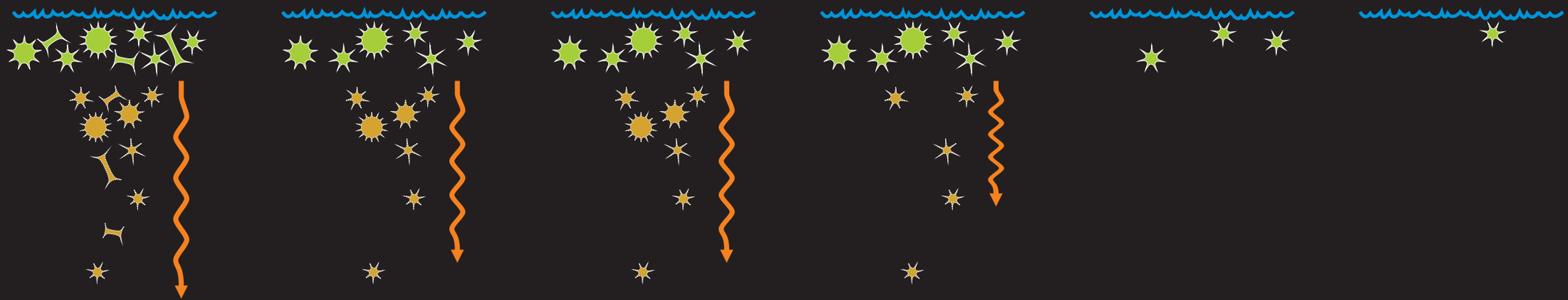
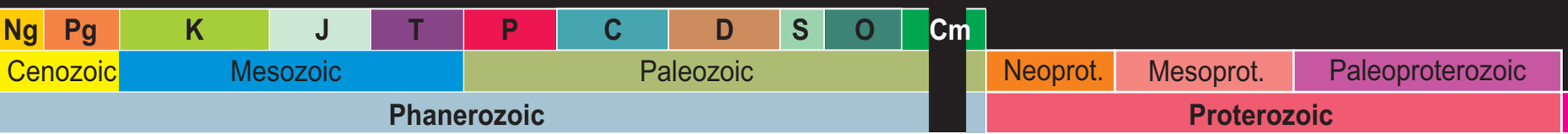
The Biologically-Driven Ocean Carbon Pumps:
The Ocean Carbon Pumps: From Ancient to Future Oceans

Biological carbon pumping in 'deep time': The Force Awakens

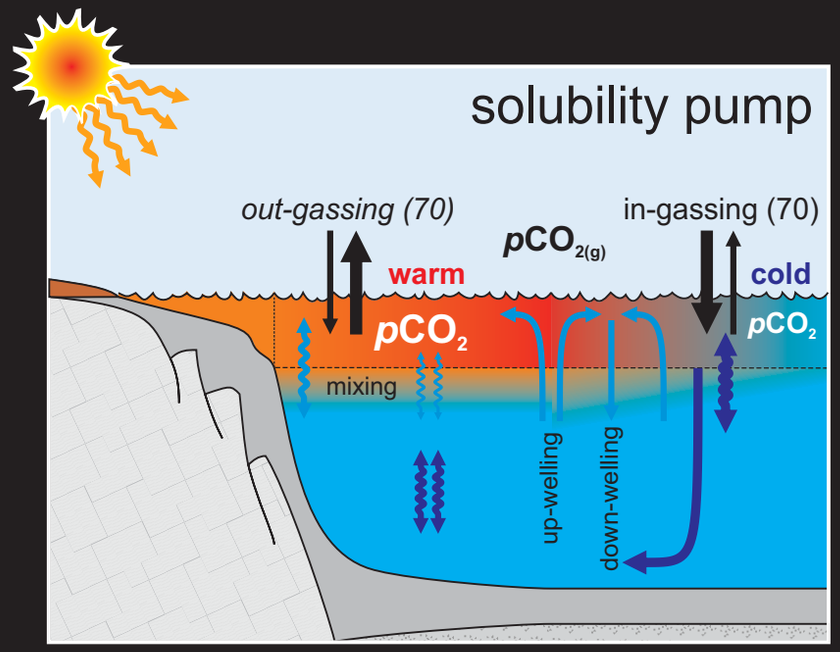
Andy Ridgwell

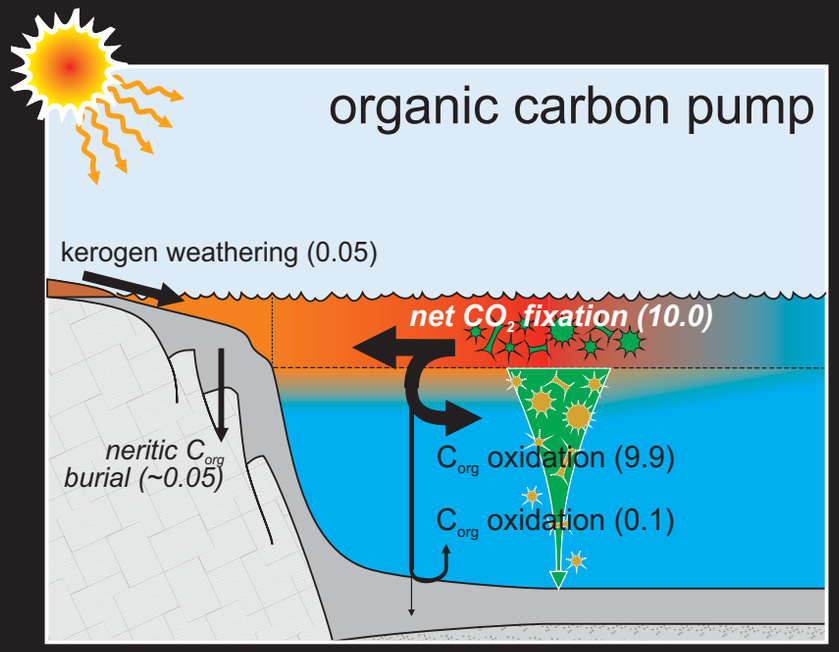
University of California – Riverside
University of Bristol

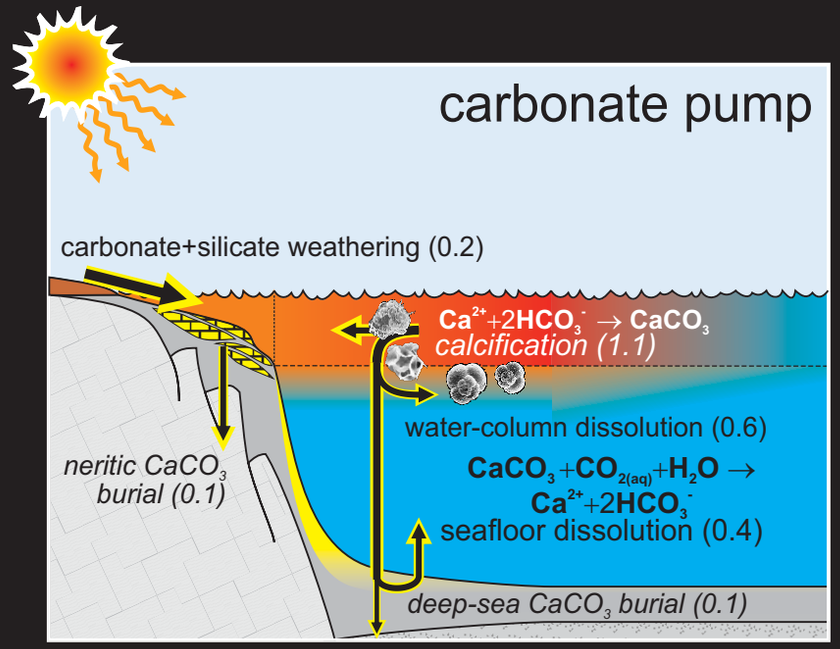


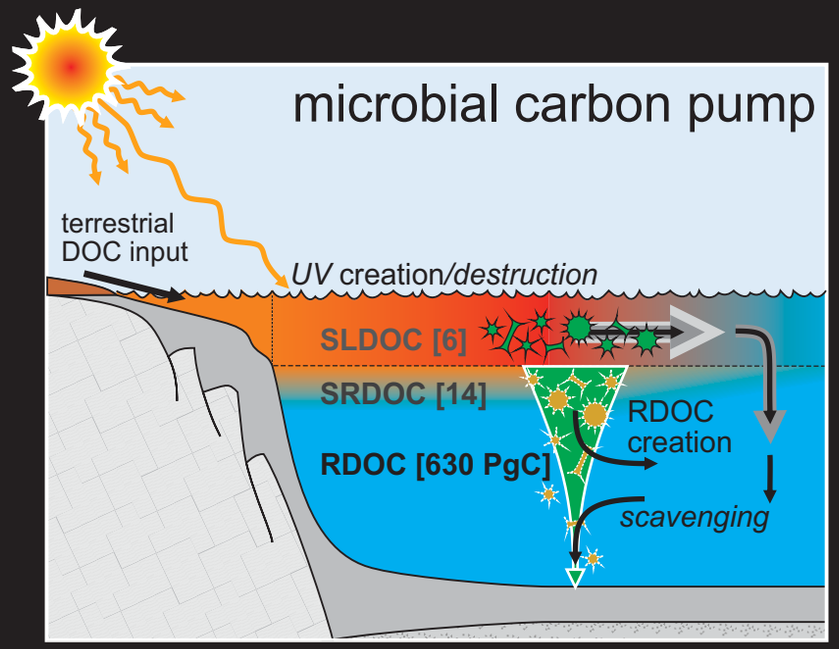


Outline







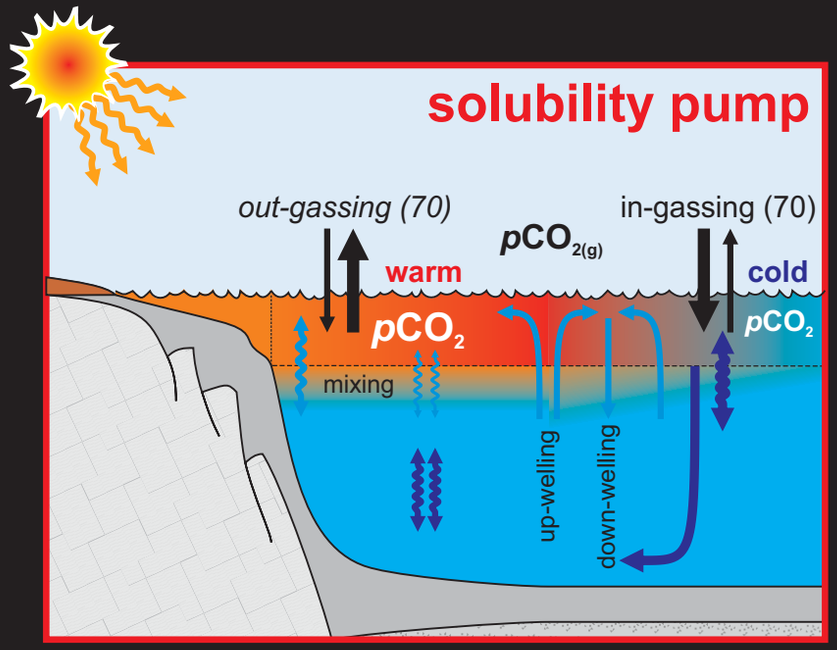


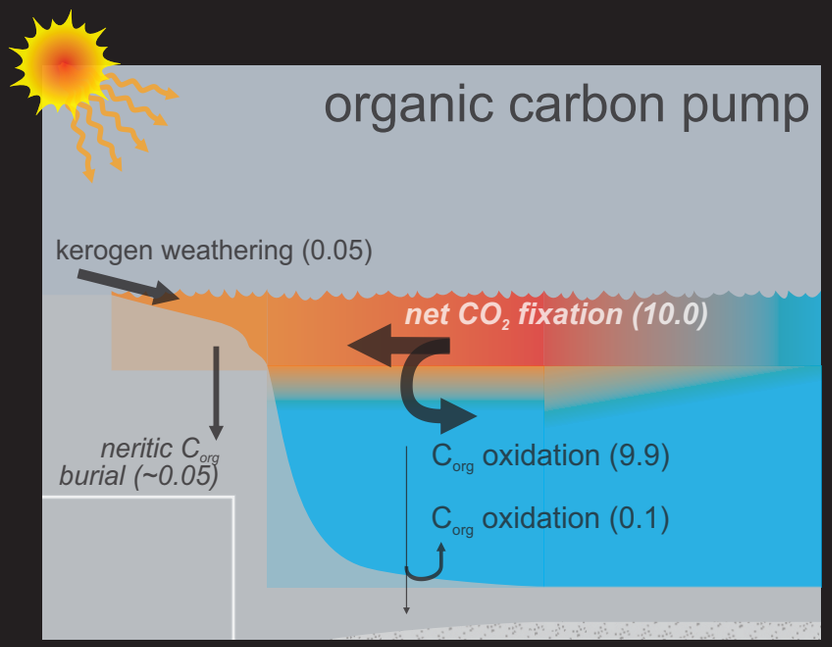
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

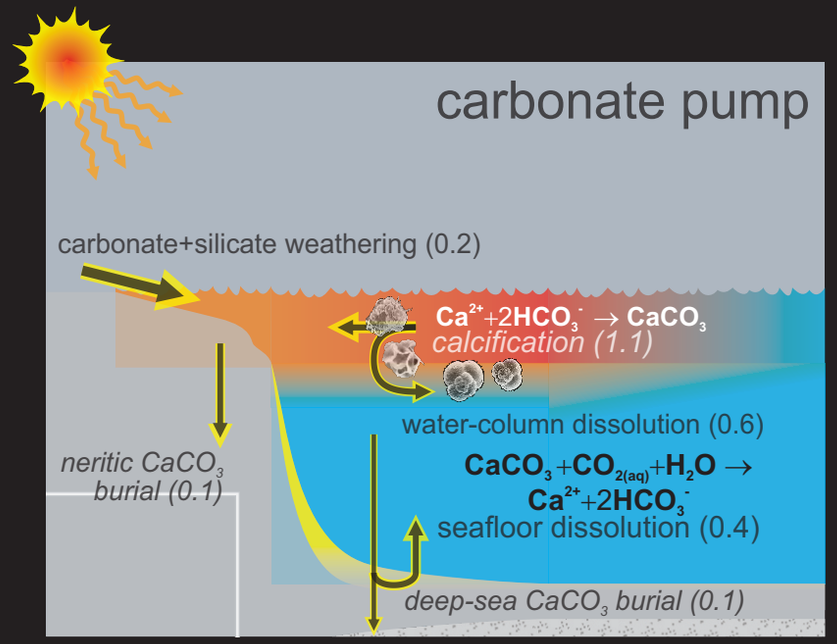
Neoprot.	Mesoprot.	Paleoproterozoic	Archean
Proterozoic			

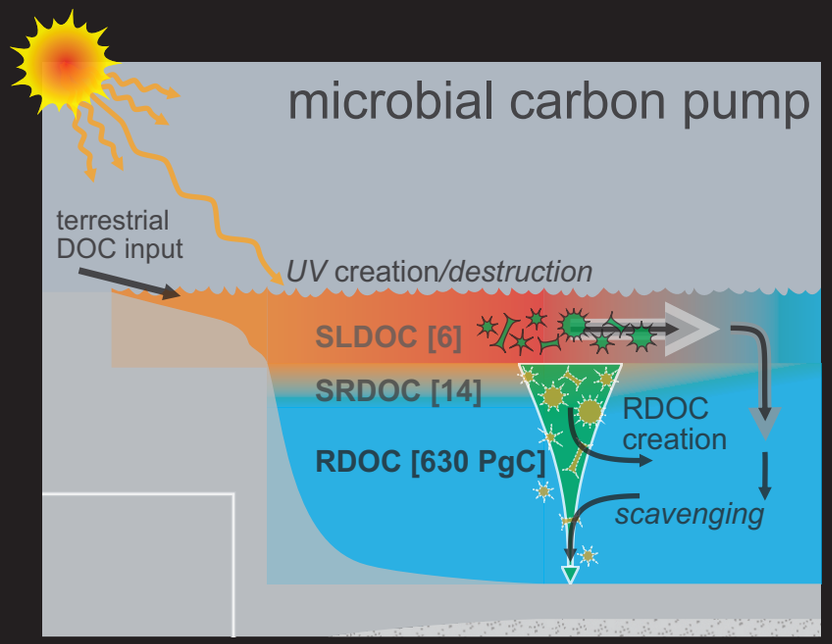
Outline

pump = *f*(ocean circulation, pole-to-equator SST, atm pCO_2, surface fCO_2)







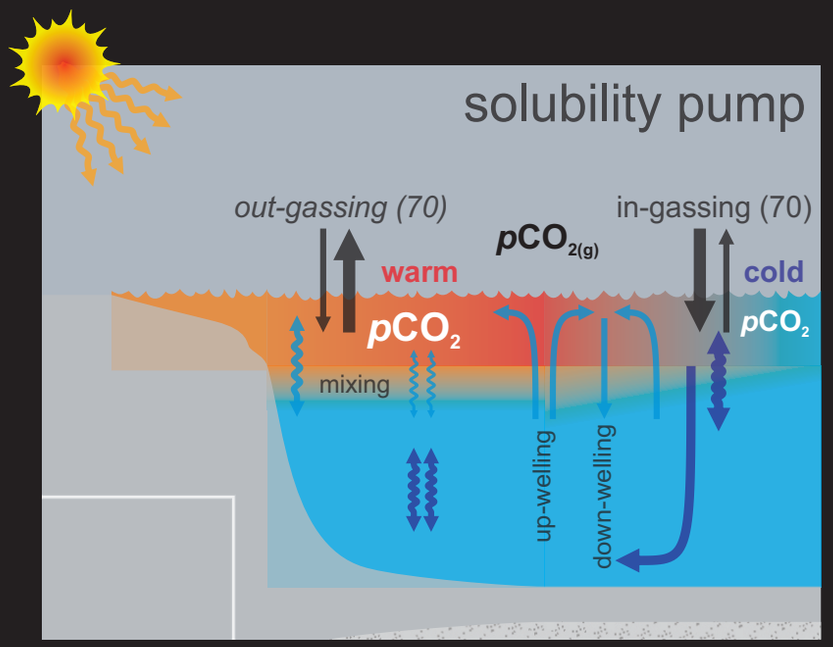


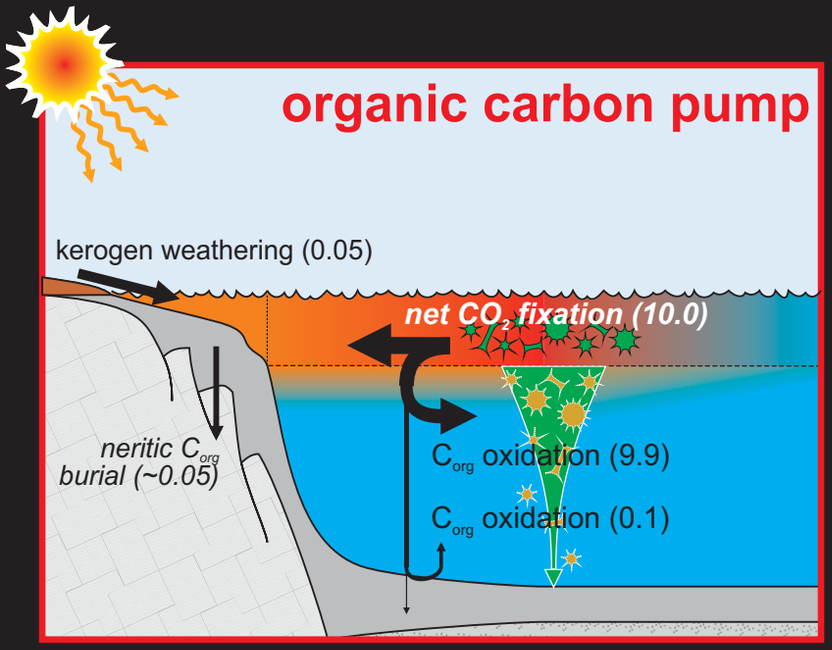
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

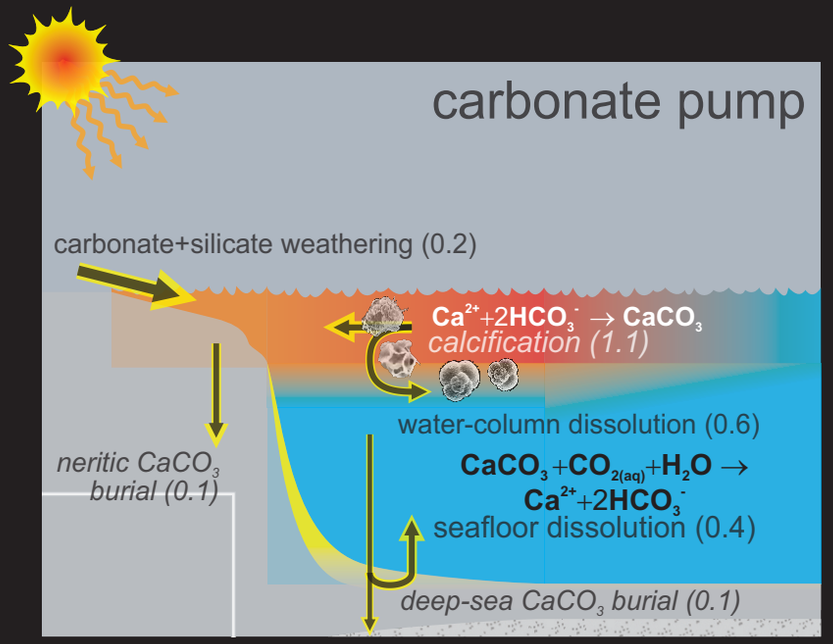
Neoprot.	Mesoprot.	Paleoproterozoic	
Proterozoic			Archean

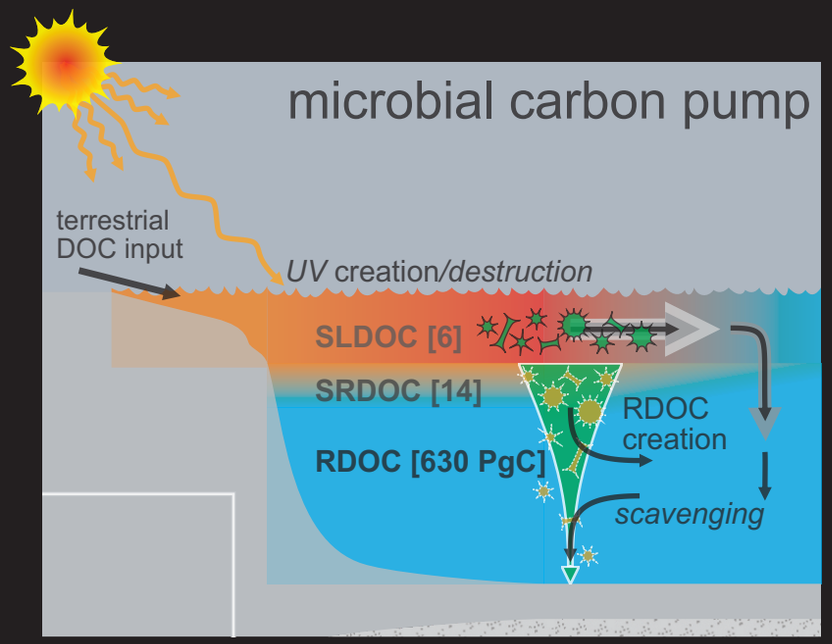
Outline

pump = *f*(biological export (*f*(...)), **remineralization** (*f*(...)))







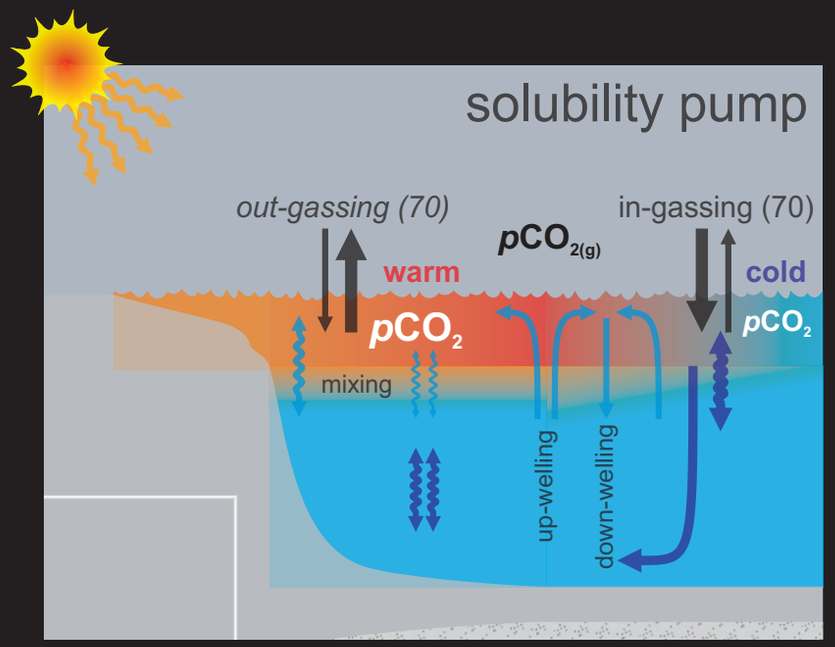


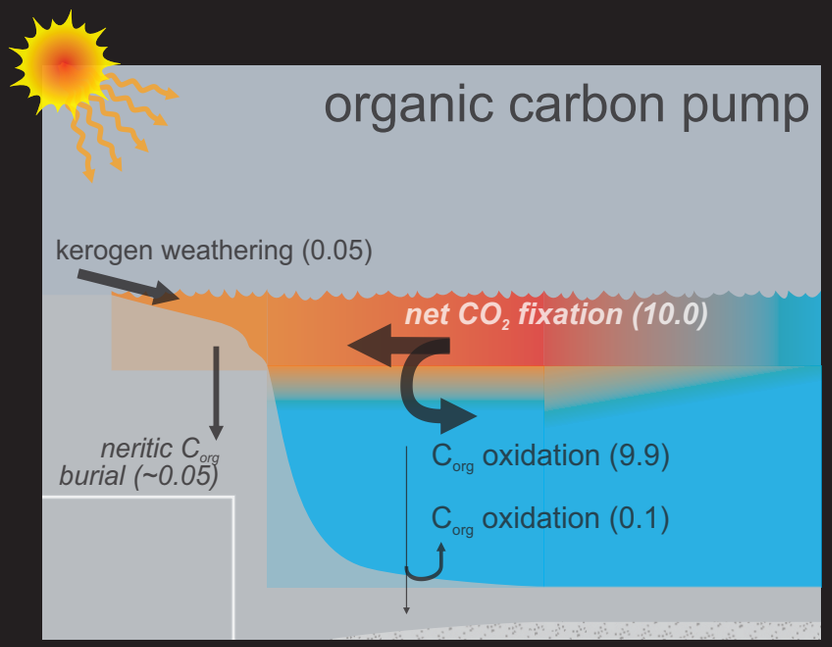
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

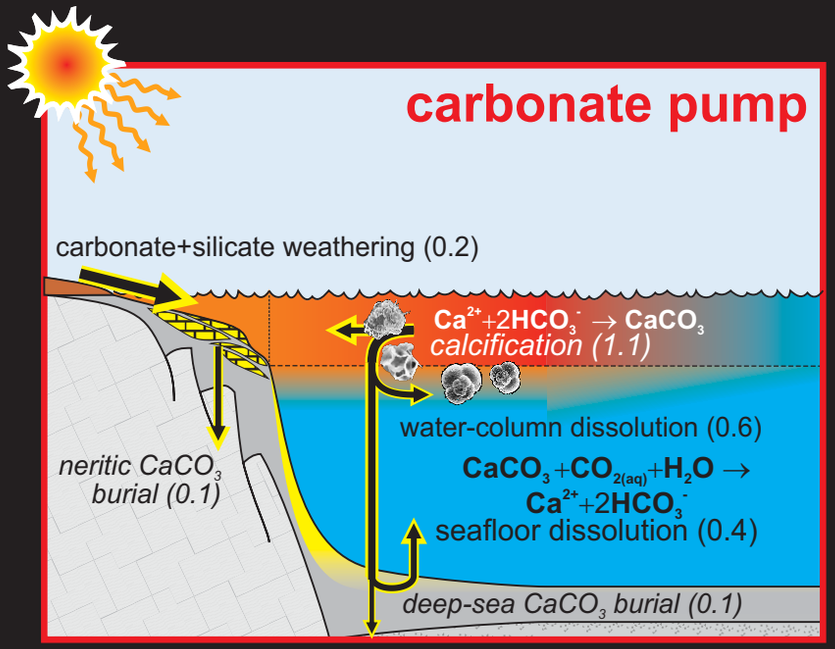
Neoprot.	Mesoprot.	Paleoproterozoic	Archean
Proterozoic			

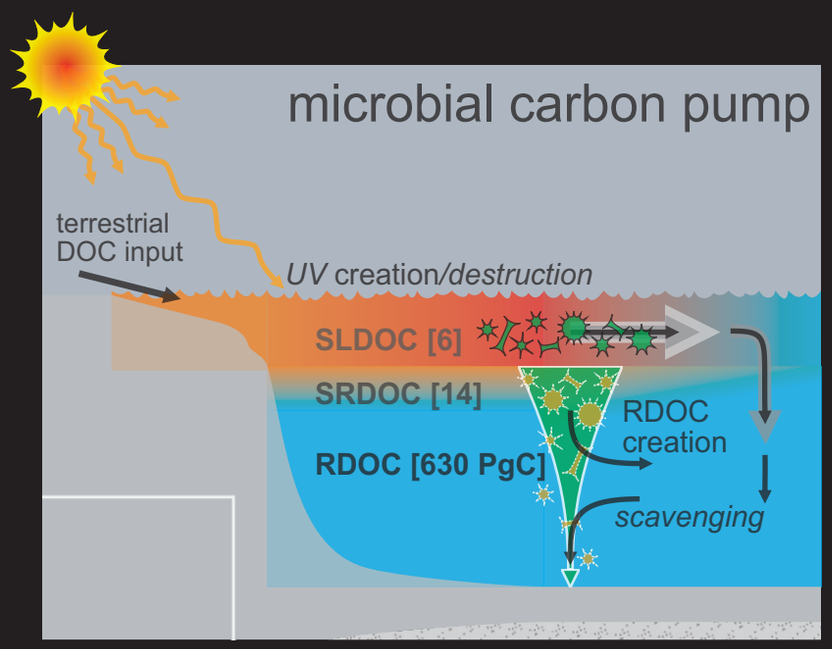
Outline

pump = *f*(biological export (*f*(...)), **remineralization** (*f*(...)))







