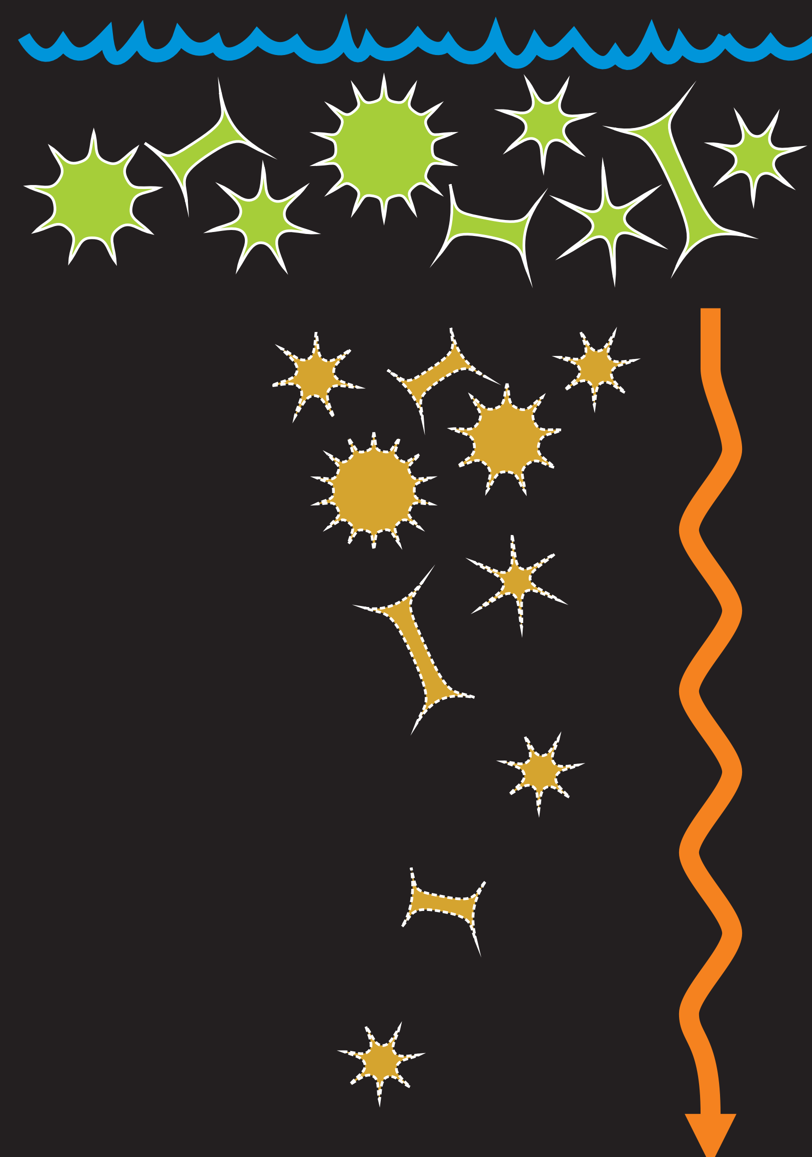
Evolution of the Ocean's Biological Pump (*in silico*)

Andy Ridgwell



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Evolution of the Biological Pump

The processes that govern the partitioning of carbon (and alkalinity) between the surface ocean (and hence atmosphere) and ocean interior, are traditionally described in terms of three conceptual 'pumps':

(1) The 'solubility' pump.

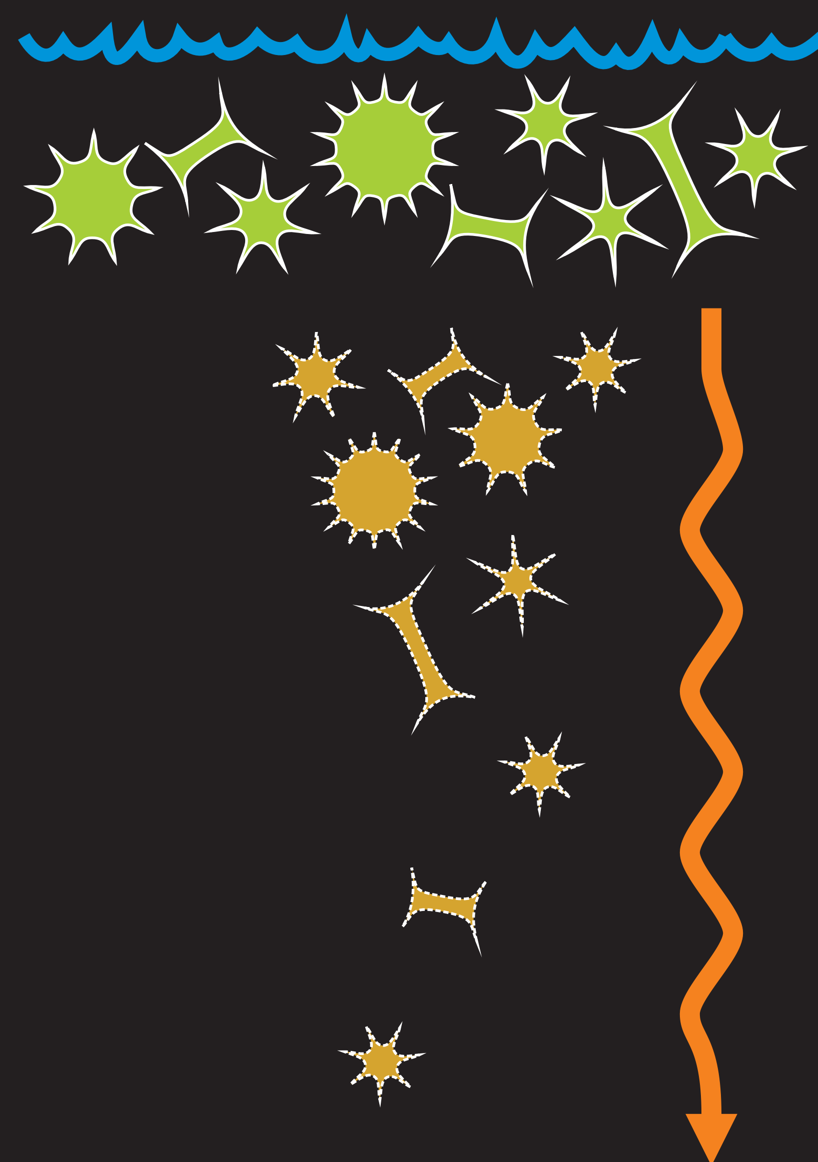
(2) The 'organic matter' (or 'soft tissue') pump.

(3) The 'carbonate' (or 'counter') pump.

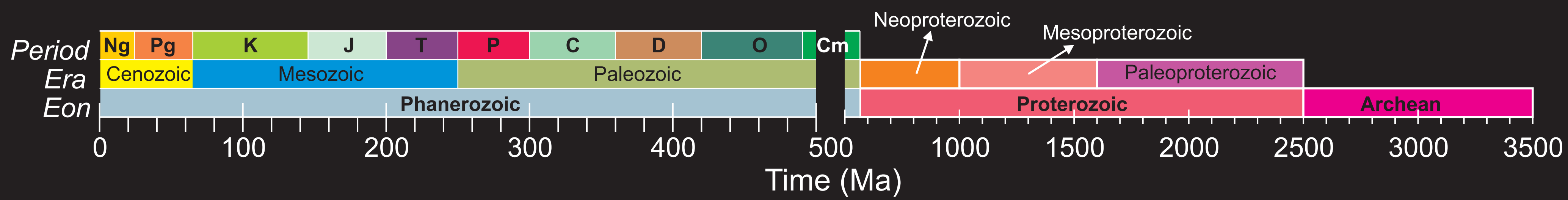
This conceptual framework has more recently extended by a fourth component:

(4) the microbial carbon pump.

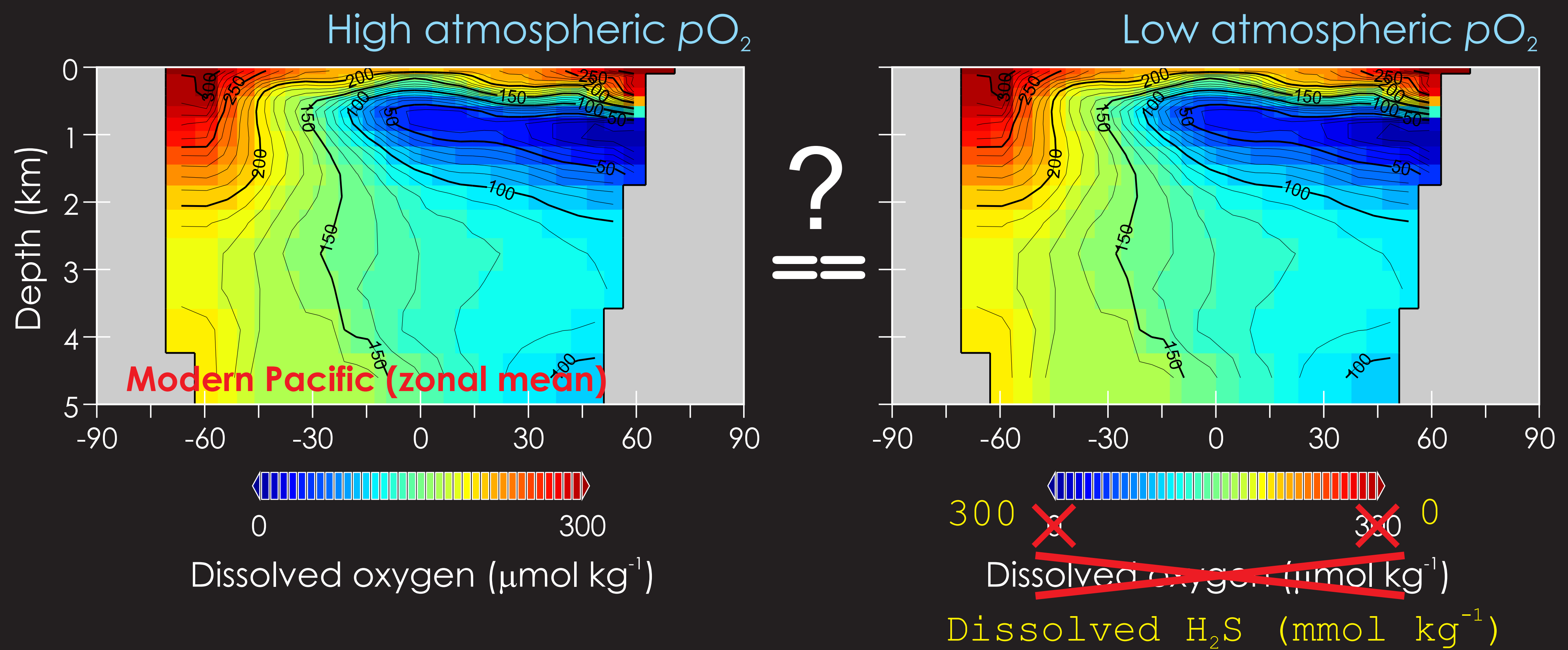
'the biological pump'

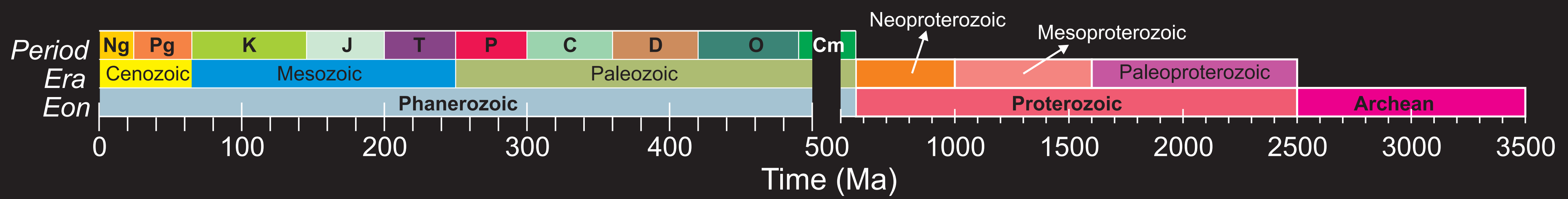


Evolution of the Biological Pump

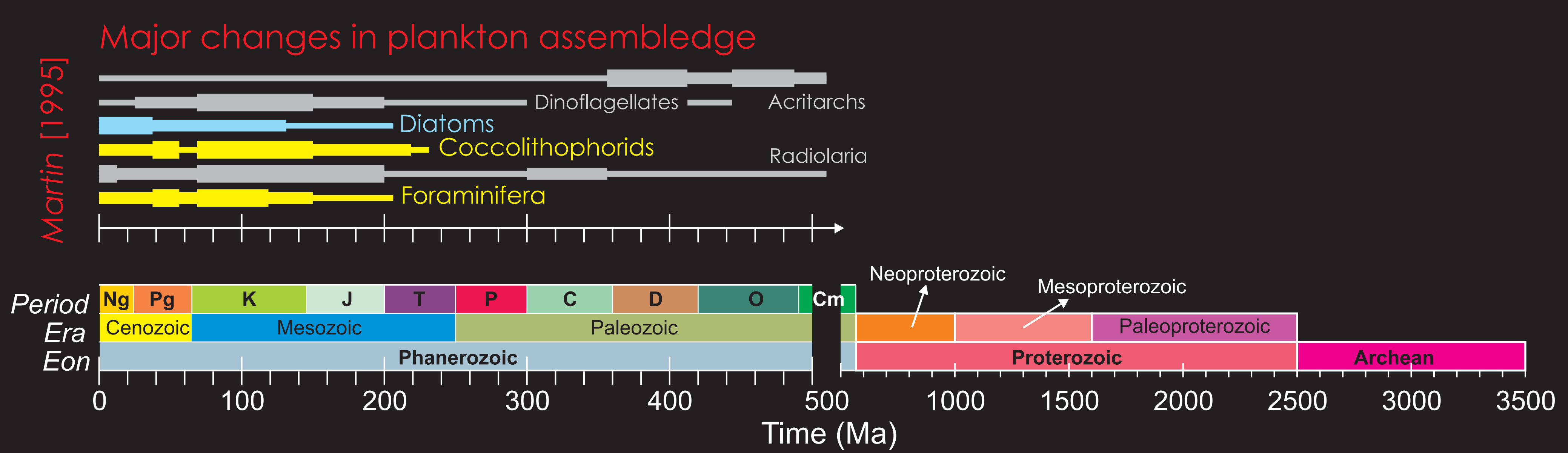


Evolution of the Biological Pump

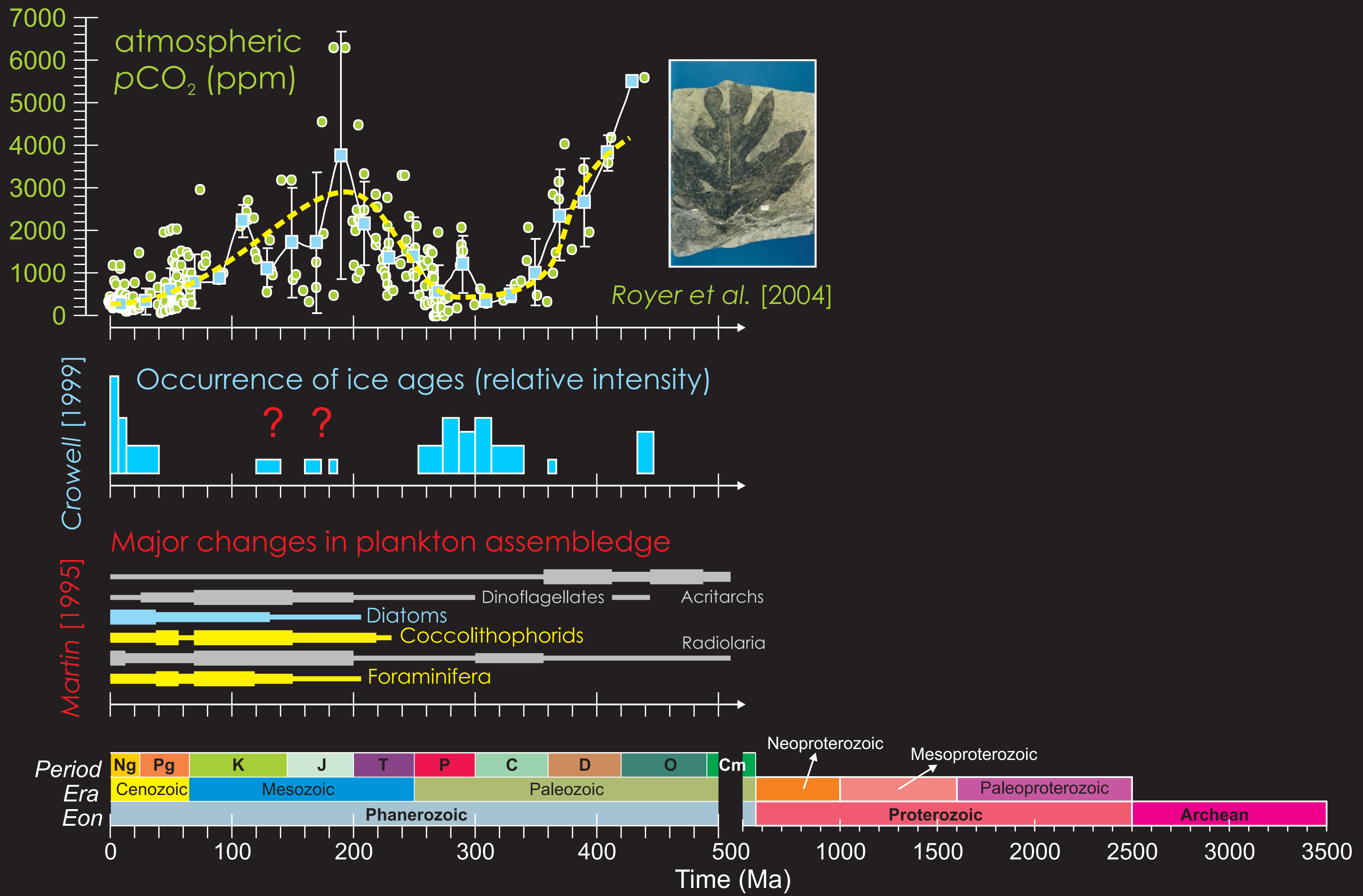




Evolution of the Biological Pump



Evolution of the Biological Pump



Evolution of the Biological Pump: TALK OUTLINE

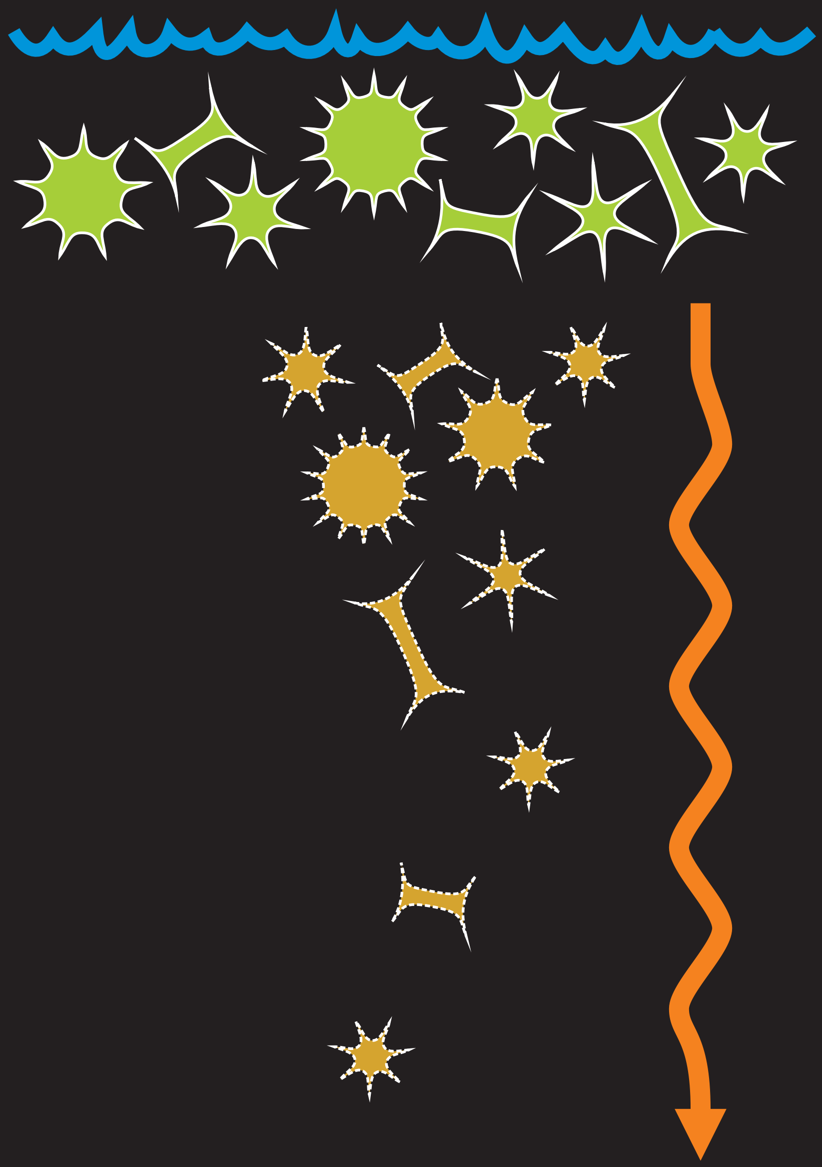
(1) Interrogating the biological pump *in silico*.

(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: The end-K as an example.

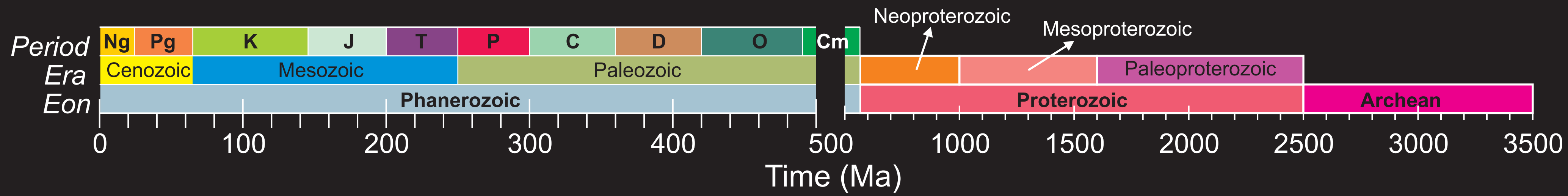
(4) The fundamental importance ... or not, of physical ocean changes and esp. warming.

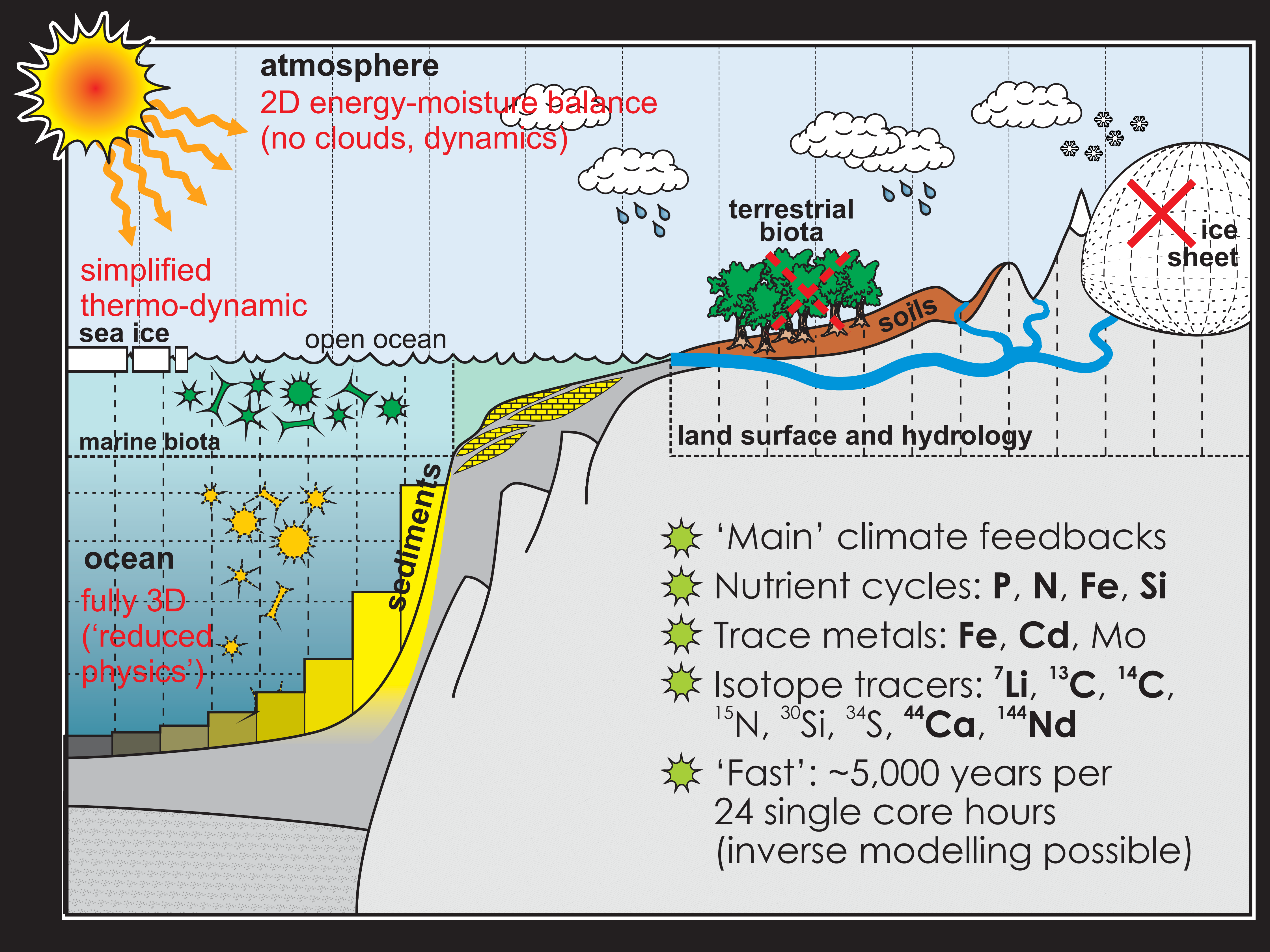
(5) Thinking outside the box.



