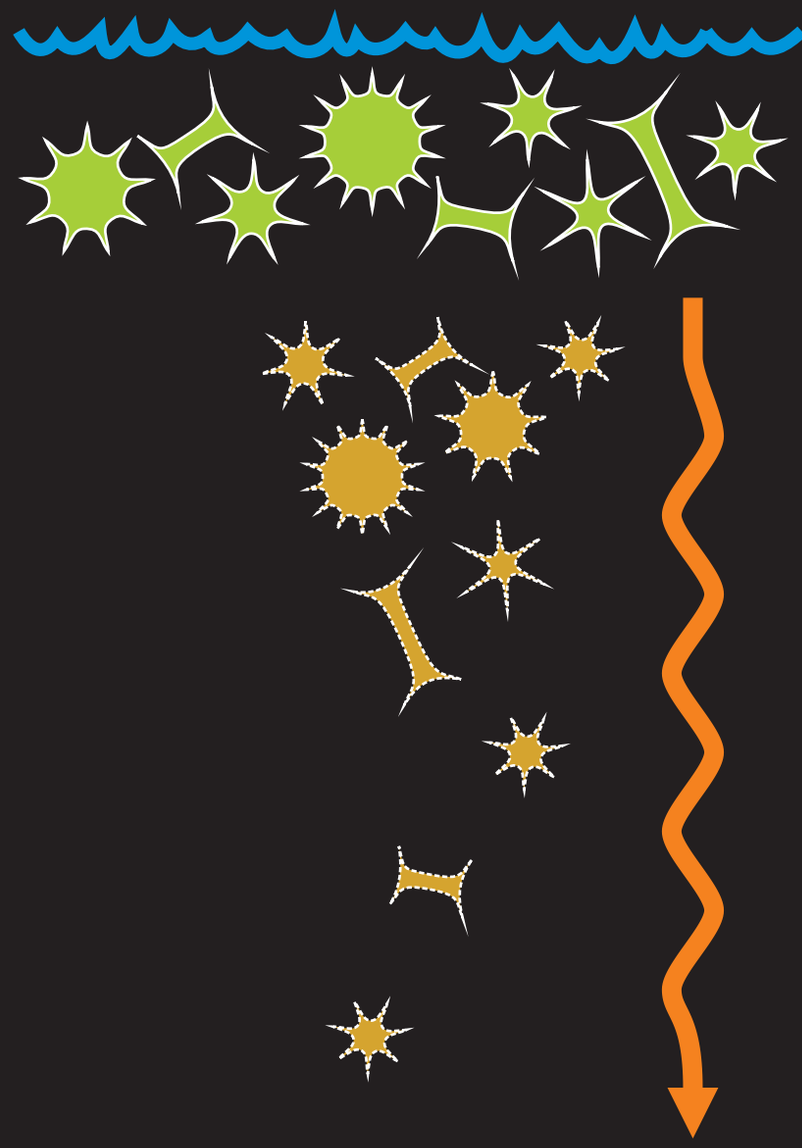
Evolution of the Ocean's Biological Pump ... *in silico*

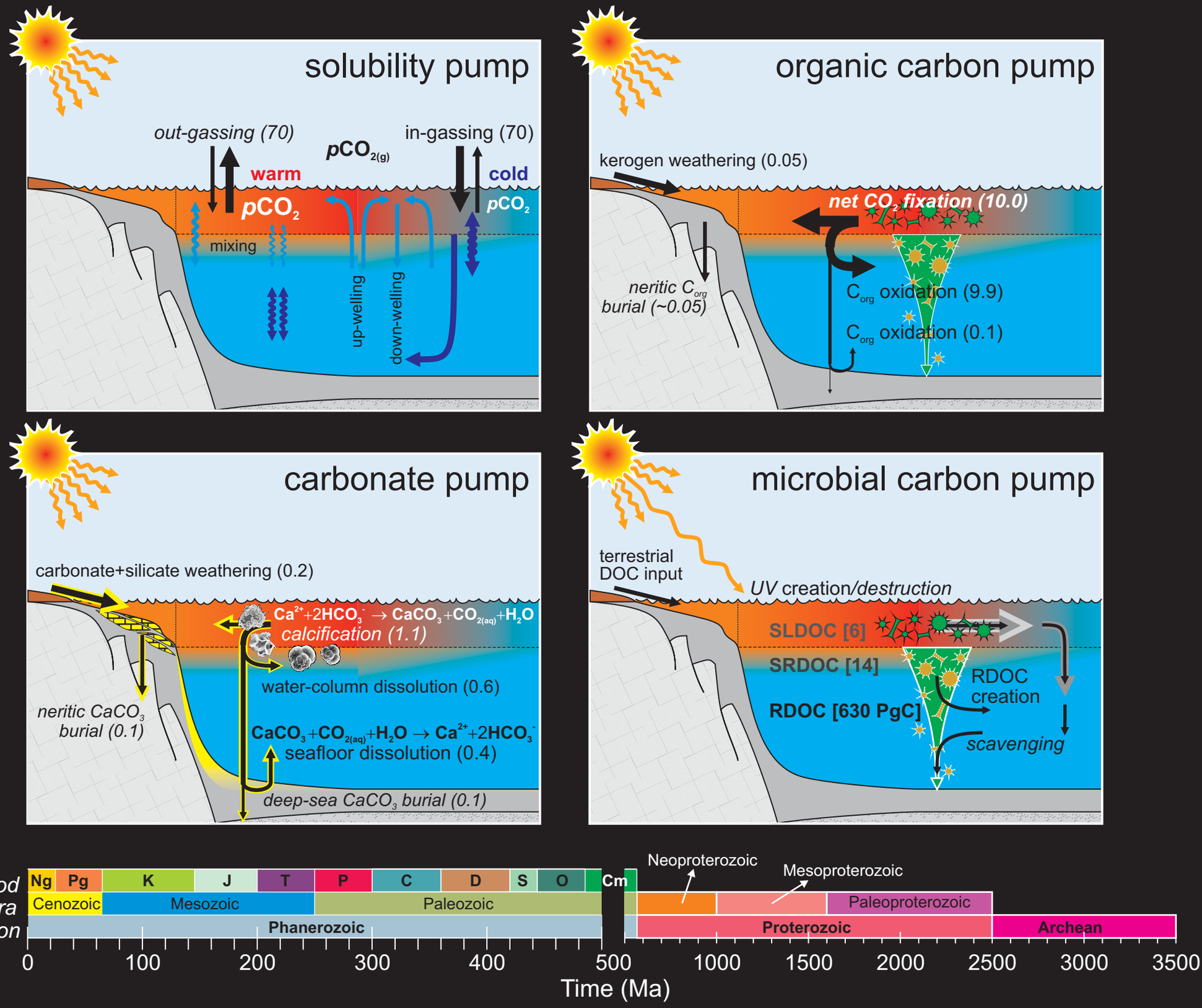
Andy Ridgwell



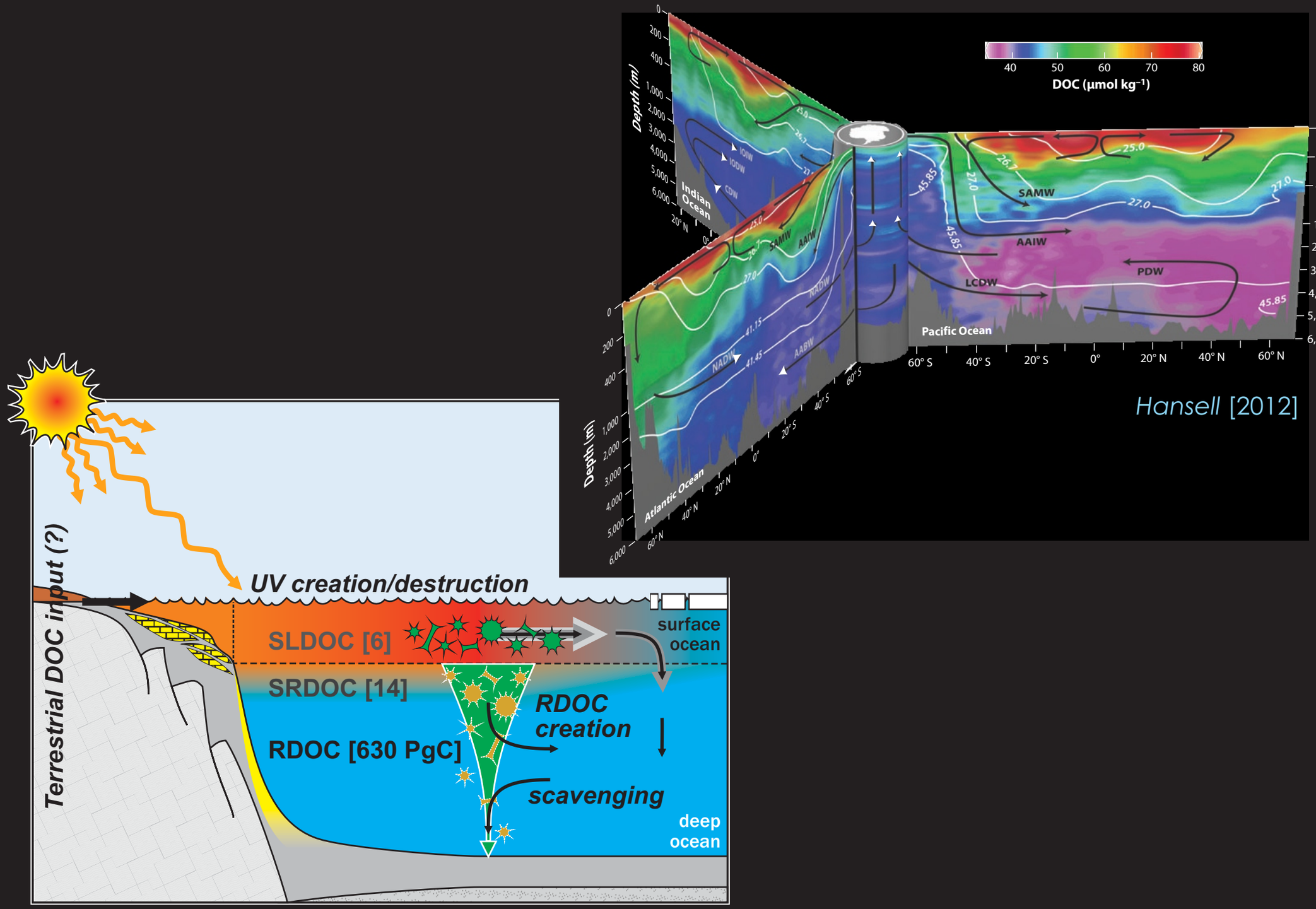
THE ROYAL SOCIETY
CELEBRATING 350 YEARS

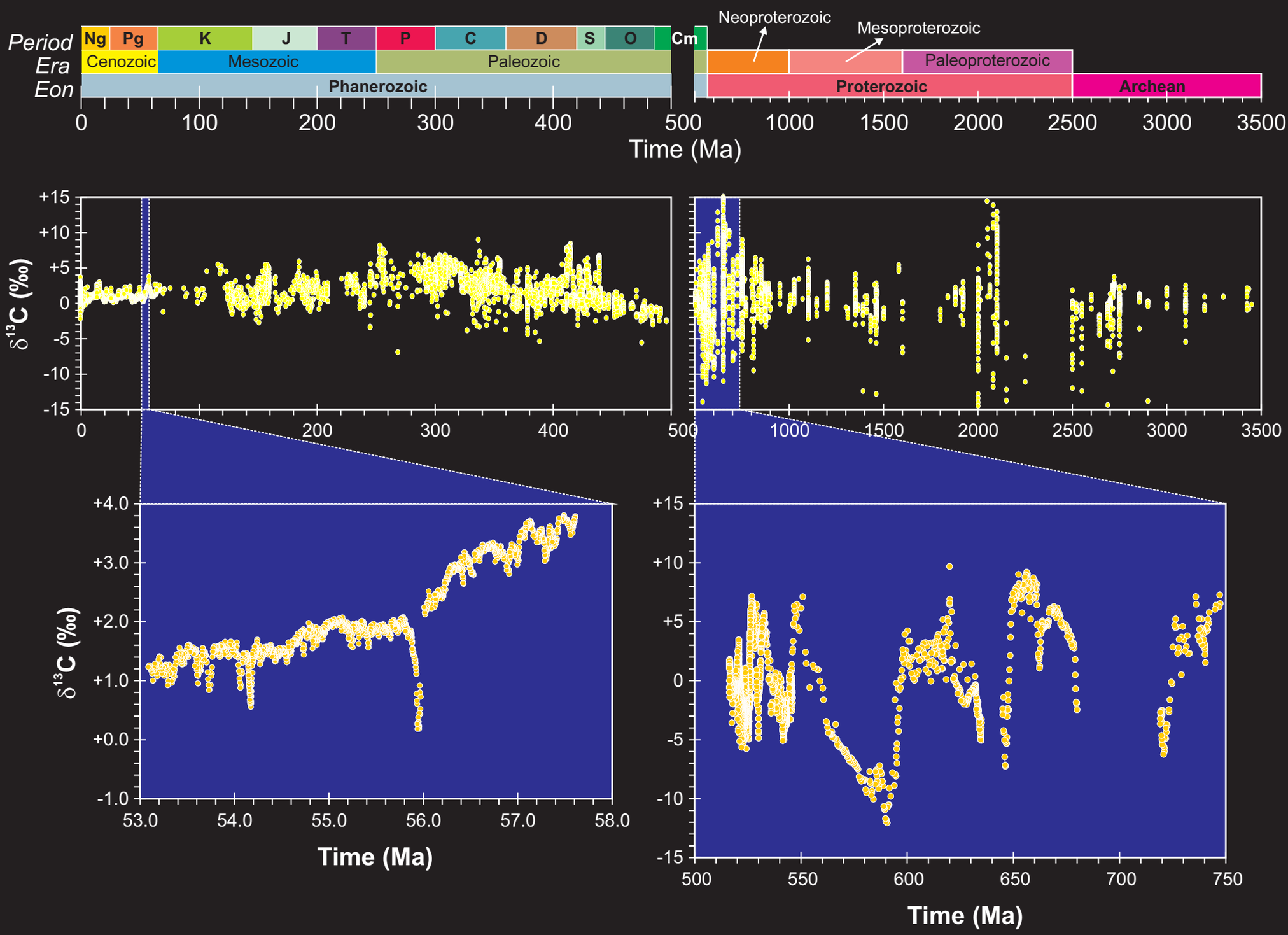
University of BRISTOL

BRIDGE

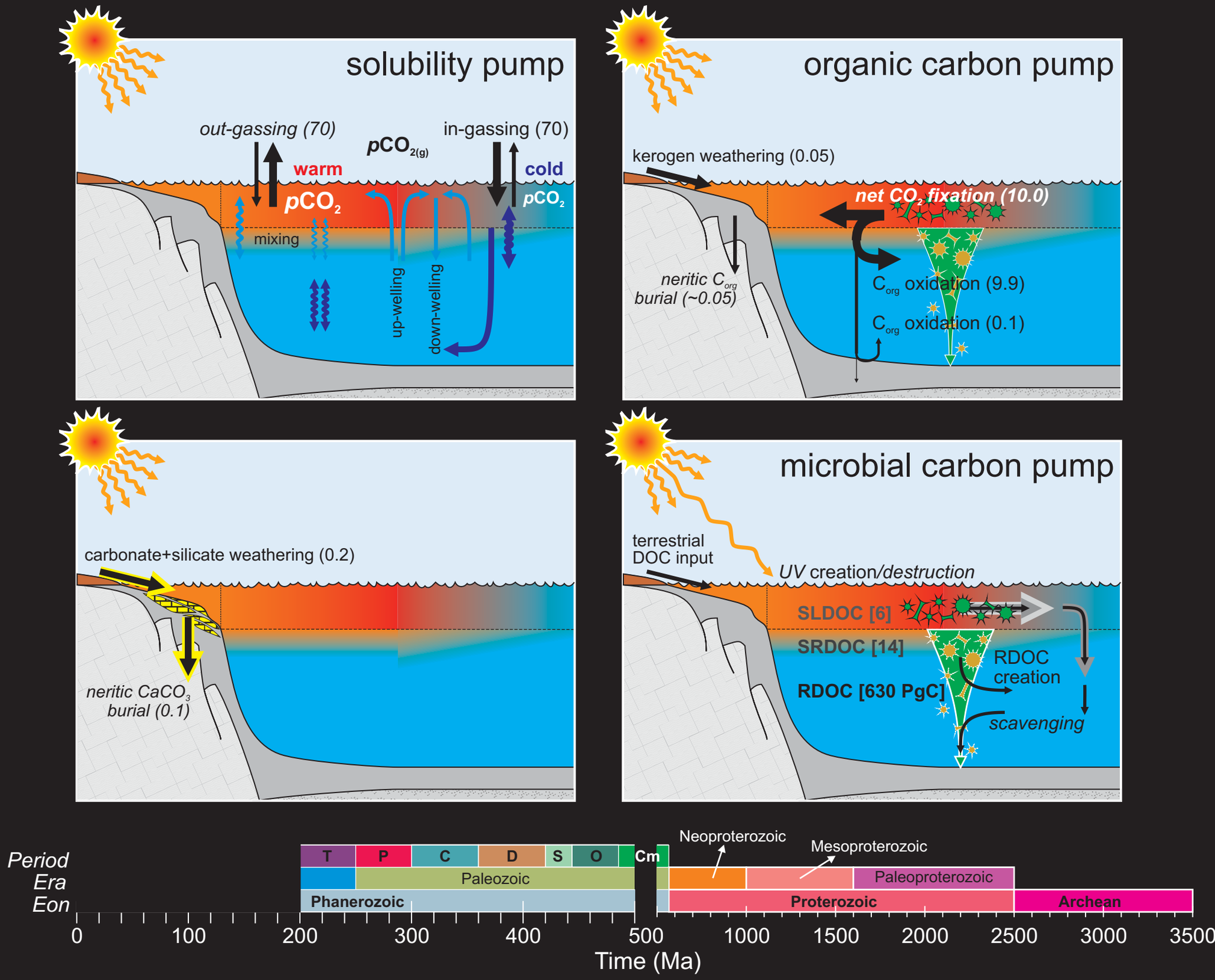

solubility pump
out-gassing (70)
in-gassing (70)
pCO2(g)
warm
cold
pCO2
pCO2
mixing
up-welling
down-welling
organic carbon pump
kerogen weathering (0.05)
net CO2 fixation (10.0)
neritic Corg burial (~0.05)
Corg oxidation (9.9)
Corg oxidation (0.1)
carbonate pump
carbonate+silicate weathering (0.2)
Ca2+ +2HCO3- → CaCO3 +CO2(aq) +H2O
calcification (1.1)
water-column dissolution (0.6)
neritic CaCO3 burial (0.1)
CaCO3 +CO2(aq) +H2O → Ca2+ +2HCO3-
seafloor dissolution (0.4)
deep-sea CaCO3 burial (0.1)
microbial carbon pump
terrestrial DOC input
UV creation/destruction
SLDOC [6]
SRDOC [14]
RDOC [630 PgC]
RDOC creation
scavenging
Period
Era
Eon
Ng
Pg
K
J
T
P
C
D
S
O
Cm
Cenozoic
Mesozoic
Paleozoic
Phanerozoic
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

