Goldschmidt 2018

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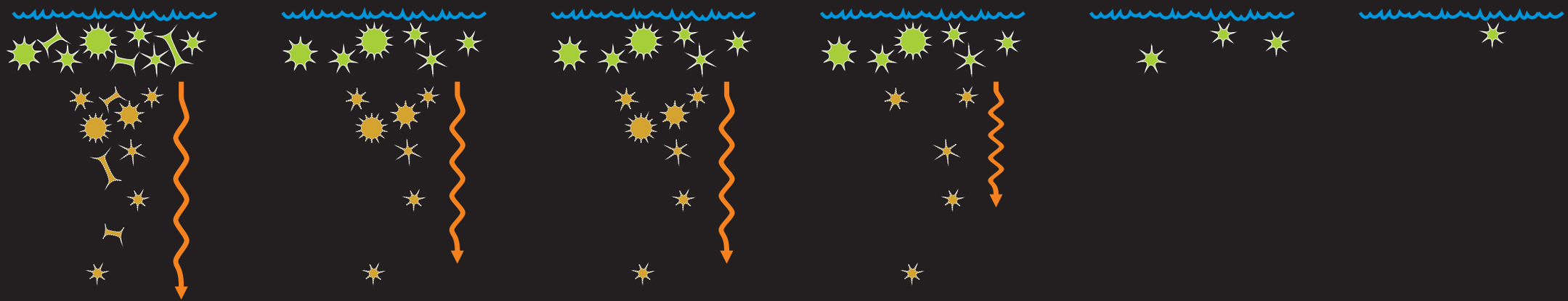
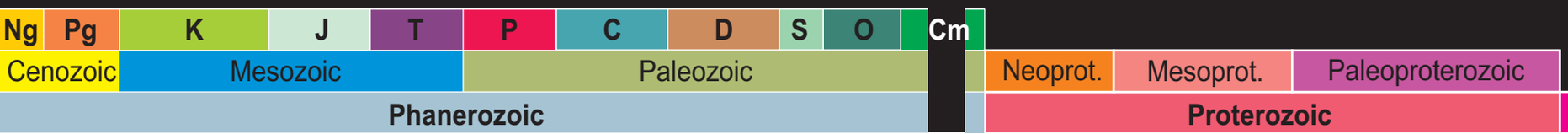
UCR

Evolution of The Biological Pump (alternative ocean carbon facts in a fake World)

Andy Ridgwell

University of California – Riverside
University of Bristol



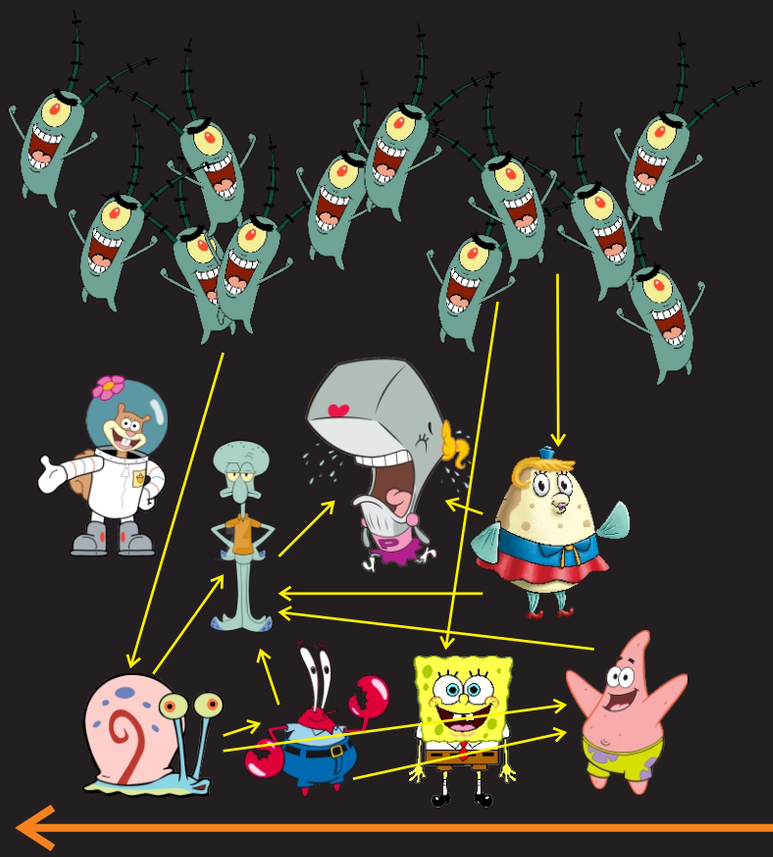


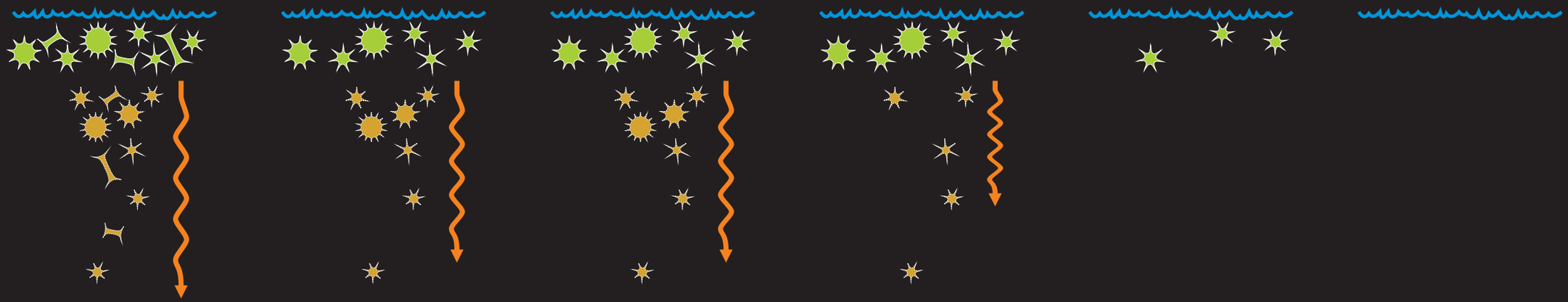
Outline

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

Neoprot.	Mesoprot.	Paleoproterozoic	
Proterozoic			Archean

Outline





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

Neoprot.	Mesoprot.	Paleoproterozoic	
Proterozoic			Archean

Twitter Outline

There has never been so much biological pumping!

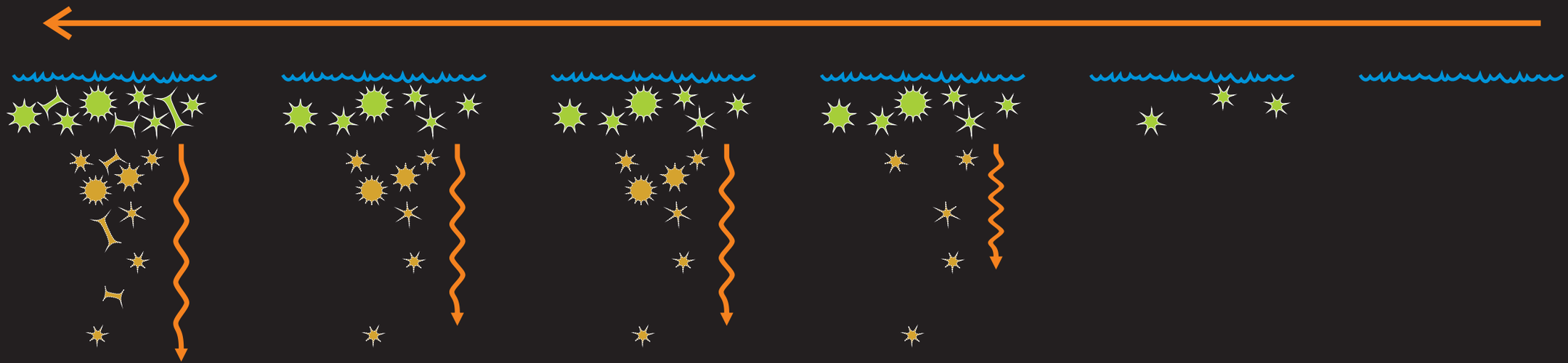
Most primary production EVER!

Many more trophic levels than during the Obama-ian geological Period!

Hadean Dems left behind NO BIOLOGICAL CYCLING OF CARBON IN THE OCEAN! SAD!

NO COLLUSION between phytoplankton and zooplankton! Witch hunt!

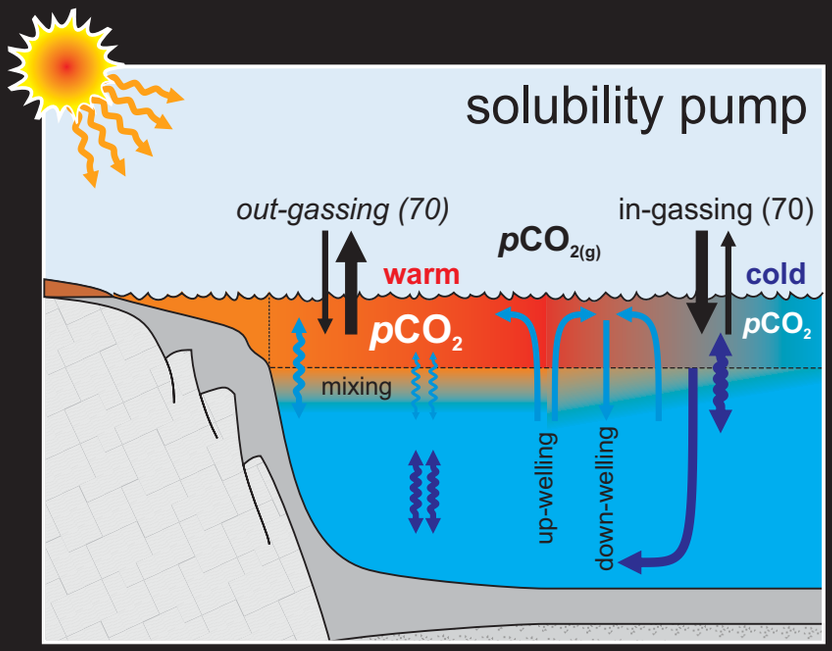
Make the ocean biological pump great again!

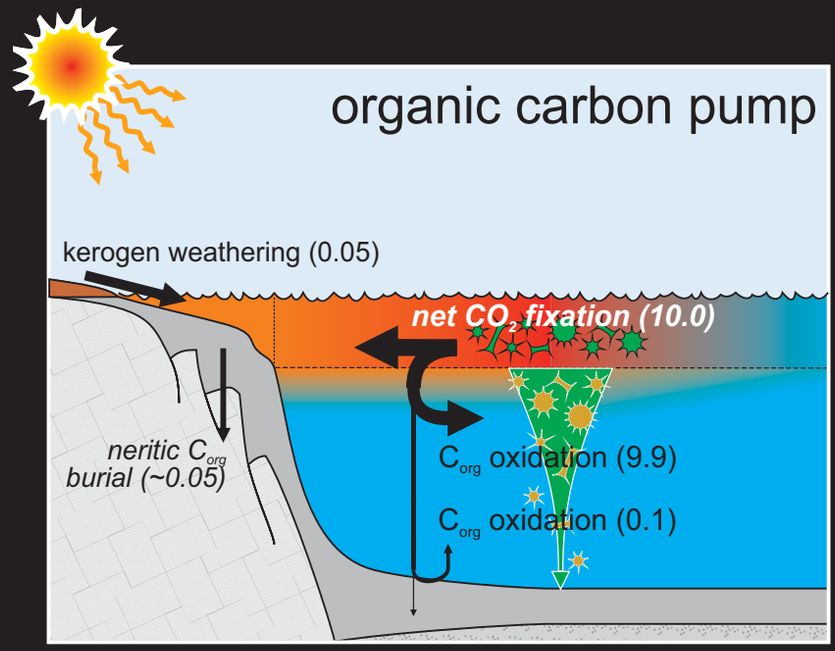


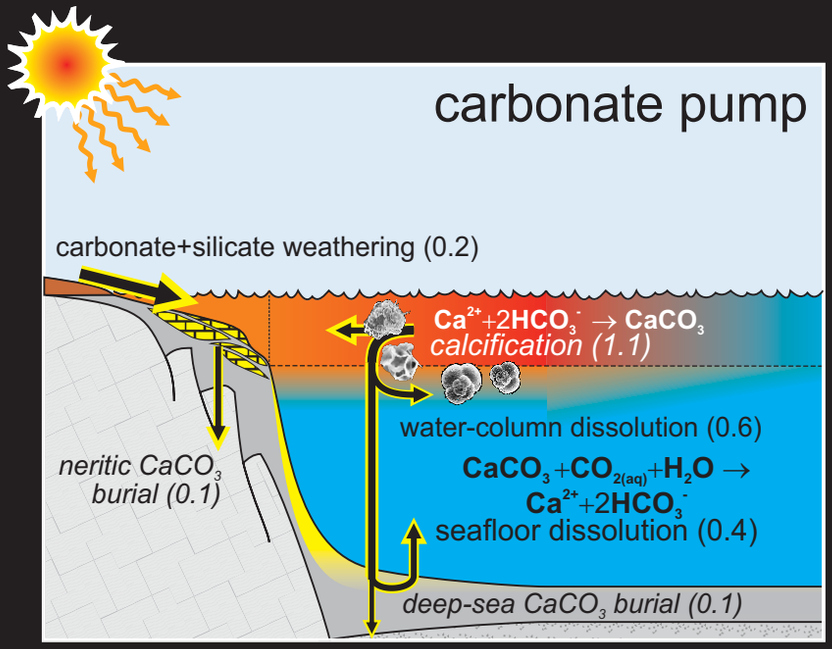
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

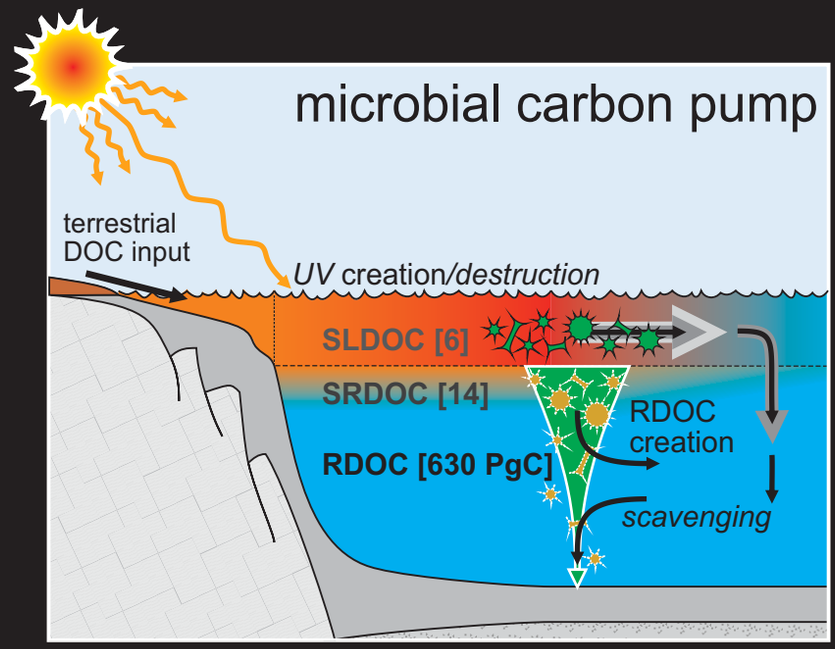
Neoprot.	Mesoprot.	Paleoproterozoic	
Proterozoic			Archean

Background







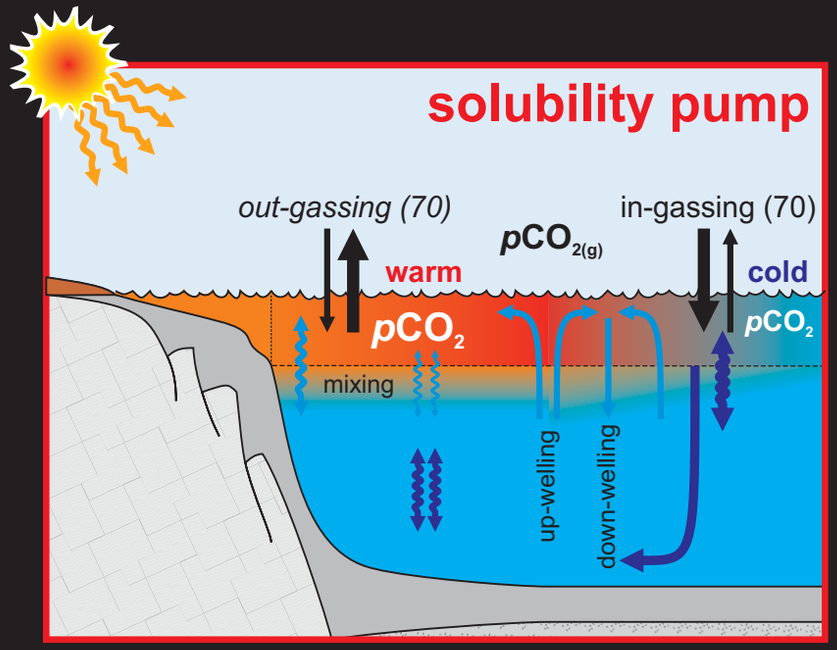


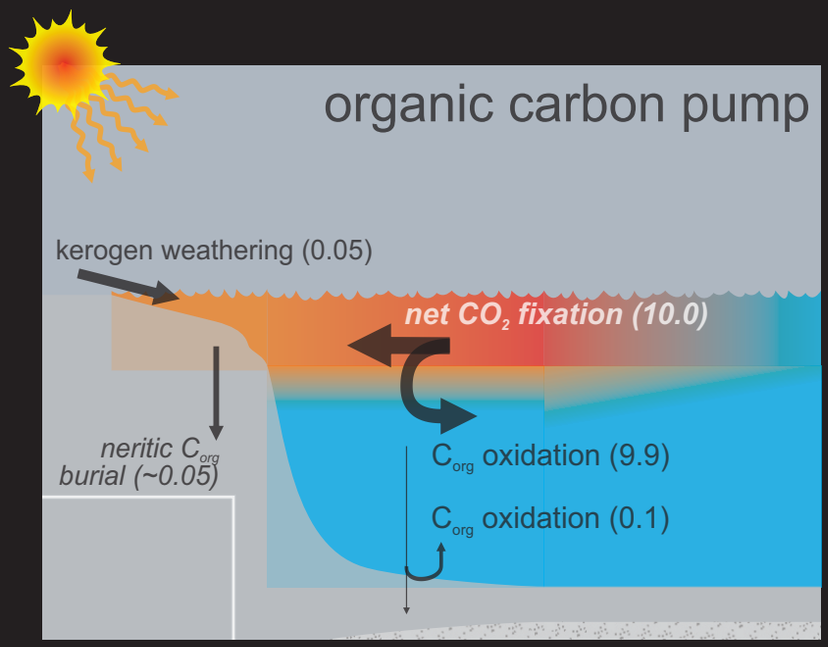
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