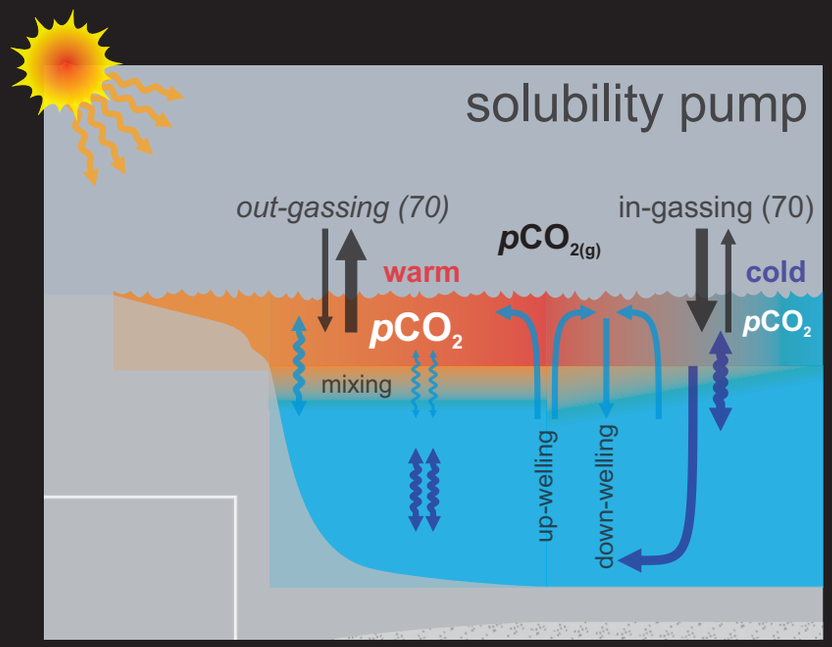


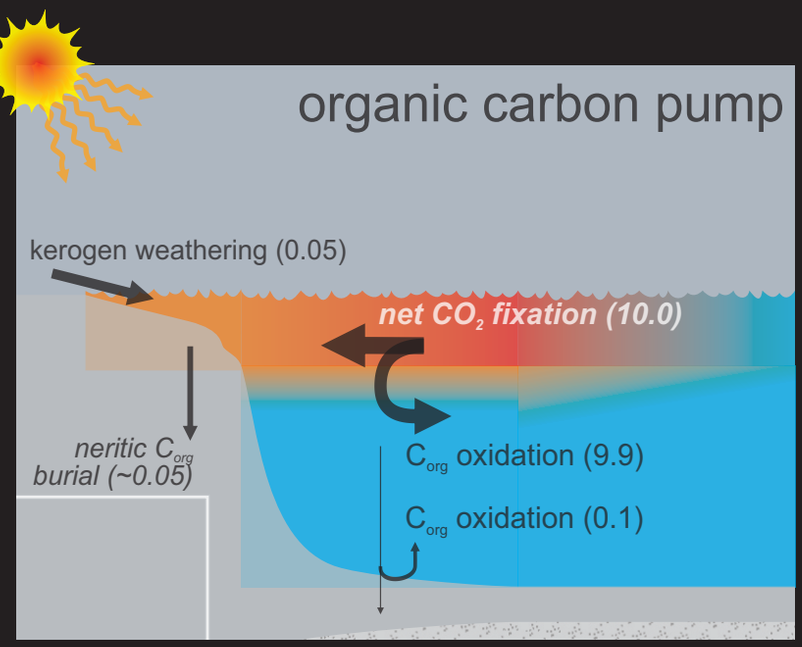
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

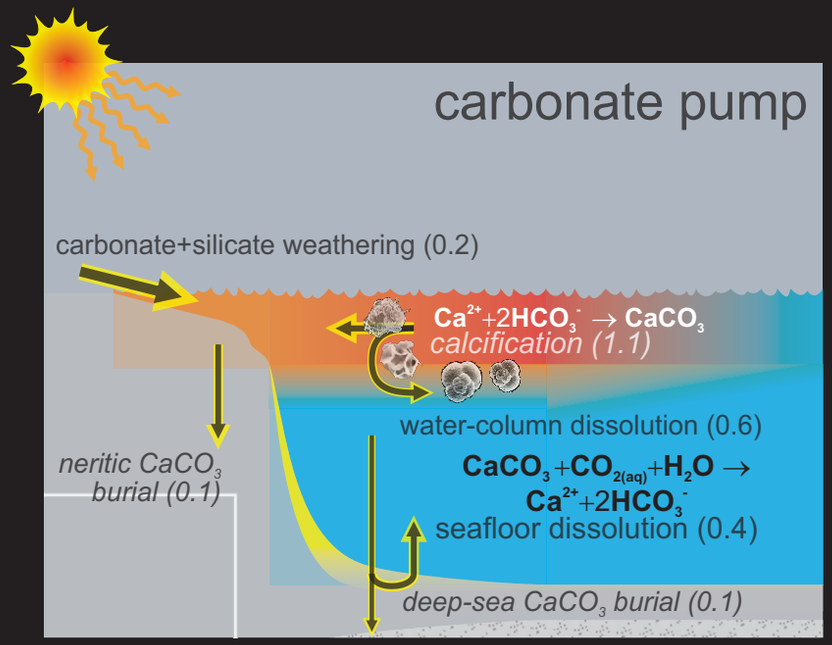
Neoprot.	Mesoprot.	Paleoproterozoic	
Proterozoic			Archean

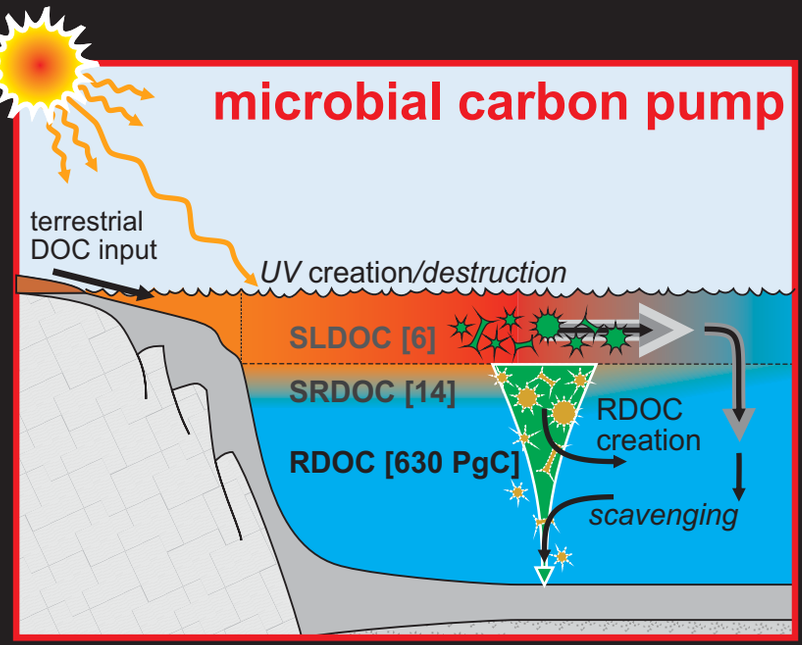
Outline

pump = *f*((circulation, biological pump), POM/DOM quality, redox???, ???)







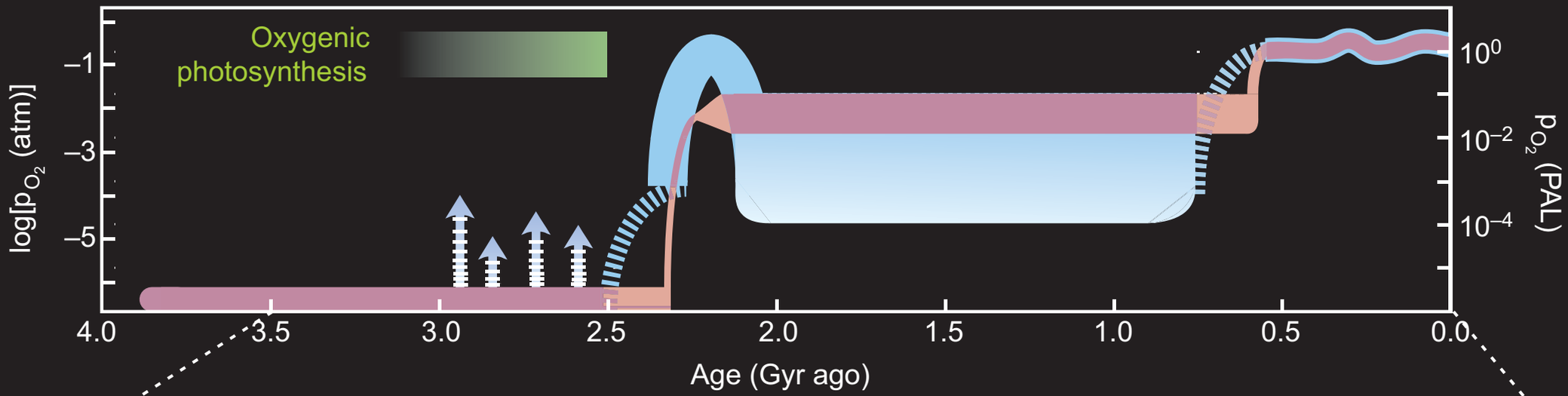


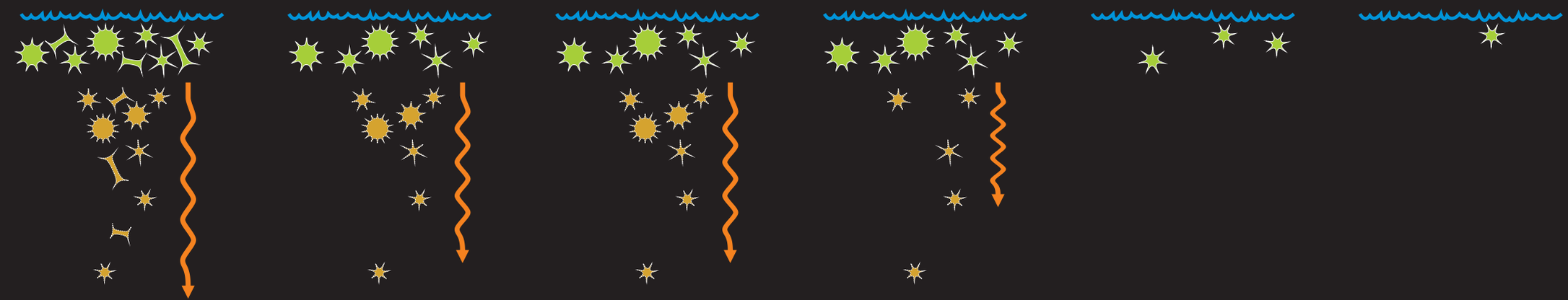
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

Neoprot.	Mesoprot.	Paleoproterozoic	Archean
Proterozoic			

Outline

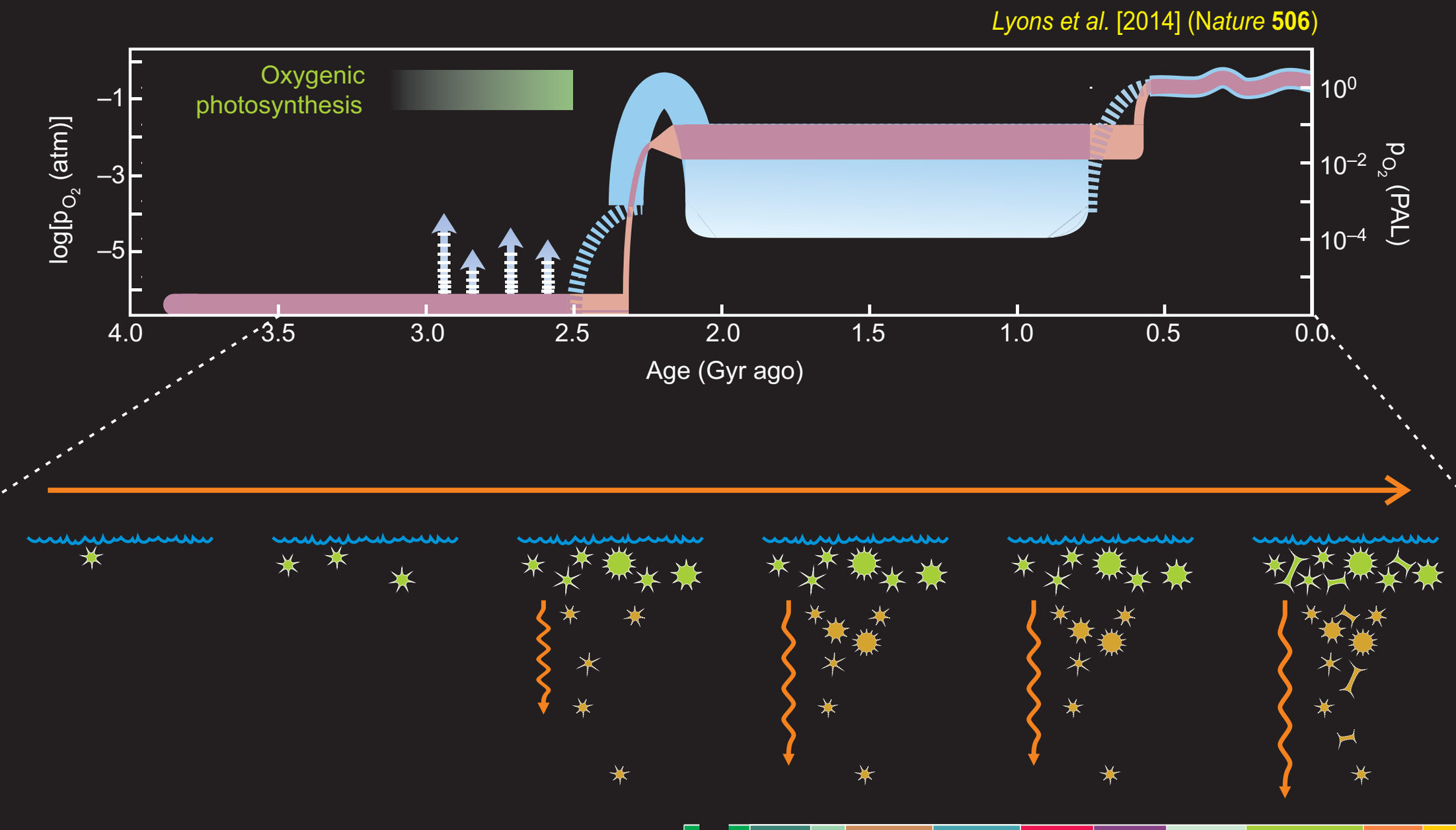
Lyons et al. [2014] (*Nature* **506**)





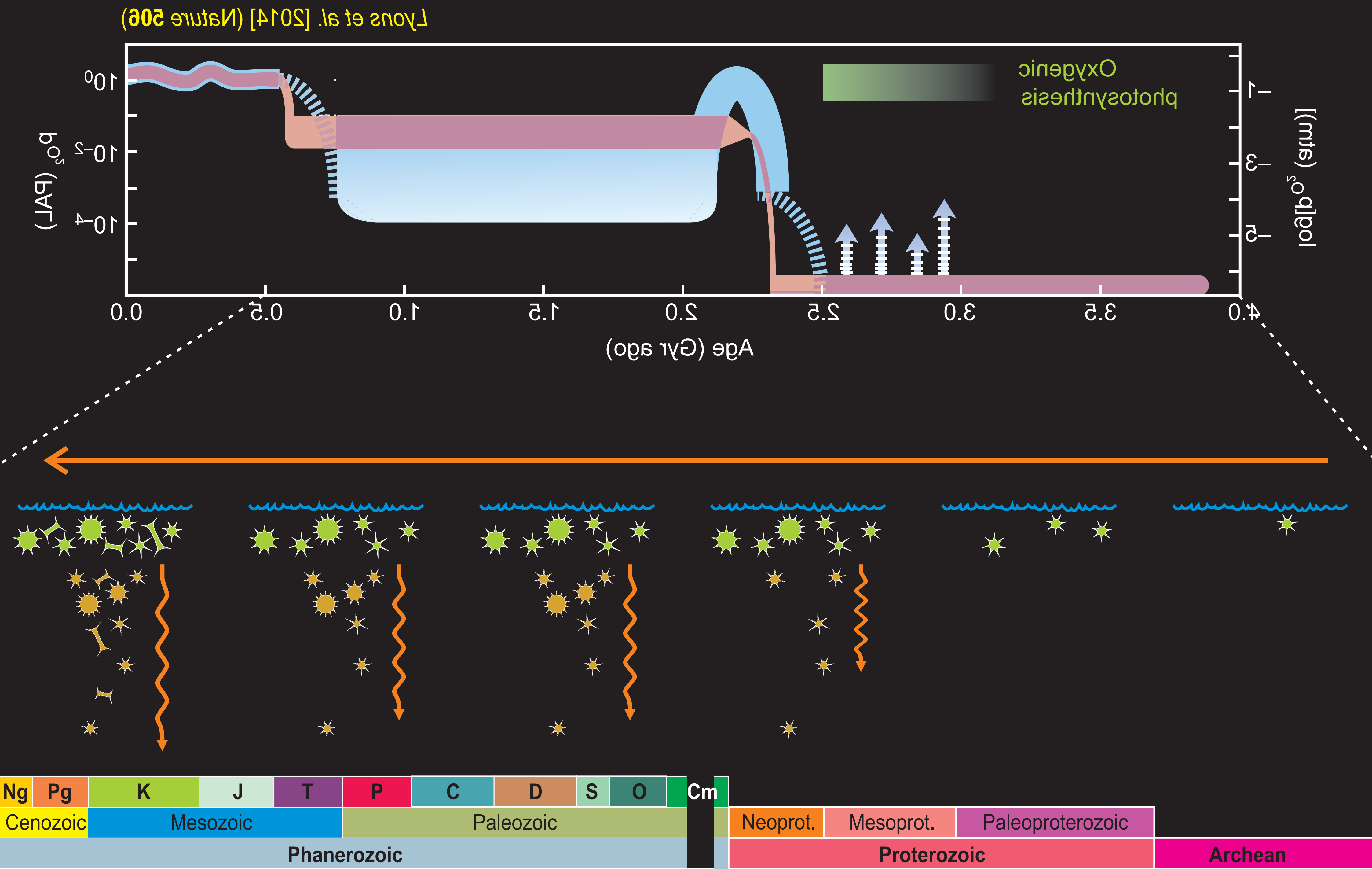
Ng	Pg	K	J	T	P	C	D	S	O	Cm				
Cenozoic		Mesozoic			Paleozoic						Neoprot.	Mesoprot.	Paleoproterozoic	
Phanerozoic											Proterozoic			Archean

Outline


Lyons et al. [2014] (Nature 506)
Oxygenic photosynthesis
log[p$_{O_2}$ (atm)]
–1
–3
–5
10^0
10^{-2}
10^{-4}
p$_{O_2}$ (PAL)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Age (Gyr ago)

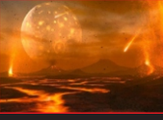

Cm
O
S
D
C
P
T
J
K
Pg
Ng
Neoprot.
Mesoprot.
Paleoprotero.
Paleozoic
Mesozoic
Cenozoic
Archean
Proterozoic
Phanerozoic

Outline



Lyons et al. [2014] (Nature **506**)
Oxygenic photosynthesis
pO_2 (PAL)
10^0
10^{-2}
10^{-4}
$\log[pO_2$ (atm)]
−1
−3
−5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Age (Gyr ago)
Ng
Pg
K
J
T
P
C
D
S
O
Cm
Cenozoic
Mesozoic
Paleozoic
Neoprot.
Mesoprot.
Paleoproterozoic
Phanerozoic
Proterozoic
Archean

Origins ...

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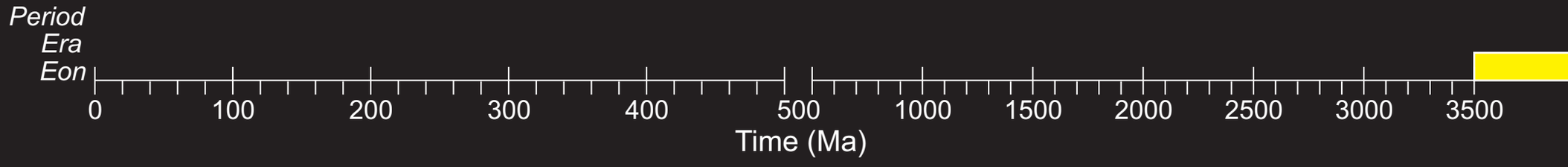
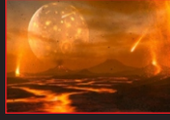

Period
Era
Eon
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)



solubility pump

?

organic carbon pump

?

carbonate pump

?

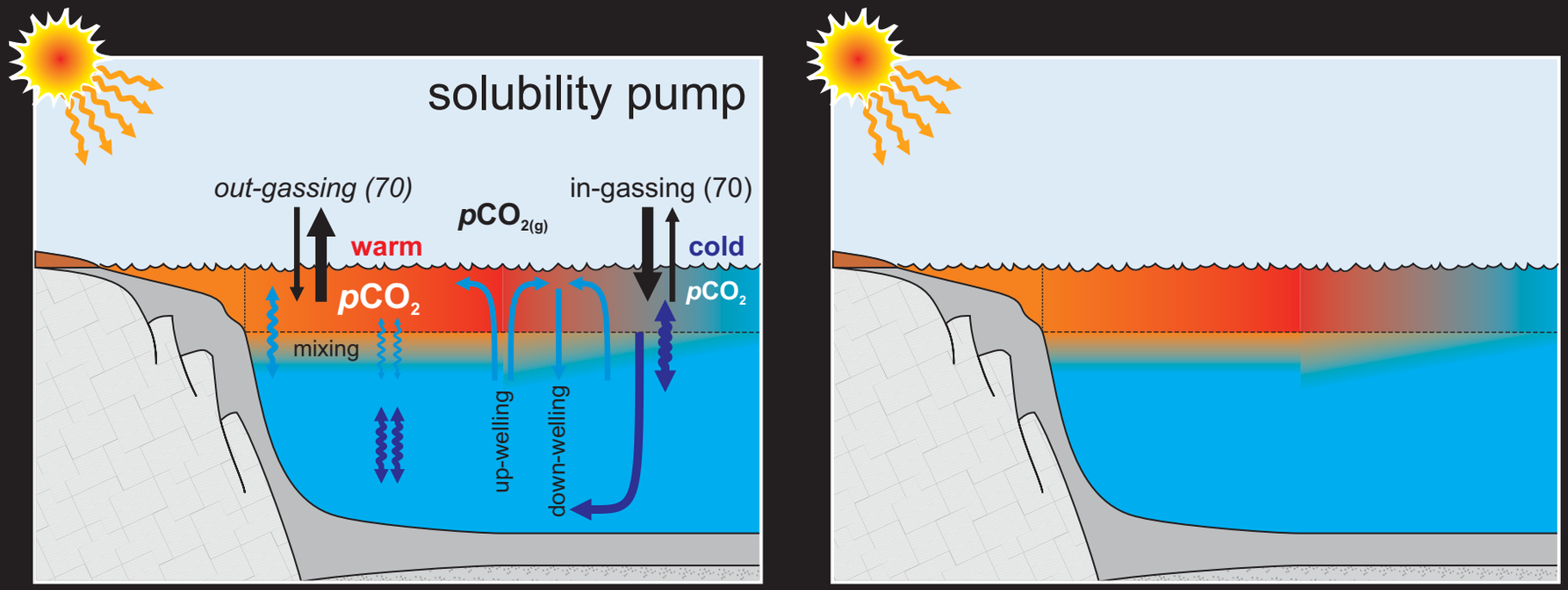
microbial carbon pump

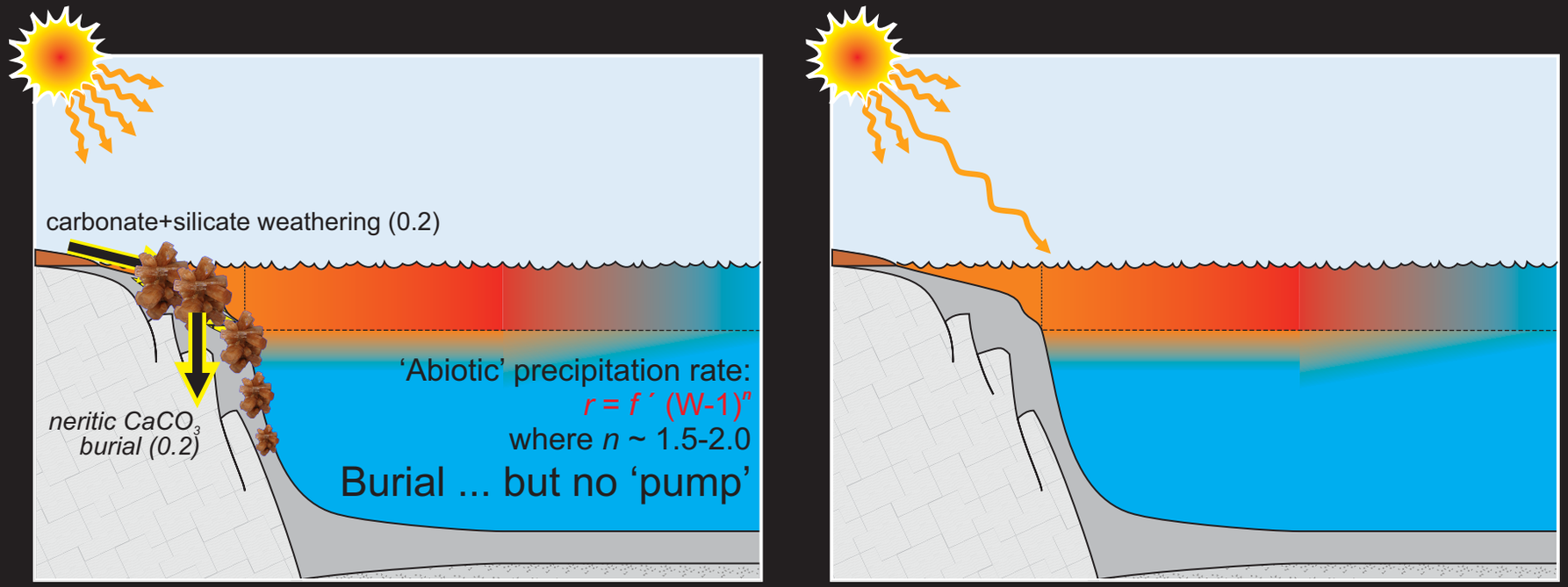
?

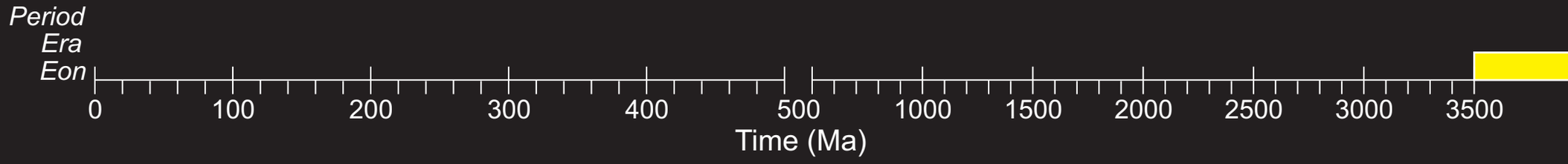
Period
Era
Eon

0 100 200 300 400 500 1000 1500 2000 2500 3000 3500

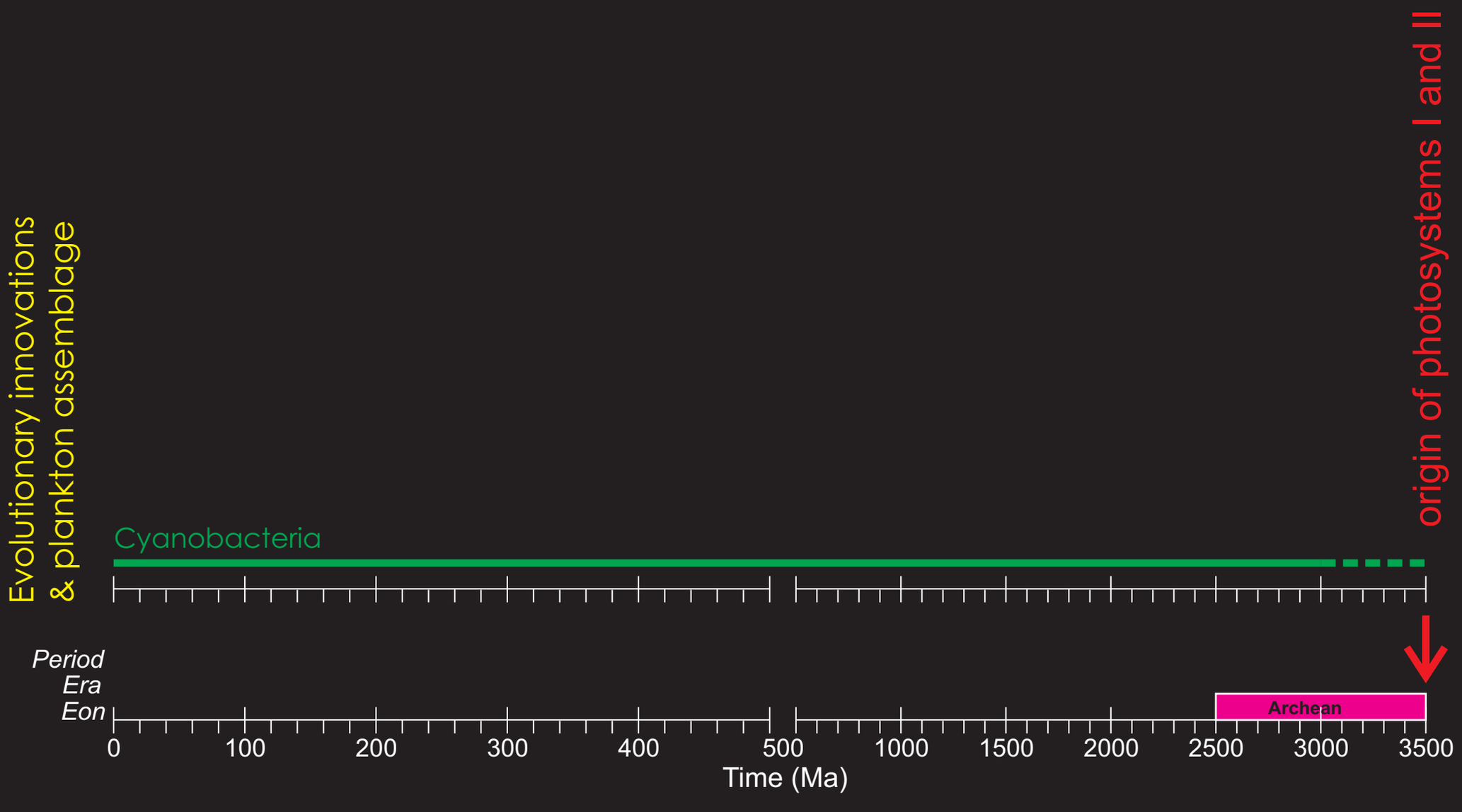
Time (Ma)


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


carbonate+silicate weathering (0.2)
neritic CaCO3 burial (0.2)
'Abiotic' precipitation rate:
r = f ´ (W-1)n
where n ~ 1.5-2.0
Burial ... but no 'pump'


Period
Era
Eon
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

The Force awakens ... ???



solubility pump

?

organic carbon pump

?

carbonate pump

?

microbial carbon pump

?