Evolution of the Biological Pump





Ridgwell and Arndt [submitted]


solubility pump
out-gassing (70)
in-gassing (70)
$pCO_{2(g)}$
warm
cold
pCO_2
pCO_2
mixing
up-welling
down-welling
organic carbon pump
kerogen weathering (0.05)
net CO_2 fixation (10.0)
neritic C_{org} burial (~0.05)
C_{org} oxidation (9.9)
C_{org} oxidation (0.1)
carbonate+silicate weathering (0.2)
neritic $CaCO_3$ burial (0.1)
microbial carbon pump
terrestrial DOC input
UV creation/destruction
SLDOC [6]
SRDOC [14]
RDOC [630 PgC]
RDOC creation
scavenging
Period
Era
Eon
T
P
C
D
S
O
Cm
Paleozoic
Phanerozoic
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean
0
100
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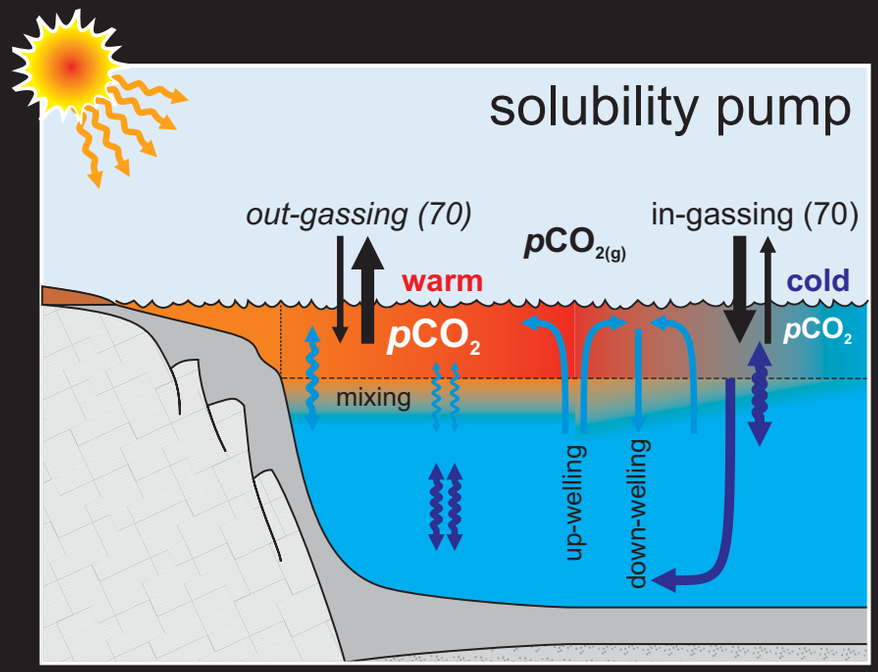
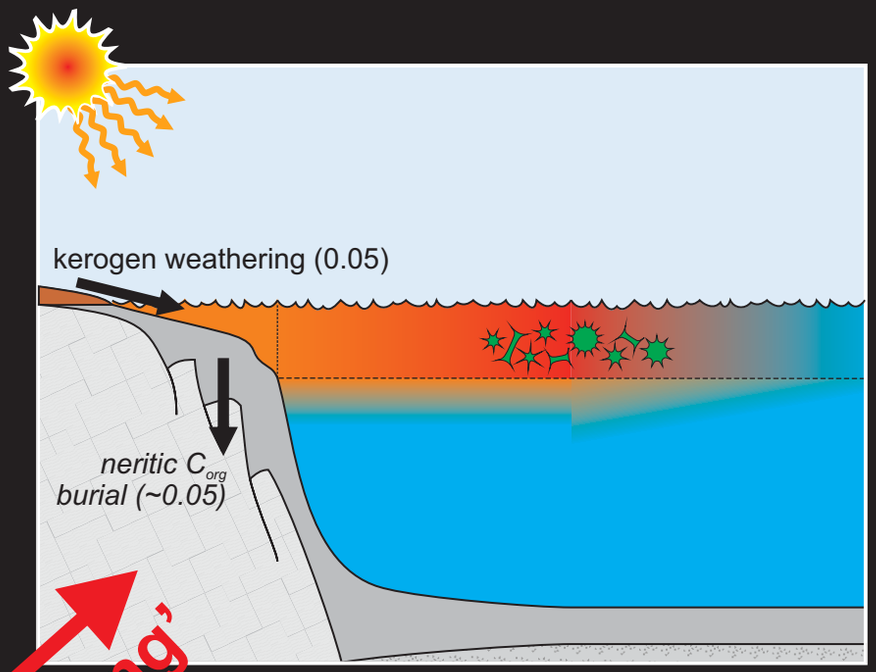
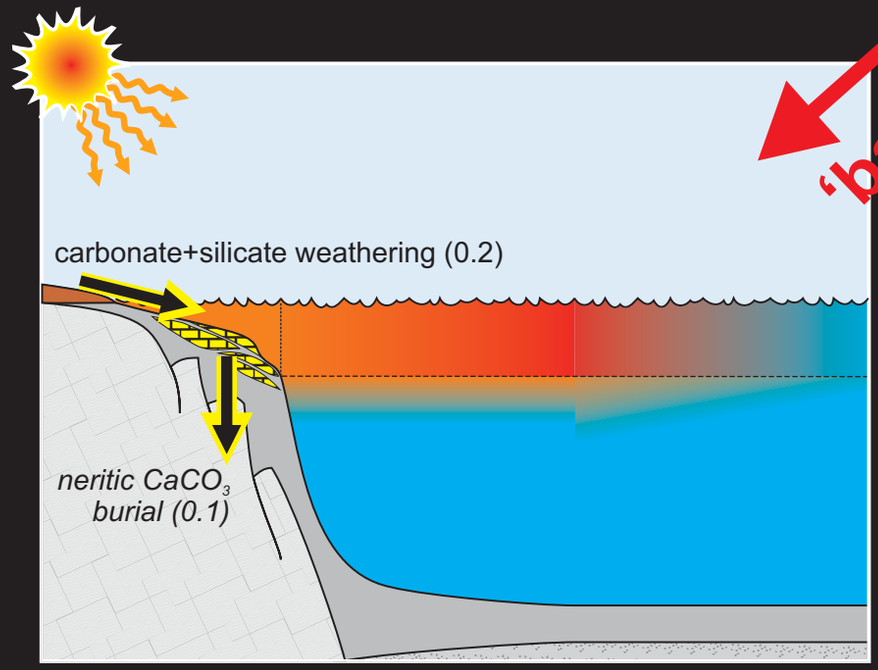
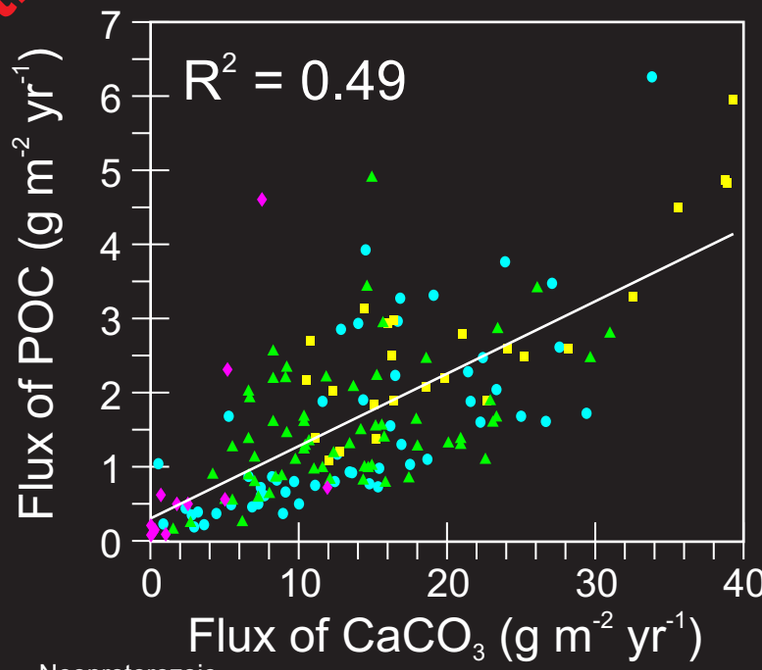
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

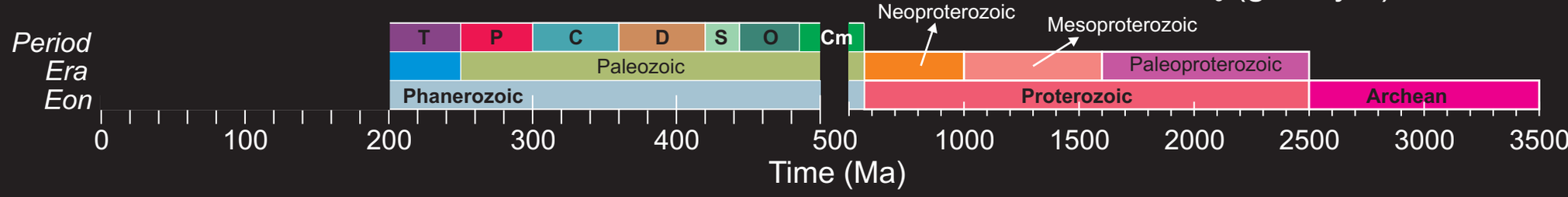

solubility pump
out-gassing (70)
in-gassing (70)
pCO2(g)
warm
cold
pCO2
pCO2
mixing
up-welling
down-welling

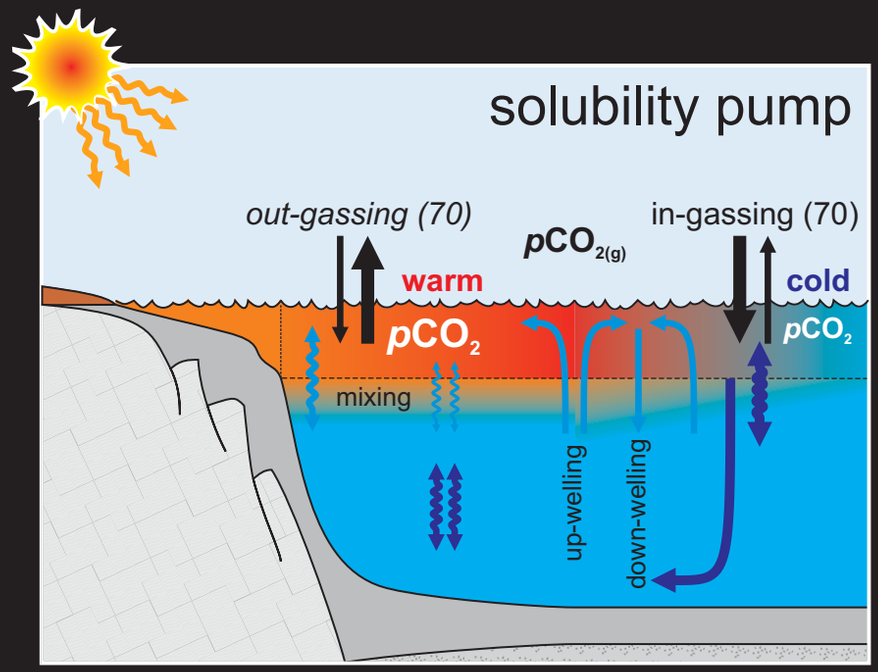

kerogen weathering (0.05)
neritic Corg
burial (~0.05)

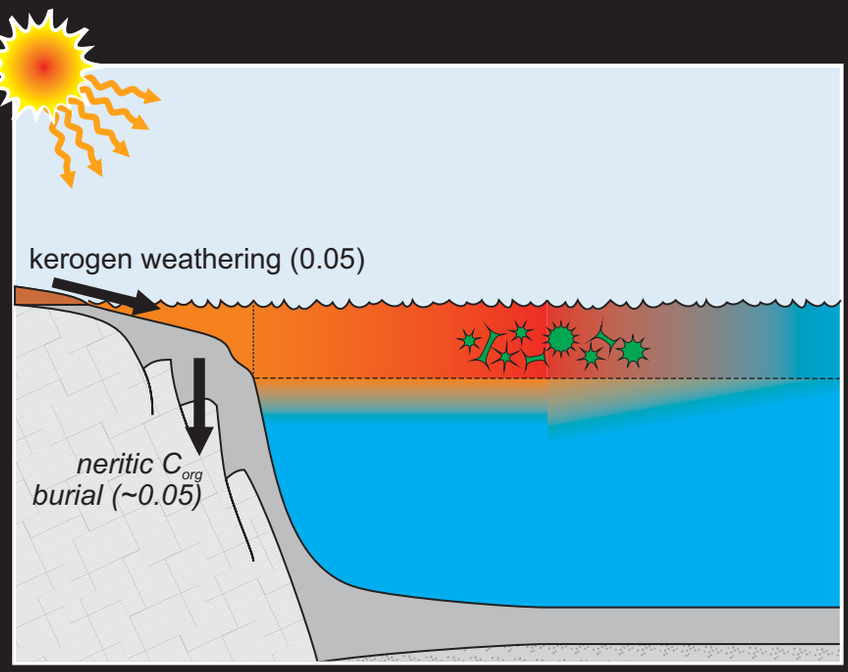

carbonate+silicate weathering (0.2)
neritic CaCO3
burial (0.1)

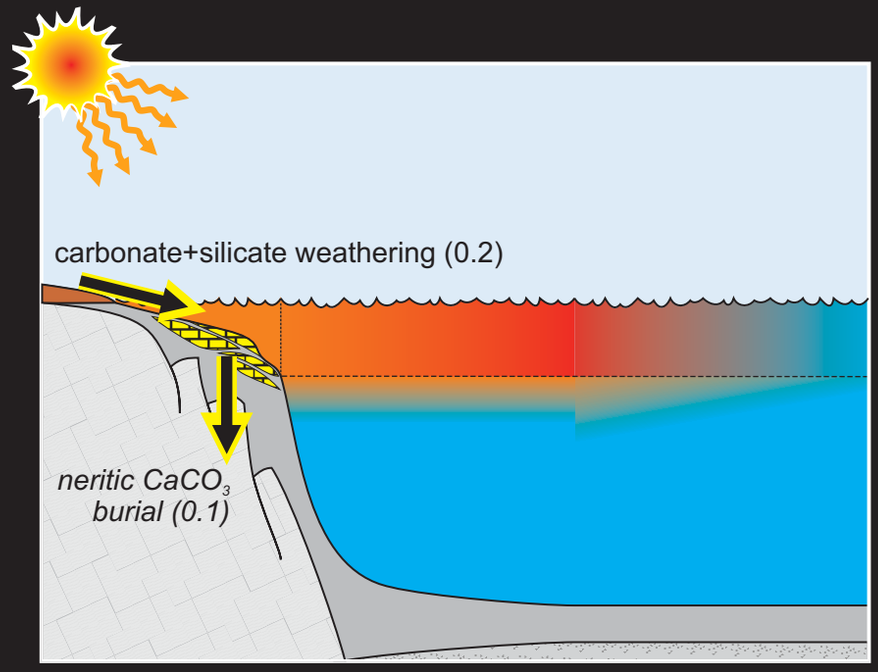
'ballasting'

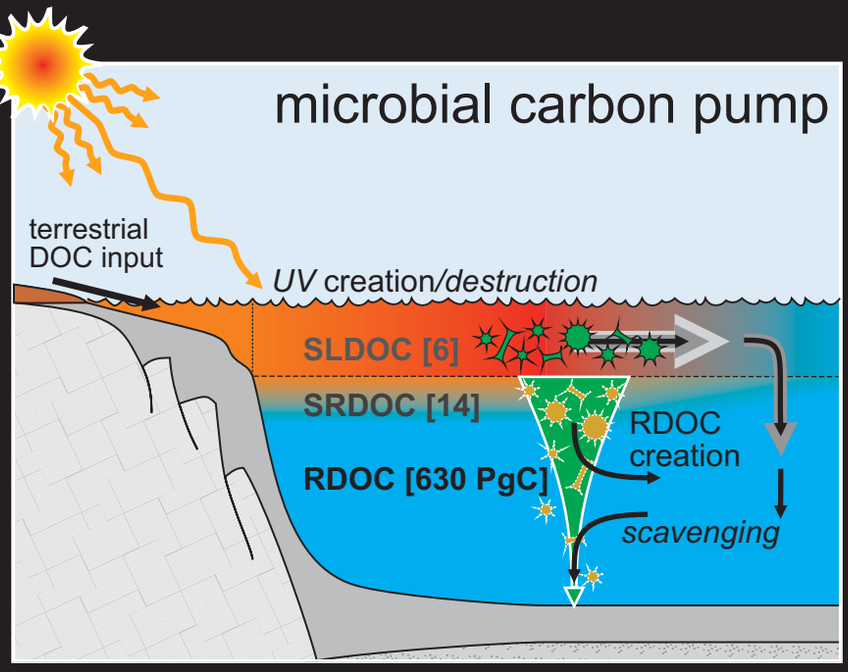

R2 = 0.49
Flux of POC (g m-2 yr-1)
Flux of CaCO3 (g m-2 yr-1)
0
1
2
3
4
5
6
7
0
10
20
30
40

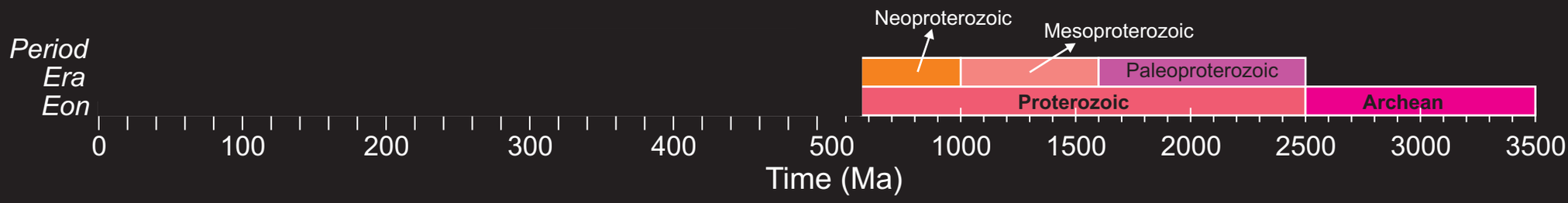

Period
Era
Eon
T
P
C
D
S
O
Cm
Paleozoic
Phanerozoic
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)


solubility pump
out-gassing (70)
in-gassing (70)
$pCO_{2(g)}$
warm
cold
pCO_2
pCO_2
mixing
up-welling
down-welling


kerogen weathering (0.05)
neritic C_{org} burial (~0.05)


carbonate+silicate weathering (0.2)
neritic $CaCO_3$ burial (0.1)


microbial carbon pump
terrestrial DOC input
UV creation/destruction
SLDOC [6]
SRDOC [14]
RDOC [630 PgC]
RDOC creation
scavenging


Period
Era
Eon
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Proterozoic
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0
100
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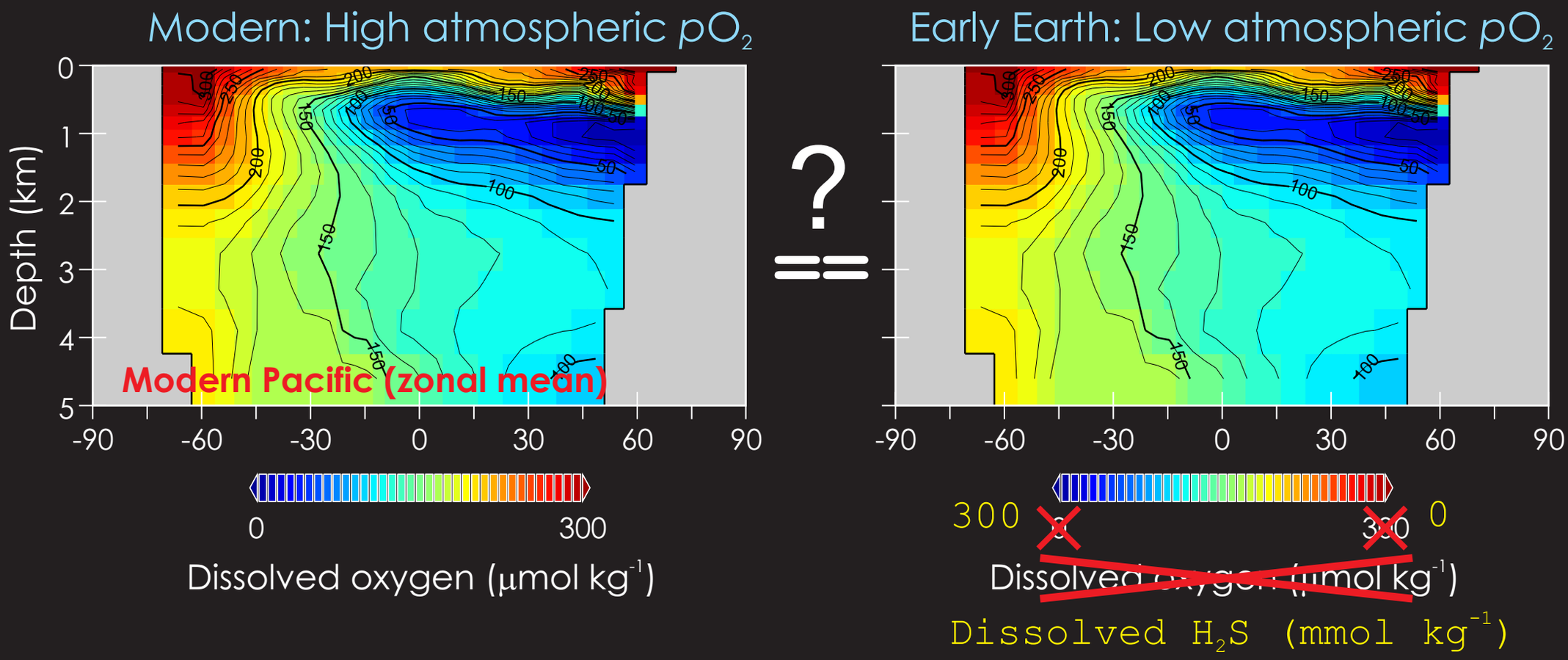
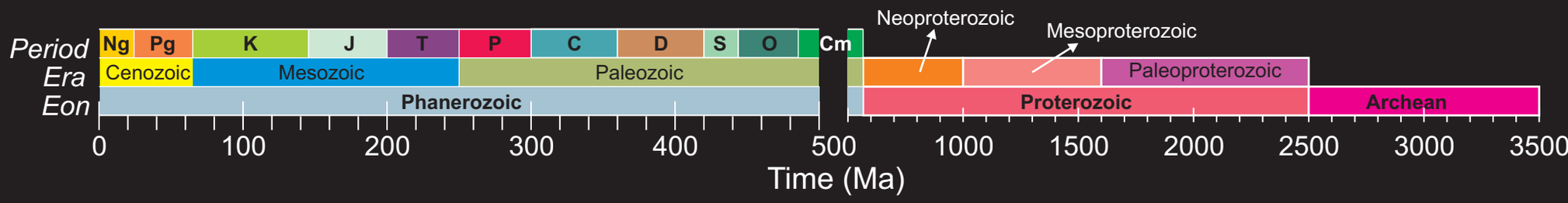
Time (Ma)

