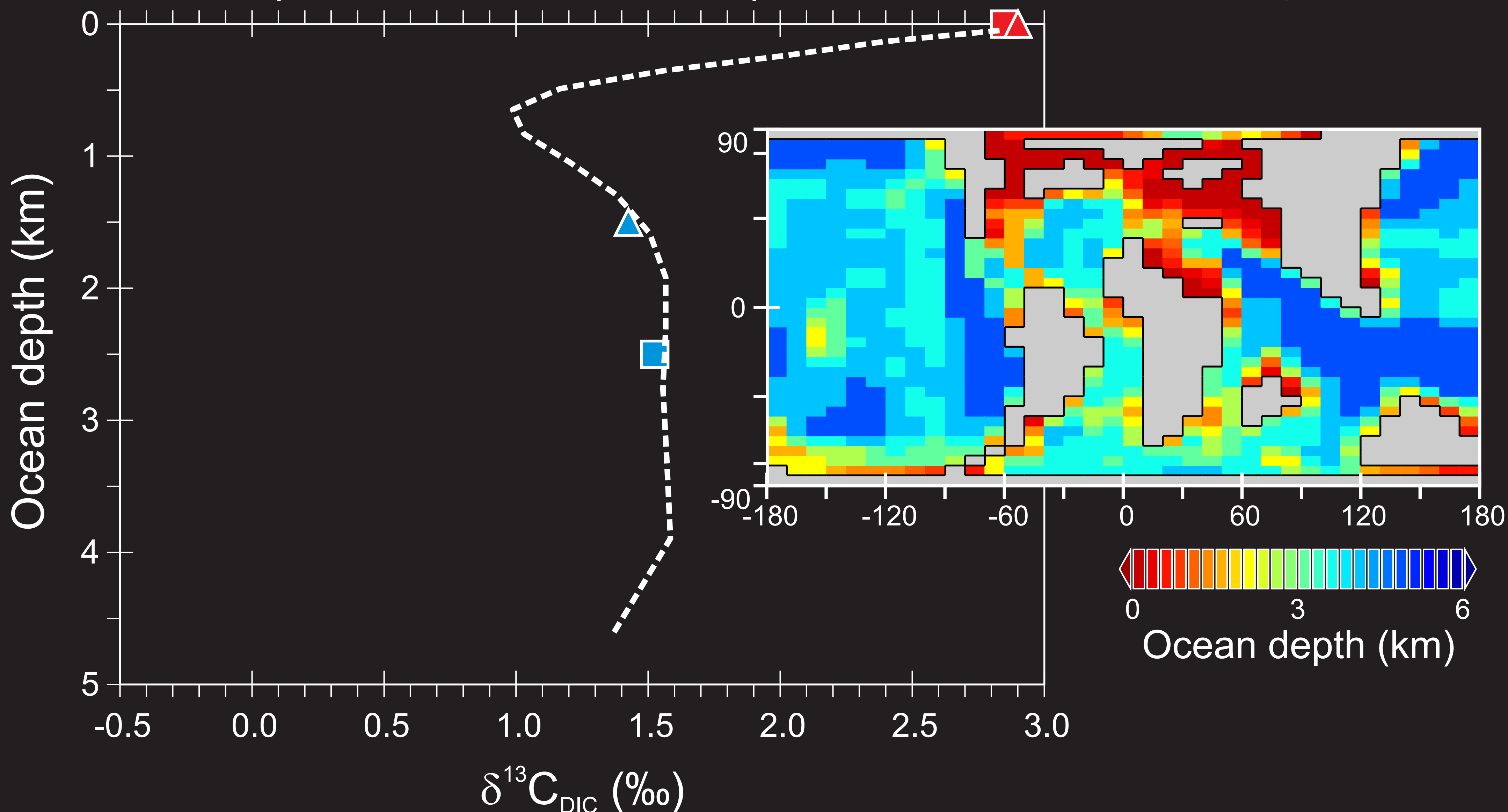
Evolution of the Biological Pump: 'Hiccups'

model vs. modern observations

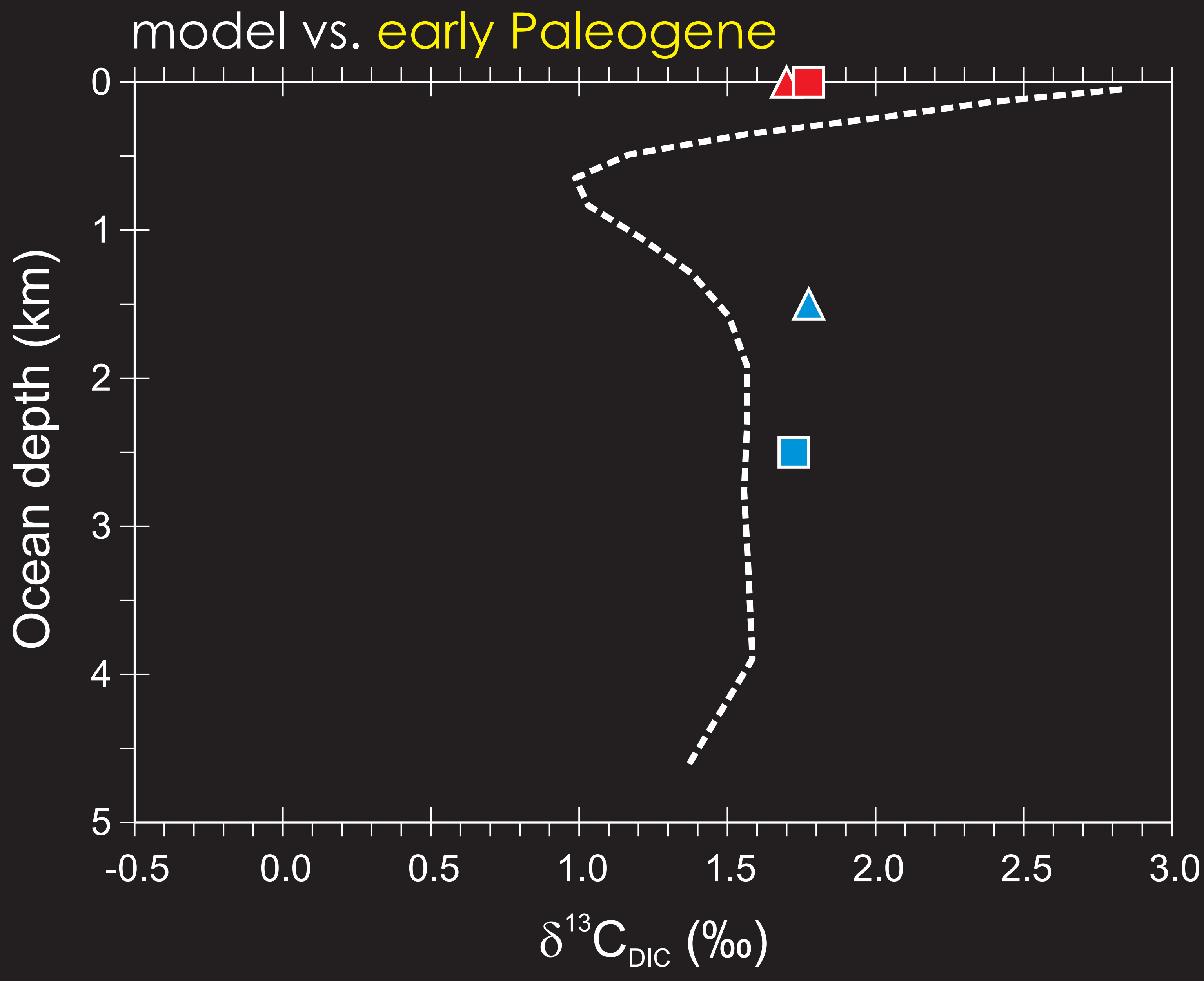


Evolution of the Biological Pump: 'Hiccups'

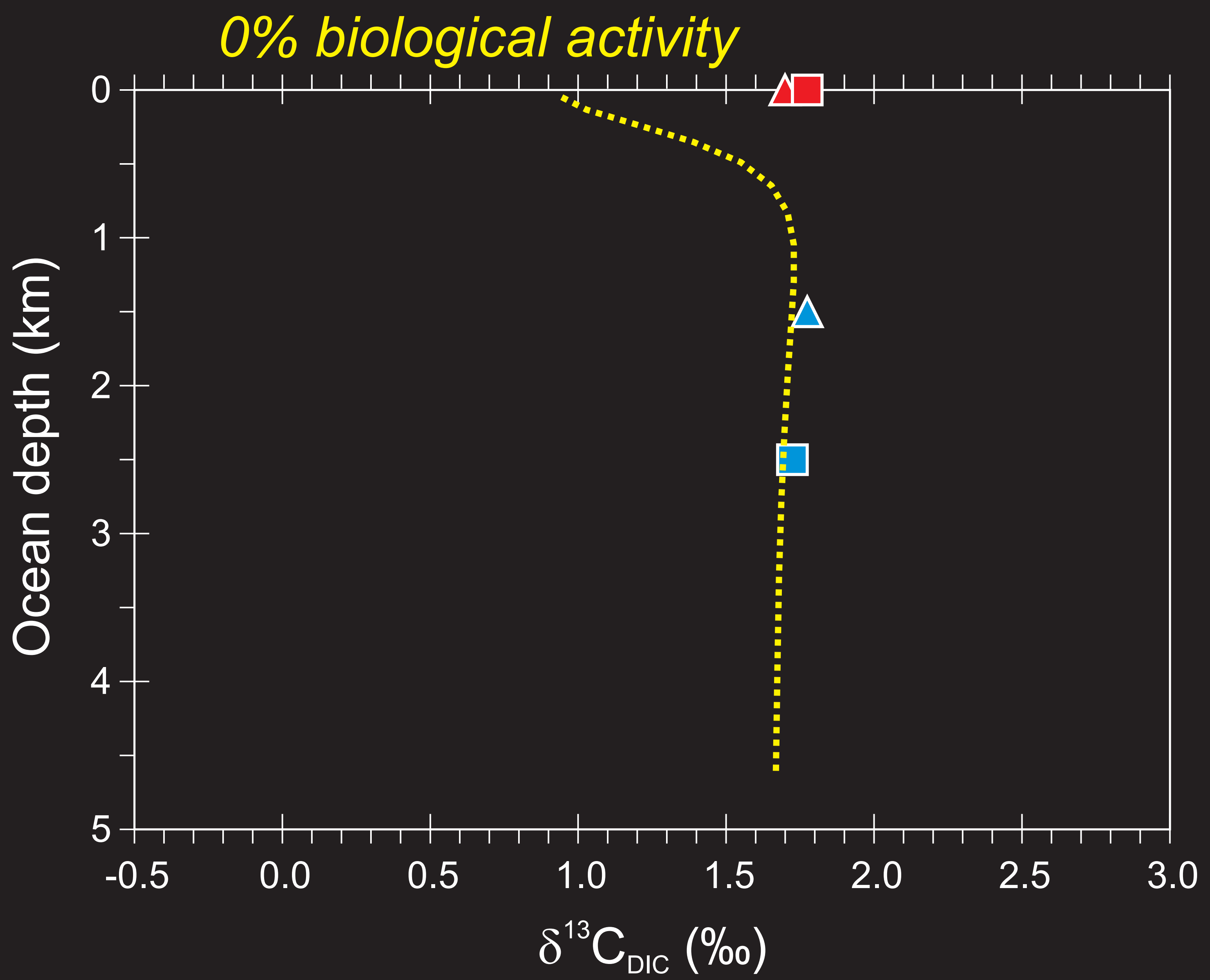
model (choosing: $\delta^{13}C_{atm}$ = -4.5‰) vs. latest Maastrichtian proxies



Evolution of the Biological Pump: 'Hiccups'