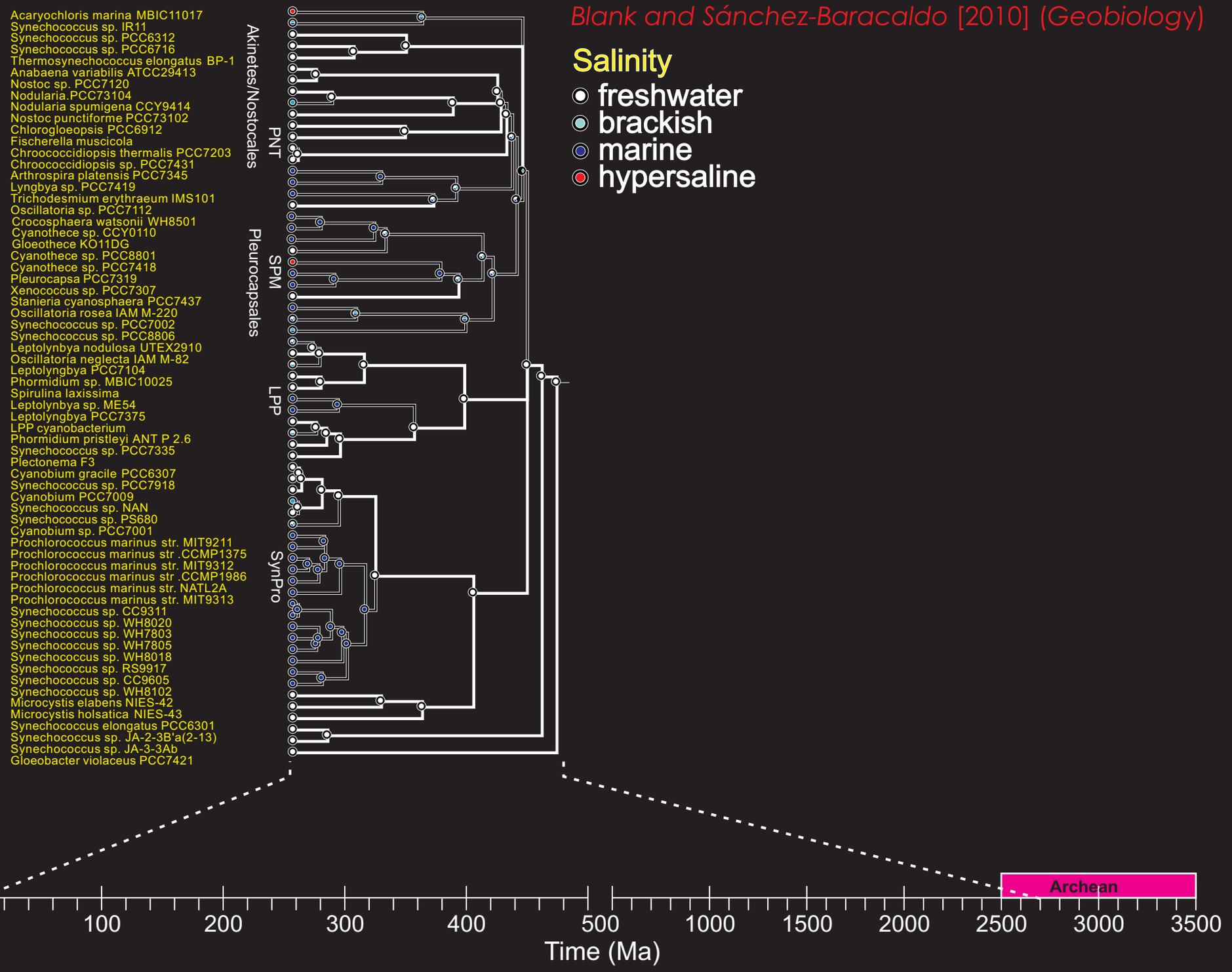
Period
Era
Eon

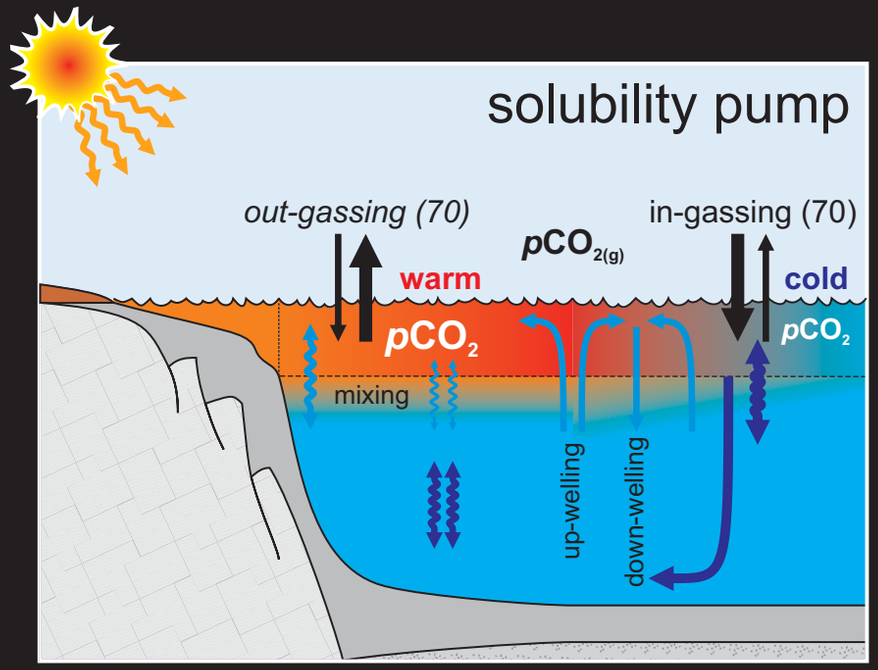
Archean

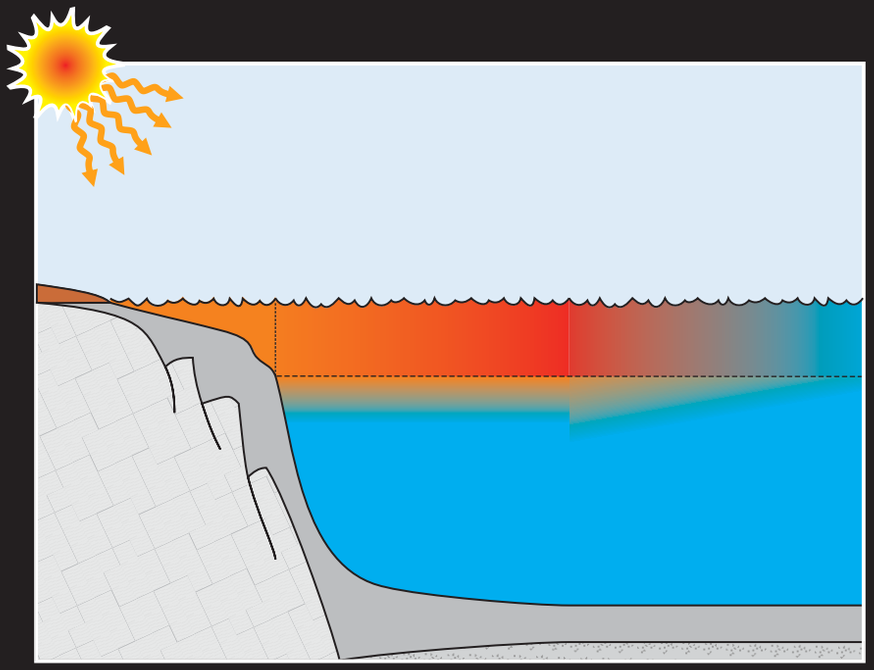
0 100 200 300 400 500 1000 1500 2000 2500 3000 3500

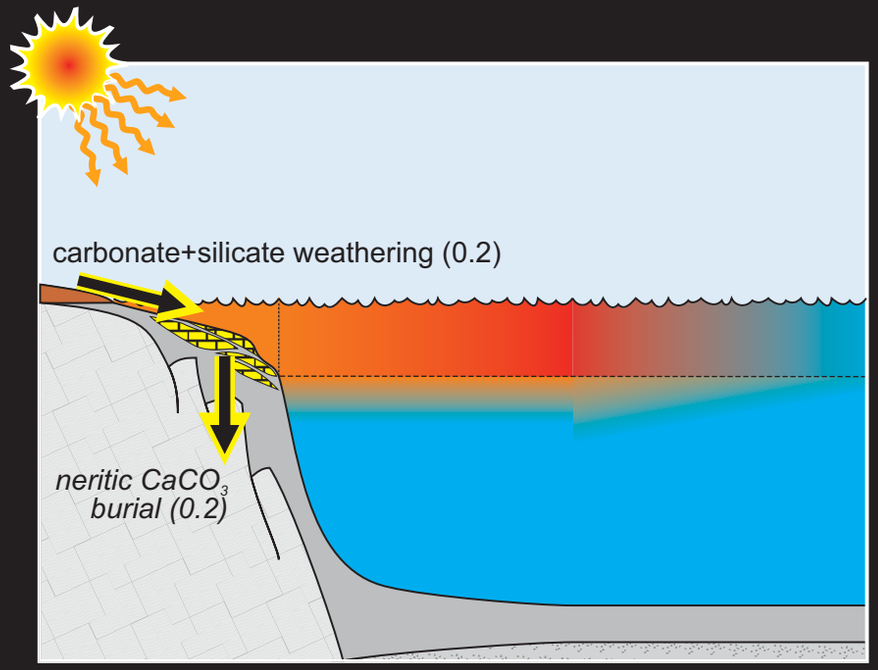
Time (Ma)

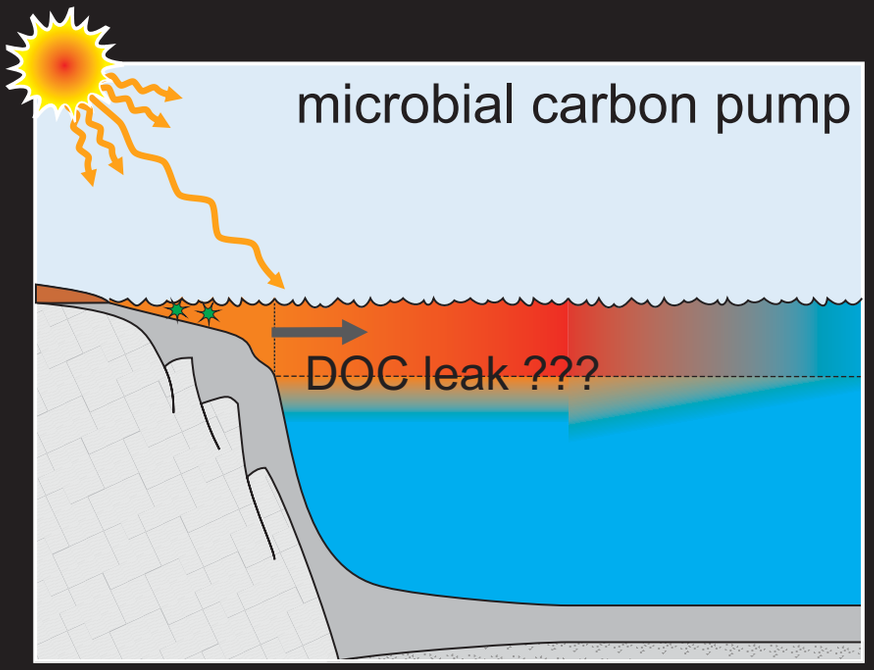
The Force awakens ... ???

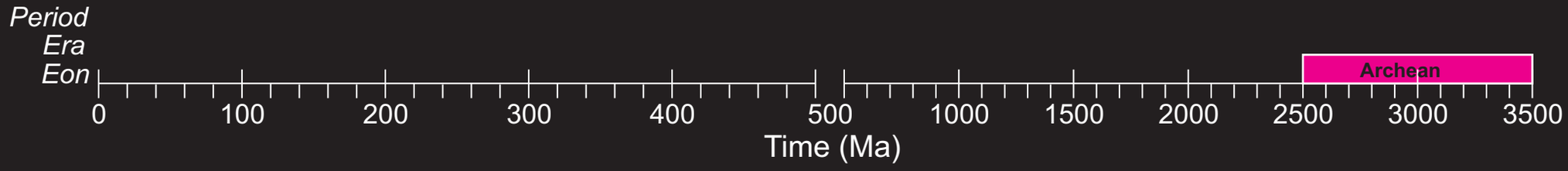



solubility pump
out-gassing (70)
in-gassing (70)
$pCO_{2(g)}$
warm
cold
pCO_2
pCO_2
mixing
up-welling
down-welling

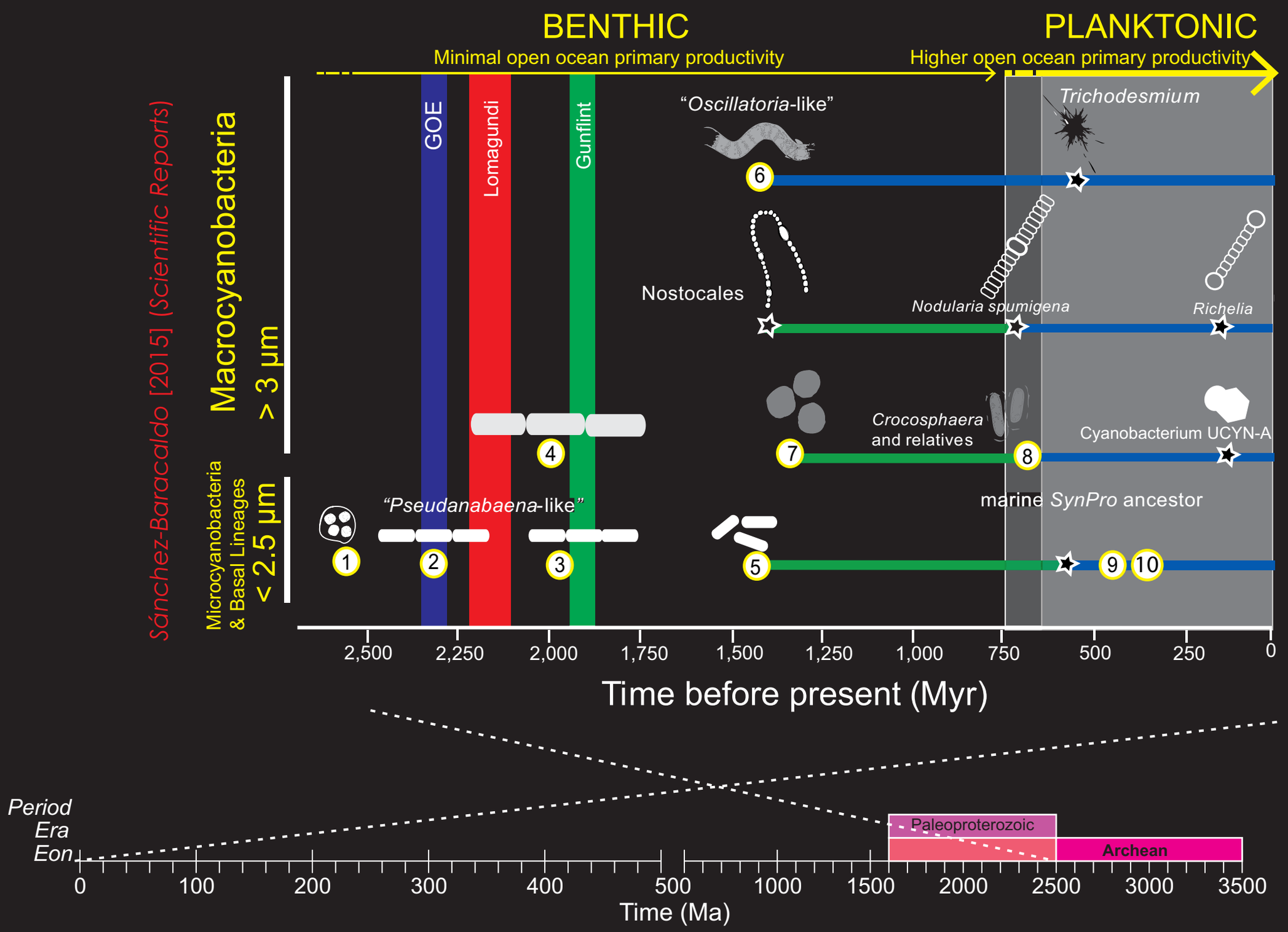


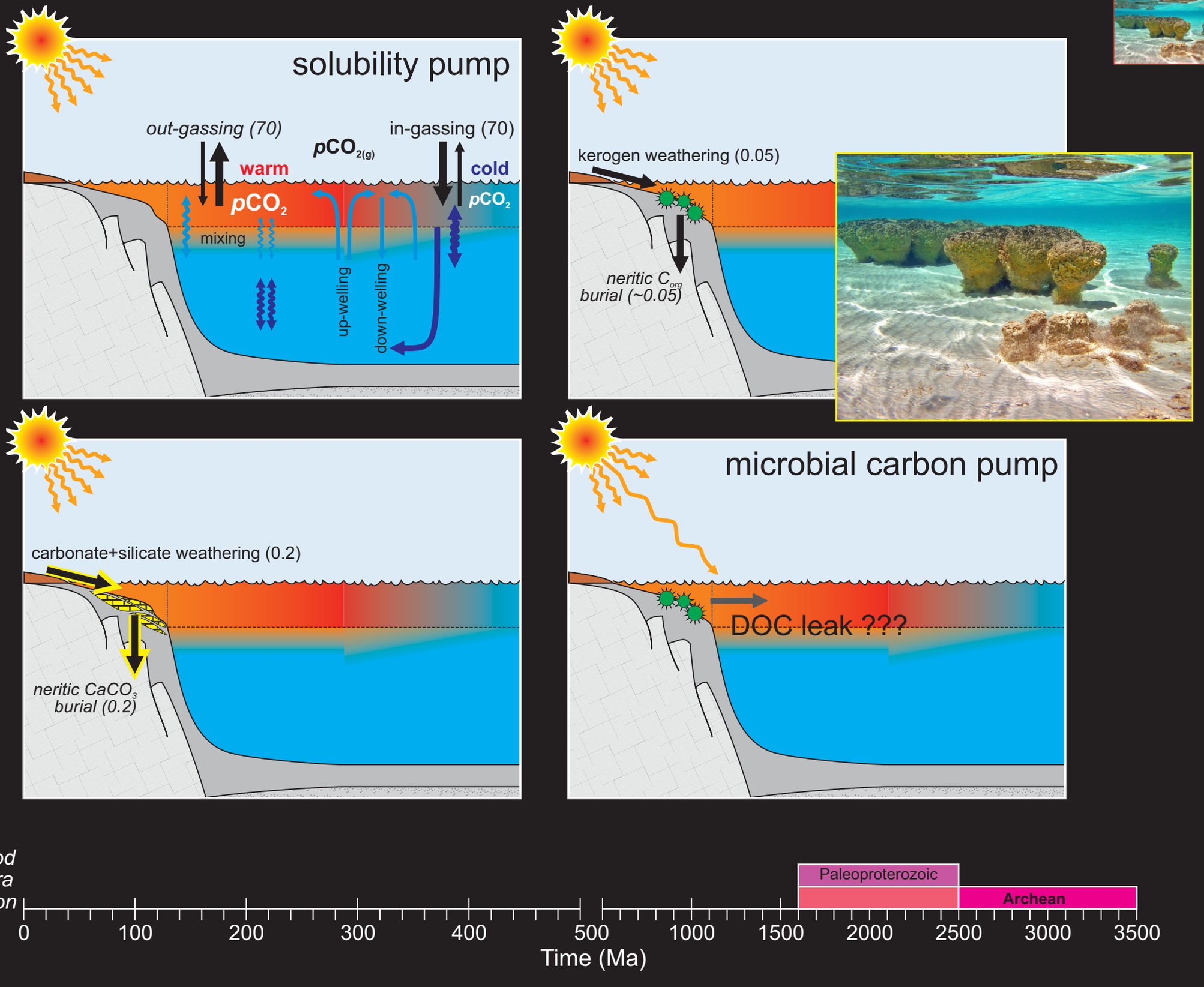

carbonate+silicate weathering (0.2)
neritic $CaCO_3$ burial (0.2)


microbial carbon pump
DOC leak ???

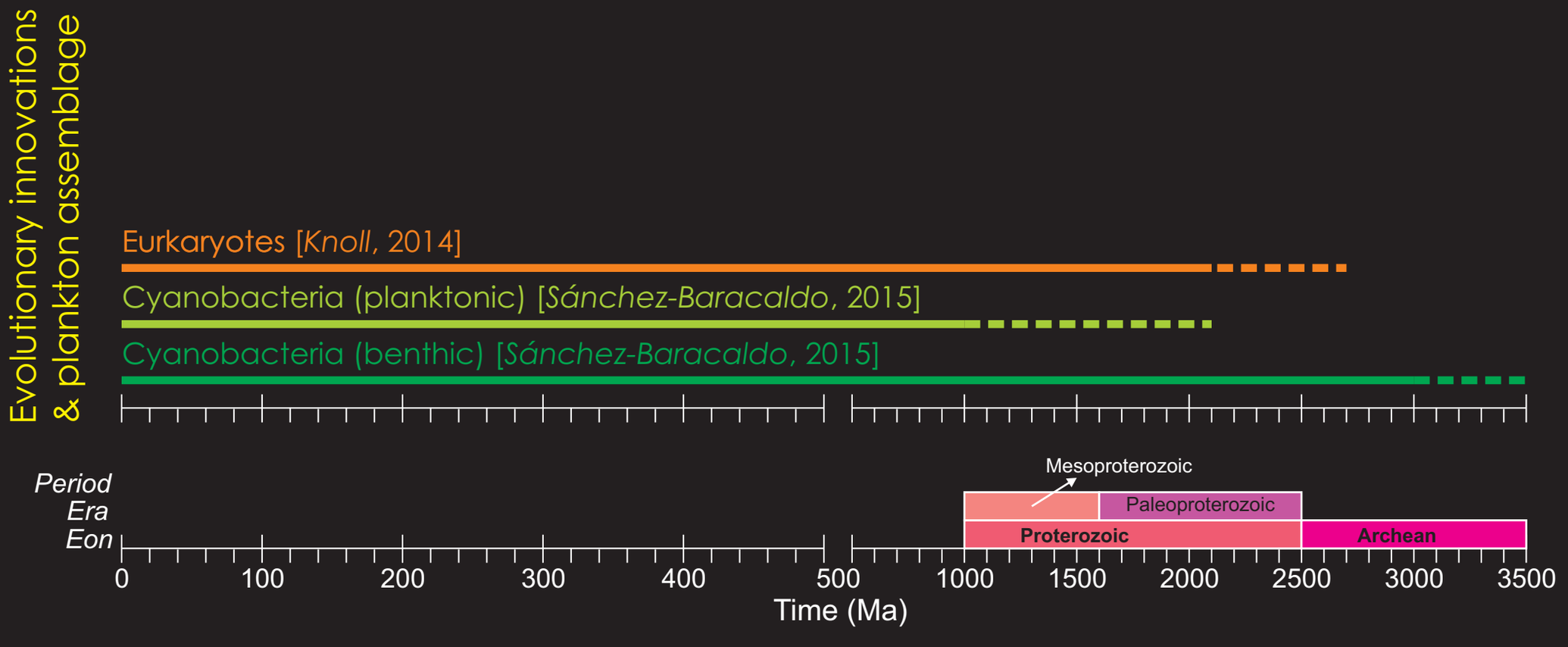

Period
Era
Eon
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

The Force awakens ... ???




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 (0.2)
microbial carbon pump
DOC leak ???
Period
Era
Eon
Paleoproterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

The Force awakens ... ???



solubility pump

?

organic carbon pump

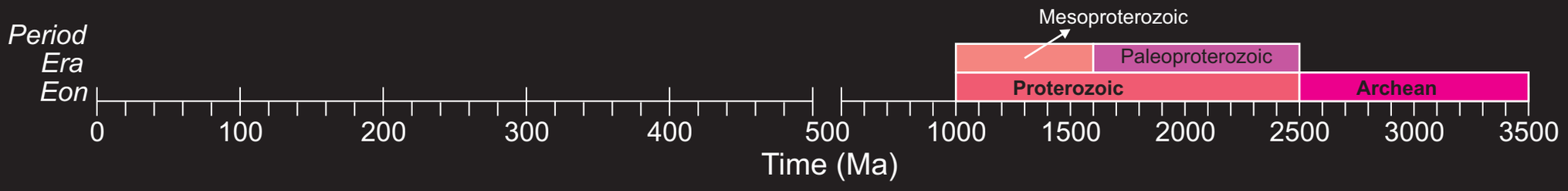
?

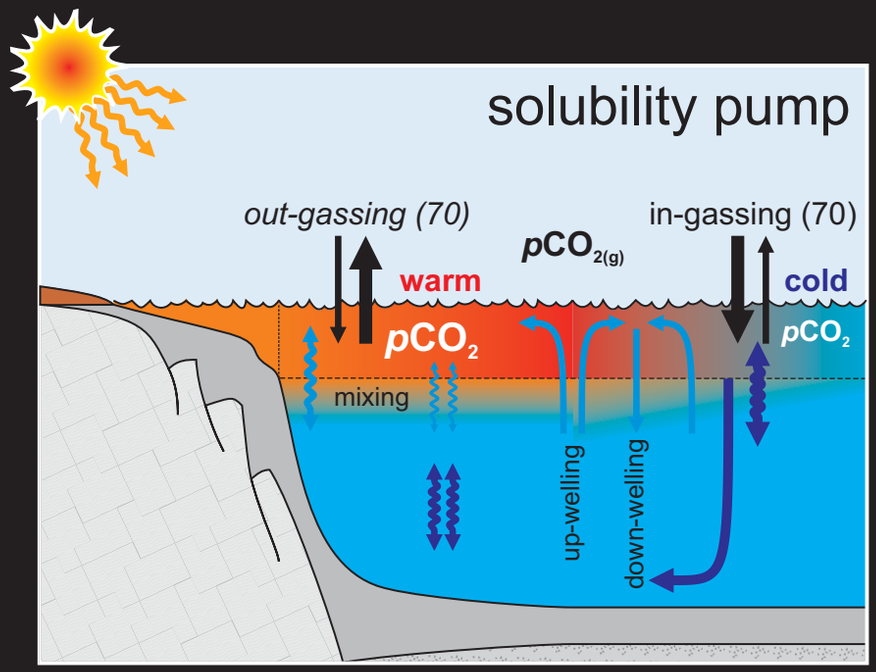
carbonate pump

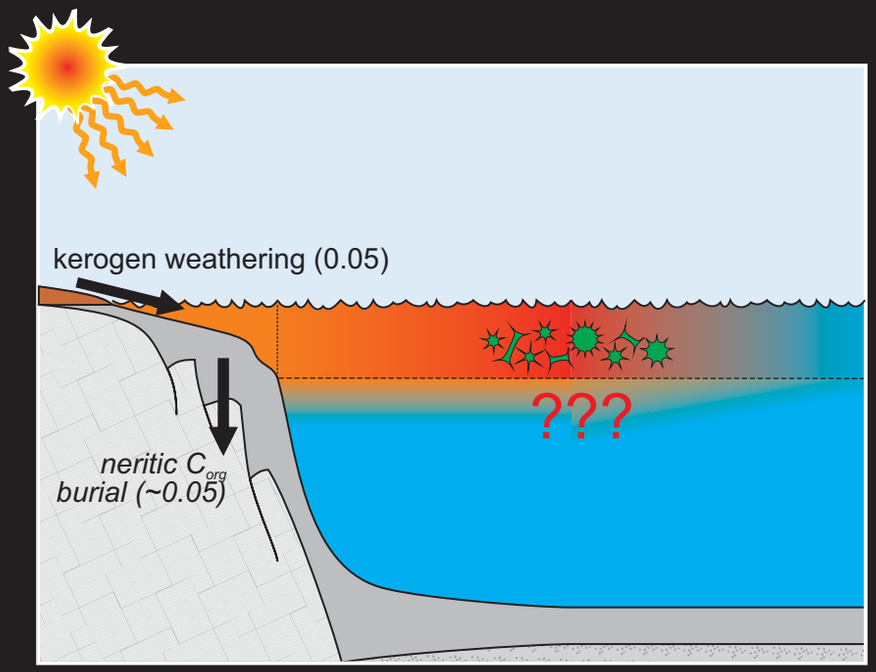
?

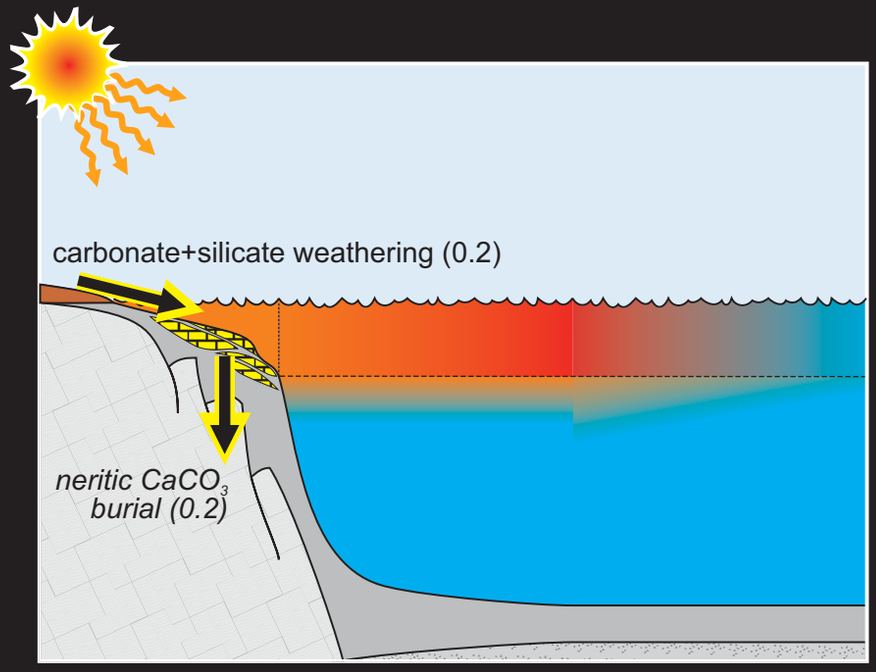
microbial carbon pump

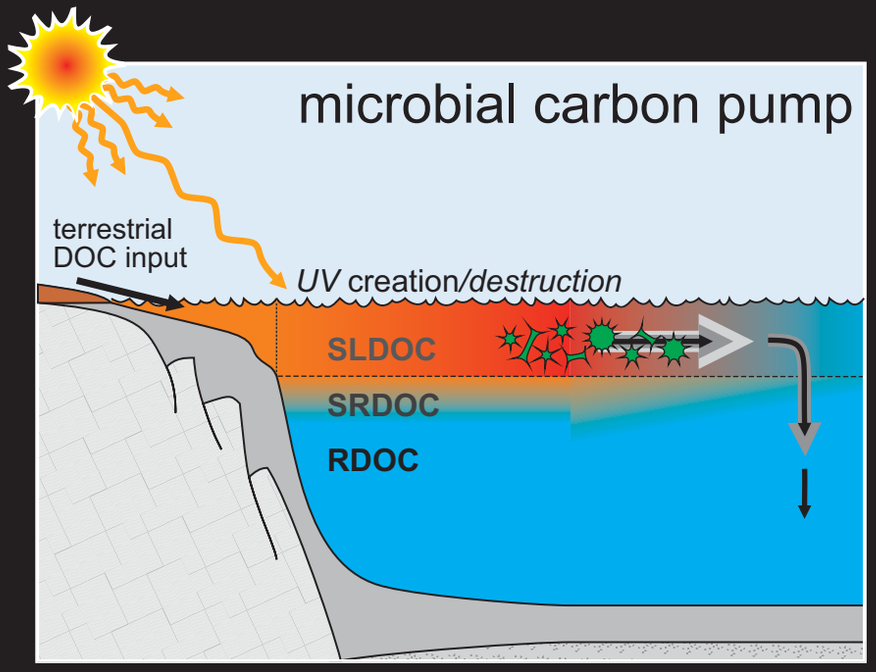
?