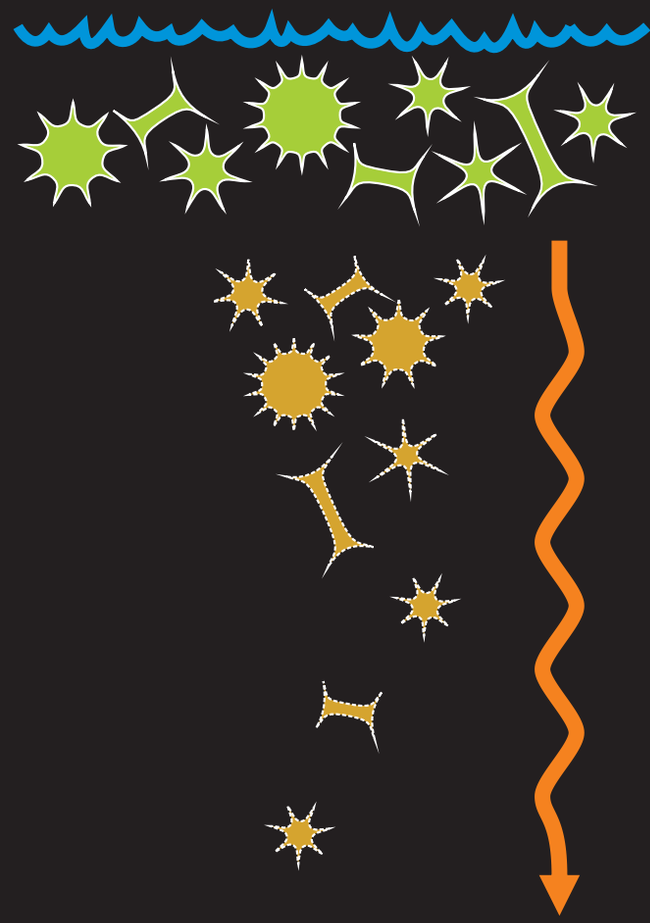
Evolution of the Biological Pump

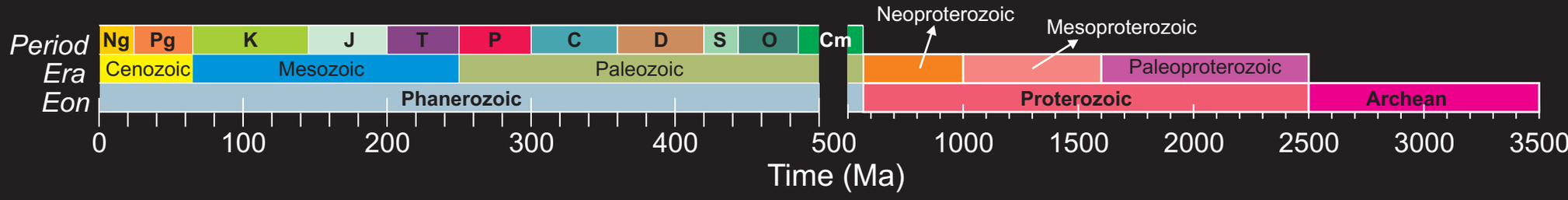


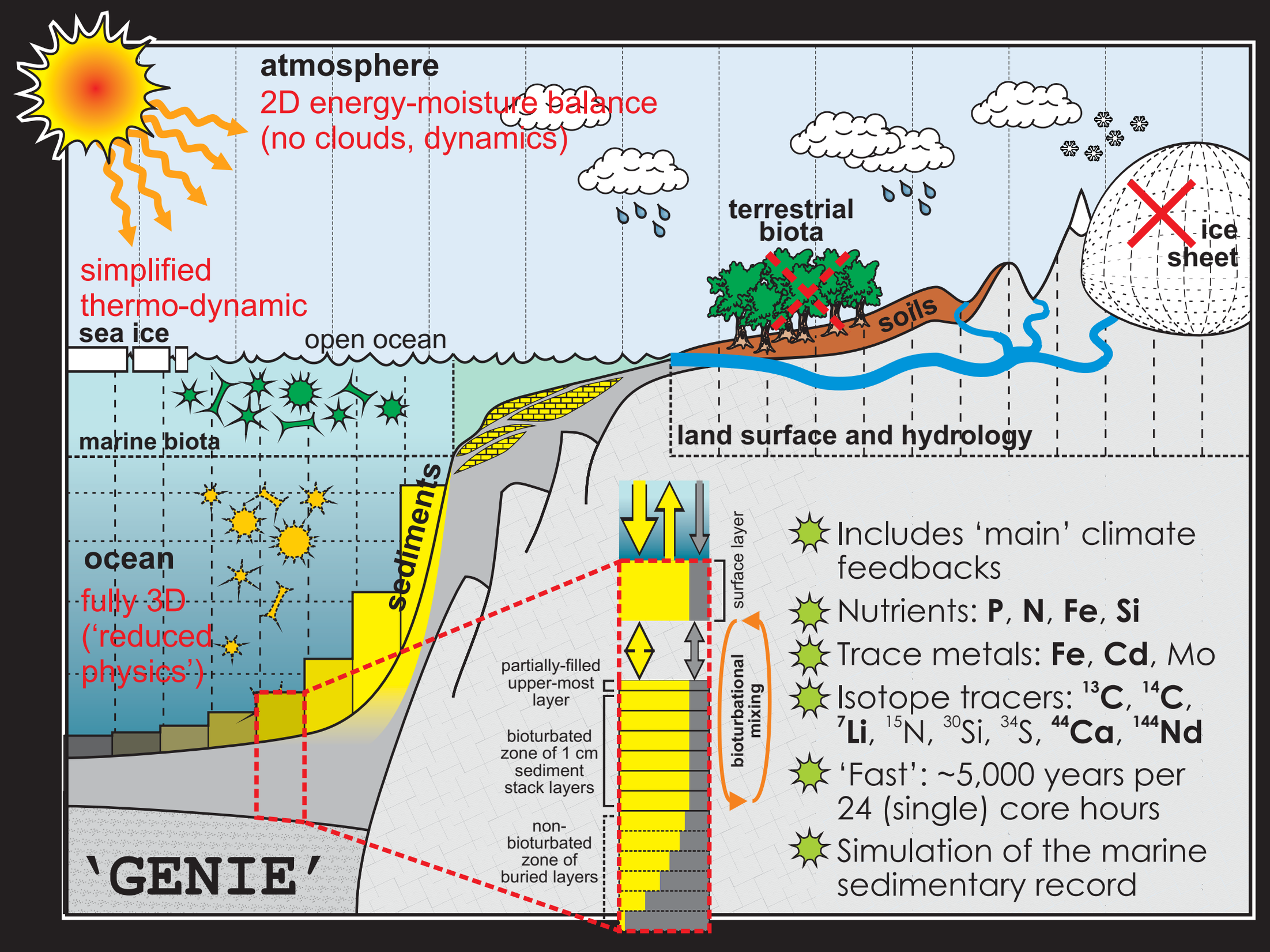


Exploring the evolution of the biological pump *in silico*

```
! 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
```

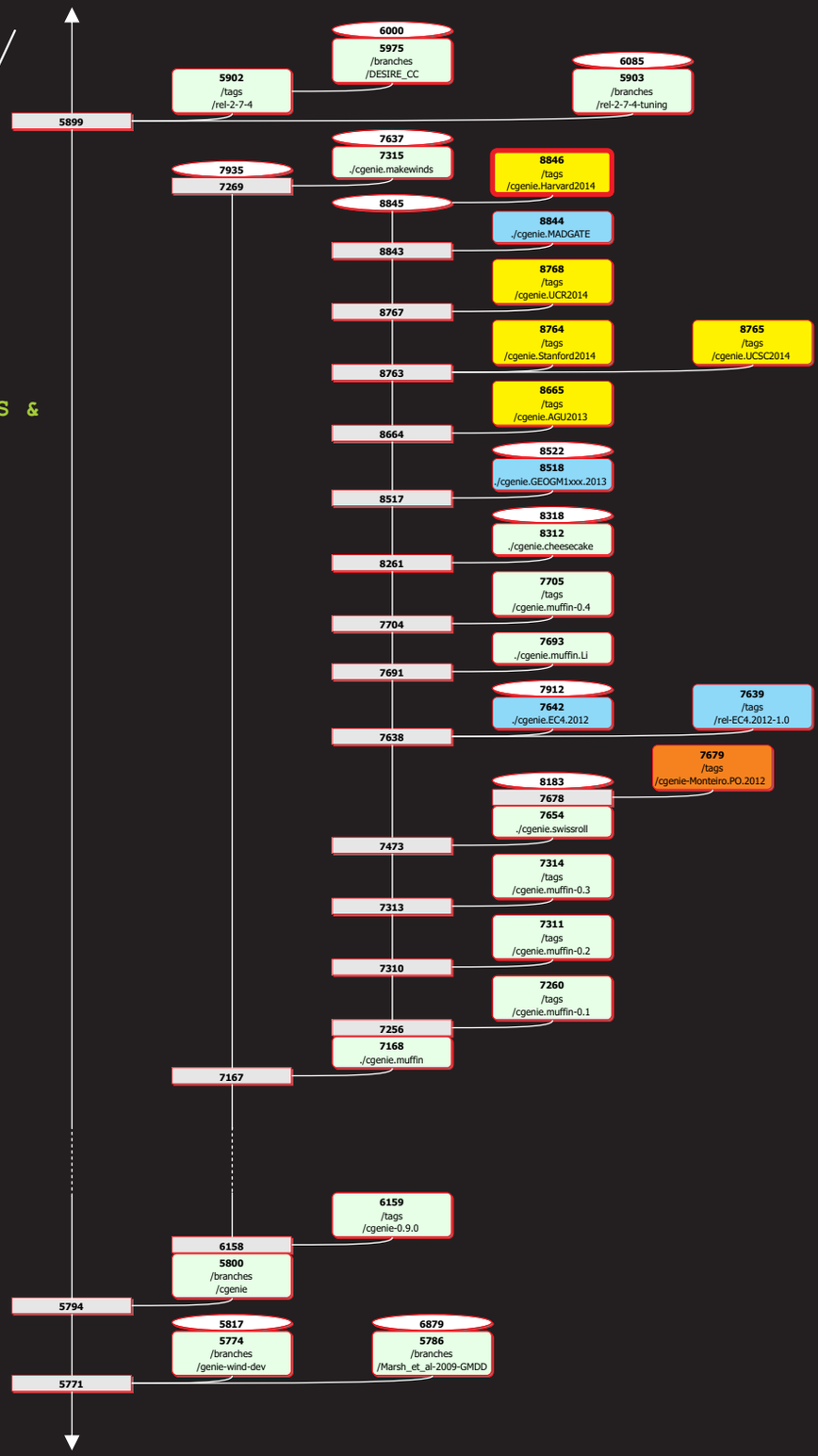




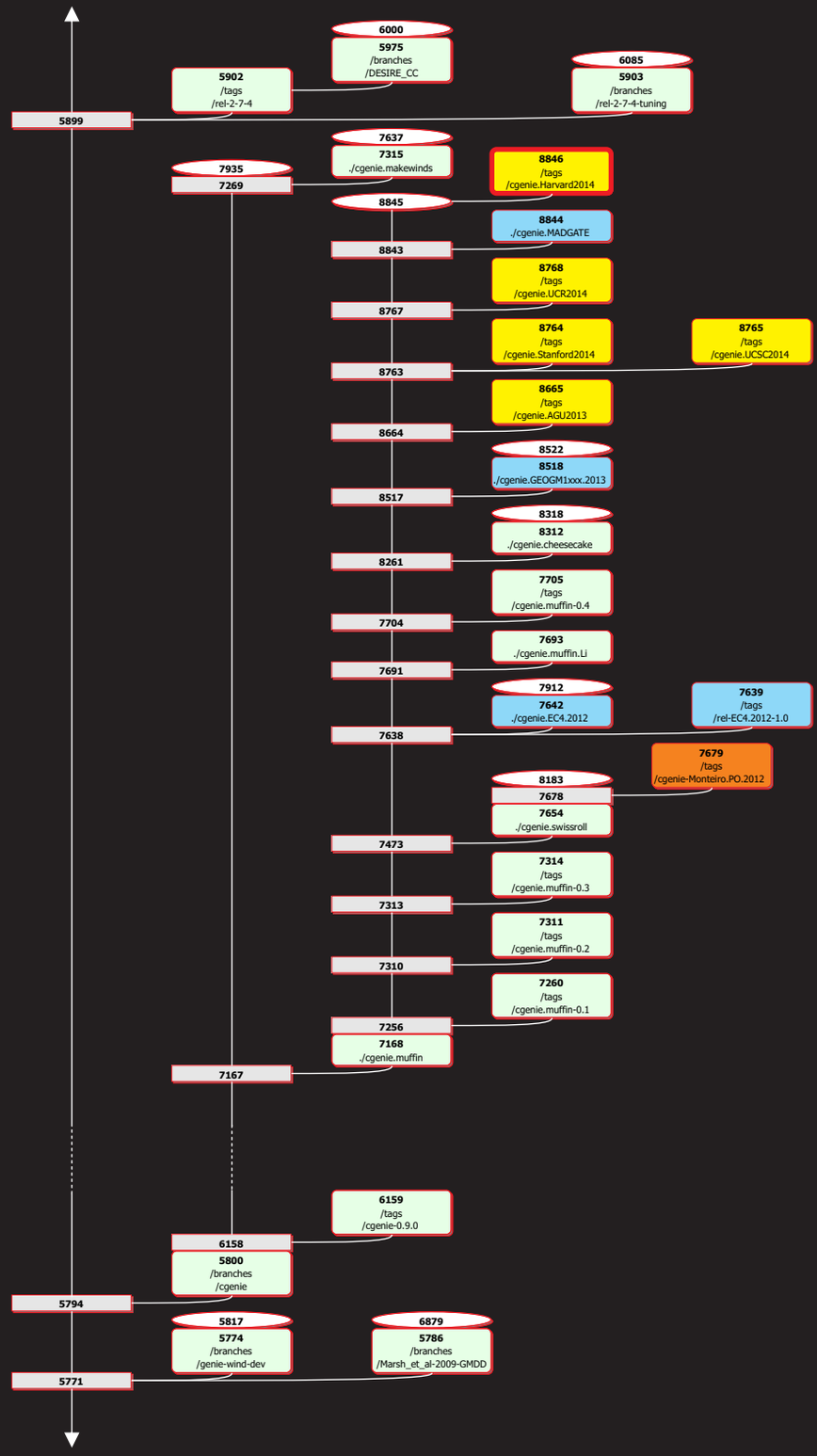

atmosphere
2D energy-moisture balance
(no clouds, dynamics)
simplified
thermo-dynamic
sea ice
open ocean
terrestrial
biota
soils
ice
sheet
marine biota
land surface and hydrology
sediments
ocean
fully 3D
('reduced
physics')
surface layer
partially-filled
upper-most
layer
bioturbated
zone of 1 cm
sediment
stack layers
non-
bioturbated
zone of
buried layers
bioturbational
mixing
'GENIE'
Includes 'main' climate feedbacks
Nutrients: P, N, Fe, Si
Trace metals: Fe, Cd, Mo
Isotope tracers: 13C, 14C, 7Li, 15N, 30Si, 34S, 44Ca, 144Nd
'Fast': ~5,000 years per 24 (single) core hours
Simulation of the marine sedimentary record

https://svn.ggy.bris.ac.uk/subversion/genie/tags/cgenie.Harvard2014

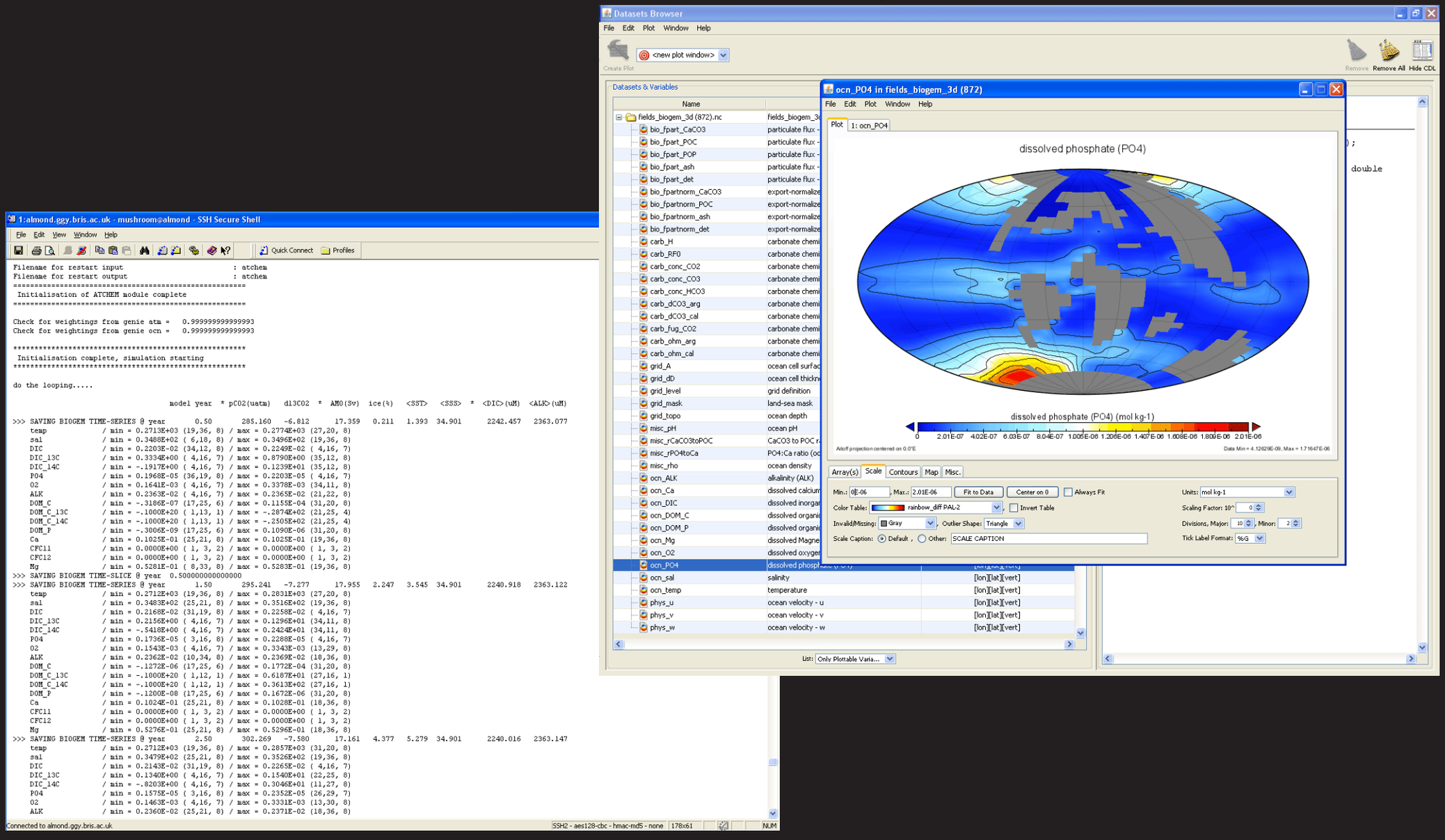
```
! calculate carbonate alkalinity

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
```