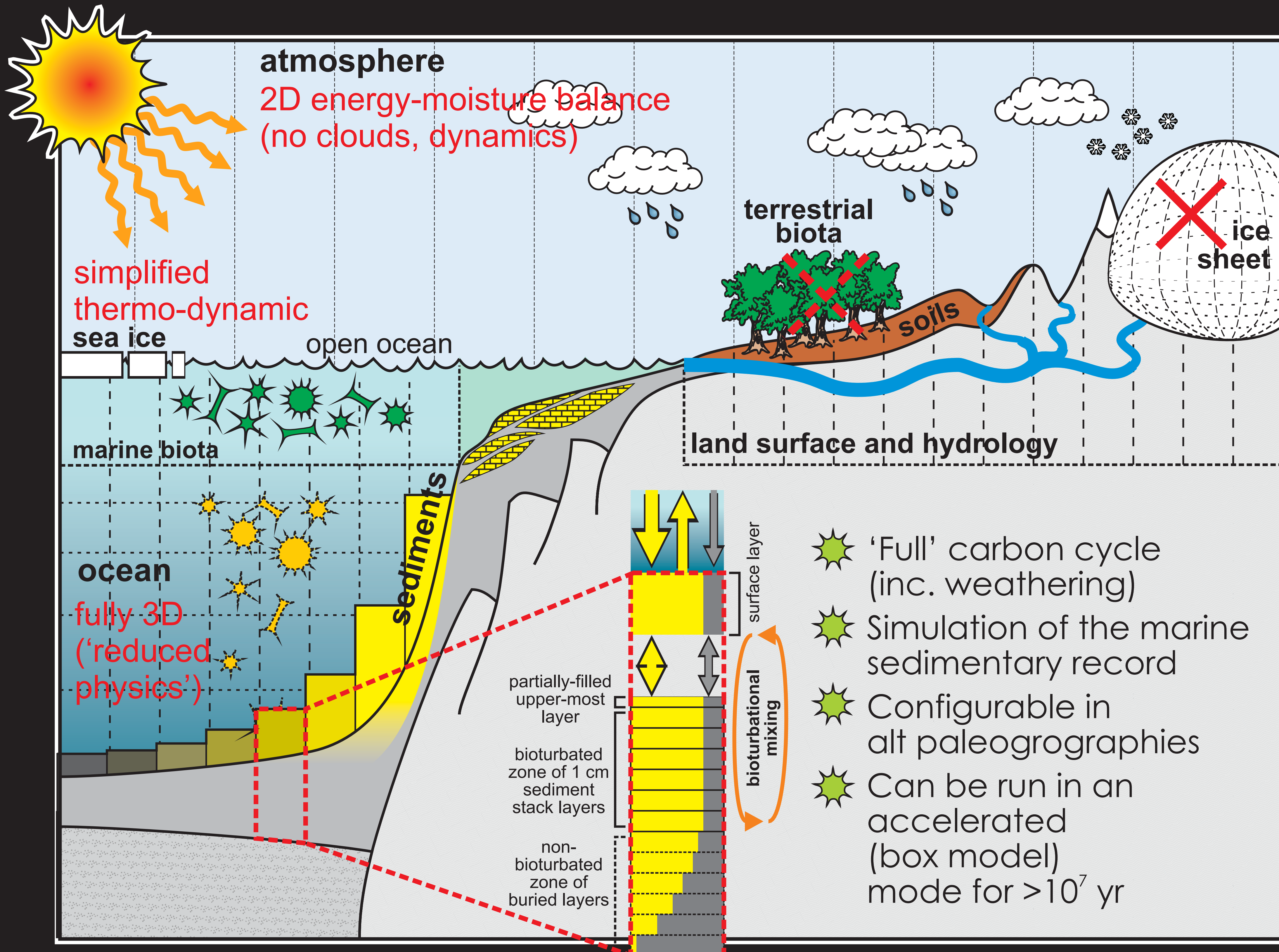
Evolution of the Biological Pump: in silico

```
! 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)
terrestrial
biota
ice
sheet
simplified
thermo-dynamic
sea ice
open ocean
soils
marine biota
land surface and hydrology
sediments
ocean
fully 3D
('reduced
physics')
'Main' climate feedbacks
Nutrient cycles: P, N, Fe, Si
Trace metals: Fe, Cd, Mo
Isotope tracers: ^{7}Li, ^{13}C, ^{14}C,
^{15}N, ^{30}Si, ^{34}S, ^{44}Ca, ^{144}Nd
'Fast': ~5,000 years per
24 single core hours
(inverse modelling possible)


atmosphere
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sea ice
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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
'Full' carbon cycle
(inc. weathering)
Simulation of the marine
sedimentary record
Configurable in
alt paleogrographies
Can be run in an
accelerated
(box model)
mode for >10^7 yr

cGENIE Stanford 2014 version: README

Andy Ridgwell

February 17, 2014

1. To get an exact (read-only) copy of the ('muffin' development branch) cGENIE source code used for the Stanford presentation – in linux, (ideally from your home directory) type:
   svn co https://svn.ggy.bris.ac.uk/subversion/genie/tags/cgenie.Stanford2014 --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: 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