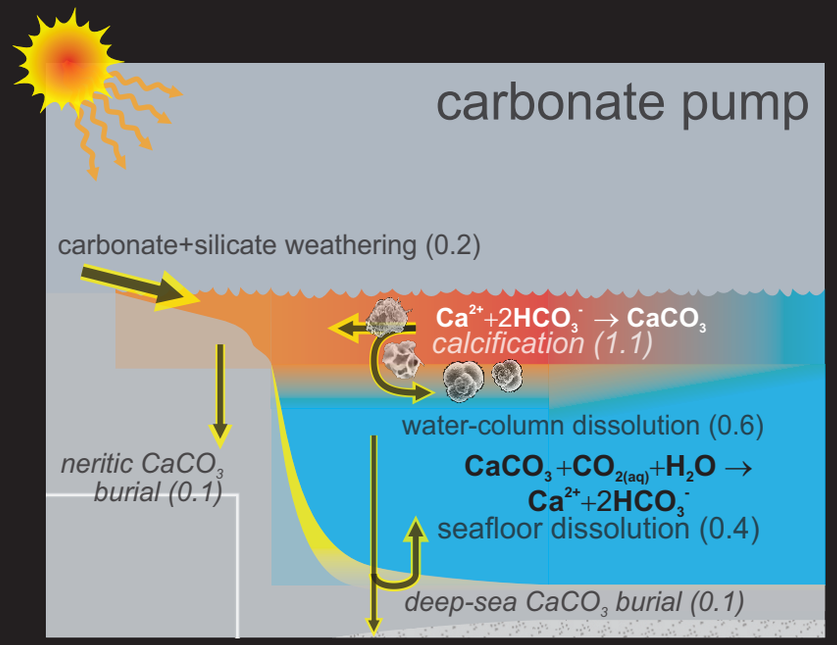
Neoprot.	Mesoprot.	Paleoproterozoic	Archean
Proterozoic			

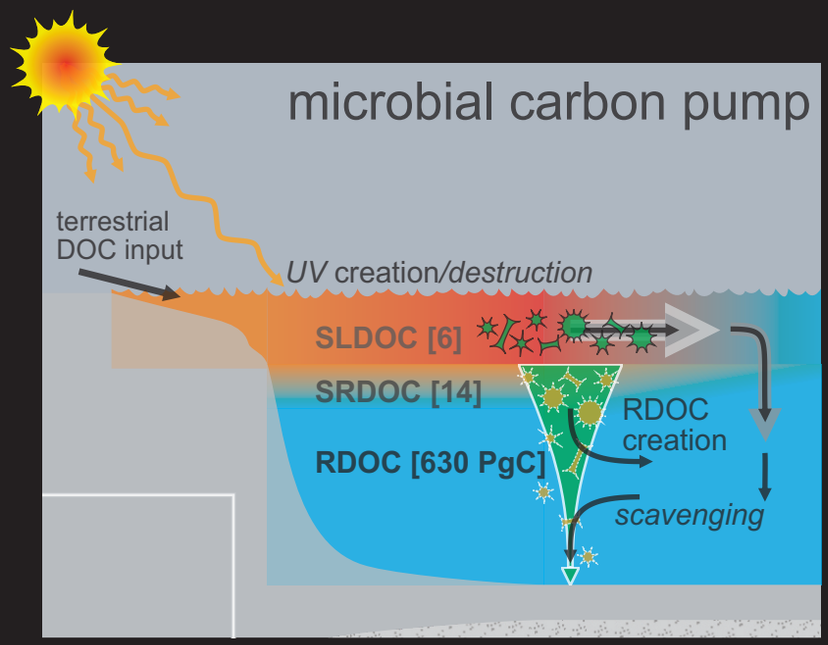
Background

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







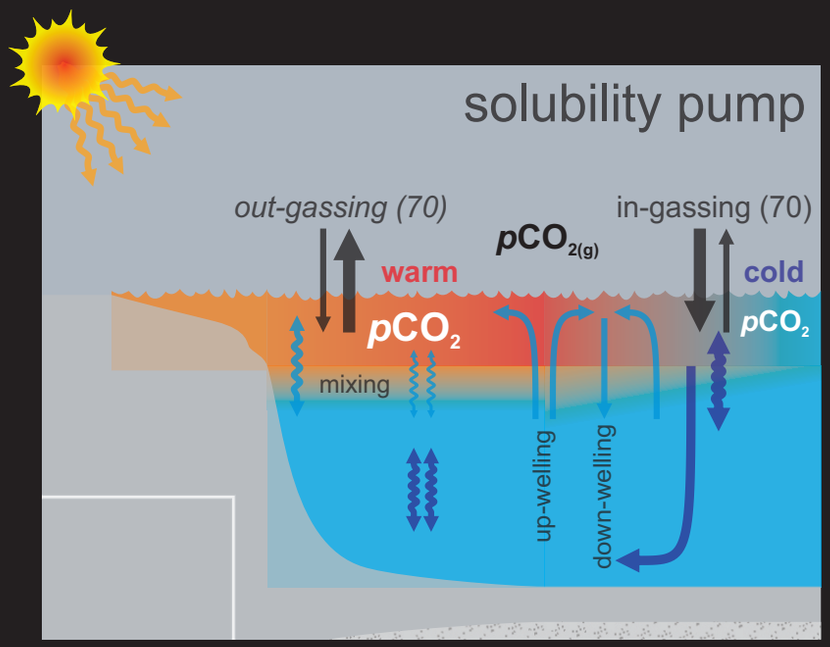


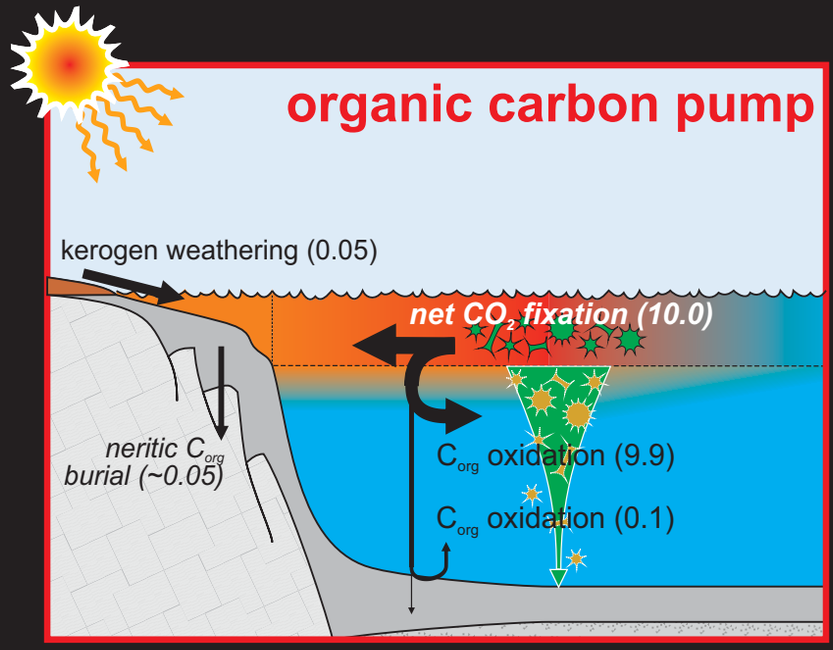
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

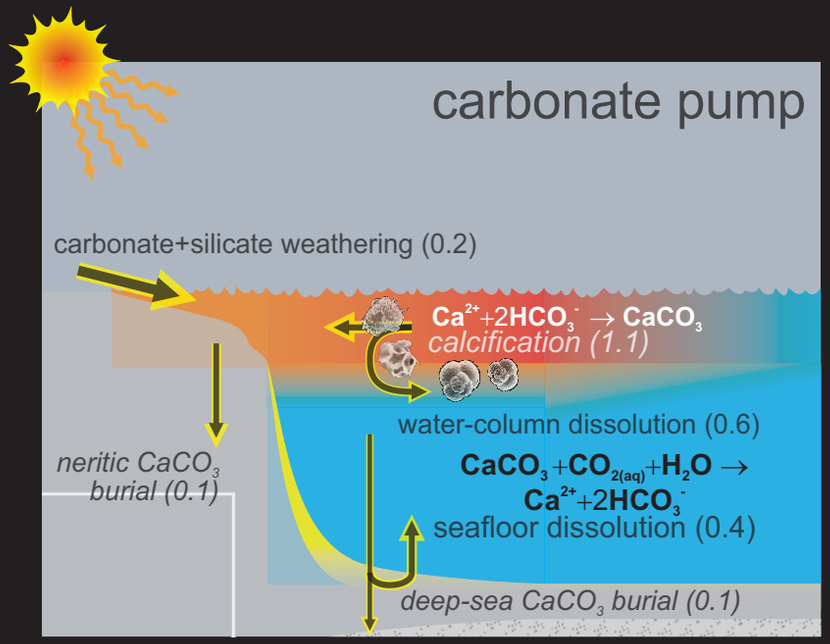
Neoprot.	Mesoprot.	Paleoproterozoic	
Proterozoic			Archean

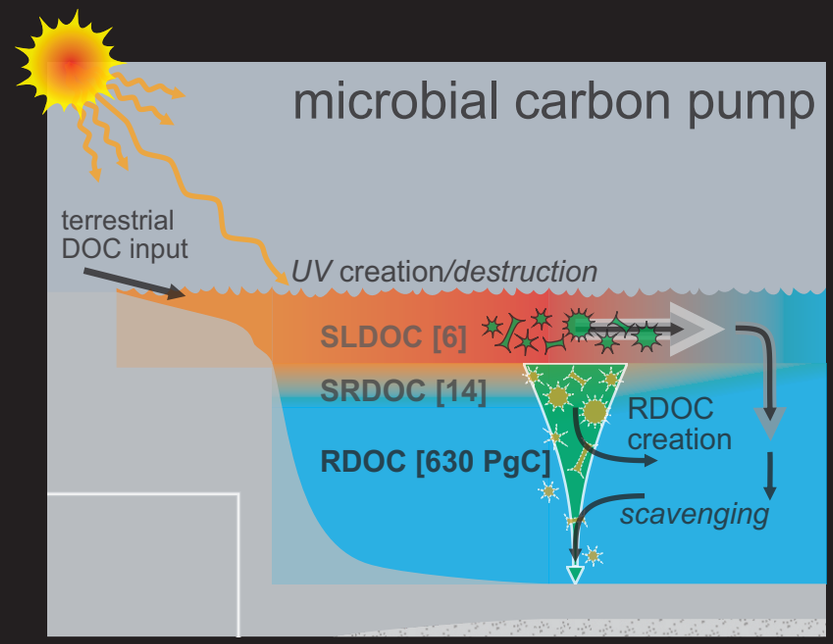
Background

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







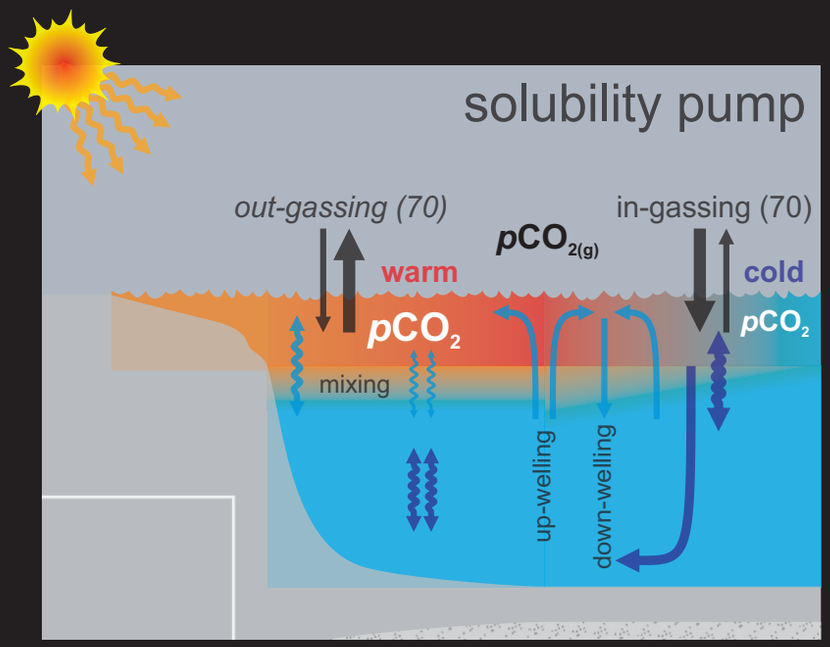


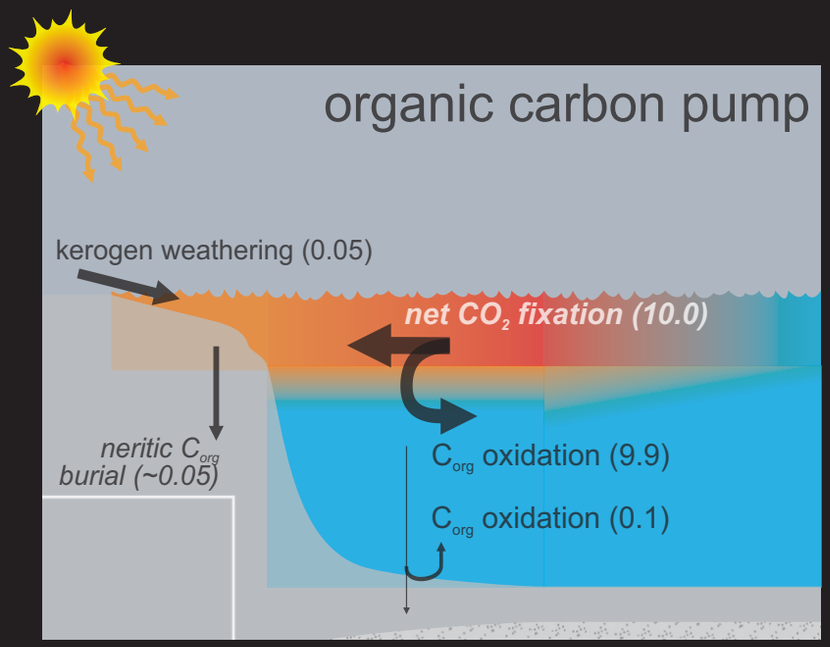
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

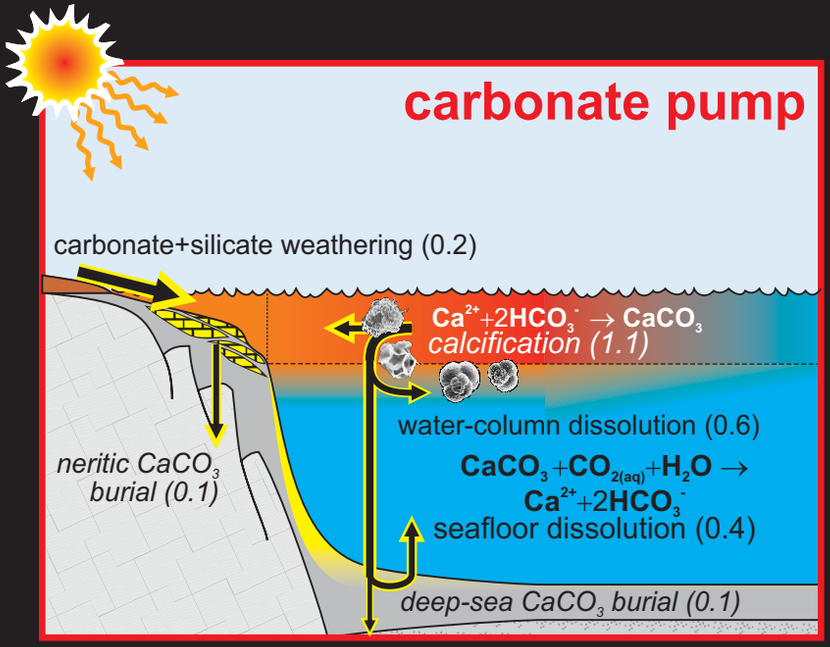
Neoprot.	Mesoprot.	Paleoproterozoic	
Proterozoic			Archean

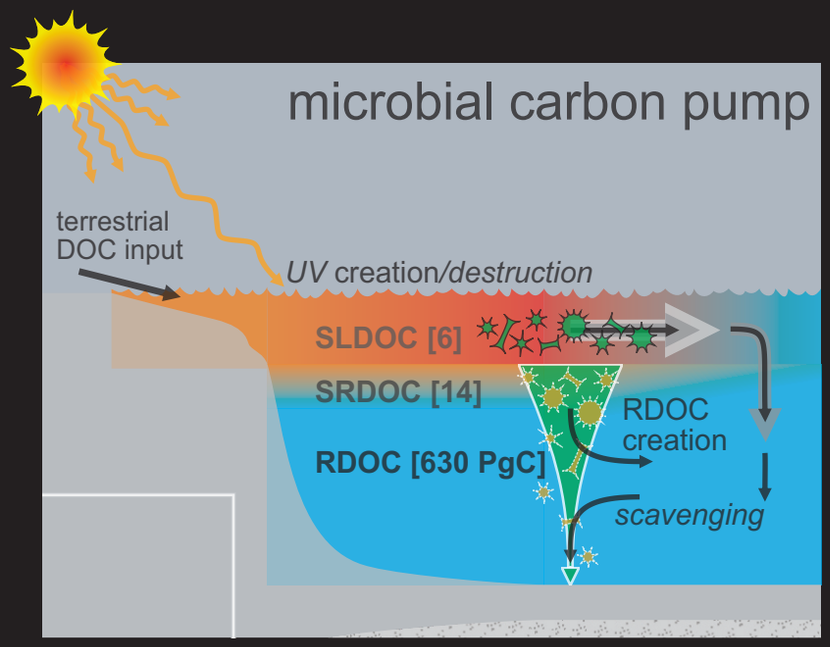
Background

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







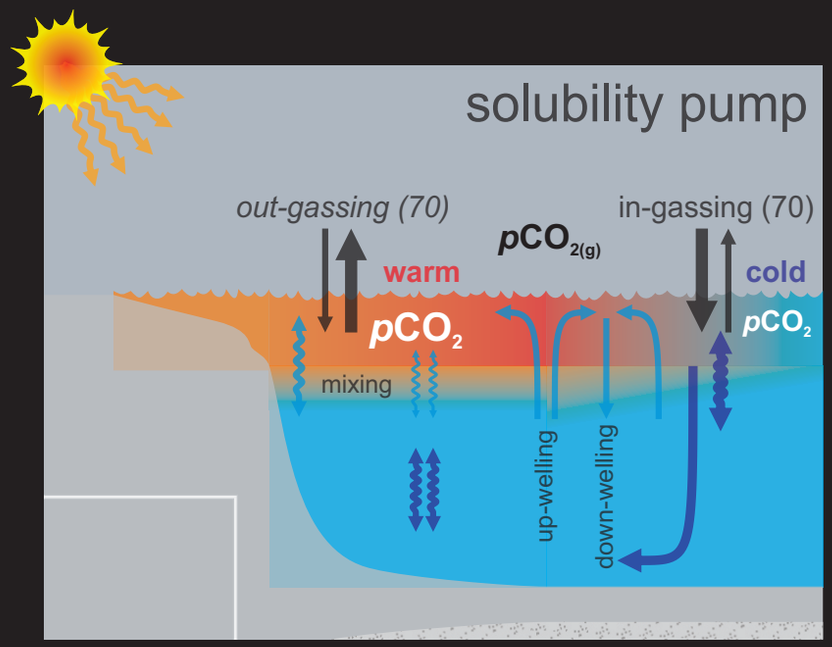


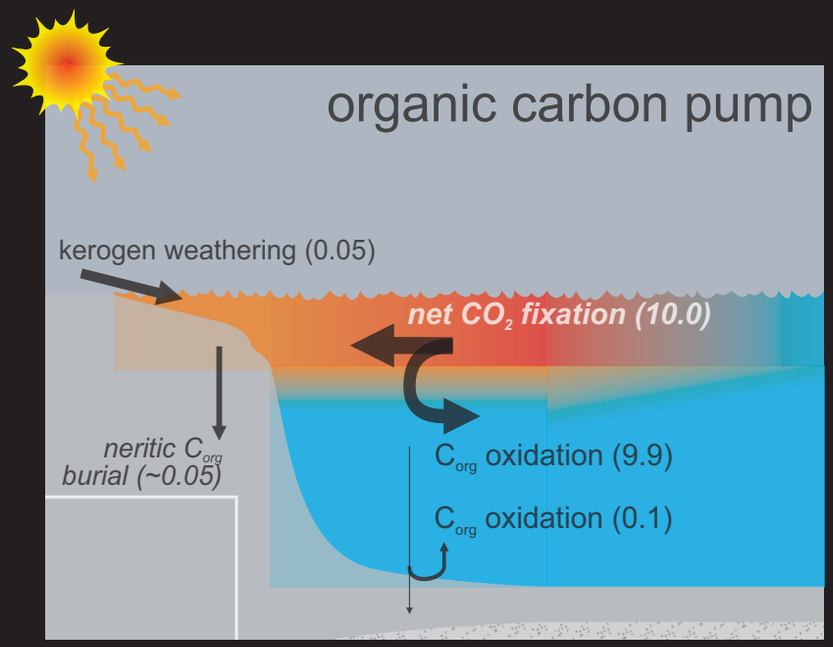
Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