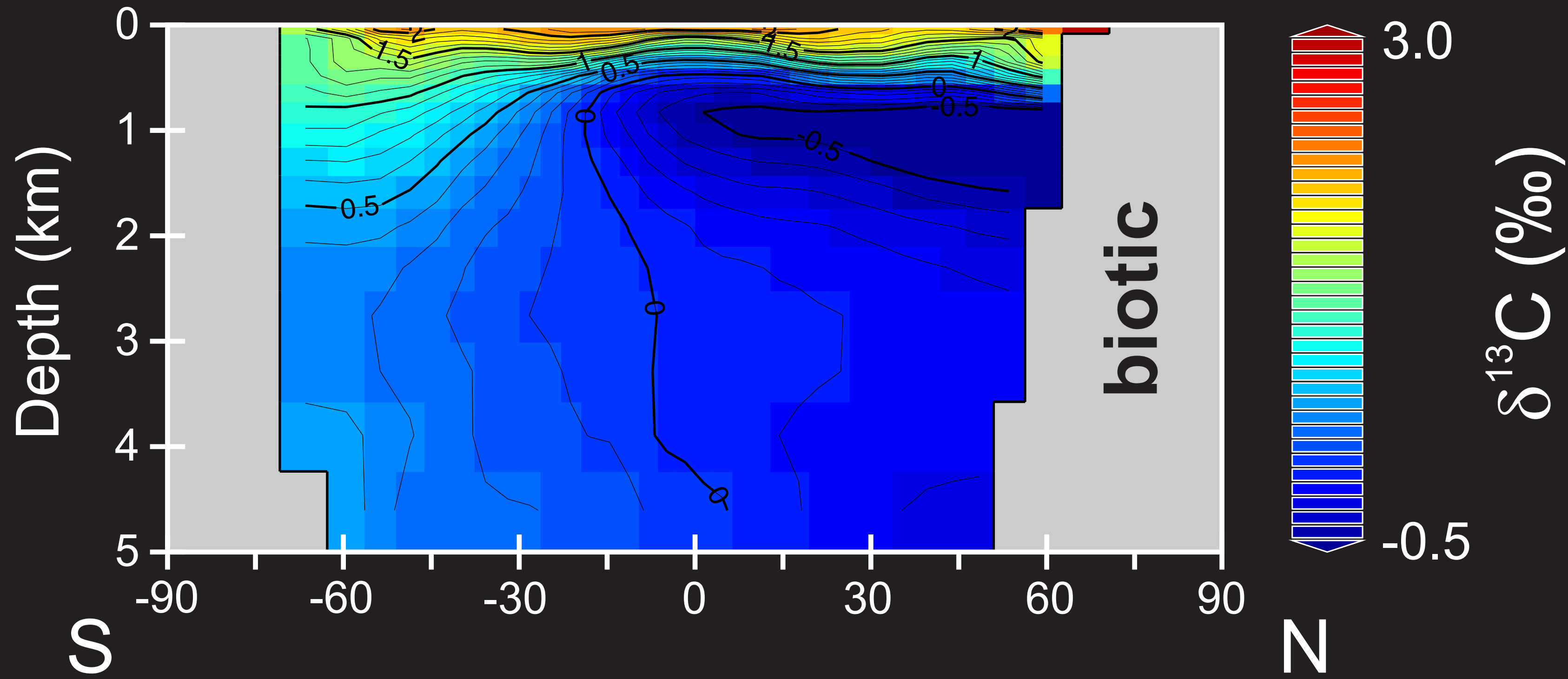


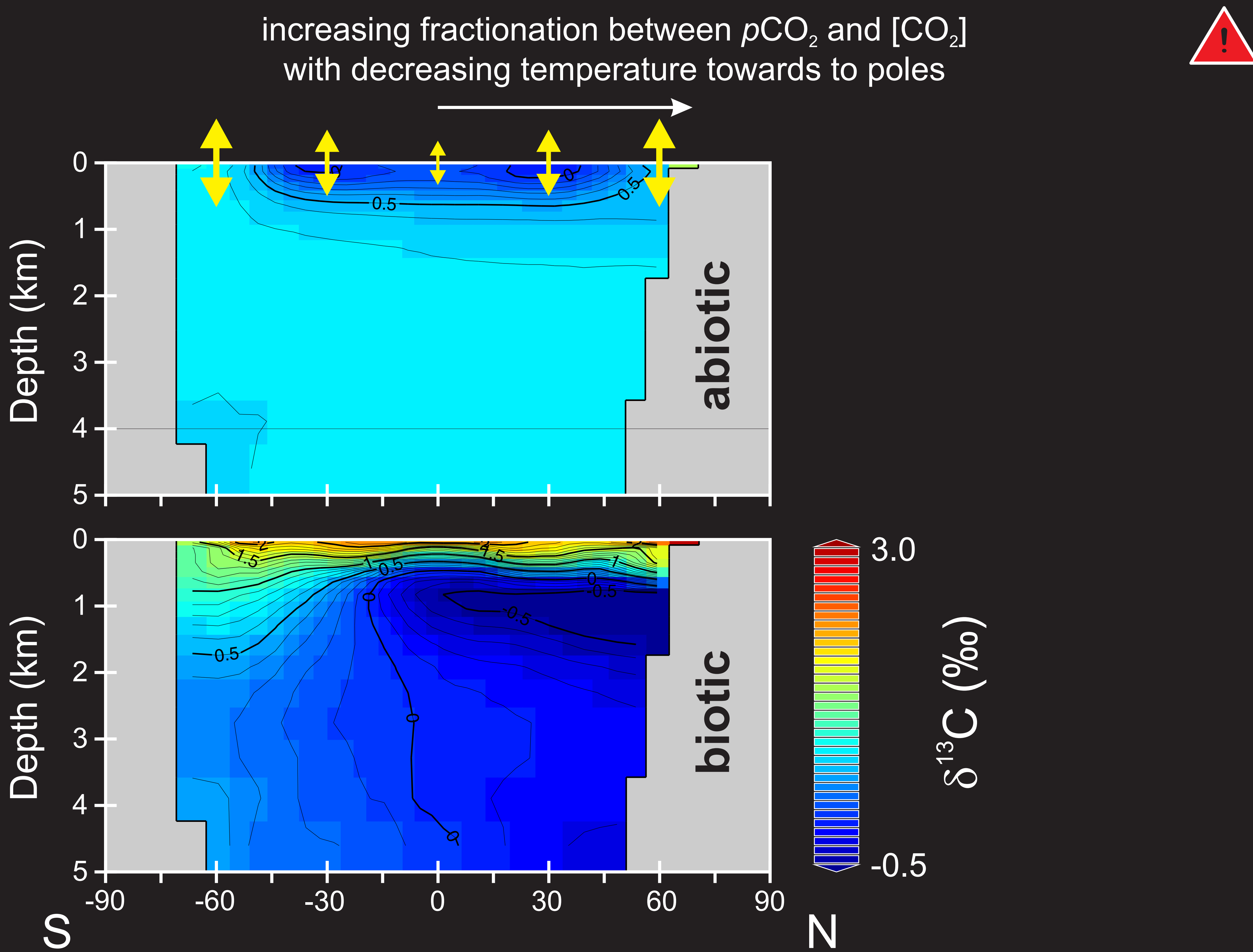
Evolution of the Biological Pump: 'Hiccups'



Evolution of the Biological Pump: 'Hiccups'

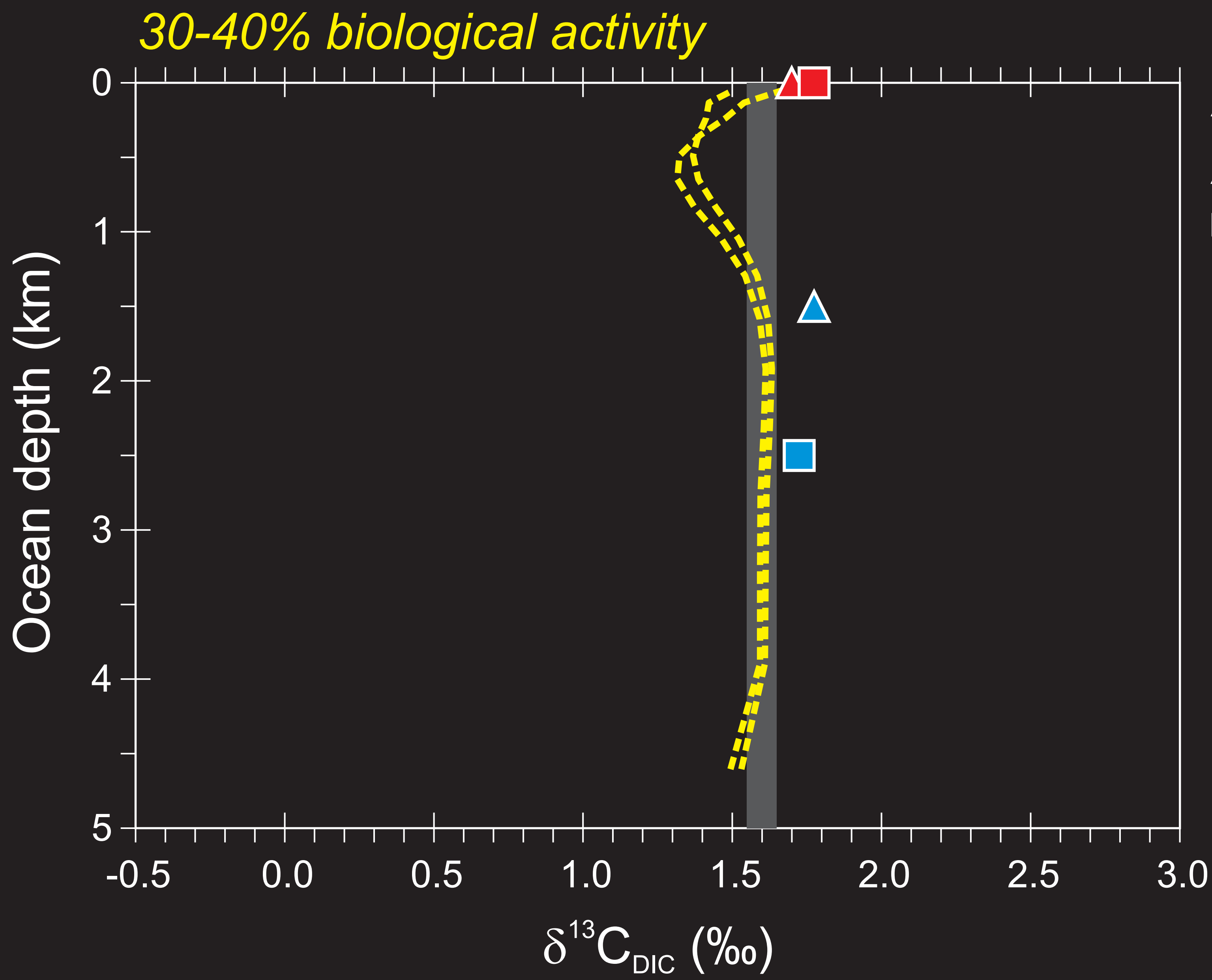
Modern Pacific zonal $\delta^{13}C_{(DIC)}$ profile





increasing fractionation between pCO_2 and $[CO_2]$
with decreasing temperature towards to poles
Depth (km)
abiotic
biotic
$\delta^{13}C$ (‰)
3.0
-0.5
-90
-60
-30
0
30
60
90
S
N

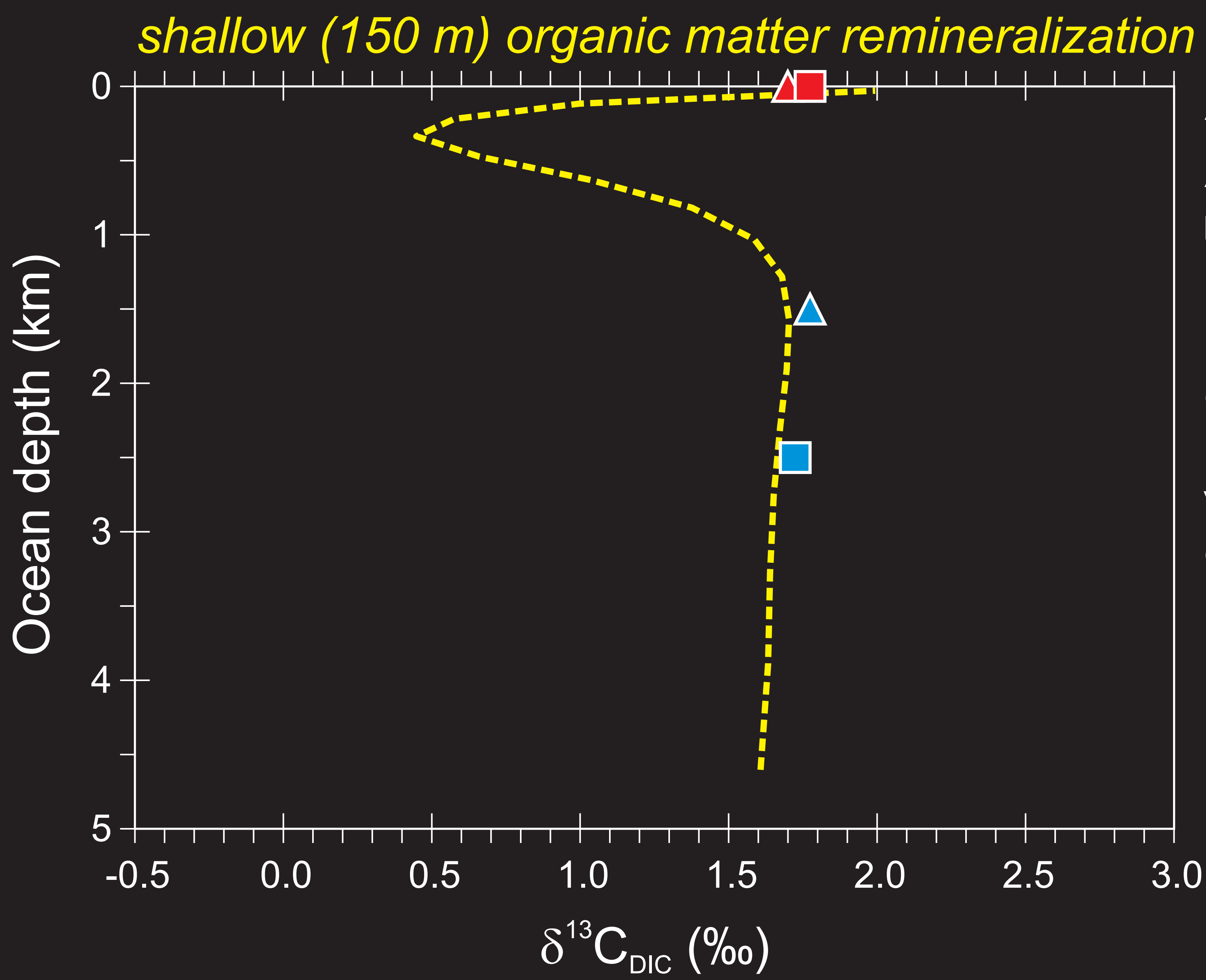
Evolution of the Biological Pump: 'Hiccups'



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?