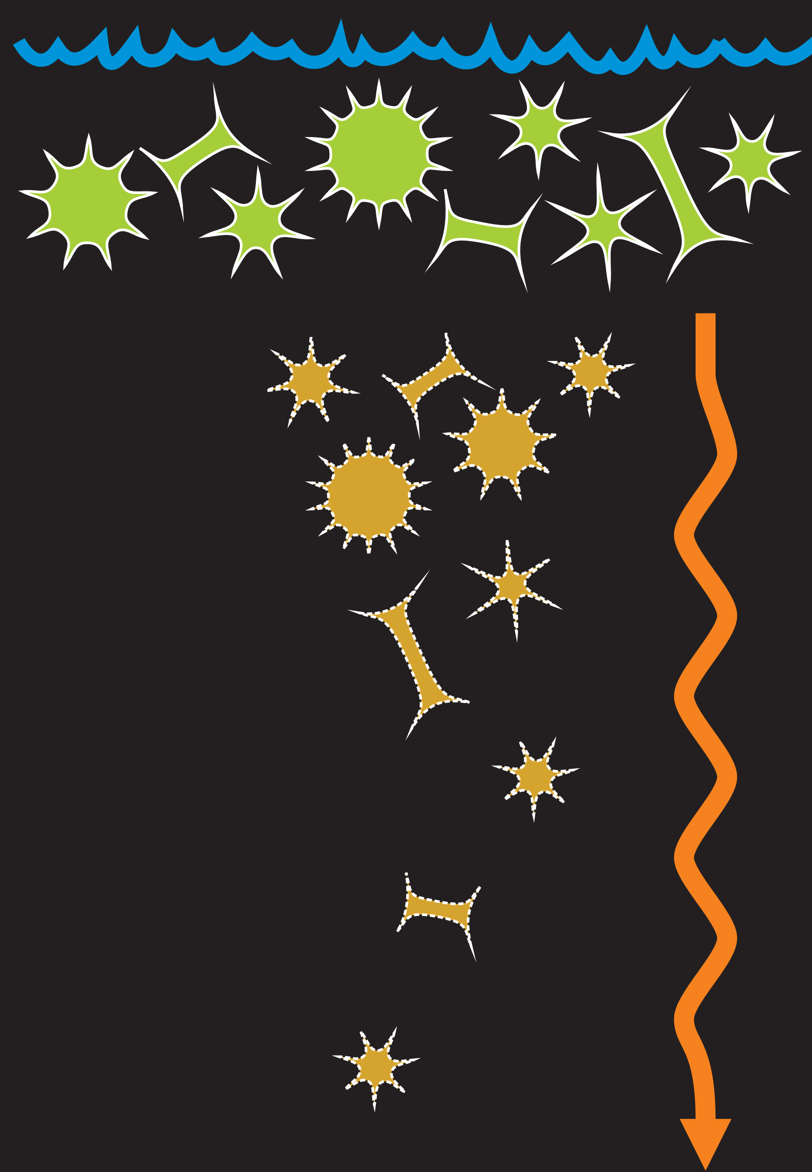
That is is for the basic installation. To run the model, it is a matter of calling the 'runmuffin.sh' shell script from genie-main and supplying a couple of parameter values, e.g.:

./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:

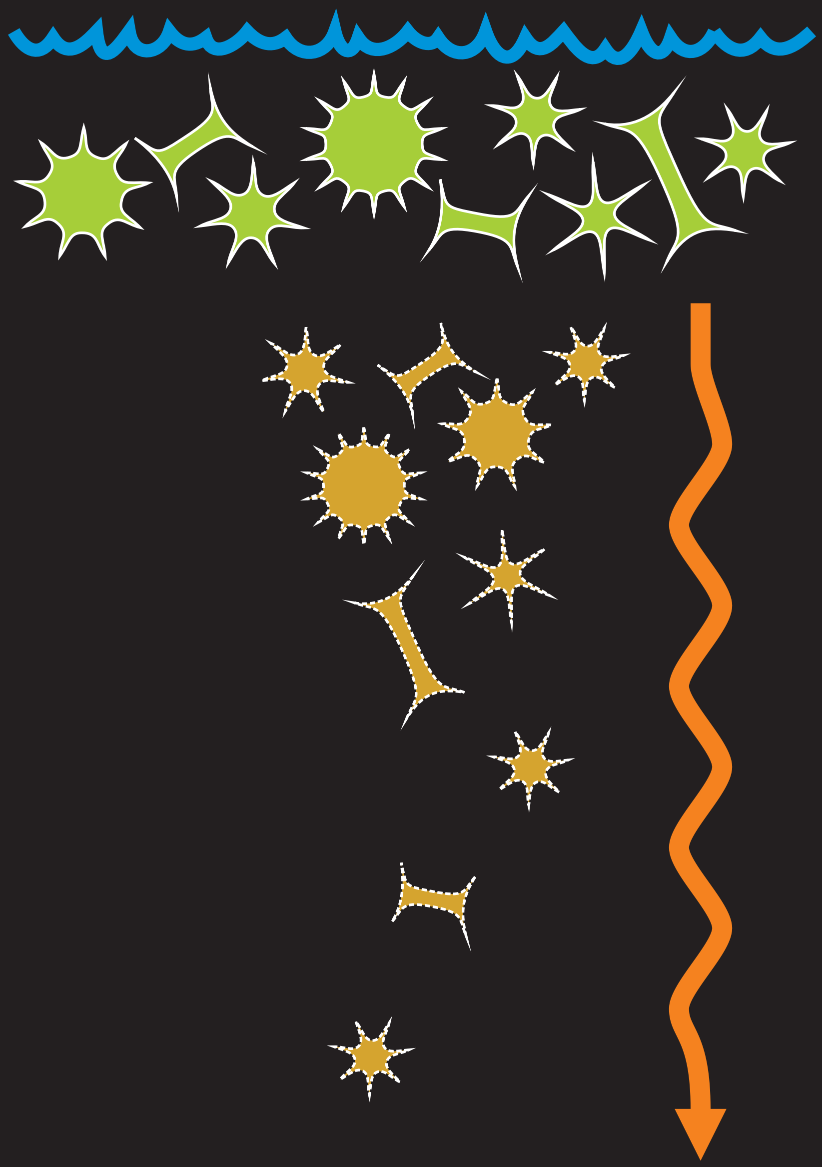
http://www.seao2.info/cgenie/labs/EC4.2013/GEOGM1110andM1404.2013-14.cGENIE_LAB.0000.pdf

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

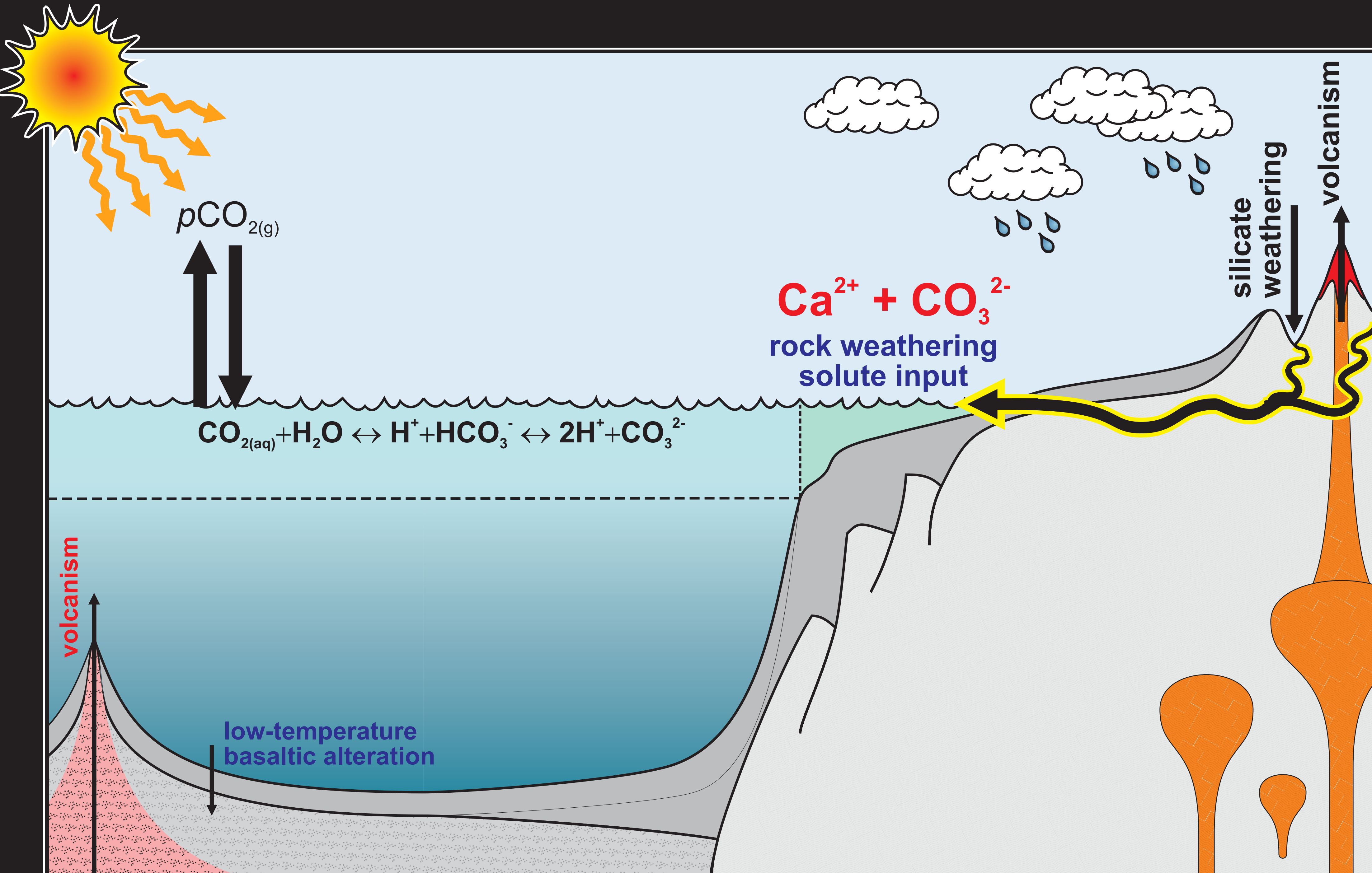


Evolution of the Biological Pump: in silico

tinyurl.com/meqy9pb



Evolution of the Biological Pump: In the beginning ...



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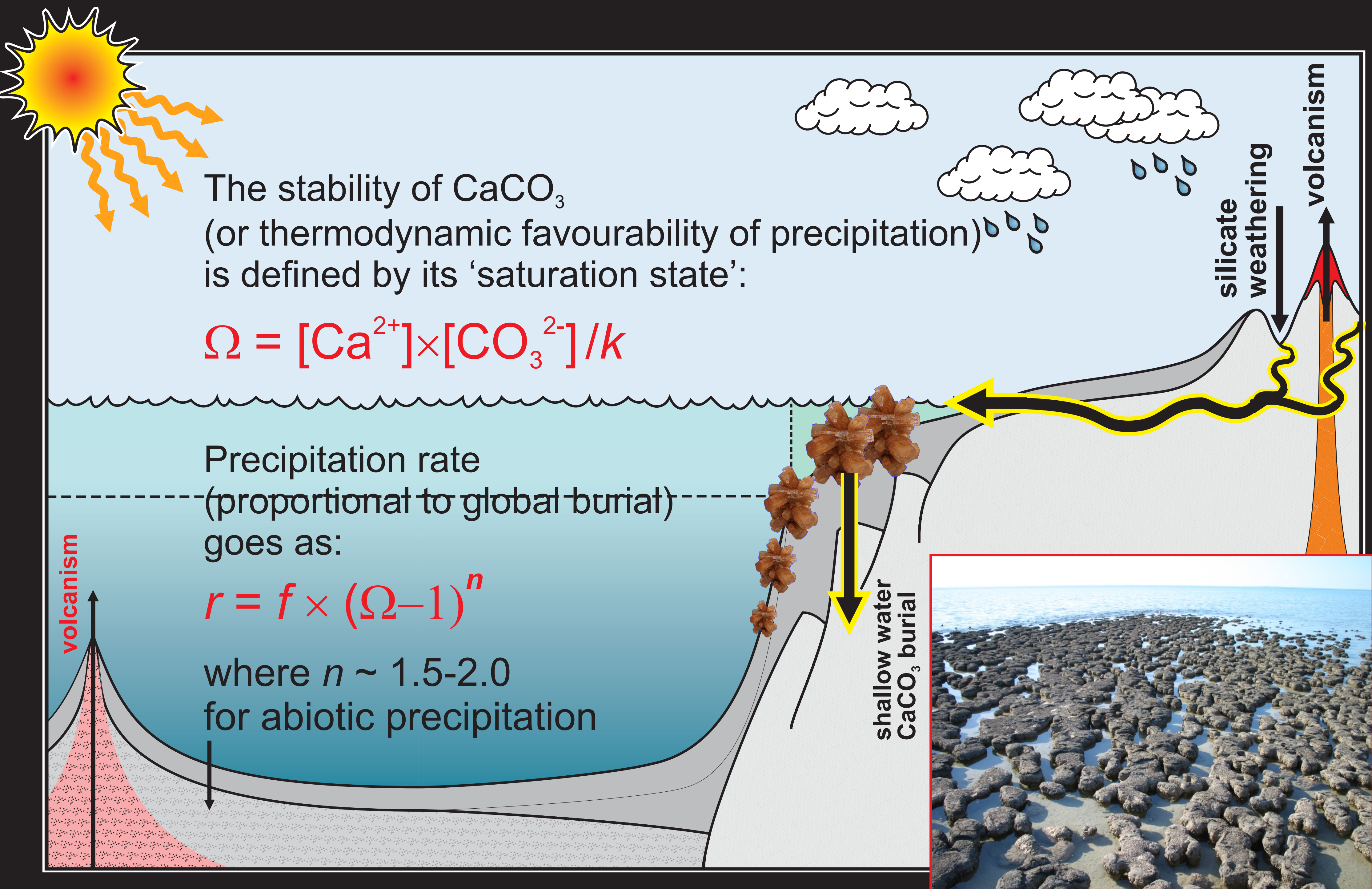

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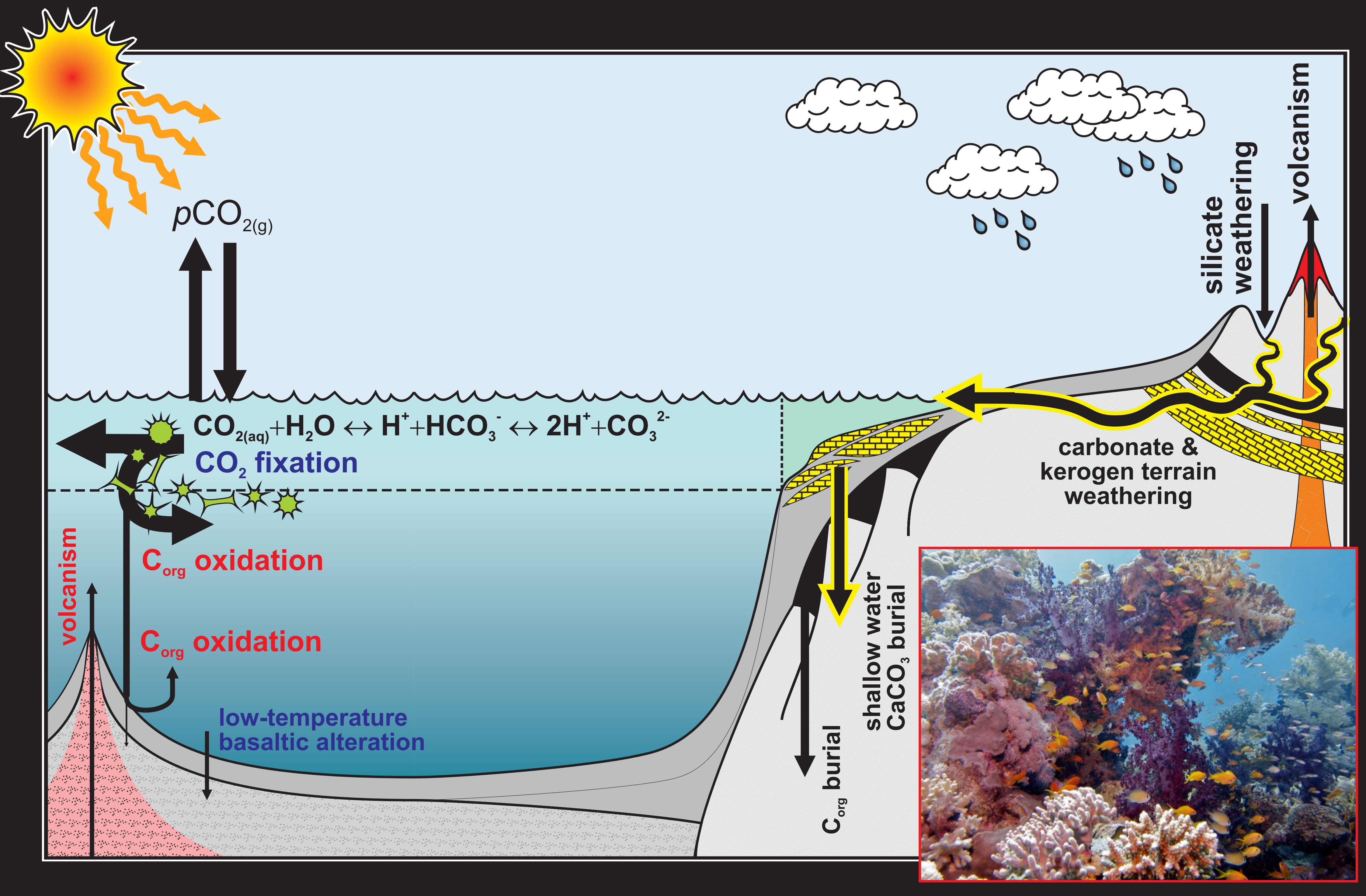

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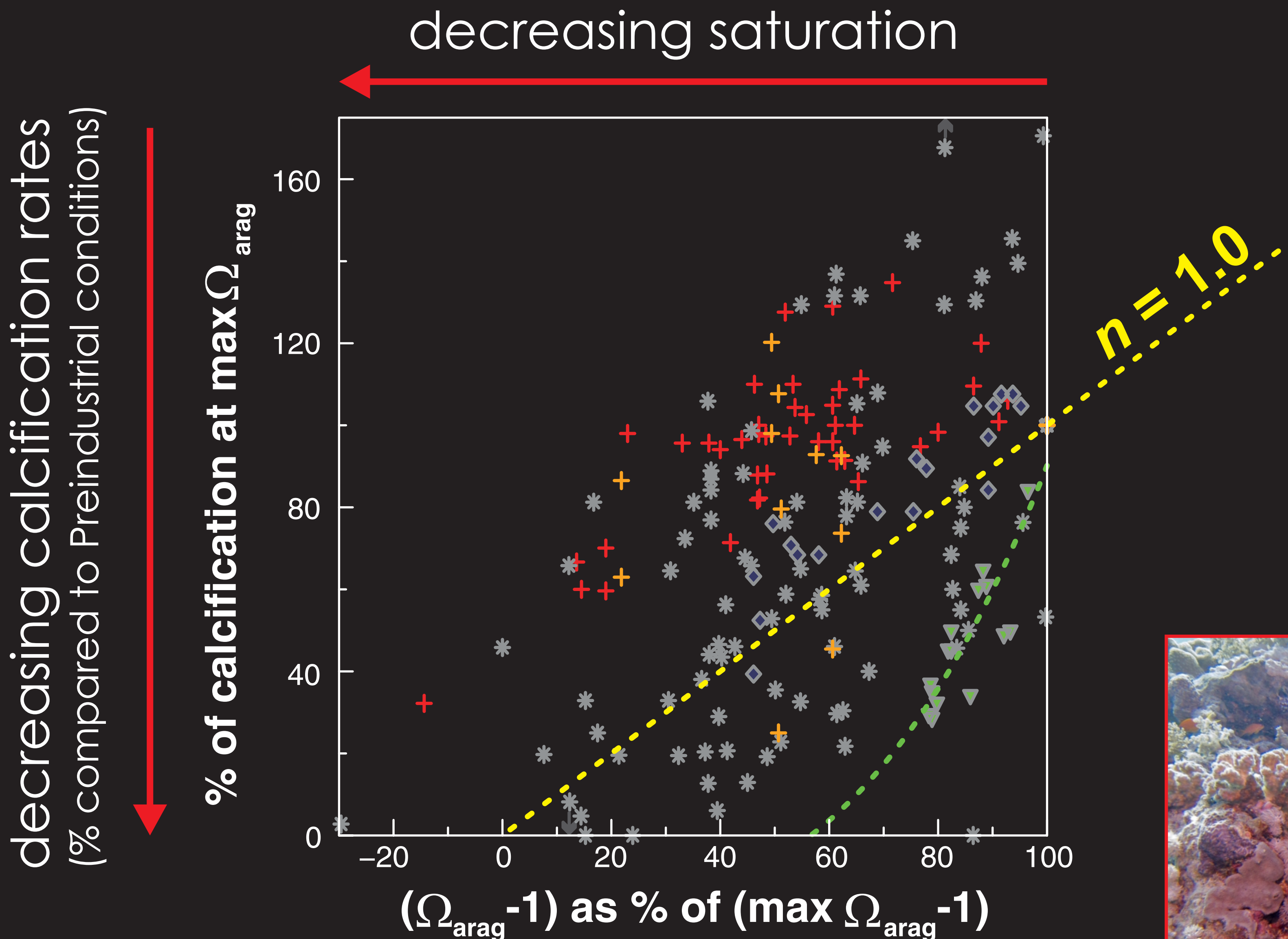
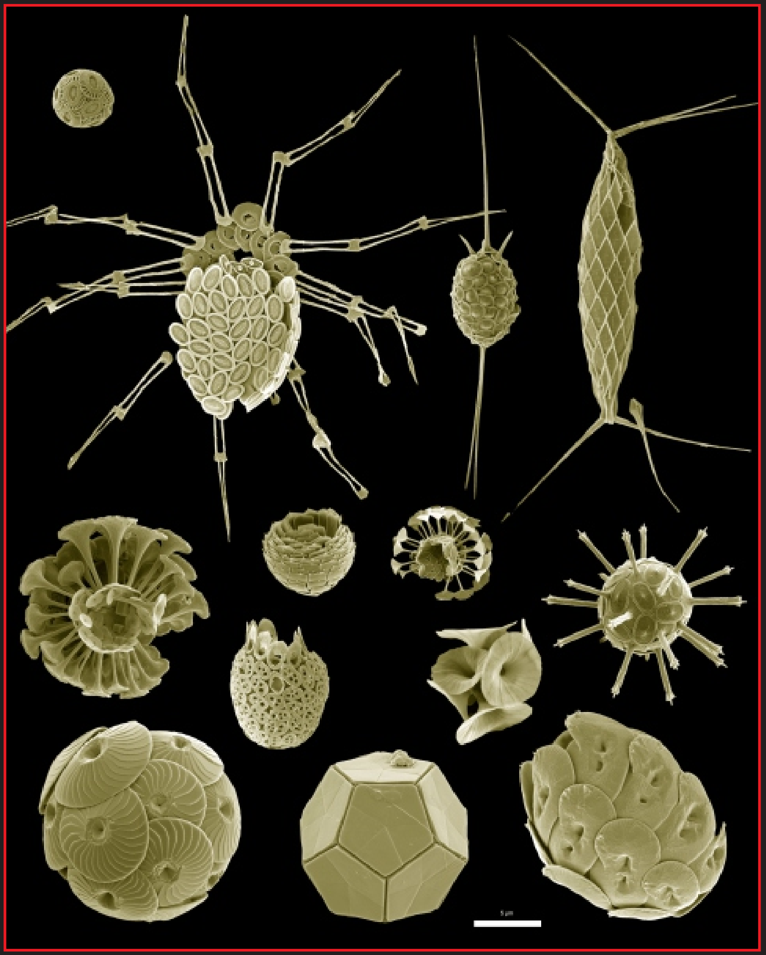
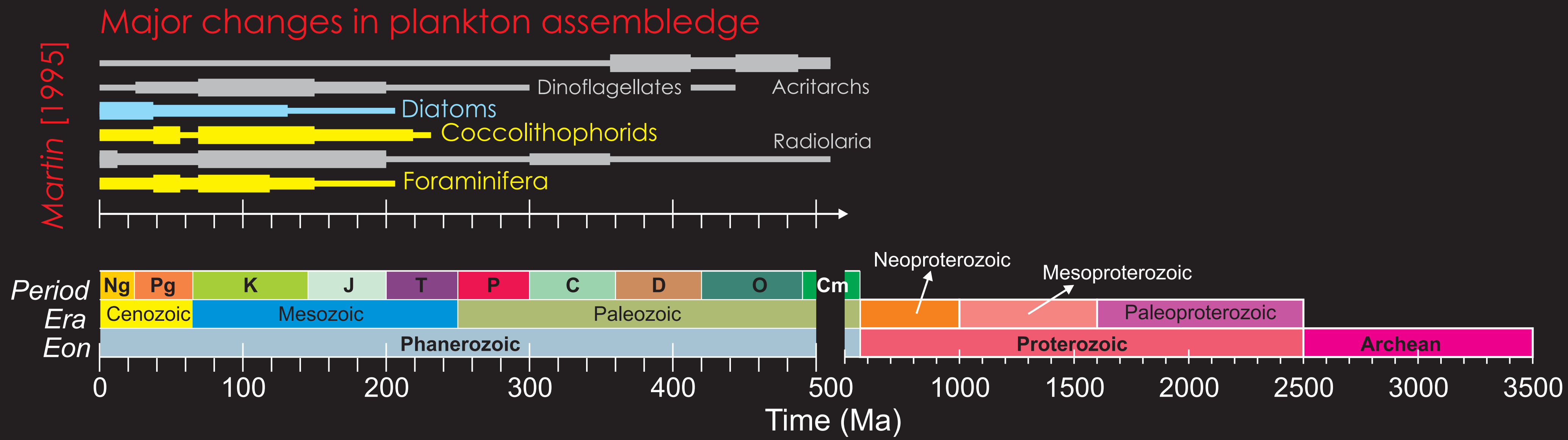


Pandolfi et al. [2011] (*Science*)

Evolution of the Biological Pump:

The Mesozoic planktic calcifier revolution





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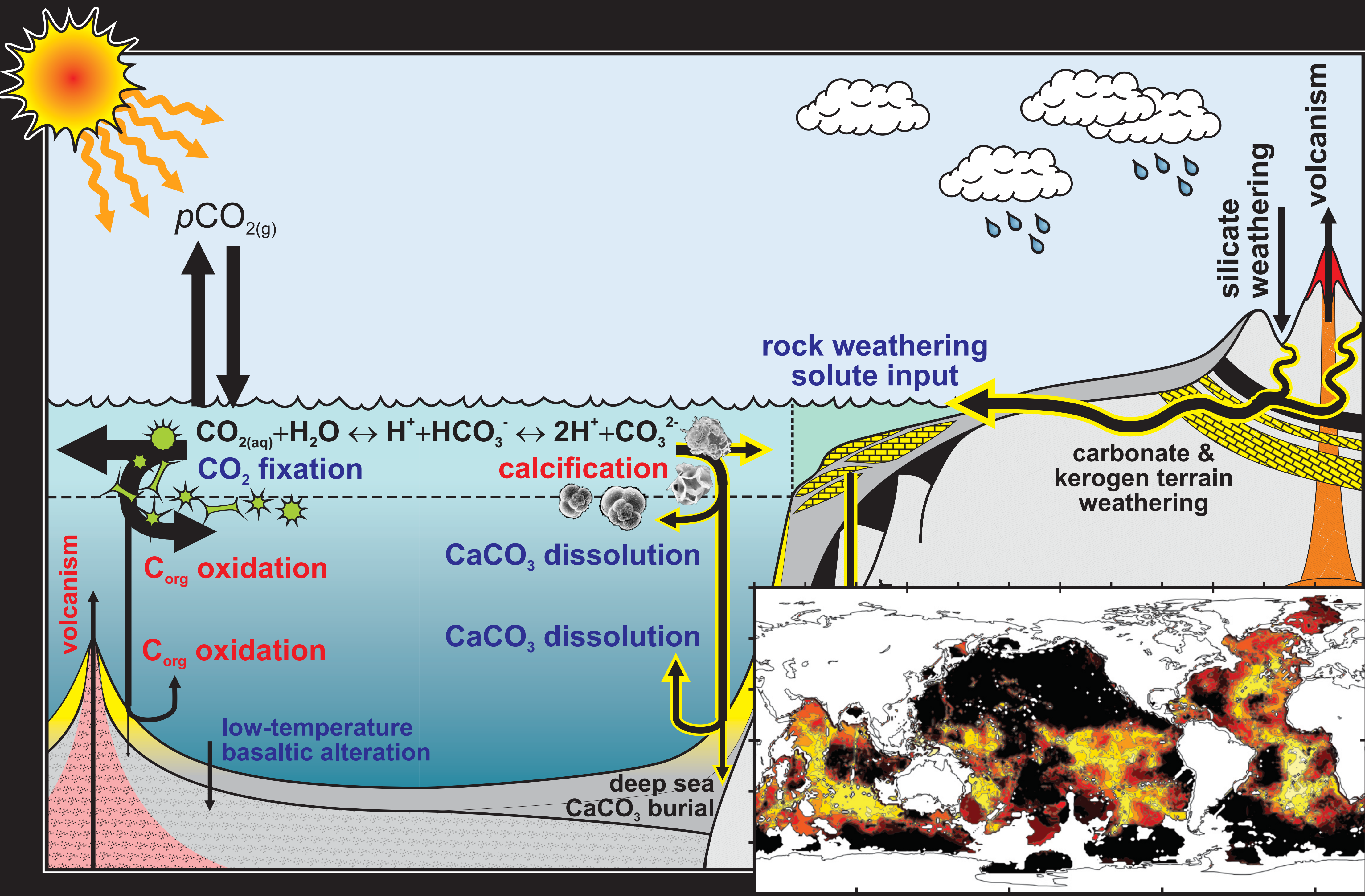

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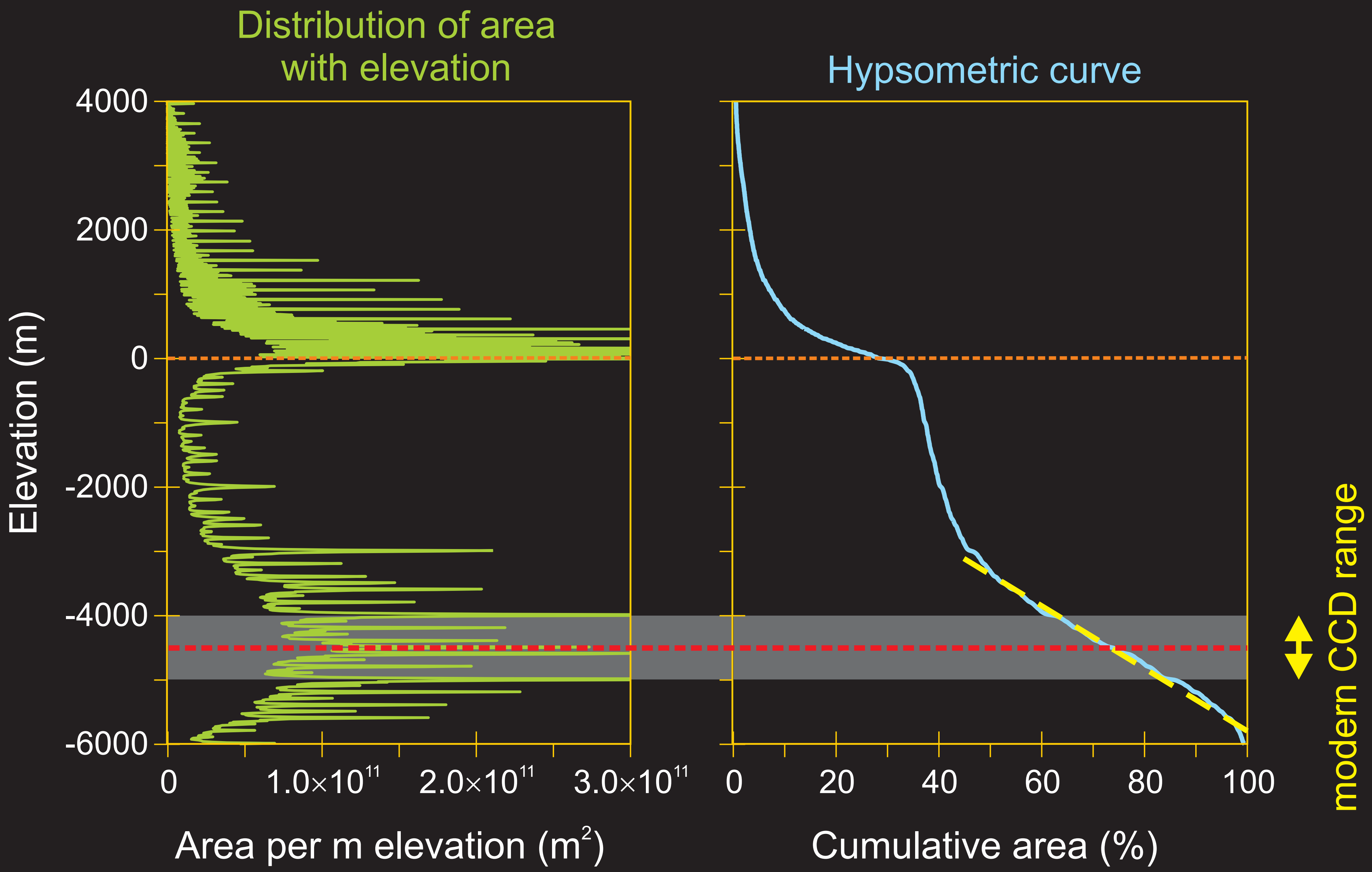