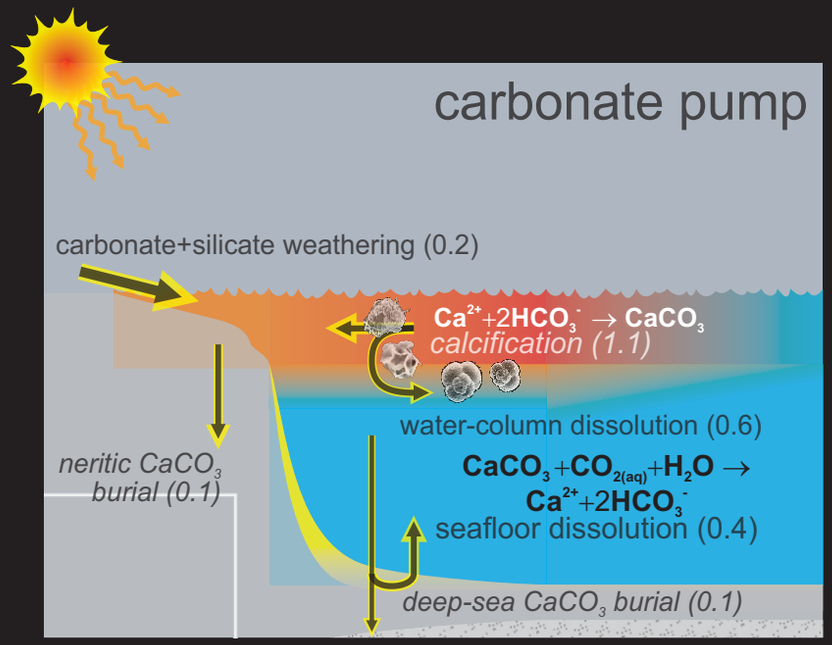
Neoprot.	Mesoprot.	Paleoproterozoic	
Proterozoic			Archean

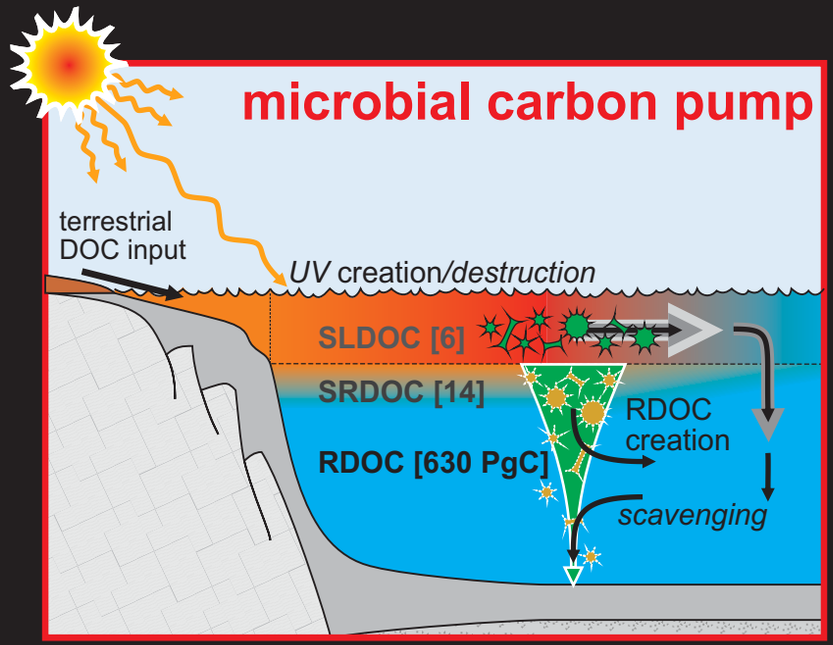
Background

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



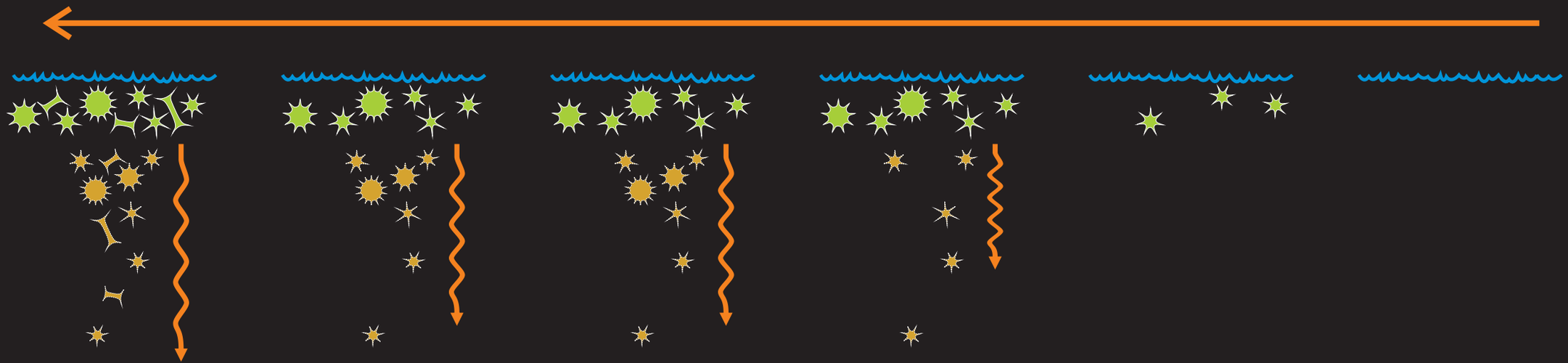






Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic			Paleozoic					
Phanerozoic										

Neoprot.	Mesoprot.	Paleoproterozoic	Archean
Proterozoic			



Ng	Pg	K	J	T	P	C	D	S	O	Cm
Cenozoic		Mesozoic				Paleozoic				
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Neoprot.	Mesoprot.	Paleoproterozoic	
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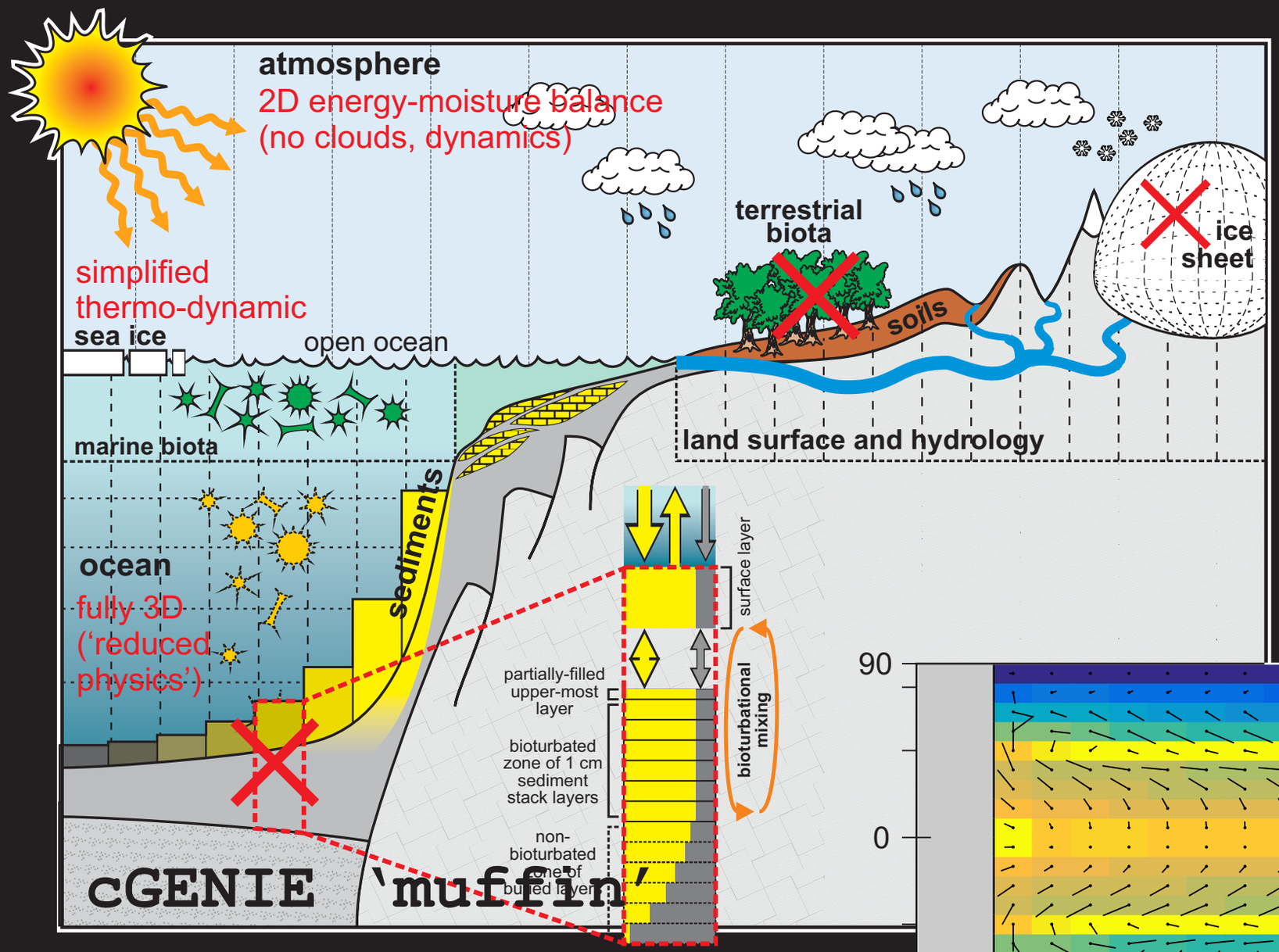
Numerical modelling – Approach

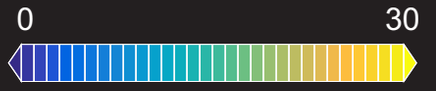


18x18 grid resolution (20 degrees longitude).

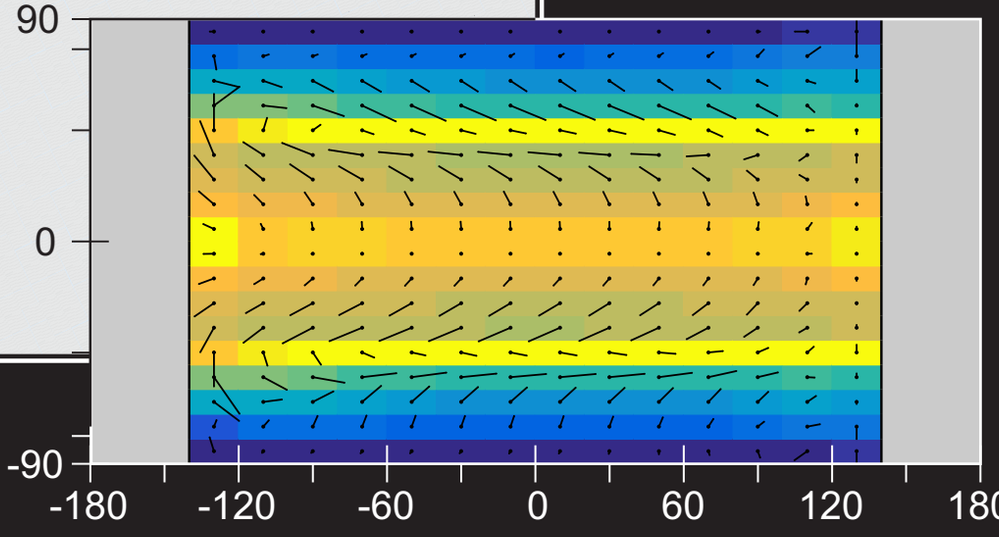
16 ocean levels.

Seasonally forced.

Reduced, ca. Neoproterozoic solar constant, elevated pCO_2.

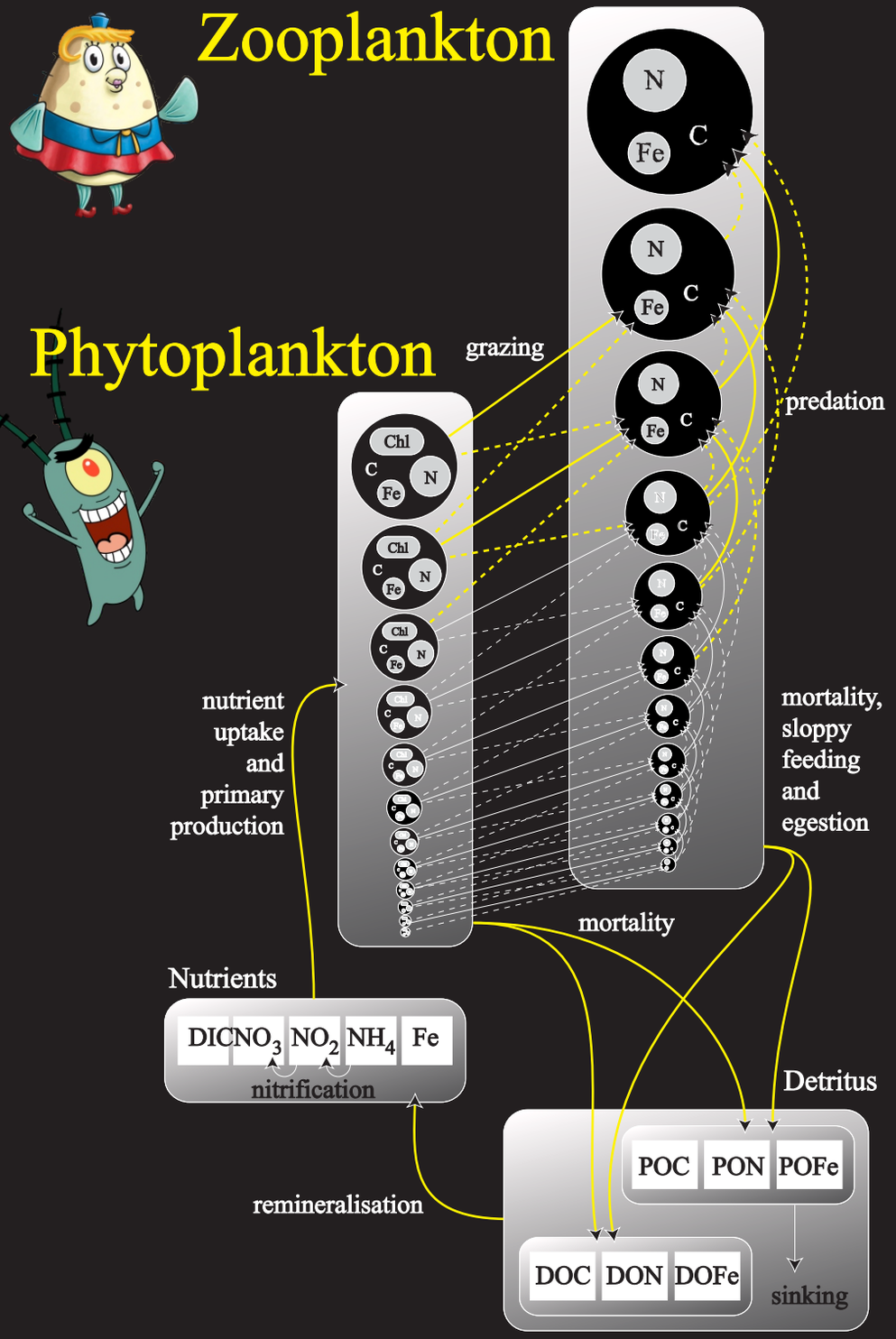


Ocean surface temperature



github.com/derpycode/cgenie.muffin

Numerical modelling – Approach



'ECOGEM' size-structured plankton ecological model [*Ward et al.*, 2018 (*GMD*)].

Can define *n* phytoplankton and *m* zooplankton (and/or mixotrophs).

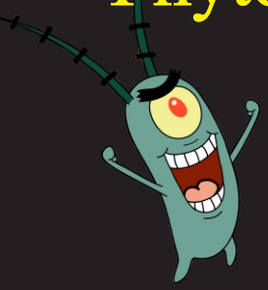
Traits scale with the master variable, cell size.

Each plankton has 'quotas' for C, N, P, Fe, so variable elemental stoichiometry possible (just C and P used here).