www.seao2.info/misc_harvard2014.html



Exploring the evolution of the biological pump *in silico*



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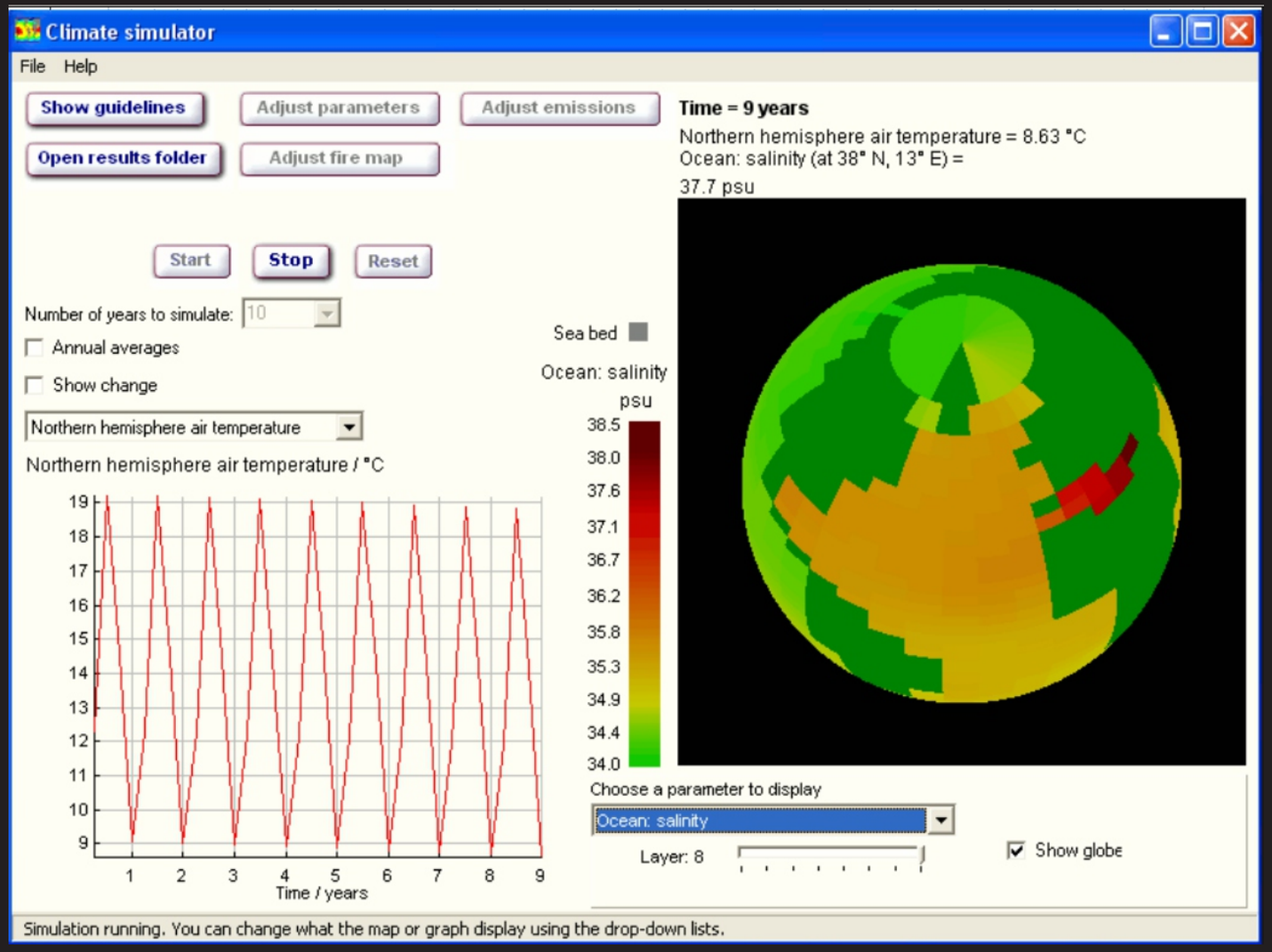
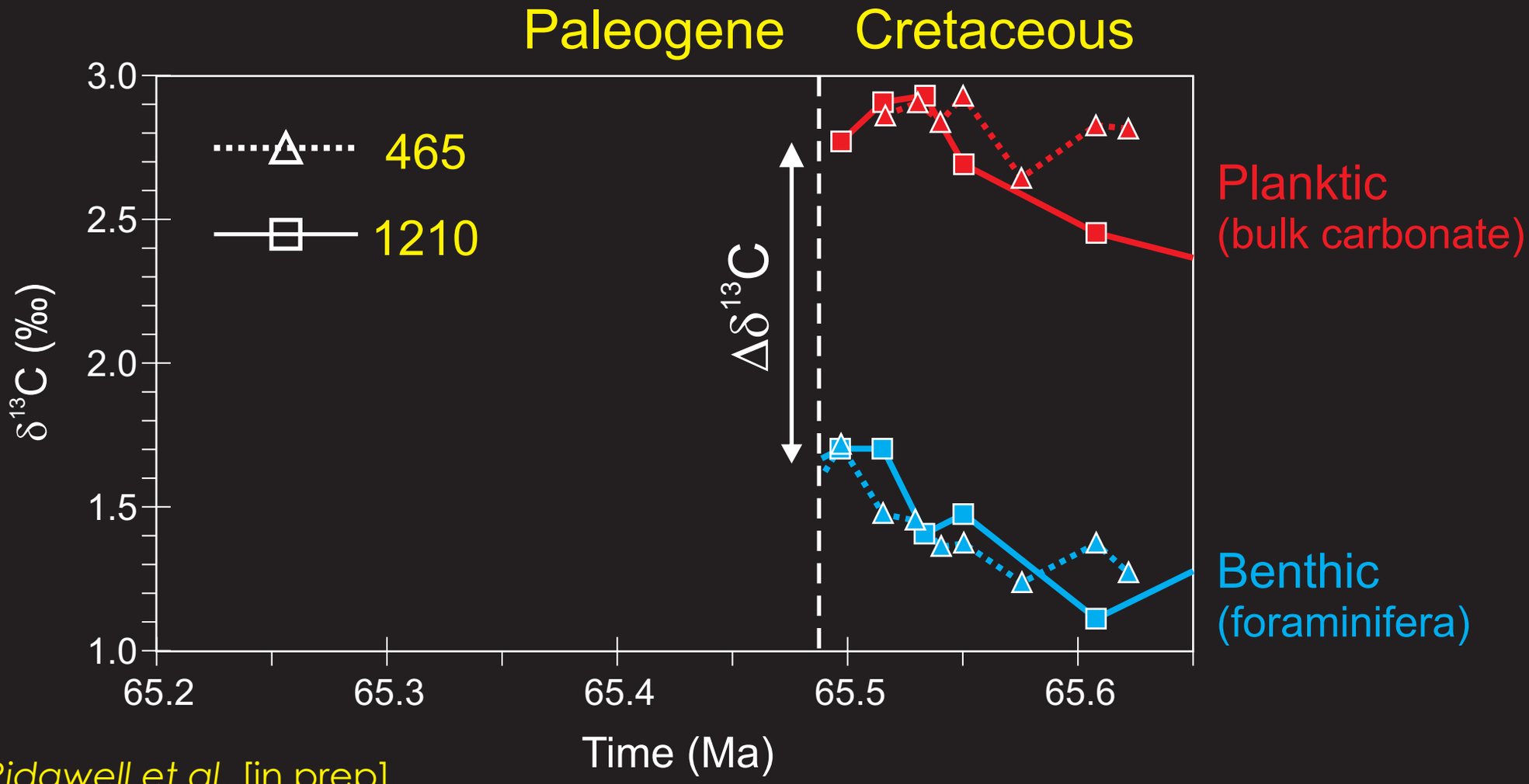


Evolution of the Biological Pump *in silico* #1



Ridgwell et al. [in prep]

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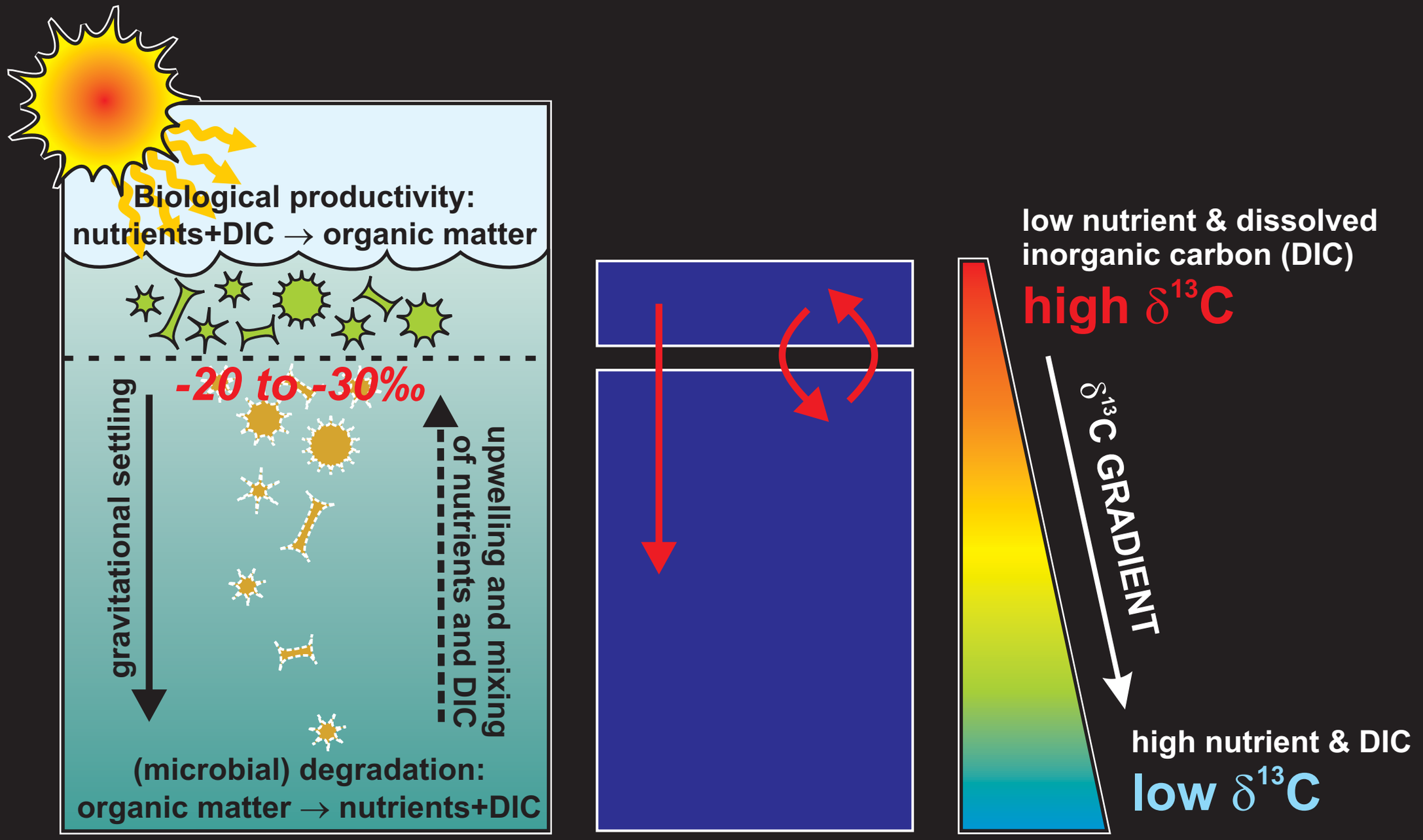

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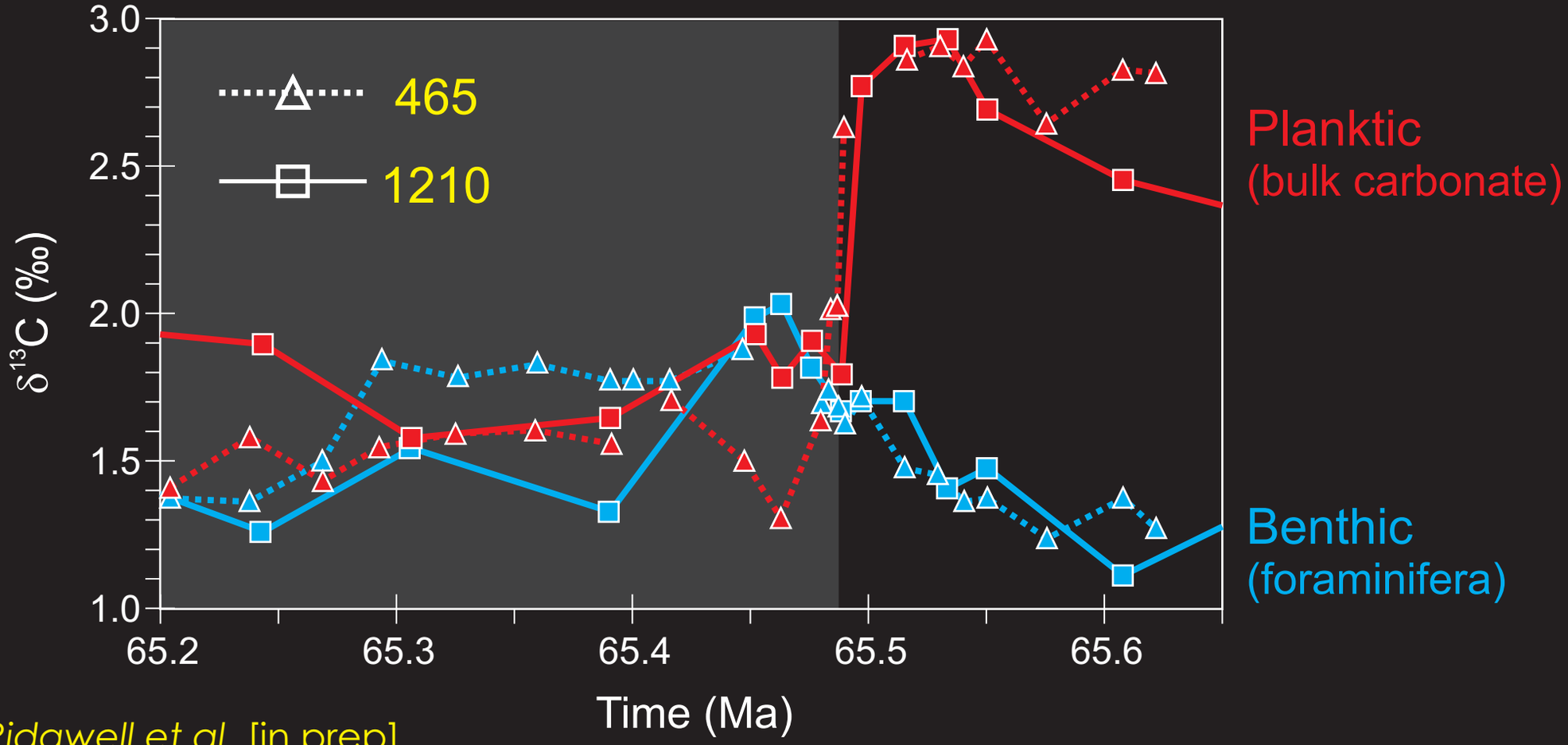

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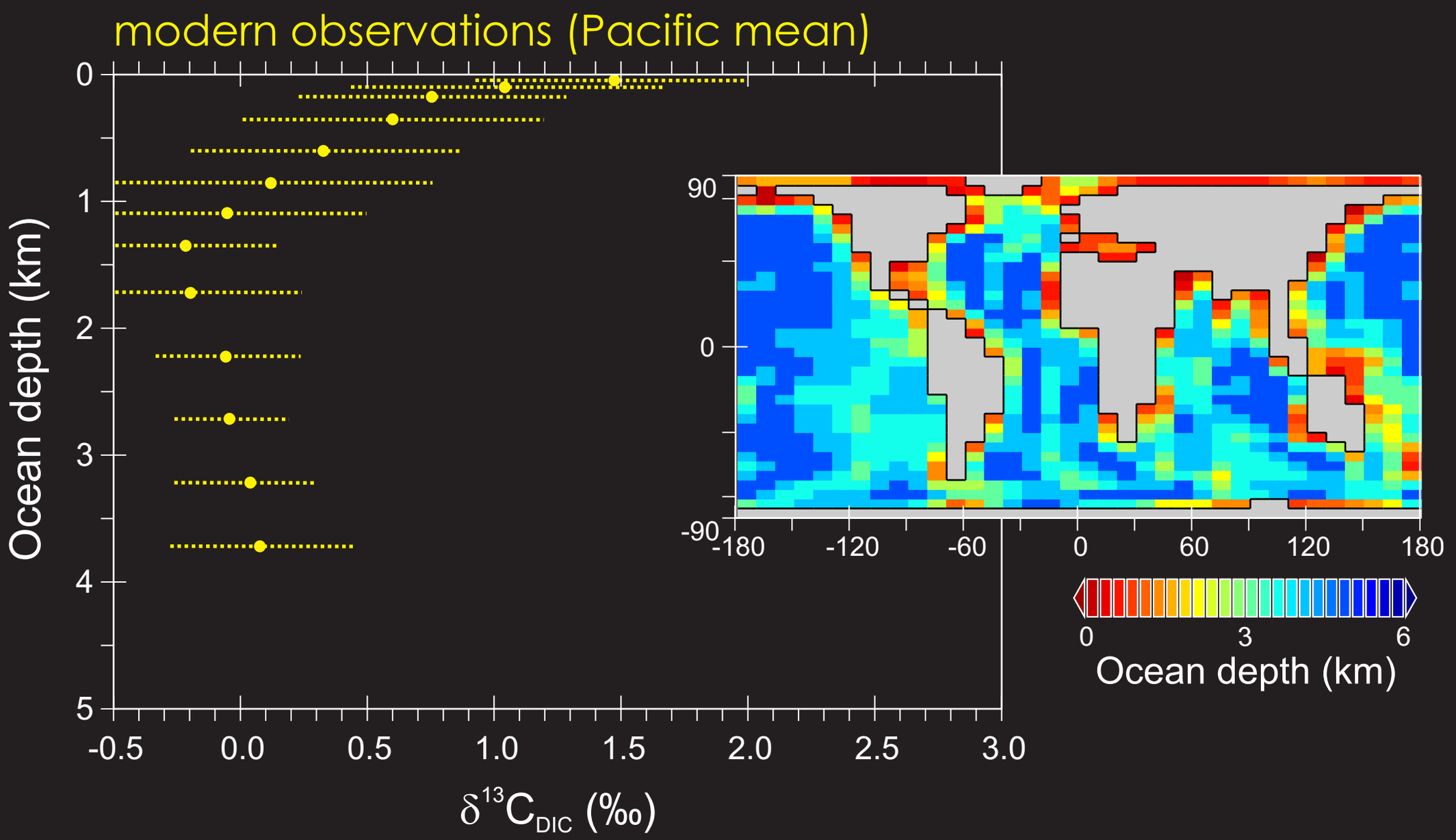
Evolution of the Biological Pump *in silico* #1