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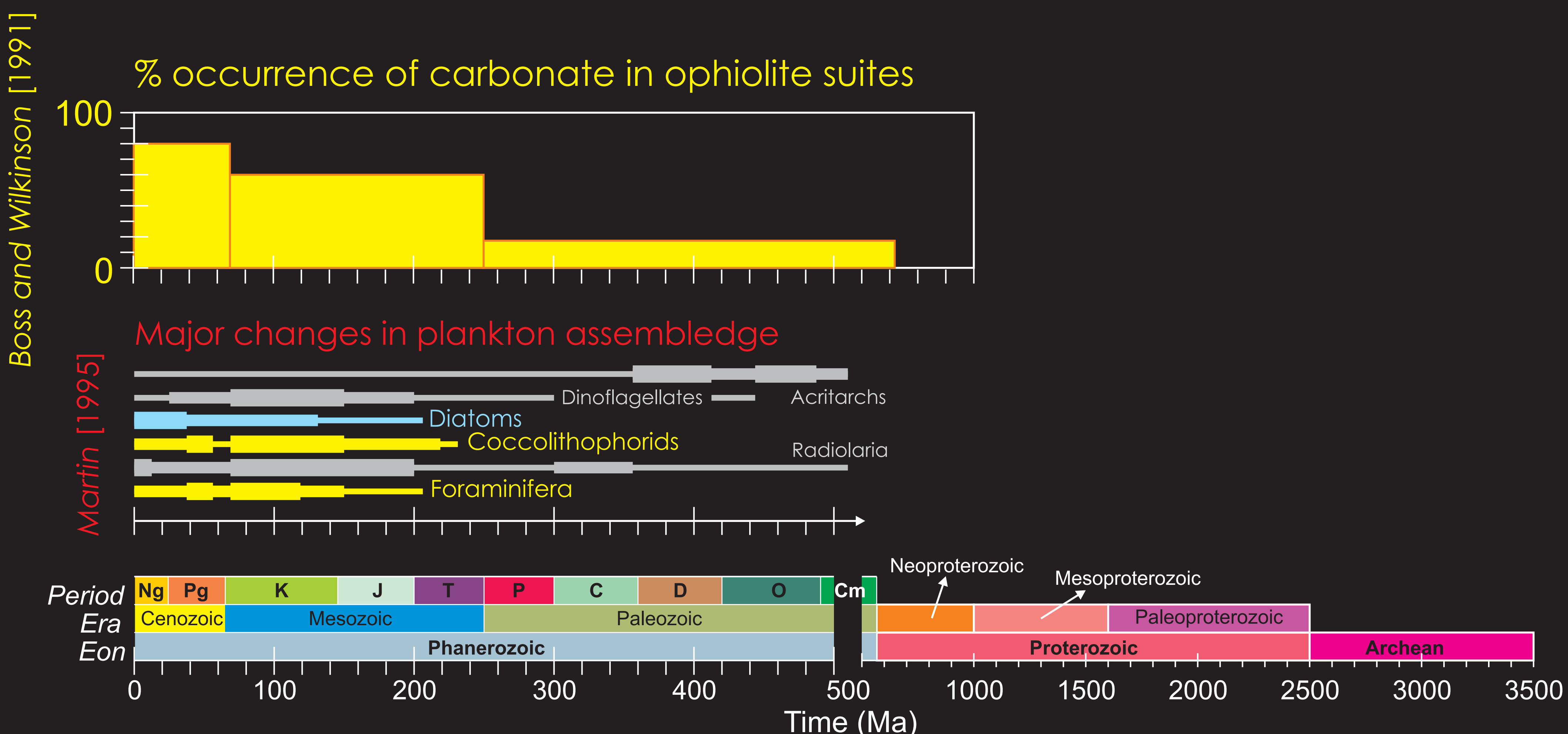

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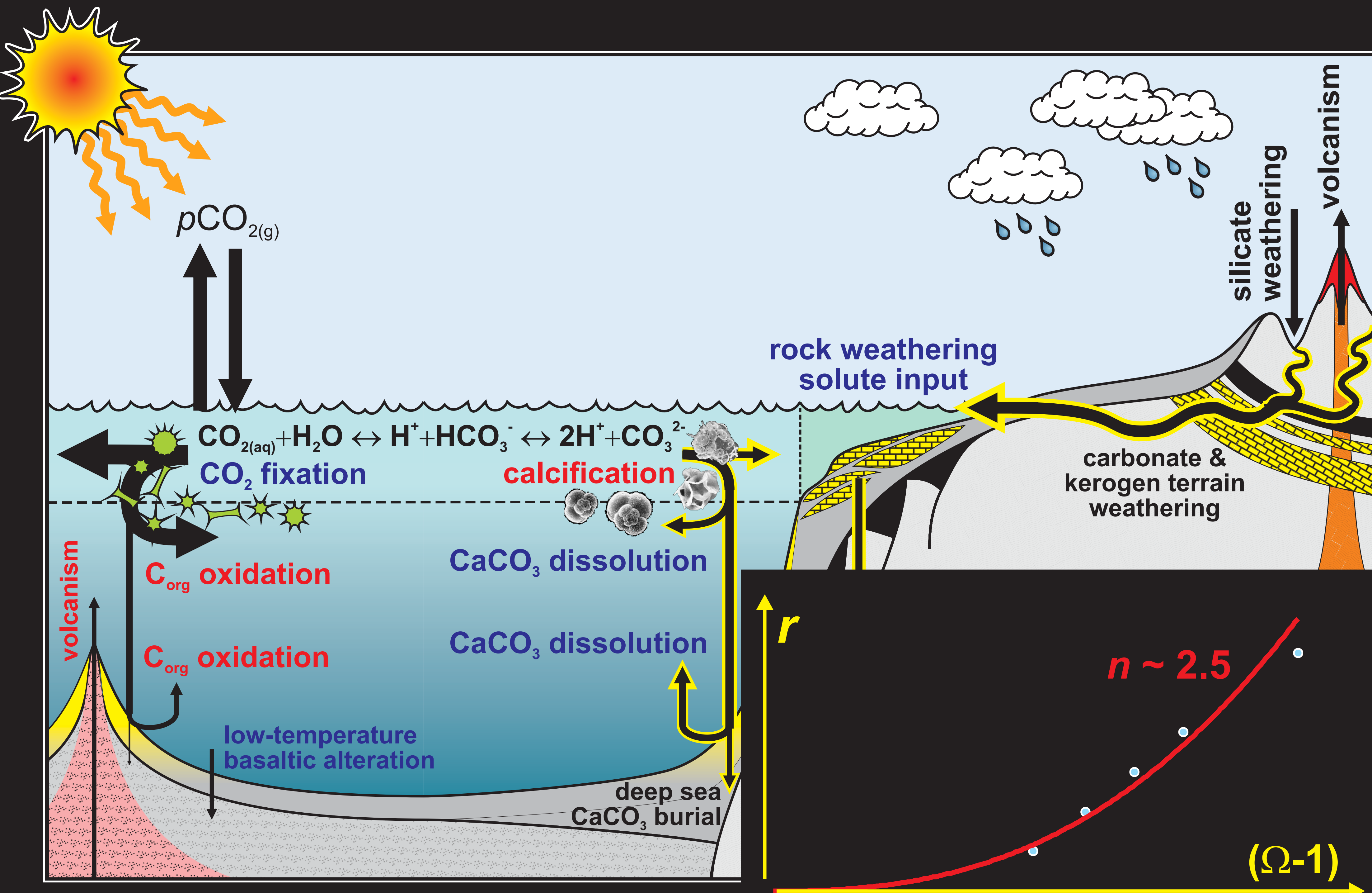
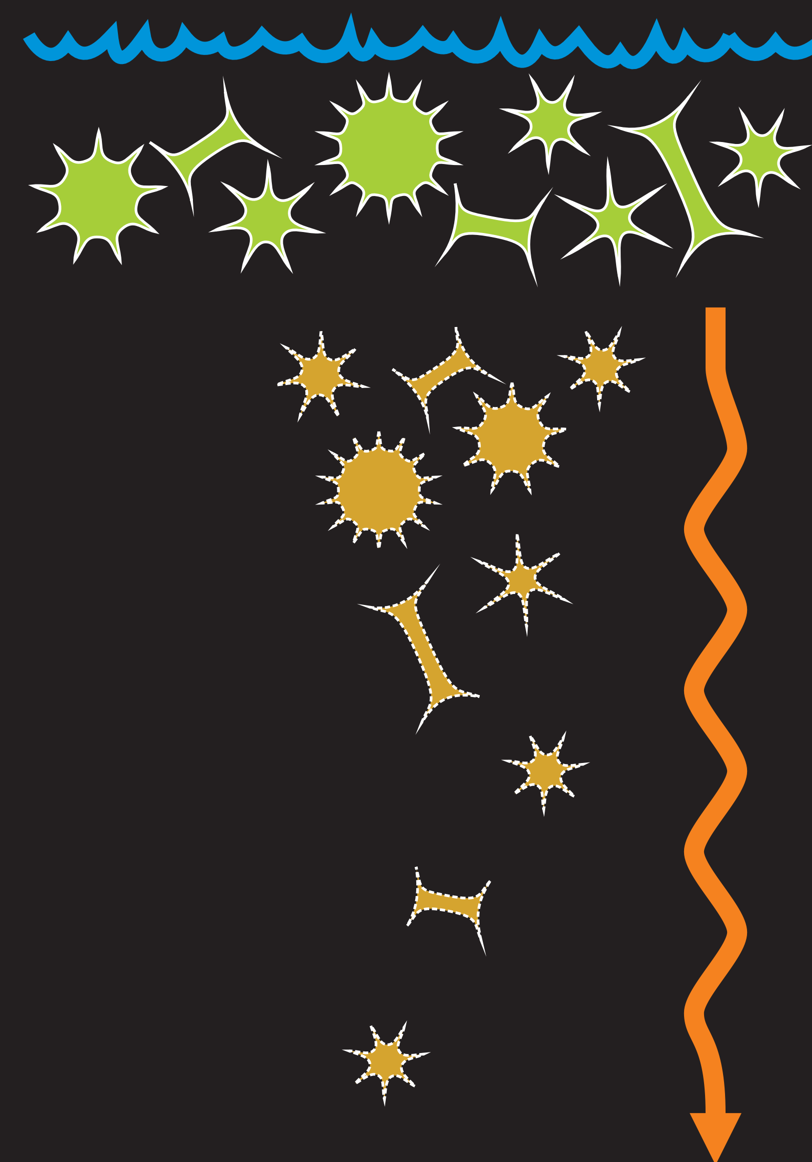
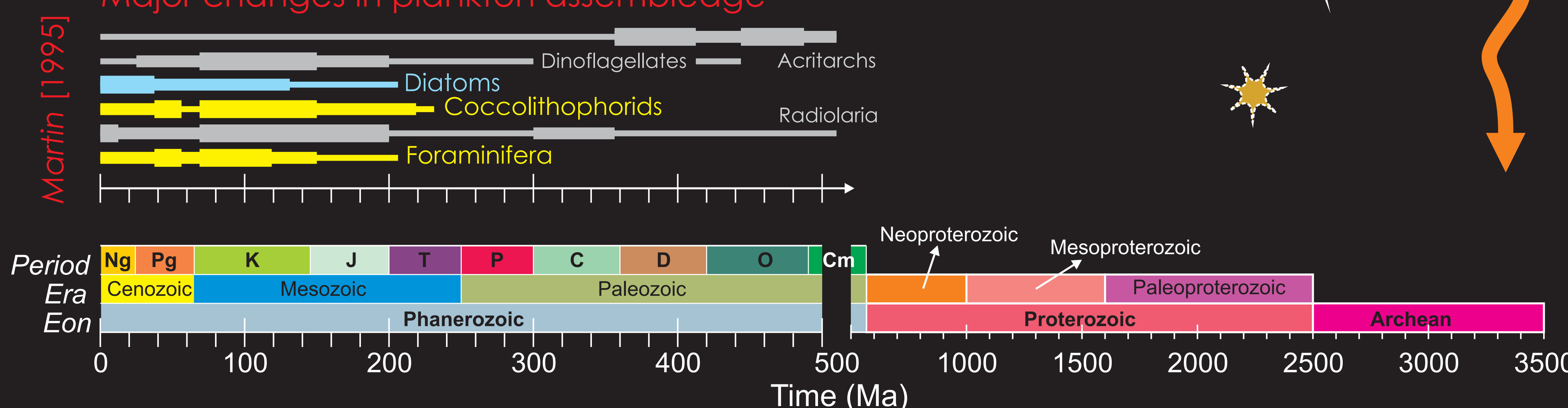




Major changes in plankton assembledge



Evolution of the Biological Pump:

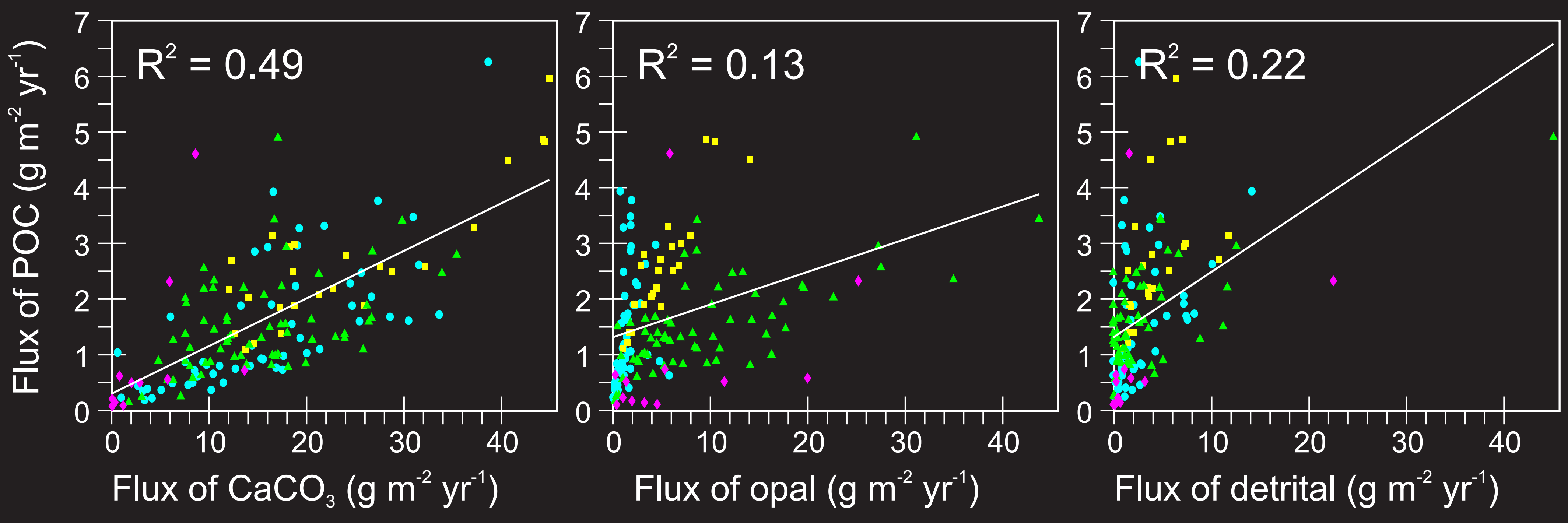
Planktic carbonate production and 'ballasting'

Compilation of sediment trap observations:

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

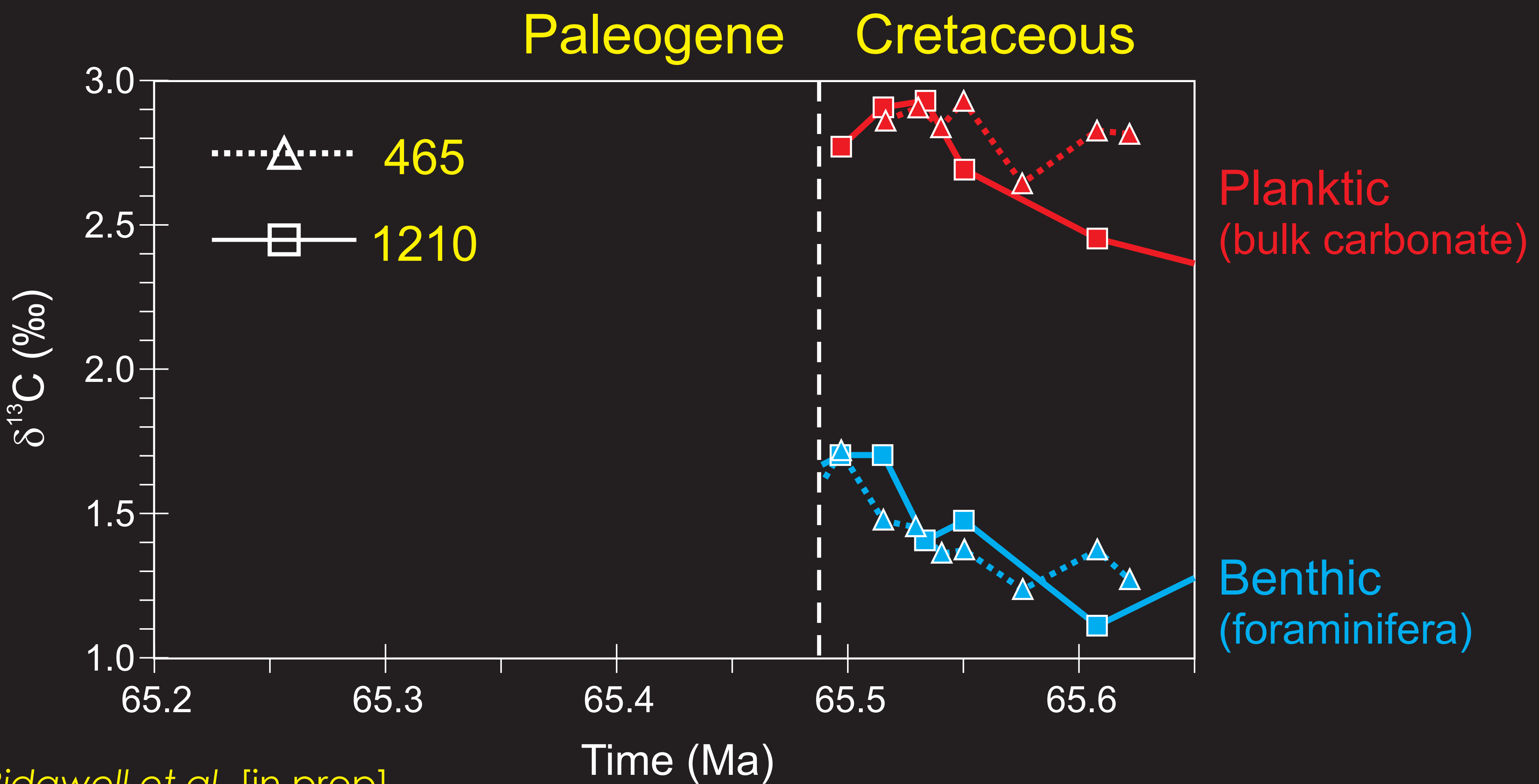
cyan == Atl, yellow == Ind, green == Pac, magenta == SO.

[*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]

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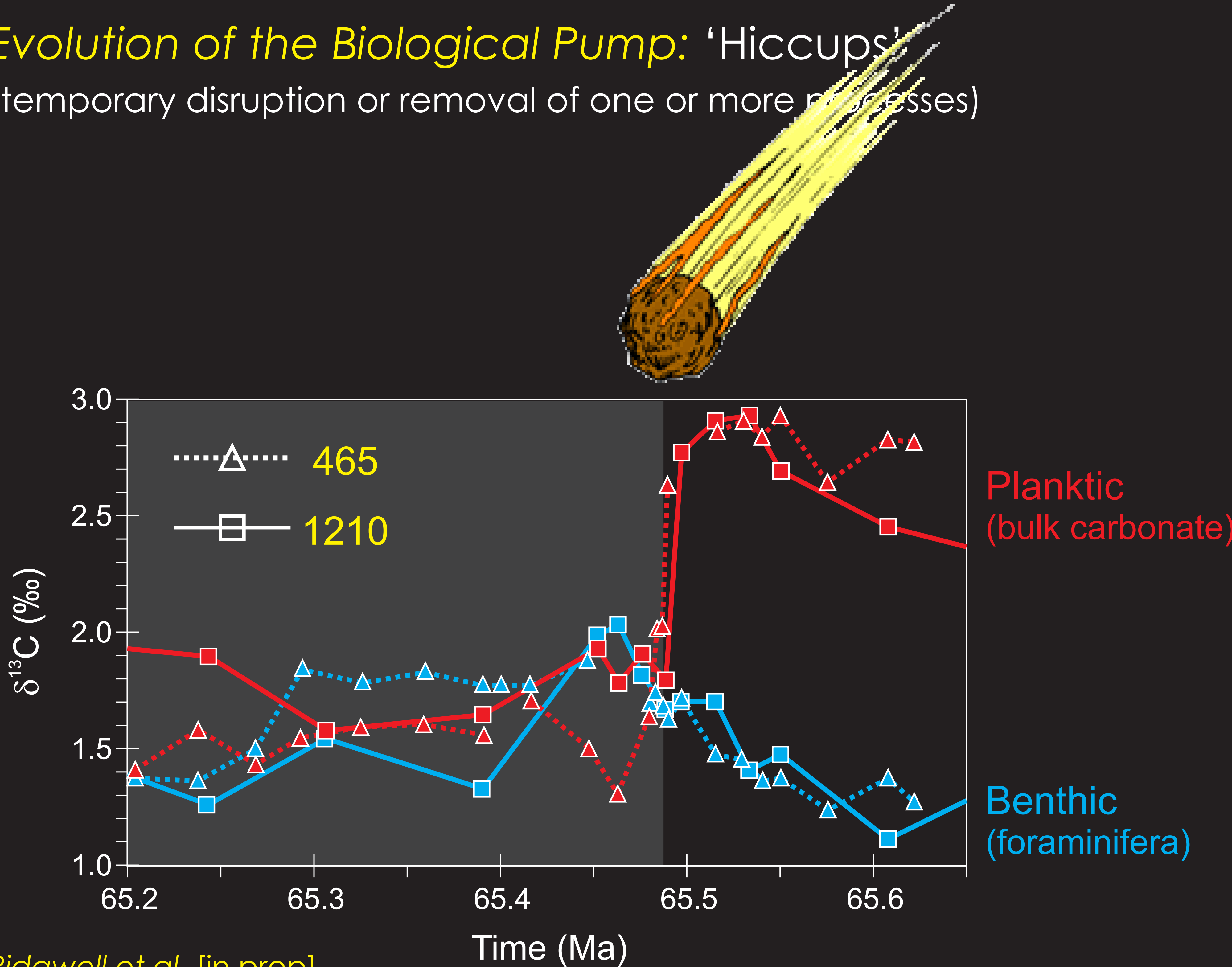

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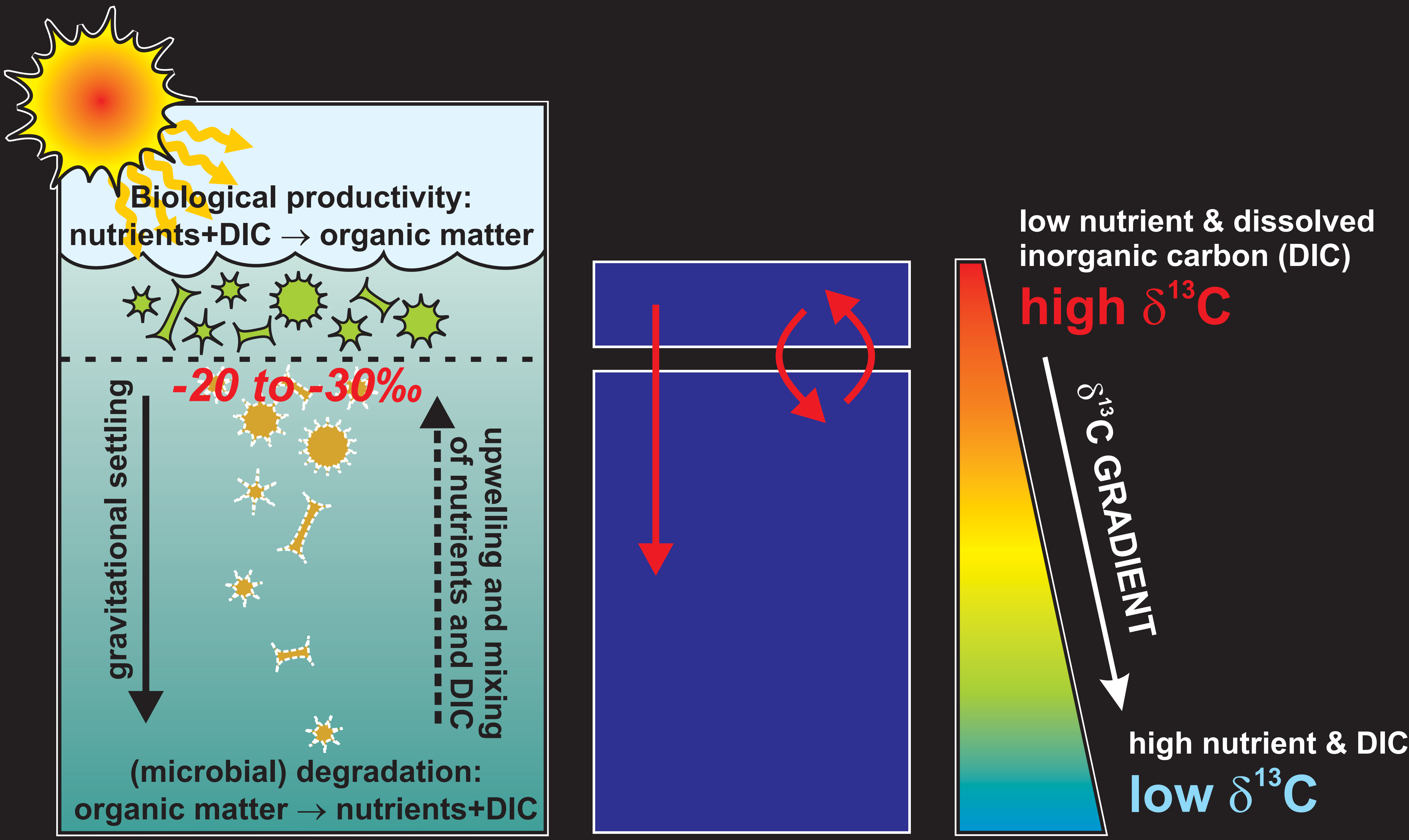
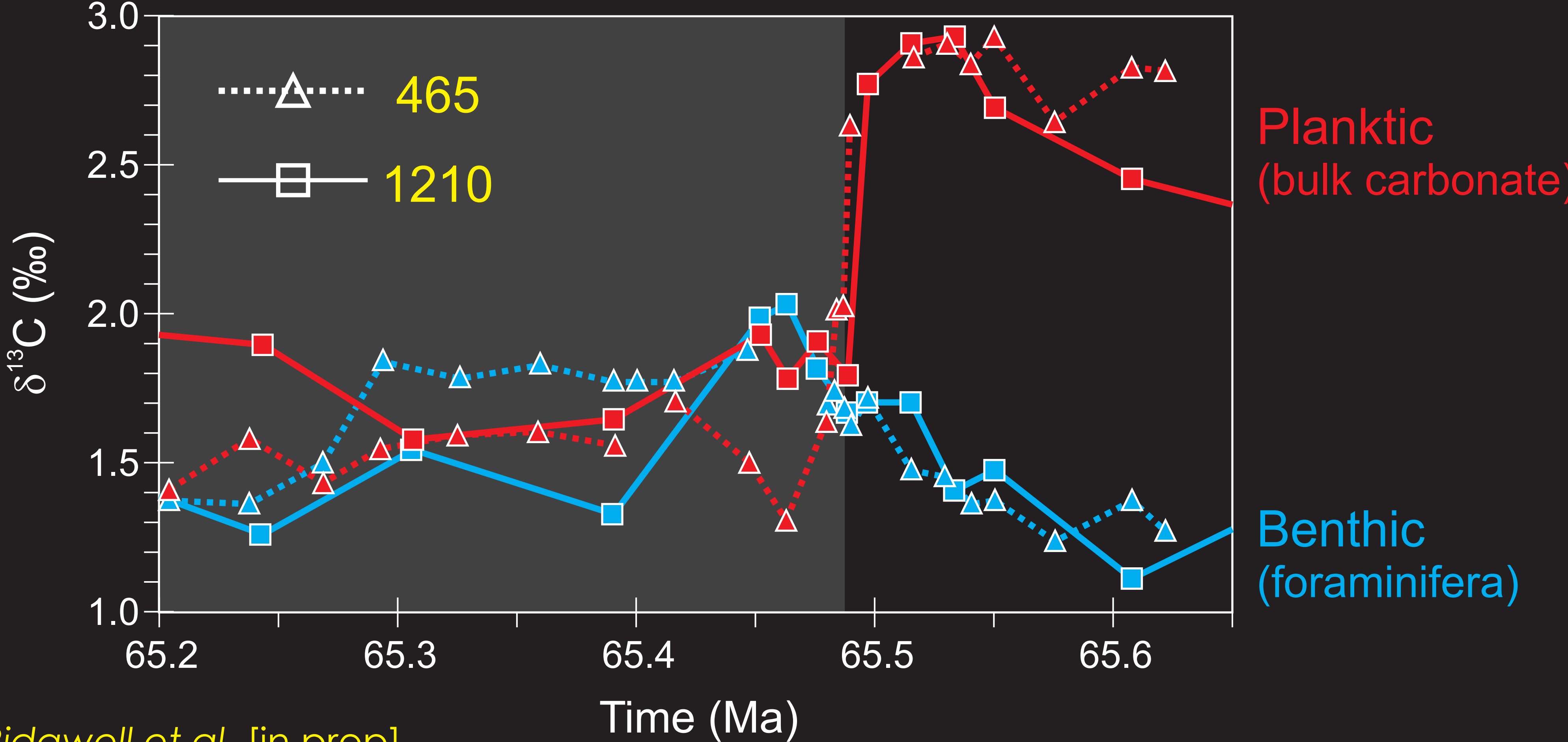


Evolution of the Biological Pump: 'Hiccups'

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

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



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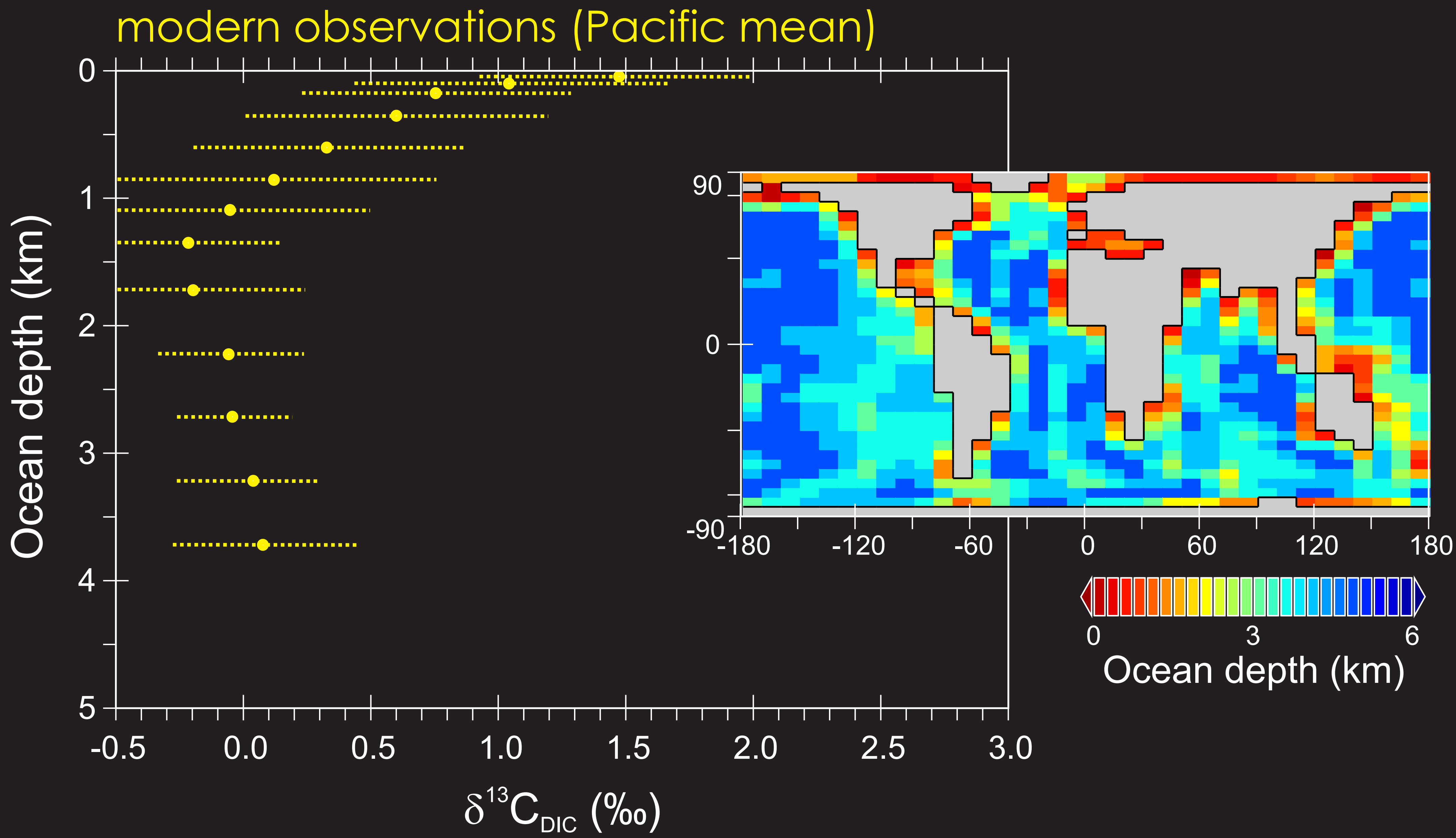

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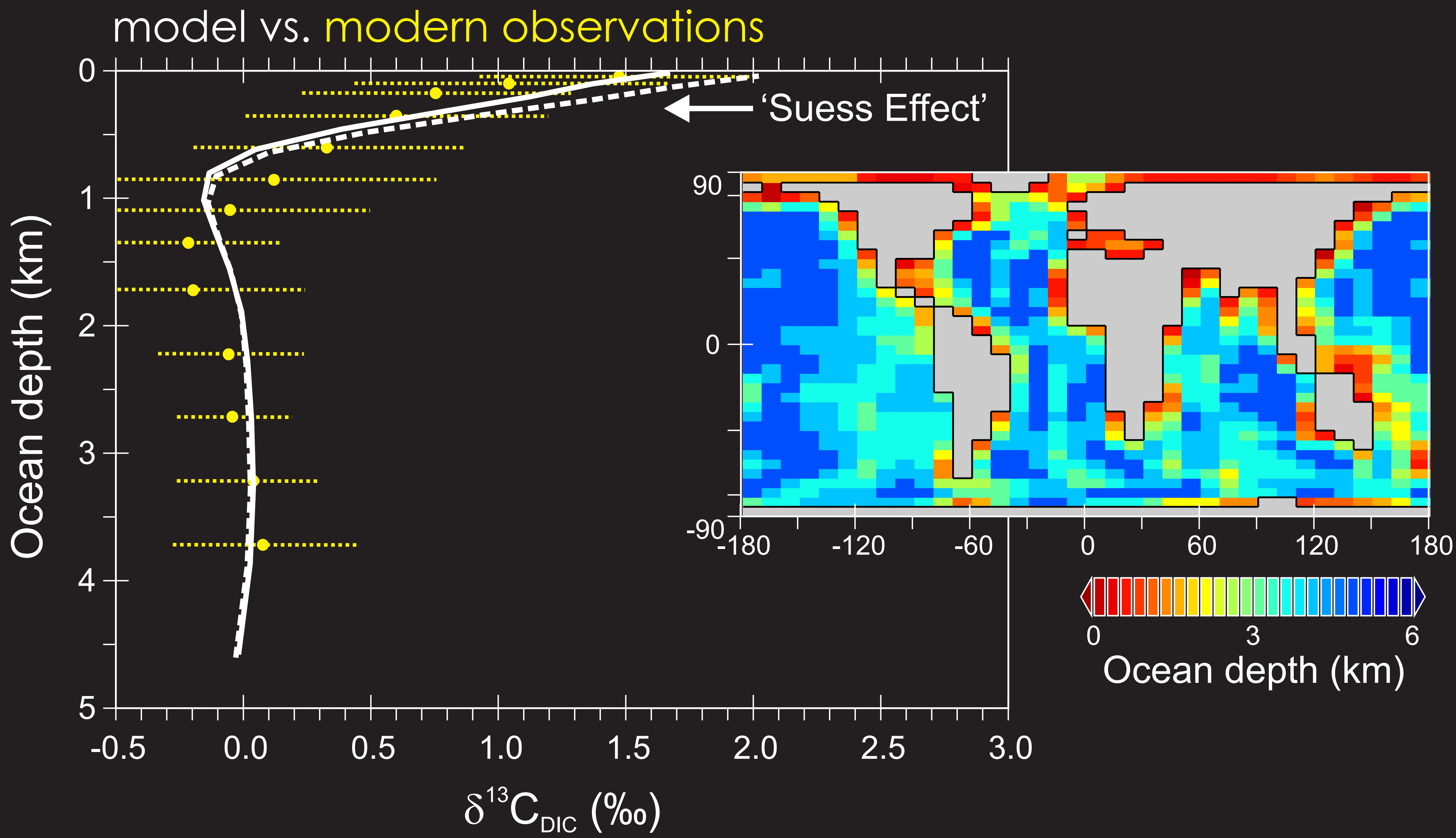
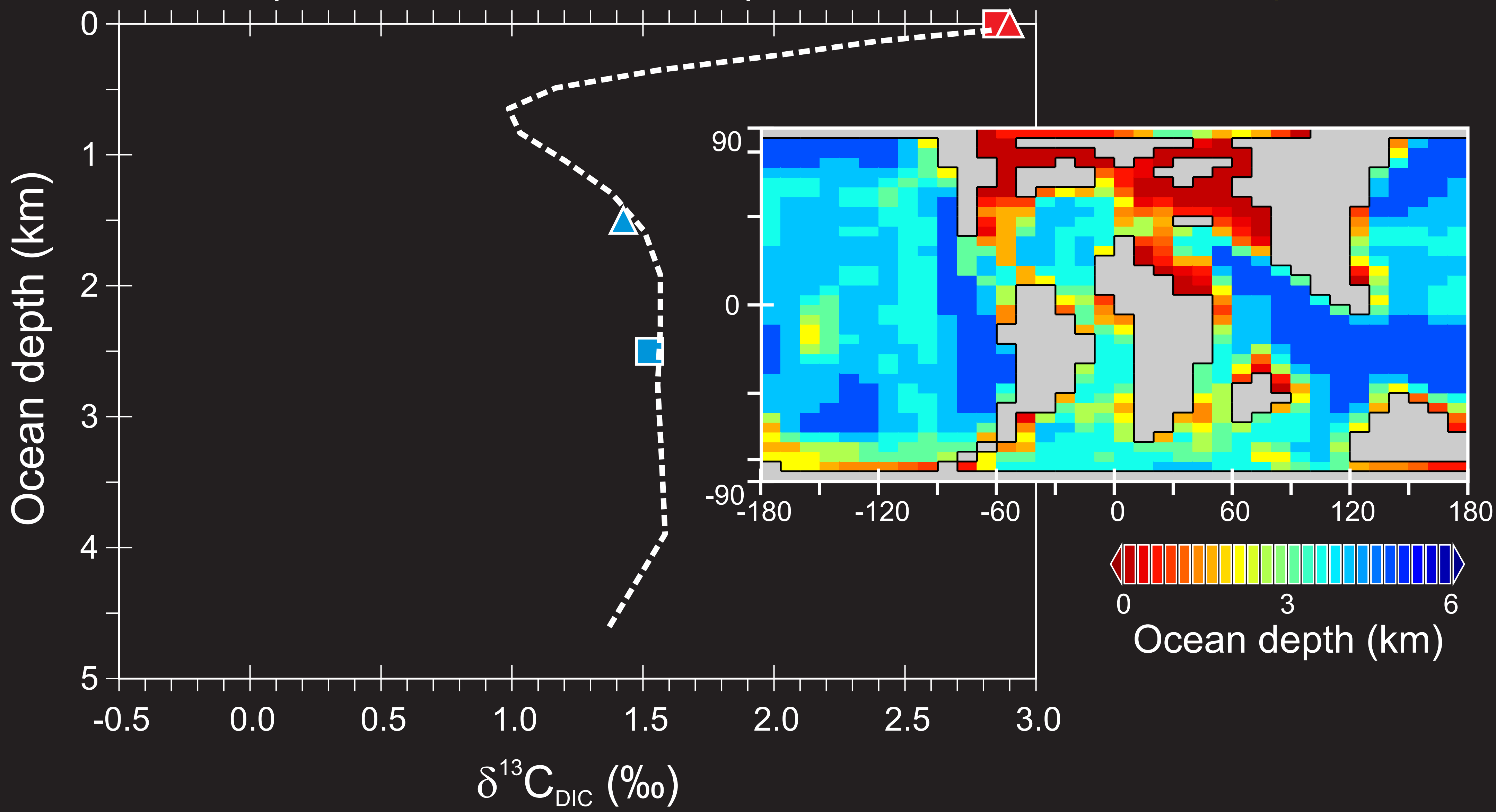
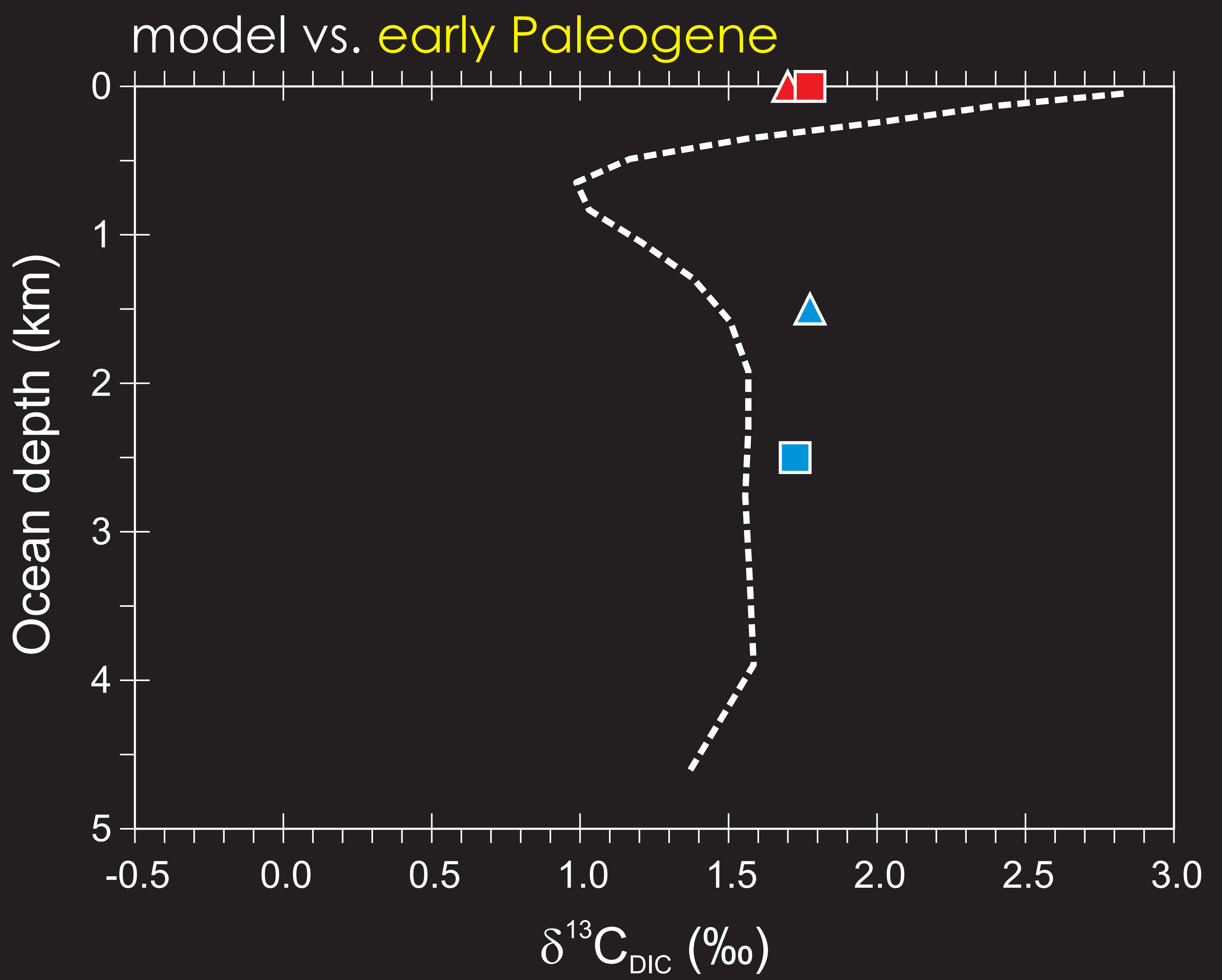