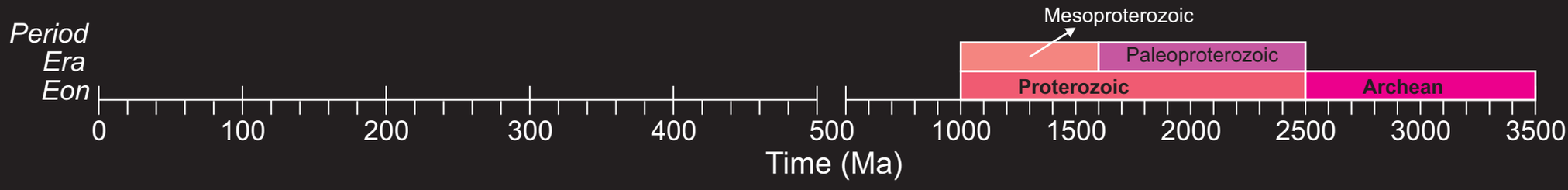


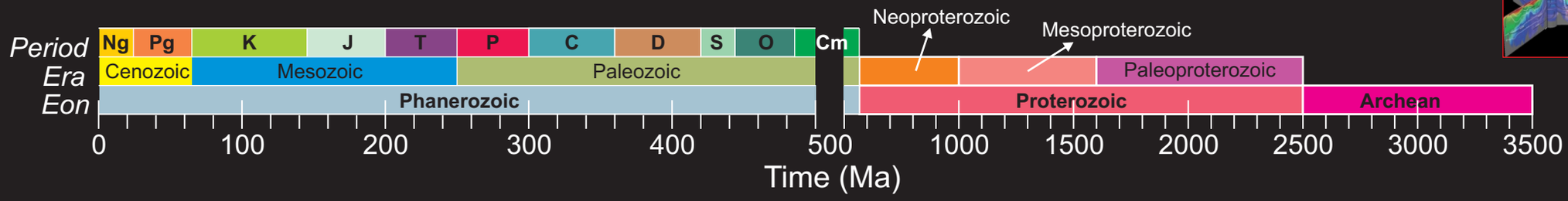

solubility pump
out-gassing (70)
in-gassing (70)
$pCO_{2(g)}$
warm
cold
pCO_2
pCO_2
mixing
up-welling
down-welling

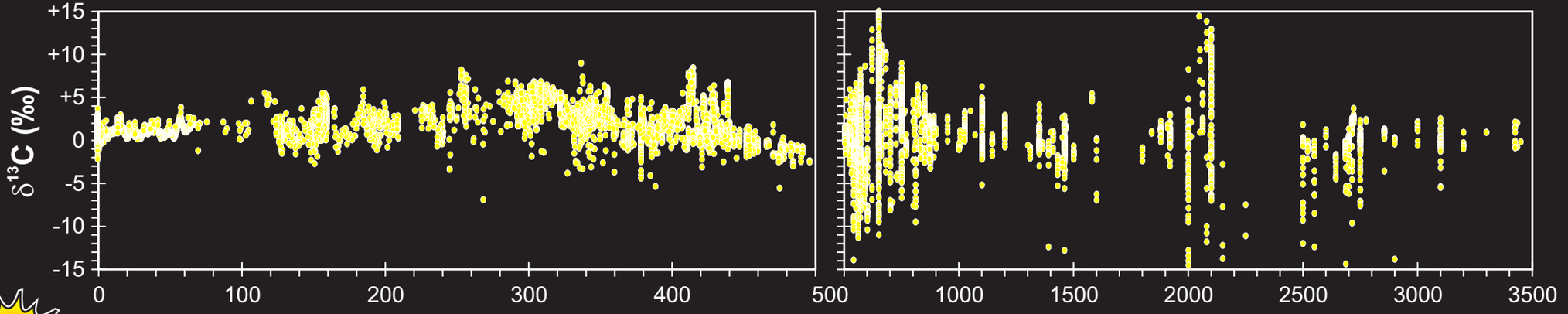

kerogen weathering (0.05)
???
neritic C_{org} burial (~0.05)

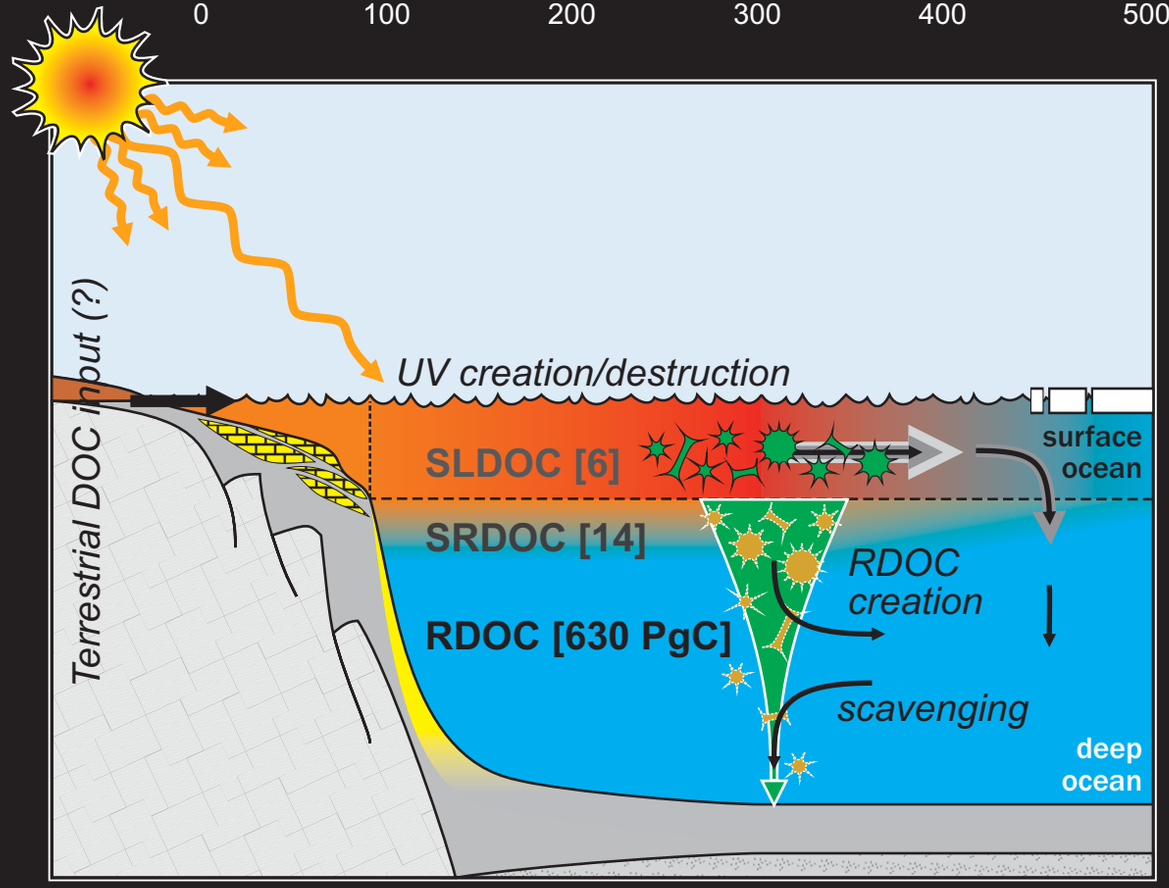

carbonate+silicate weathering (0.2)
neritic $CaCO_3$ burial (0.2)


microbial carbon pump
terrestrial DOC input
UV creation/destruction
SLDOC
SRDOC
RDOC

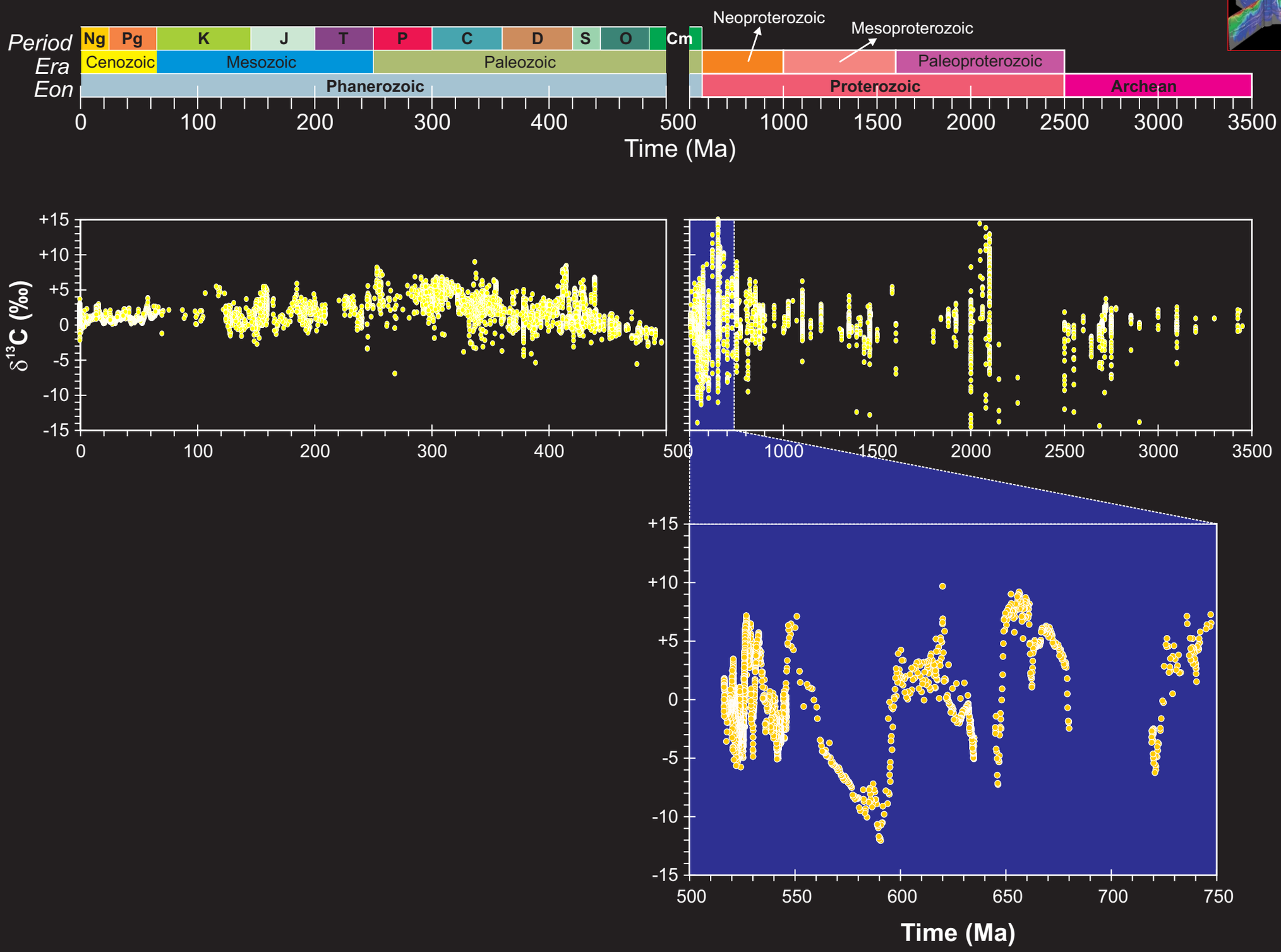

Period
Era
Eon
Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)





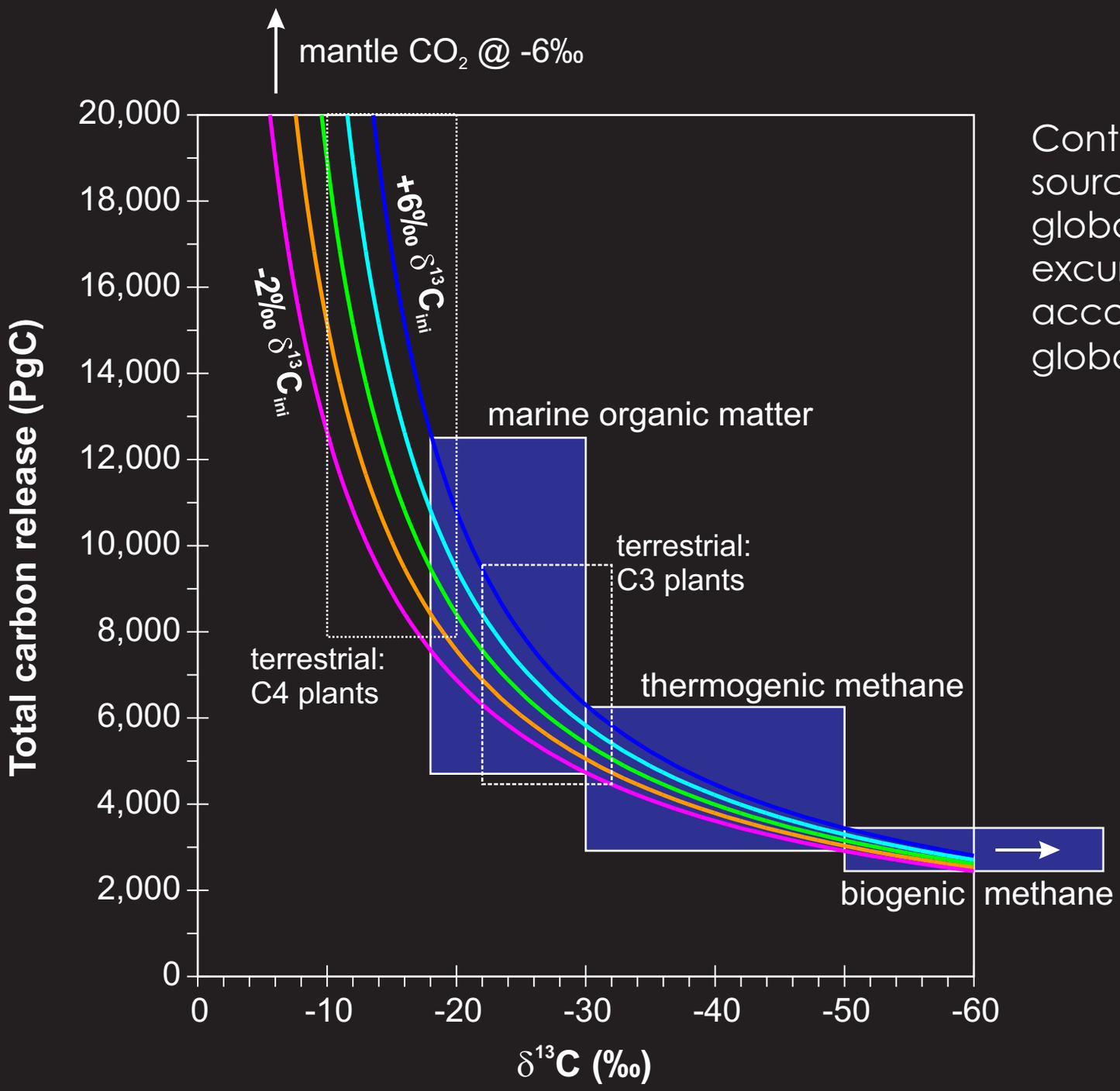


Ridgwell and Arndt [2014]



Ridgwell and Arndt [2014]

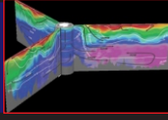
When RDOM ruled the World(?)

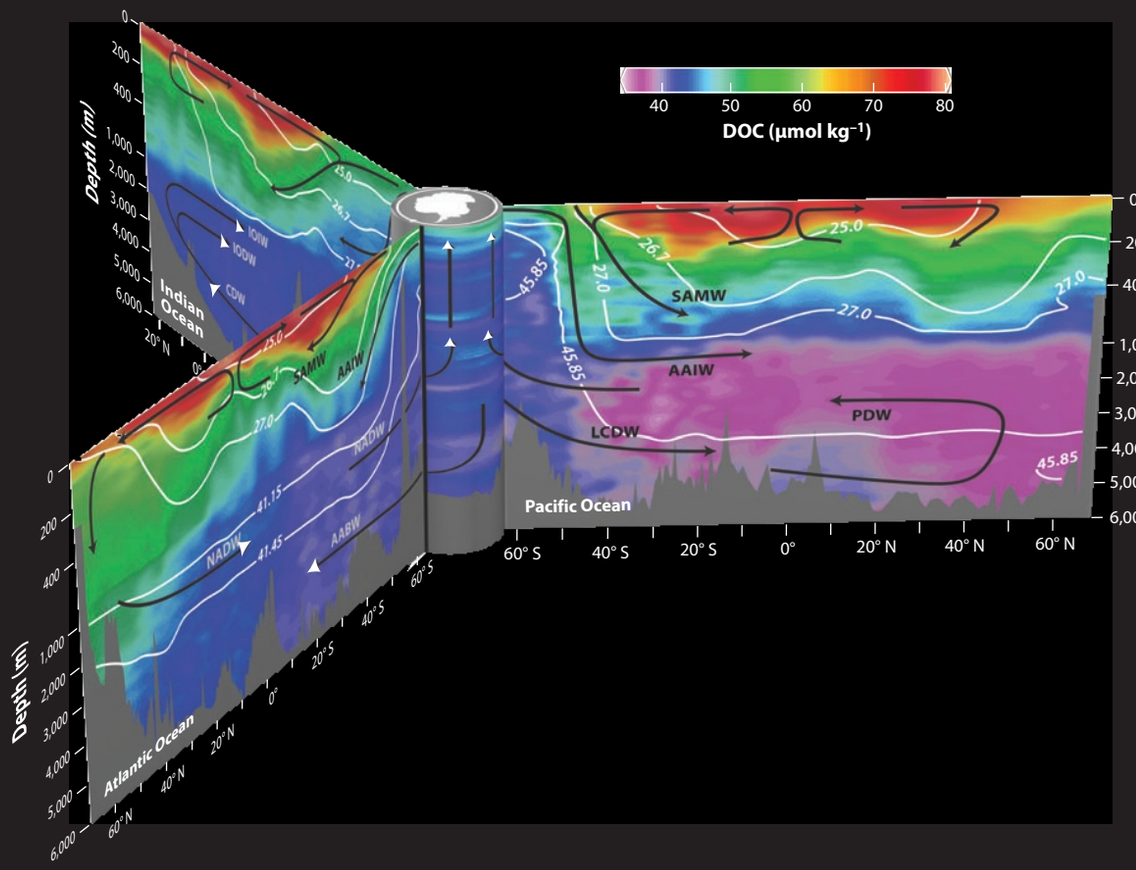


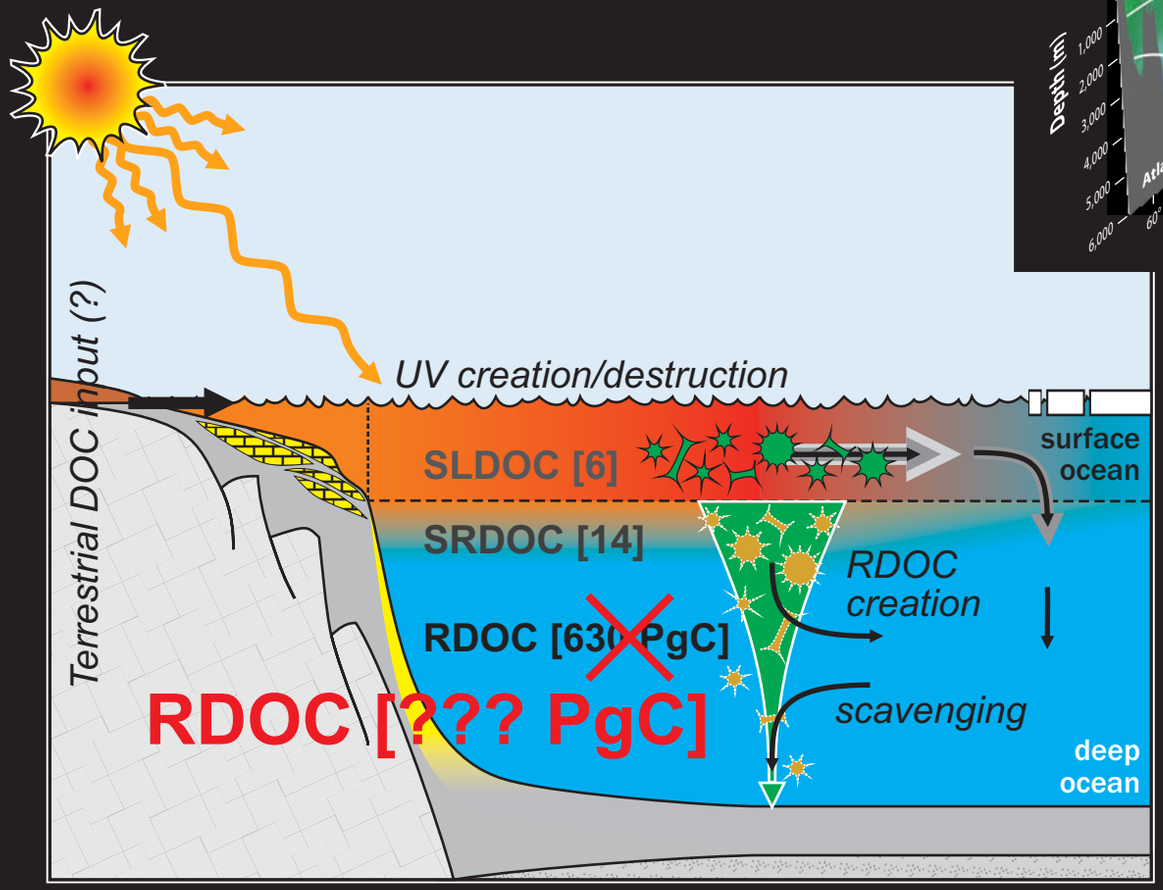
Contours of carbon release vs. source isotopic signature for a global -4‰ carbon isotopic excursion. Contours differ according to the initial mean global $\delta^{13}C$.

Ridgwell and Arndt [2014]

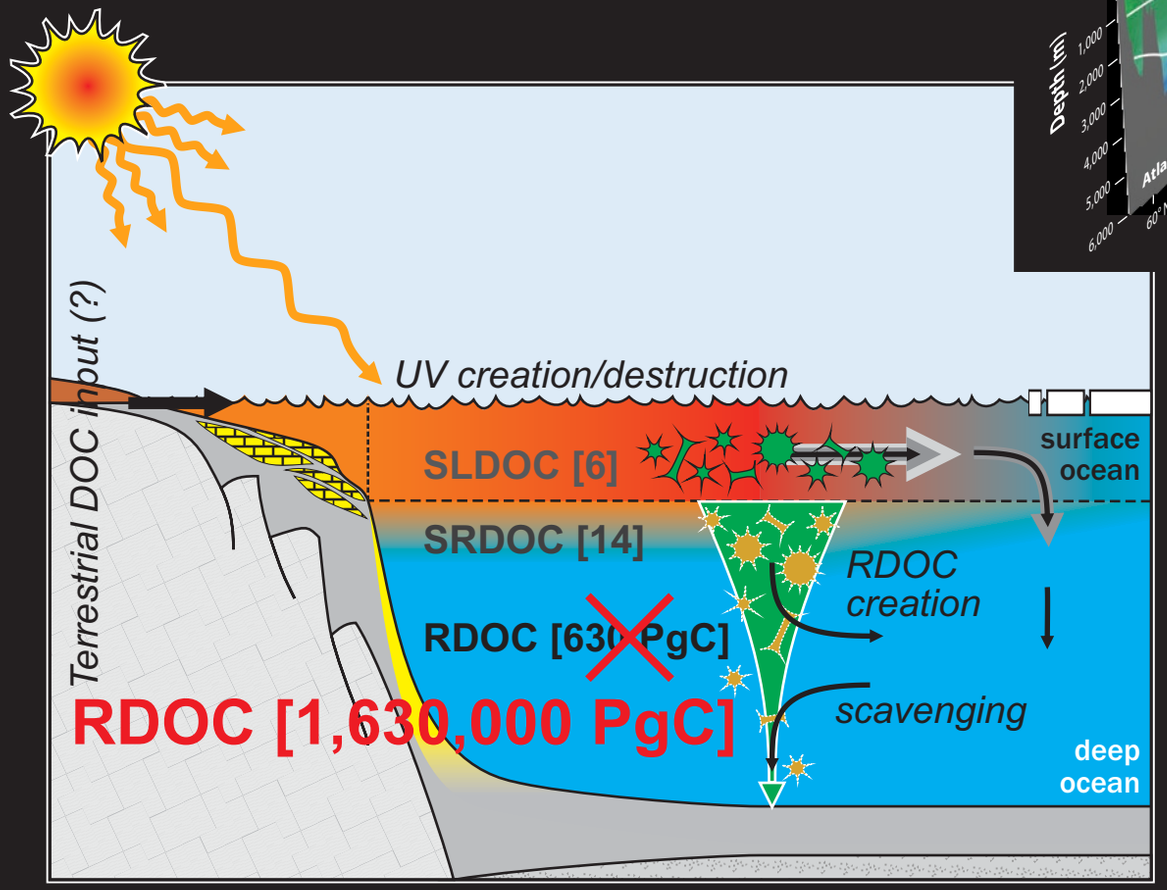
When RDOM ruled the World(?)

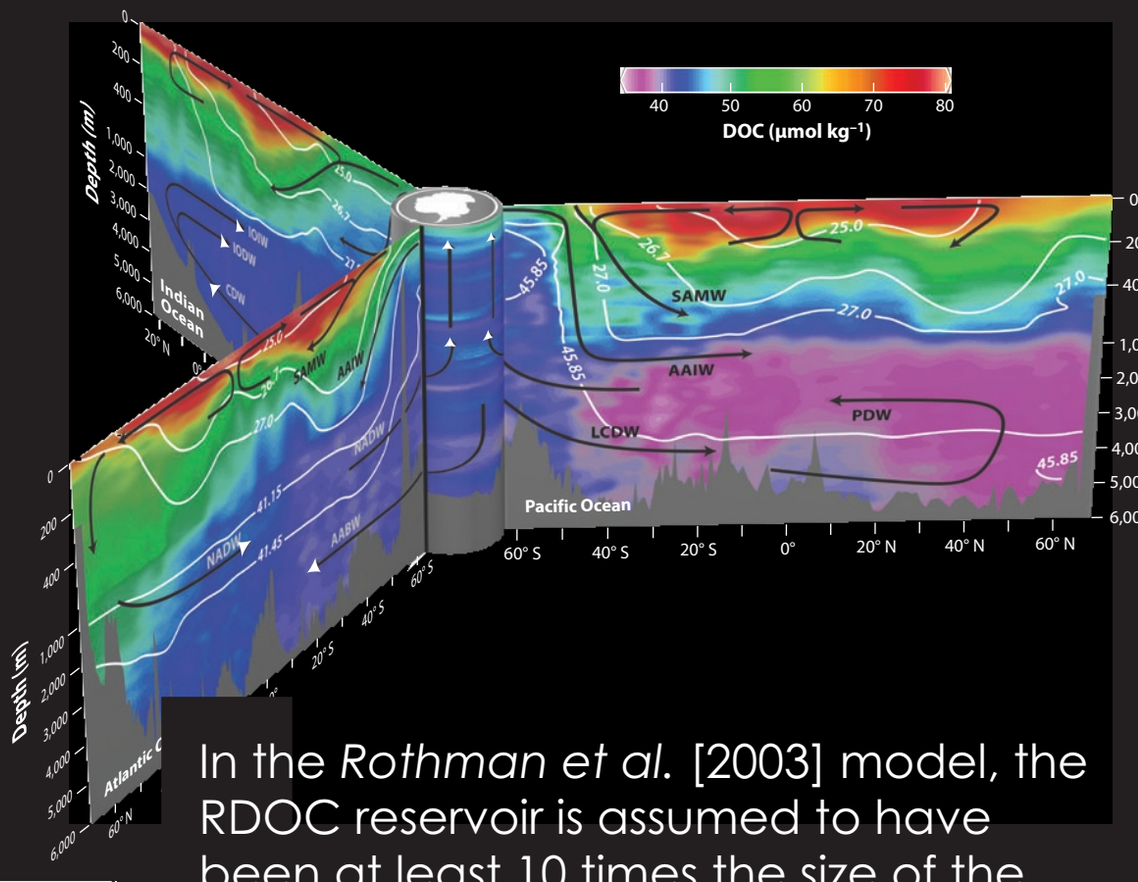






When RDOM ruled the World(?)

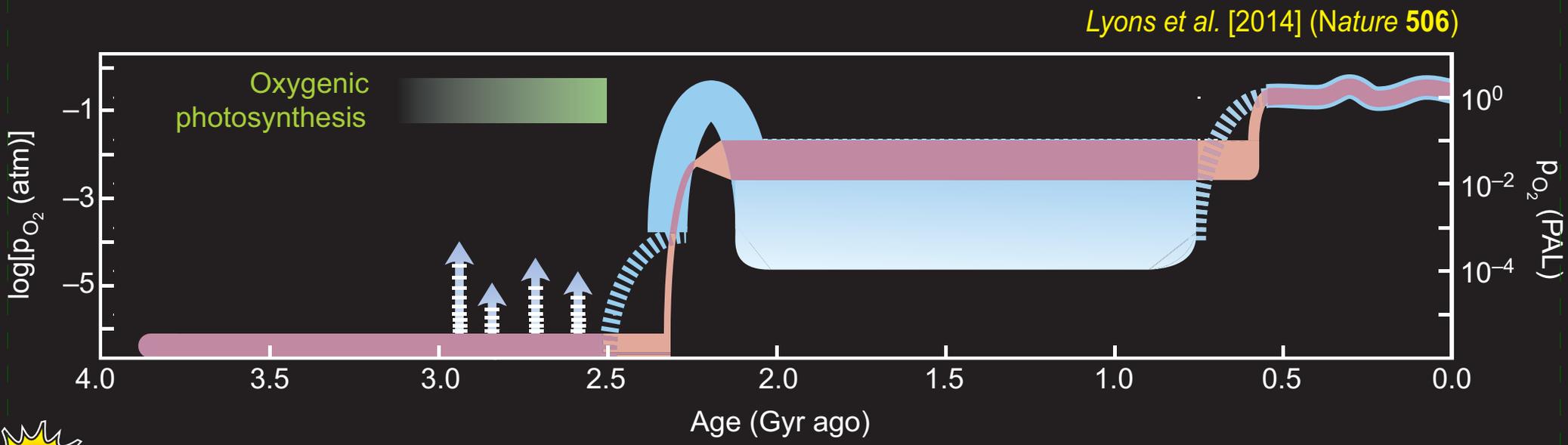


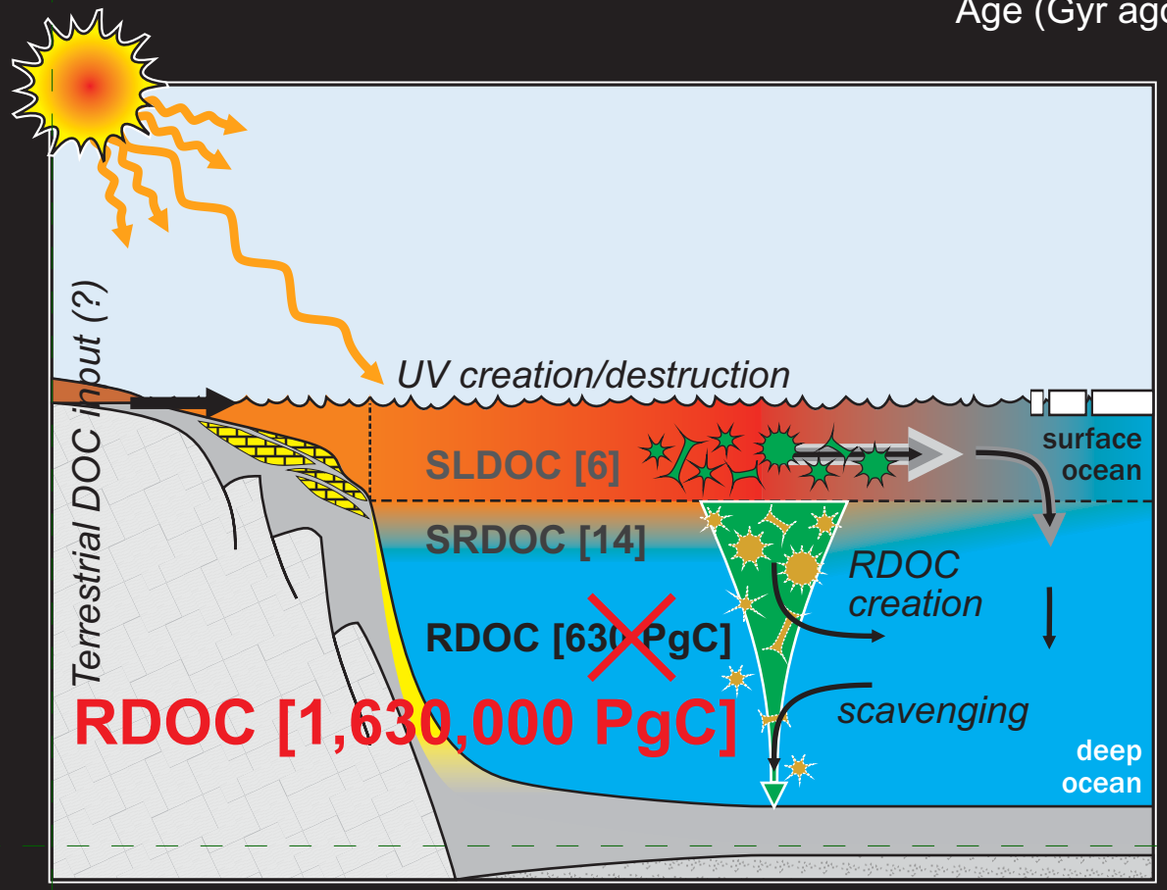


In the *Rothman et al.* [2003] model, the RDOC reservoir is assumed to have been at least 10 times the size of the inorganic (ocean DIC + atmospheric pCO_2) reservoir. For a modern DIC + pCO2 reservoir of 39,000 PgC, this mean 390,000 PgC of DOC – more than 500 times larger than modern).

(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^-.)

When RDOM ruled the World(?)