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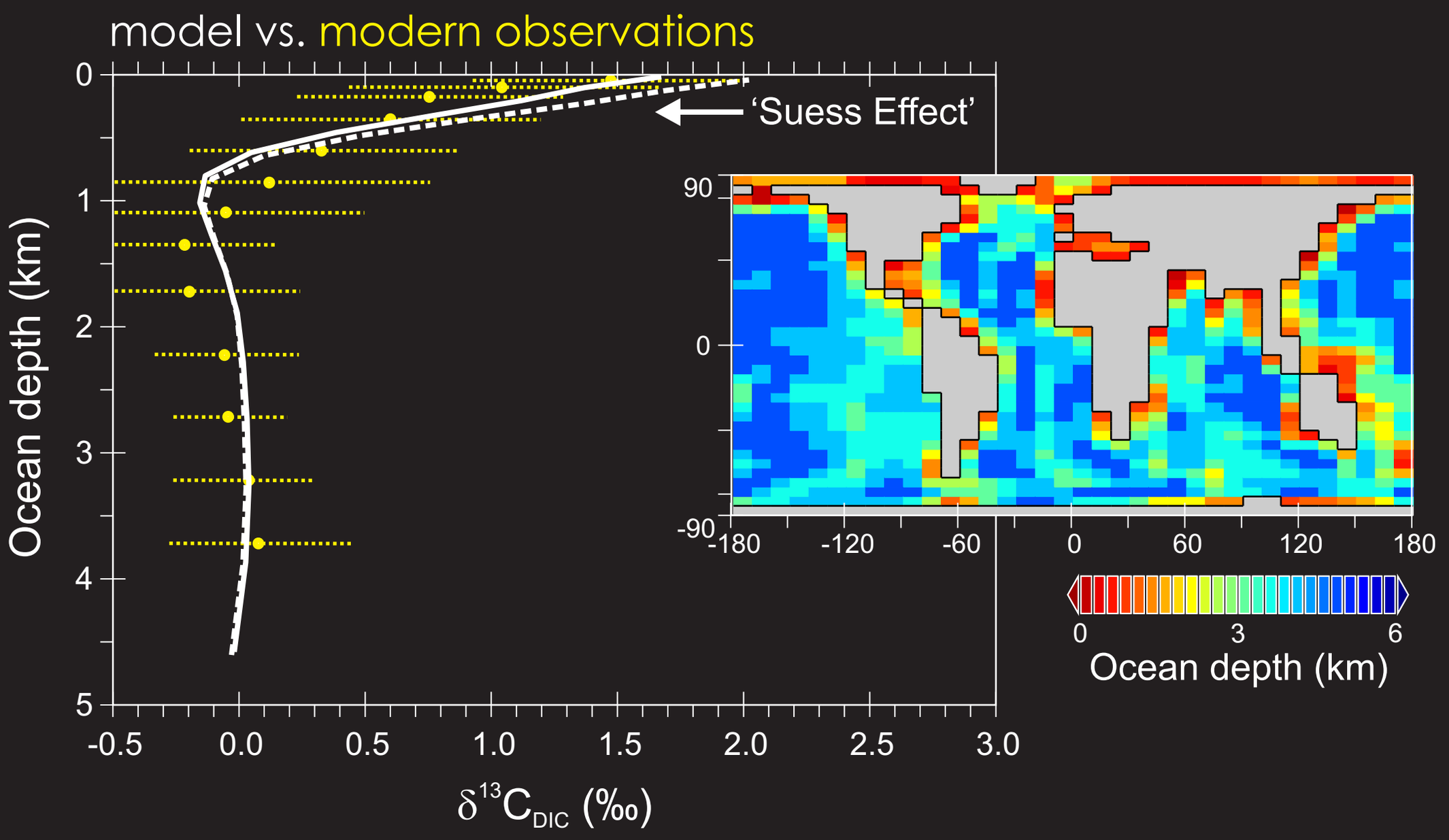

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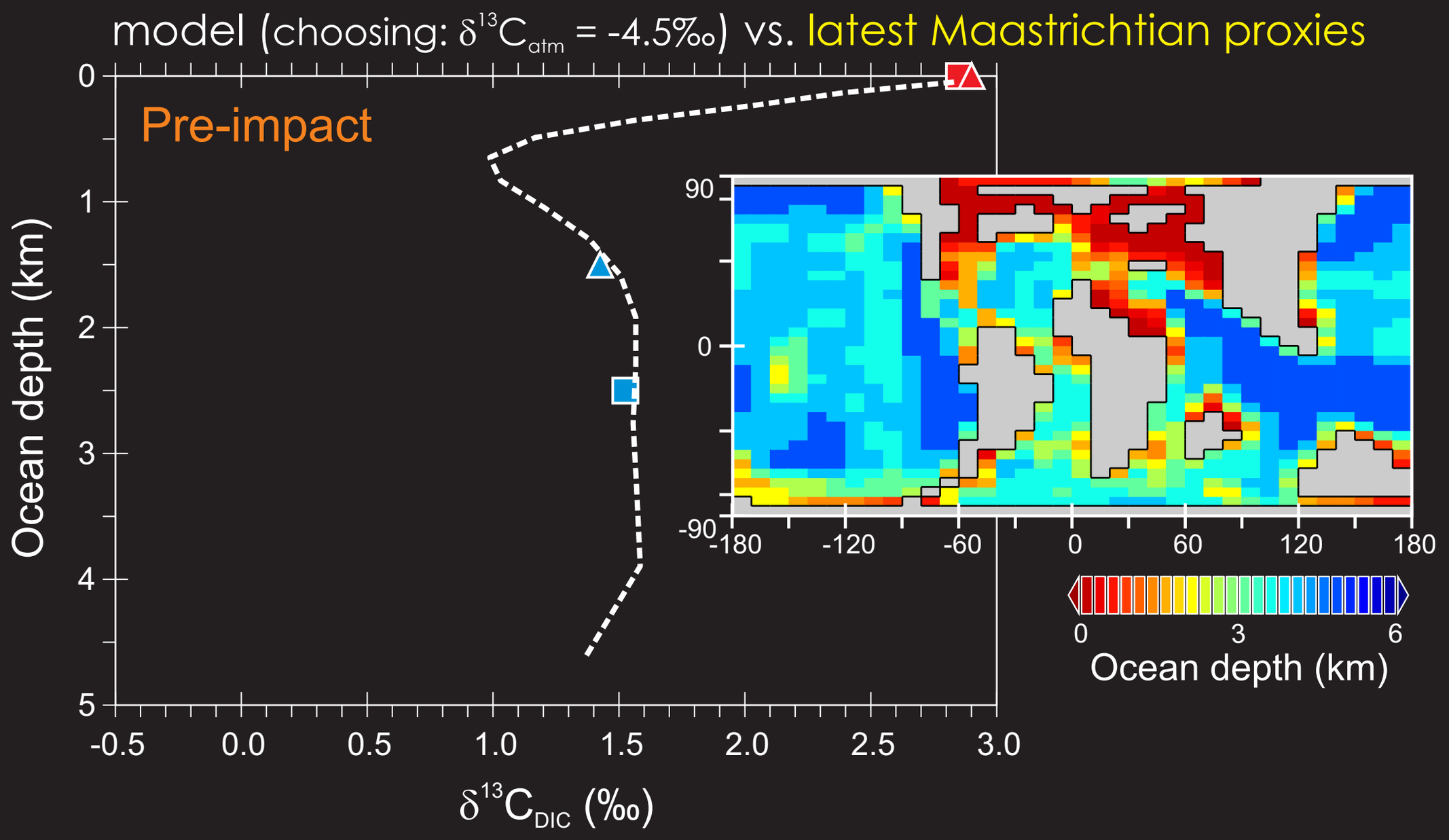

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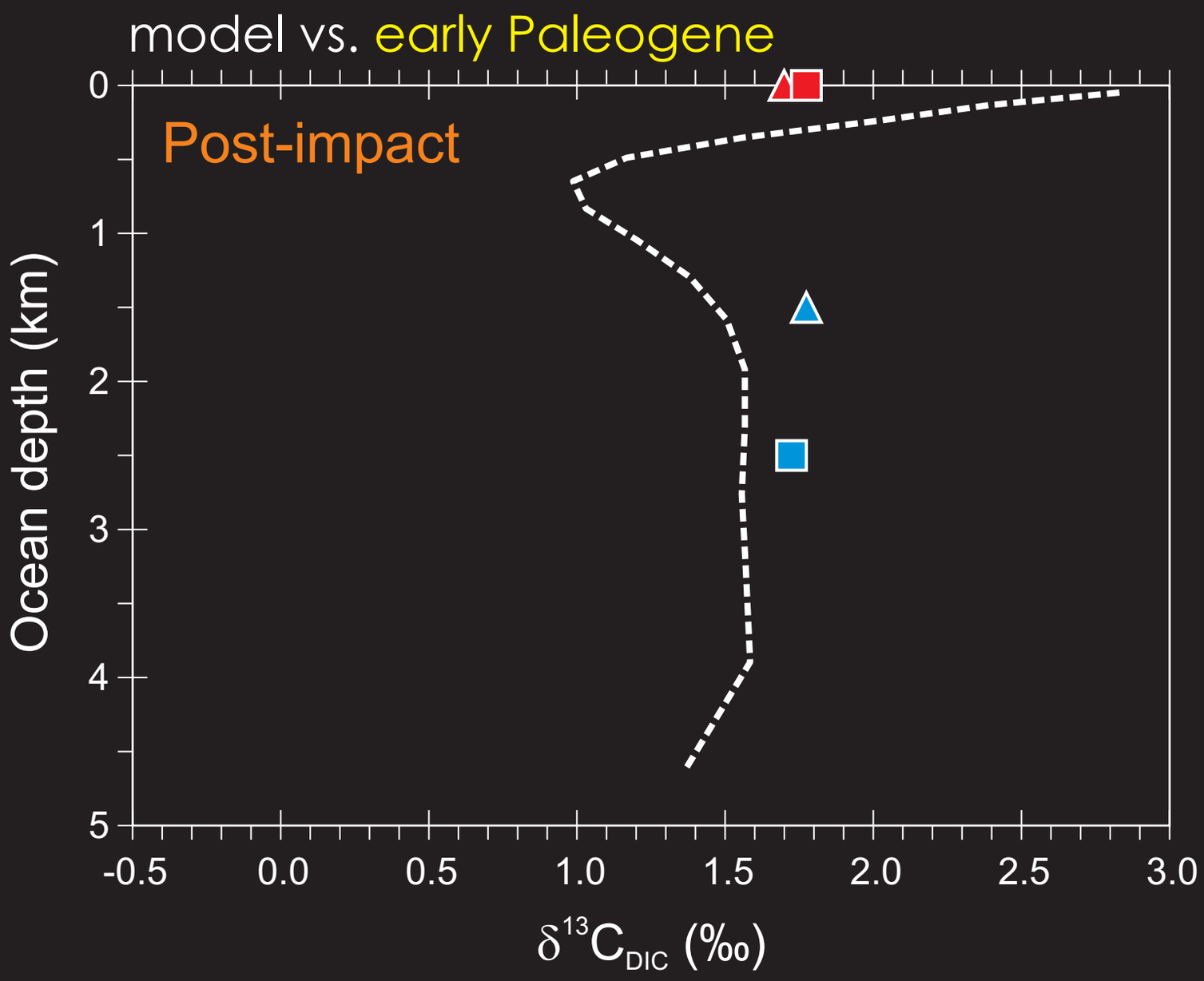

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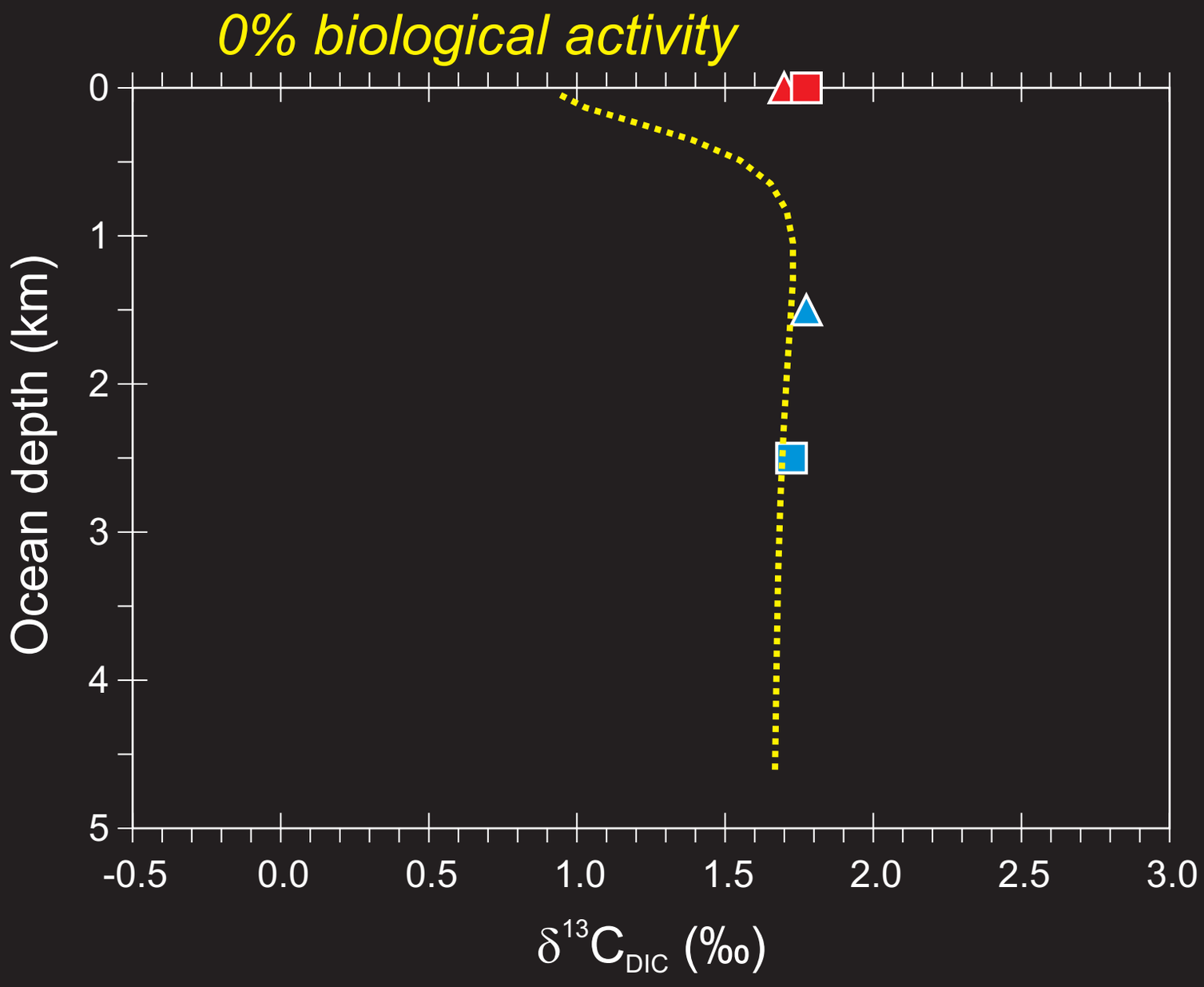
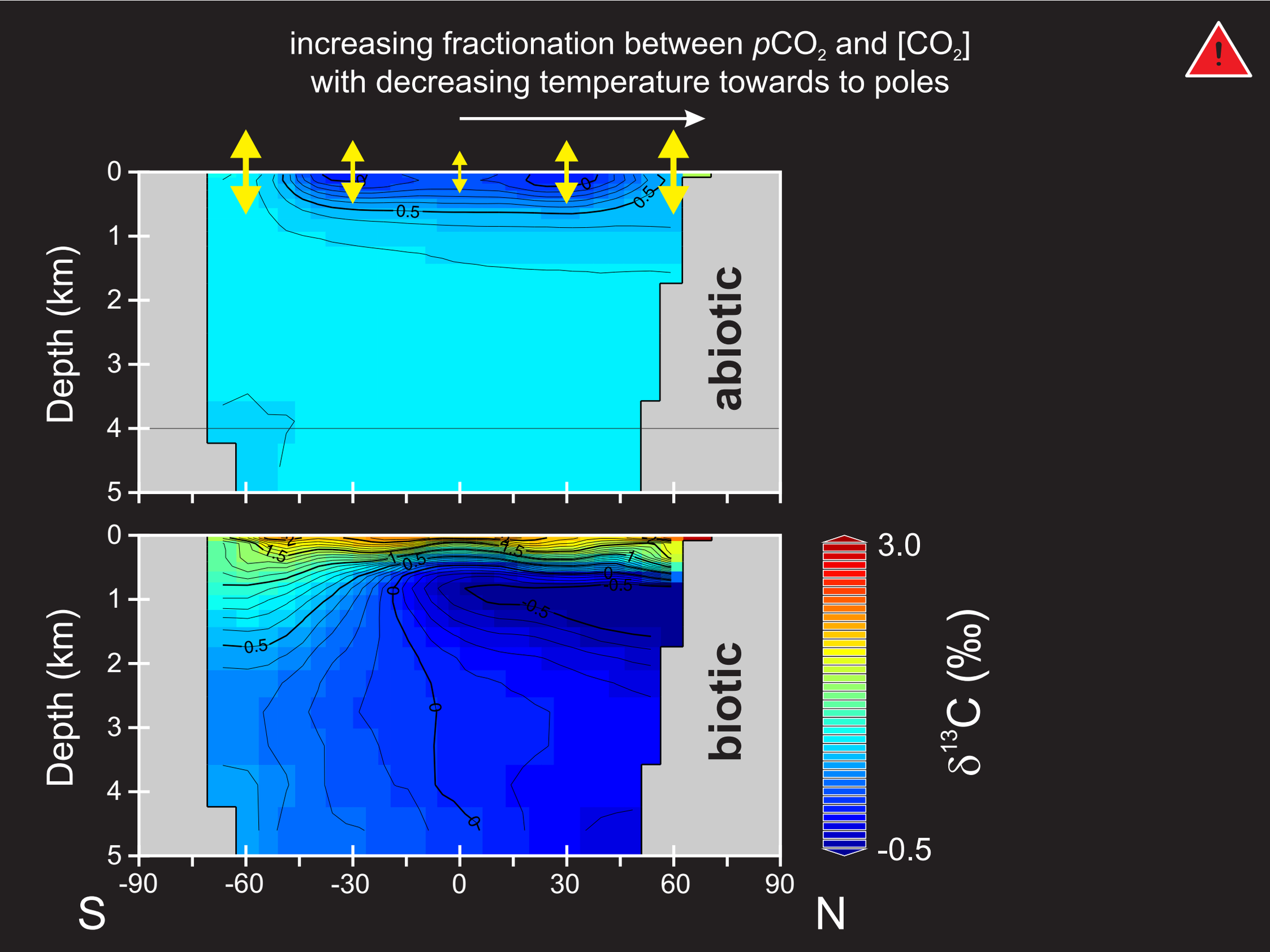
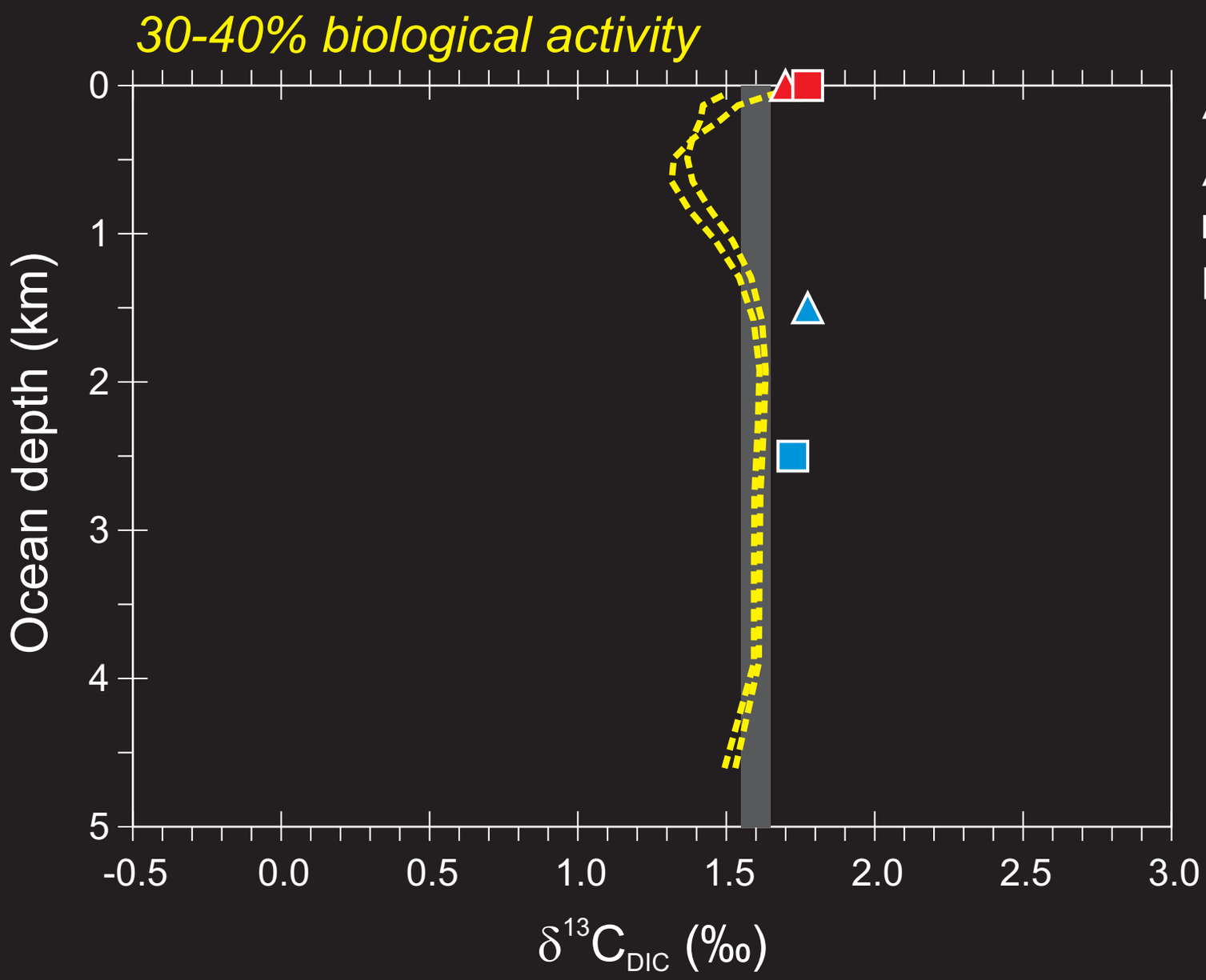



increasing fractionation between pCO_2 and $[CO_2]$
with decreasing temperature towards to poles
Depth (km)
0
1
2
3
4
5
abiotic
biotic
0.5
-0.5
-1.5
-2
-4.5
-7
3.0
-0.5
$\delta^{13}C$ (‰)
-90
-60
-30
0
30
60
90
S
N