Evolution of the Biological Pump: 'Hiccups'

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



Evolution of the Biological Pump: 'Hiccups'



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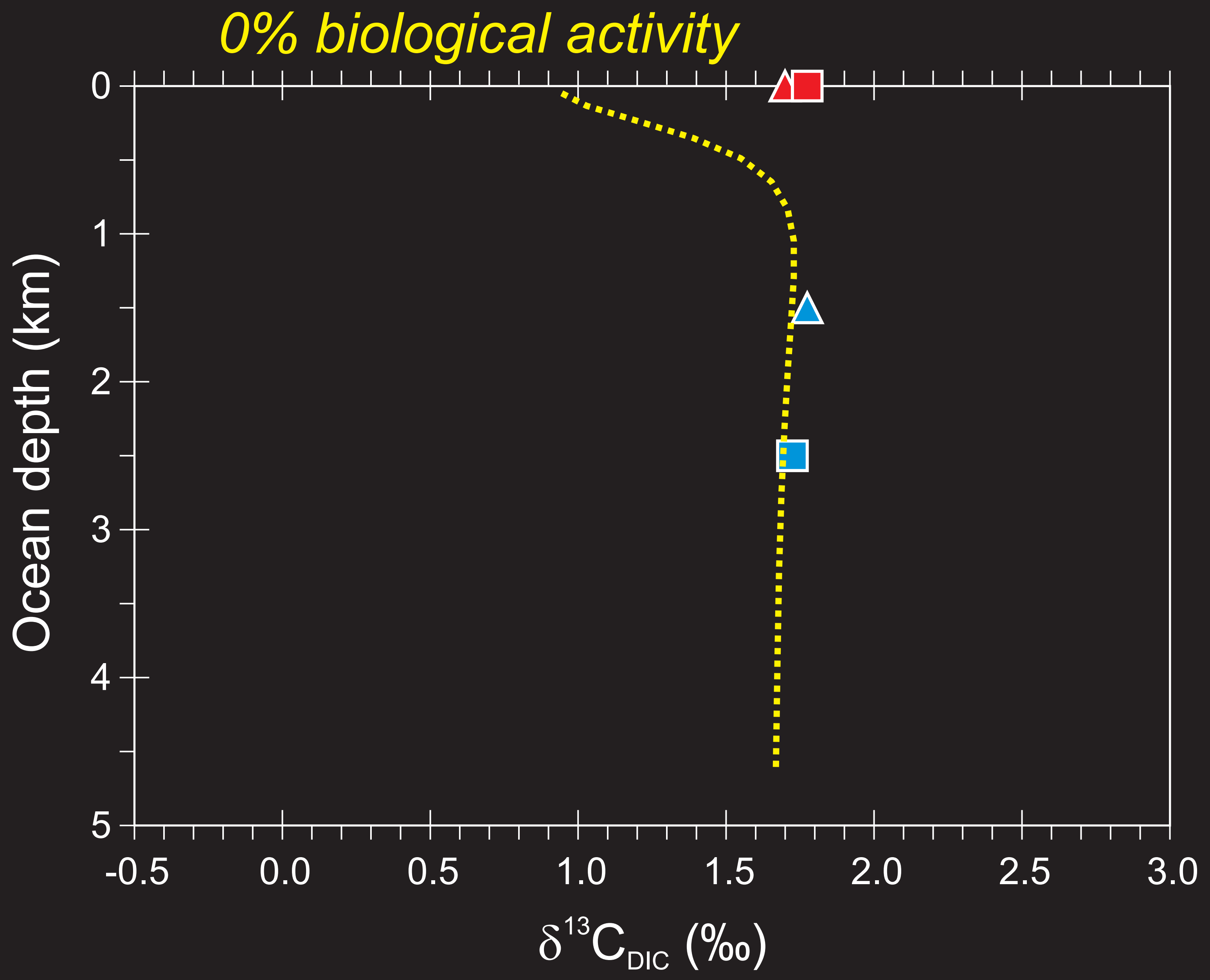
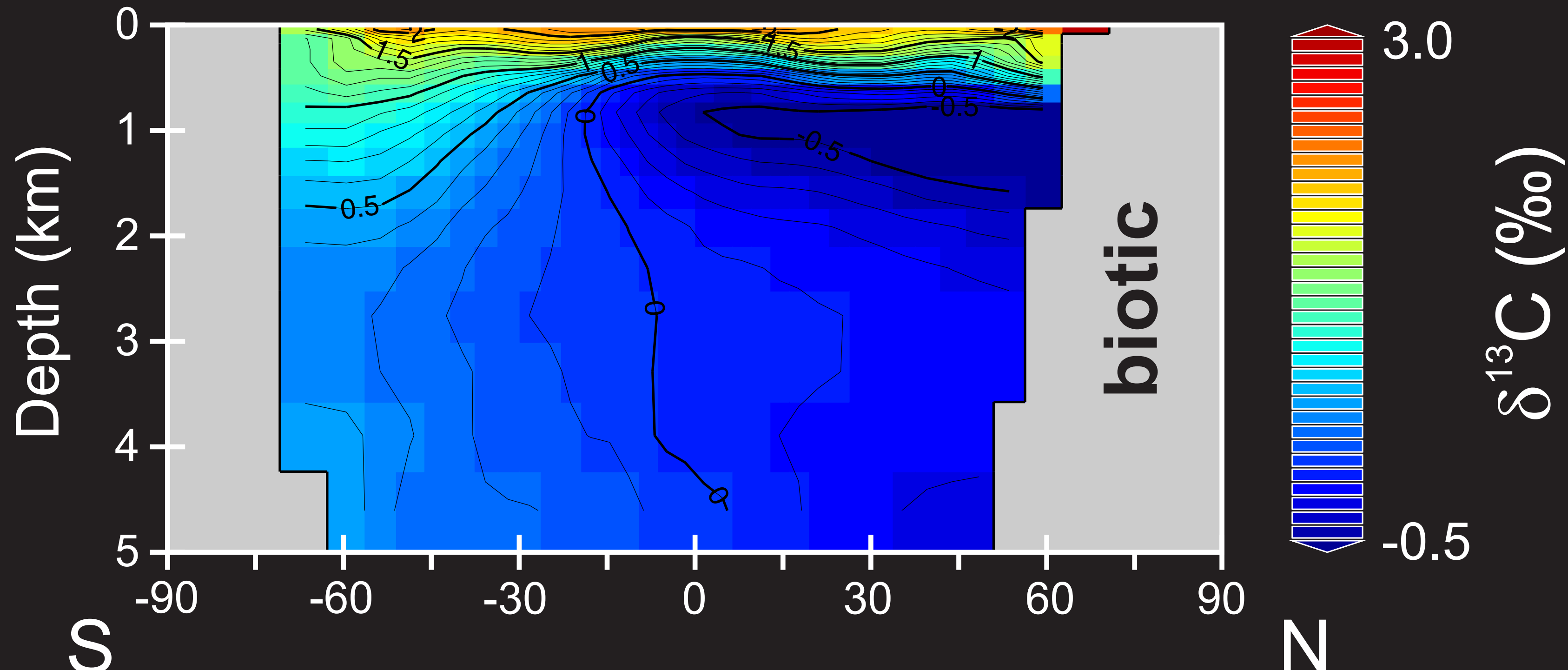
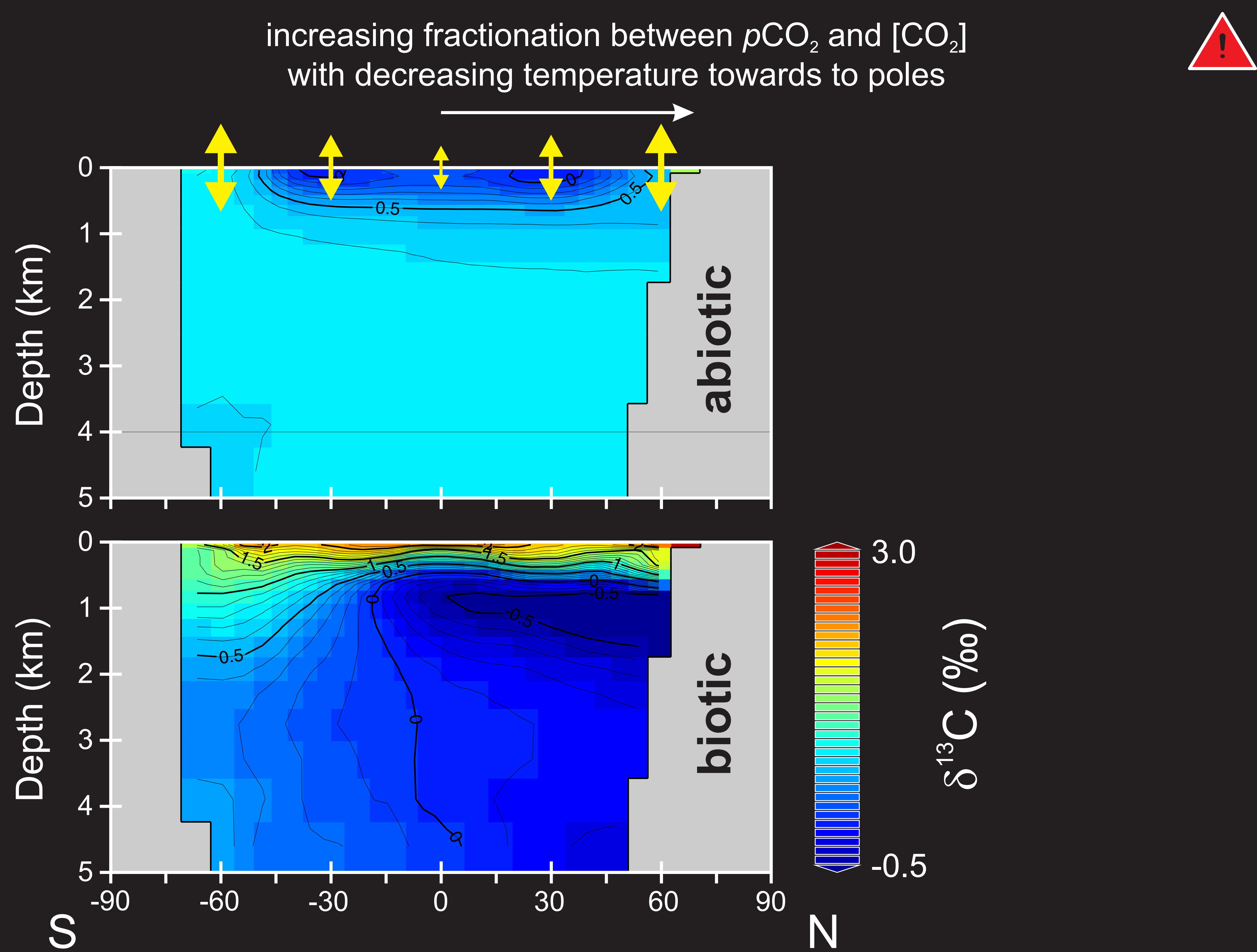


Evolution of the Biological Pump: 'Hiccups'

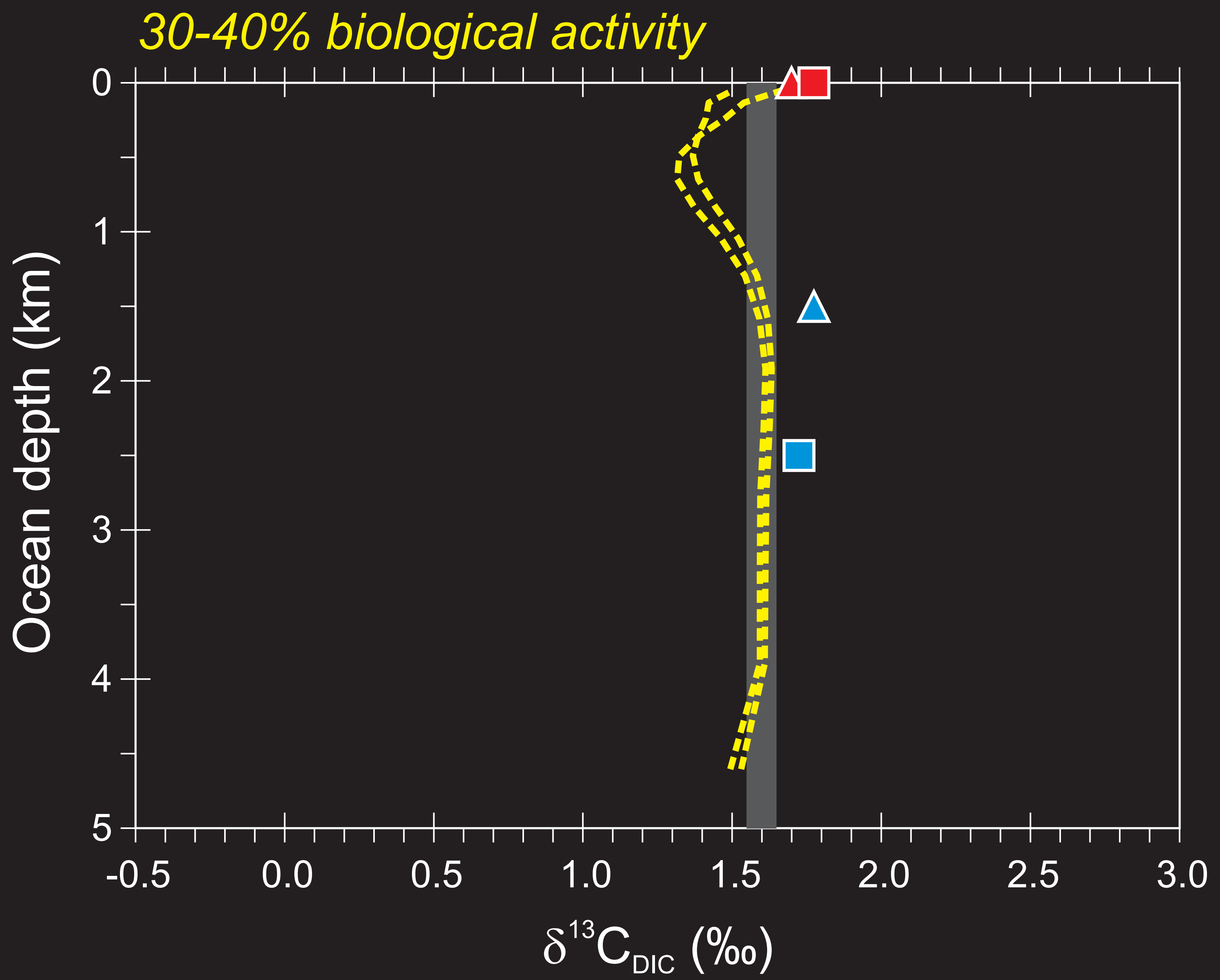
Modern Pacific zonal $\delta^{13}C_{(DIC)}$ profile





increasing fractionation between pCO_2 and $[CO_2]$
with decreasing temperature towards to poles
abiotic
biotic
Depth (km)
Depth (km)
0
1
2
3
4
5
-90
-60
-30
0
30
60
90
S
N
0.5
-0.5
1.5
1
0
$\delta^{13}C$ (‰)
3.0
-0.5

Evolution of the Biological Pump: 'Hiccups'



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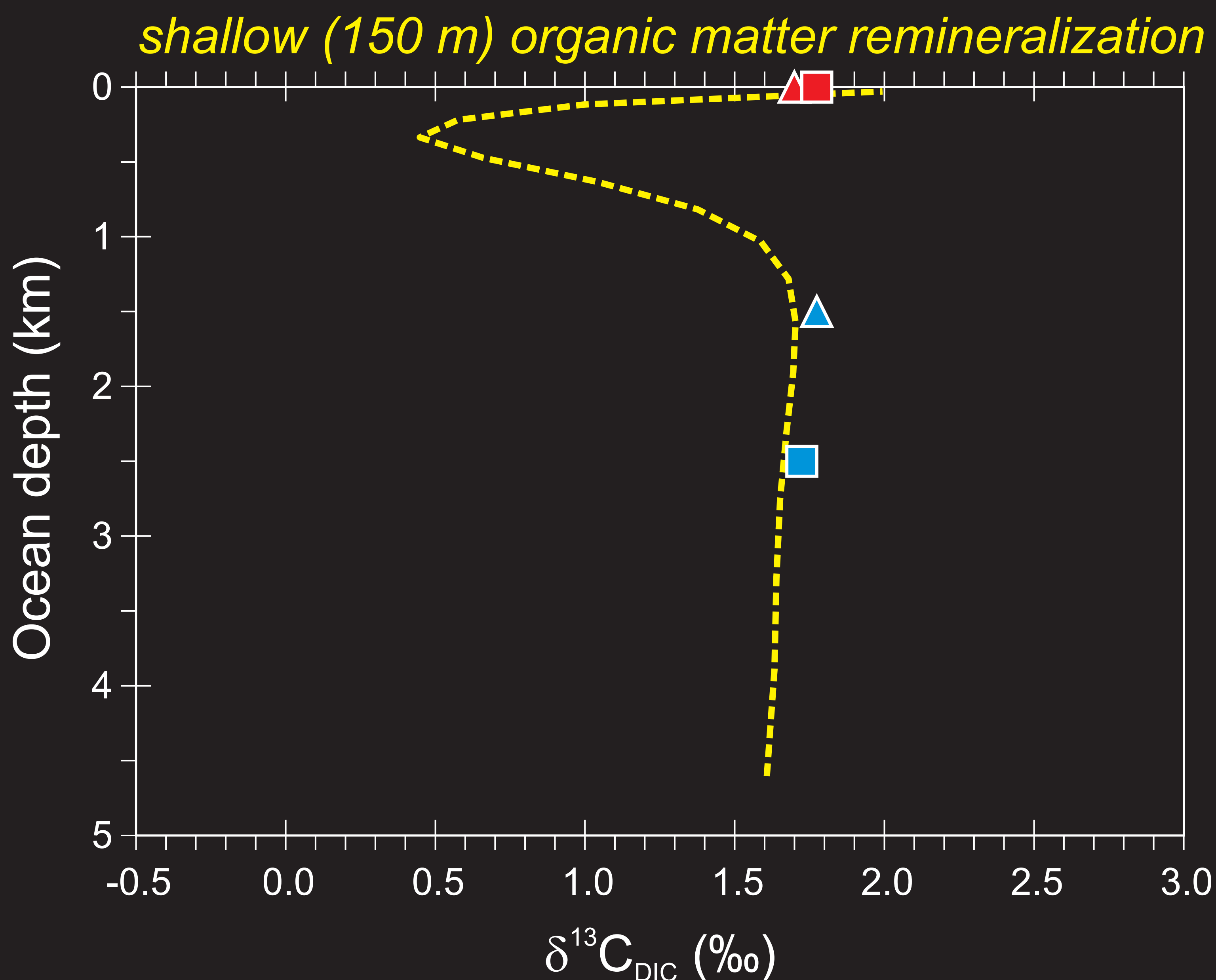

Evolution of the Biological Pump:

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depths >= 2000 m to exclude hydrodynamically distorted fluxes and relationships, and differentiated by basin: cyan == Atl, yellow == Ind, green == Pac, magenta == SO.

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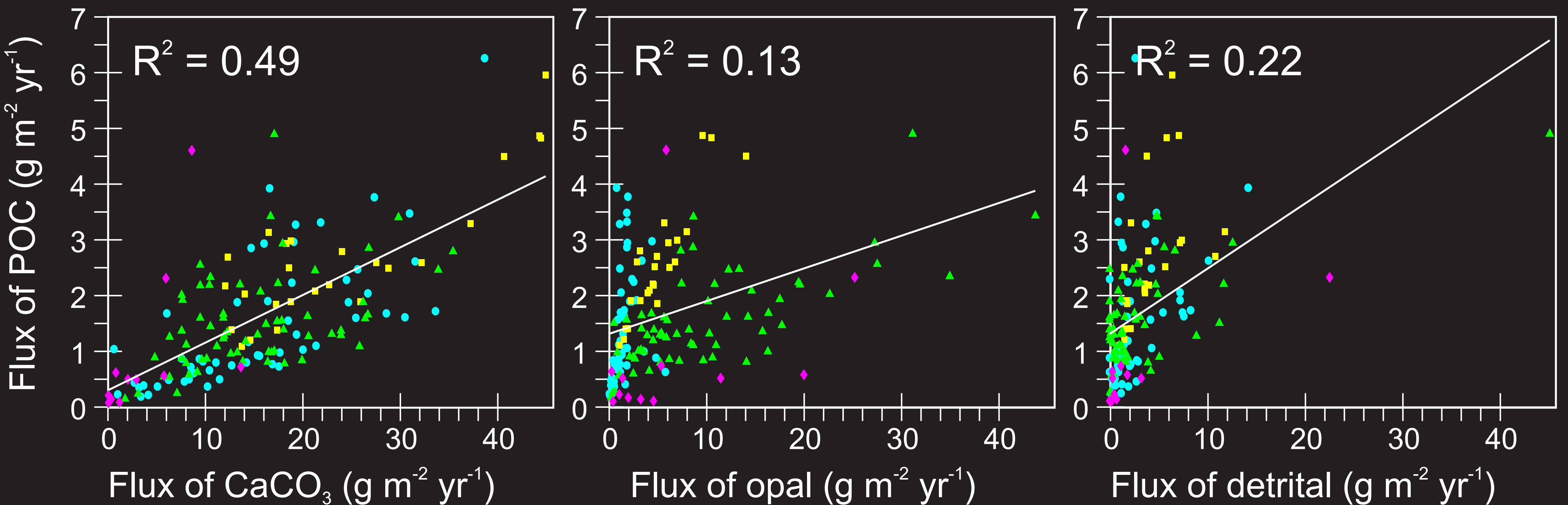

Evolution of the Biological Pump:

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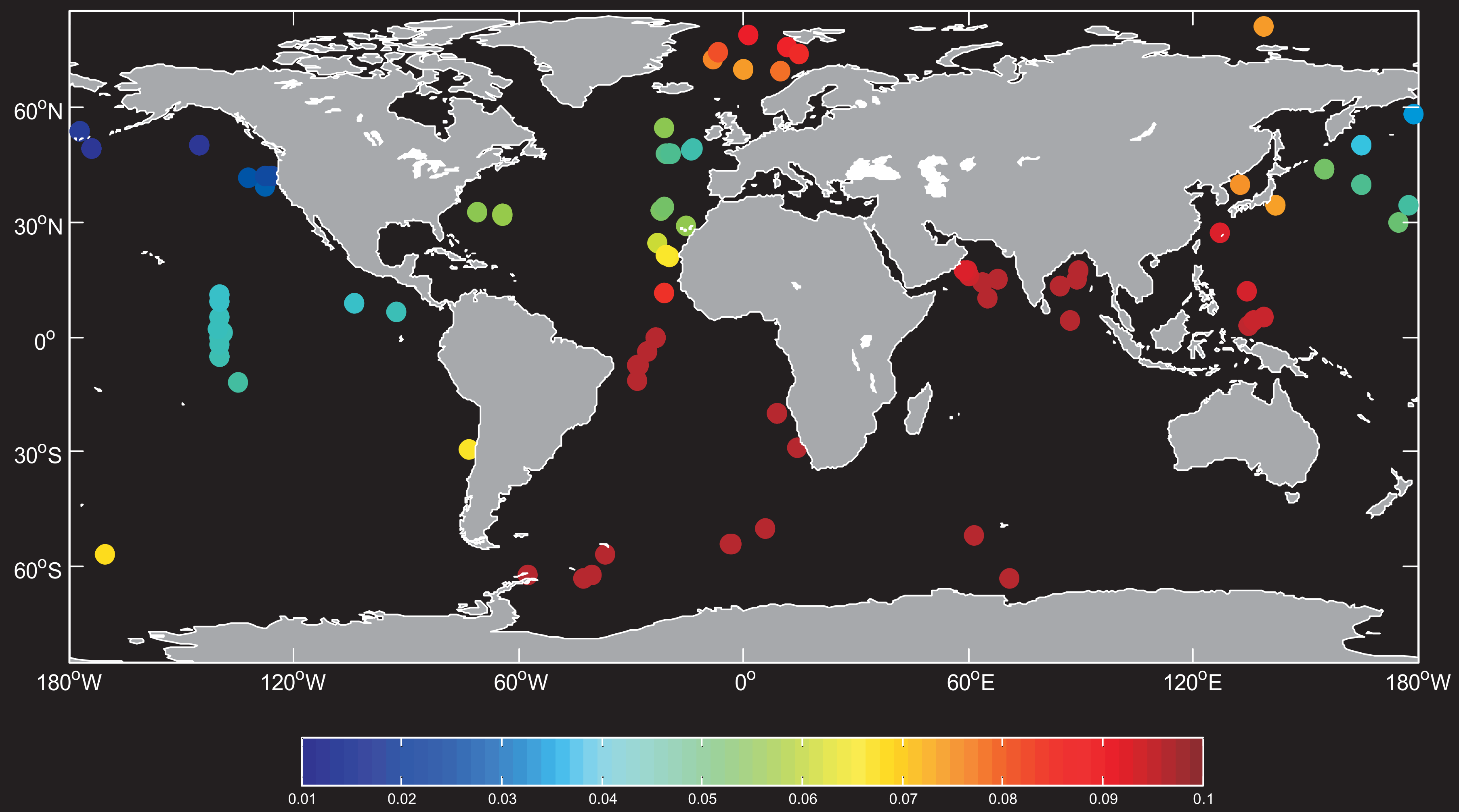
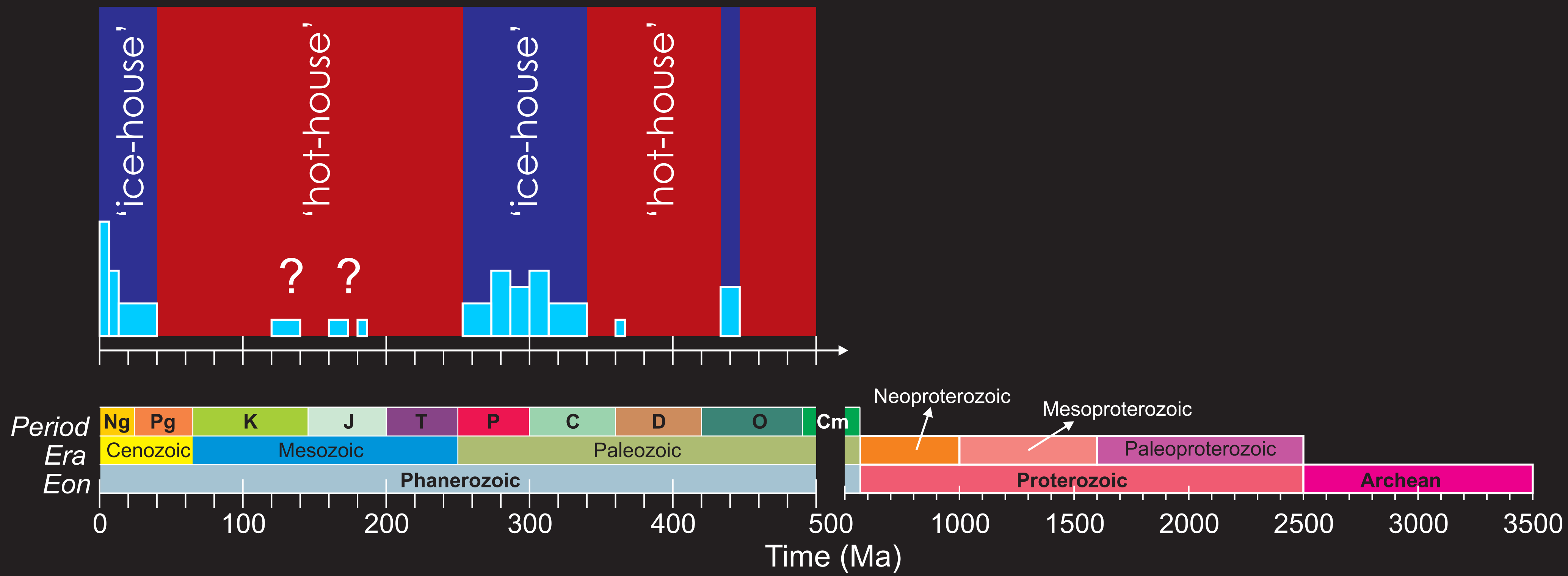