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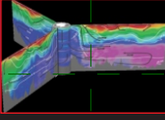
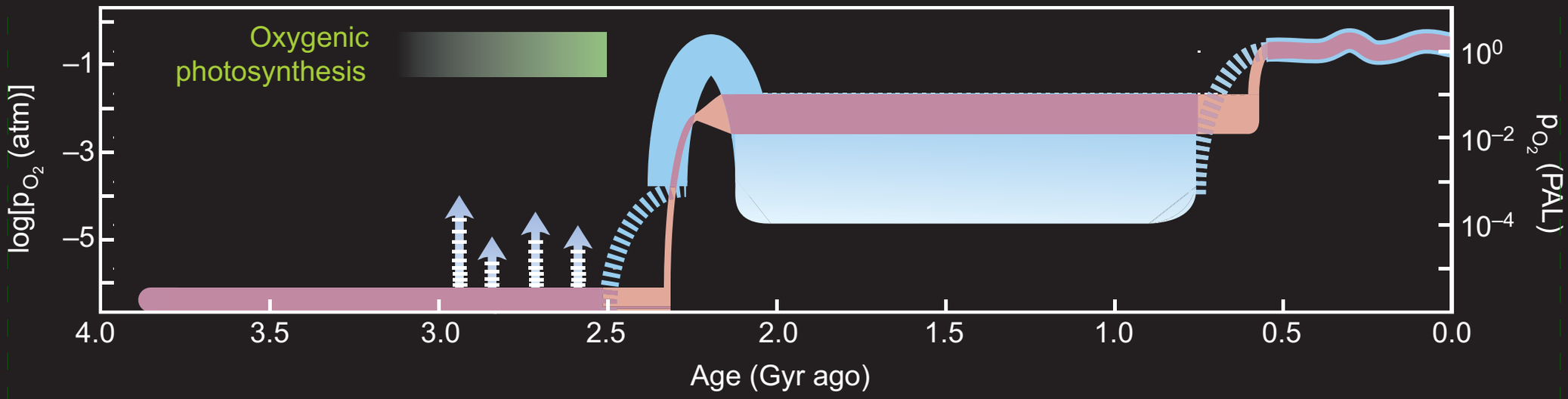
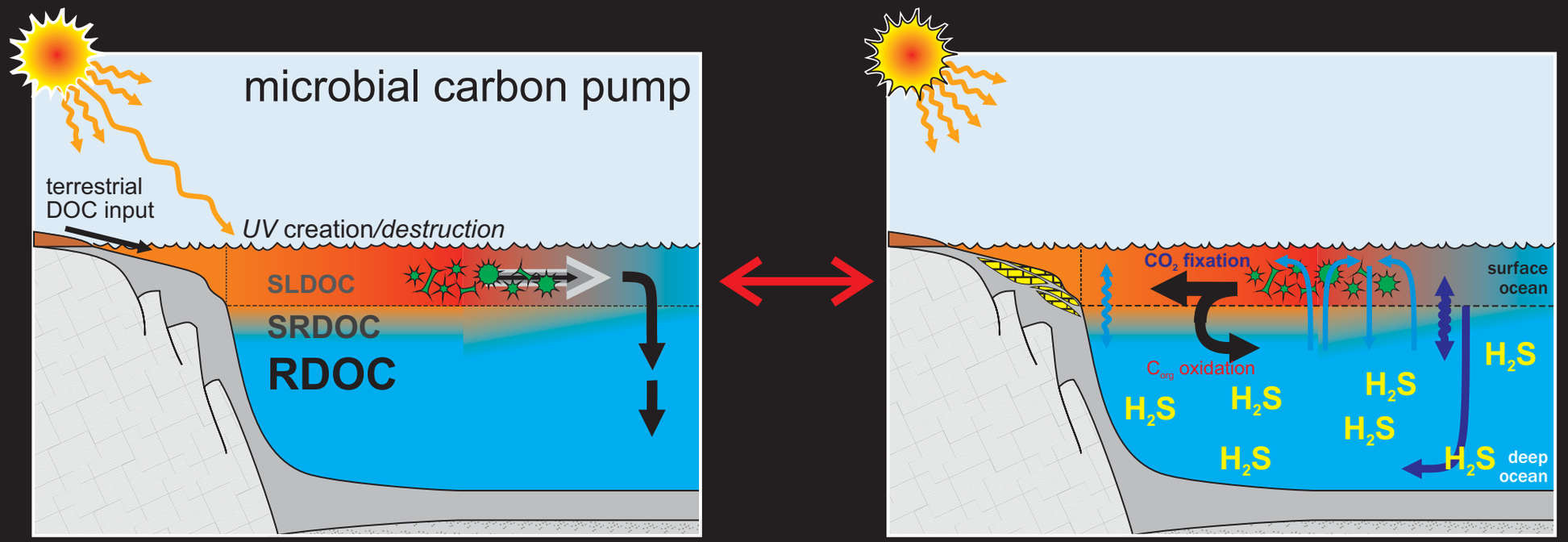
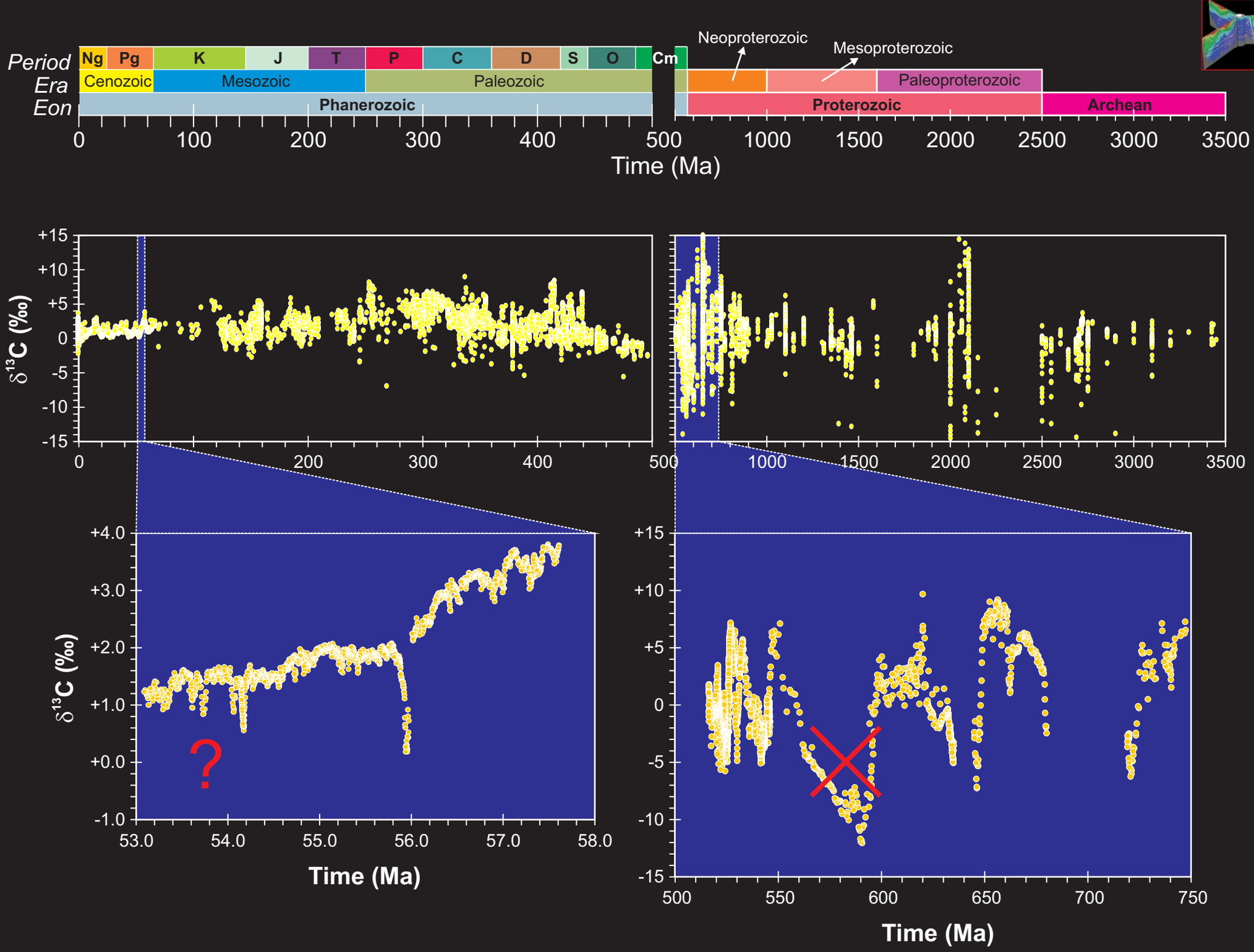
When RDOM ruled the World(?)



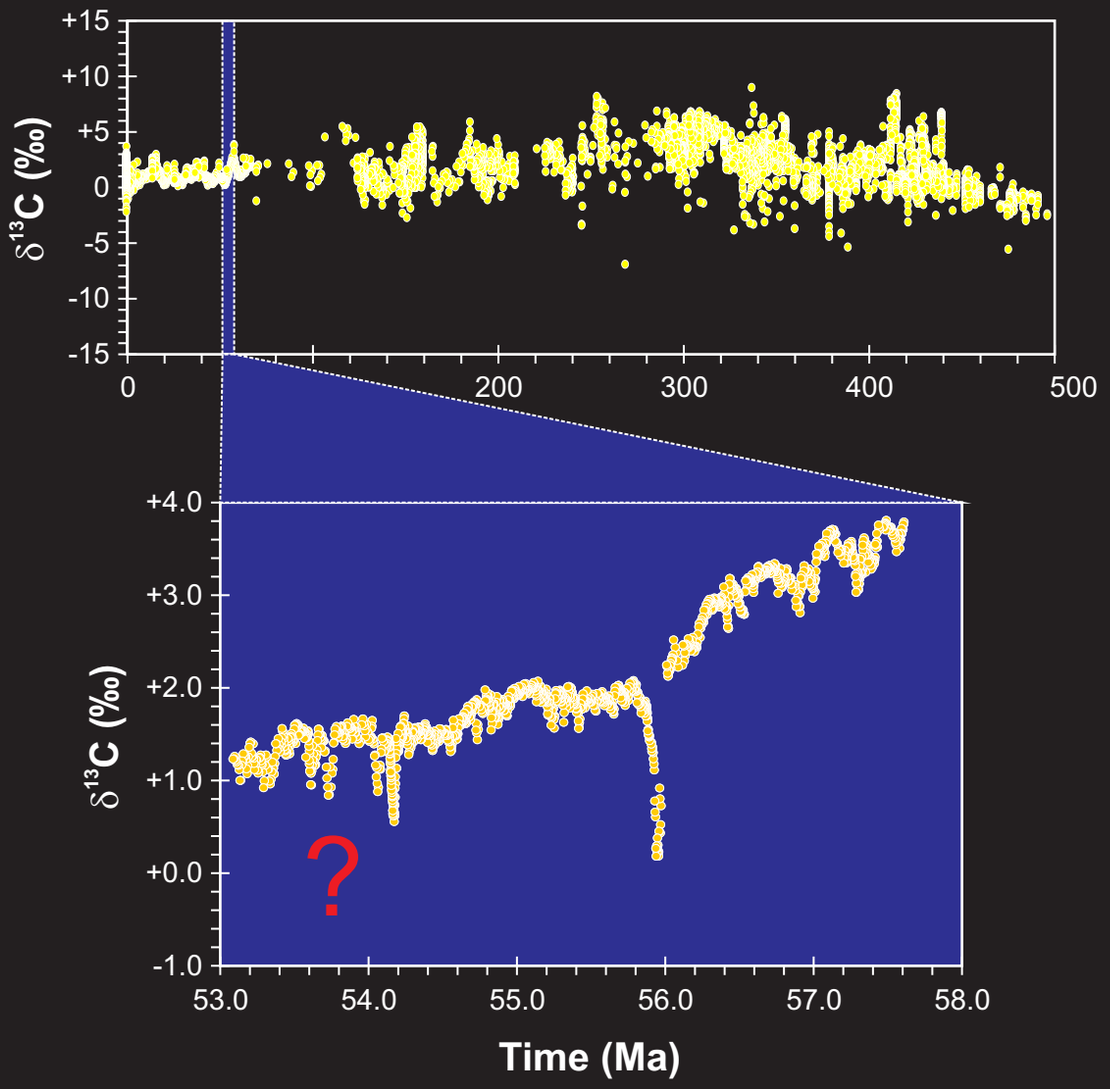
Lyons et al. [2014] (*Nature* **506**)

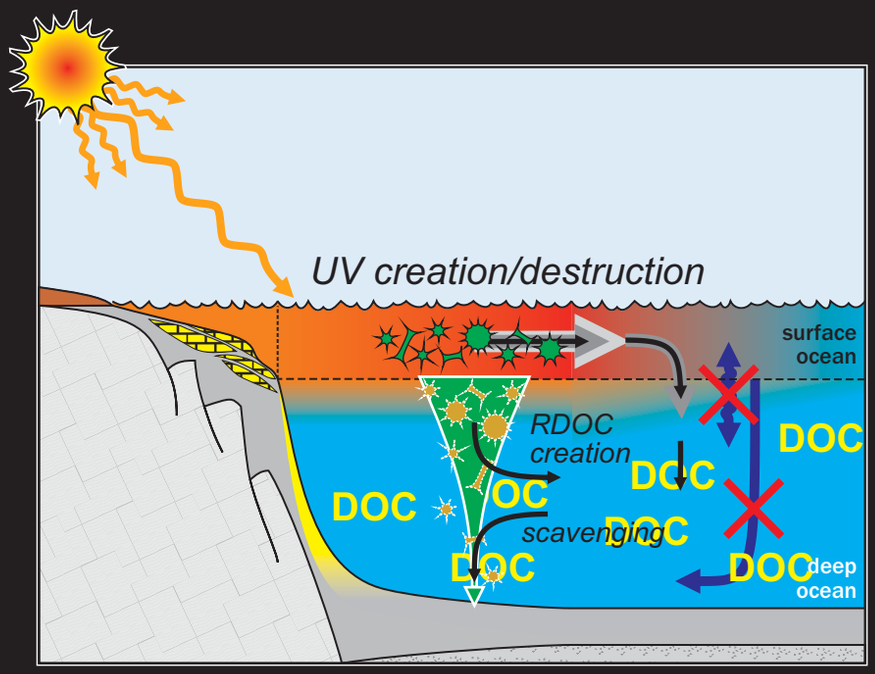





Period
Era
Eon
Ng
Pg
K
J
T
P
C
D
S
O
Cm
Cenozoic
Mesozoic
Paleozoic
Phanerozoic
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)
δ13C (‰)
+15
+10
+5
0
-5
-10
-15
+4.0
+3.0
+2.0
+1.0
+0.0
-1.0
53.0
54.0
55.0
56.0
57.0
58.0
?
Time (Ma)
500
550
600
650
700
750
Time (Ma)

When RDOM ruled the World(?)



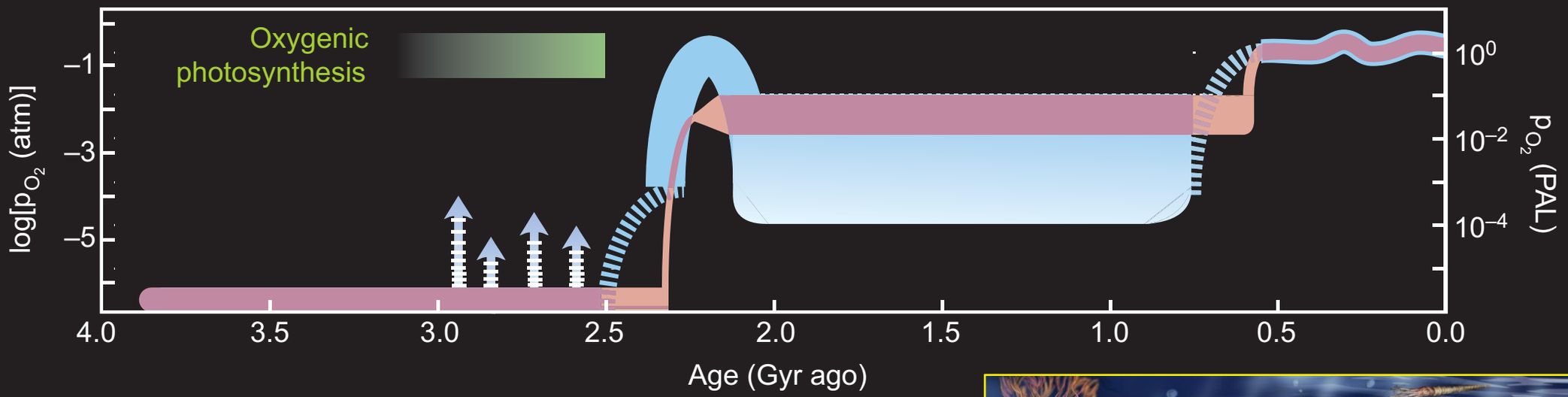


Sexton et al. [2011]

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-dedregation.

The Force awakens ... for sure this time ... ???

Lyons et al. [2014] (*Nature* **506**)



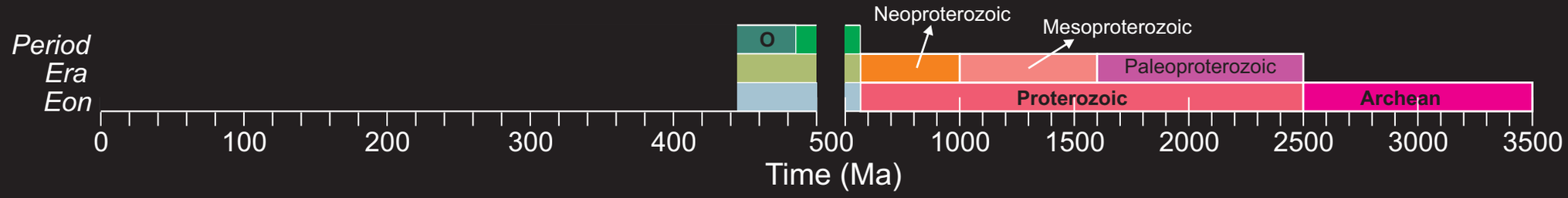
Evolutionary innovations & plankton assemblage

Animals! (metzoans)

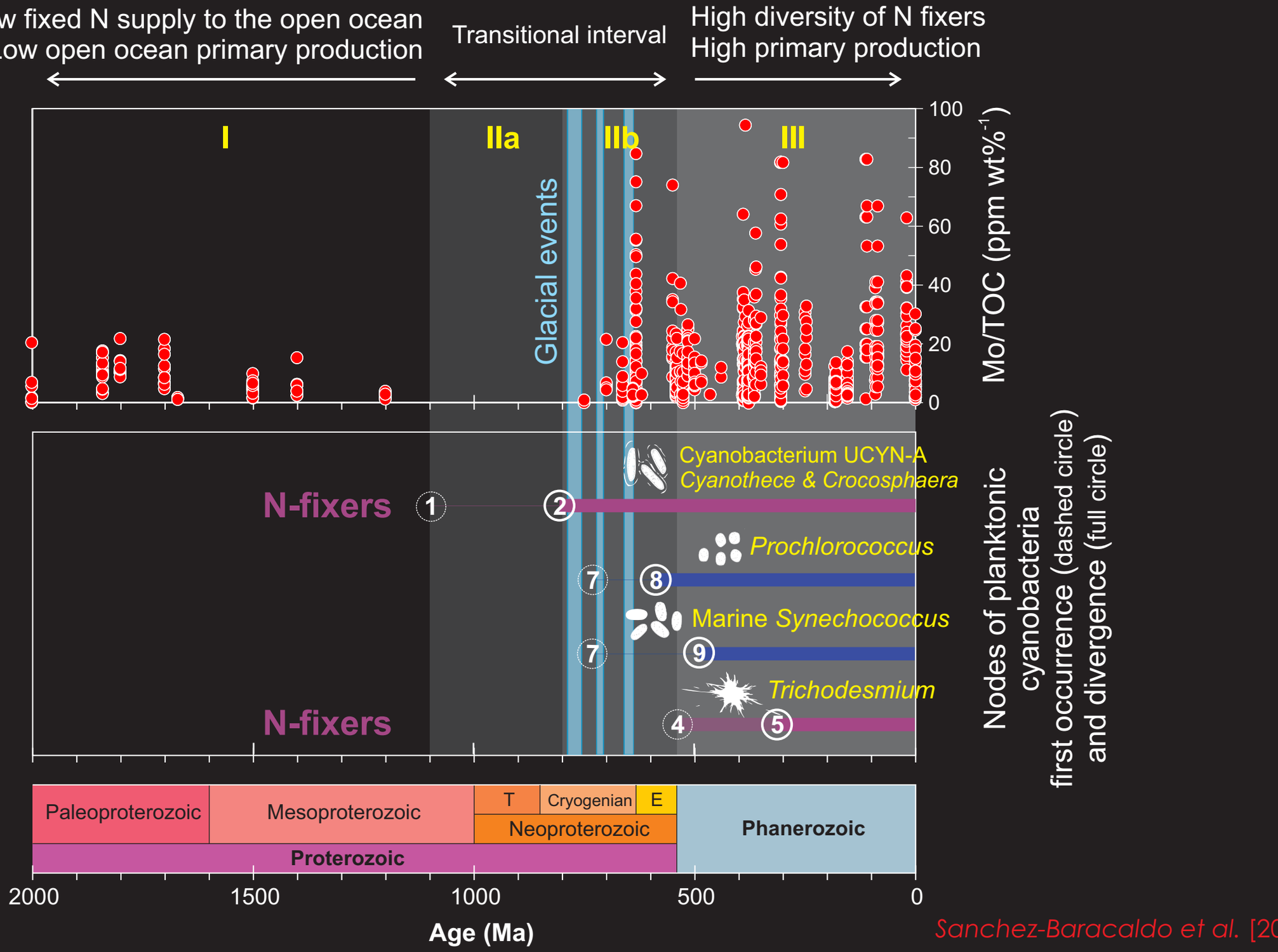
Eurkaryotes [*Knoll*, 2014]

Cyanobacteria (planktonic) [*Sánchez-Baracaldo*, 2015]

Cyanobacteria (benthic) [*Sánchez-Baracaldo*, 2015]



The Force awakens ... for sure this time ... ???



Sanchez-Baracaldo et al. [2014]

solubility pump

?

organic carbon pump

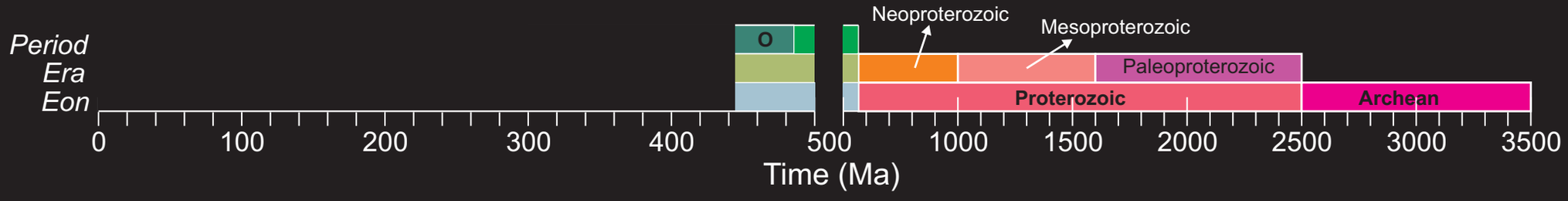
?

carbonate pump

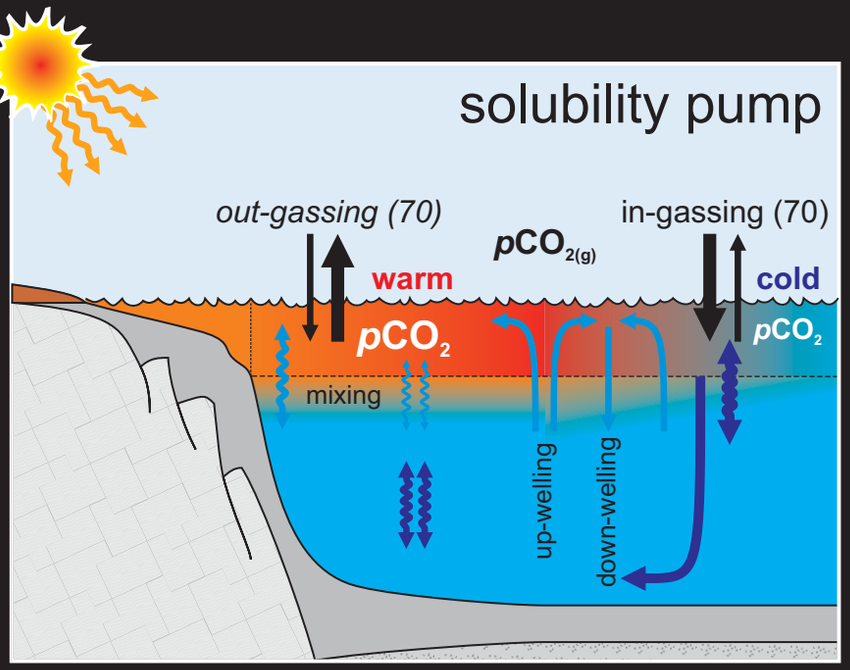
?

microbial carbon pump

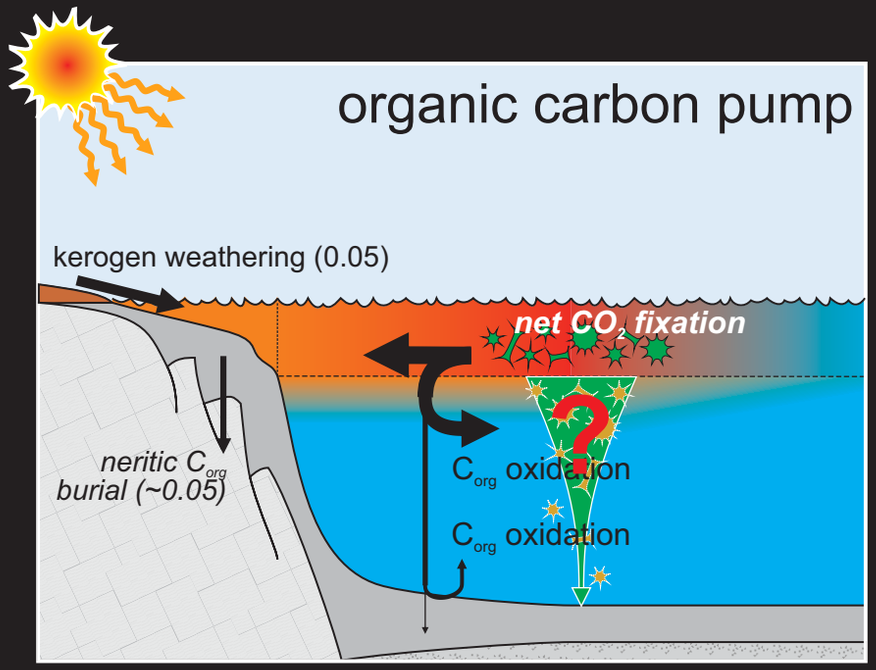
?

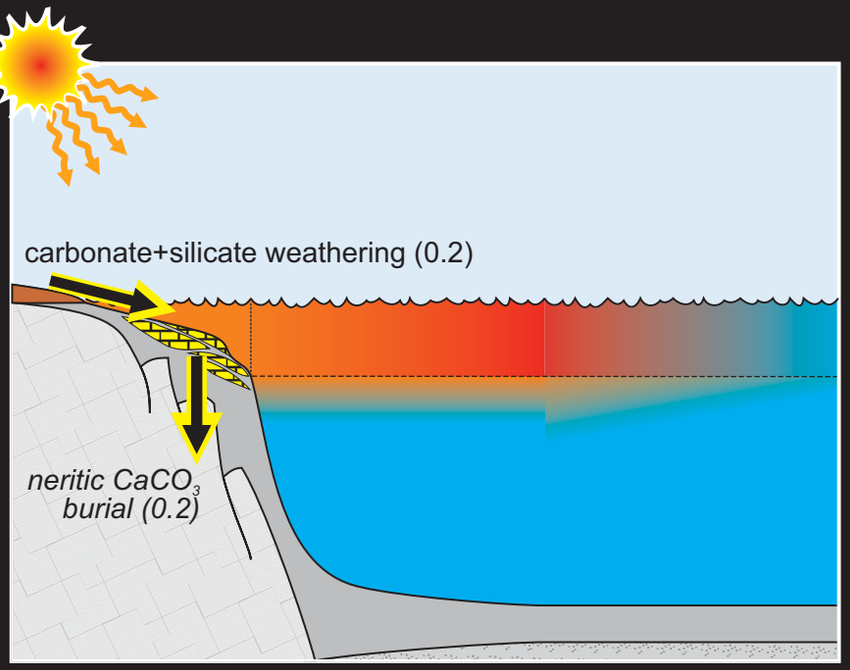


solubility pump

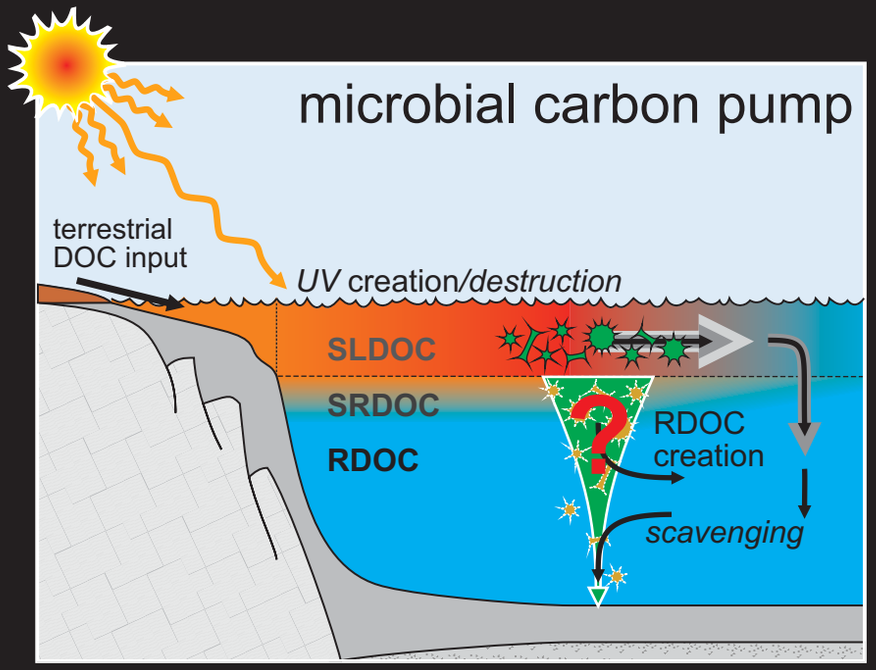


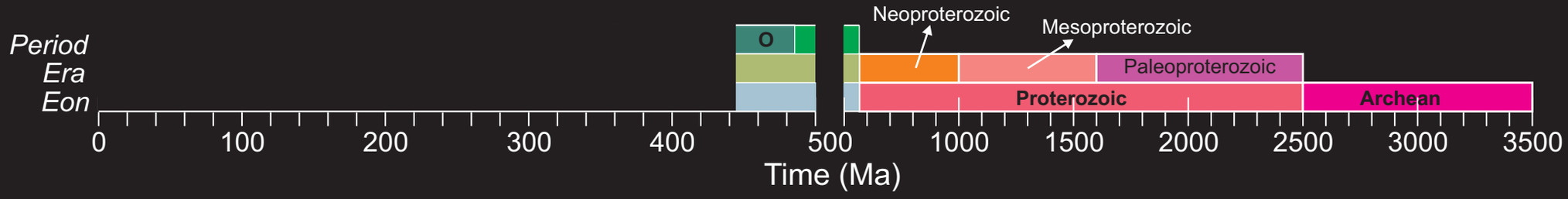
organic carbon pump

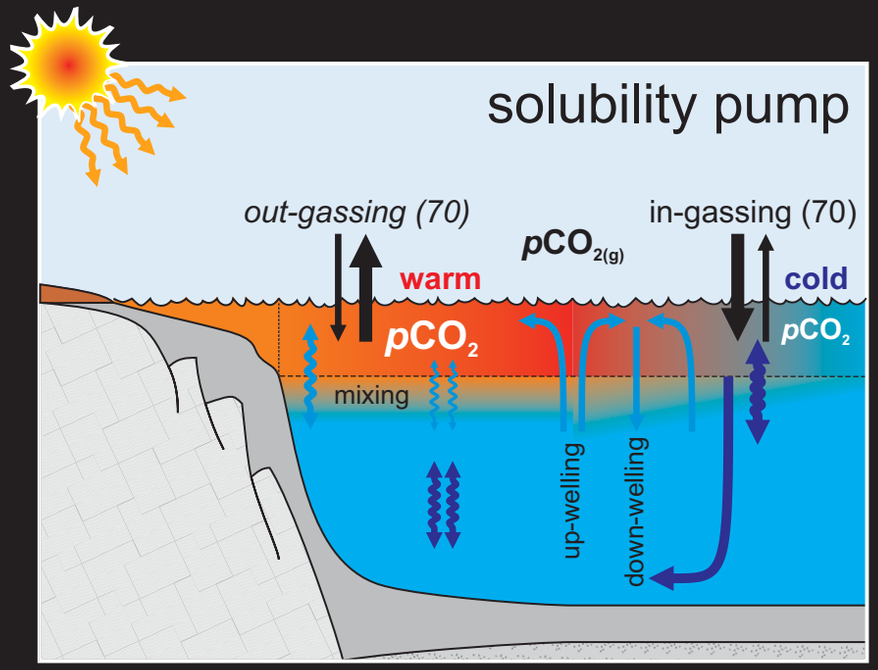


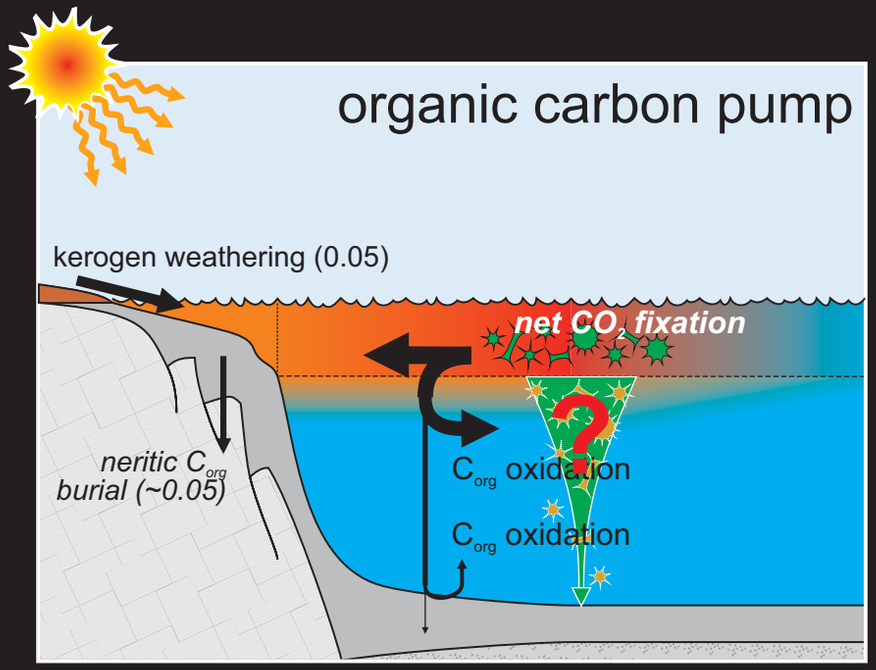


microbial carbon pump

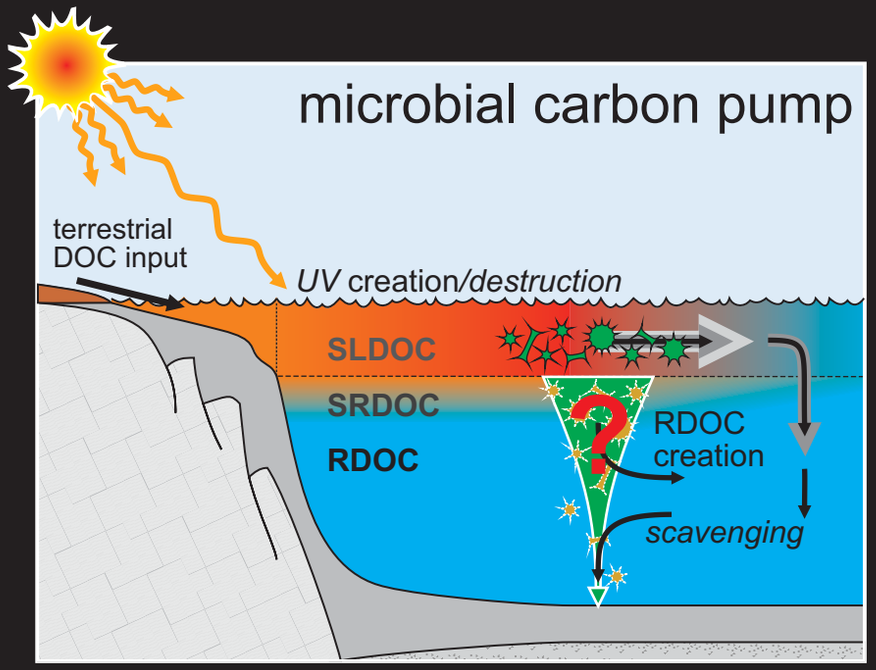


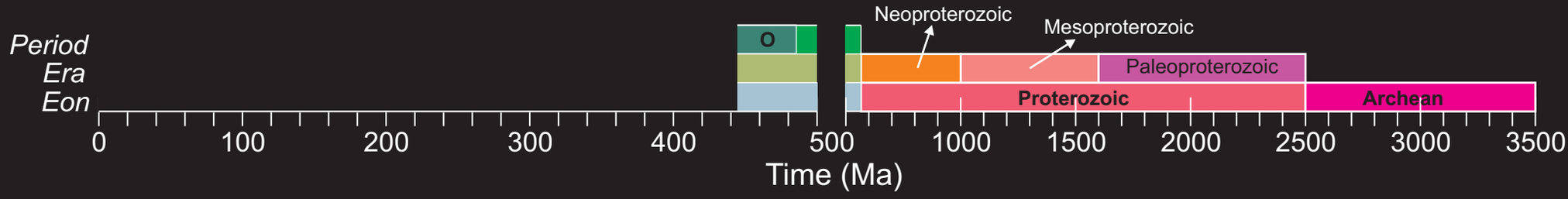


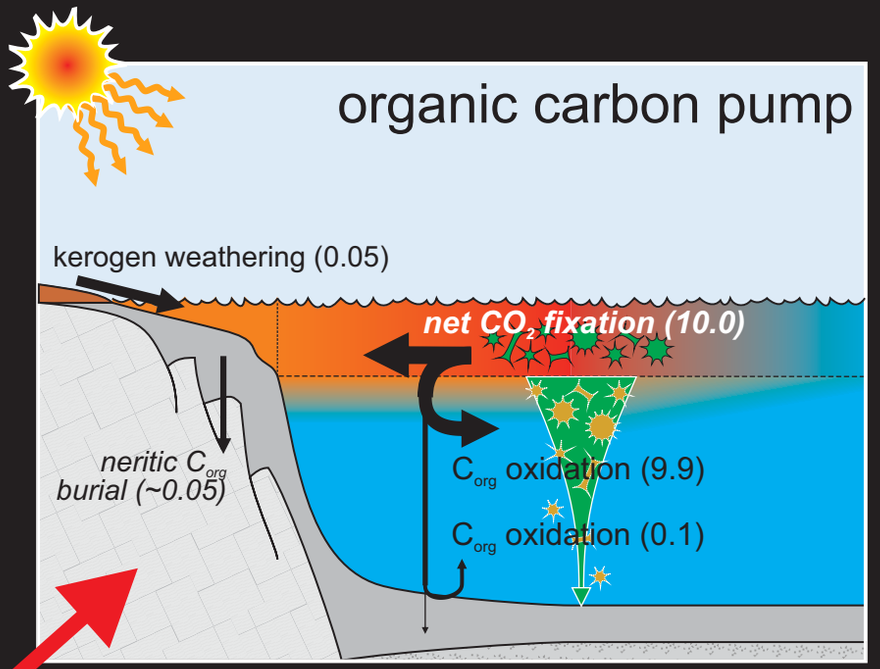

solubility pump
out-gassing (70)
in-gassing (70)
$pCO_{2(g)}$
warm
cold
pCO_2
pCO_2
mixing
up-welling
down-welling


organic carbon pump
kerogen weathering (0.05)
net CO_2 fixation
neritic C_{org} burial (~0.05)
C_{org} oxidation
C_{org} oxidation