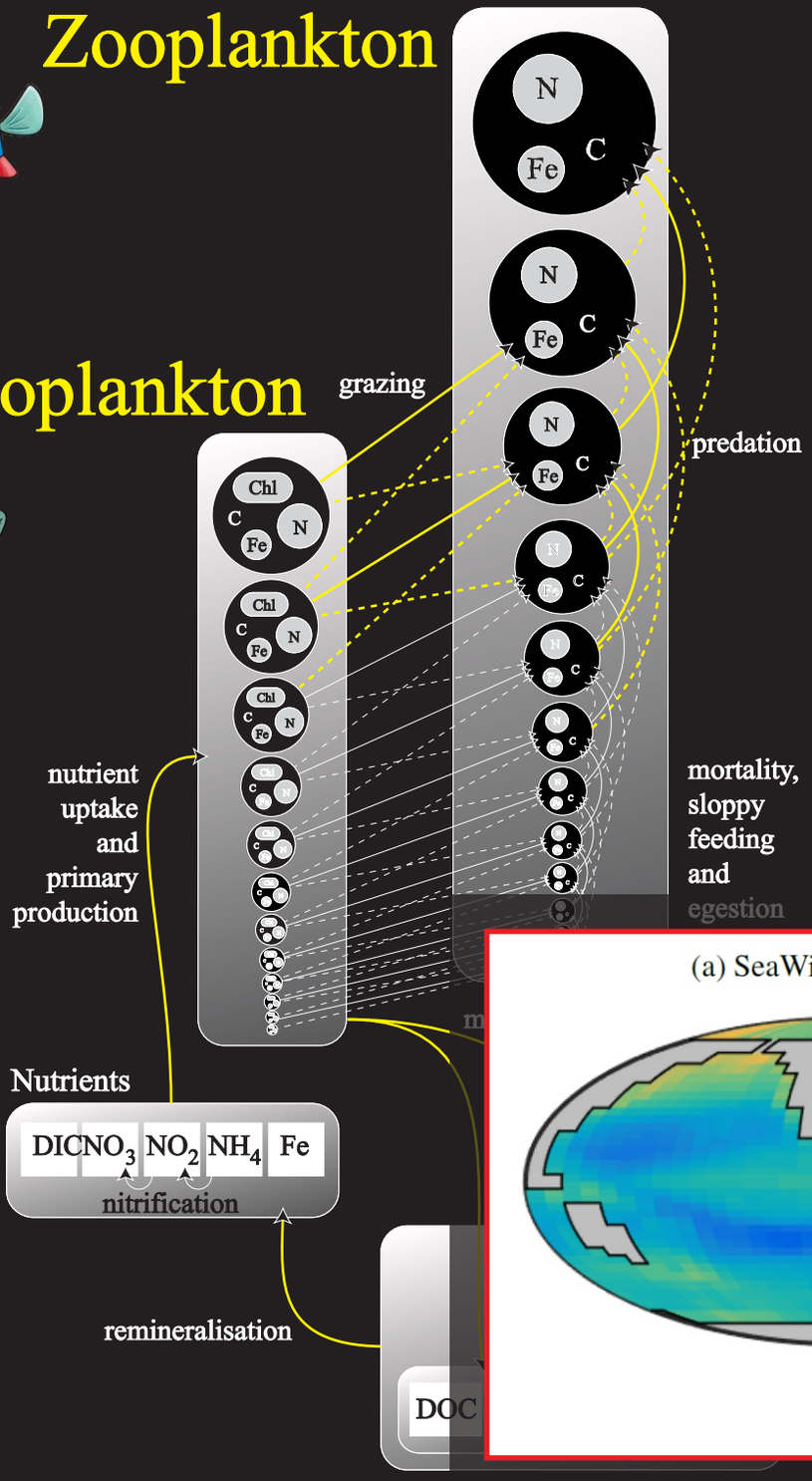
'Standard' functional type ecosystem model grazing formulation (with size preference).

Numerical modelling – Approach

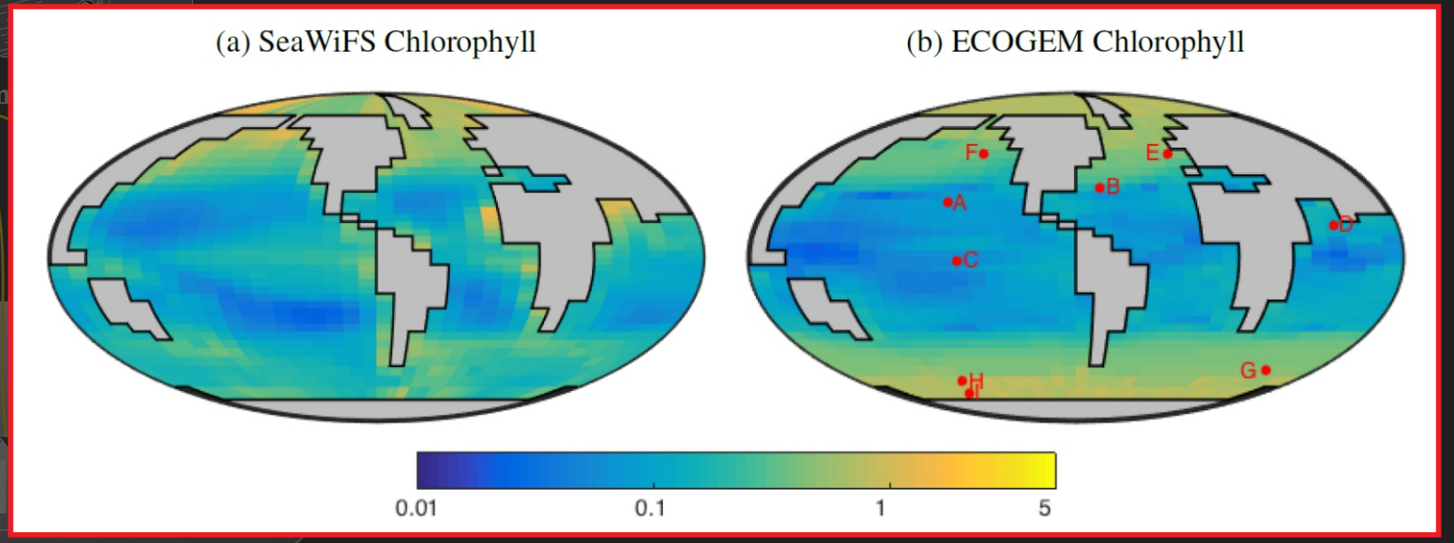
Zooplankton



Phytoplankton

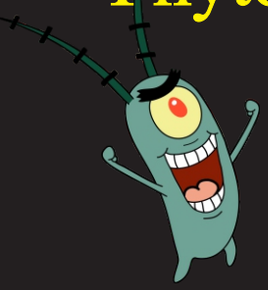


[Ward et al., 2018 (GMD)]

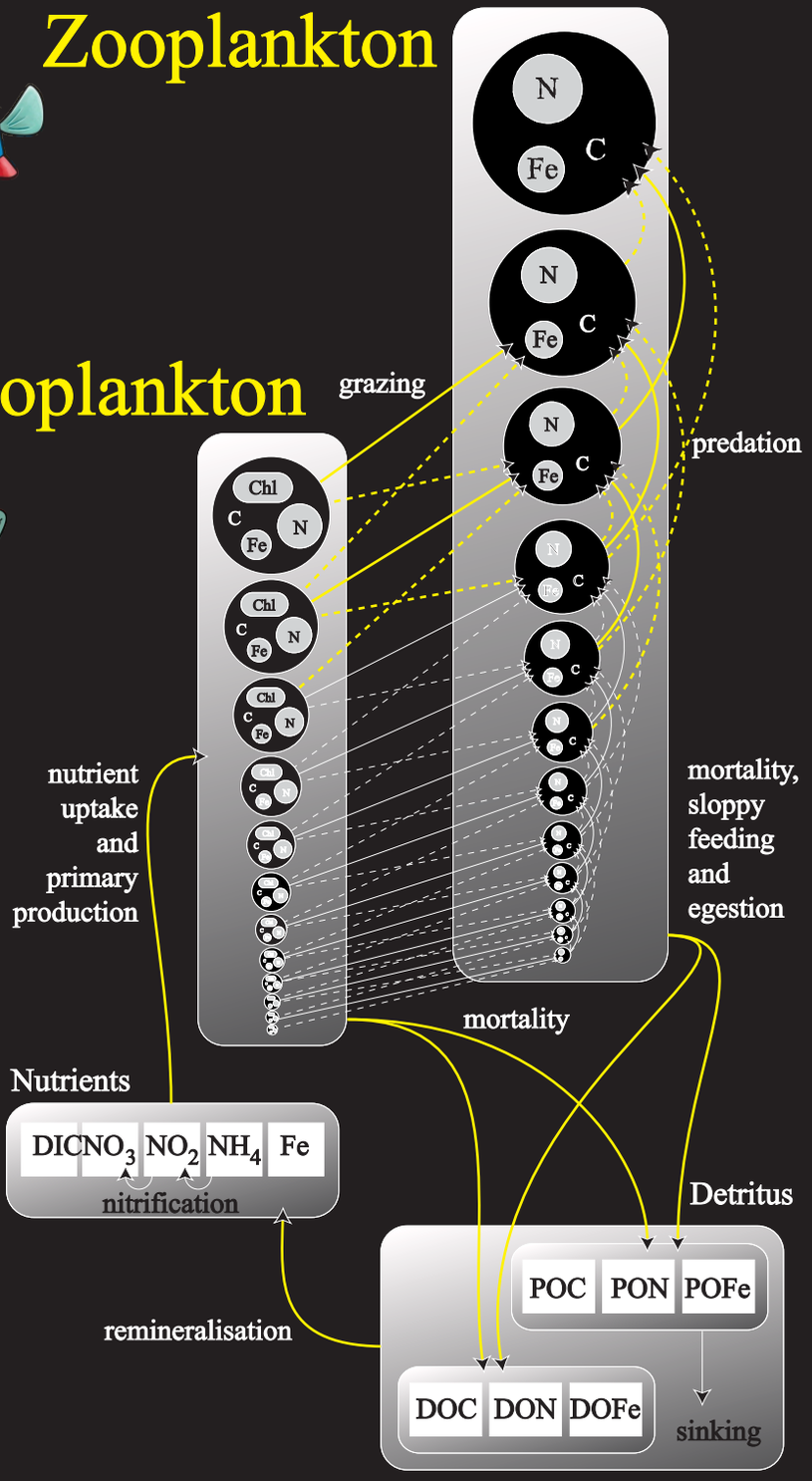


Numerical modelling – Approach

Zooplankton



Phytoplankton



'ECOGEM' size-structured plankton ecological model [*Ward et al.*, 2018 (*GMD*)].

Can define *n* phytoplankton and *m* zooplankton (and/or mixotrophs).

Here:

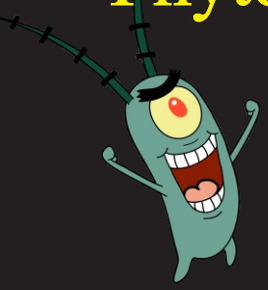
`0-8 phytoplankton size possible classes`
`0-8 zooplankton size possible classes`

i.e. making no *a priori* assumptions about any particular ecosystem structure corresponding to any particular past geological interval.

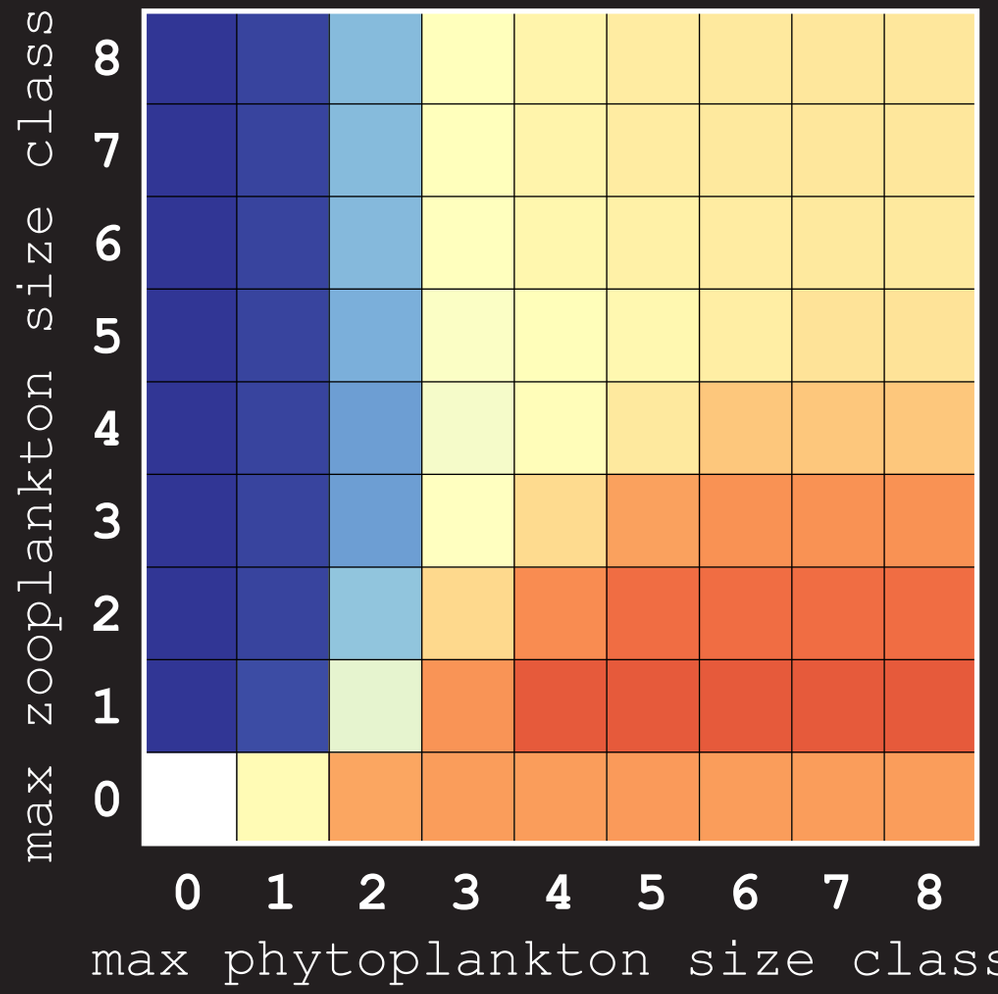
(Already 16 plankton maximum × 3 cellular 'quotas' == 48 ocean tracers, hence low resolution ocean model advantage.)

Numerical modelling – Approach

Zooplankton

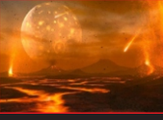


Phytoplankton

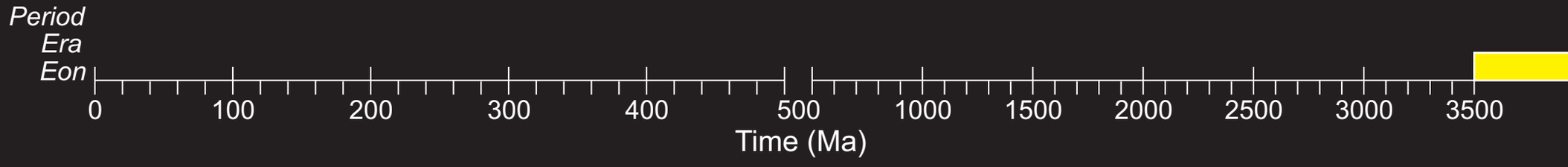


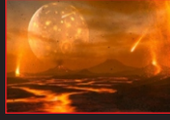

```
0 == no plankton
1 ==  0.6 µm
2 ==  1.9 µm
3 ==  6.0 µm
4 == 19.0 µm
5 == ...
```

Origins ...




© Mark Garlick/Science Photo Library/Corbis


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



solubility pump

?

organic carbon pump

?

carbonate pump

?

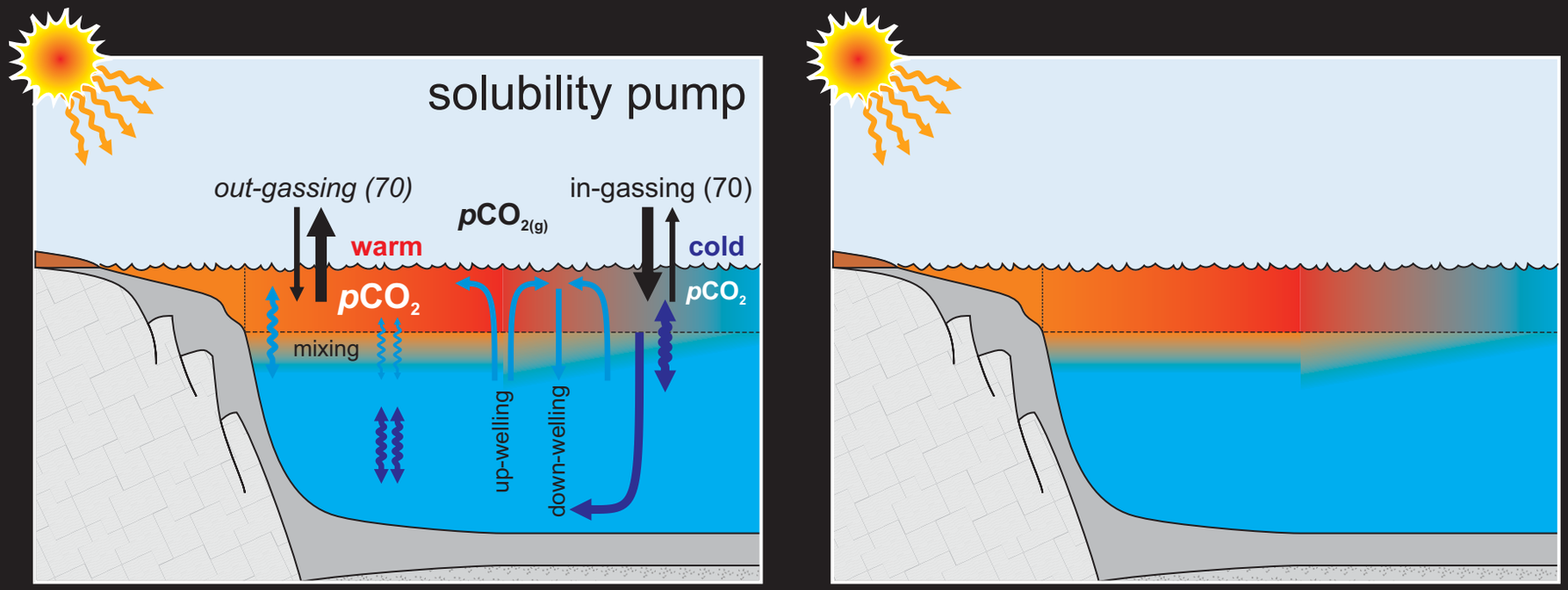
microbial carbon pump

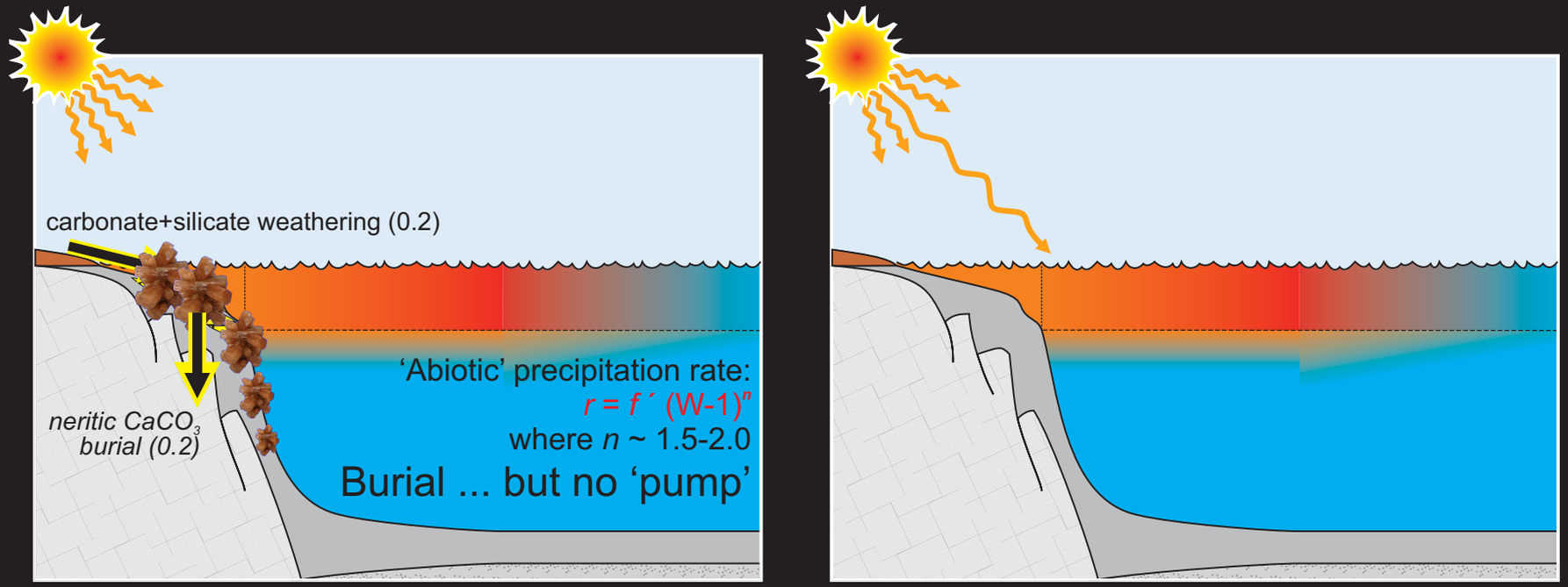
?