Spatial distribution of carrying capacity (ballasting) coefficients calculated using geographically weighted regression analysis for $CaCO_3$.

Wilson et al. [2012]

Evolution of the Biological Pump:
Ocean Carbon Cycling and Oxygenation in Warm Climates



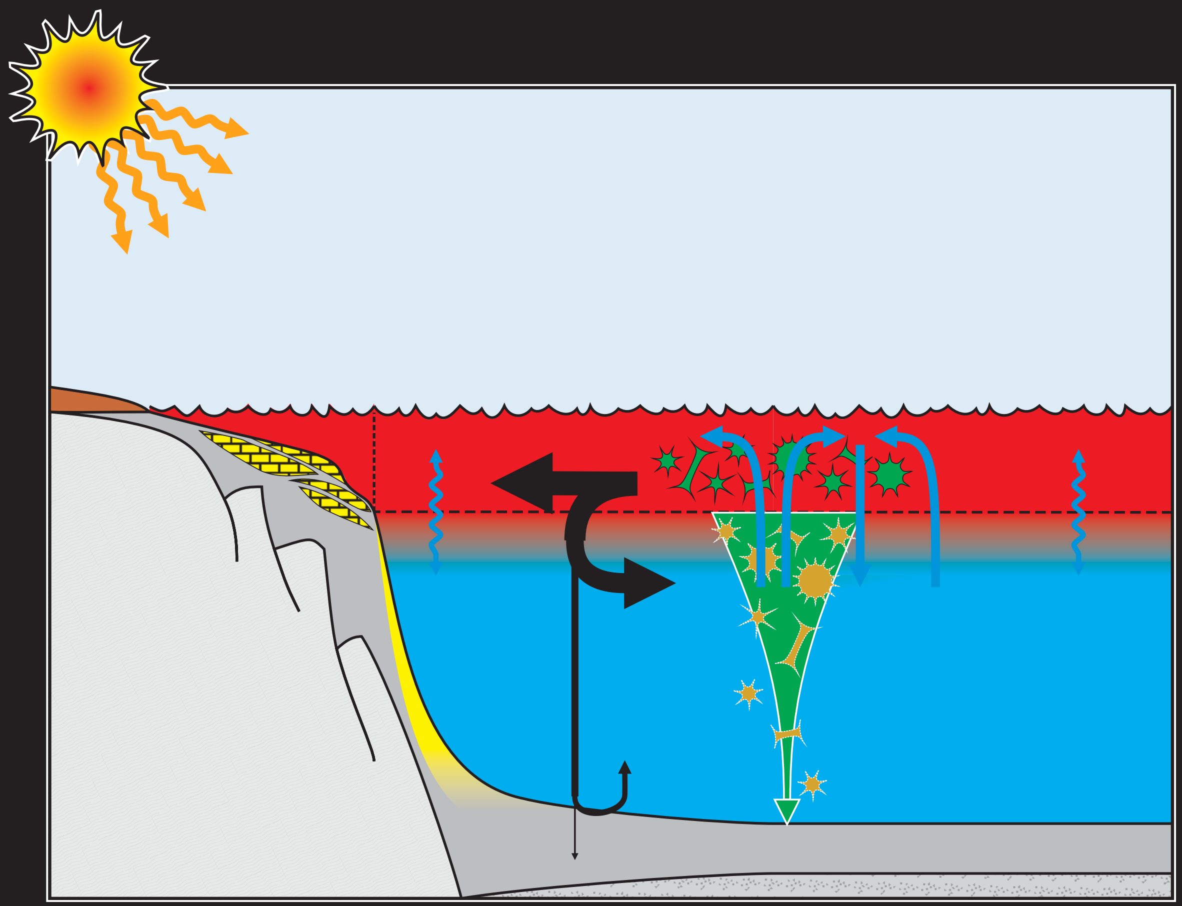
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates

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

???

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



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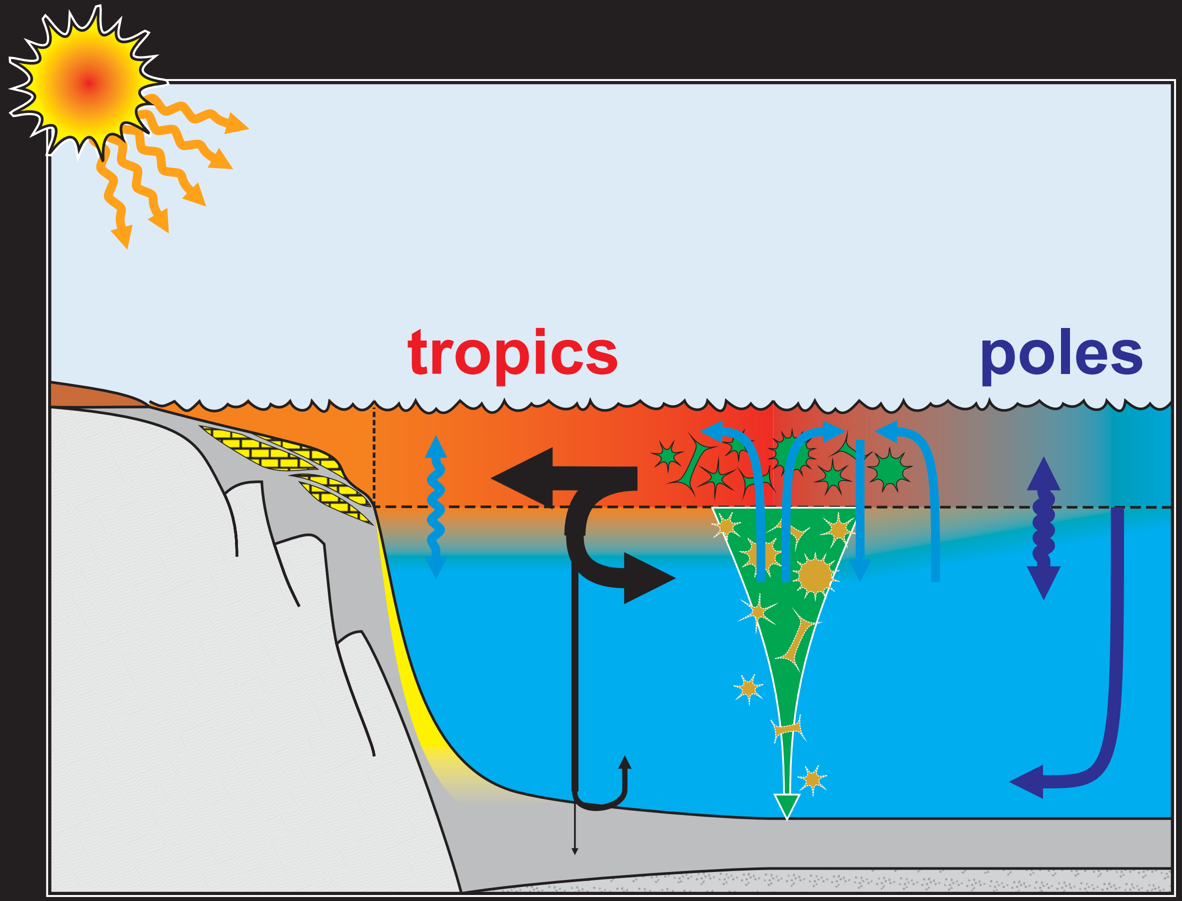
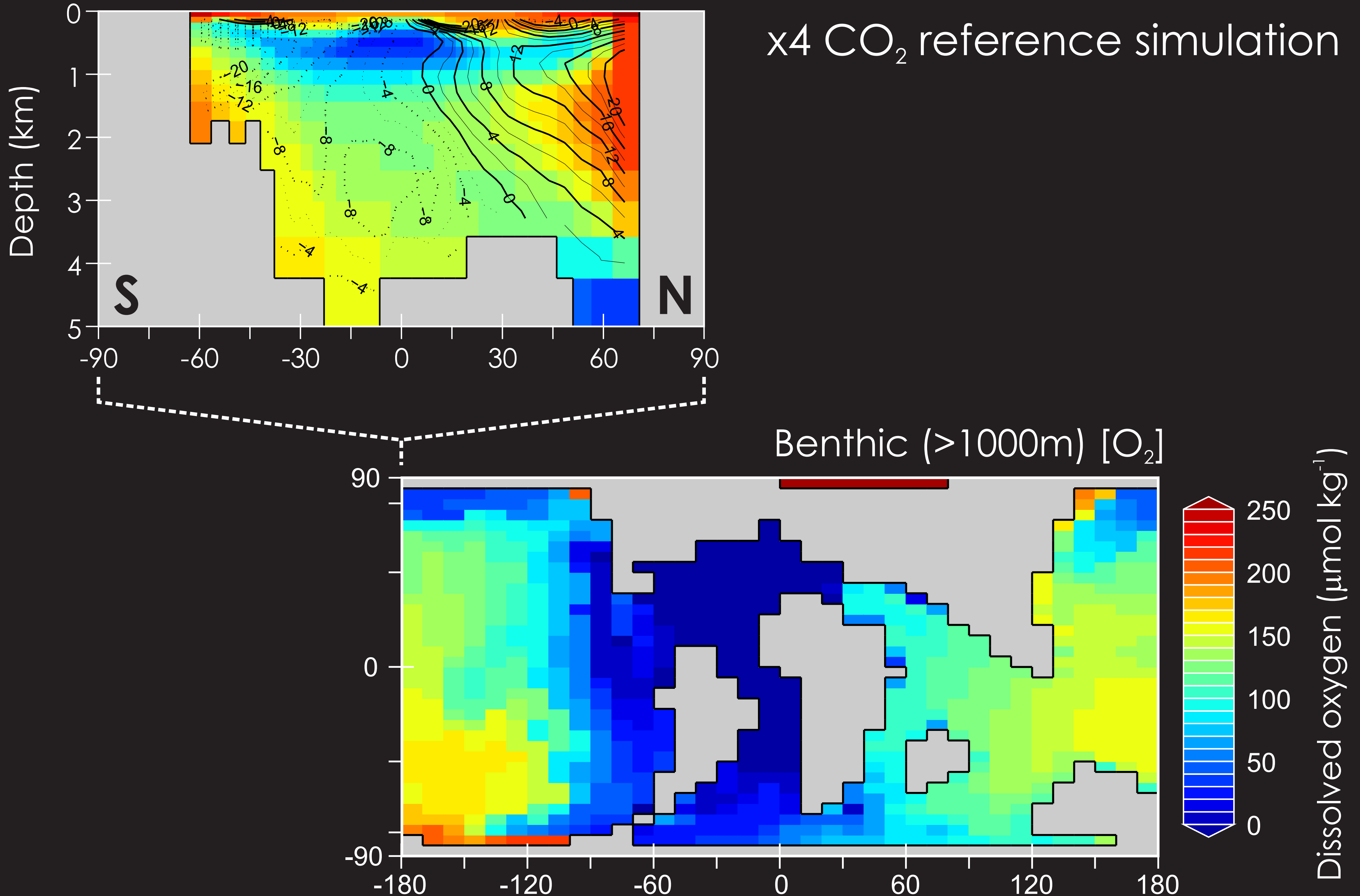
Ocean Carbon Cycling and Oxygenation in Warm Climates



Evolution of the Biological Pump:

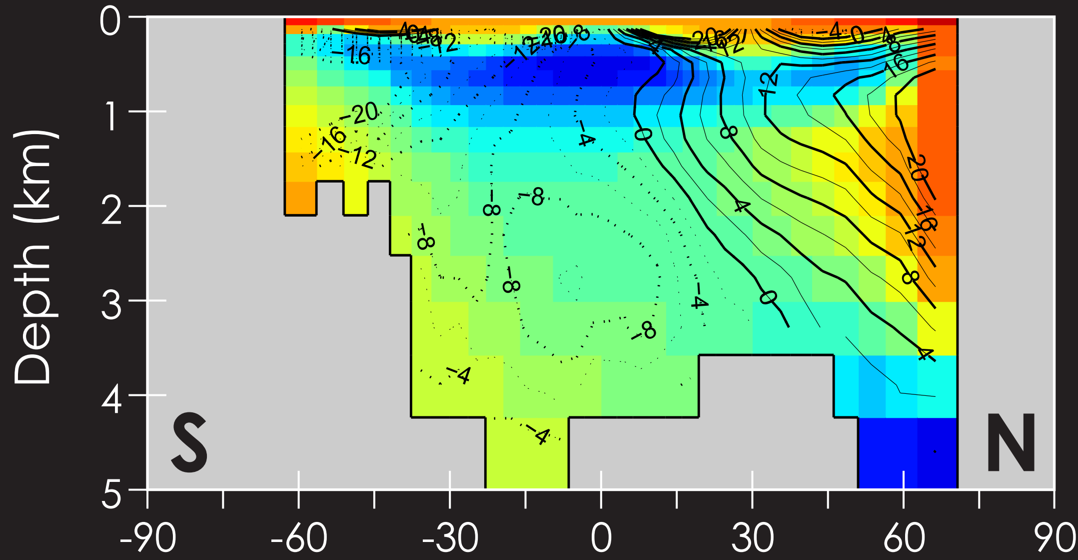
Ocean Carbon Cycling and Oxygenation in Warm Climates

x4 CO_2 reference simulation



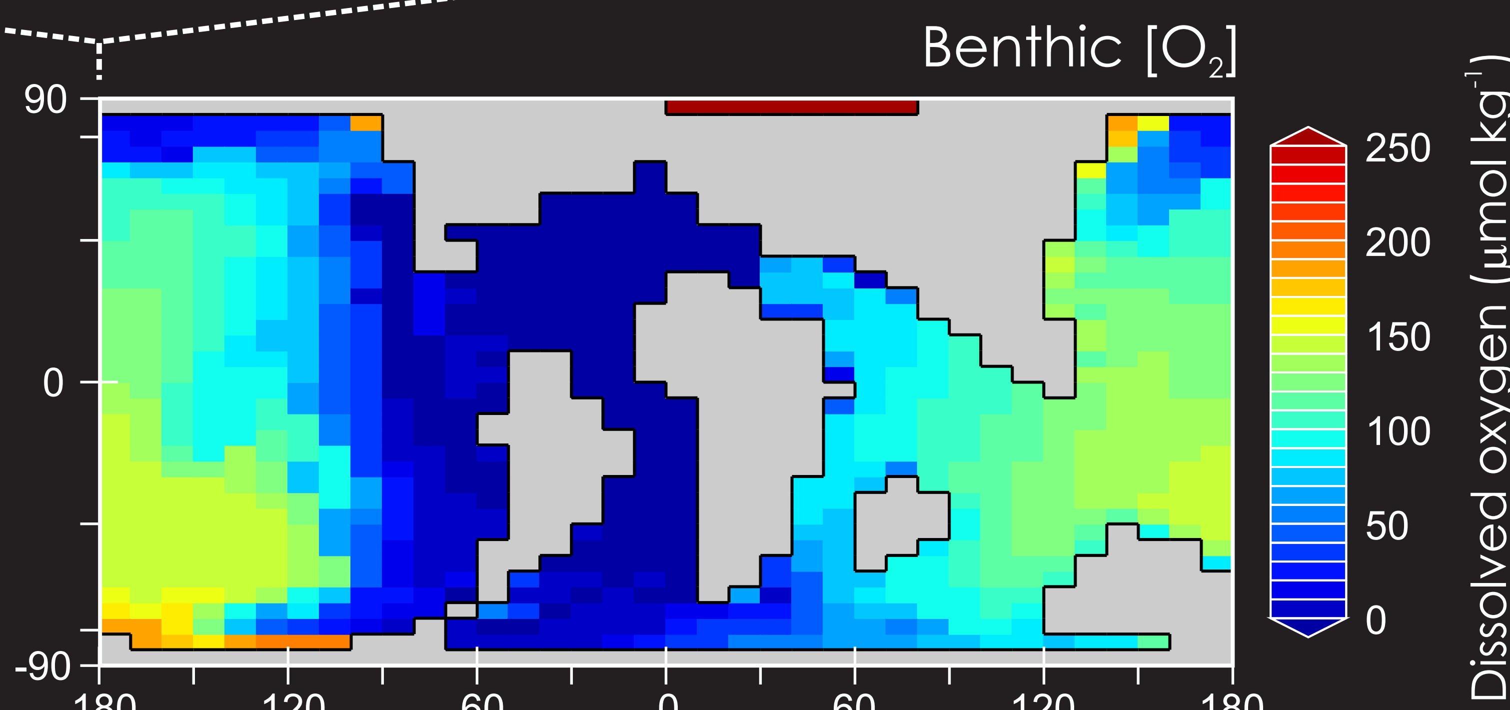
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



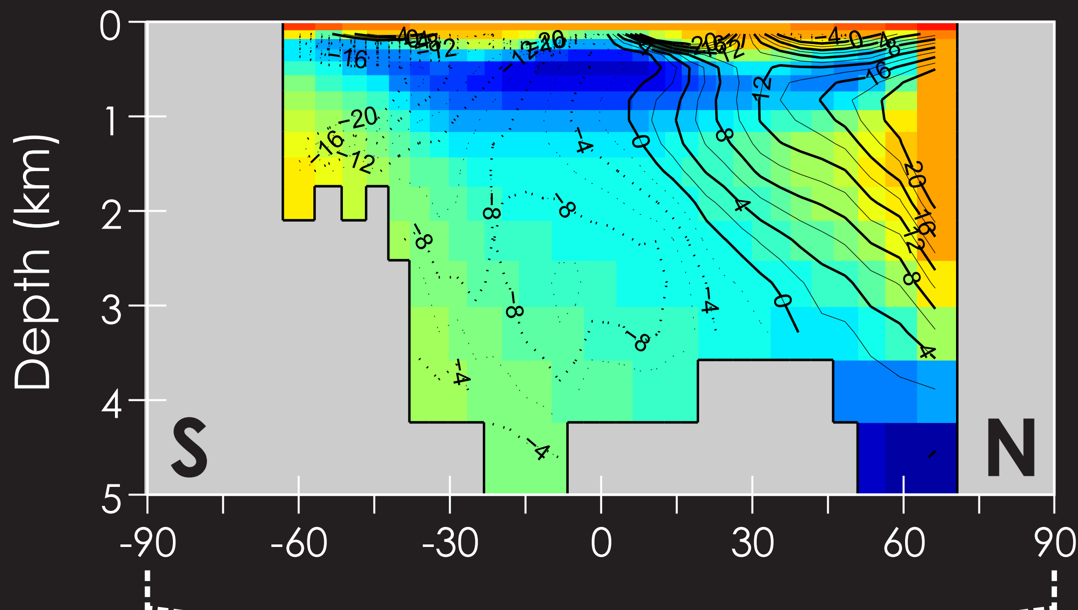
x8 CO_2 @ 10,000 yrs

(started from end of the x4 simulation)



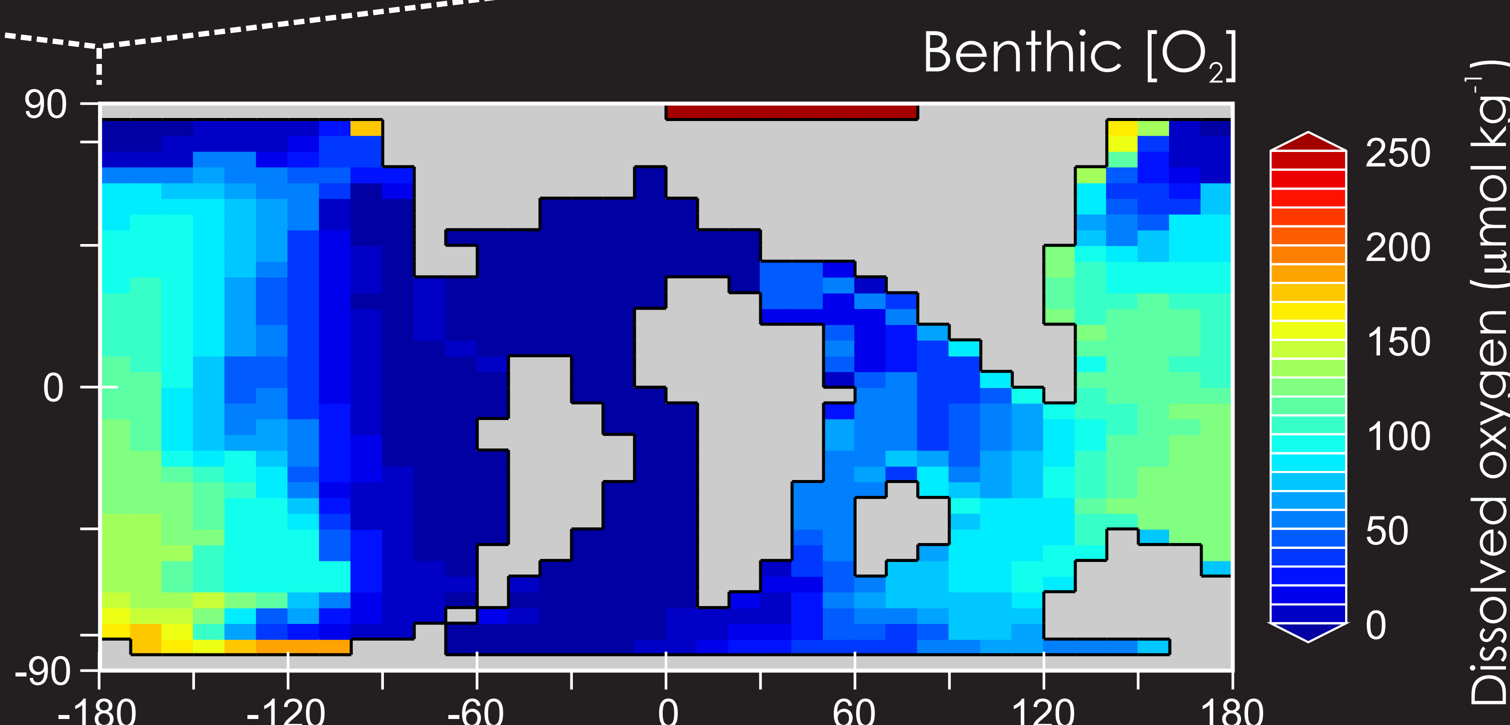
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates



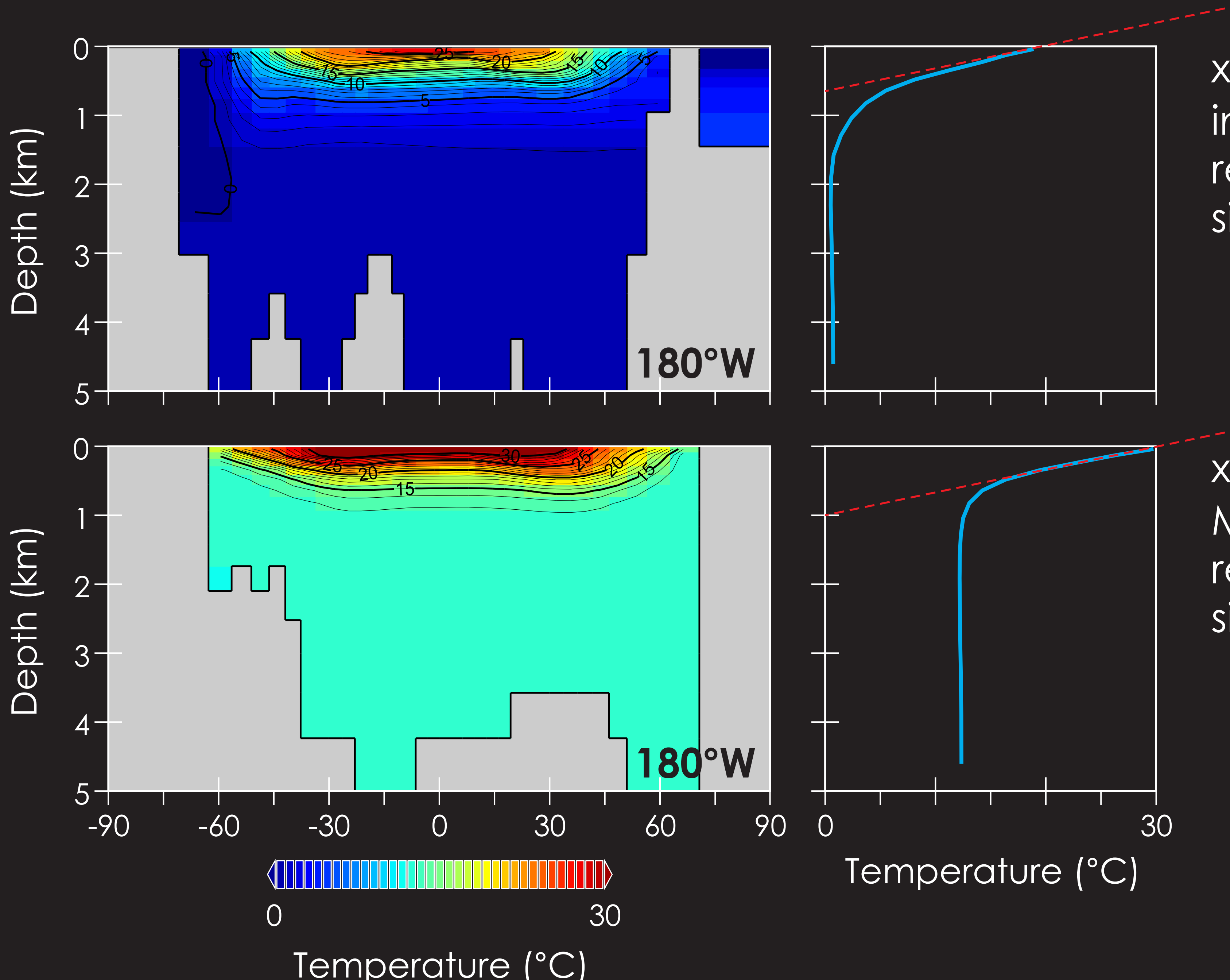
x16 CO_2 @ 10,000 yrs

(started from end of the x4 simulation)



Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates

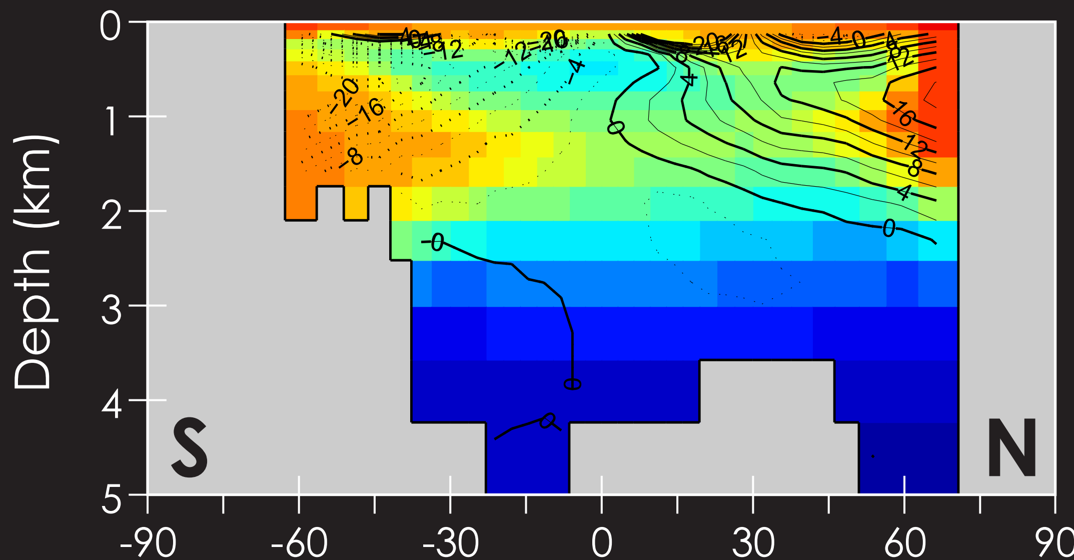