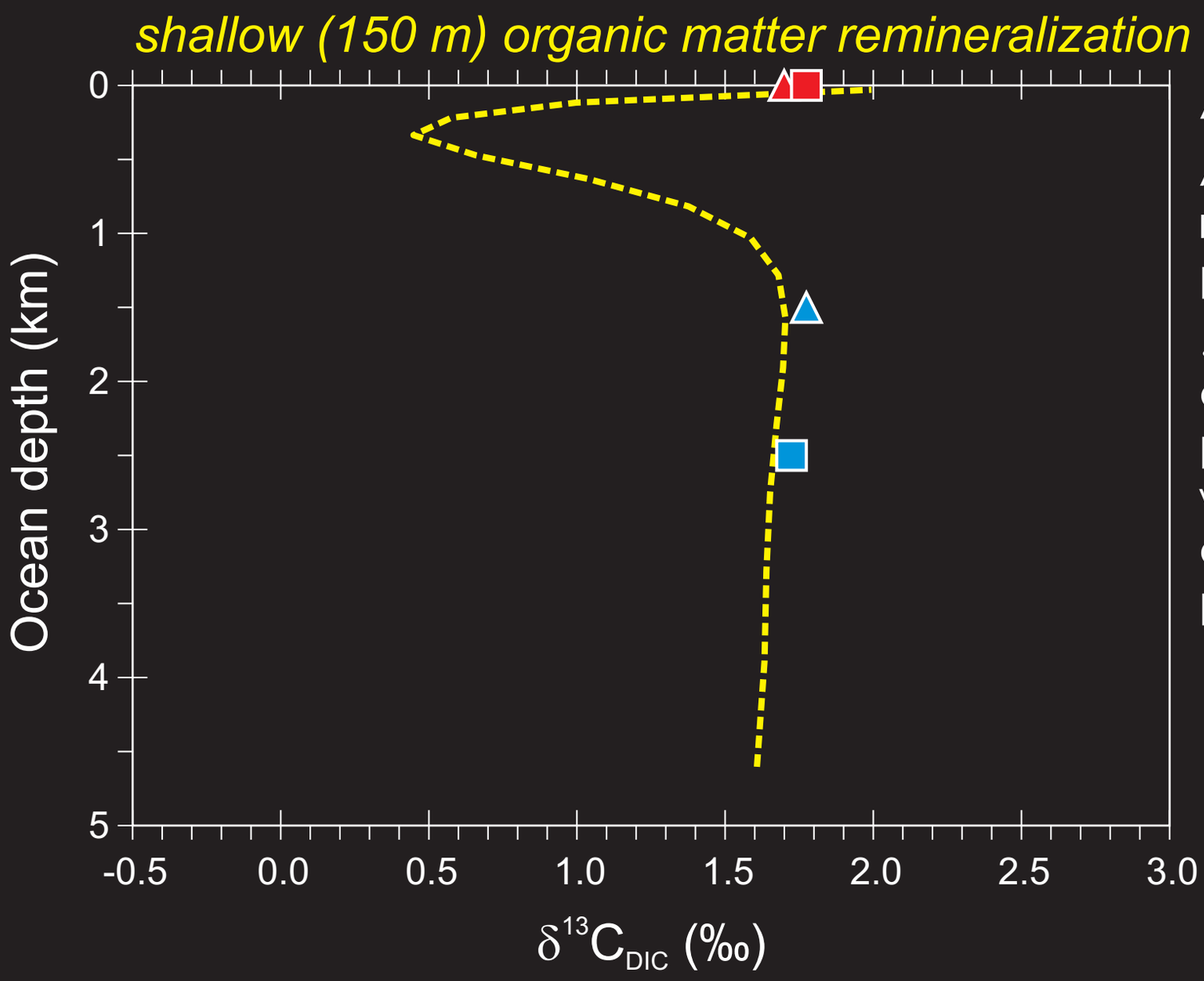
Evolution of the Biological Pump *in silico* #1



Answer:

A somewhat reduced biological pump ...

Evolution of the Biological Pump *in silico* #1

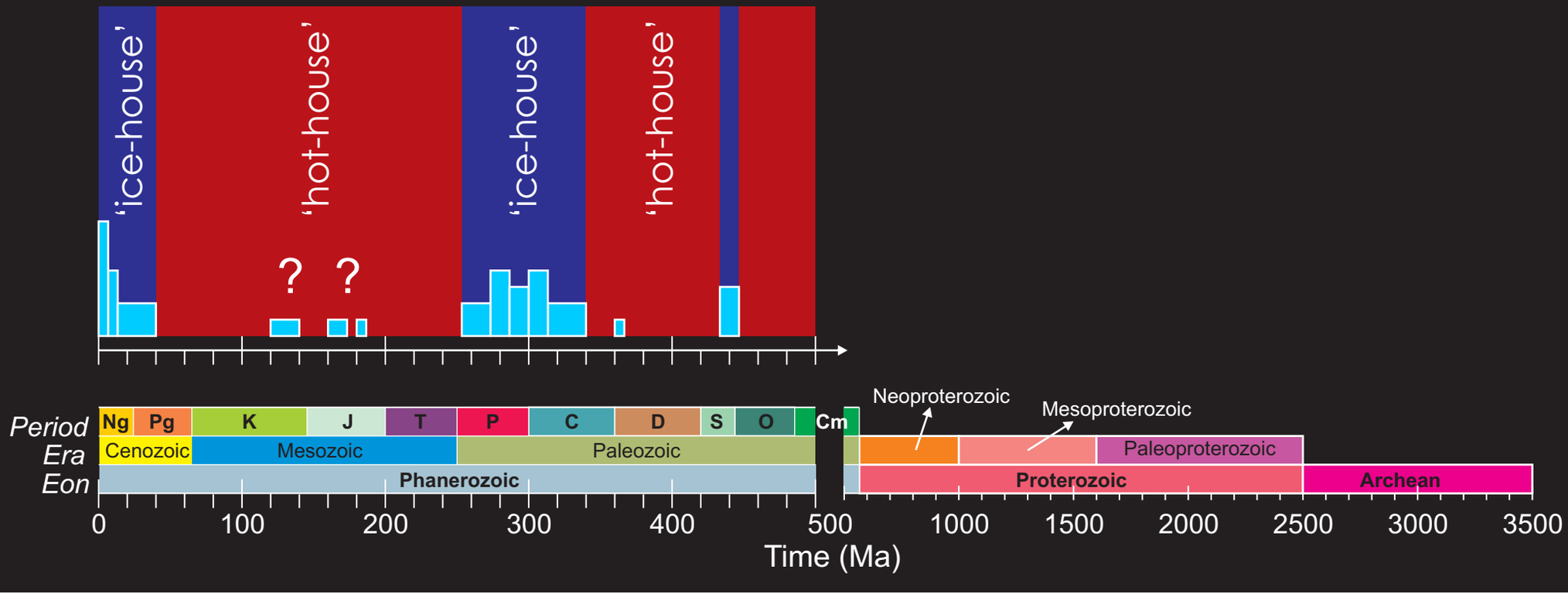


Answer:

A somewhat reduced biological pump ...

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

Evolution of the Biological Pump *in silico* #2

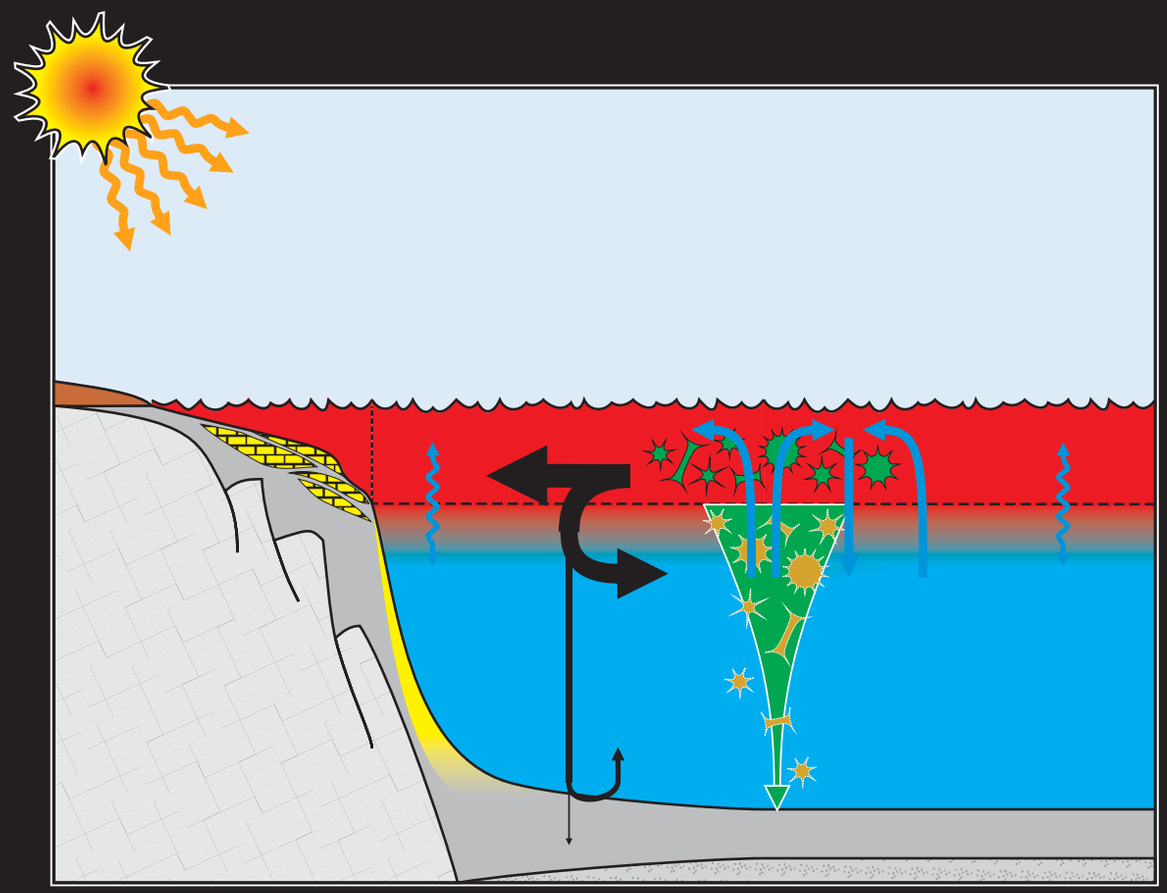


Evolution of the Biological Pump *in silico* #2

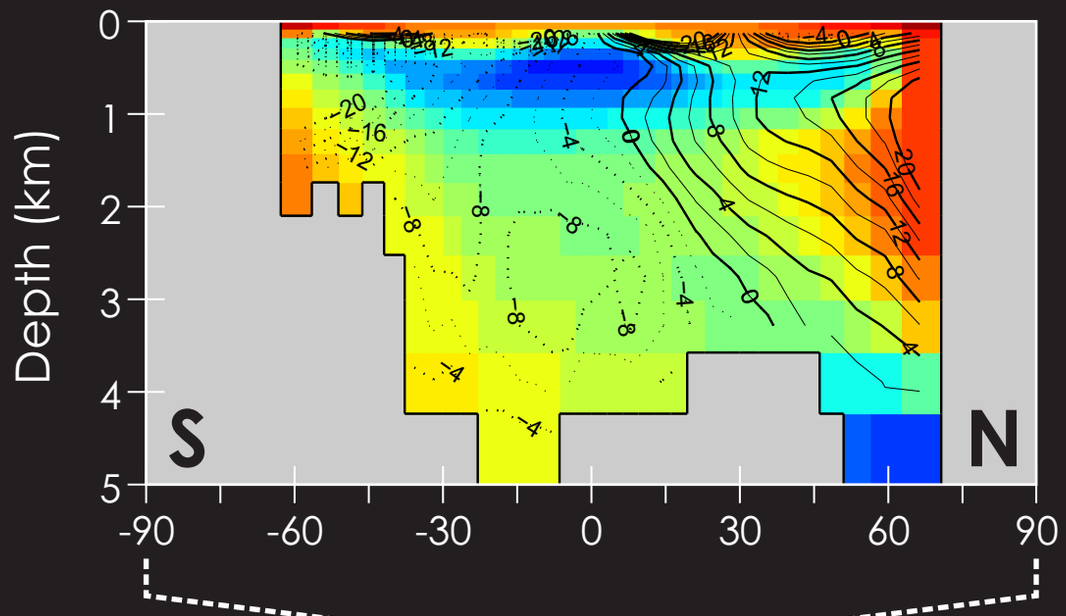
```
(warm == stratified) && (stratified == anoxic) == .true.
```

???

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

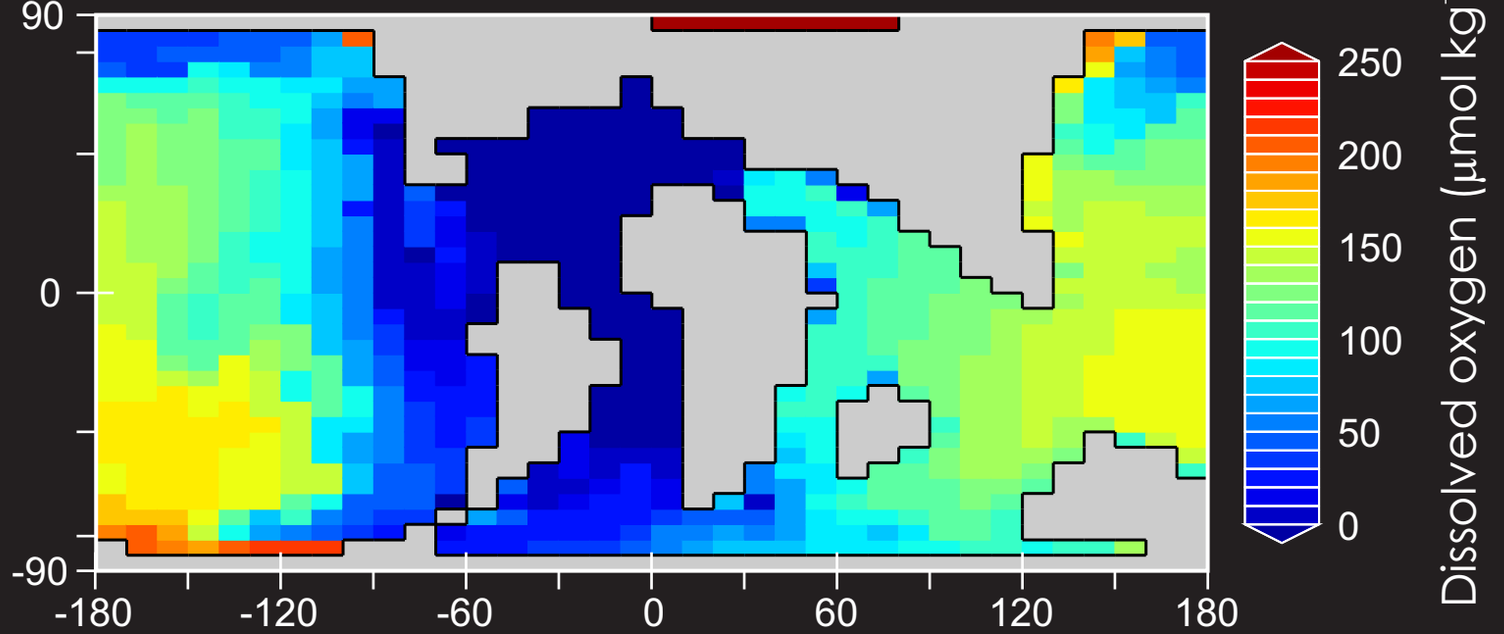


Evolution of the Biological Pump *in silico* #2

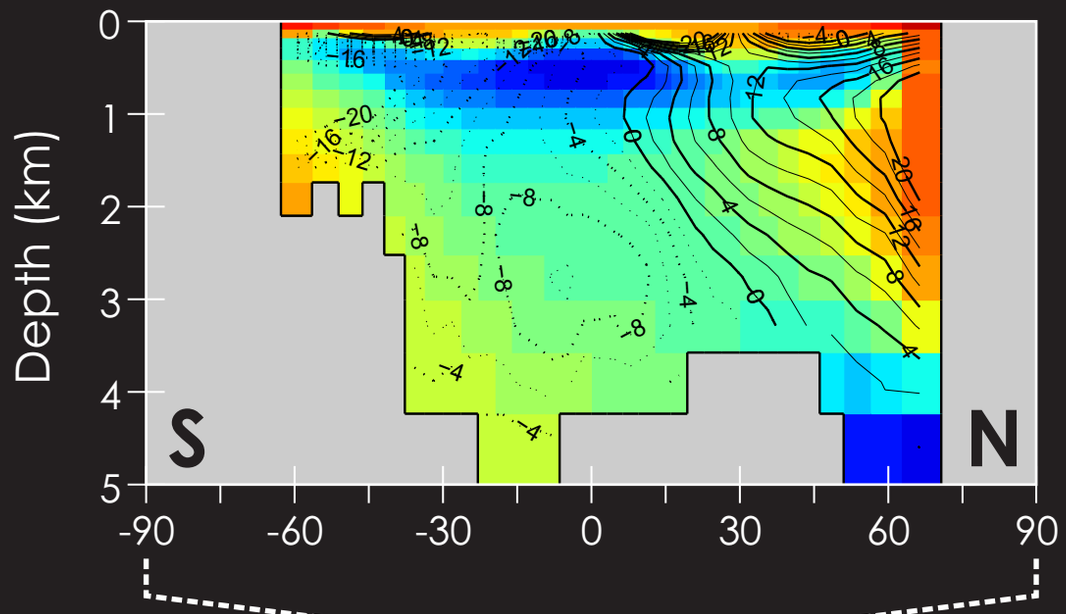


x4 CO_2 reference simulation

Benthic (>1000m) [O_2]