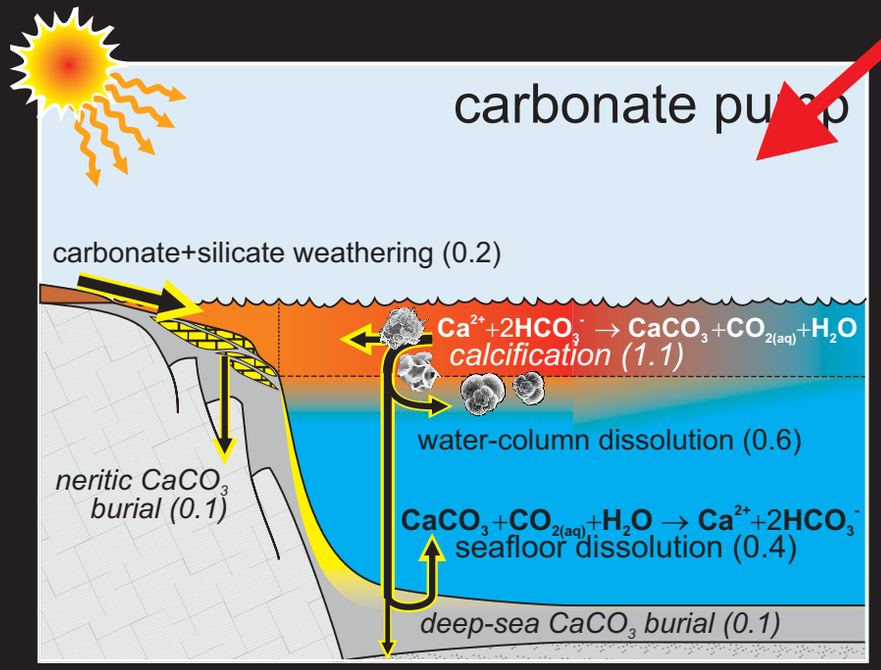

carbonate pump
?

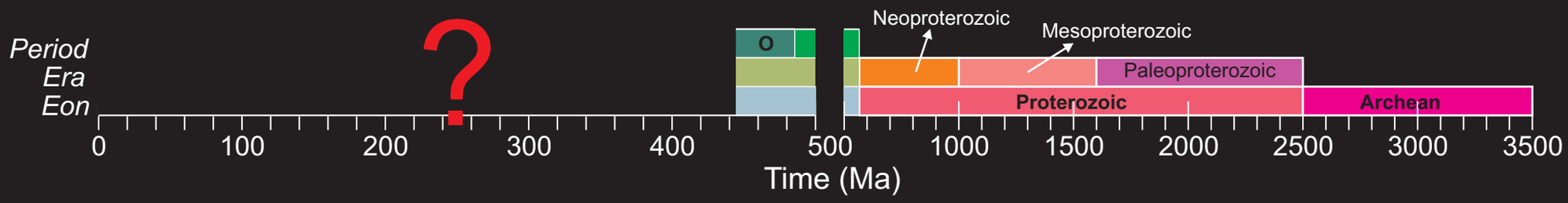

microbial carbon pump
terrestrial DOC input
UV creation/destruction
SLDOC
SRDOC
RDOC
RDOC creation
scavenging


Period
Era
Eon
O
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

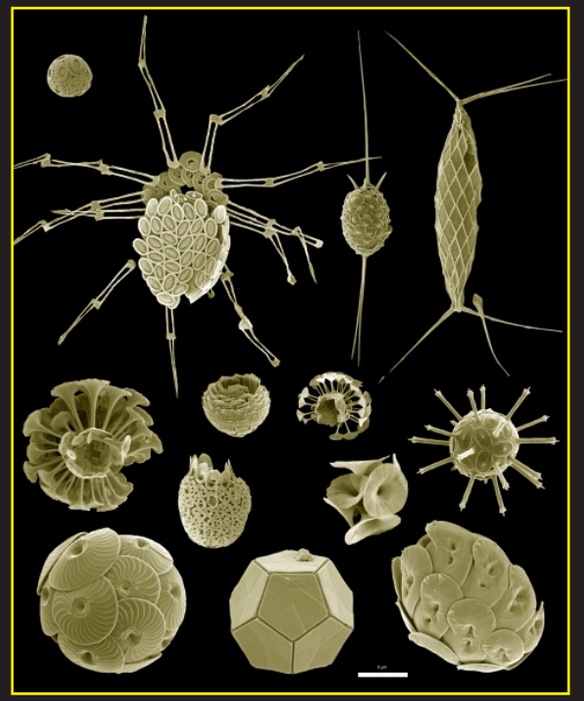

organic carbon pump
kerogen weathering (0.05)
net CO_2 fixation (10.0)
neritic C_{org} burial (~0.05)
C_{org} oxidation (9.9)
C_{org} oxidation (0.1)

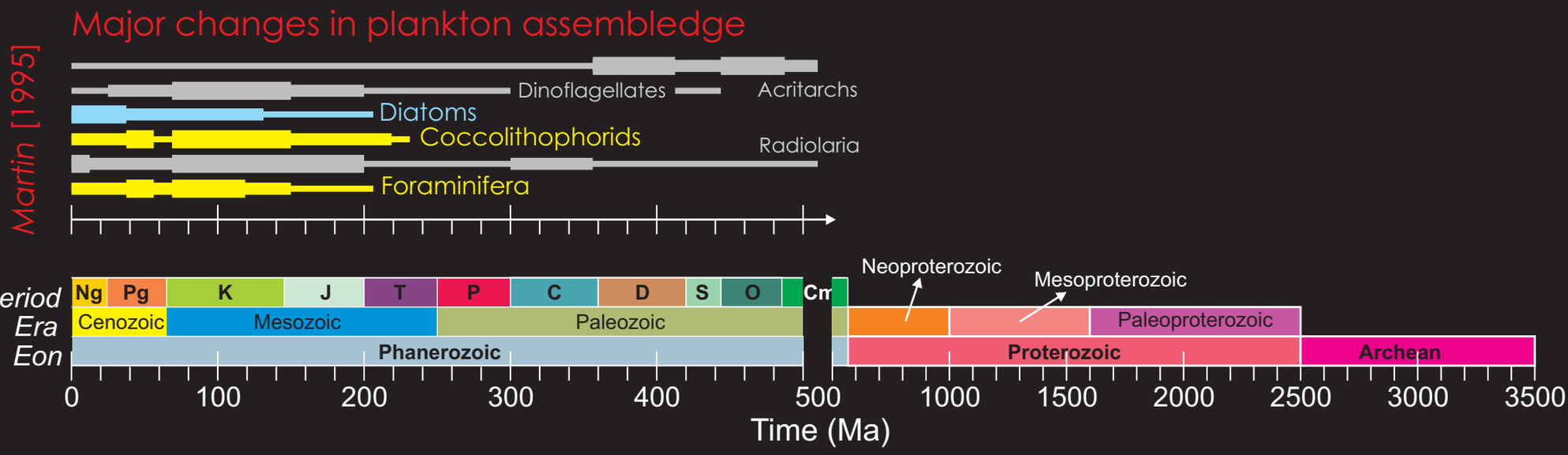
?


carbonate pump
carbonate+silicate weathering (0.2)
$Ca^{2+}+2HCO_3^- \rightarrow CaCO_3+CO_{2(aq)}+H_2O$
calcification (1.1)
water-column dissolution (0.6)
neritic $CaCO_3$ burial (0.1)
$CaCO_3+CO_{2(aq)}+H_2O \rightarrow Ca^{2+}+2HCO_3^-$
seafloor dissolution (0.4)
deep-sea $CaCO_3$ burial (0.1)

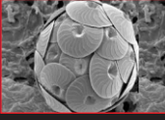

Period
Era
Eon
?
O
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

The Force awakens!



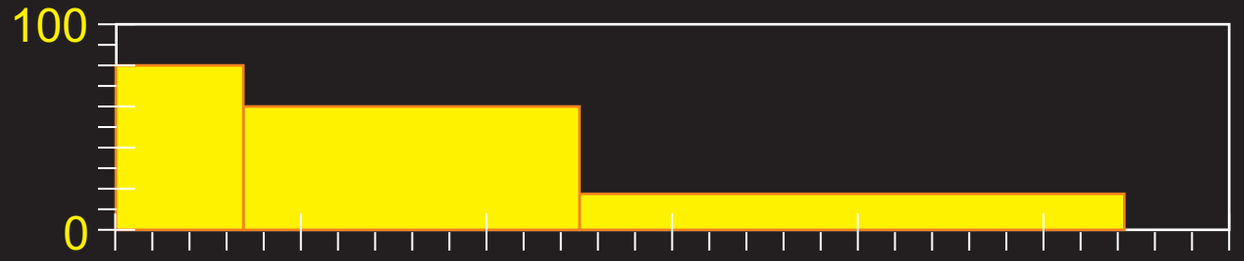


The Force awakens!



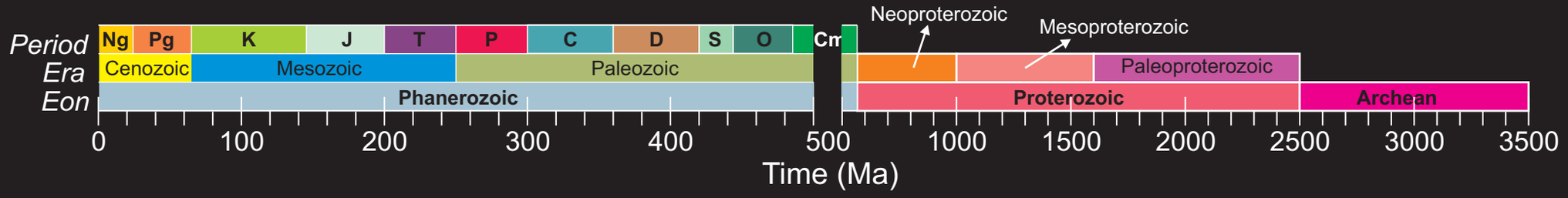
Boss and Wilkinson [1991]

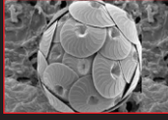
% occurrence of carbonate in ophiolite suites

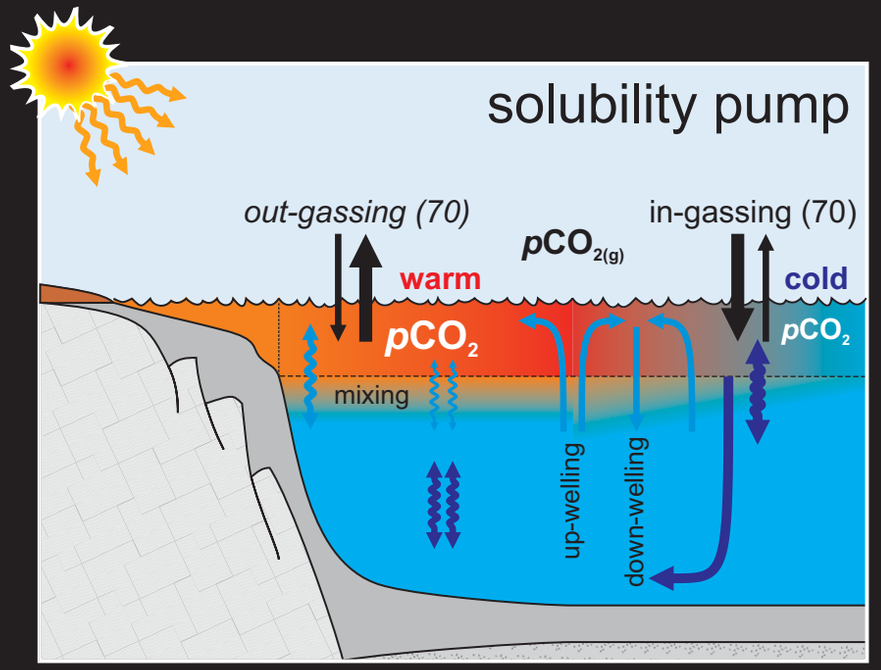


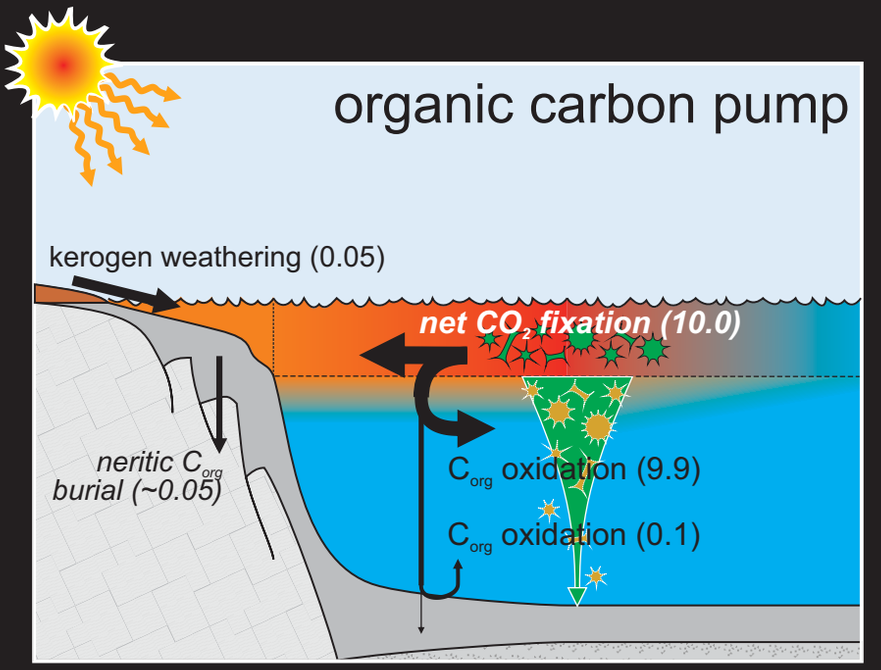
Martin [1995]

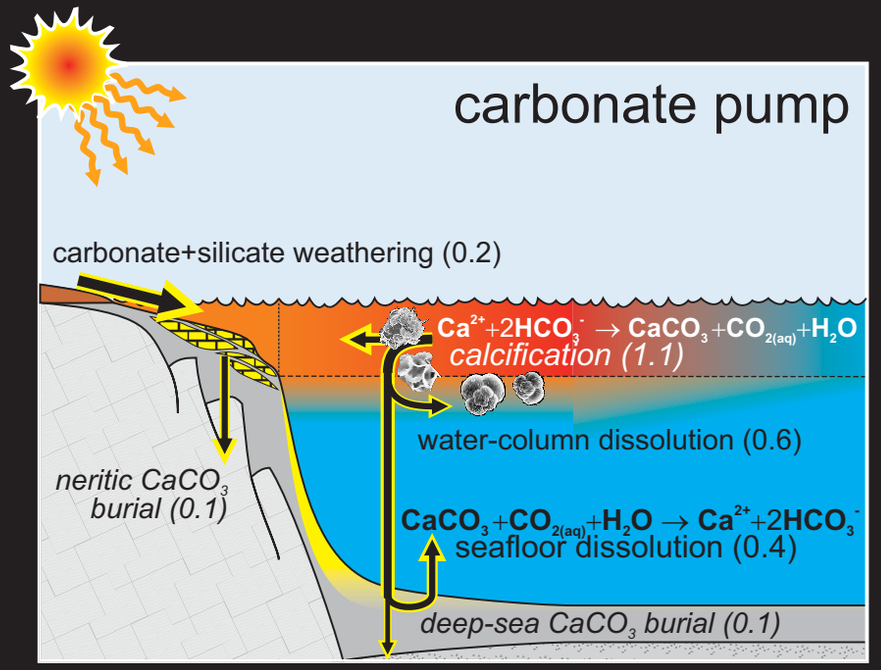
Major changes in plankton assembledge

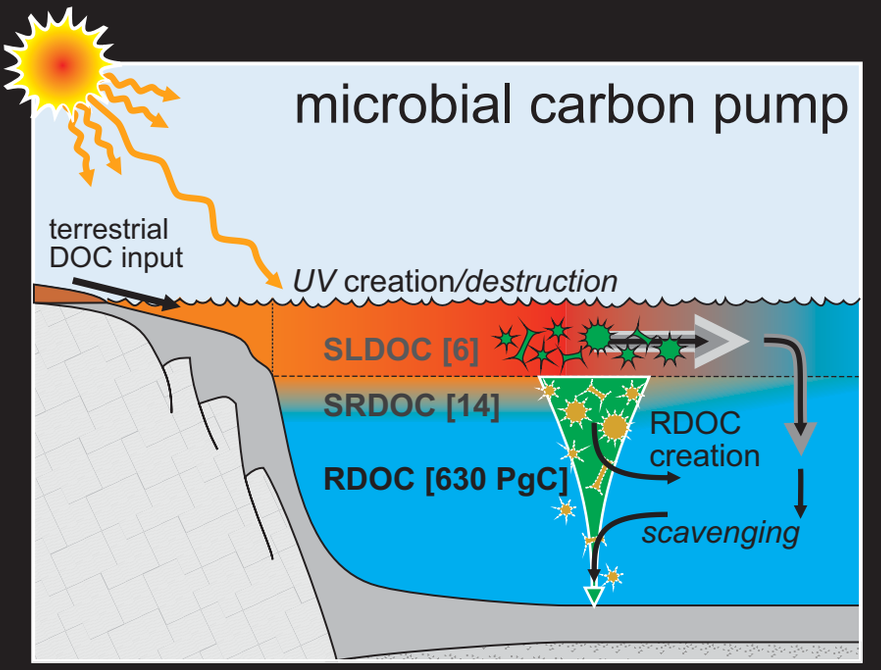


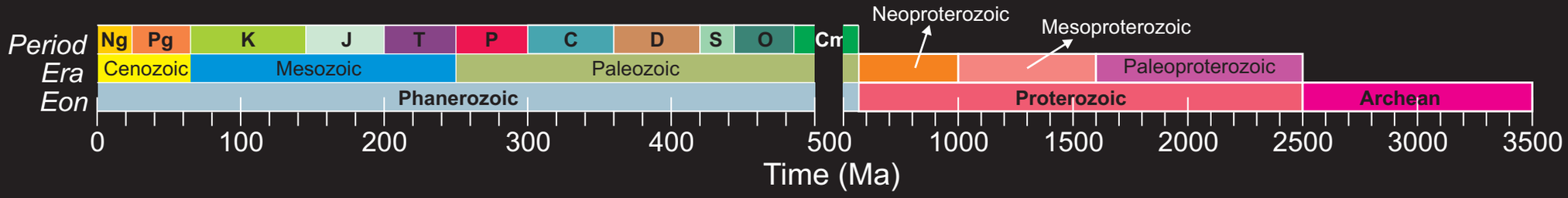


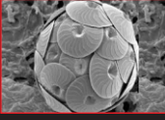

solubility pump
out-gassing (70)
in-gassing (70)
$pCO_{2(g)}$
warm
cold
pCO_2
pCO_2
mixing
up-welling
down-welling

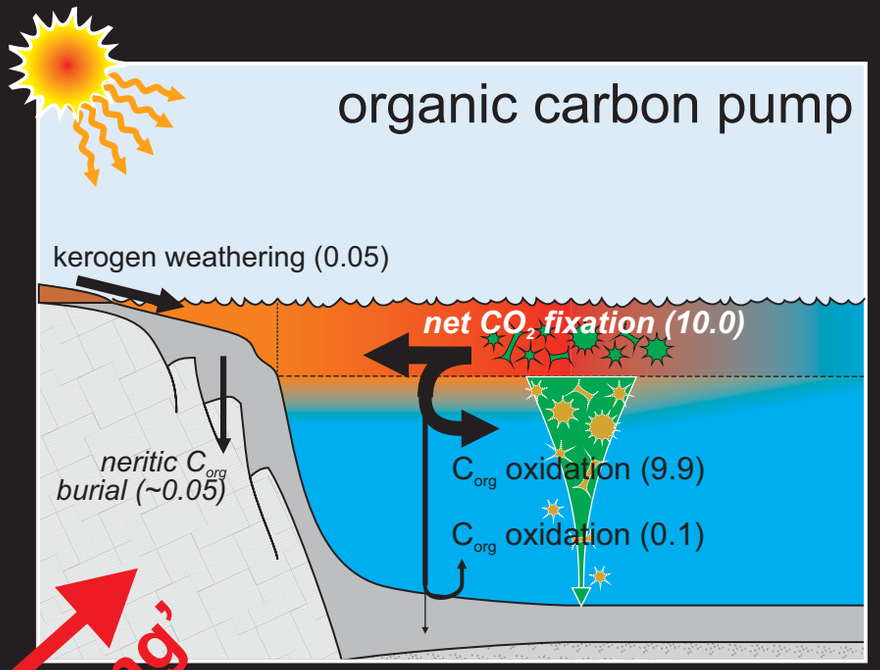

organic carbon pump
kerogen weathering (0.05)
net CO_2 fixation (10.0)
neritic C_{org} burial (~0.05)
C_{org} oxidation (9.9)
C_{org} oxidation (0.1)


carbonate pump
carbonate+silicate weathering (0.2)
$Ca^{2+}+2HCO_3^- \rightarrow CaCO_3+CO_{2(aq)}+H_2O$
calcification (1.1)
water-column dissolution (0.6)
neritic $CaCO_3$ burial (0.1)
$CaCO_3+CO_{2(aq)}+H_2O \rightarrow Ca^{2+}+2HCO_3^-$
seafloor dissolution (0.4)
deep-sea $CaCO_3$ burial (0.1)

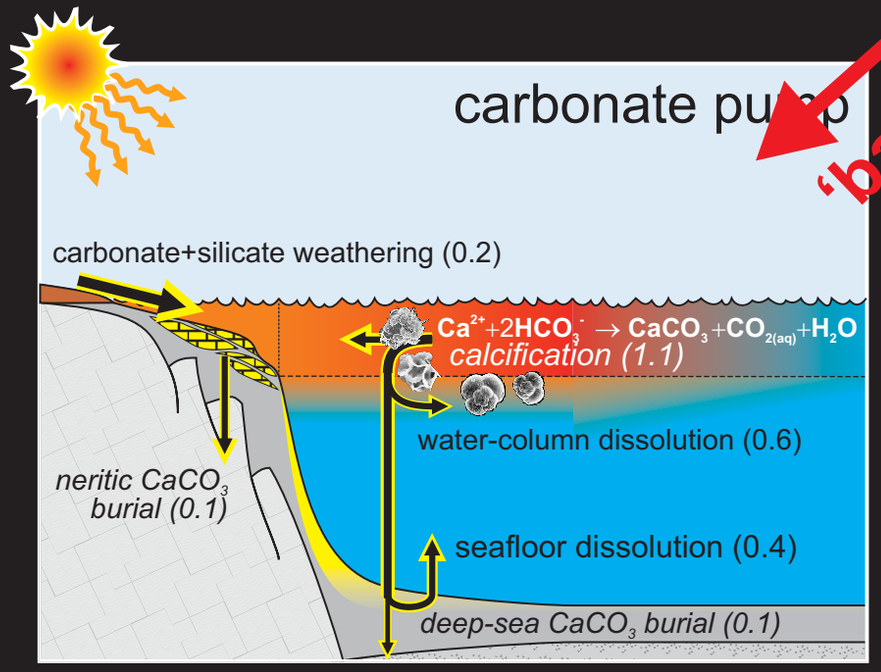

microbial carbon pump
terrestrial DOC input
UV creation/destruction
SLDOC [6]
SRDOC [14]
RDOC [630 PgC]
RDOC creation
scavenging

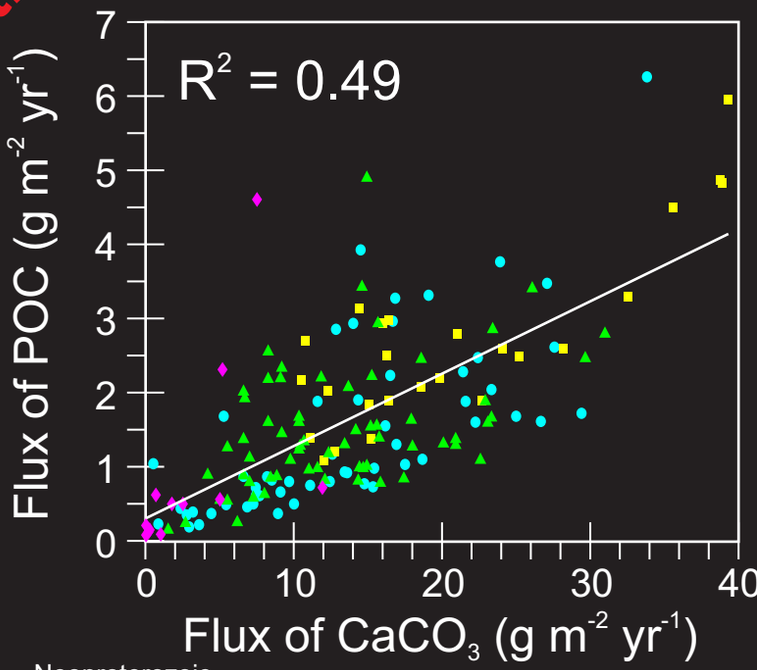

Period
Era
Eon
Ng
Pg
K
J
T
P
C
D
S
O
Cm
Cenozoic
Mesozoic
Paleozoic
Phanerozoic
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

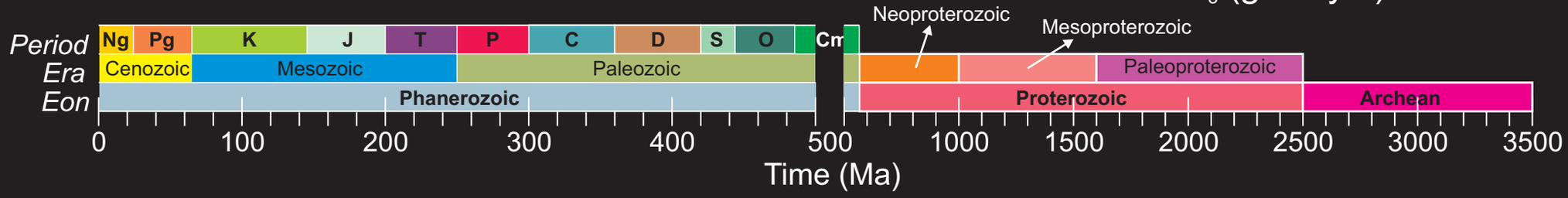



organic carbon pump
kerogen weathering (0.05)
net CO_2 fixation (10.0)
neritic C_{org} burial (~0.05)
C_{org} oxidation (9.9)
C_{org} oxidation (0.1)

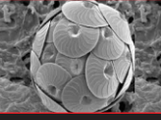
'ballasting'

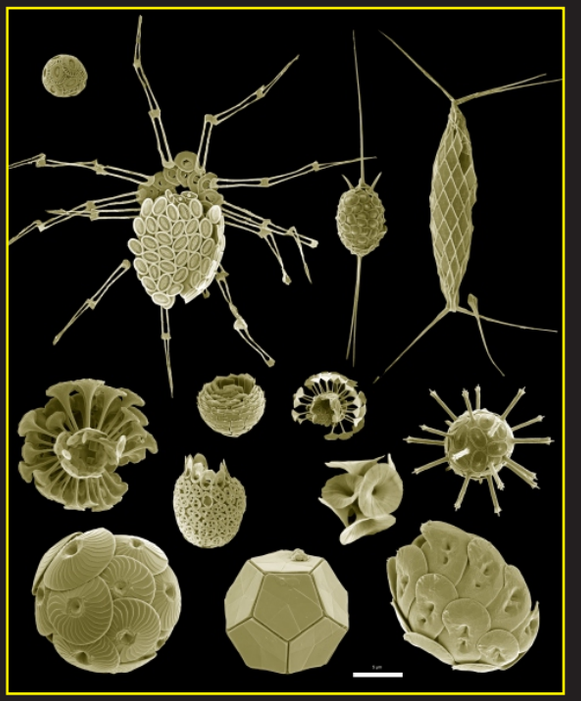

carbonate pump
carbonate+silicate weathering (0.2)
$Ca^{2+}+2HCO_3^- \rightarrow CaCO_3+CO_{2(aq)}+H_2O$
calcification (1.1)
water-column dissolution (0.6)
neritic $CaCO_3$ burial (0.1)
seafloor dissolution (0.4)
deep-sea $CaCO_3$ burial (0.1)


R^2 = 0.49
Flux of POC (g m^{-2} yr^{-1})
Flux of $CaCO_3$ (g m^{-2} yr^{-1})
0
1
2
3
4
5
6
7
0
10
20
30
40


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)

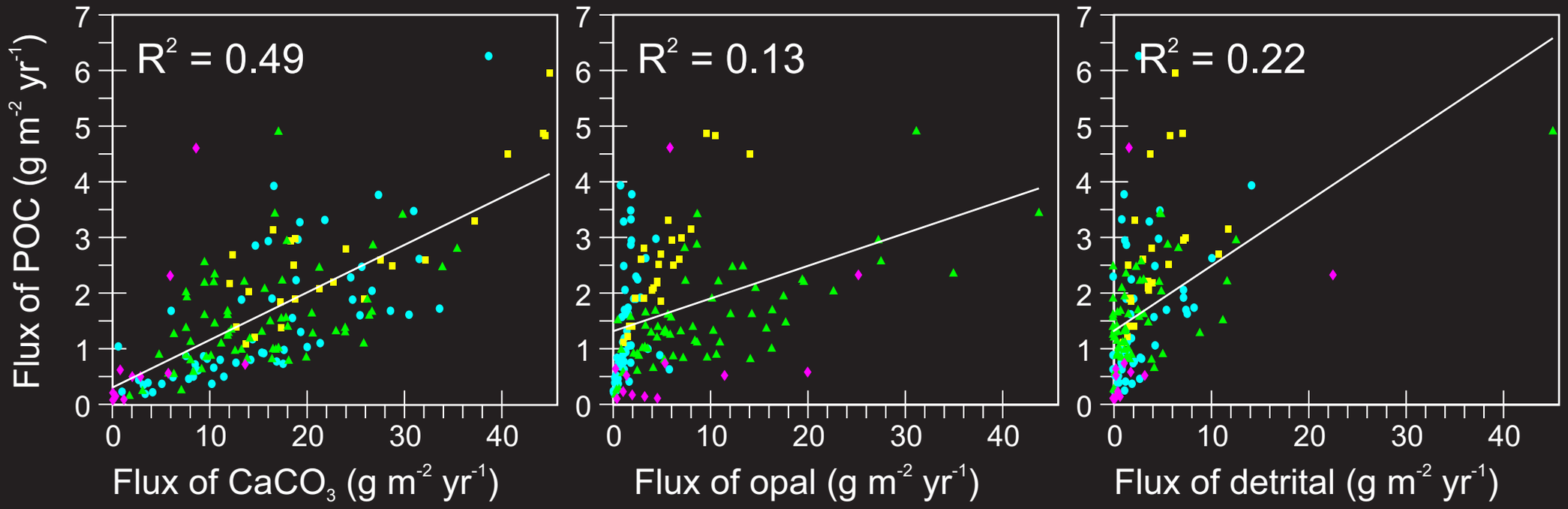
The Force awakens???