x1 CO_2 pre-industrial reference simulation

x4 CO_2 Maastrichtian reference simulation

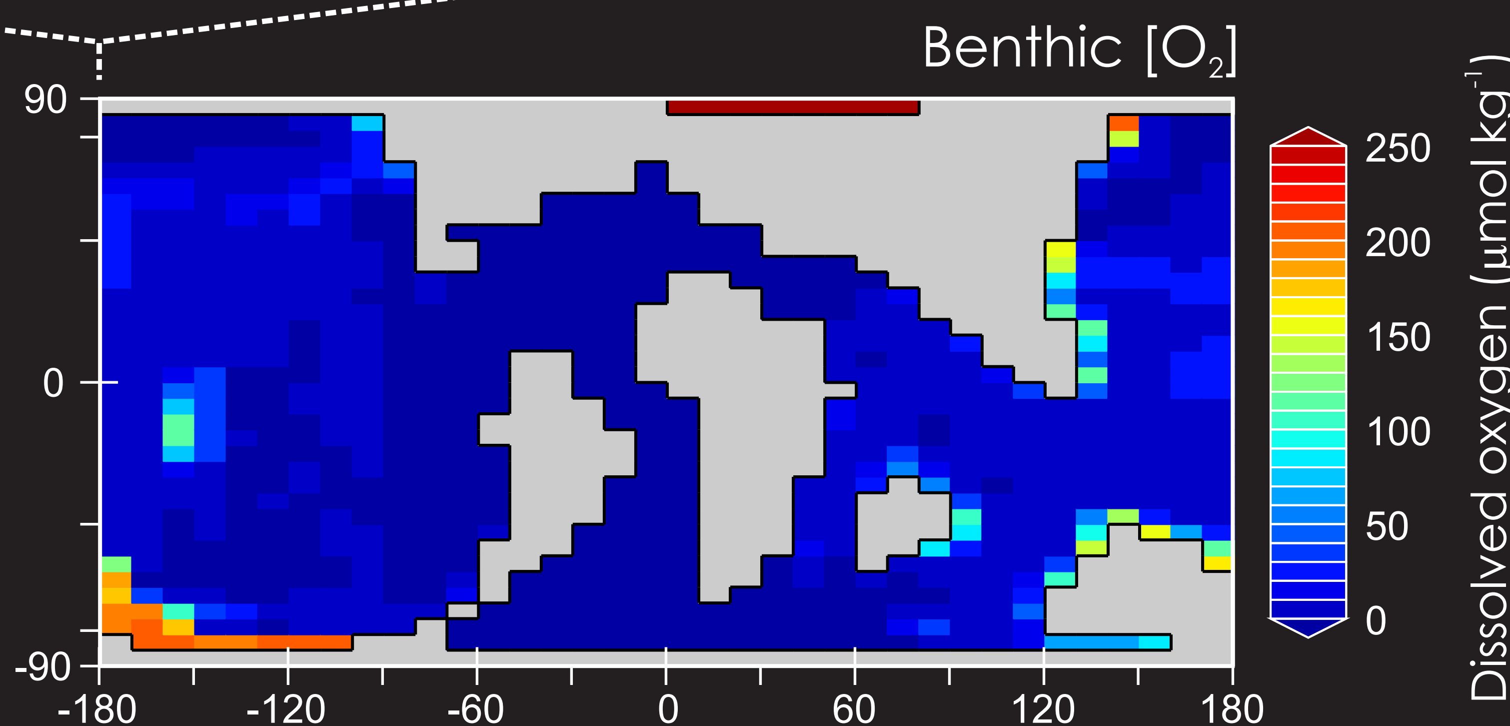
Evolution of the Biological Pump:

Ocean Carbon Cycling and Oxygenation in Warm Climates

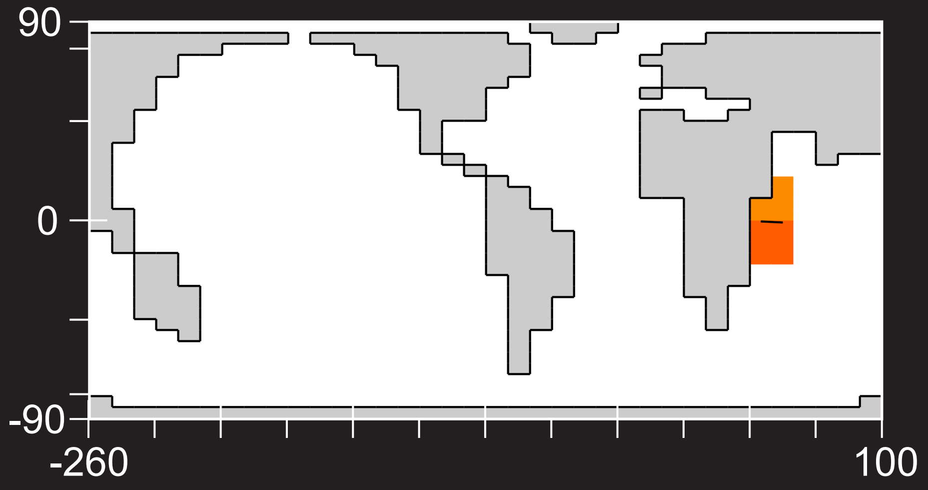


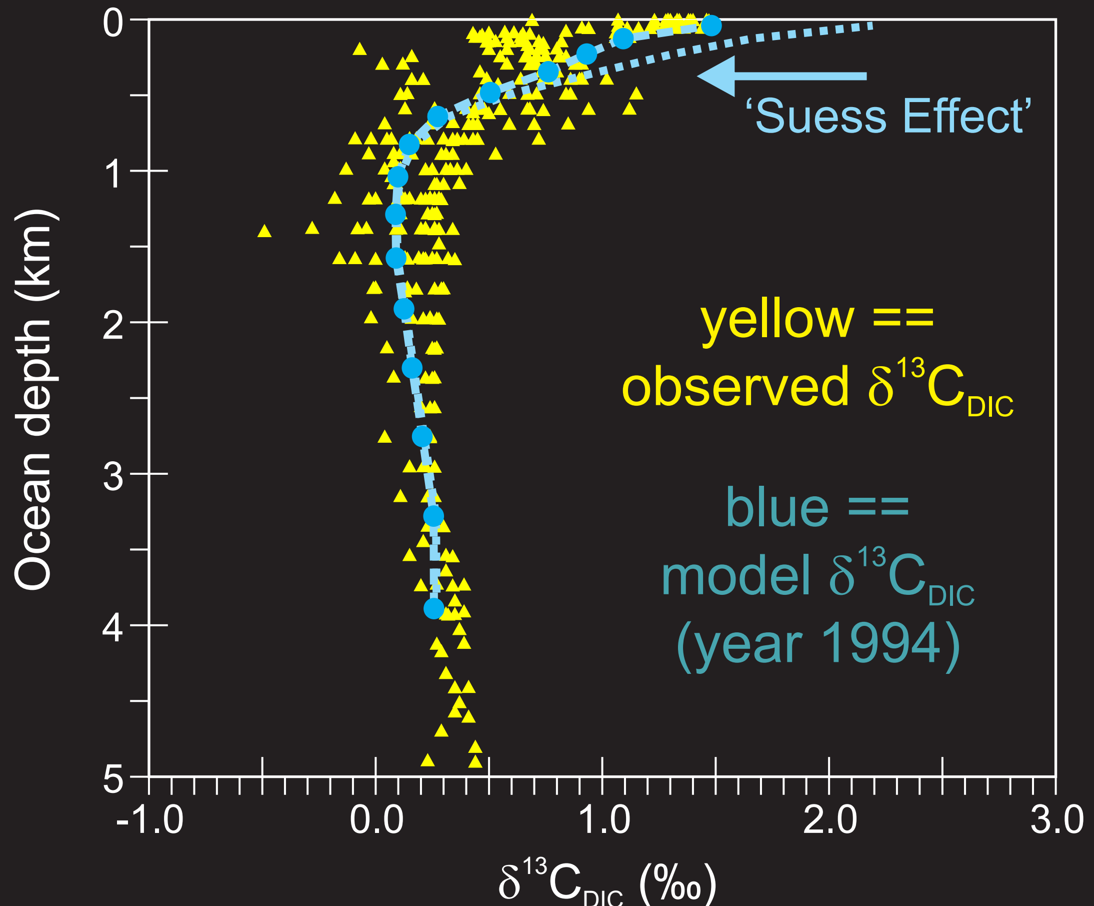
x16 CO_2 @ 2,000 yrs

transient state
(incomplete adjustment to
increased radiative forcing)

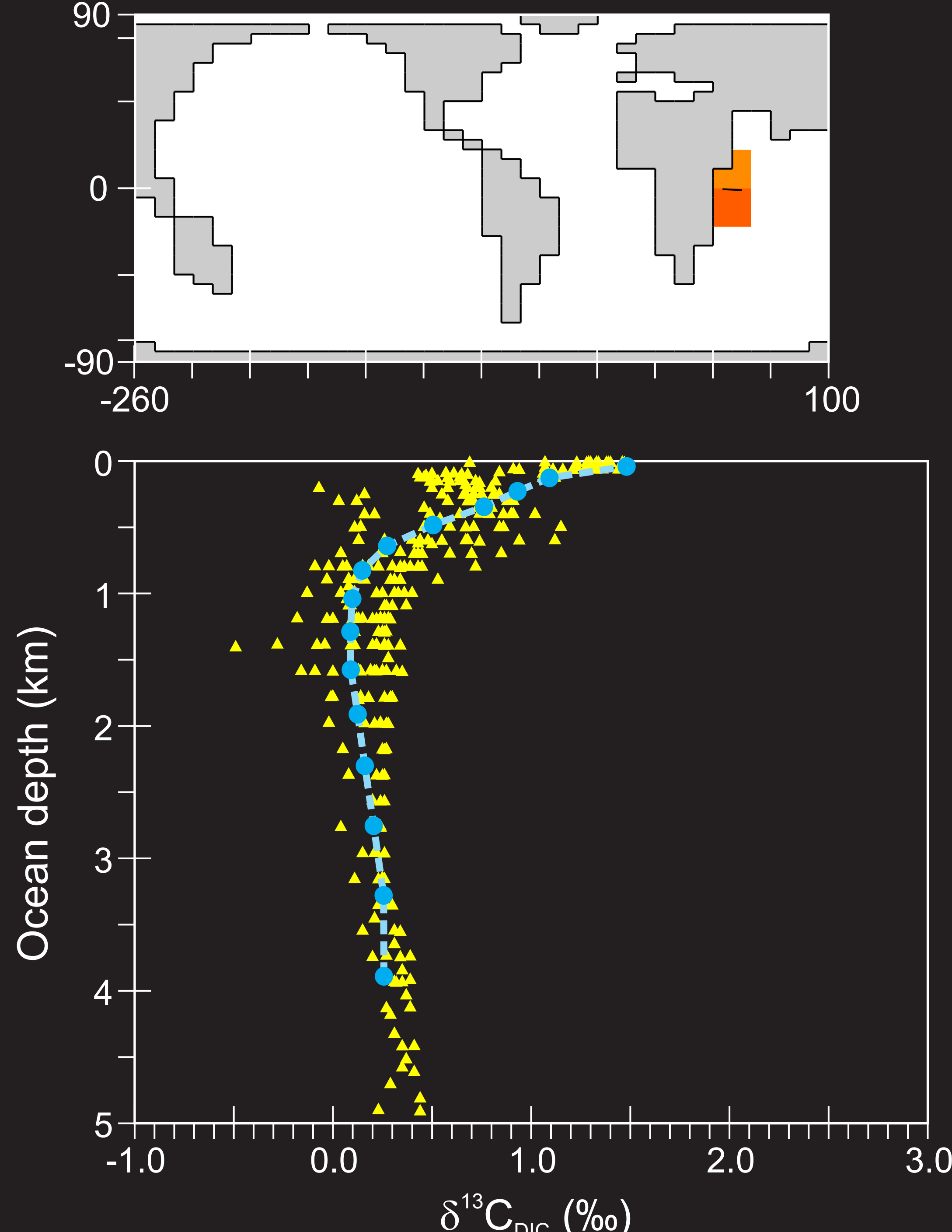


Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania

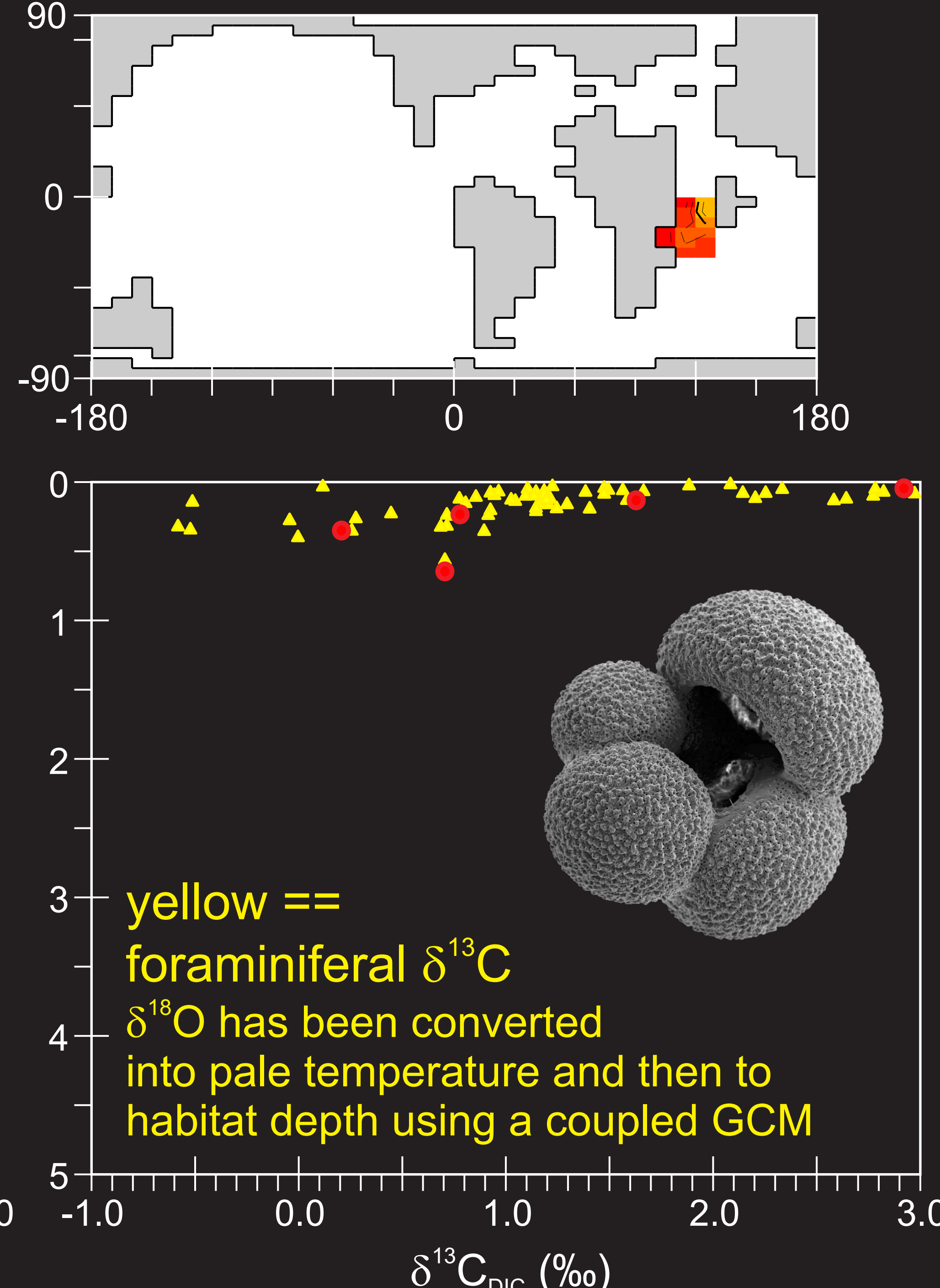




Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania

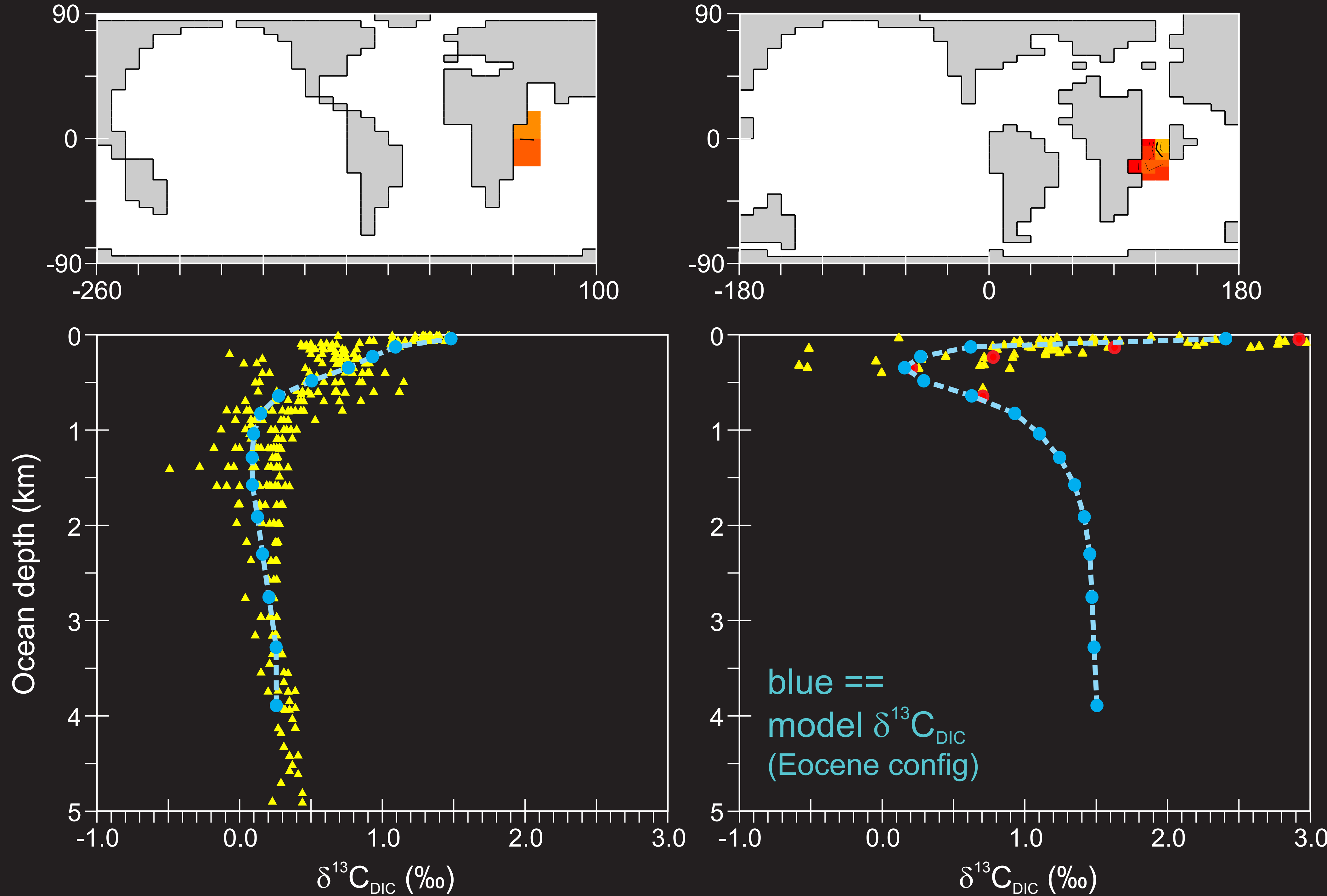


Planktic foraminiferal $\delta^{13}C$ from early Eocene Tanzania

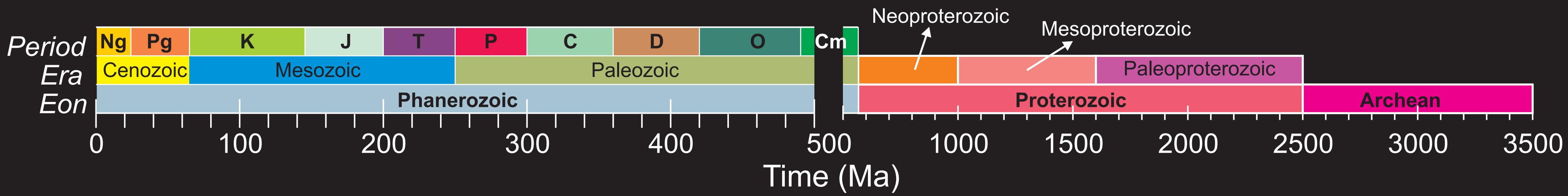


Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania

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

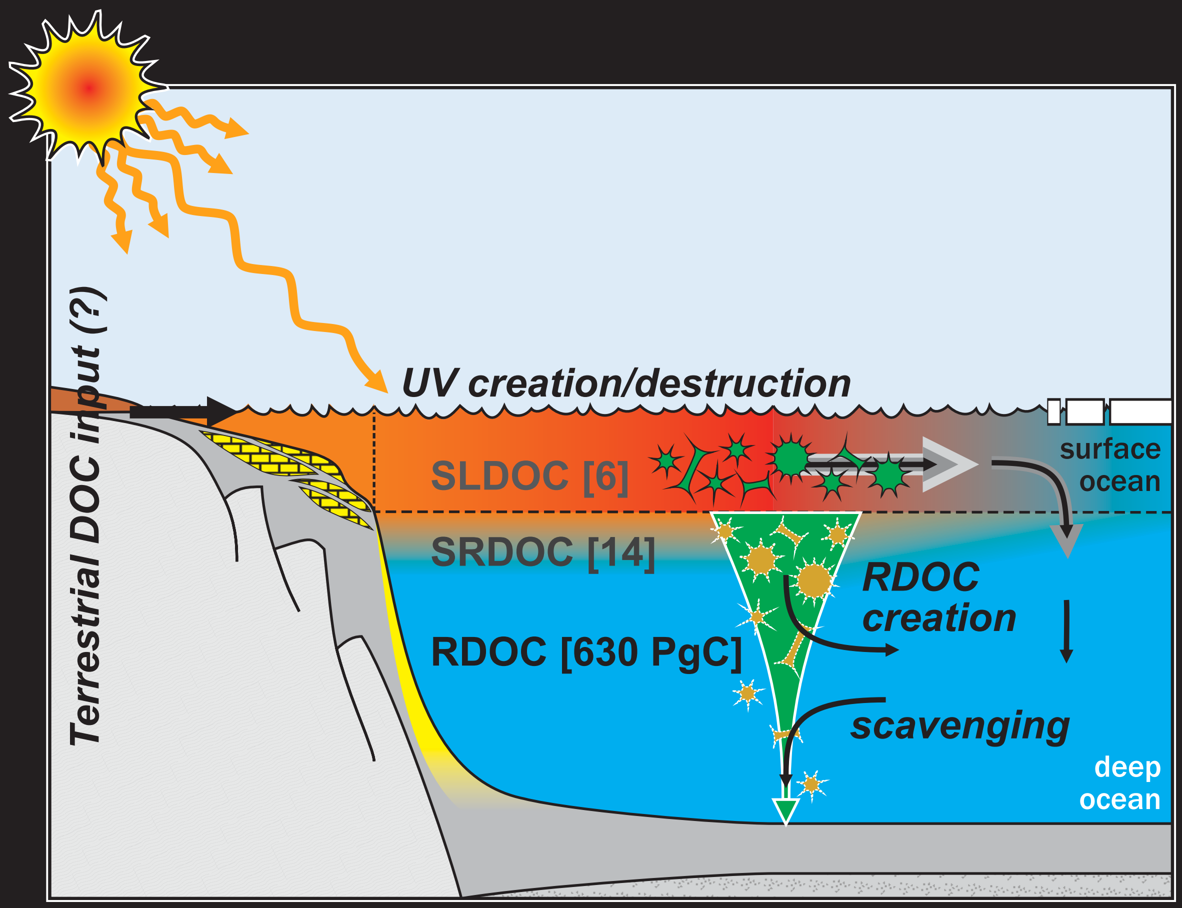


Evolution of the Biological Pump



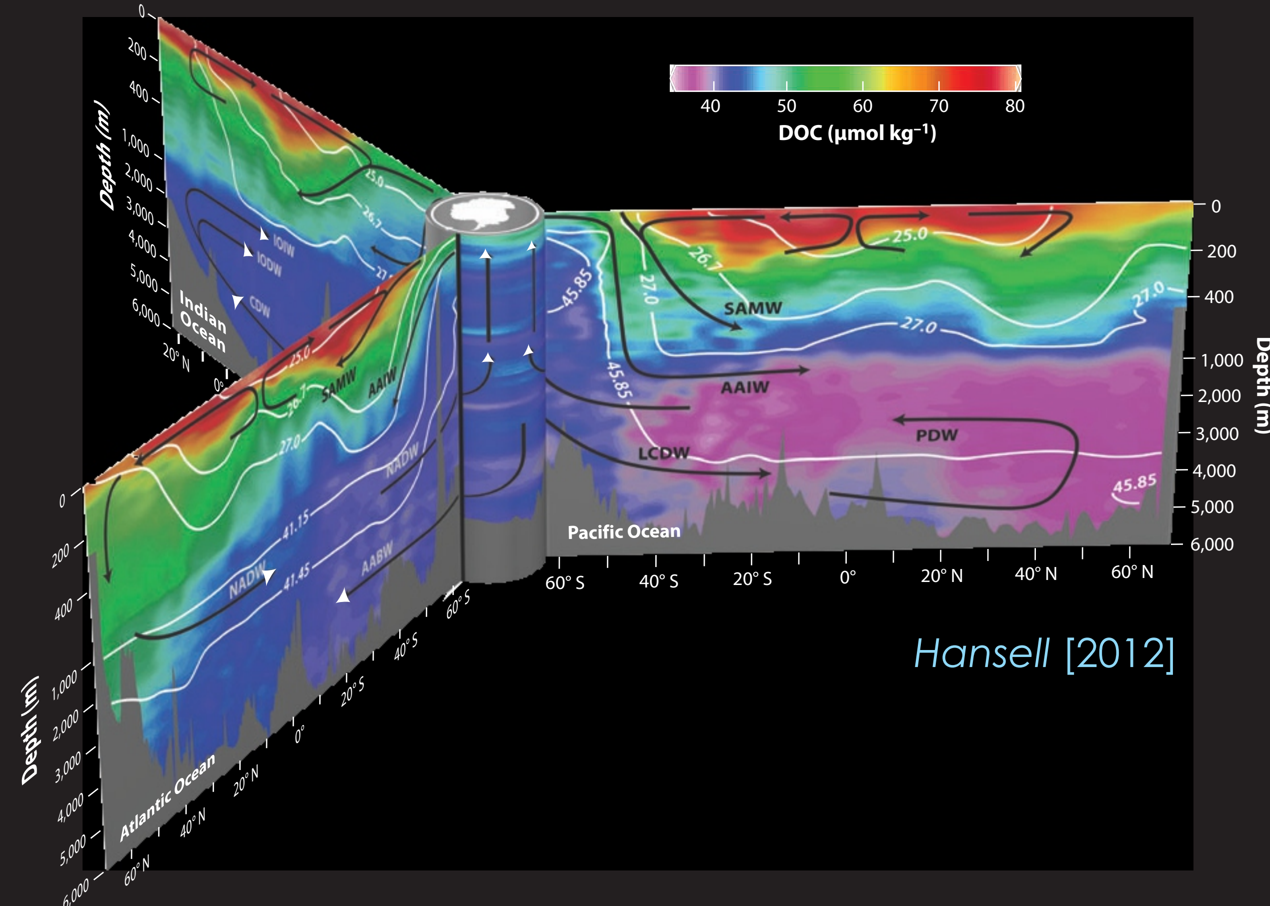
Evolution of the Biological Pump:

The Role of
Dissolved organic matter
(DOM)?

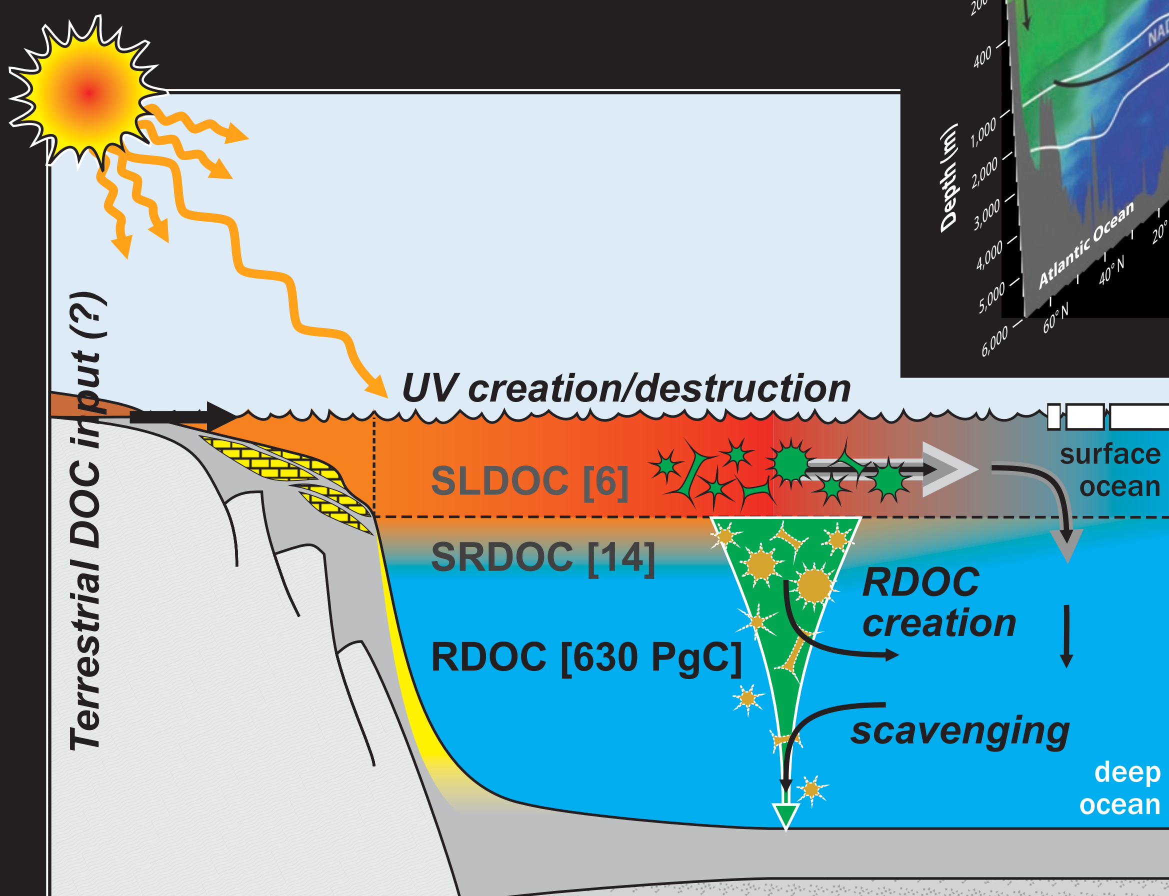


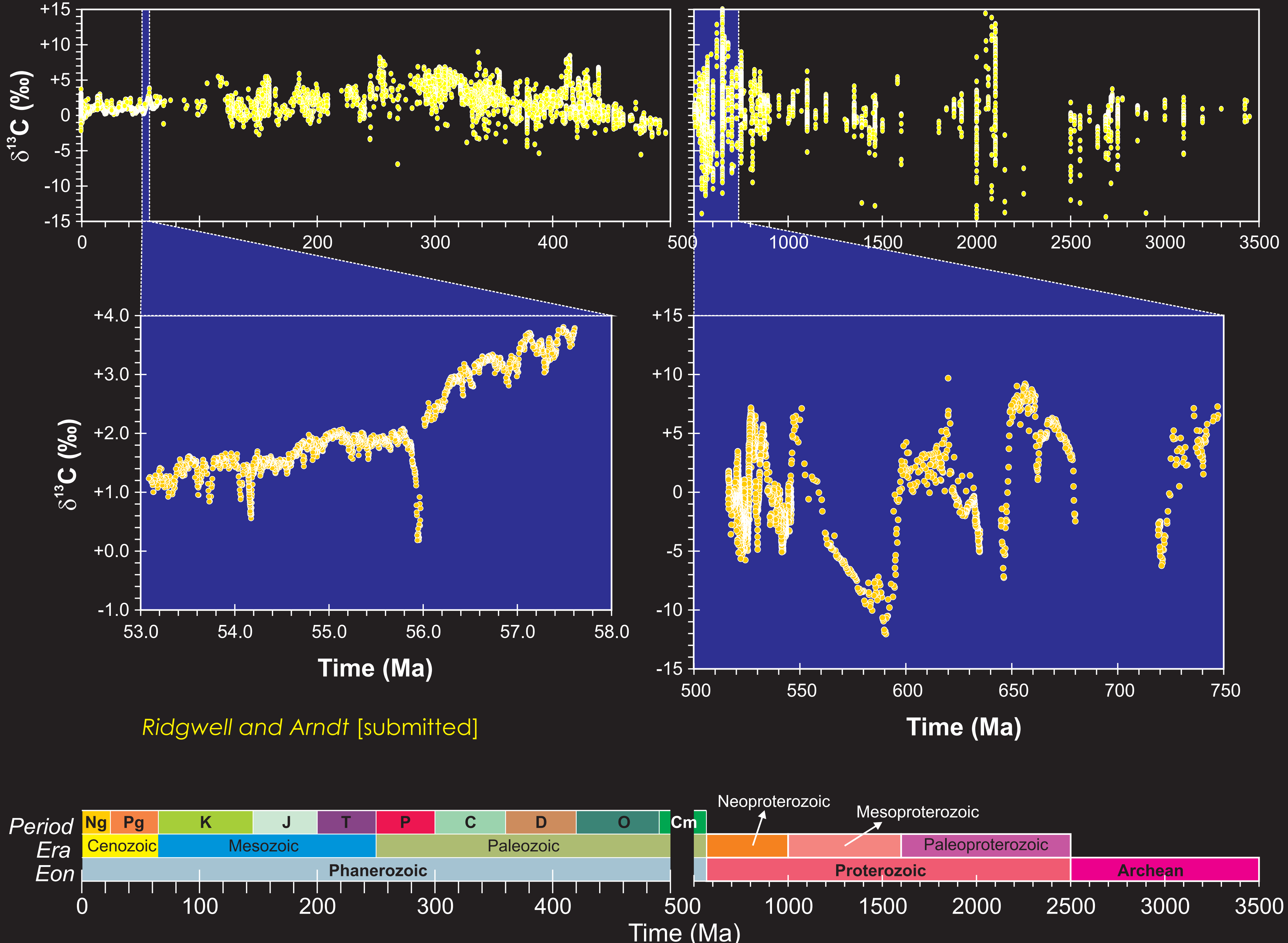
Evolution of the Biological Pump:

The Role of
Dissolved organic matter (DOM)?



Hansell [2012]

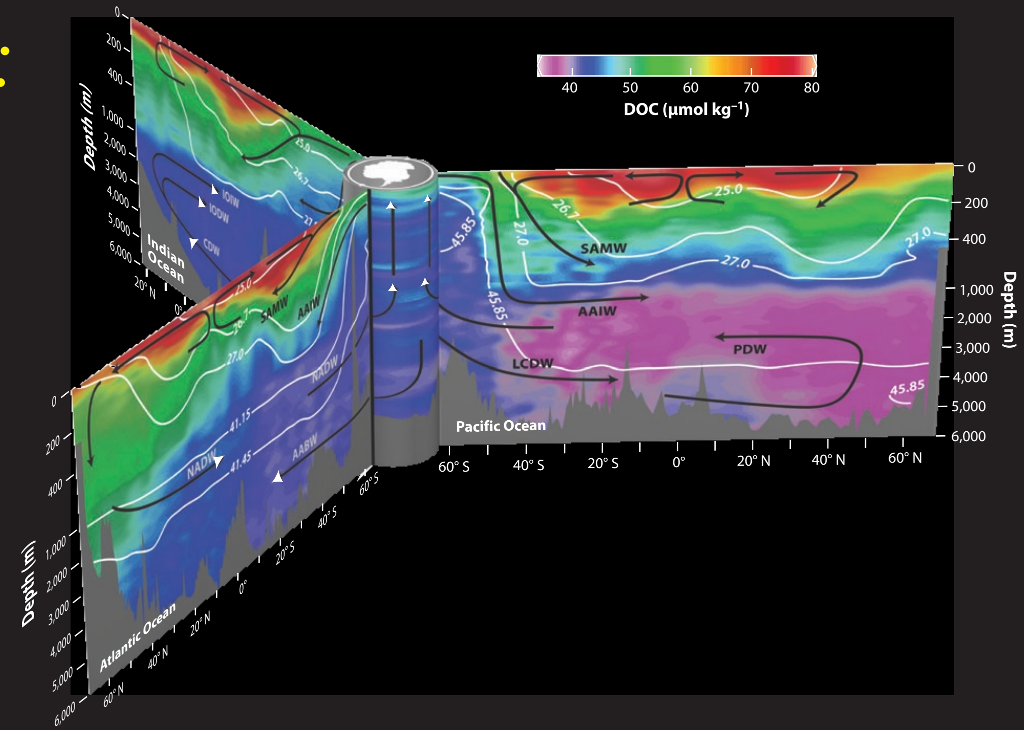


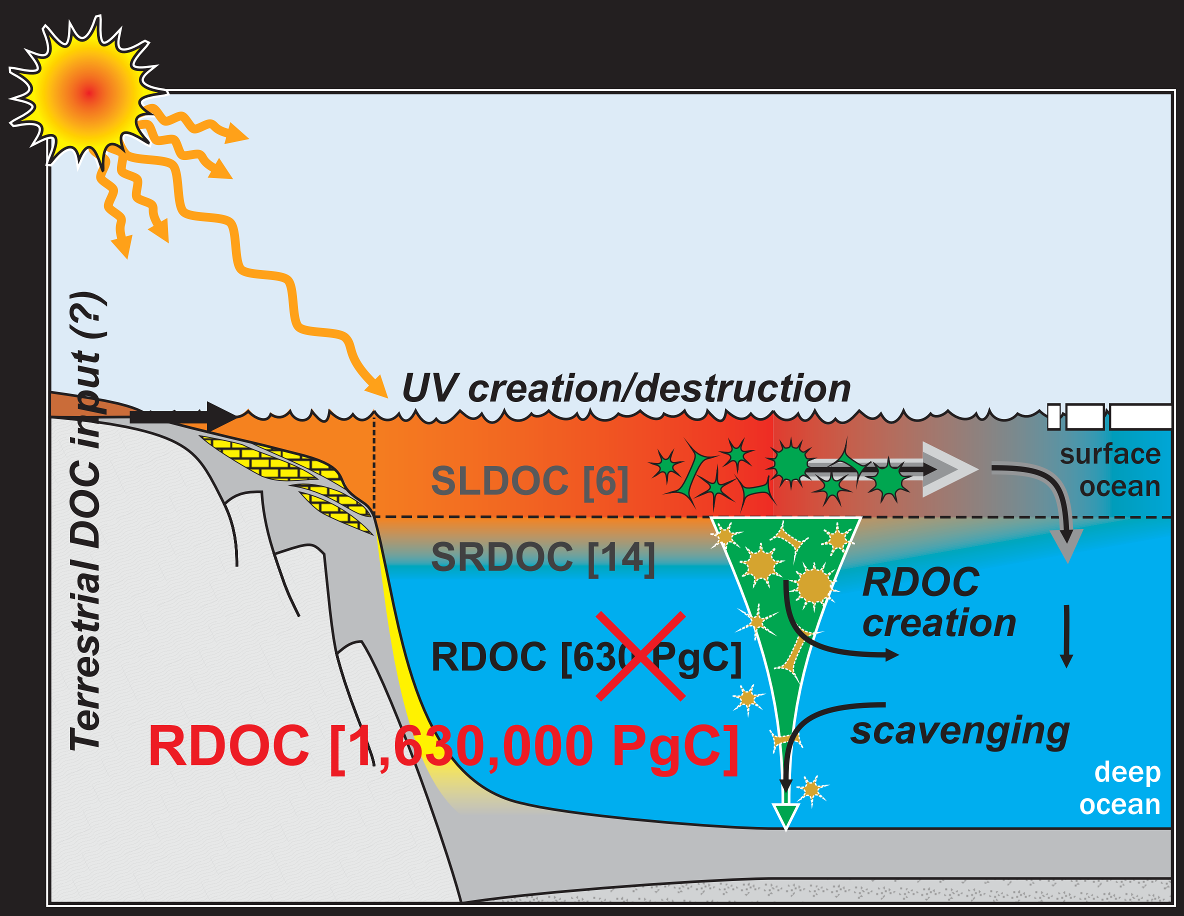