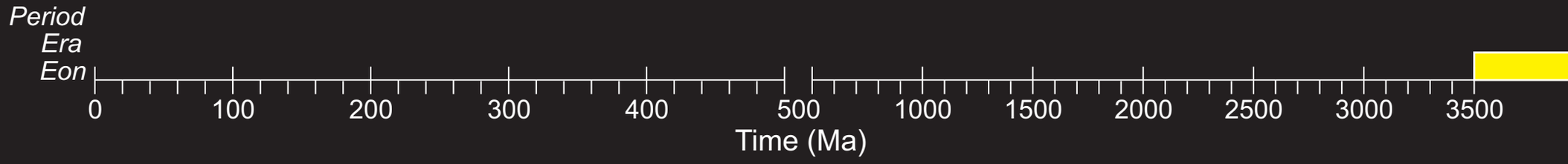
Period
Era
Eon

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

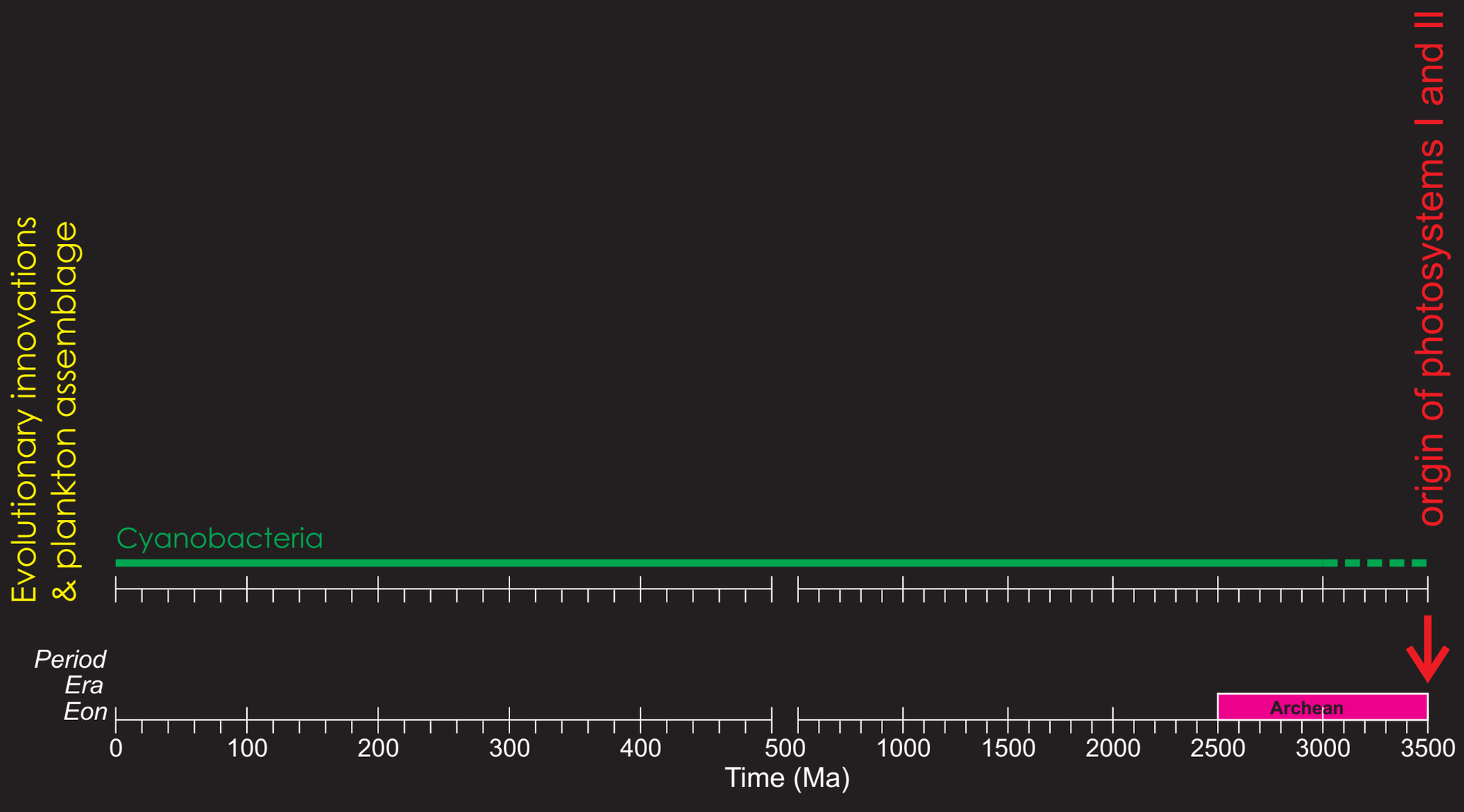
Time (Ma)


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

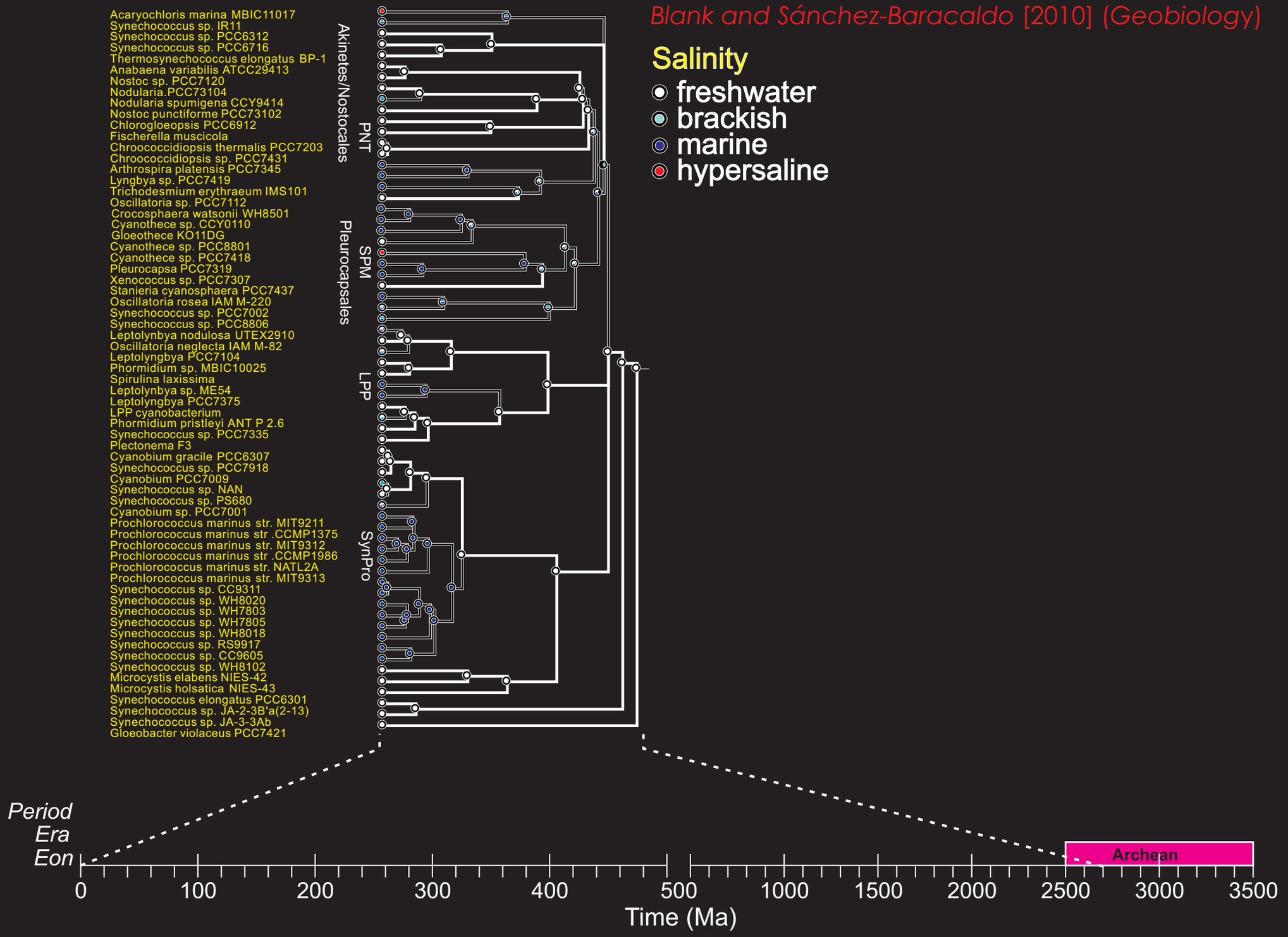

carbonate+silicate weathering (0.2)
neritic CaCO3 burial (0.2)
'Abiotic' precipitation rate:
r = f ´ (W-1)n
where n ~ 1.5-2.0
Burial ... but no 'pump'


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

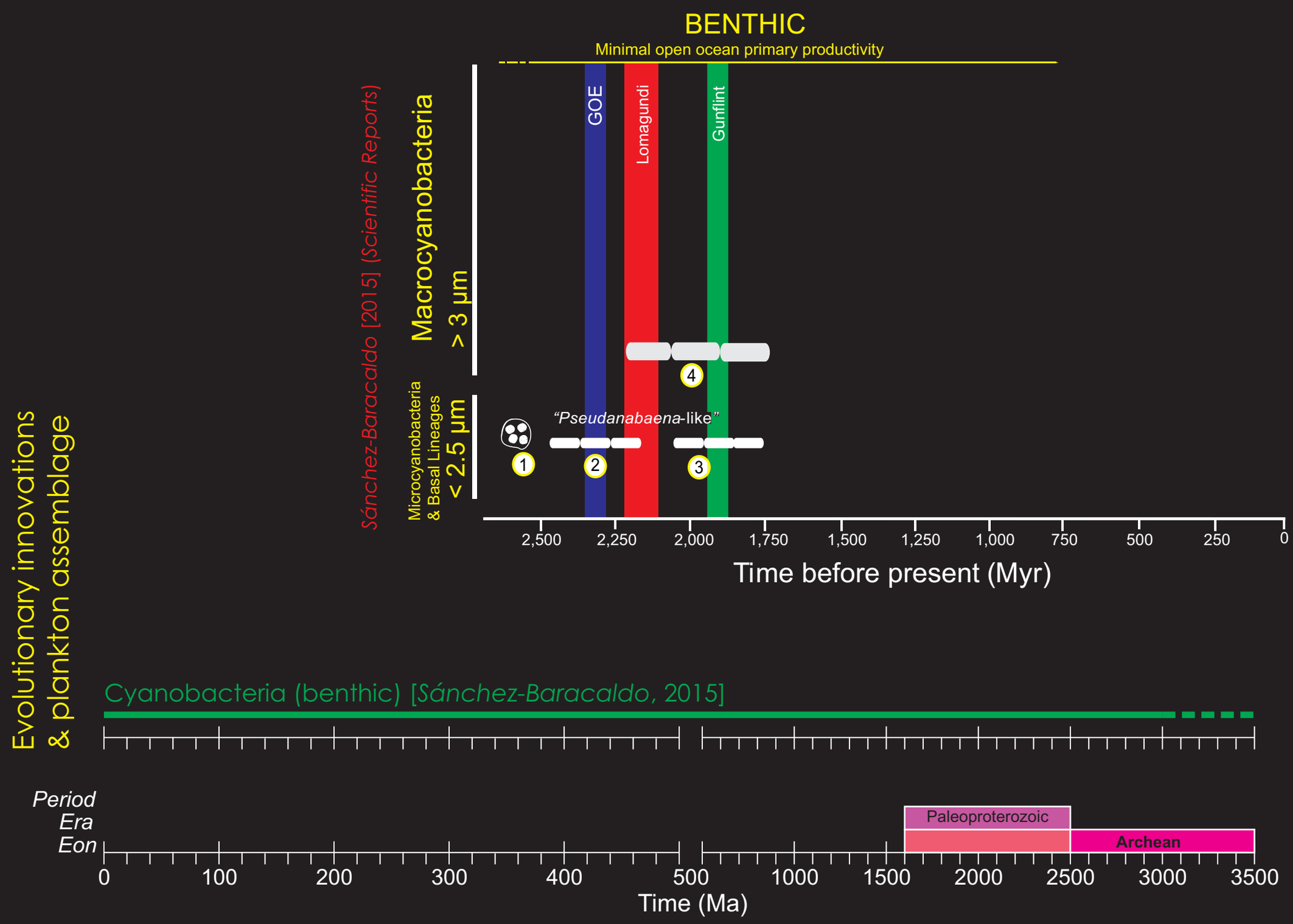
Origins ...


Evolutionary innovations
& plankton assemblage
origin of photosystems I and II
Cyanobacteria
Period
Era
Eon
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

Origins ...


Acaryochloris marina MBIC11017
Synechococcus sp. IR11
Synechococcus sp. PCC6312
Synechococcus sp. PCC6716
Thermosynechococcus elongatus BP-1
Anabaena variabilis ATCC29413
Nostoc sp. PCC7120
Nodularia.PCC73104
Nodularia spumigena CCY9414
Nostoc punctiforme PCC73102
Chlorogloeopsis PCC6912
Fischerella muscicola
Chroococcidiopsis thermalis PCC7203
Chroococcidiopsis sp. PCC7431
Arthrospira platensis PCC7345
Lyngbya sp. PCC7419
Trichodesmium erythraeum IMS101
Oscillatoria sp. PCC7112
Crocosphaera watsonii WH8501
Cyanothece sp. CCY0110
Gloeothece KO11DG
Cyanothece sp. PCC8801
Cyanothece sp. PCC7418
Pleurocapsa PCC7319
Xenococcus sp. PCC7307
Stanieria cyanosphaera PCC7437
Oscillatoria rosea IAM M-220
Synechococcus sp. PCC7002
Synechococcus sp. PCC8806
Leptolynbya nodulosa UTEX2910
Oscillatoria neglecta IAM M-82
Leptolyngbya PCC7104
Phormidium sp. MBIC10025
Spirulina laxissima
Leptolynbya sp. ME54
Leptolyngbya PCC7375
LPP cyanobacterium
Phormidium pristleyi ANT P 2.6
Synechococcus sp. PCC7335
Plectonema F3
Cyanobium gracile PCC6307
Synechococcus sp. PCC7918
Cyanobium PCC7009
Synechococcus sp. NAN
Synechococcus sp. PS680
Cyanobium sp. PCC7001
Prochlorococcus marinus str. MIT9211
Prochlorococcus marinus str .CCMP1375
Prochlorococcus marinus str. MIT9312
Prochlorococcus marinus str .CCMP1986
Prochlorococcus marinus str. NATL2A
Prochlorococcus marinus str. MIT9313
Synechococcus sp. CC9311
Synechococcus sp. WH8020
Synechococcus sp. WH7803
Synechococcus sp. WH7805
Synechococcus sp. WH8018
Synechococcus sp. RS9917
Synechococcus sp. CC9605
Synechococcus sp. WH8102
Microcystis elabens NIES-42
Microcystis holsatica NIES-43
Synechococcus elongatus PCC6301
Synechococcus sp. JA-2-3B'a(2-13)
Synechococcus sp. JA-3-3Ab
Gloeobacter violaceus PCC7421
Akinetes/Nostocales
PNT
Pleurocapsales
SPM
LPP
SynPro
Blank and Sánchez-Baracaldo [2010] (Geobiology)
Salinity
freshwater
brackish
marine
hypersaline
Period
Era
Eon
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

Origins ...