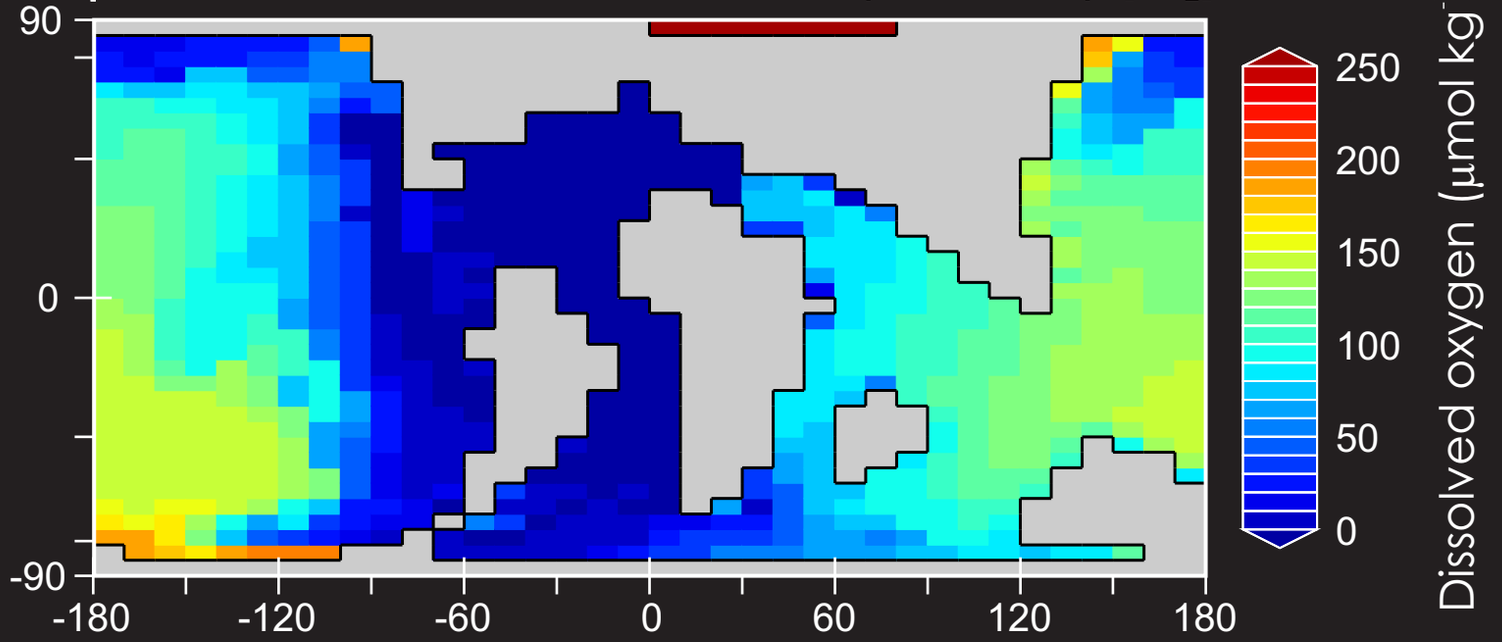


Evolution of the Biological Pump *in silico* #2

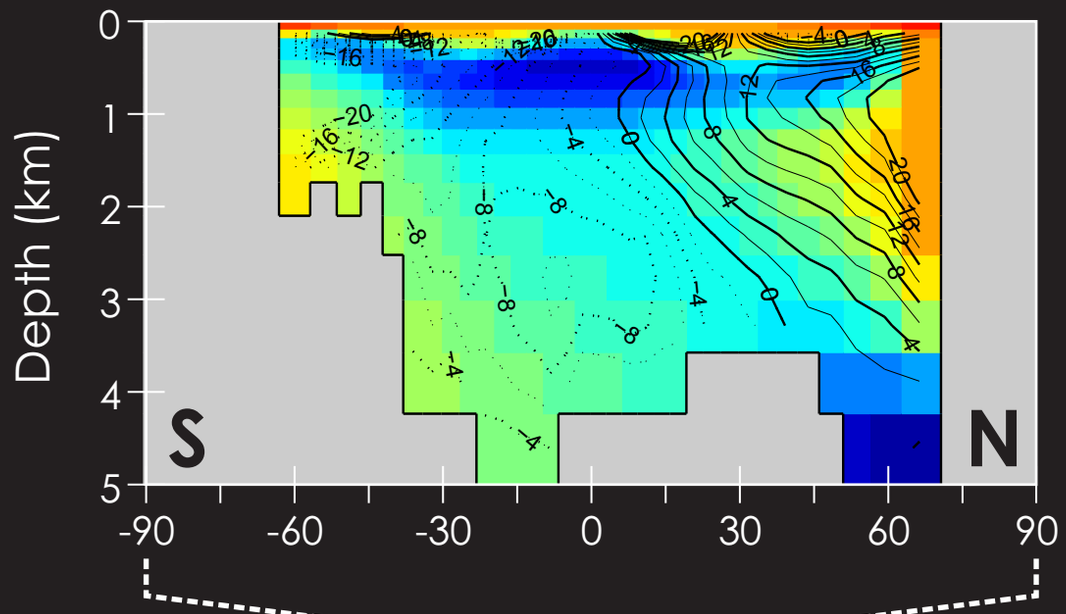


x8 CO_2 @ 10,000 yrs

(started from end of the x4 simulation)

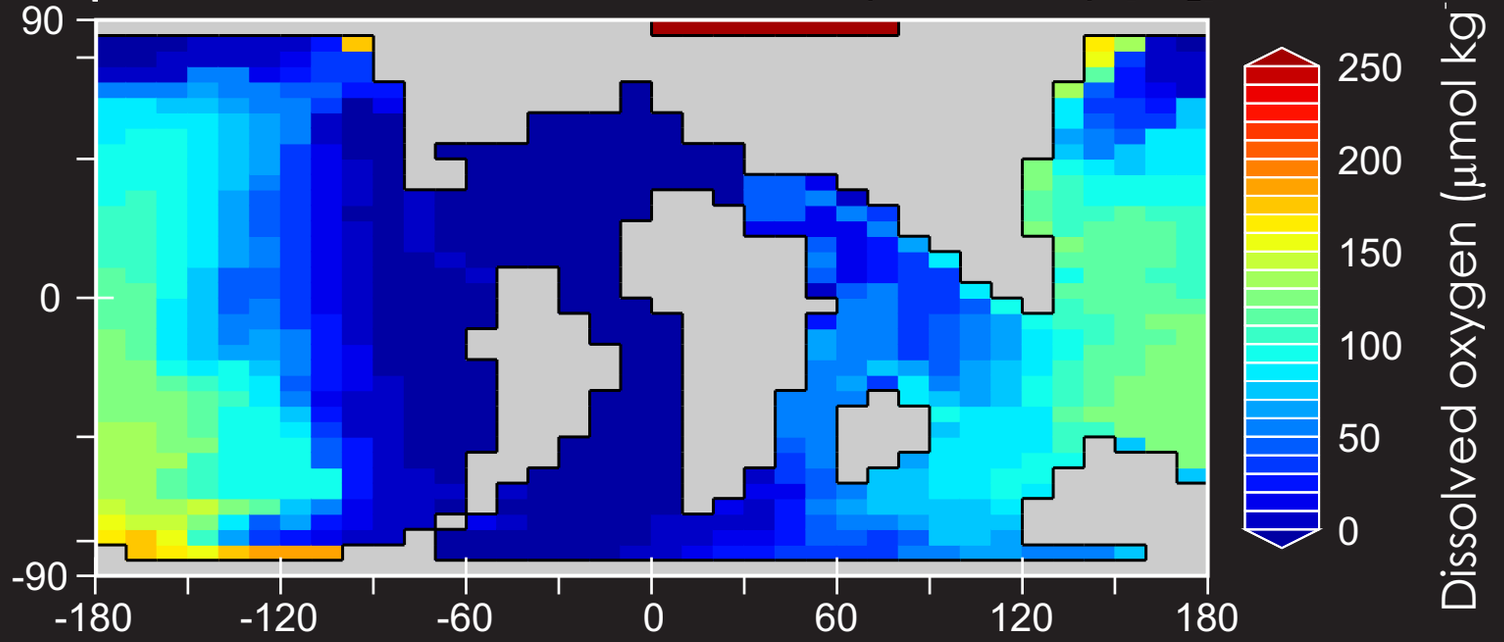


Evolution of the Biological Pump *in silico* #2

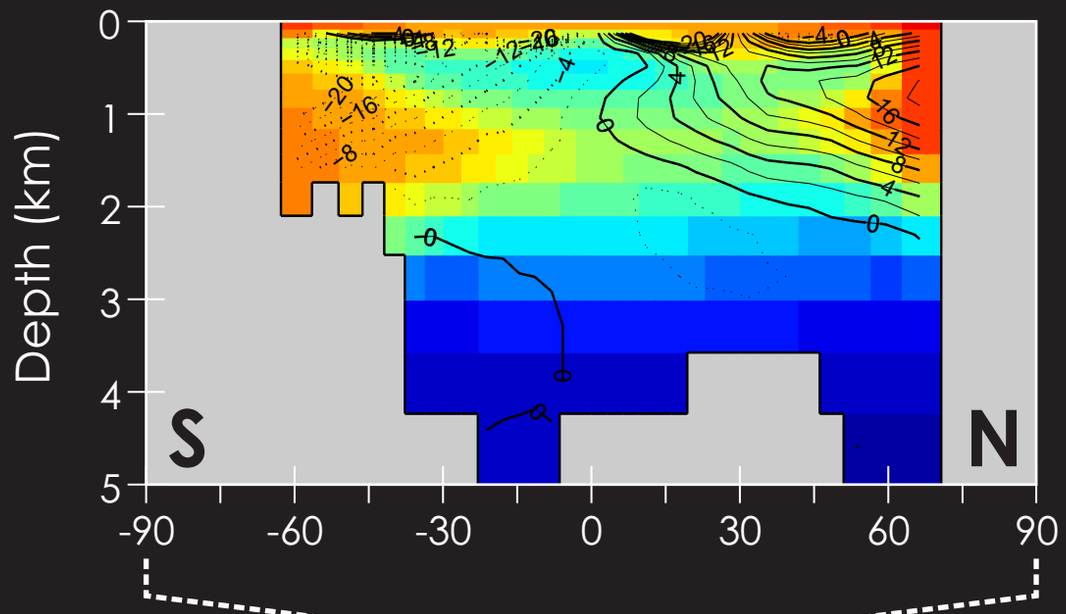


x16 CO_2 @ 10,000 yrs

(started from end of the x4 simulation)

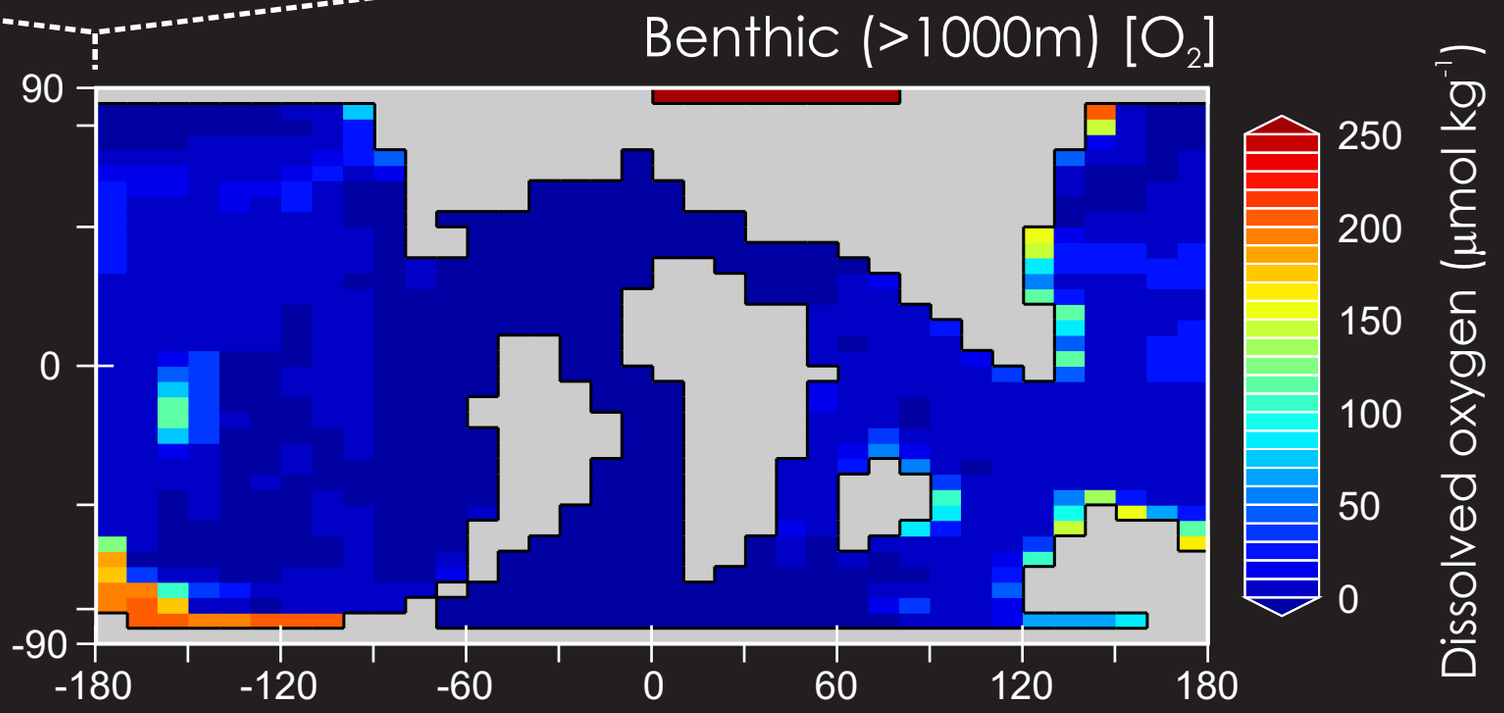


Evolution of the Biological Pump *in silico* #2

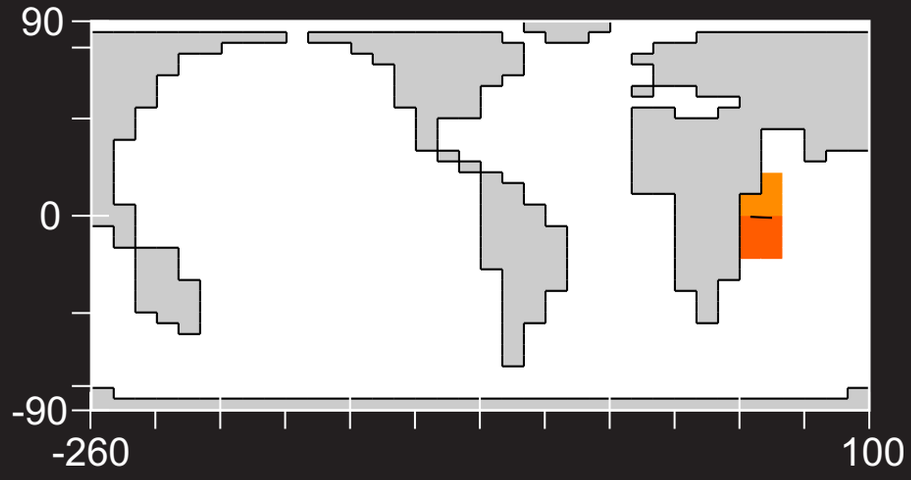


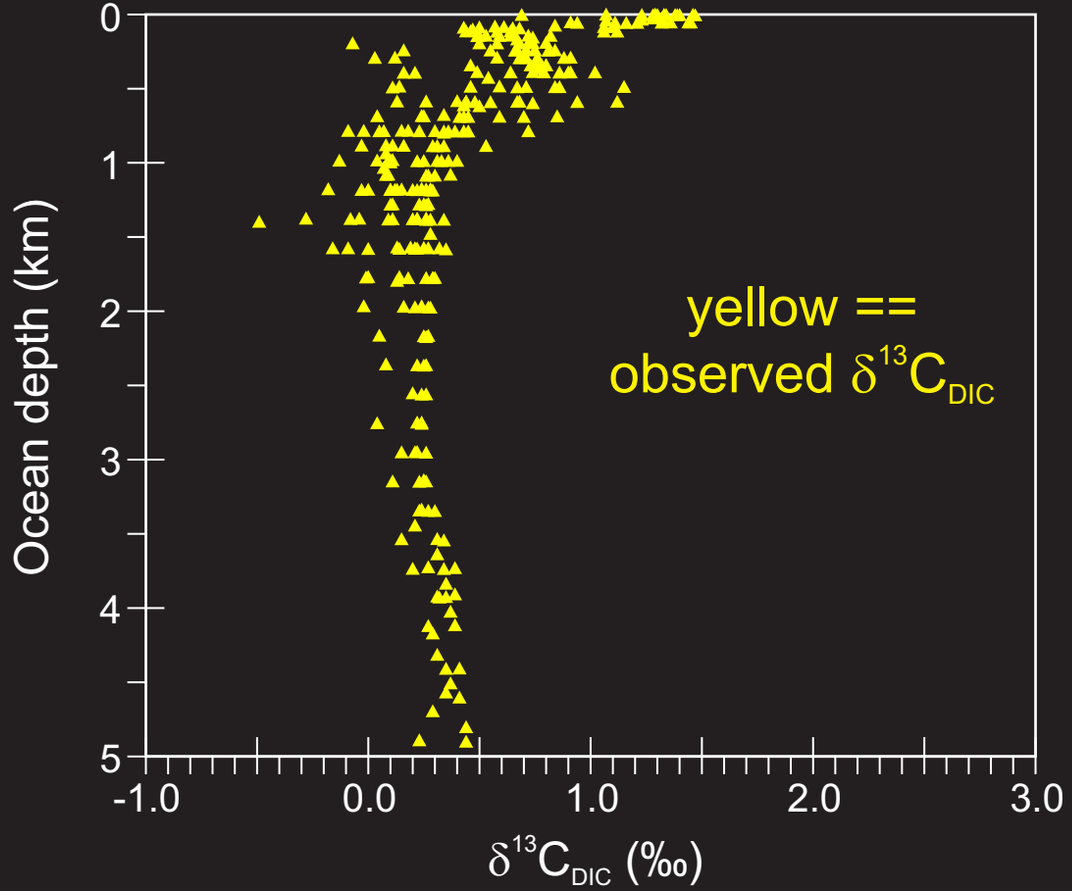
x16 CO_2 @ 2,000 yrs

transient state
(incomplete adjustment to
increased radiative forcing)

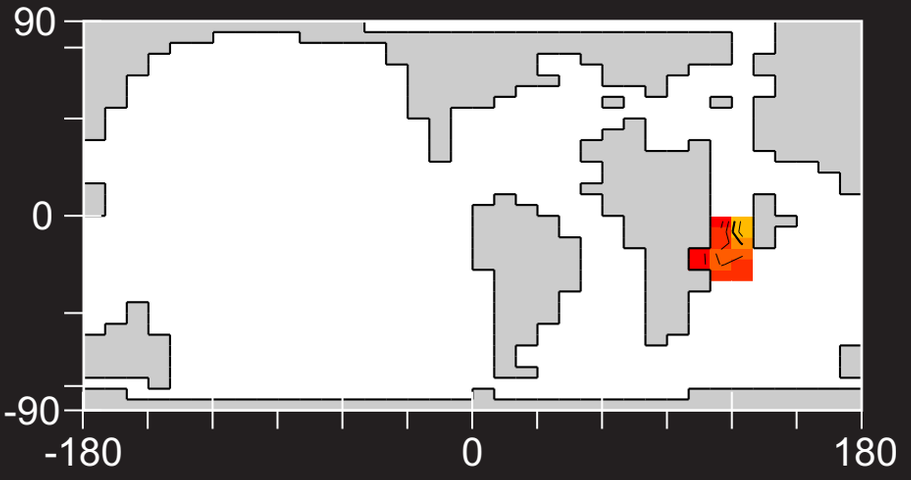


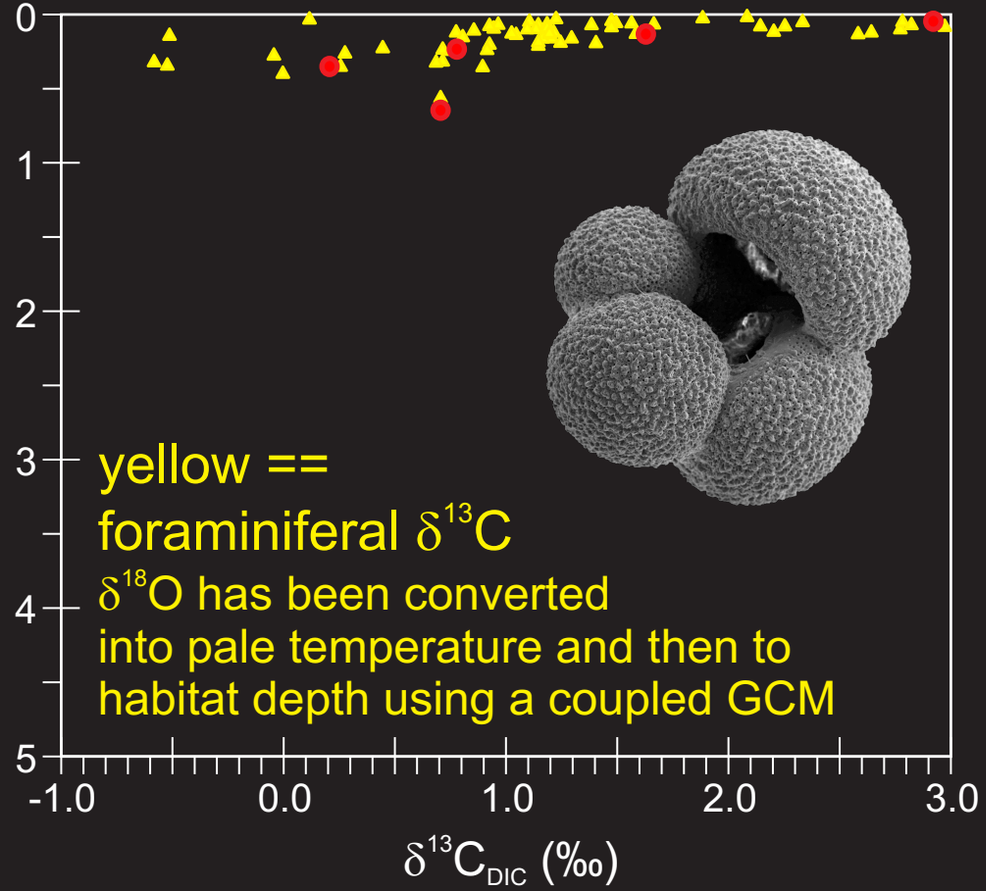
Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania



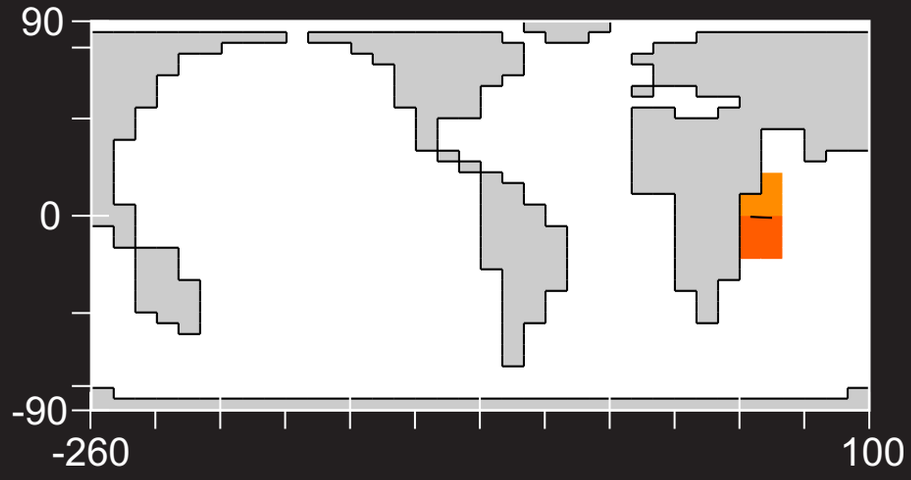


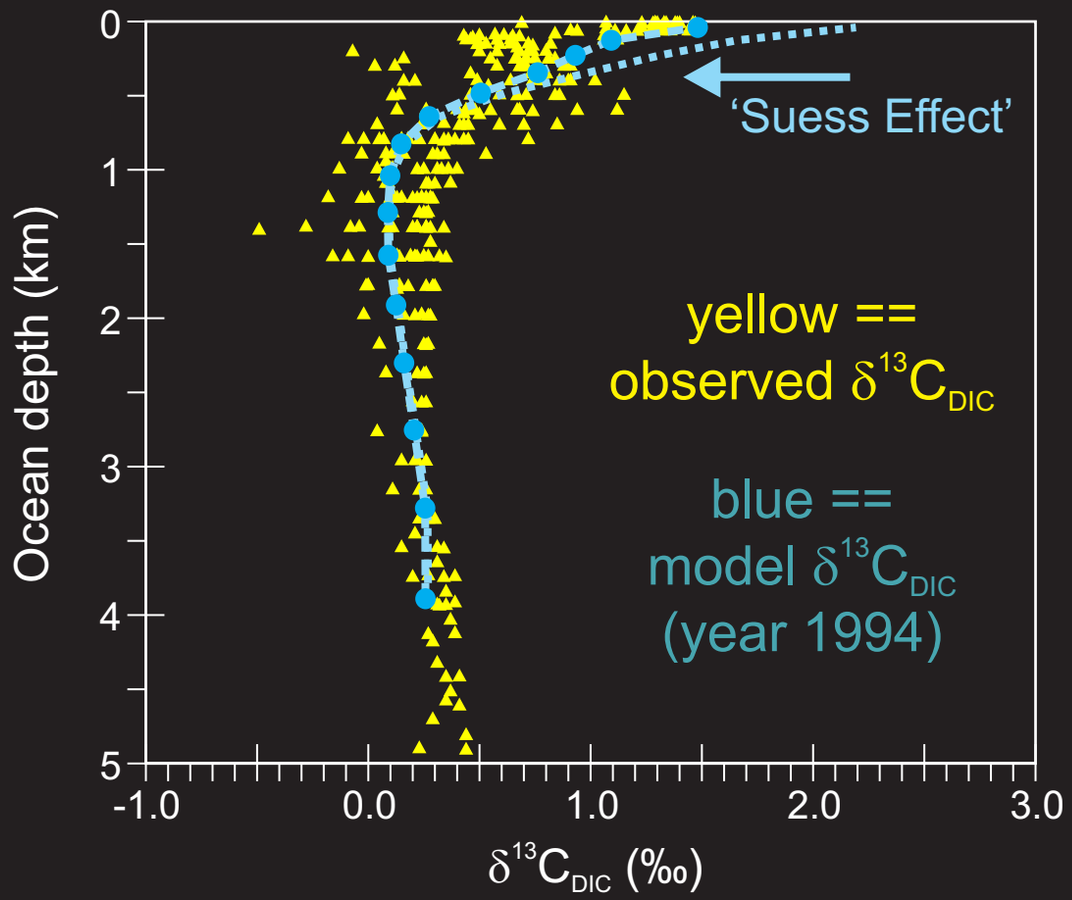
Planktic foraminiferal $\delta^{13}C$ from early Eocene Tanzania



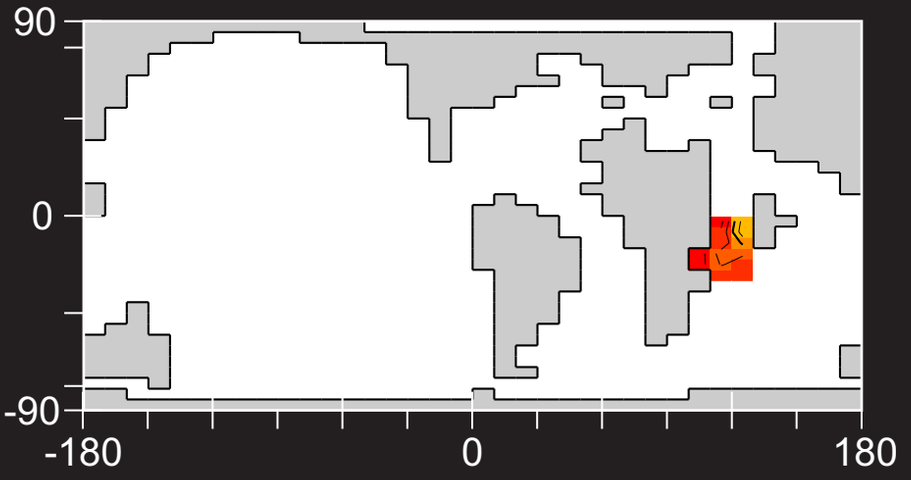


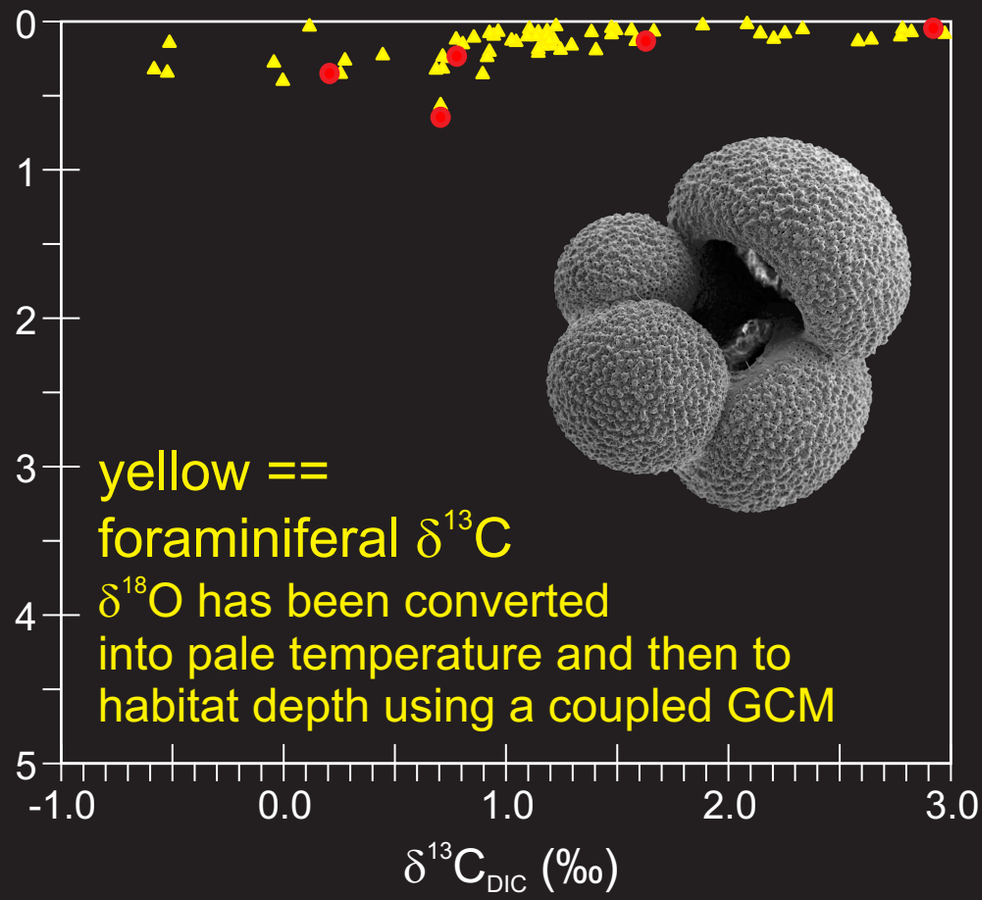
Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania

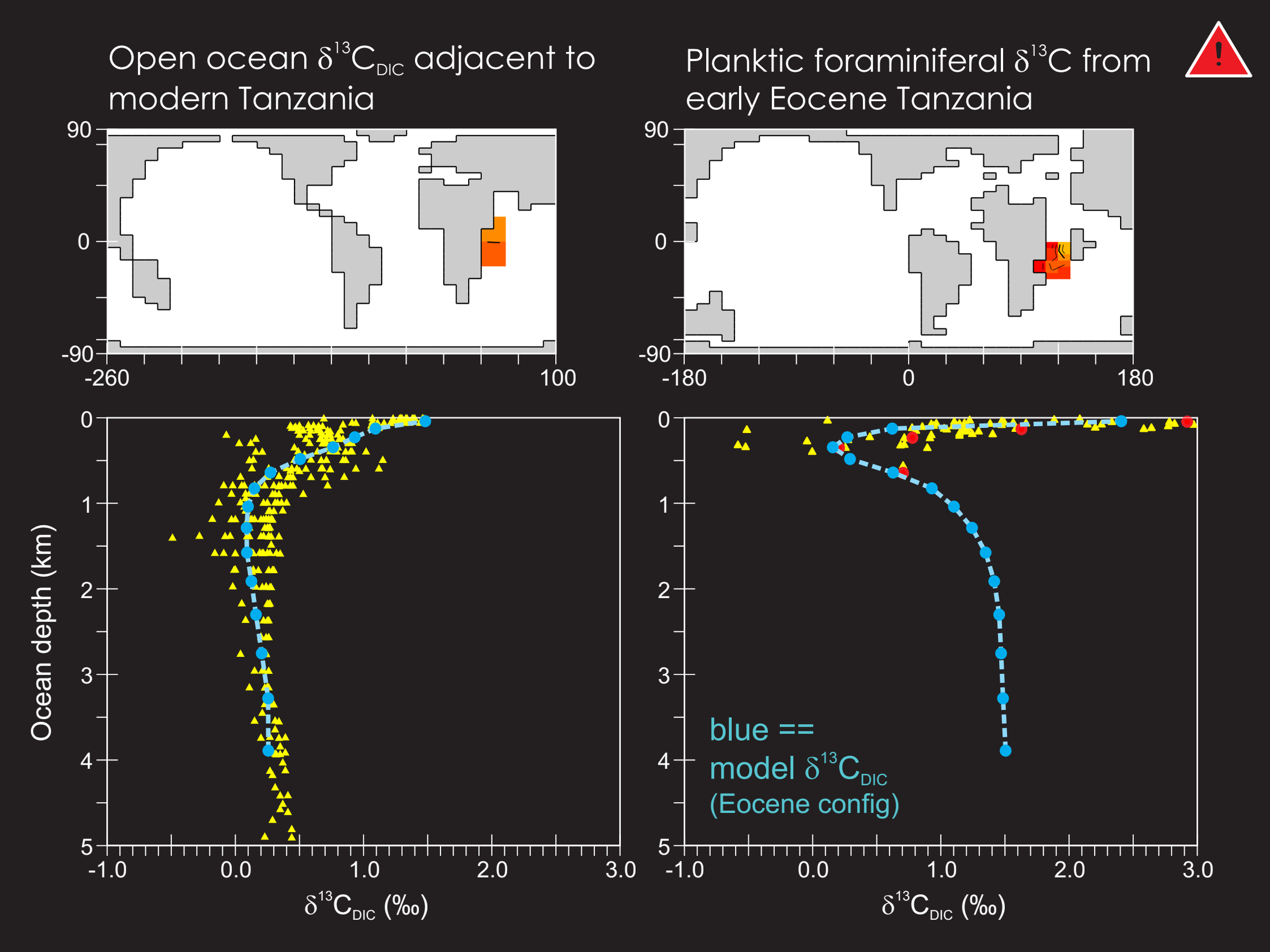




Planktic foraminiferal $\delta^{13}C$ from early Eocene Tanzania






Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania
Planktic foraminiferal $\delta^{13}C$ from early Eocene Tanzania
90
0
-90
-260
100
-180
180
Ocean depth (km)
0
1
2
3
4
5
-1.0
0.0
1.0
2.0
3.0
$\delta^{13}C_{DIC}$ (‰)
blue ==
model $\delta^{13}C_{DIC}$
(Eocene config)

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Jamie Wilson & Steve Barker,
Eleanor John, Paul Pearson [Cardiff]
Sandra Arndt, Daniela Schmidt [Bristol]
Ellen Thomas [Yale]

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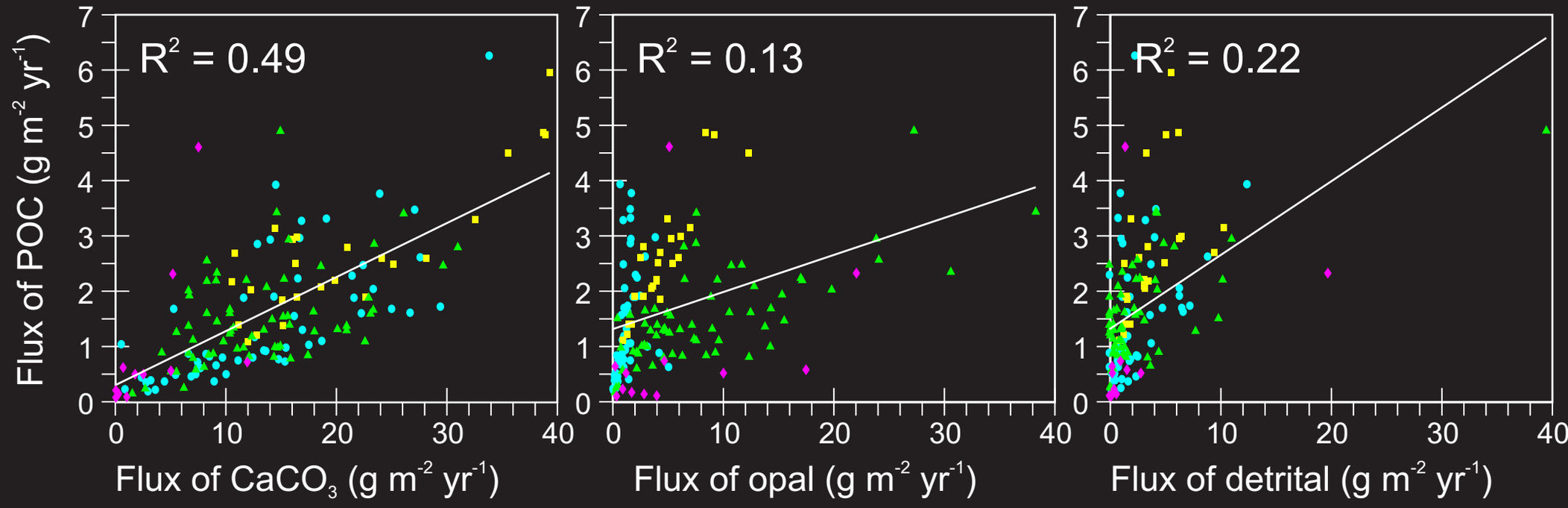
Evolution of the Biological Pump:

Planktic carbonate production and 'ballasting'

Compilation of sediment trap observations:

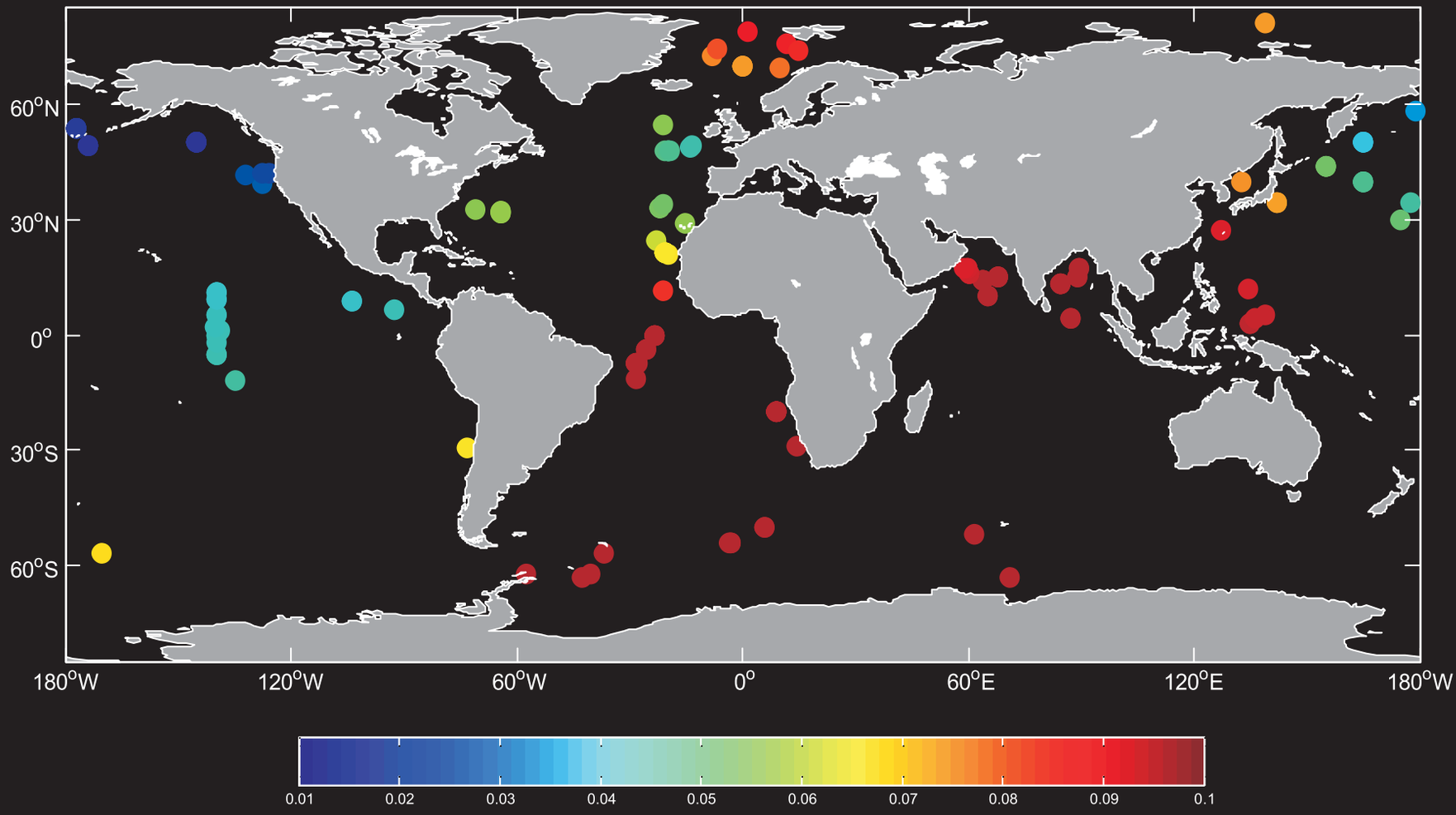
depths >= 2000 m (to exclude hydrodynamically distorted fluxes and relationships) and differentiated by basin:
cyan == Atl, yellow == Ind, green == Pac, magenta == SO.

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



Evolution of the Biological Pump:

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]