$\delta^{13}C$ (‰)
+15
+10
+5
0
-5
-10
-15
0
200
300
400
500
1000
1500
2000
2500
3000
3500
+4.0
+3.0
+2.0
+1.0
+0.0
-1.0
53.0
54.0
55.0
56.0
57.0
58.0
Time (Ma)
550
600
650
700
750
Ridgwell and Arndt [submitted]
Period
Era
Eon
Ng
Pg
K
J
T
P
C
D
O
Cm
Cenozoic
Mesozoic
Paleozoic
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Phanerozoic
Proterozoic
Archean
100

Evolution of the Biological Pump:

The Role of Dissolved organic matter (DOM)?

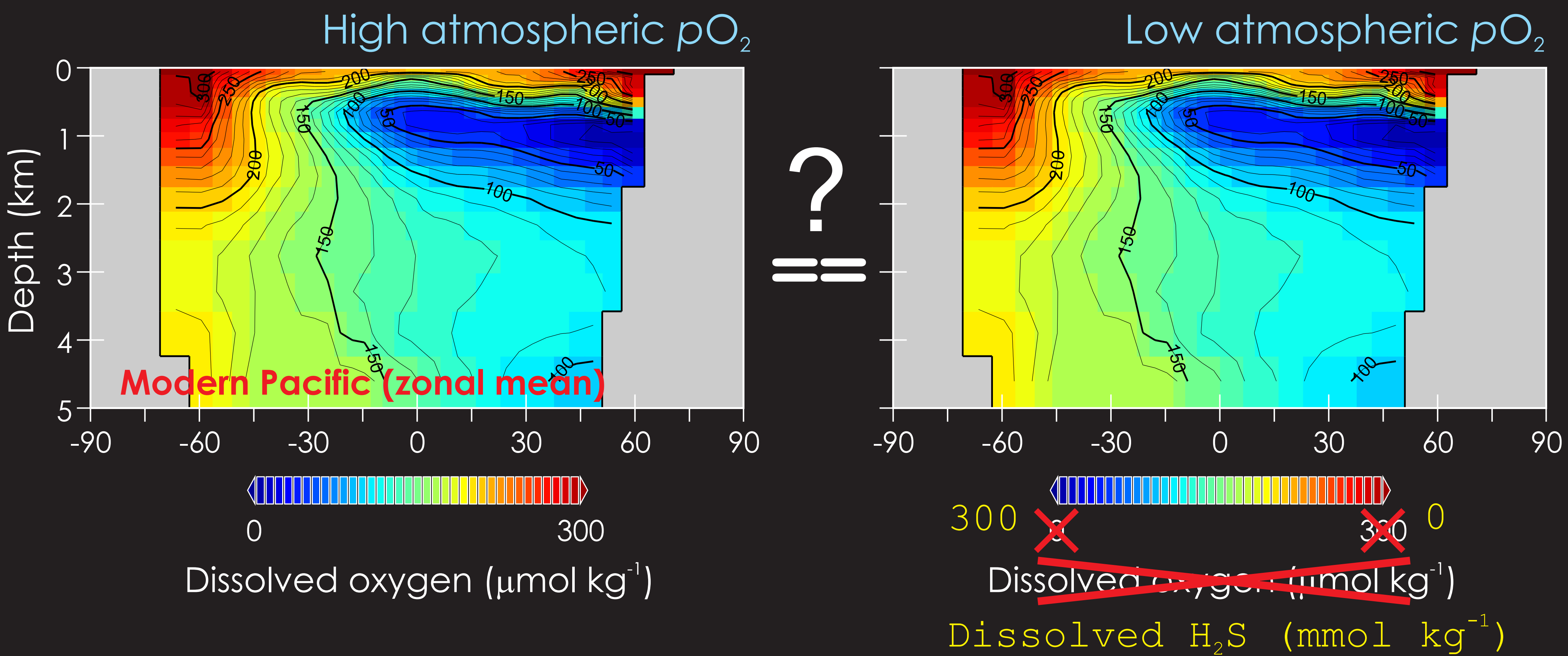


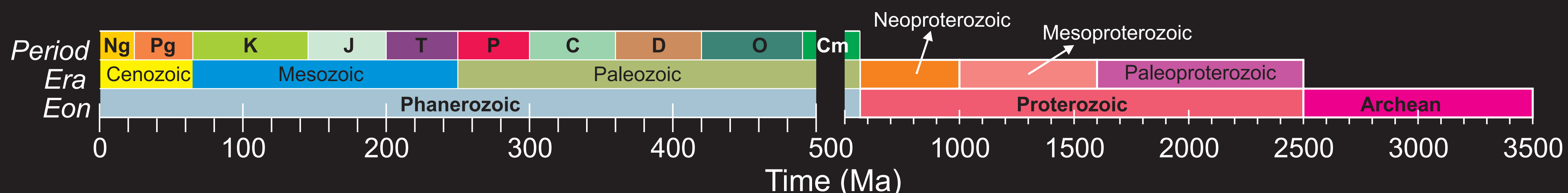


In the *Rothman et al.* [2003] model, the RDOC reservoir is assumed to have been at least 10 times the size of the inorganic (ocean DIC + atmospheric pCO_2) reservoir. For a modern DIC + pCO2 reservoir of 39,000 PgC, this mean 390,000 PgC of DOC – more than 500 times larger than modern). For a higher 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^-.

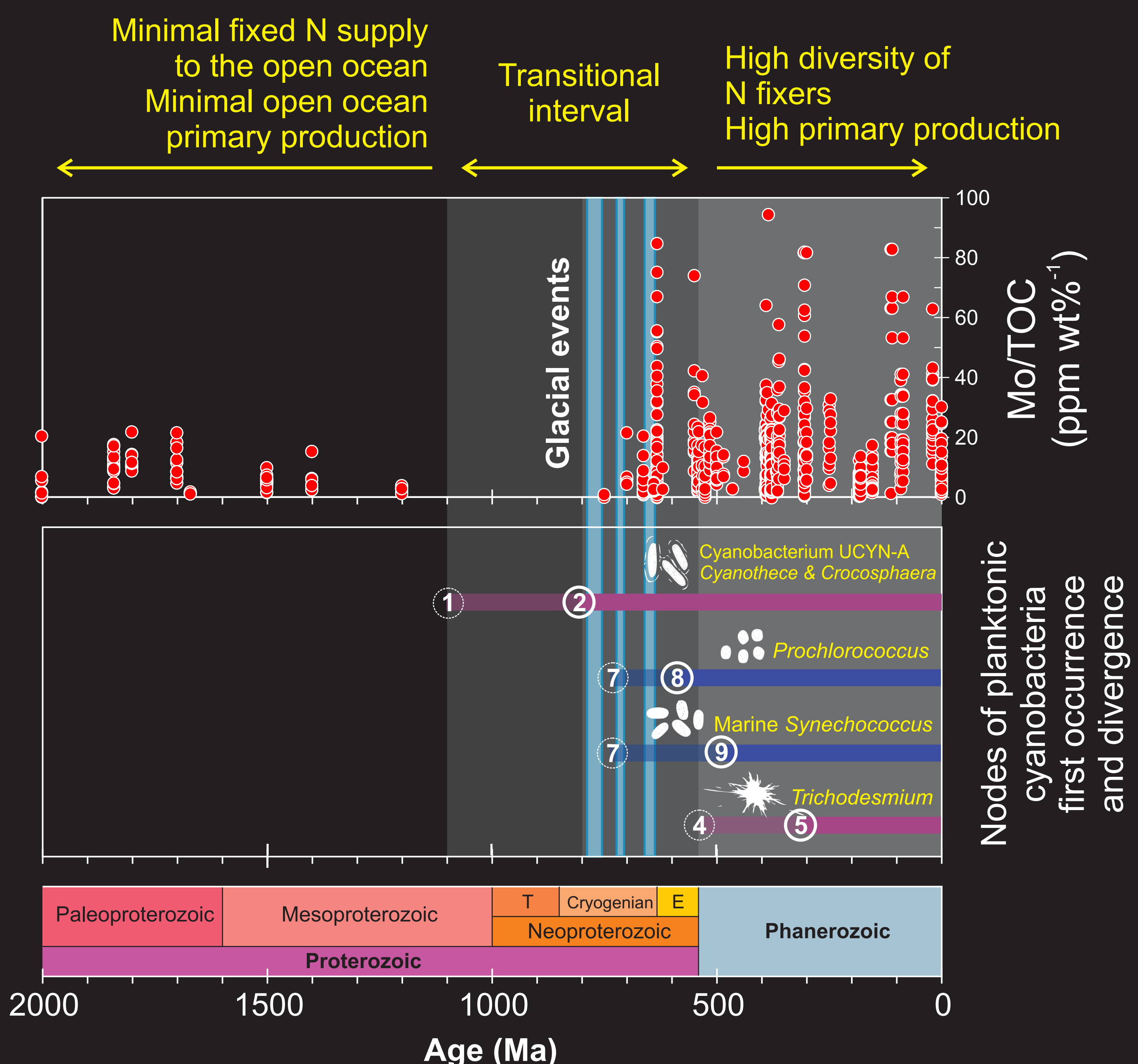
Evolution of the Biological Pump:

The Role of
Dissolved organic matter
(DOM)?





Evolution of the Biological Pump



Sanchez-Baracaldo et al. [in press]

Thanks to:

Jamie Wilson & Steve Barker,
Eleanor John, Paul Pearson [Cardiff]

Patricia Sanchez-Baracaldo,
Sandra Arndt, Daniela Schmidt [Bristol]

Ellen Thomas [Yale]

The Royal Society, Natural Environmental Research Council, EU ERC