BENTHIC
Minimal open ocean primary productivity
Sánchez-Baracaldo [2015] (Scientific Reports)
Macrocyanobacteria
> 3 µm
Microcyanobacteria
& Basal Lineages
< 2.5 µm
GOE
Lomagundi
Gunflint
"Pseudanabaena-like"
1
2
3
4
2,500
2,250
2,000
1,750
1,500
1,250
1,000
750
500
250
0
Time before present (Myr)
Evolutionary innovations
& plankton assemblage
Cyanobacteria (benthic) [Sánchez-Baracaldo, 2015]
Period
Era
Eon
Paleoproterozoic
Archean
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
Time (Ma)

solubility pump

?

organic carbon pump

?

carbonate pump

?

microbial carbon pump

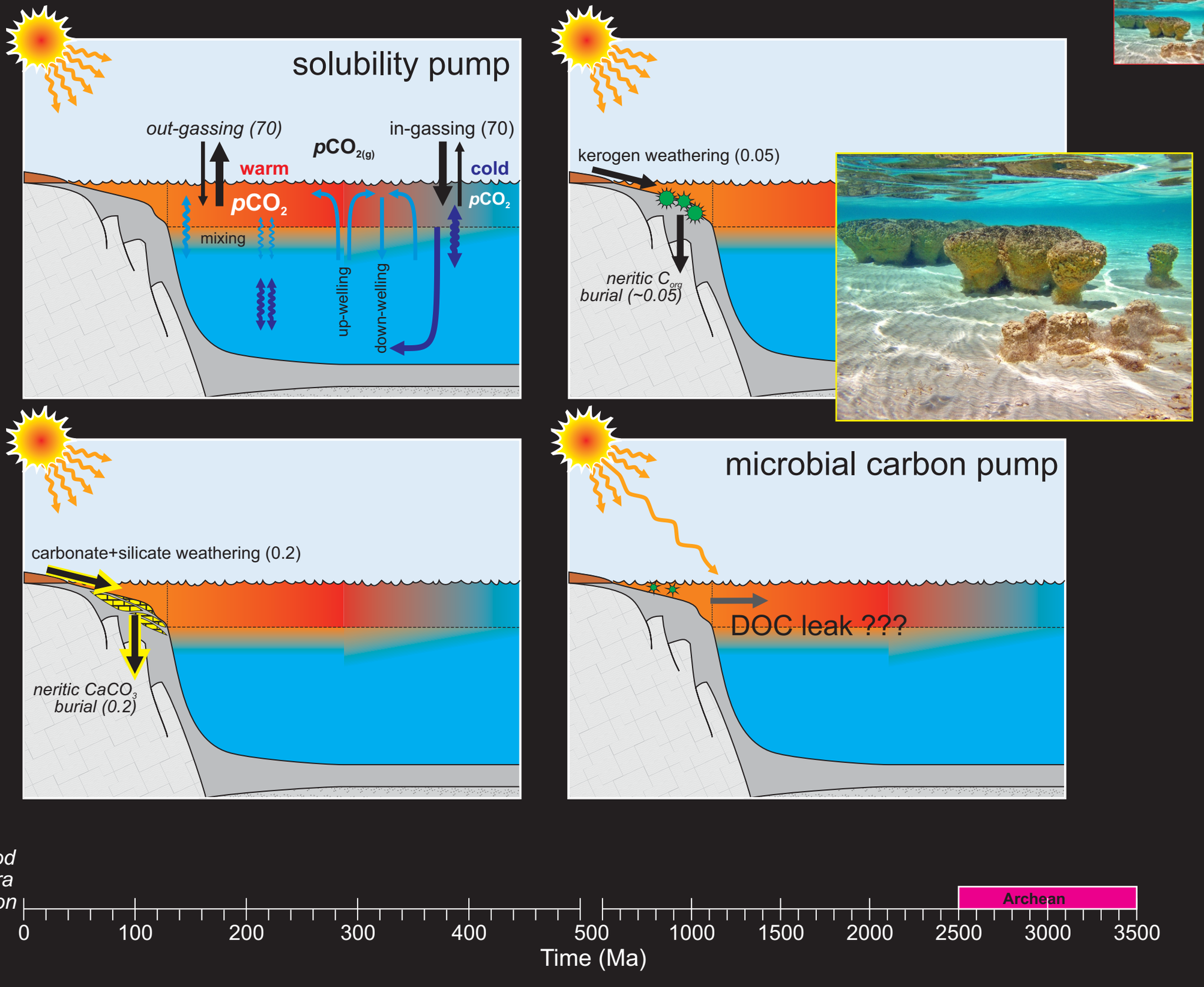
?

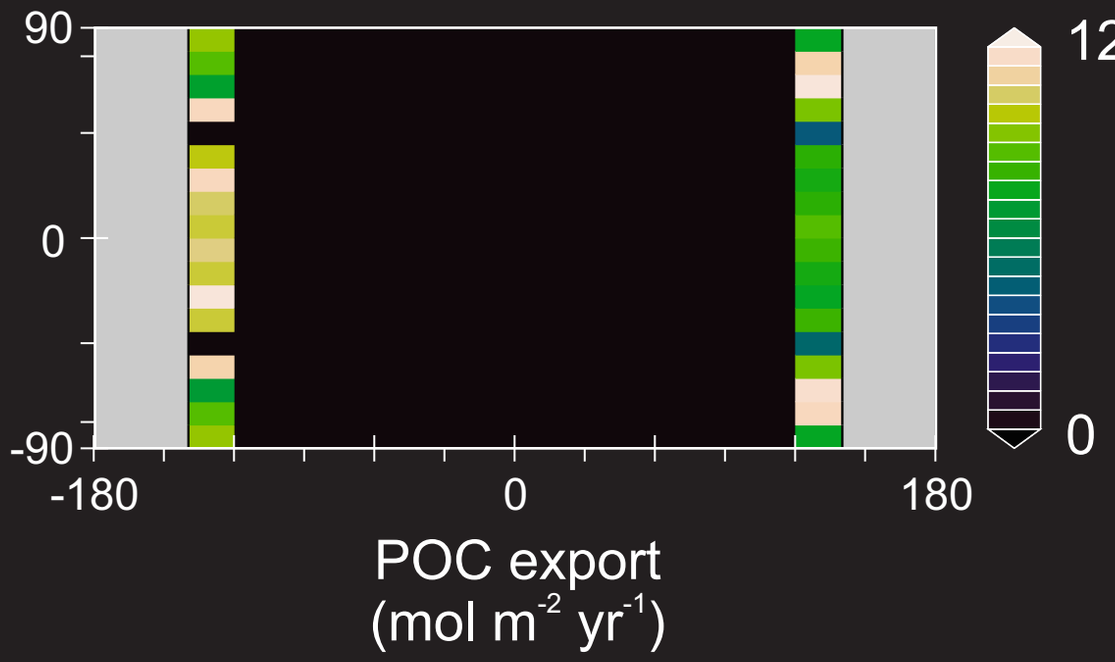
Period
Era
Eon

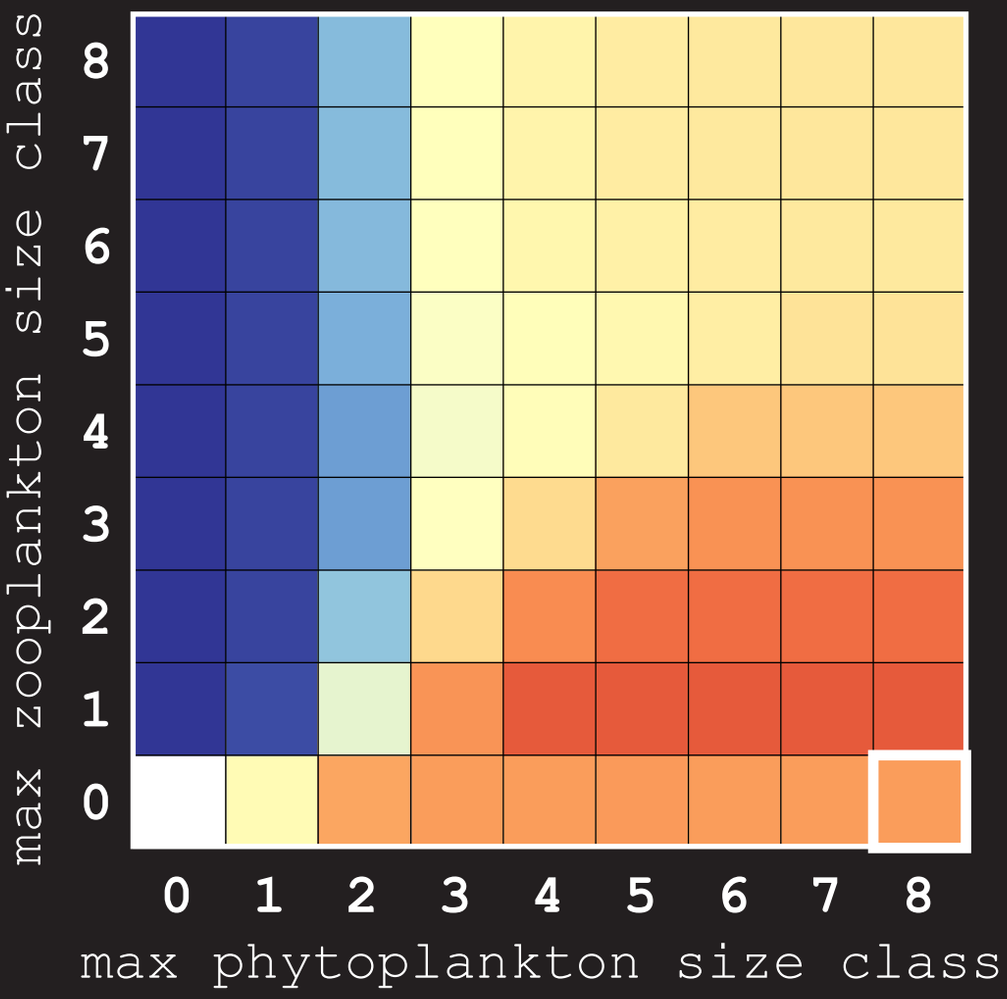
Archean

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

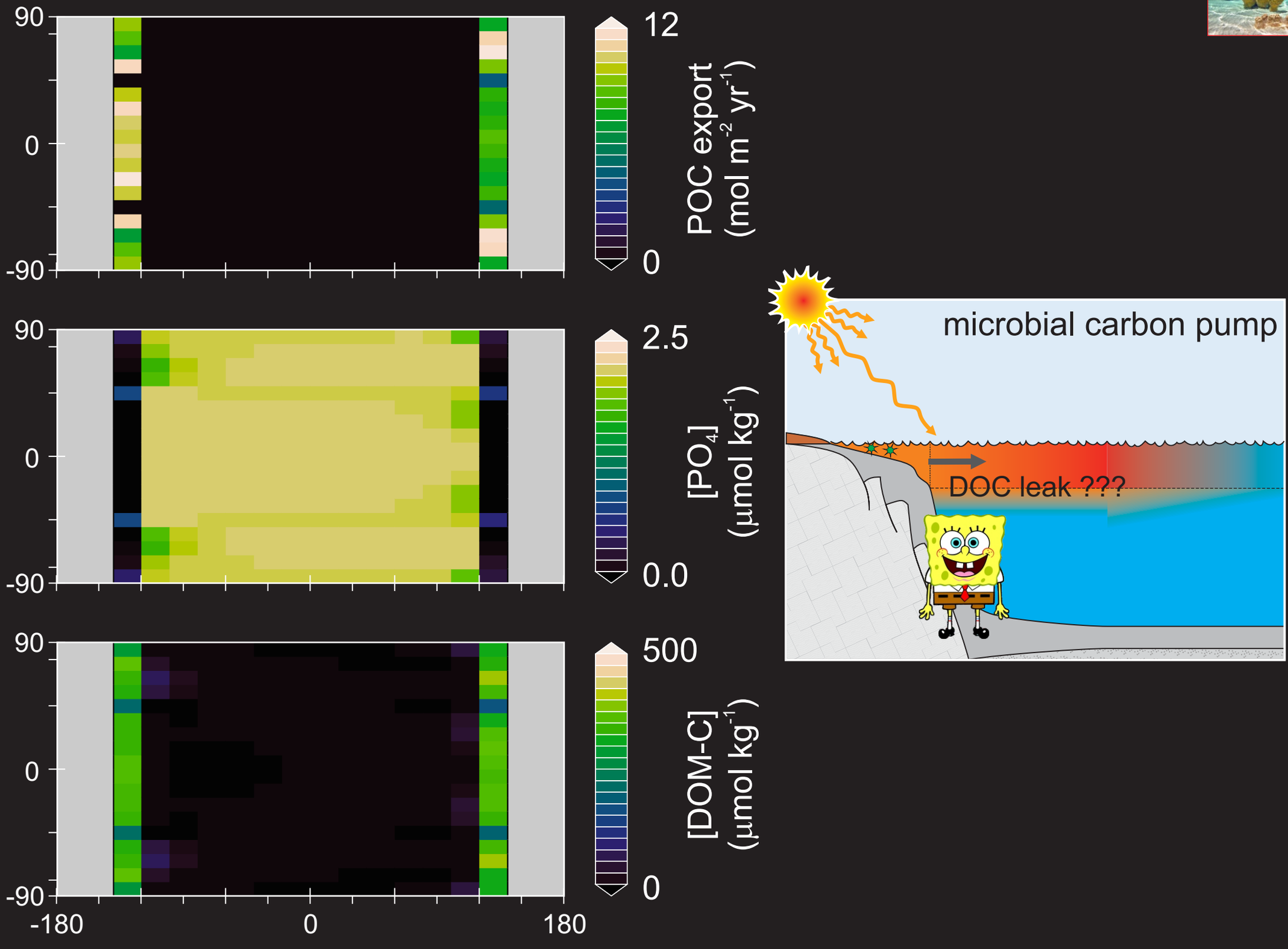
Time (Ma)


solubility pump
out-gassing (70)
in-gassing (70)
pCO2(g)
warm
cold
pCO2
pCO2
mixing
up-welling
down-welling
kerogen weathering (0.05)
neritic Corg burial (~0.05)
carbonate+silicate weathering (0.2)
neritic CaCO3 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)

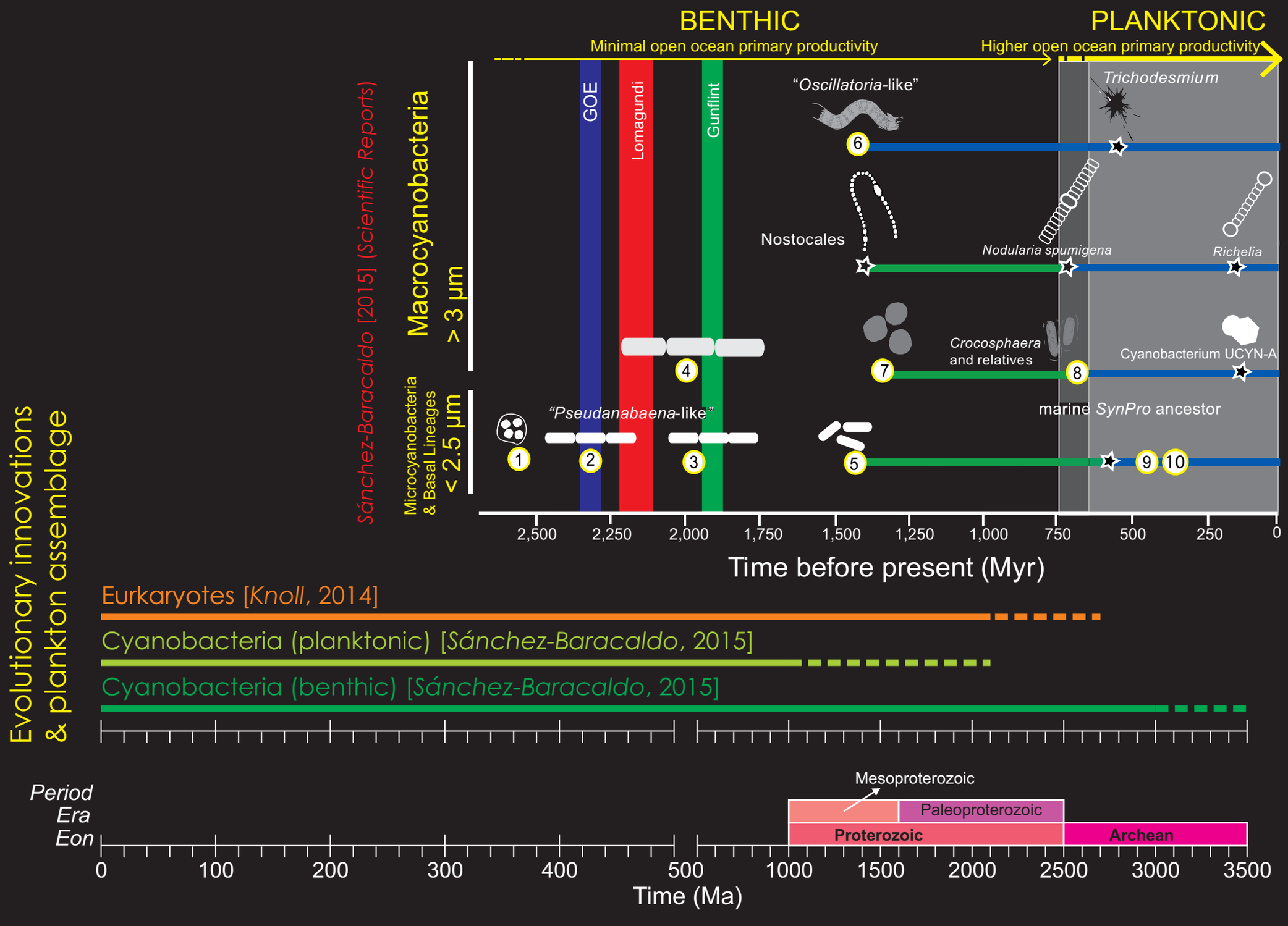




0 == no plankton
1 == 0.6 µm
2 == 1.9 µm
3 == 6.0 µm
4 == 19.0 µm
5 == ...


90
0
-90
12
0
POC export
(mol m-2 yr-1)
90
0
-90
2.5
0.0
[PO4]
(µmol kg-1)
90
0
-90
500
0
[DOM-C]
(µmol kg-1)
-180
0
180
microbial carbon pump
DOC leak ???

The Force awakens ... ???



solubility pump

?

organic carbon pump

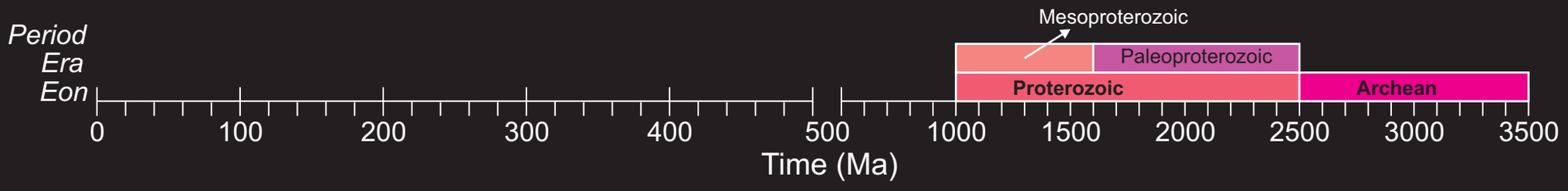
?