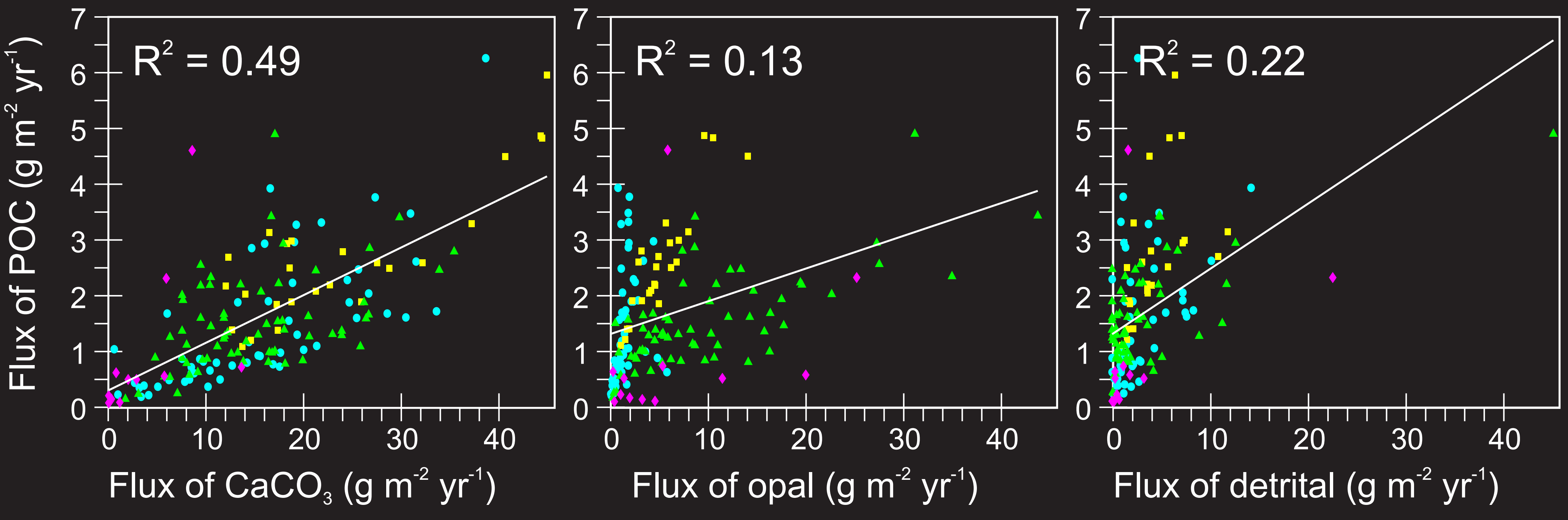
Evolution of the Biological Pump:

Planktic carbonate production and 'ballasting'

Compilation of sediment trap observations:

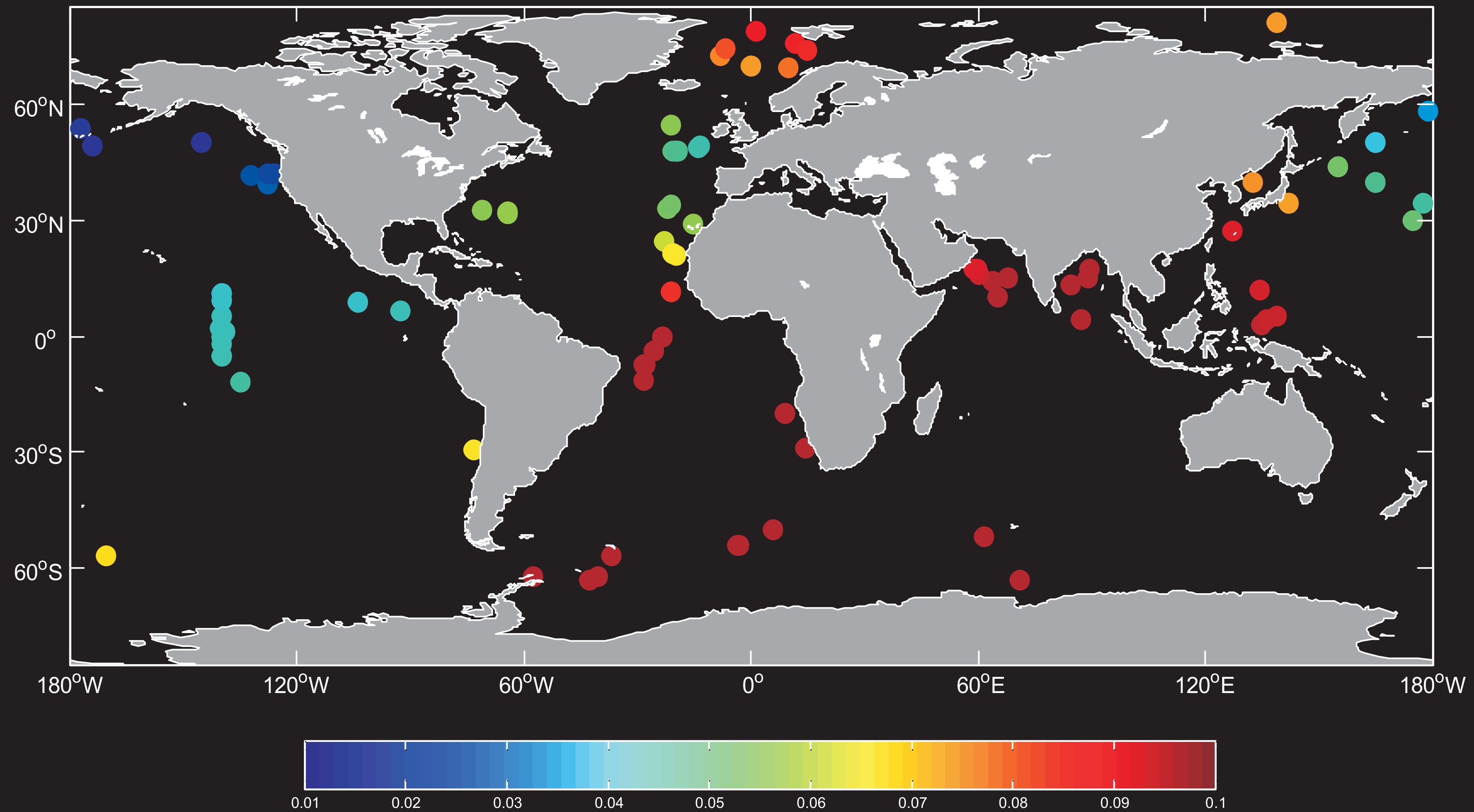
depths >= 2000 m to exclude hydrodynamically distorted fluxes and relationships, and differentiated by basin: cyan == Atlantic, yellow == Indian, green == Pacific, magenta == Southern Ocean.

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



Evolution of the Biological Pump:

Planktic carbonate production and 'ballasting'



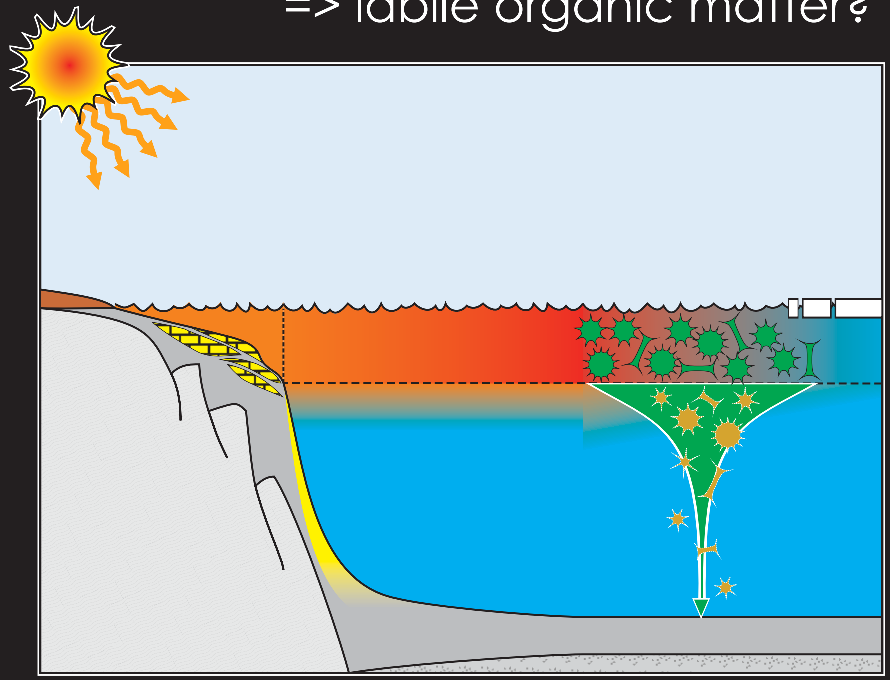
Spatial distribution of carrying capacity (ballasting) coefficients calculated using geographically weighted regression analysis for $CaCO_3$.

Wilson et al. [2012]

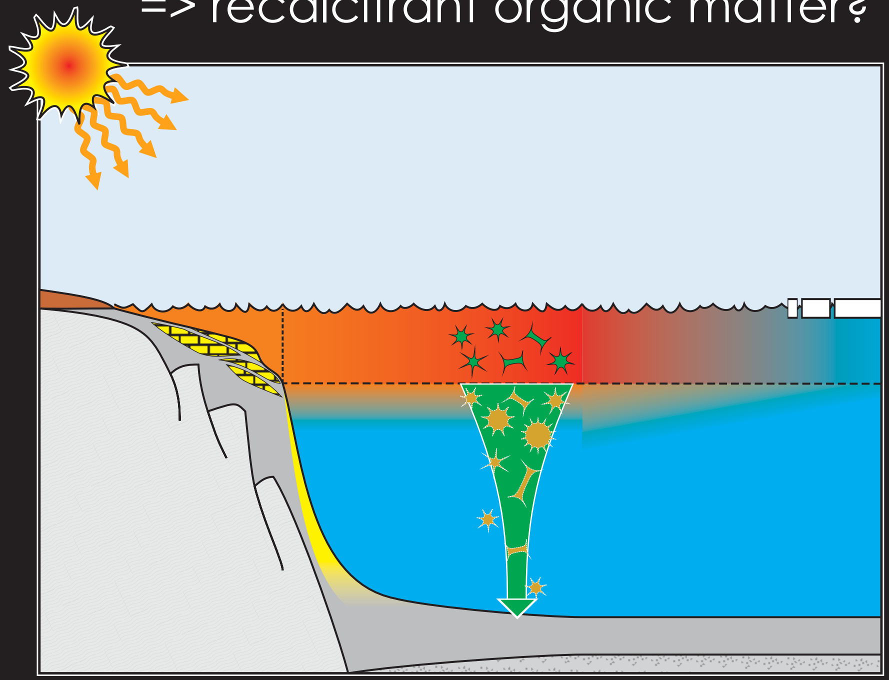
Evolution of the Biological Pump:

Planktic carbonate production and 'ballasting'

High productivity and export efficiency, but low biological pump efficiency.
=> labile organic matter?

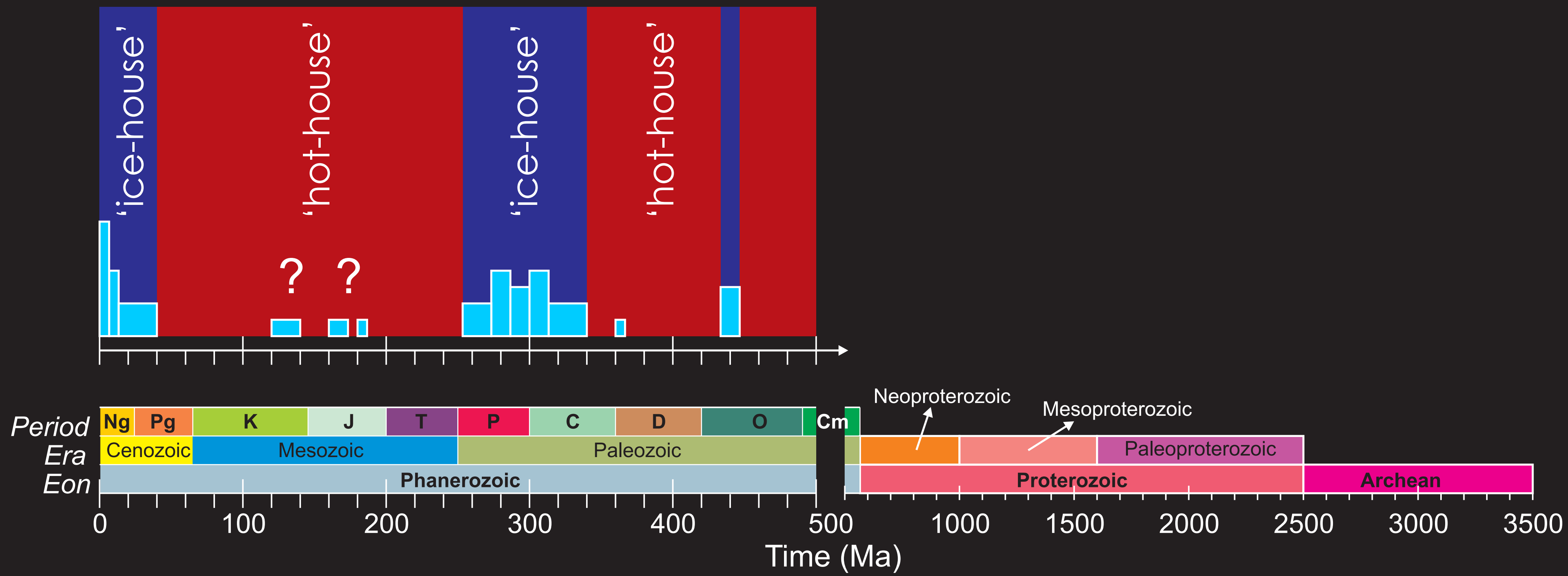


Low productivity and export efficiency, but high biological pump efficiency.
=> recalcitrant organic matter?



Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



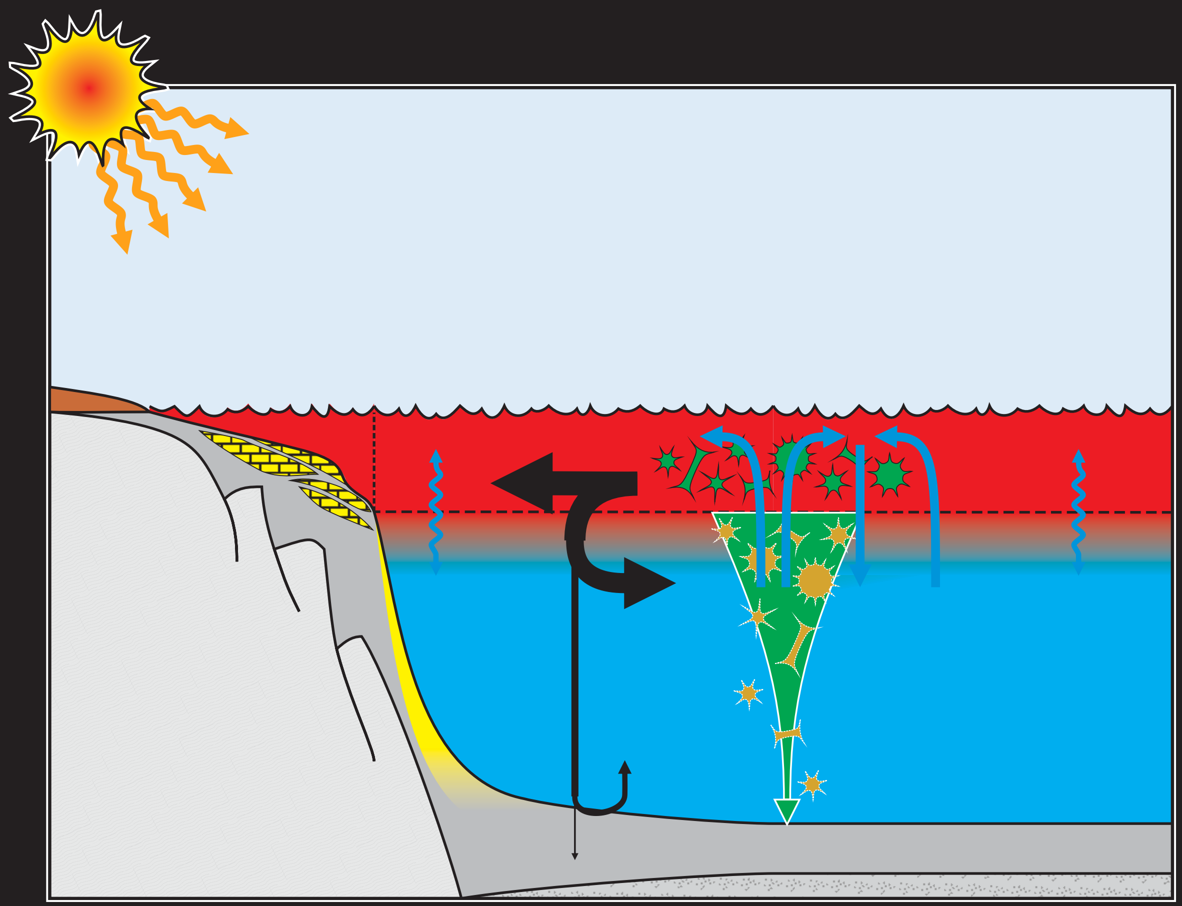
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates

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

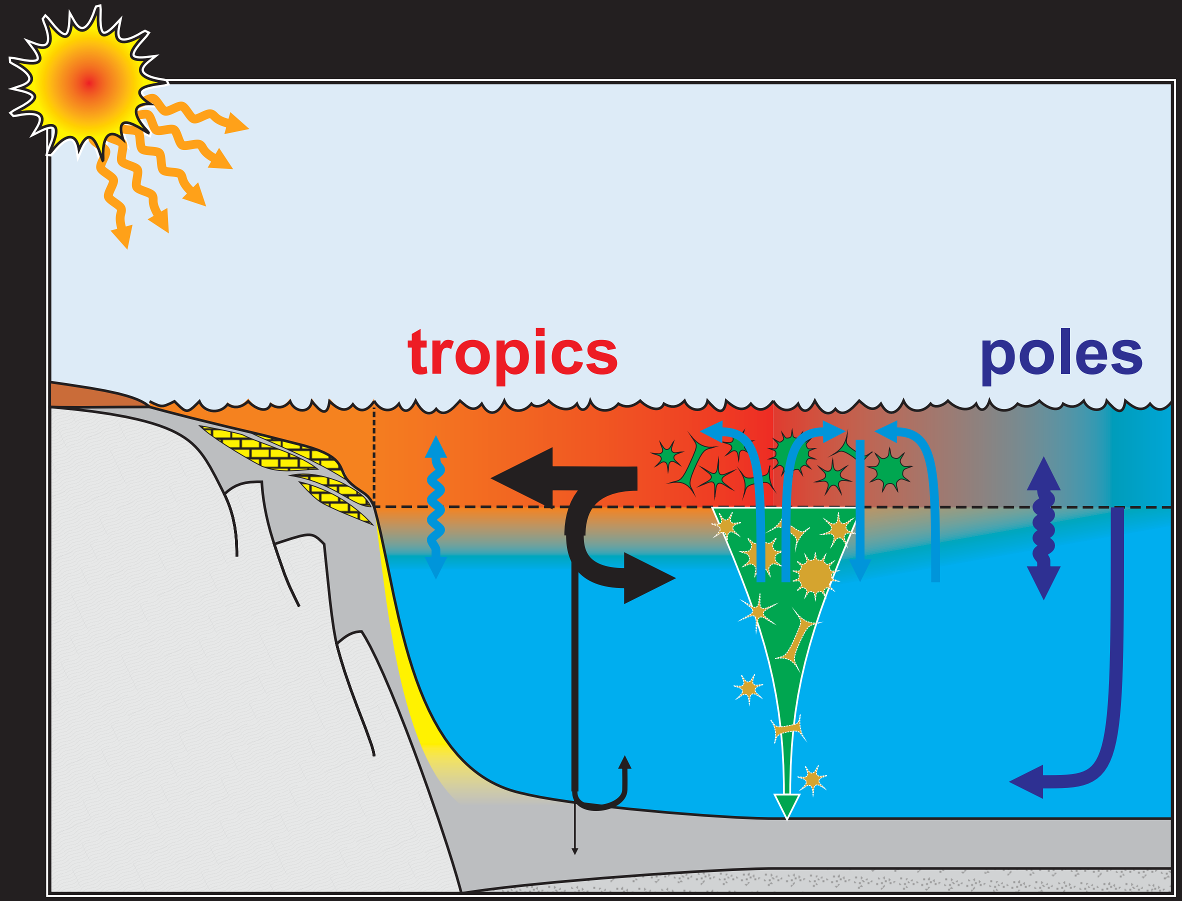
???

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



Evolution of the Biological Pump:

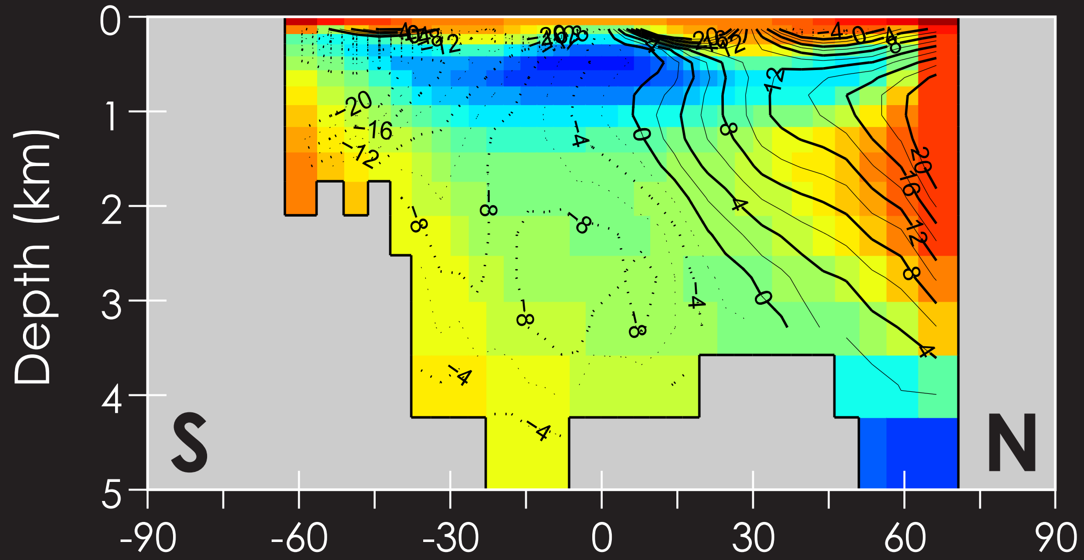
Ocean Carbon Cycling and Oxygenation in Warm Climates

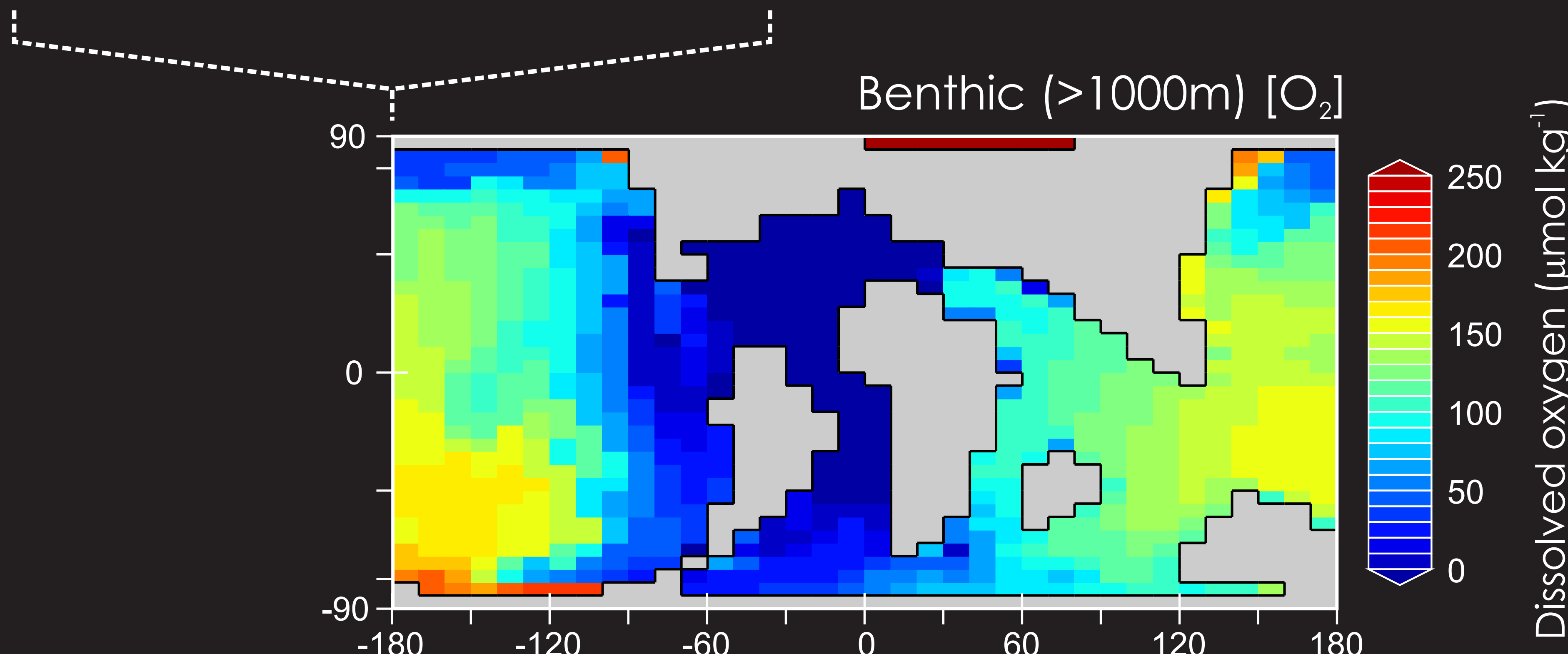


Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates

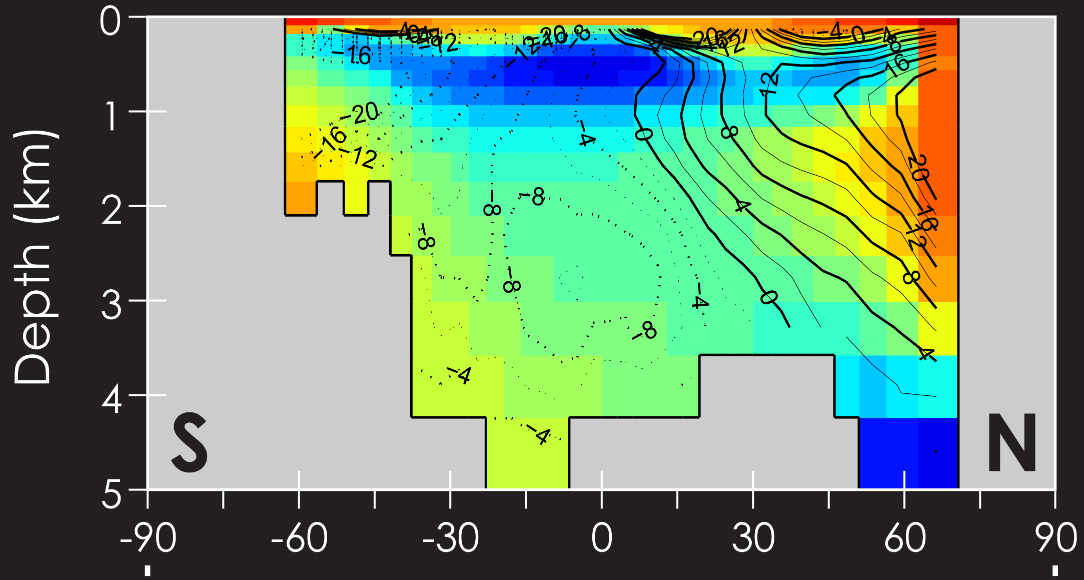
x4 CO_2 reference simulation





Evolution of the Biological Pump:

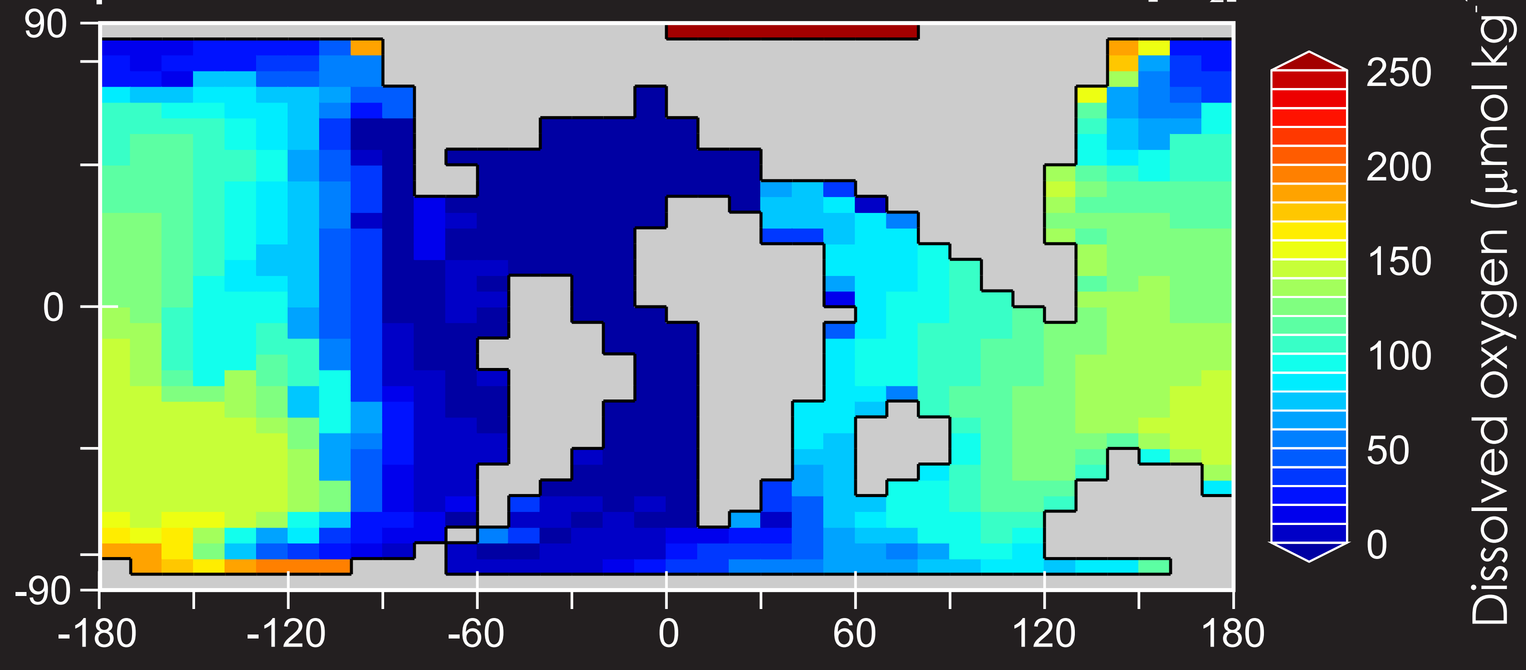
Ocean Carbon Cycling and Oxygenation in Warm Climates



x8 CO_2 @ 10,000 yrs

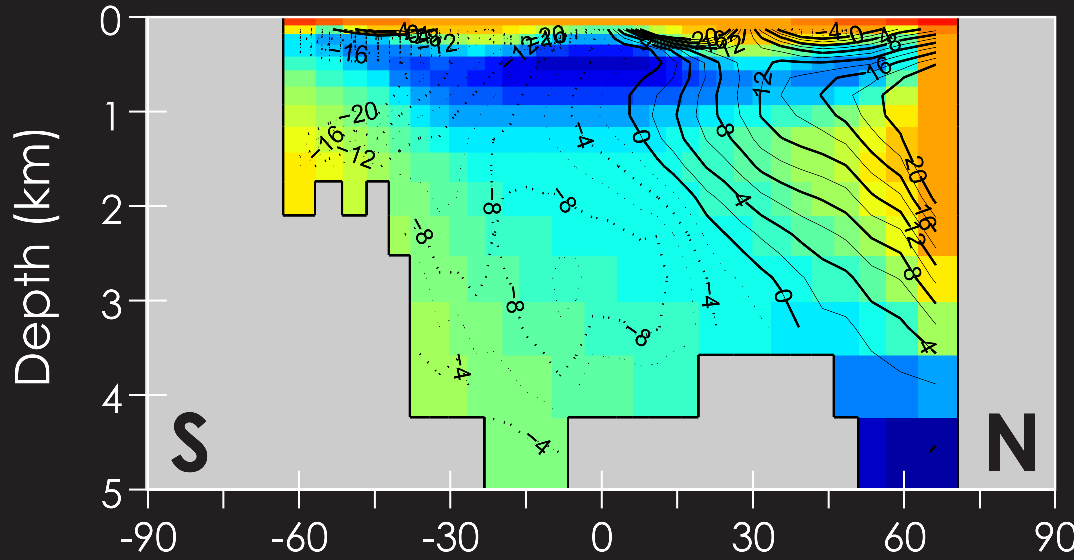
(started from end of the x4 simulation)

Benthic $[O_2]$



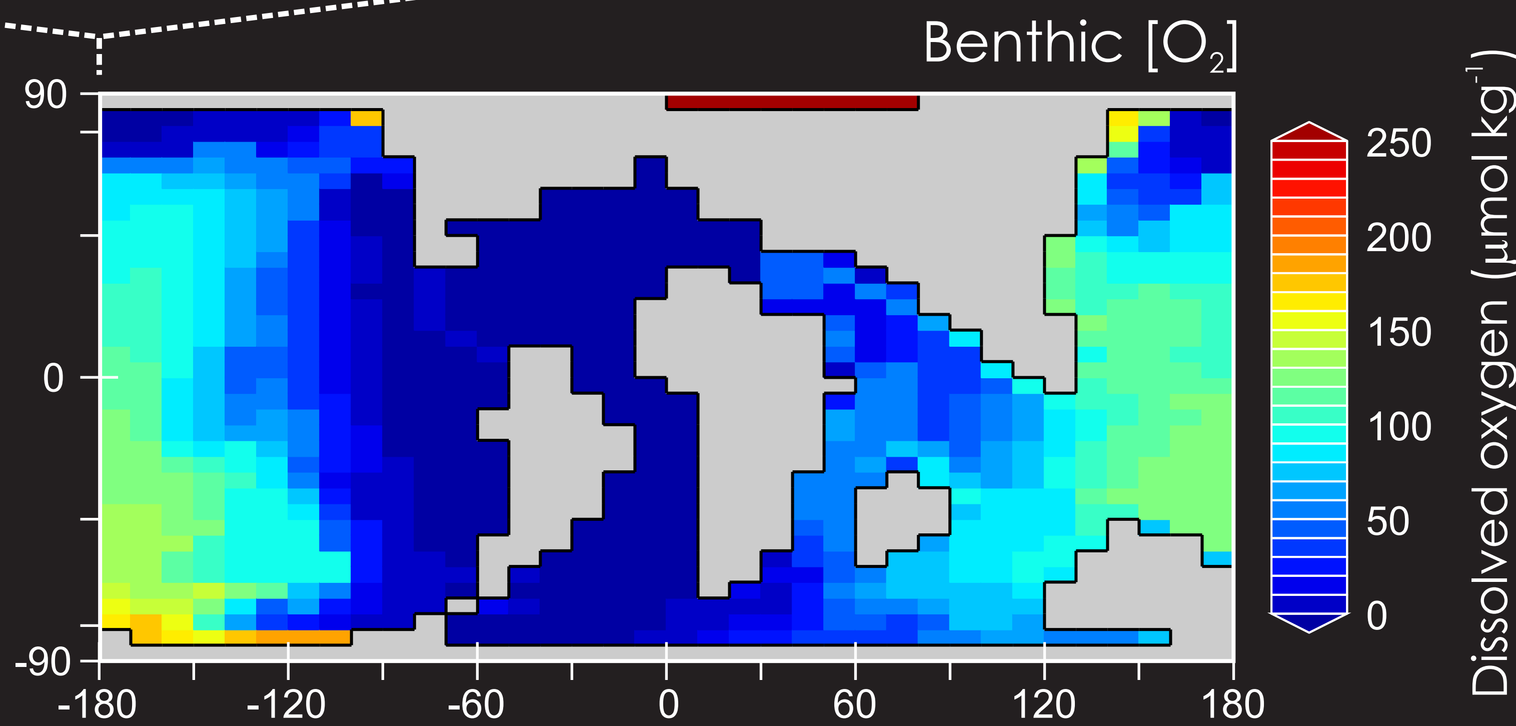
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



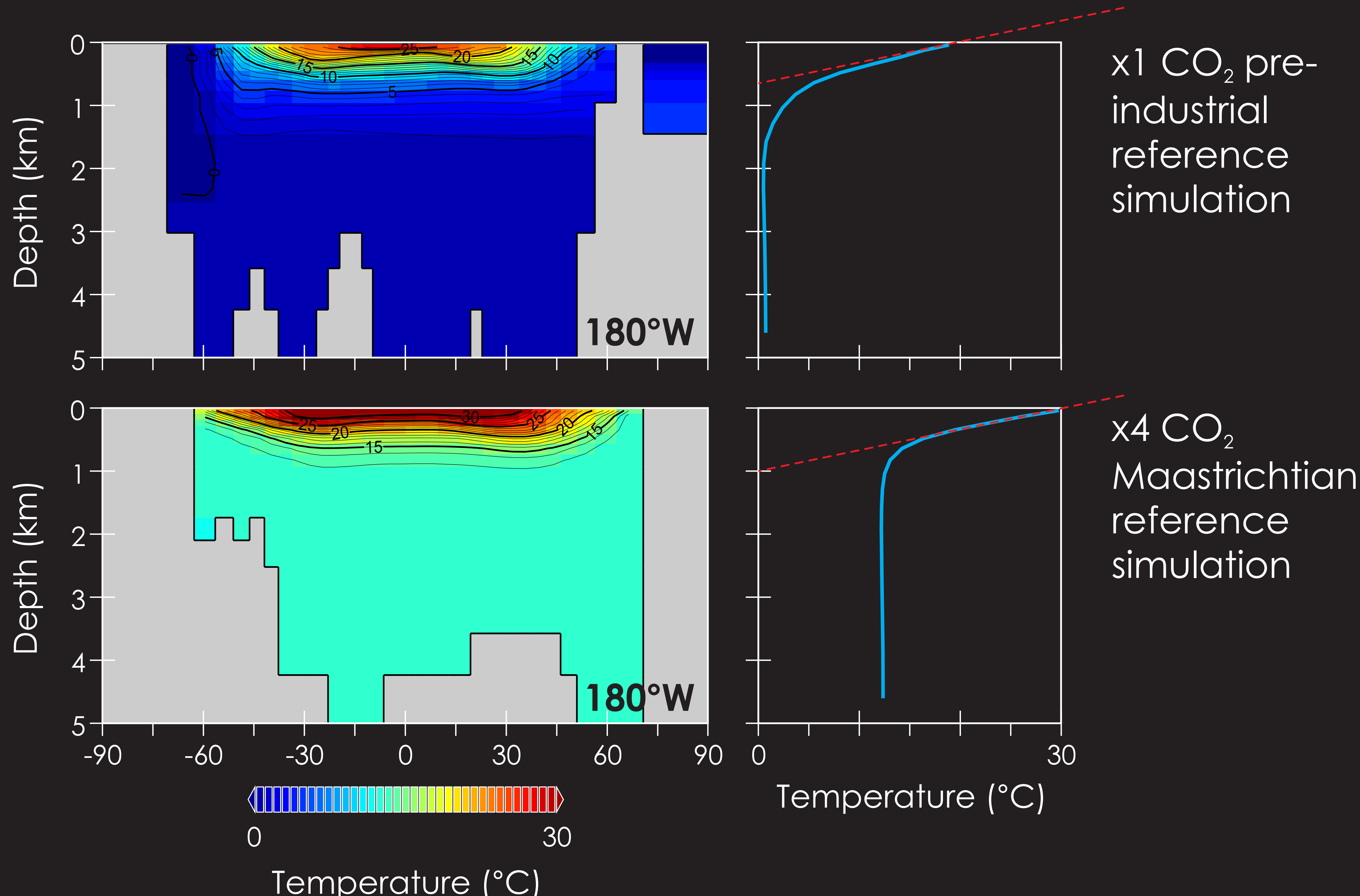
x16 CO_2 @ 10,000 yrs

(started from end of the x4 simulation)