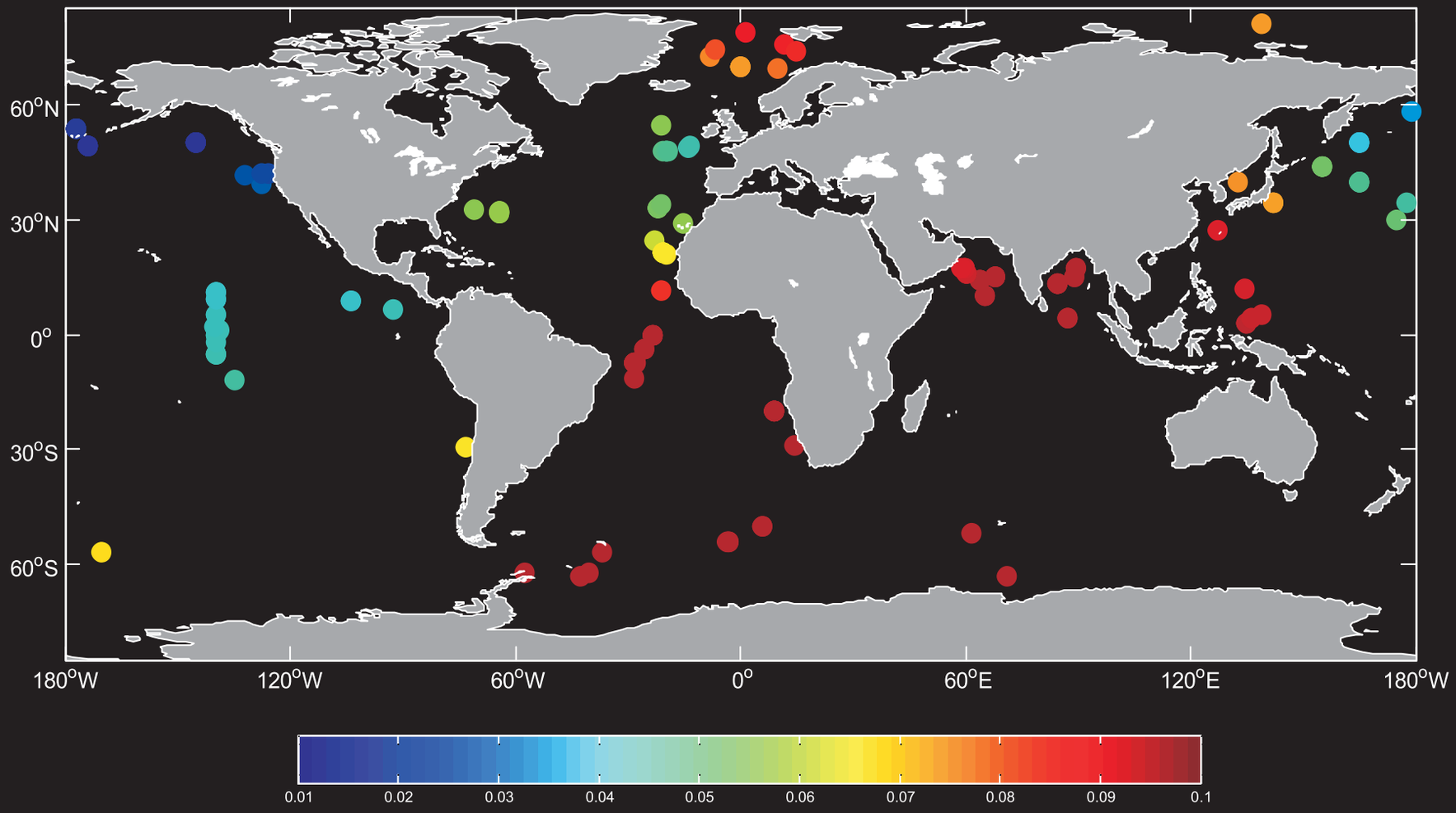


Compilation of sediment trap observations:
depths >= 2000 m (to exclude hydrodynamically distorted fluxes and relationships) and differentiated by basin:
cyan == Atl, yellow == Ind, green == Pac, magenta == SO.

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



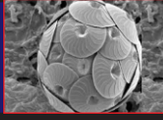
The Force awakens???

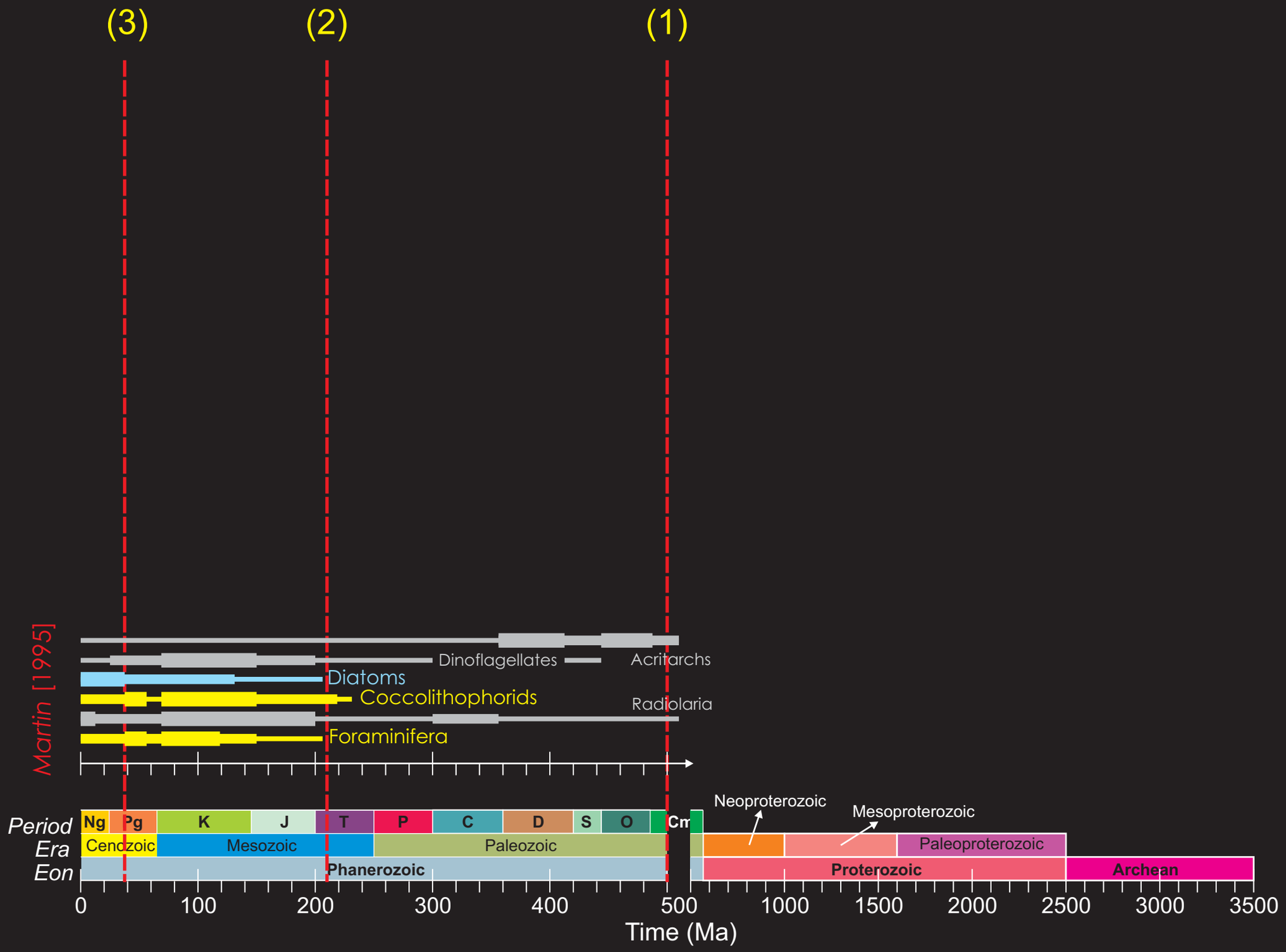


Spatial distribution of carrying capacity (ballasting) coefficients calculated using geographically weighted regression analysis for $CaCO_3$.

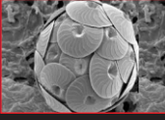
Wilson et al. [2012]

When did the Force awaken (modern biological pump form)?





When did the Force awaken (modern biological pump form)?



(3) (2) (1)

atmospheric pCO_2 (ppm)

7000 6000 5000 4000 3000 2000 1000 0

Royer et al. [2004]

Crowell [1999]

Occurrence of ice ages (relative intensity)

? ?

Martin [1995]

Dinoflagellates

Acritarchs

Diatoms

Coccolithophorids

Radiolaria

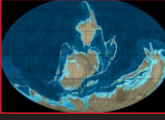
Foraminifera

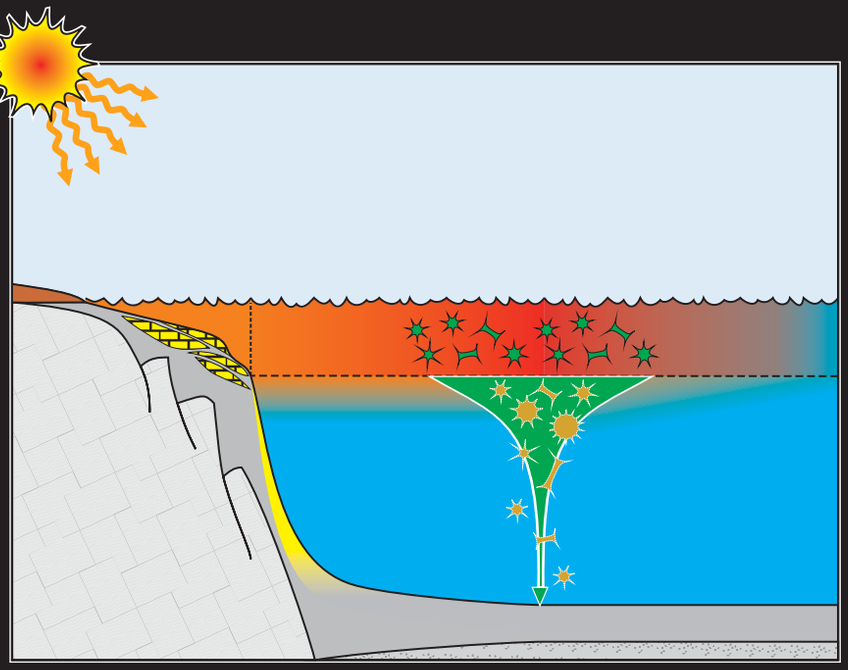
Period	Ng	Pg	K	J	T	P	C	D	S	O	Cm	Neoproterozoic	Mesoproterozoic	Paleoproterozoic	Archean
Era	Cenozoic		Mesozoic			Paleozoic									
Eon	Phanerozoic											Proterozoic			

0 100 200 300 400 500 1000 1500 2000 2500 3000 3500

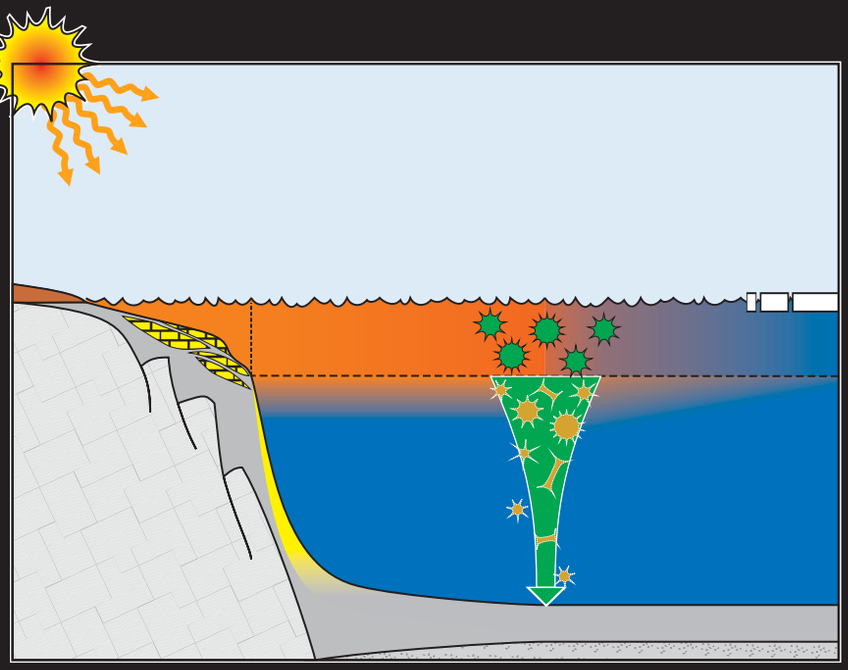
Time (Ma)

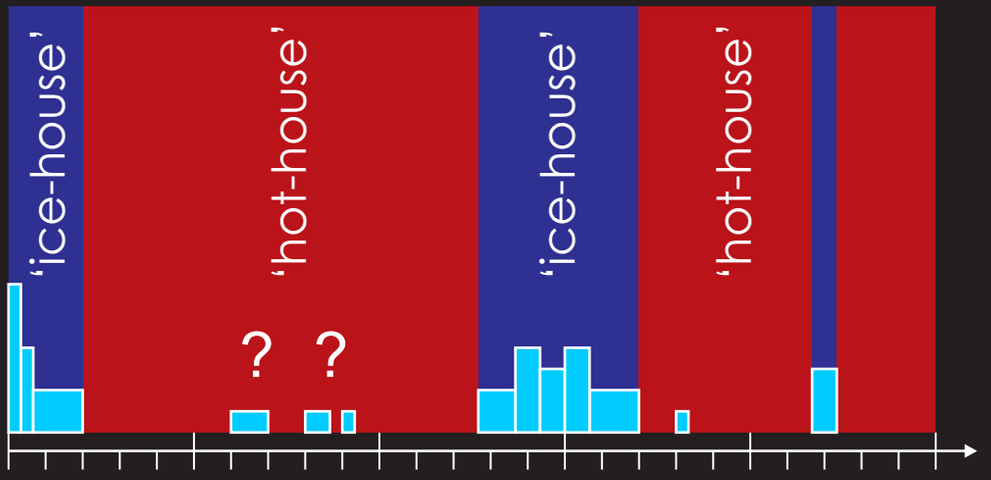
Paleo Perspectives – Extreme climate states

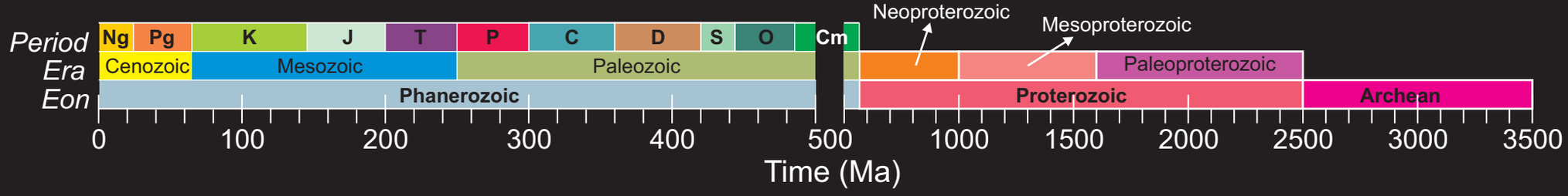




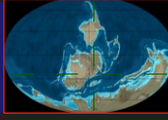
VS.







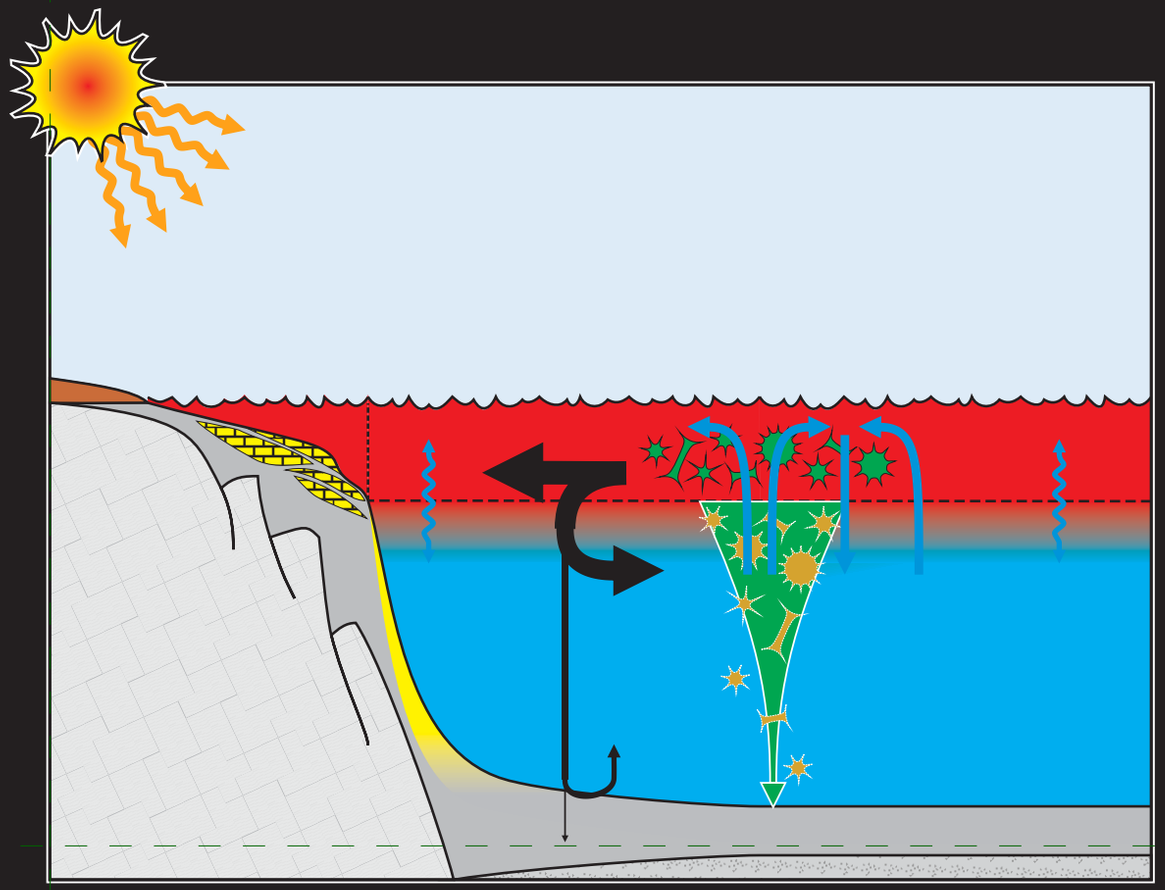
Paleo Perspectives – Extreme climate states



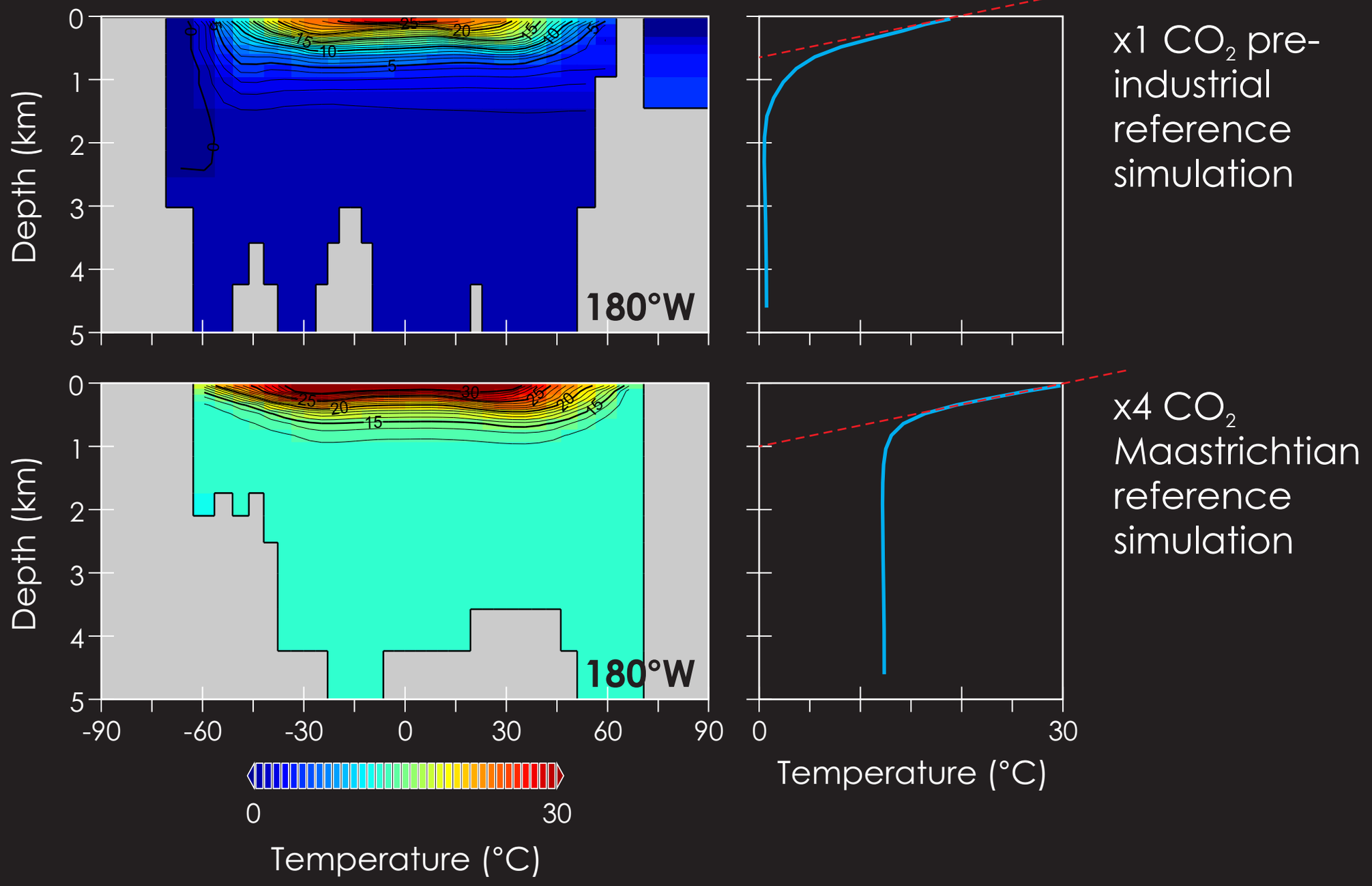
```
(warm == stratified) && (stratified == anoxic) == .true.
```

???

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



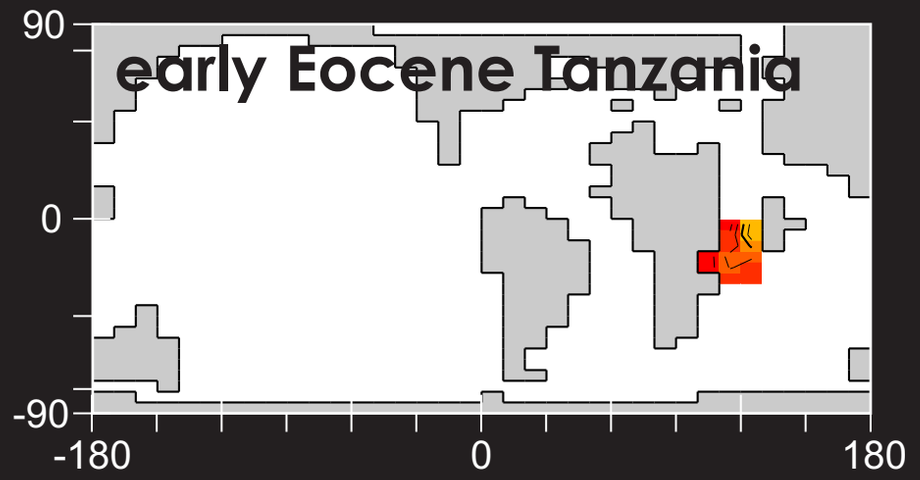
Paleo Perspectives – Extreme climate states

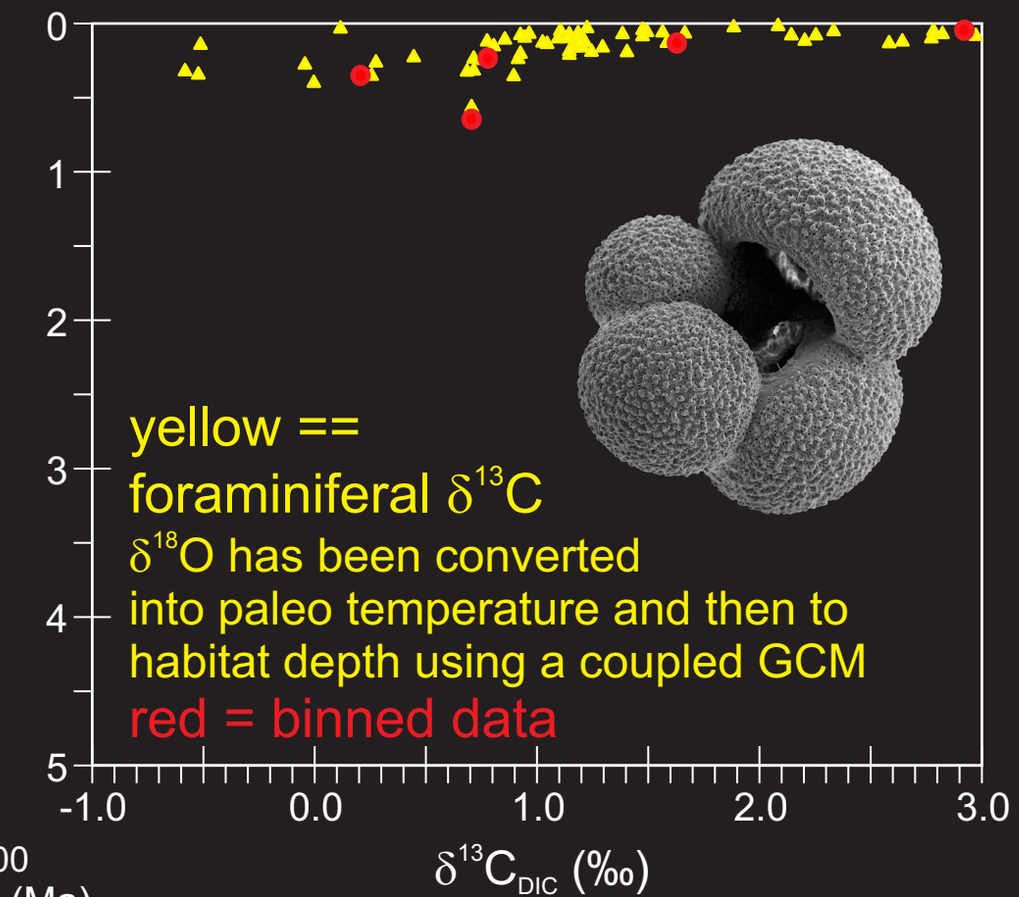


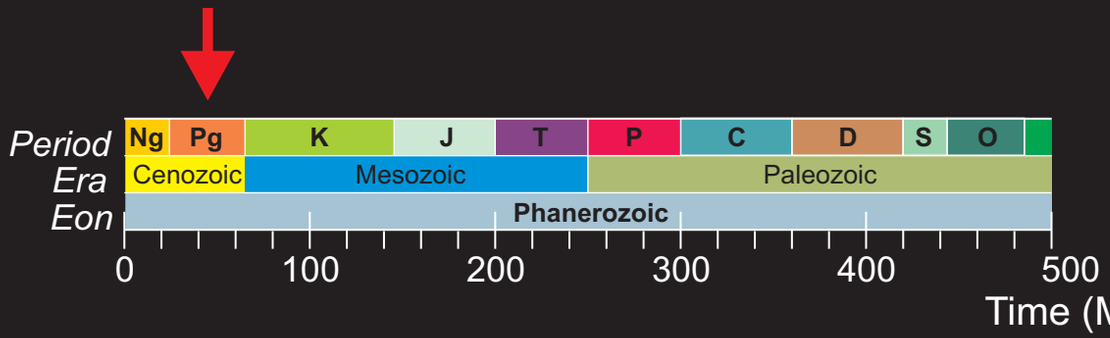
Paleo Perspectives – Testing the 'metabolic' hypothesis

(for water column POC remineralization)

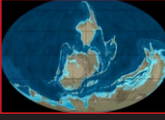
John et al. [2014] (*PPP* **413**)