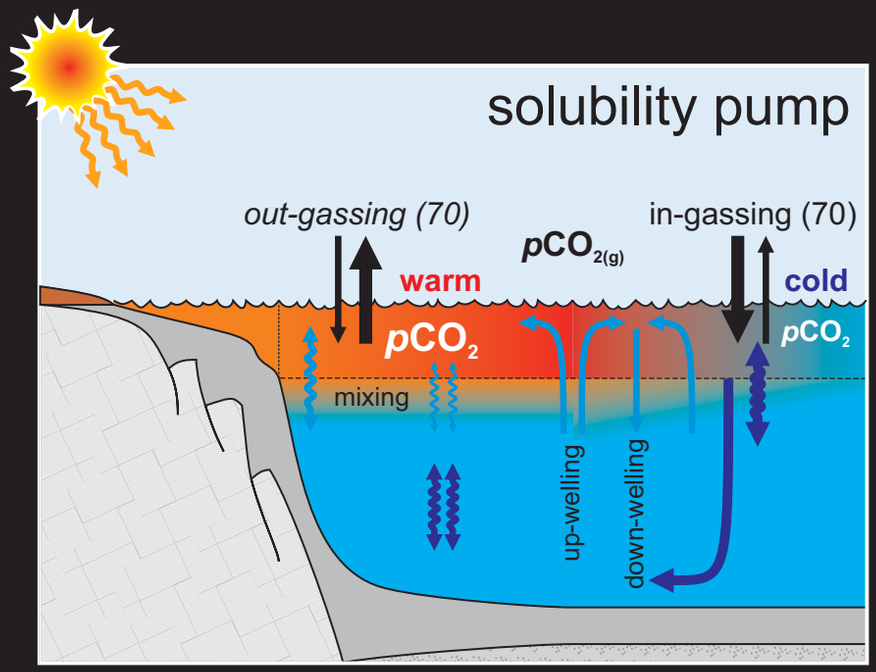
carbonate pump

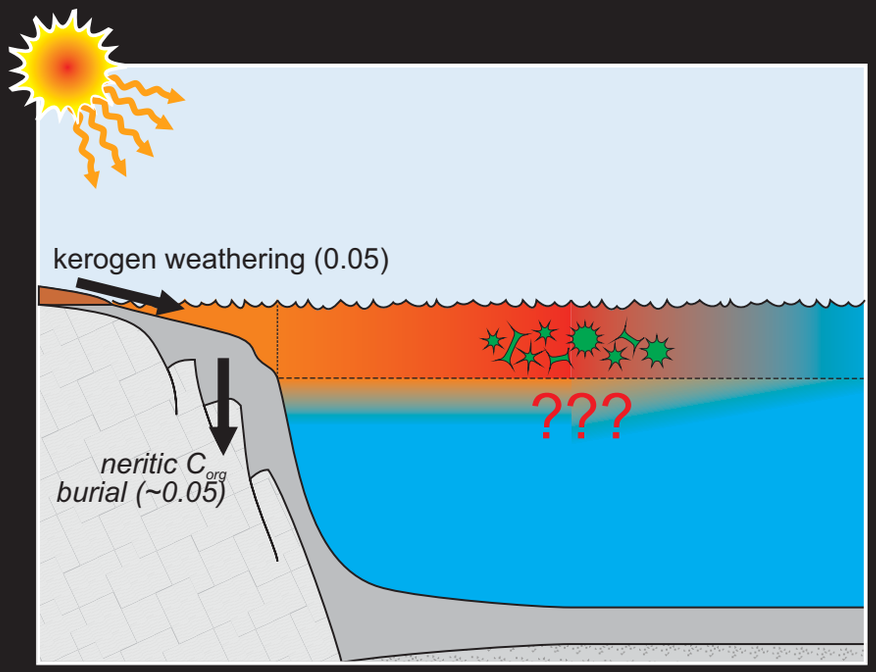
?

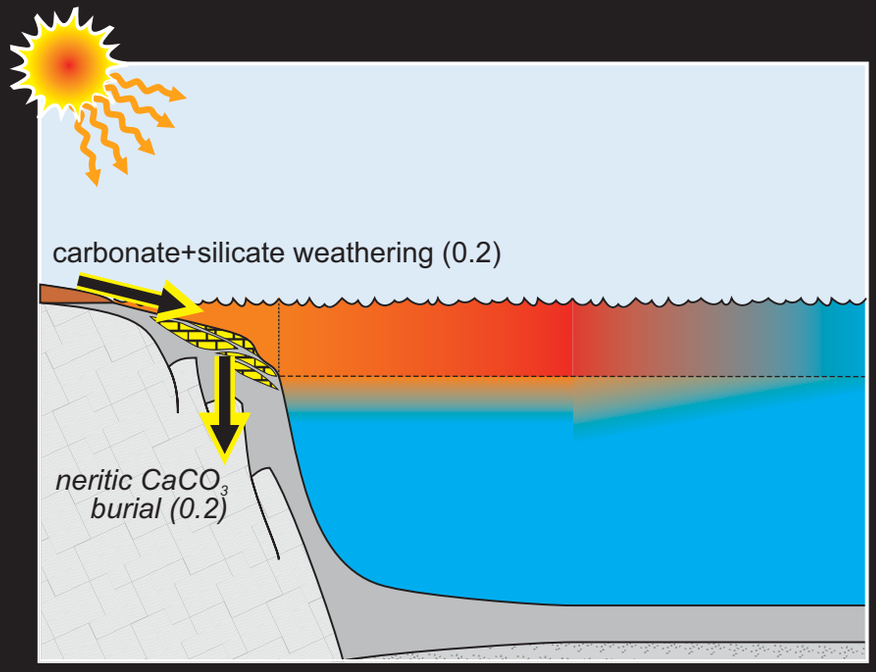
microbial carbon pump

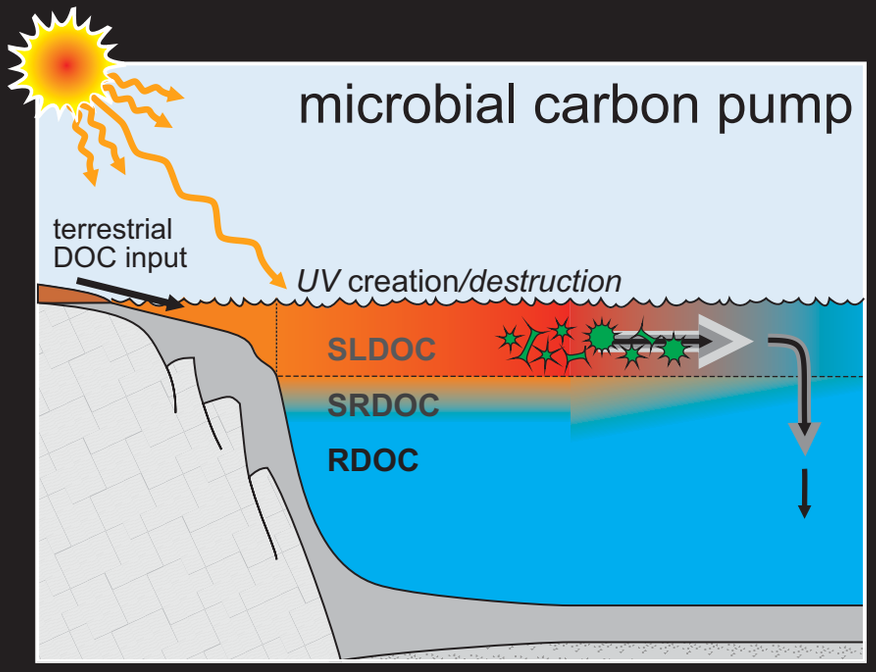
?

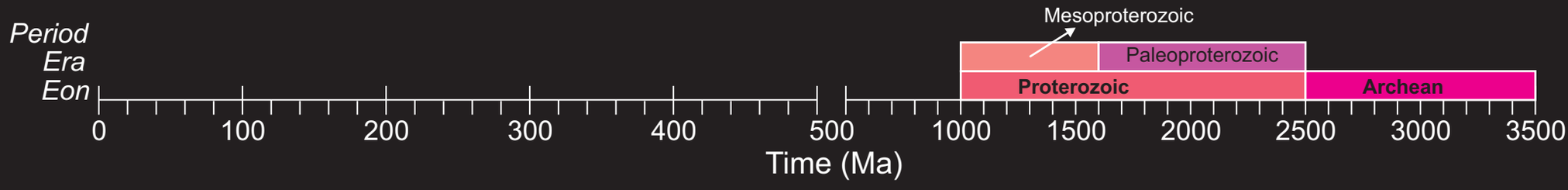



solubility pump
out-gassing (70)
in-gassing (70)
$pCO_{2(g)}$
warm
cold
pCO_2
pCO_2
mixing
up-welling
down-welling

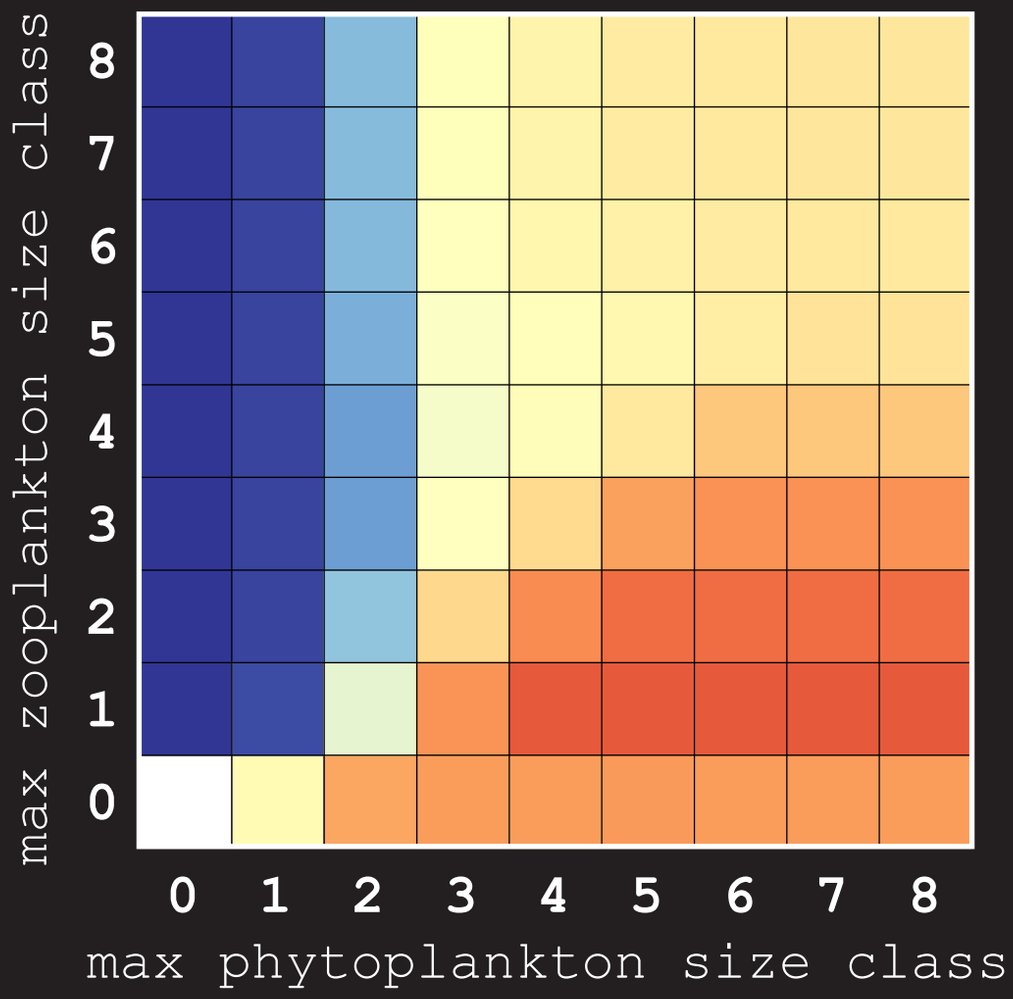

kerogen weathering (0.05)
???
neritic C_{org} burial (~0.05)


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)

The Force awakens ... ???



0 == no plankton
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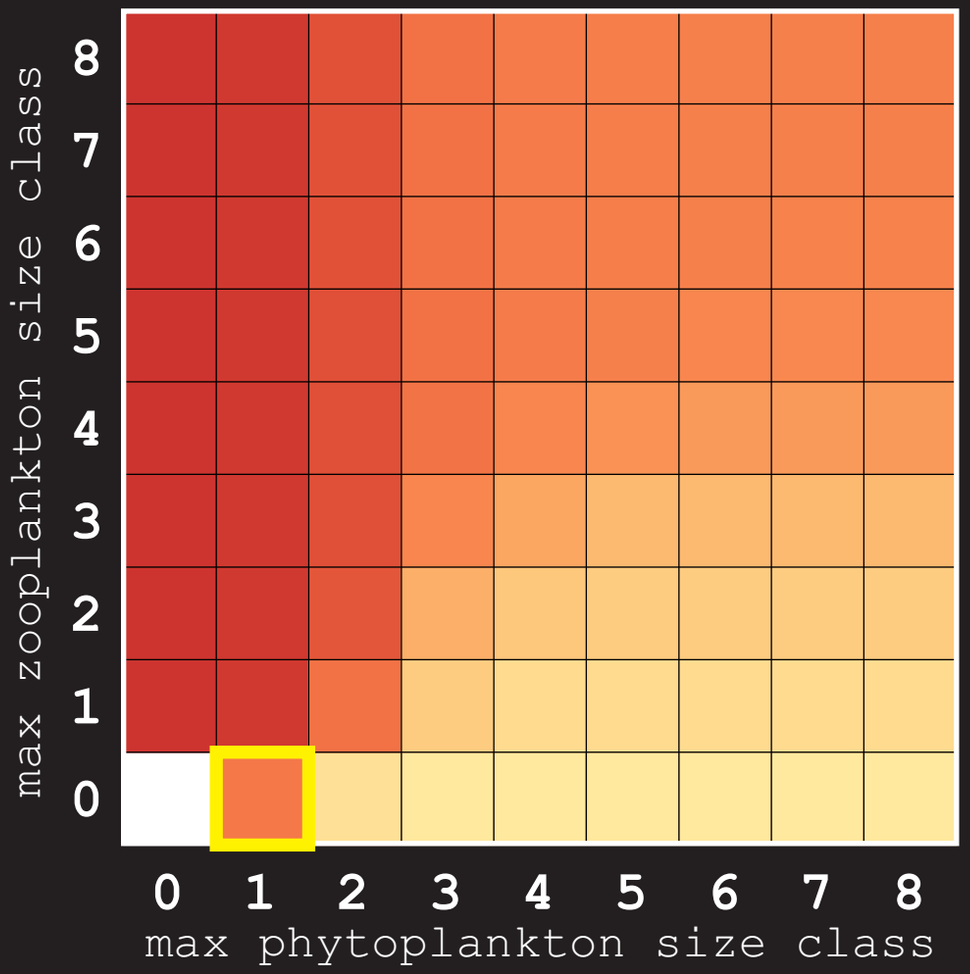
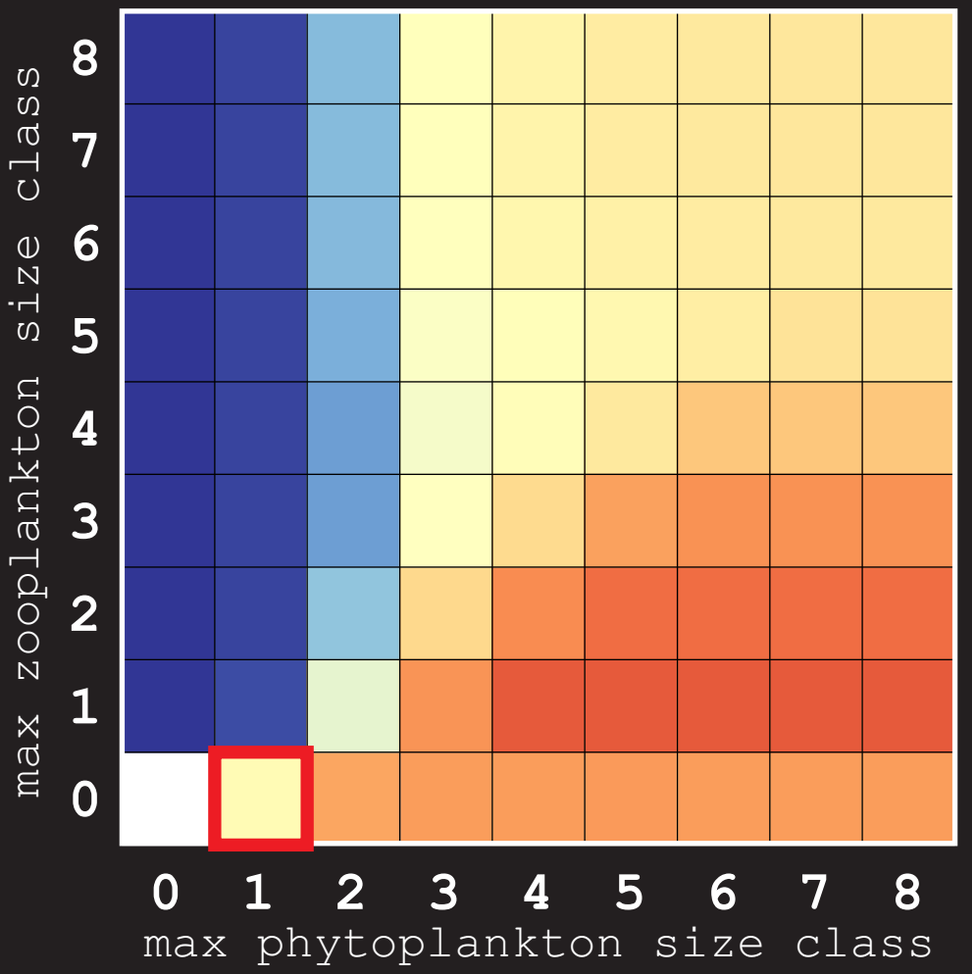
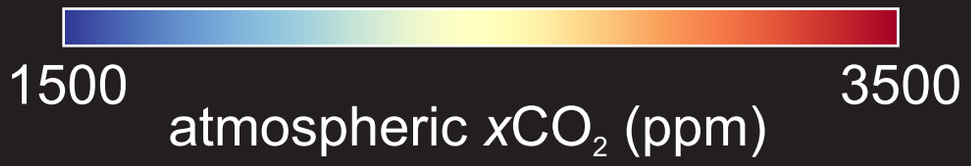
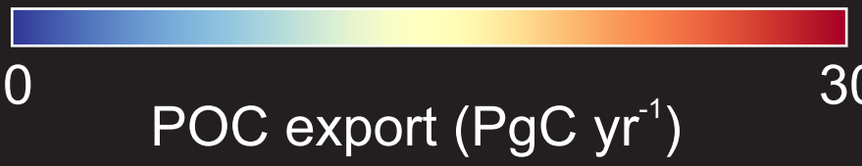
3 == 6.0 µm
4 == 19.0 µm
5 == ...