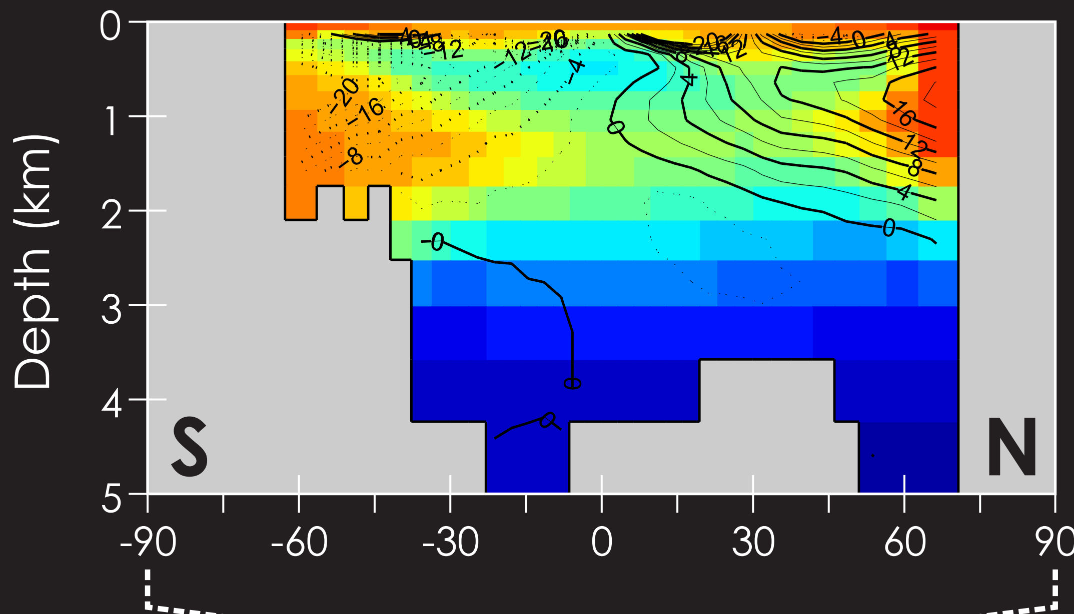
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



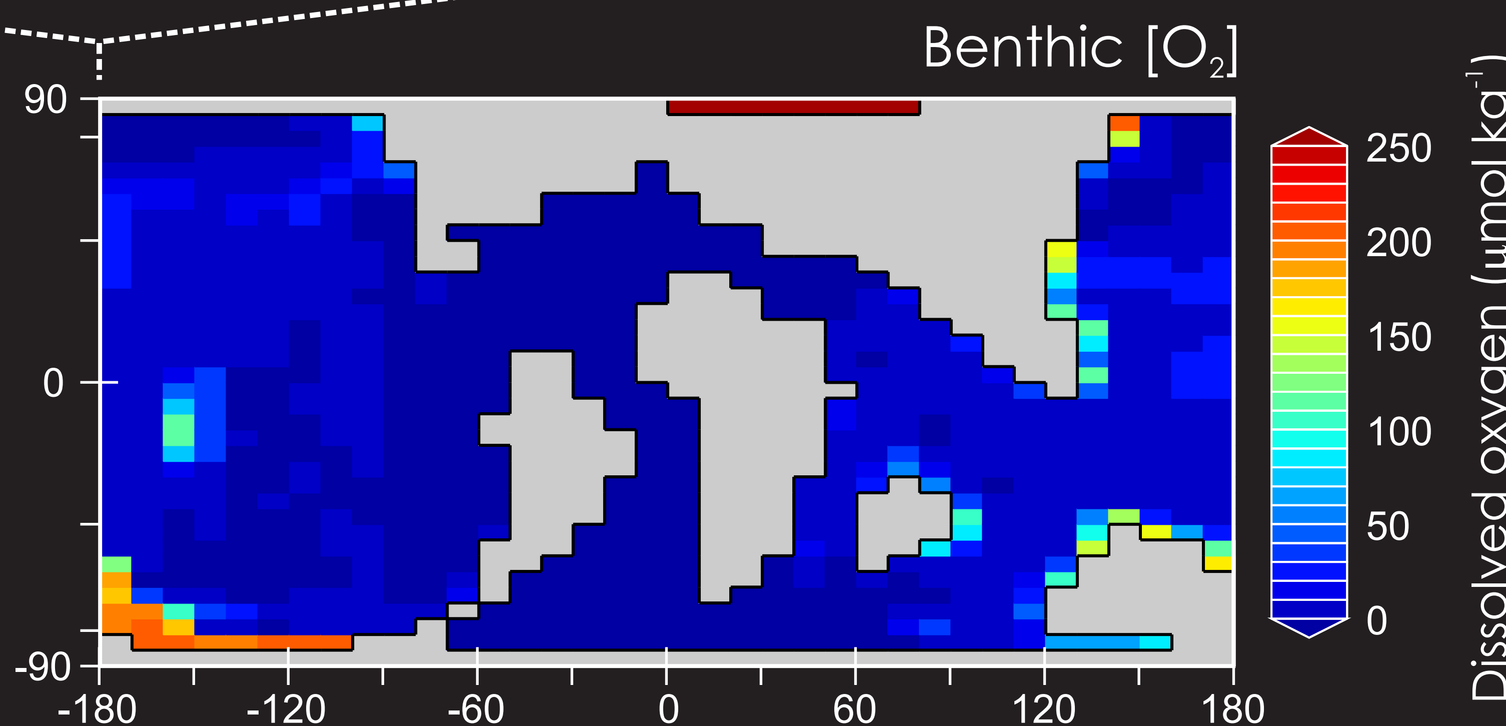
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates

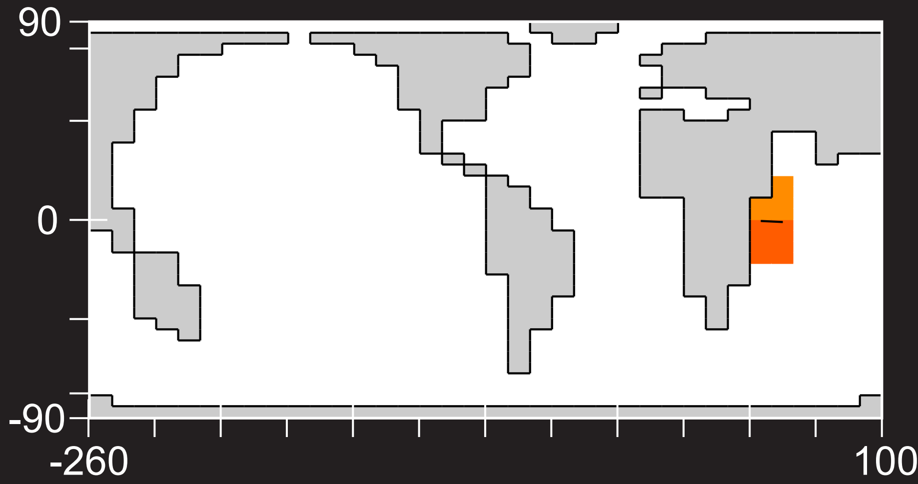


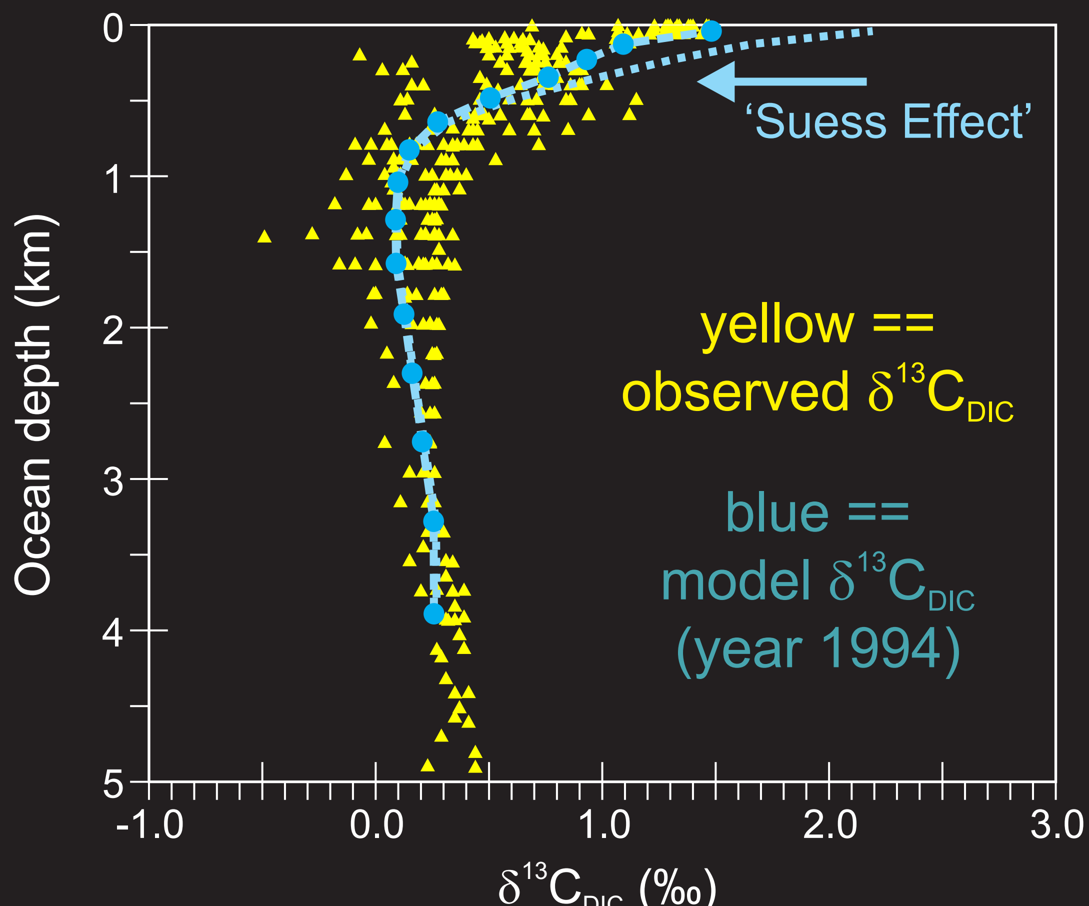
x16 CO_2 @ 2,000 yrs

transient state
(incomplete adjustment to
increased radiative forcing)



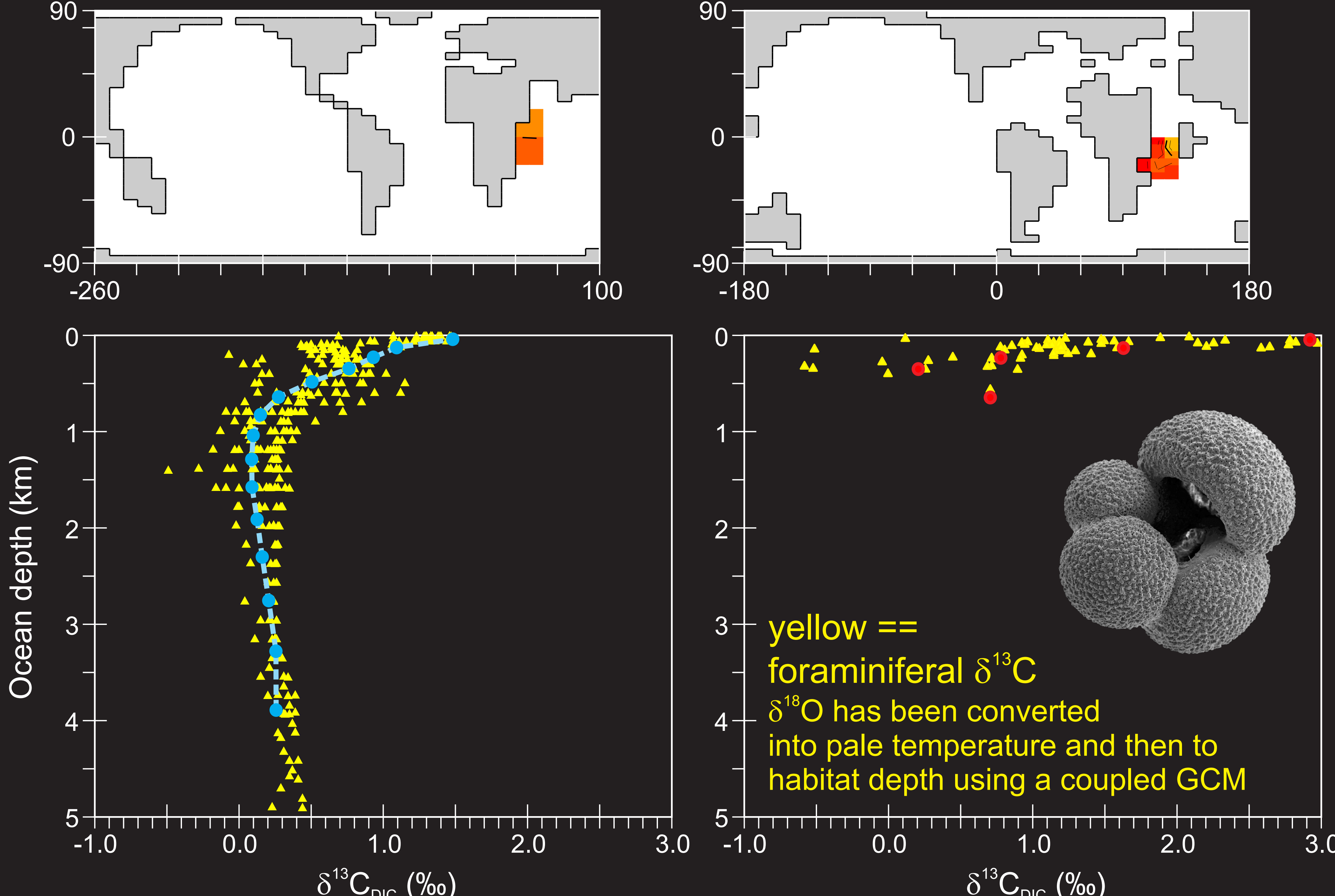
Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania



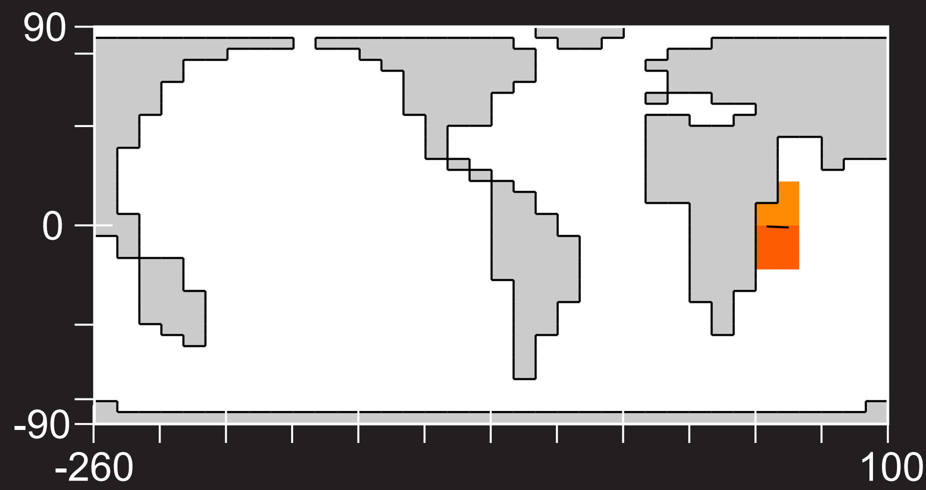


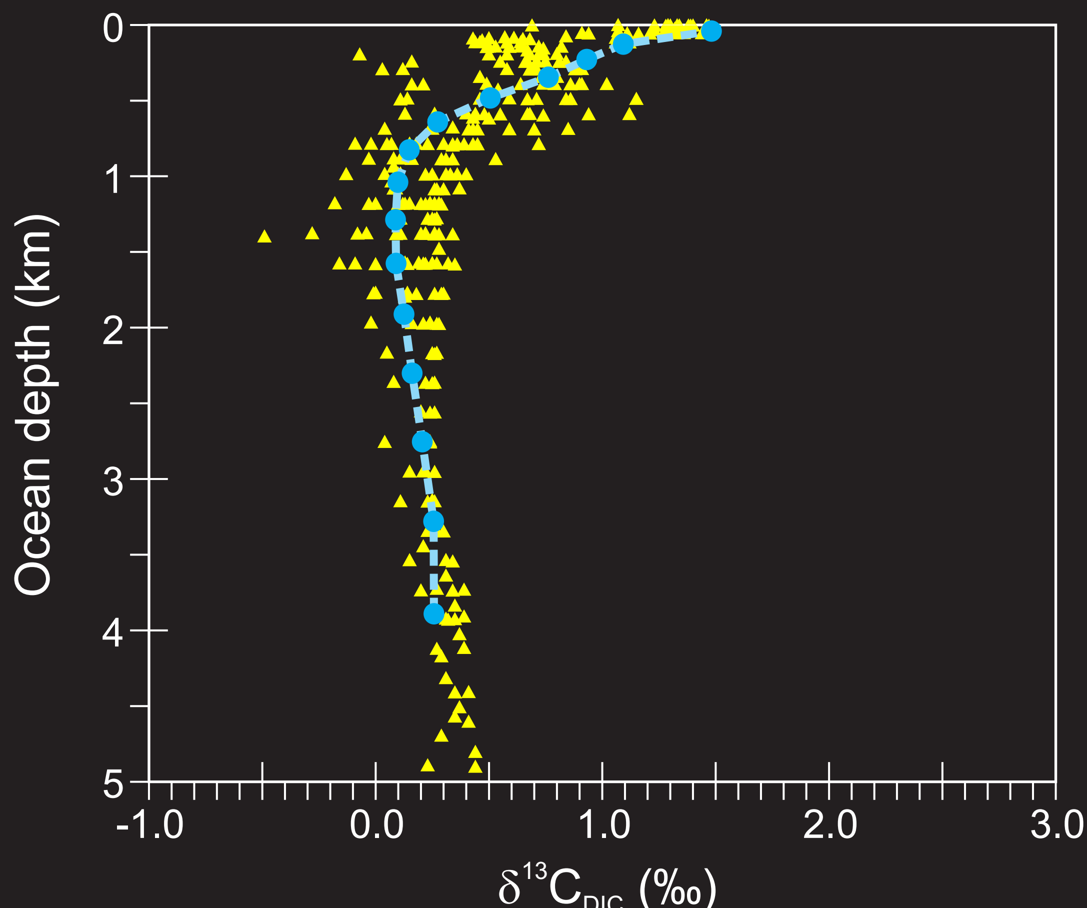
Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania

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

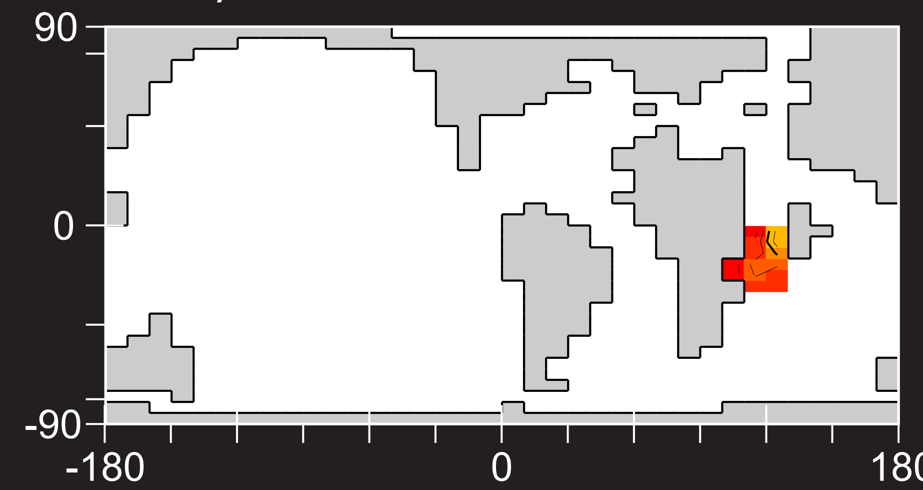


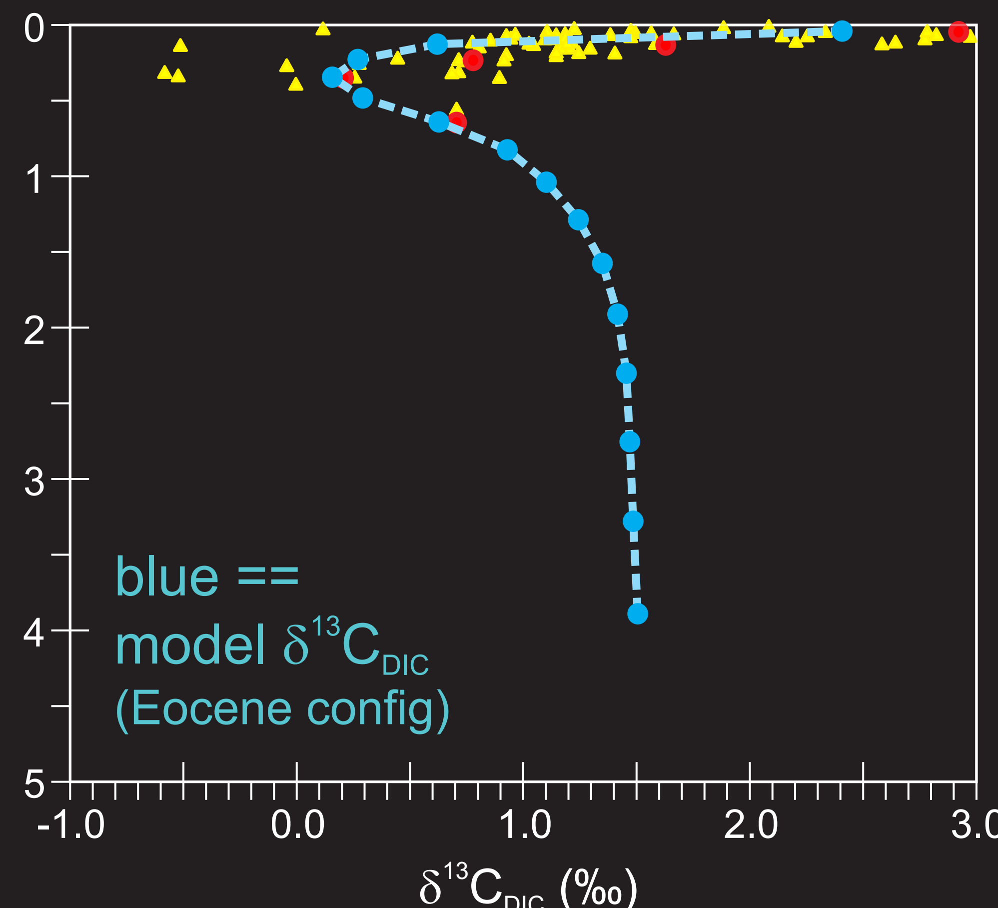
Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania



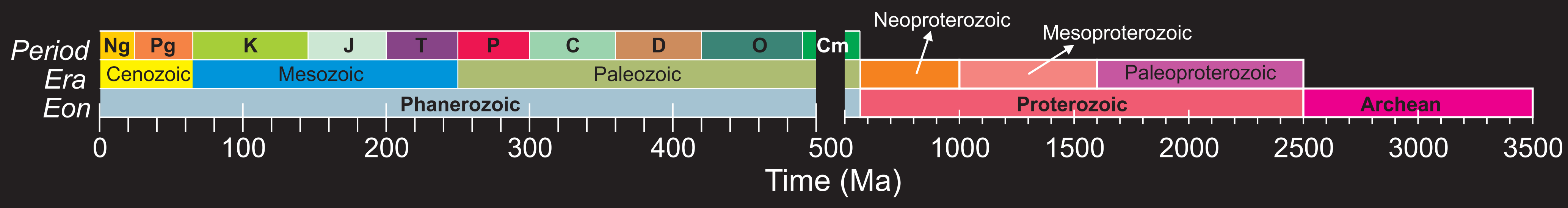


Planktic foraminiferal $\delta^{13}C$ from early Eocene Tanzania



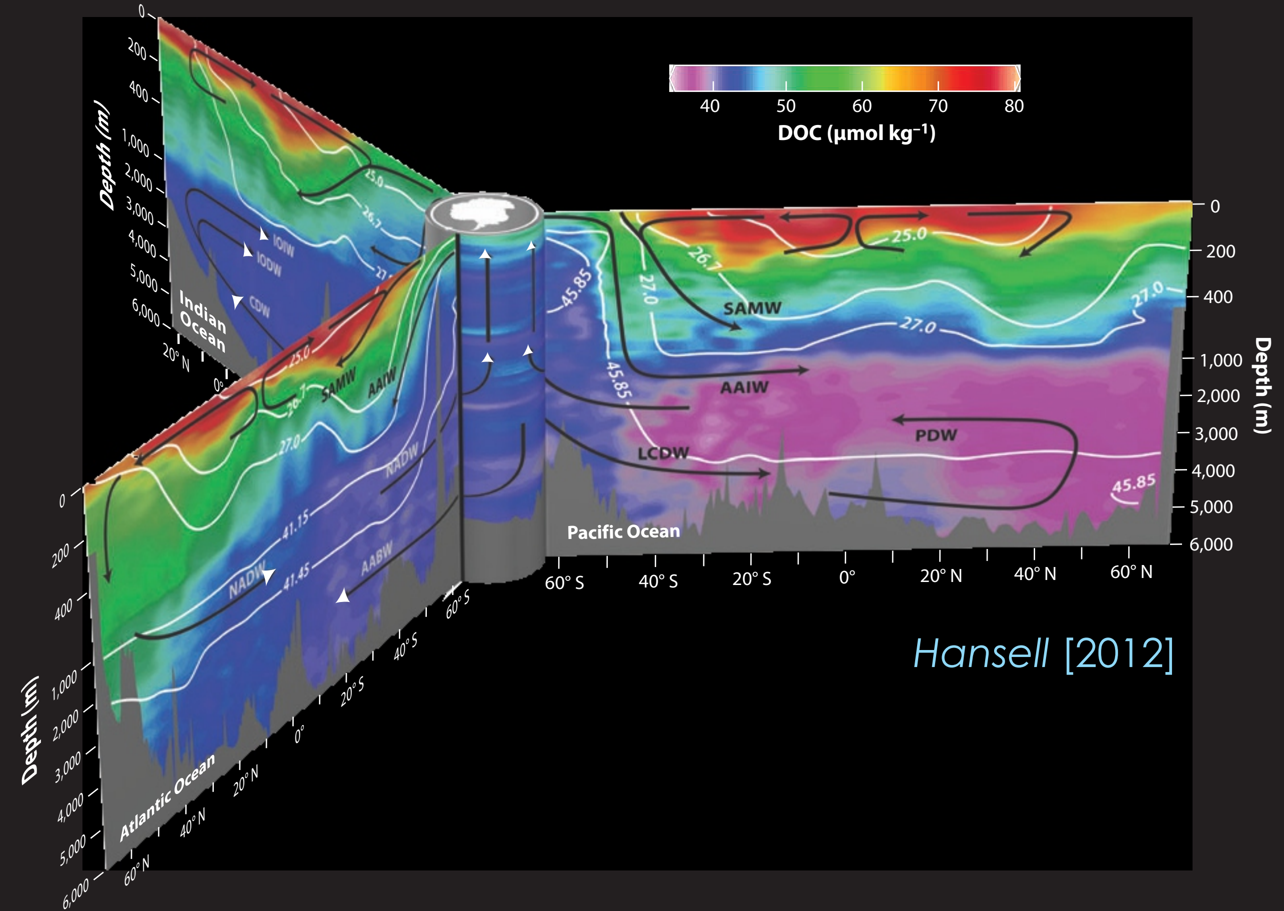


Evolution of the Biological Pump

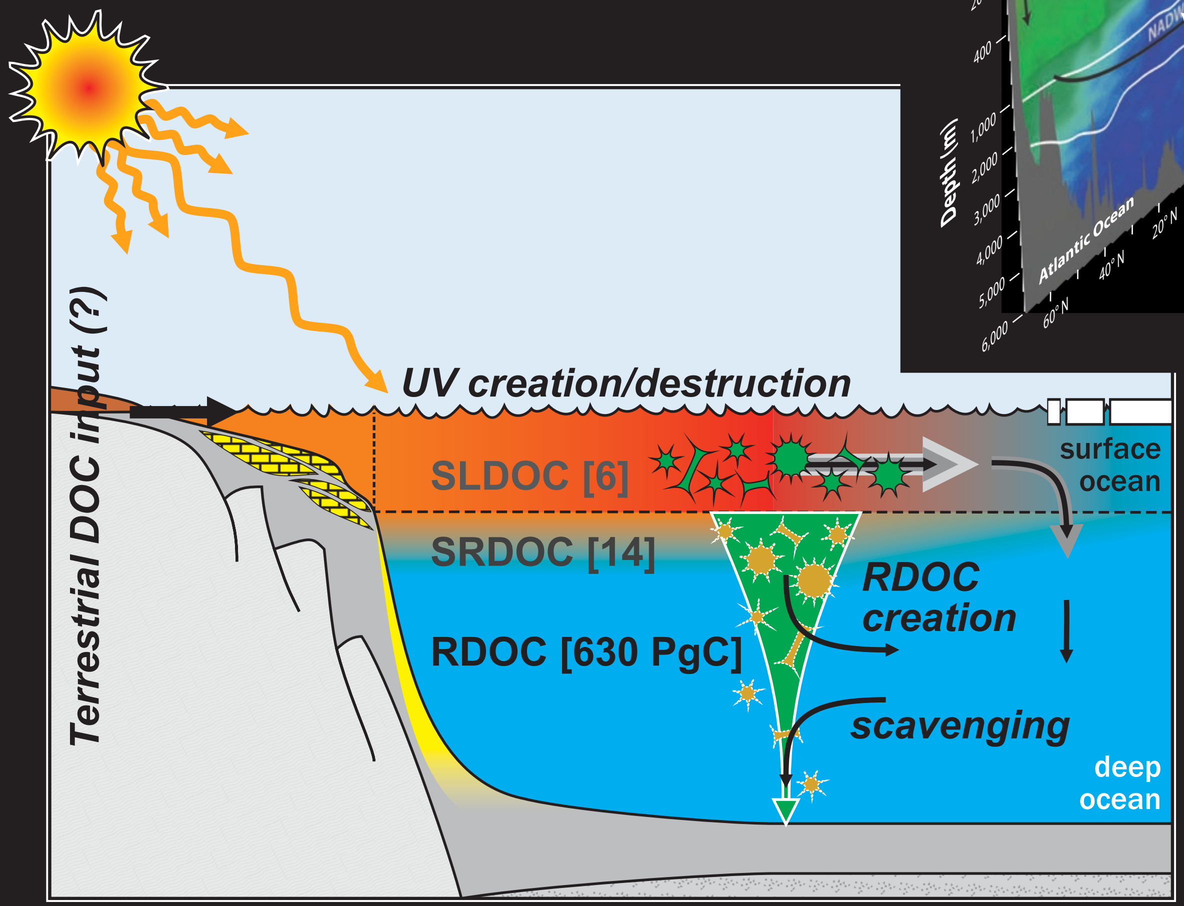


Evolution of the Biological Pump:

Dissolved organic matter

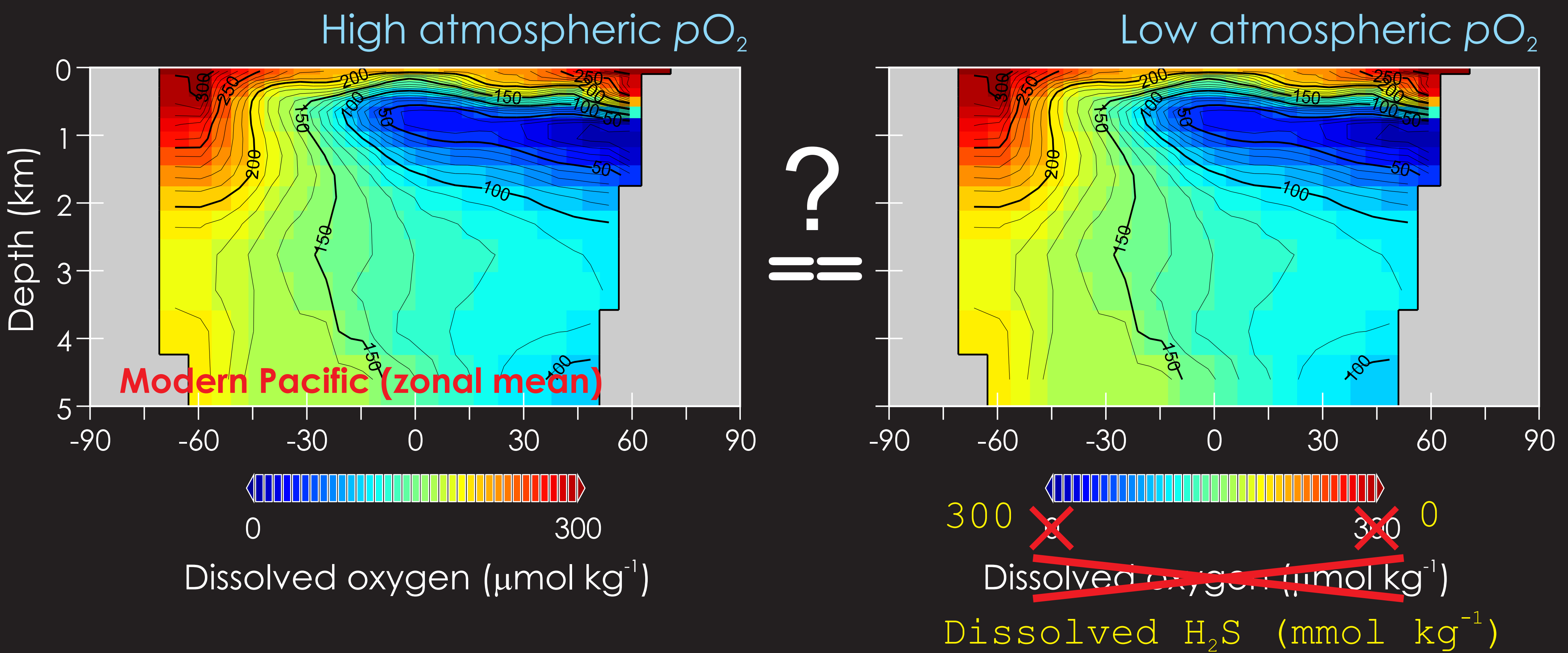


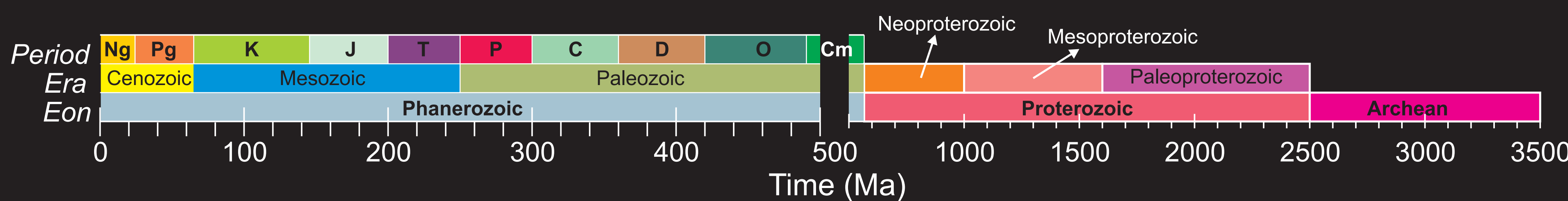
Hansell [2012]

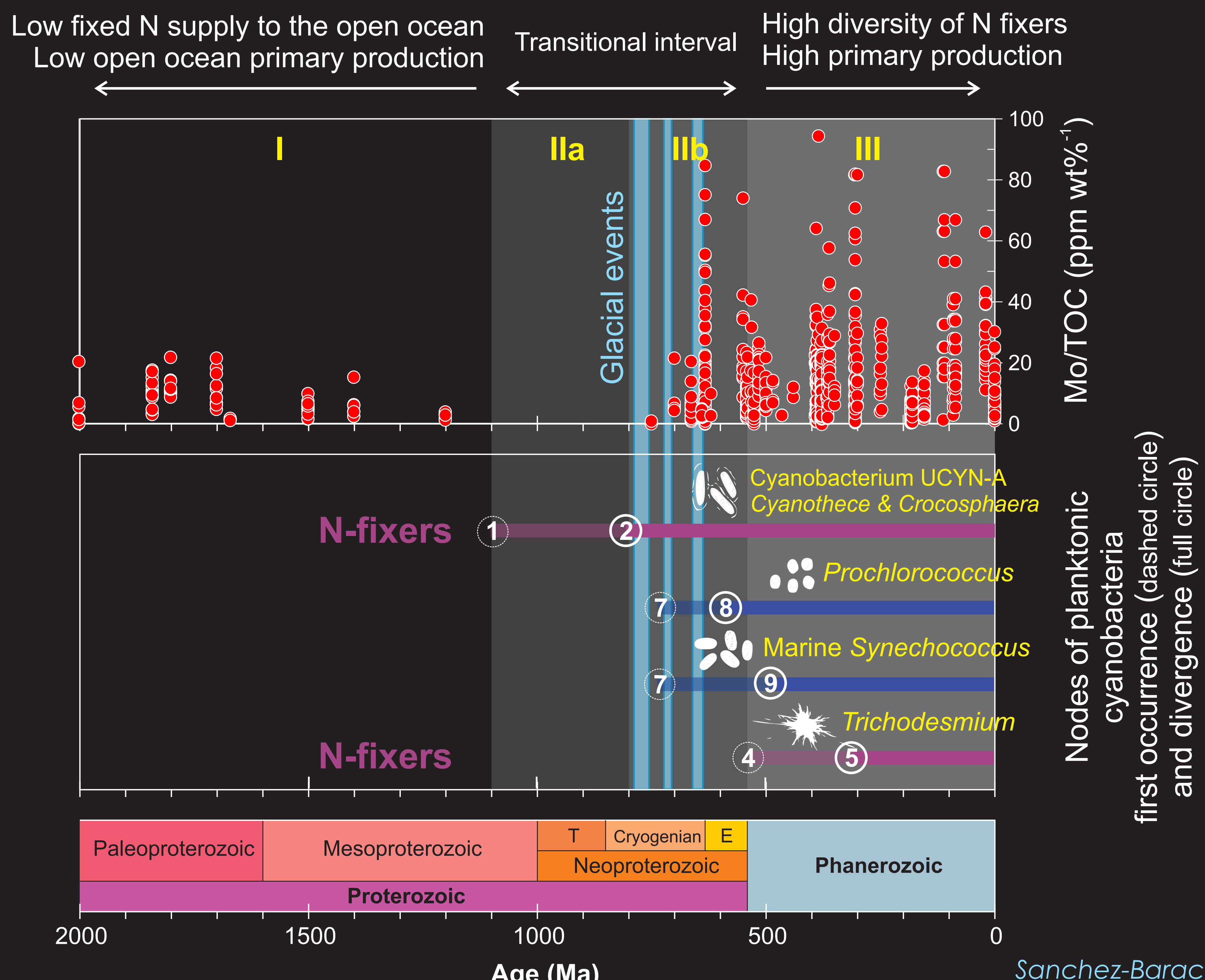


Evolution of the Biological Pump:

Dissolved organic matter







Sanchez-Baracaldo et al. [2014]

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