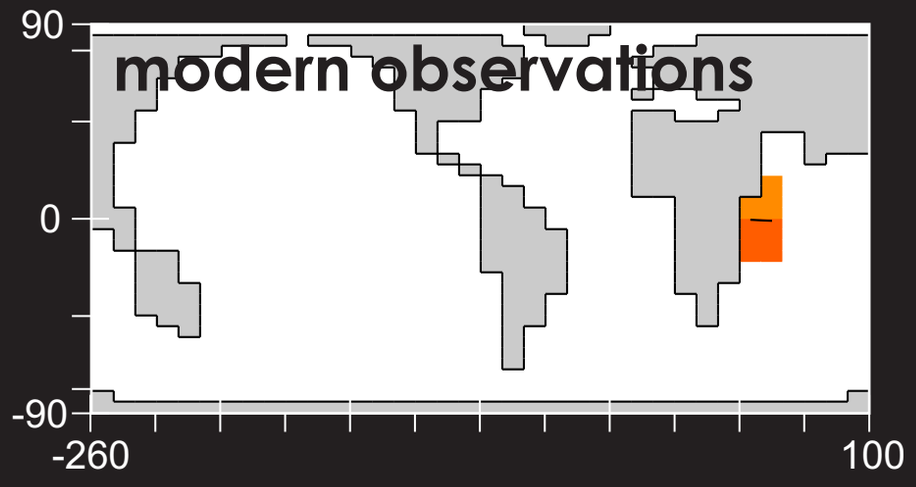


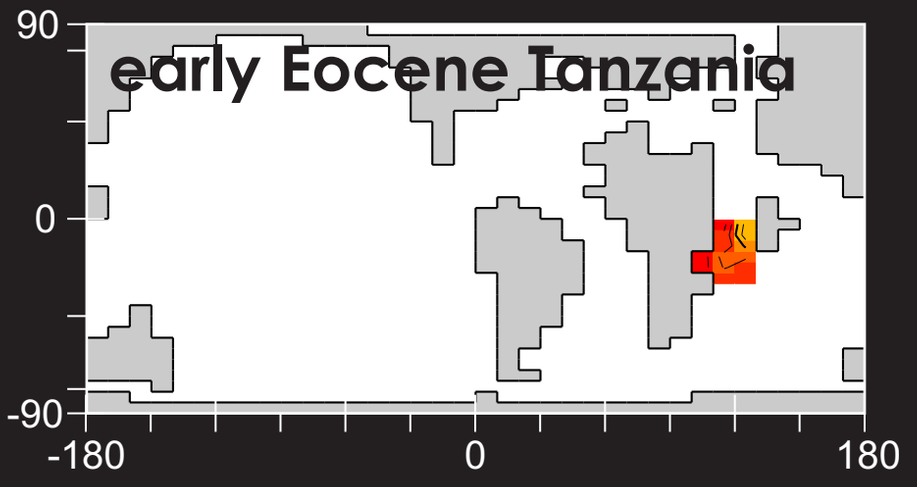


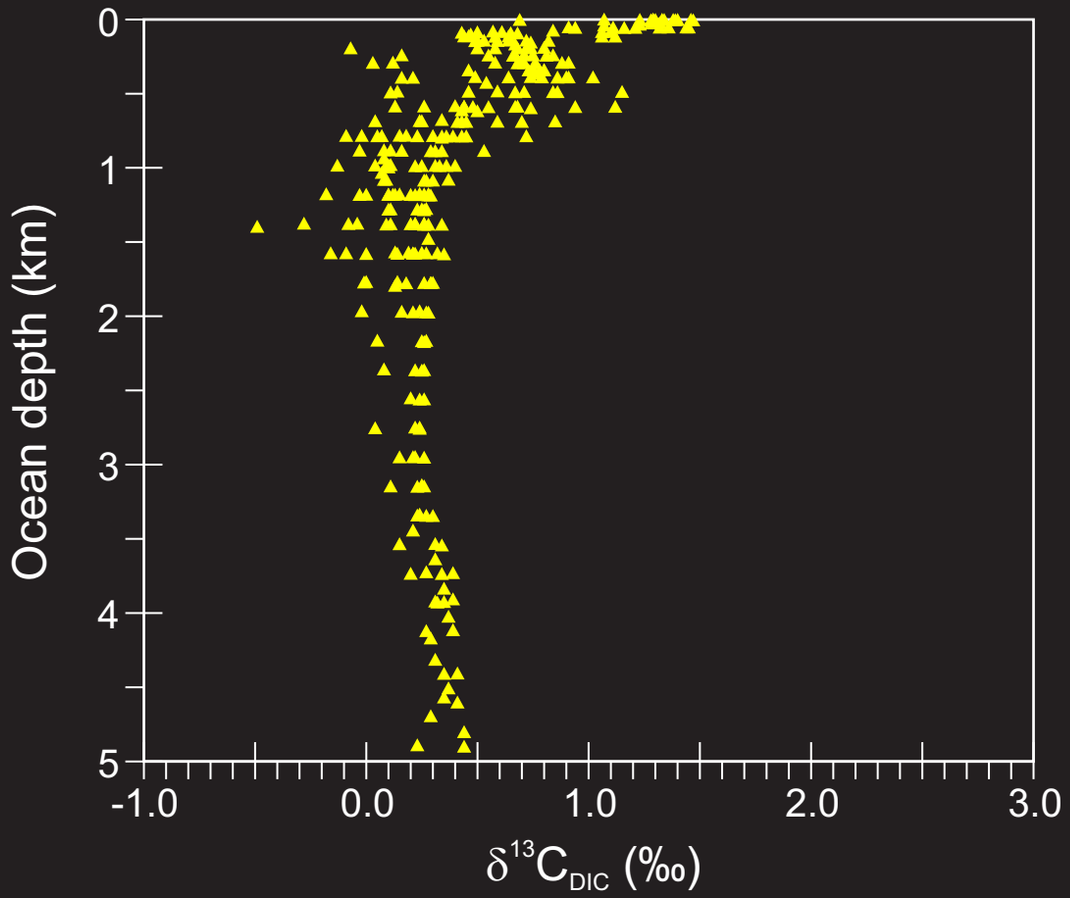


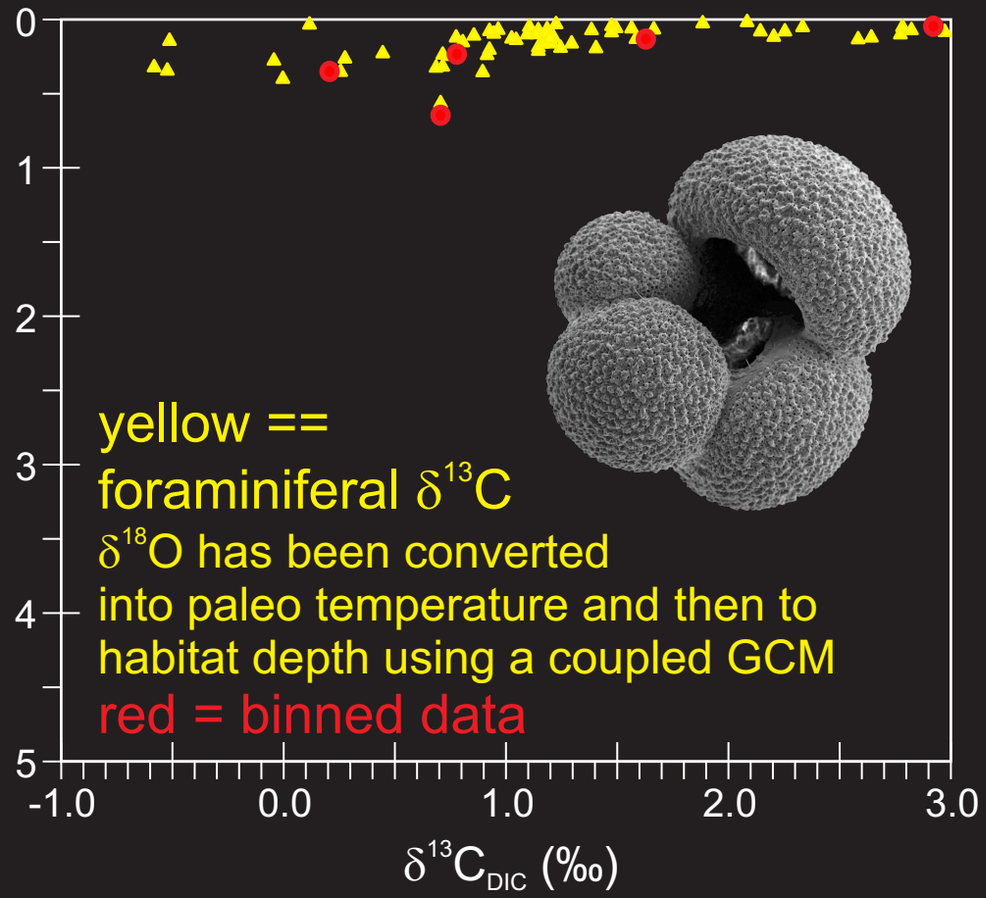
Paleo Perspectives – Testing the 'metabolic' hypothesis



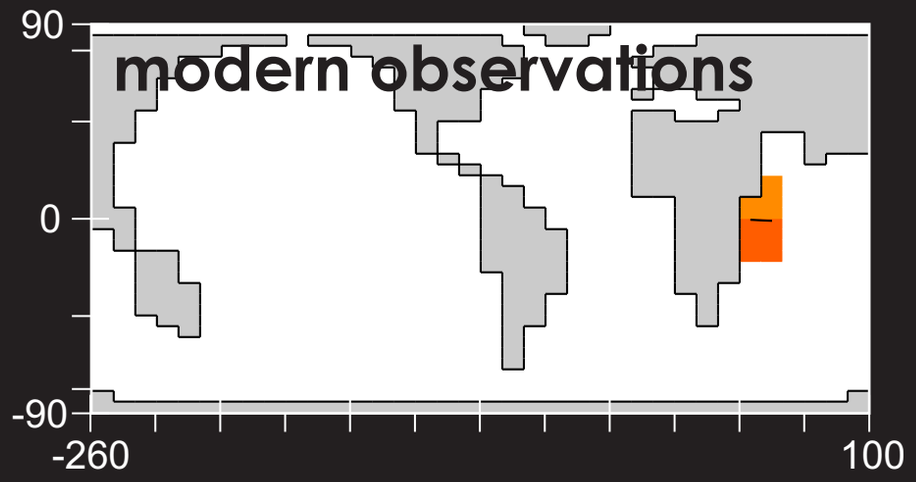


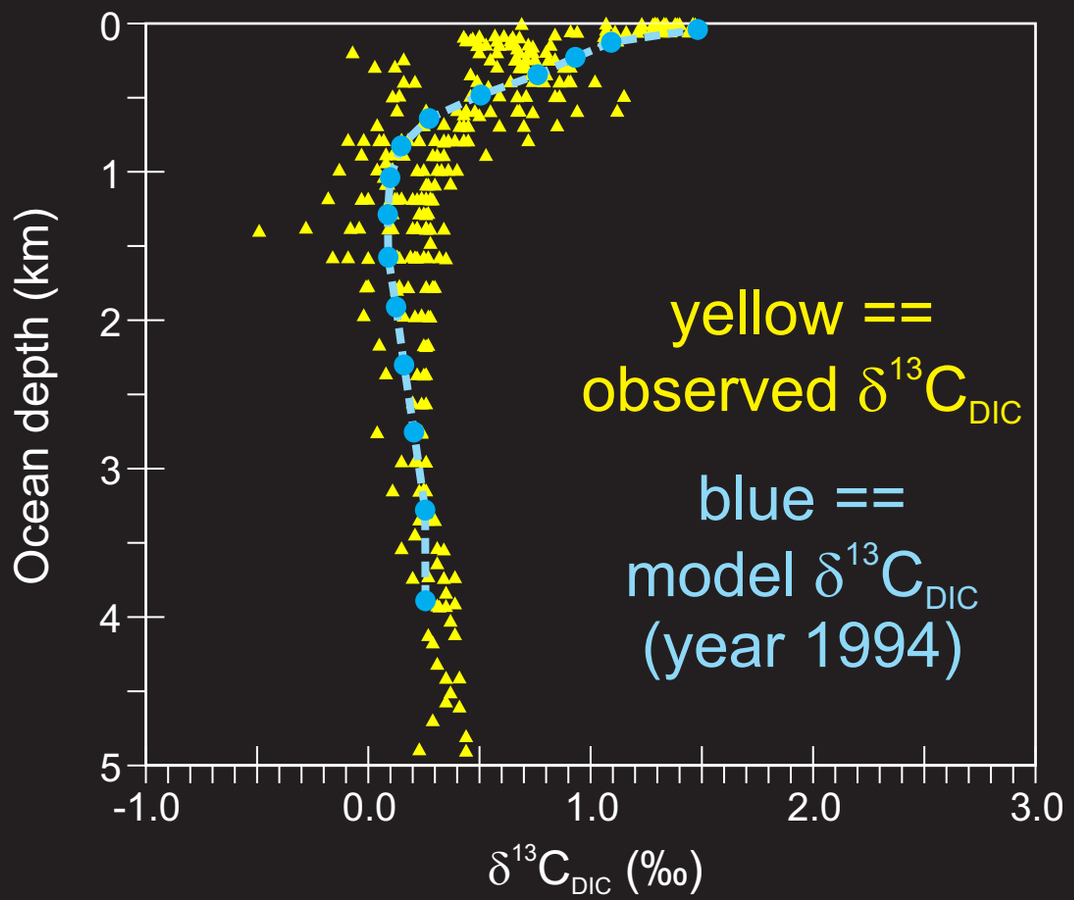




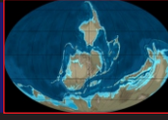


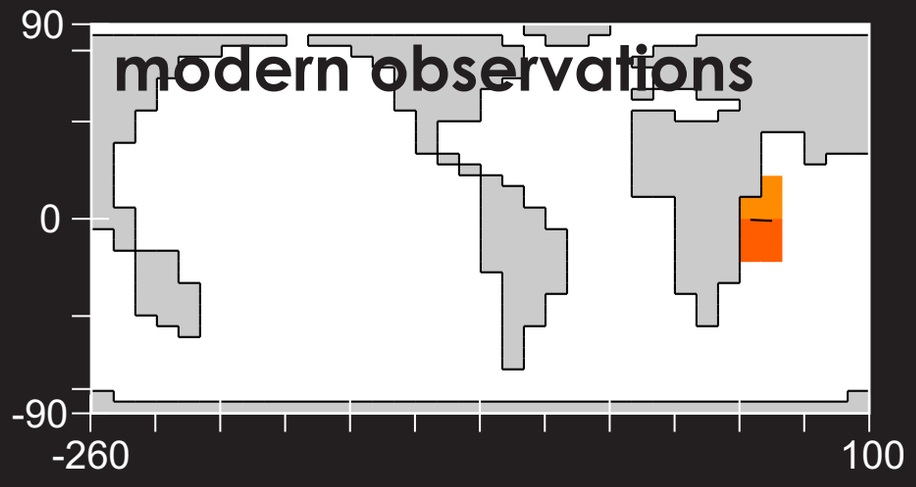
Paleo Perspectives – Testing the 'metabolic' hypothesis

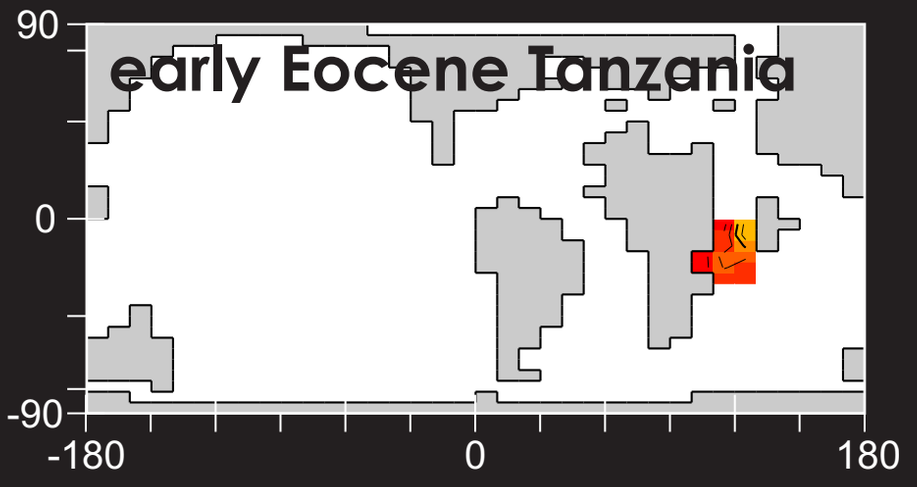


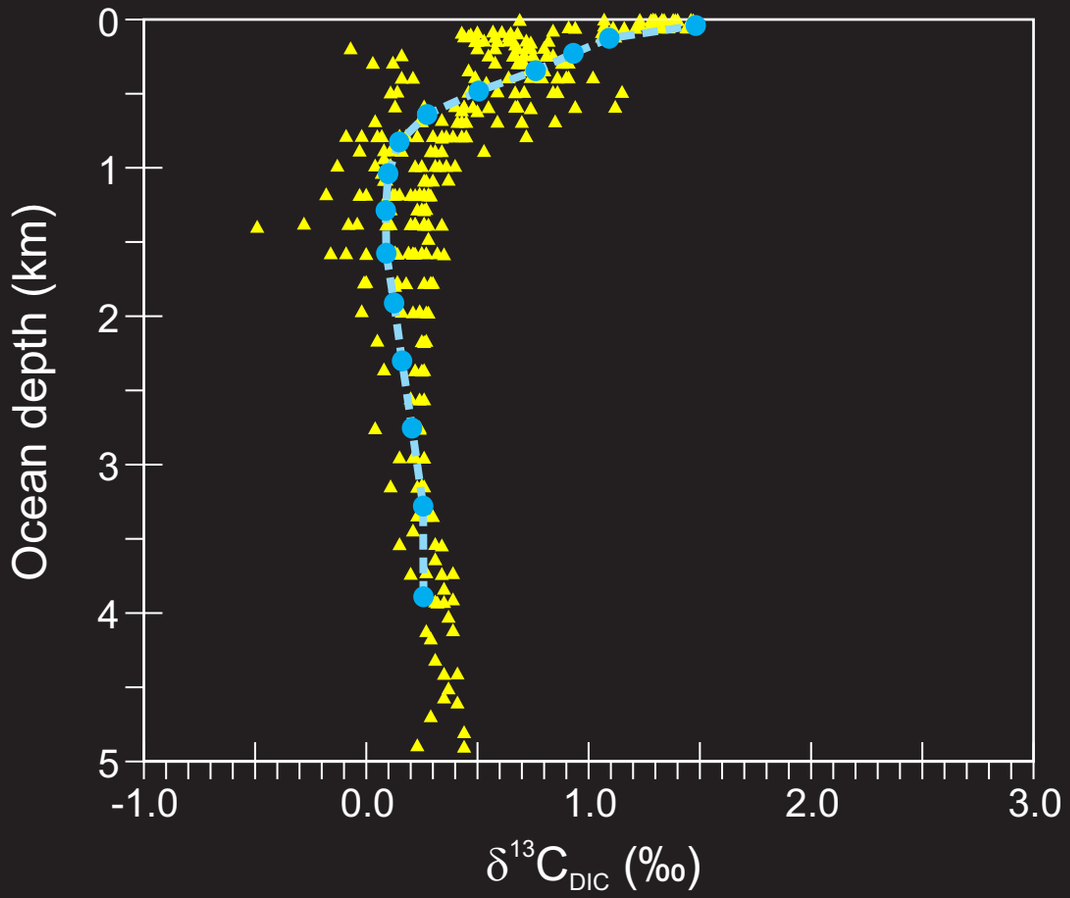


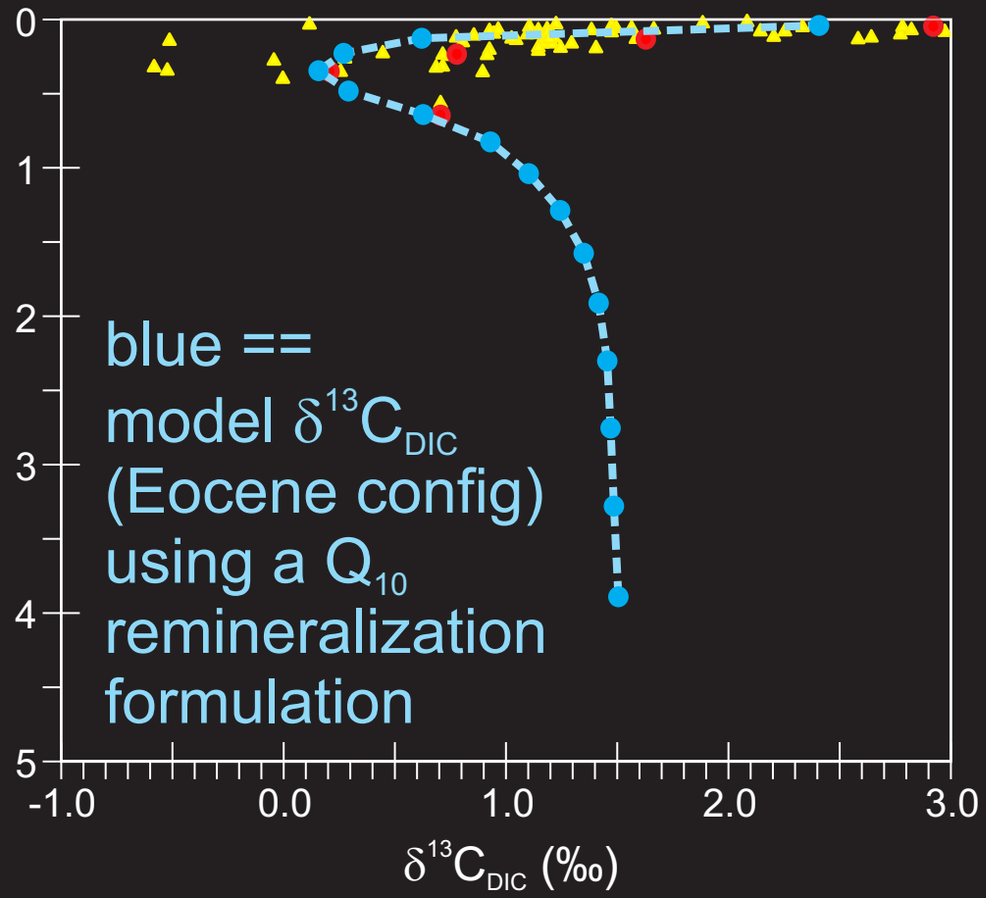
Paleo Perspectives – Testing the 'metabolic' hypothesis





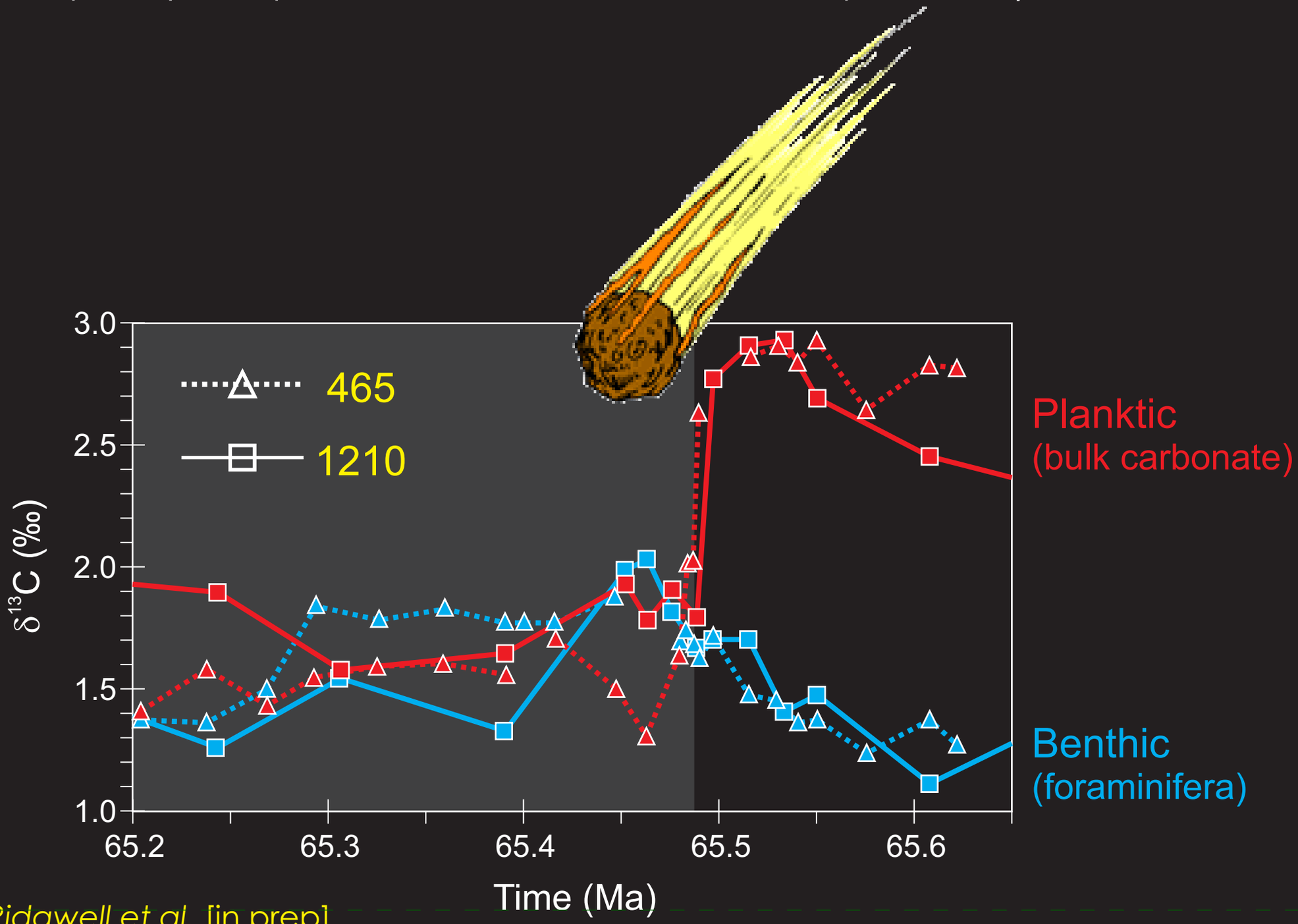






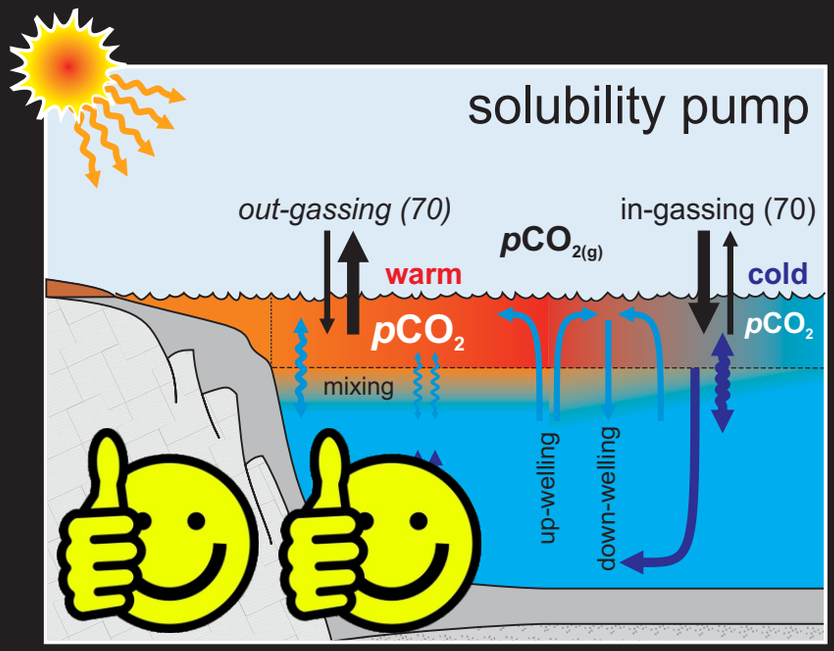
Paleo Perspectives – 'Hiccups'

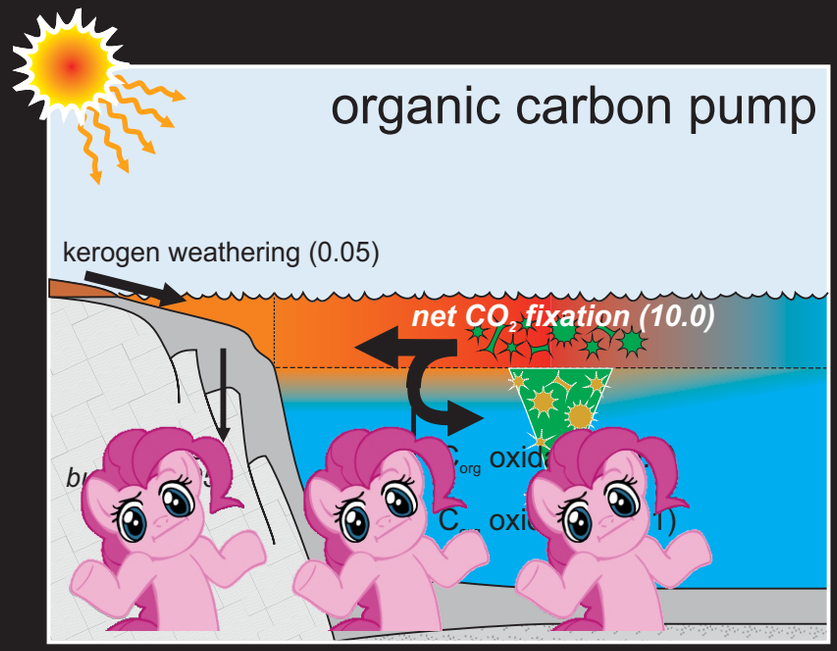
(temporary disruption or removal of one or more processes)

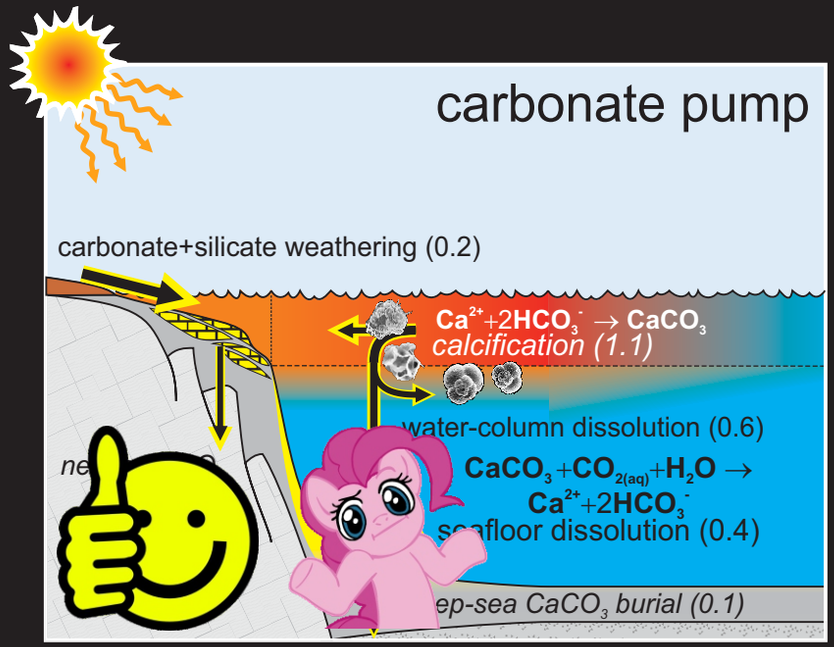


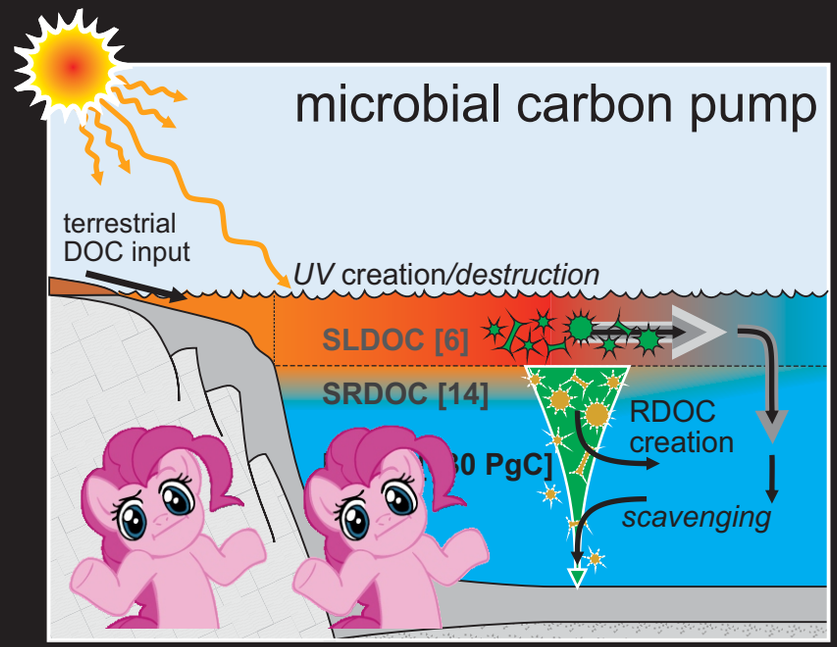
Ridgwell et al. [in prep]

Summary and Perspectives









Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

Neoprot.	Mesoprot.	Paleoproterozoic	Archean
Proterozoic			

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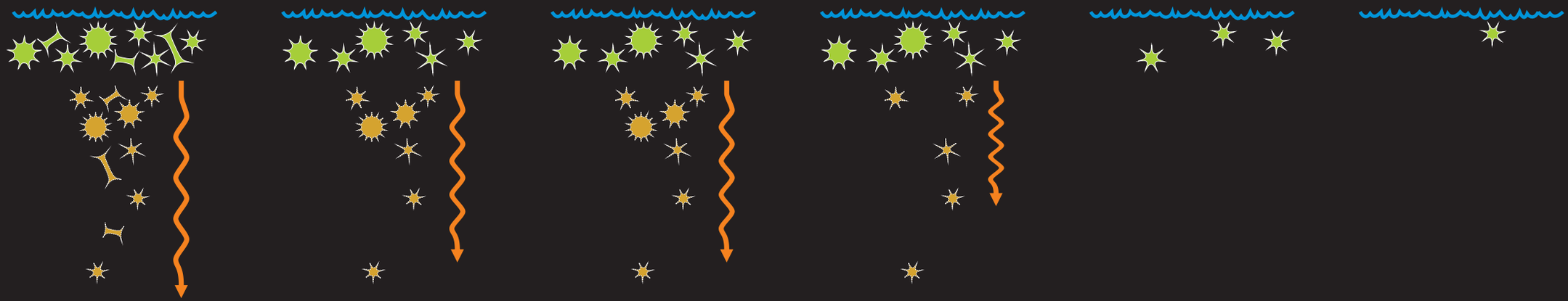

Ng	Pg	K	J	T	P	C	D	S	O	Cm				
Cenozoic		Mesozoic			Paleozoic							Neoprot.	Mesoprot.	Paleoproterozoic
Phanerozoic												Proterozoic		Archean