The Force awakens – (I) planktonic habitat (small cell size)

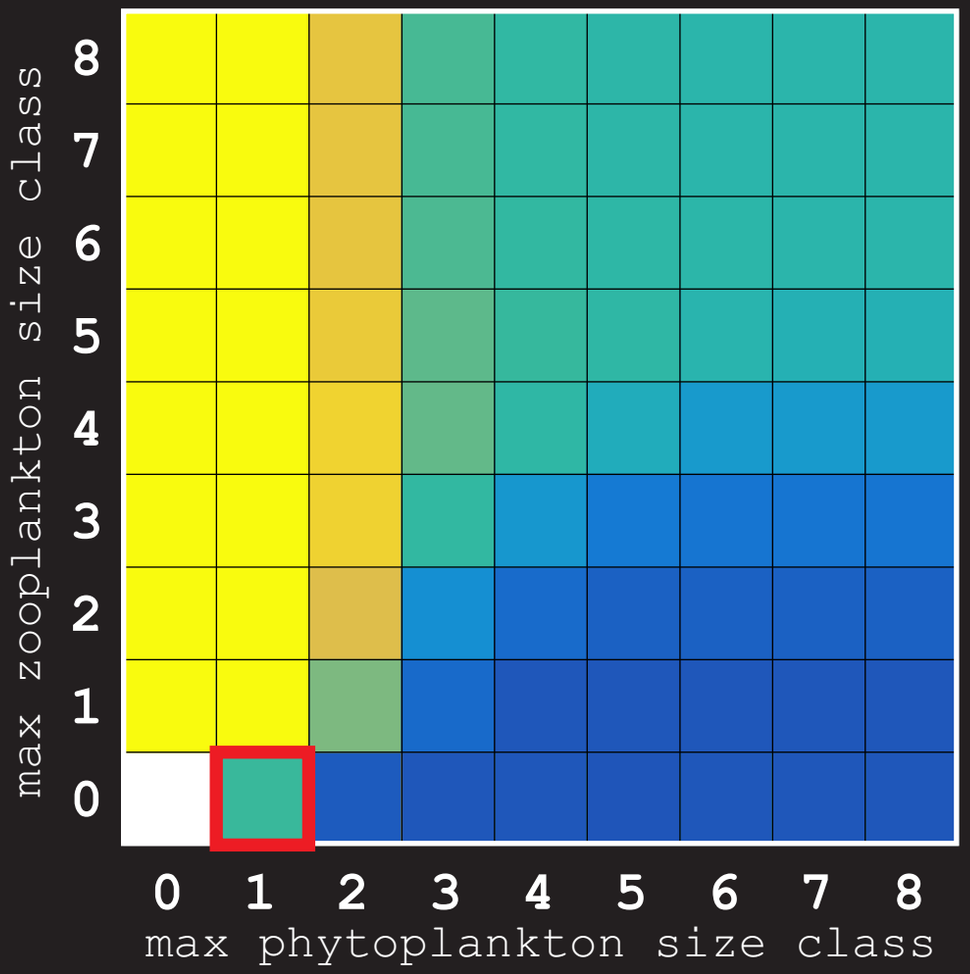


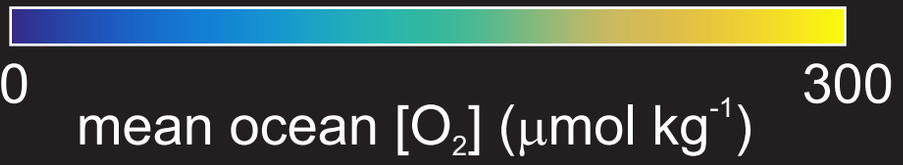


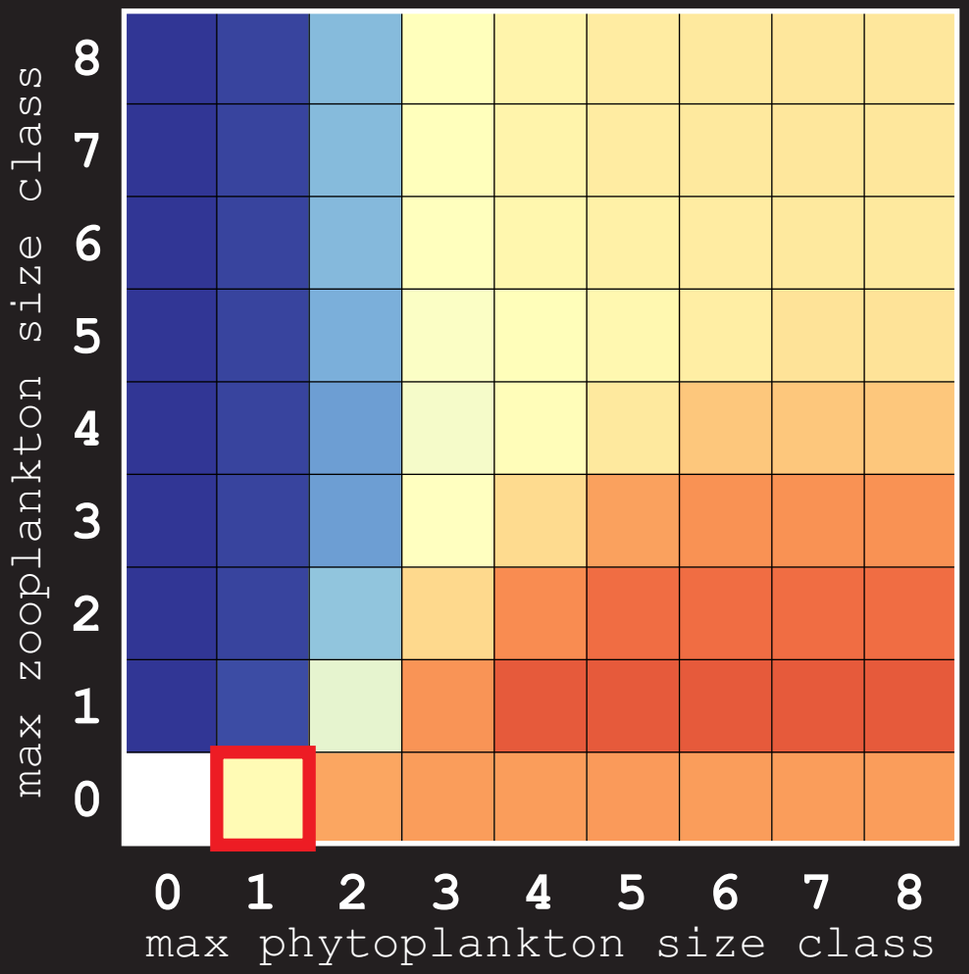




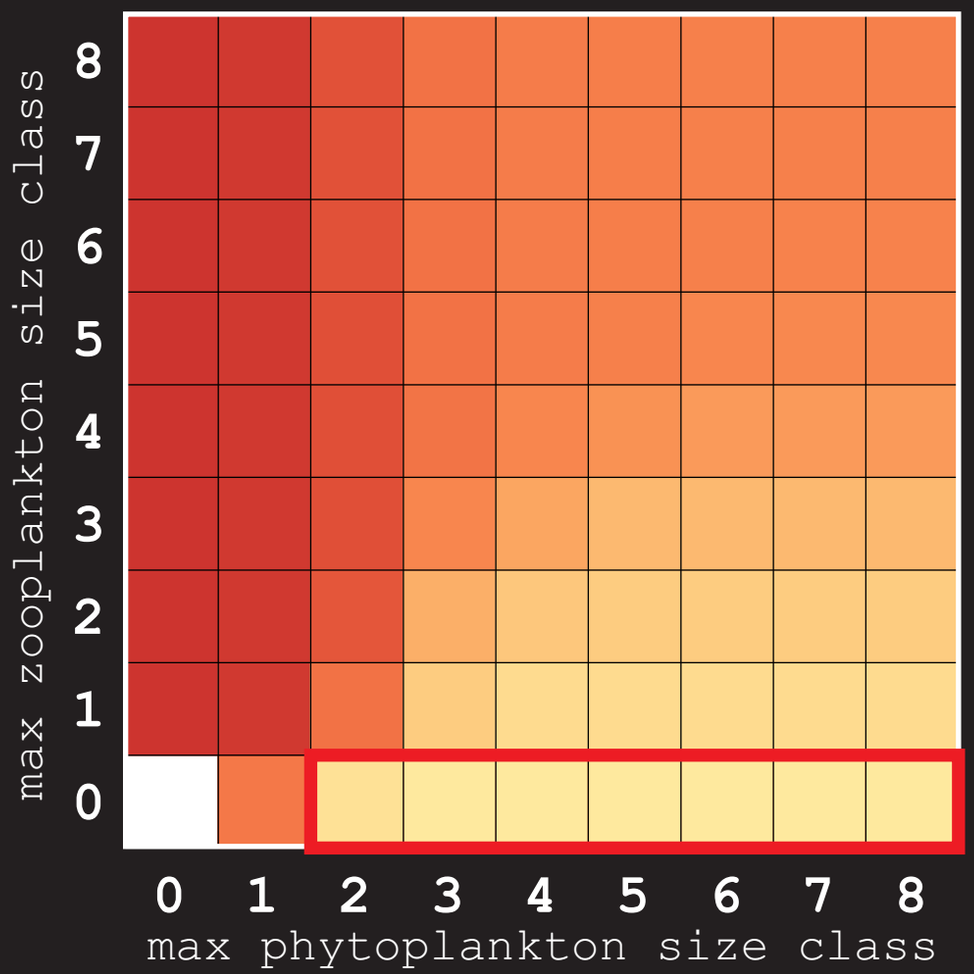
The Force awakens – (I) planktonic habitat (small cell size)

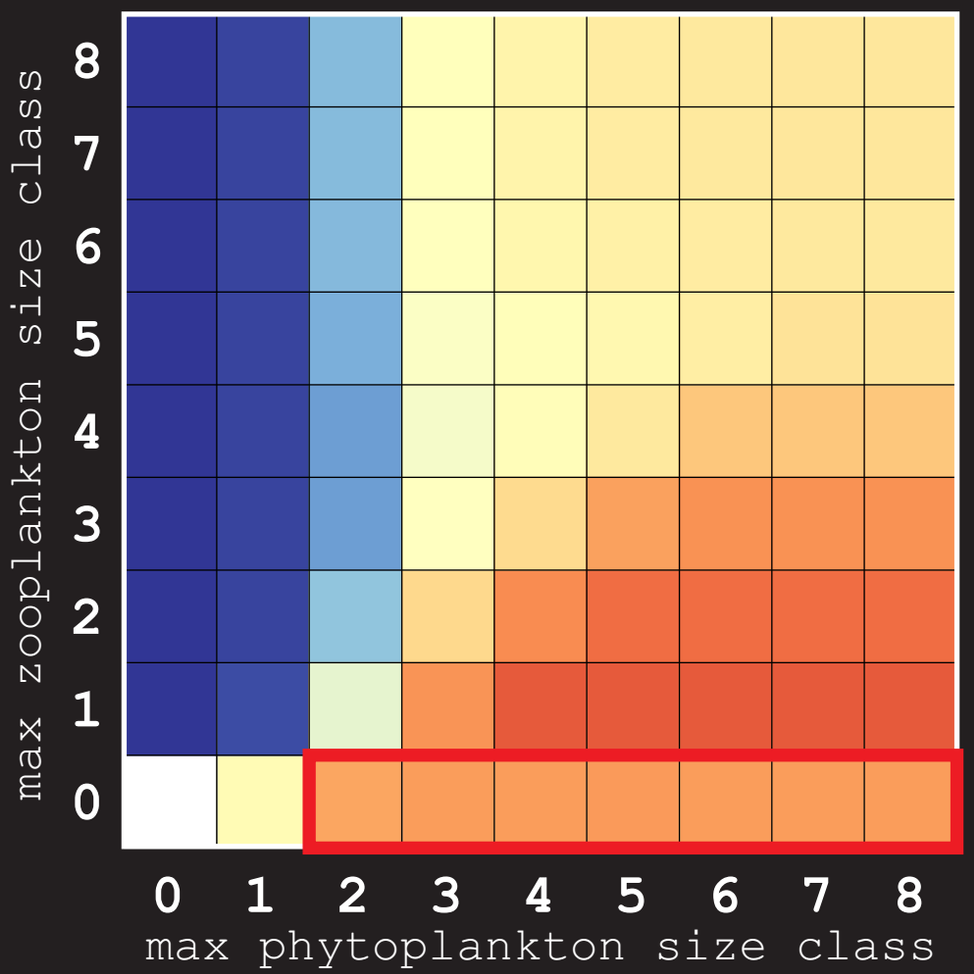




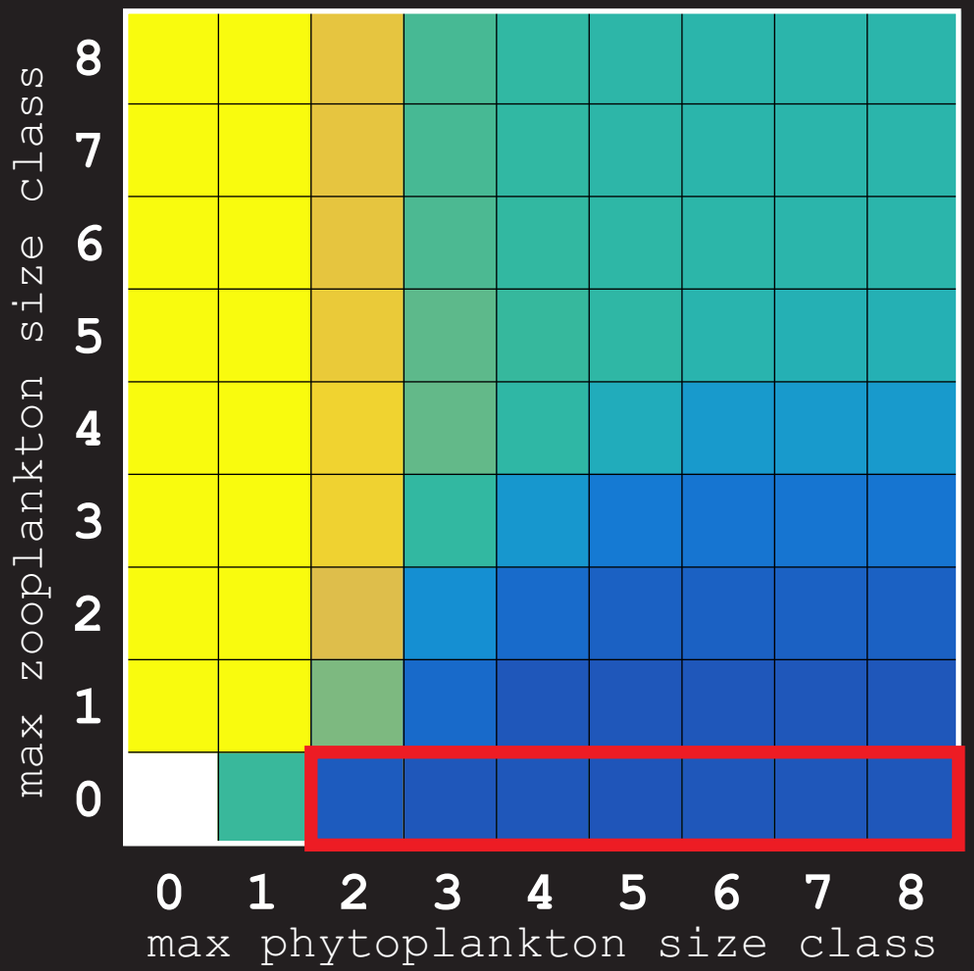


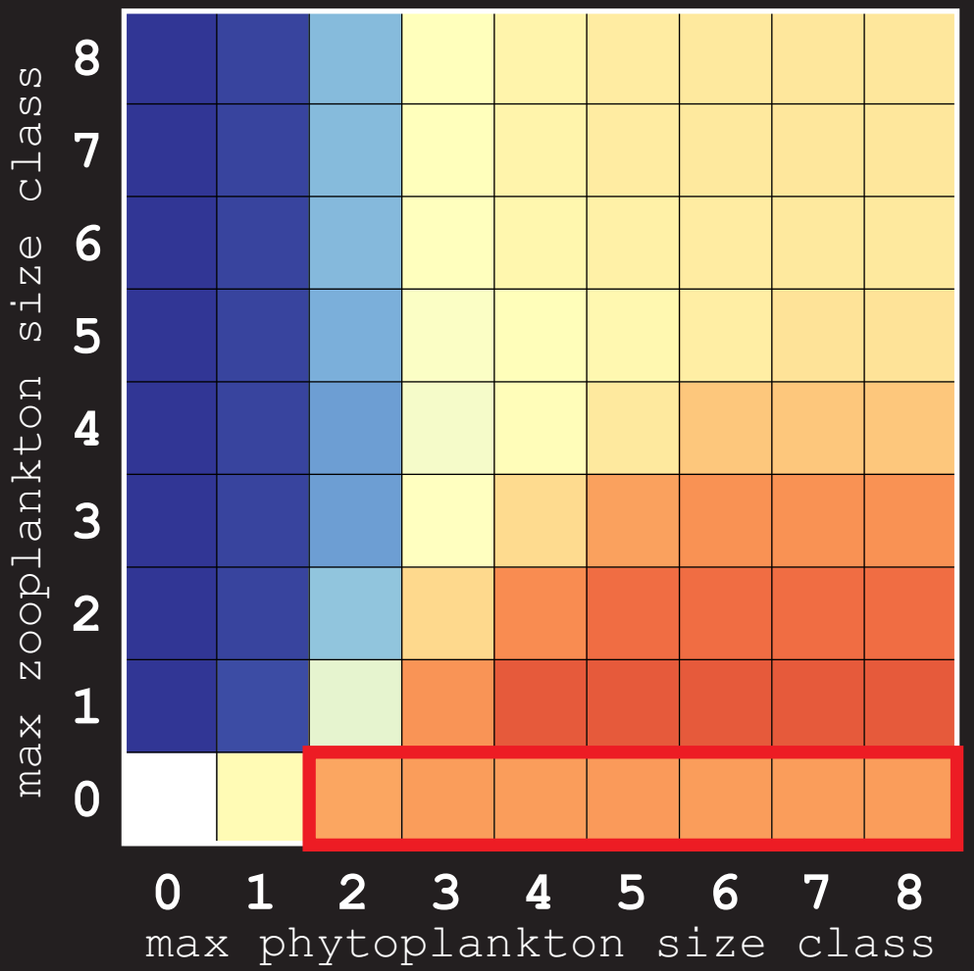
The Force awakens – (II) planktonic habitat (large size range)

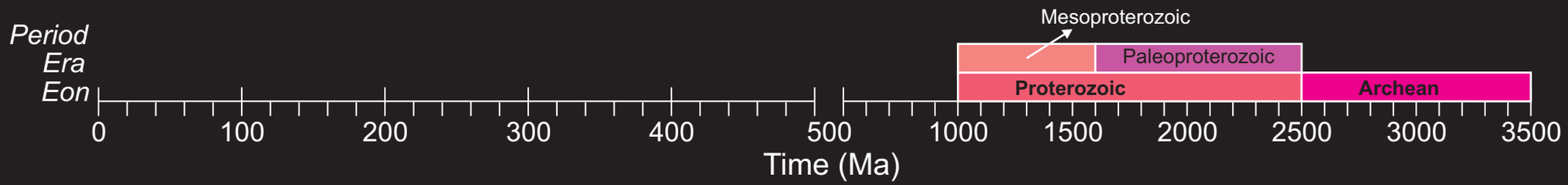




The Force awakens – (II) planktonic habitat (large size range)

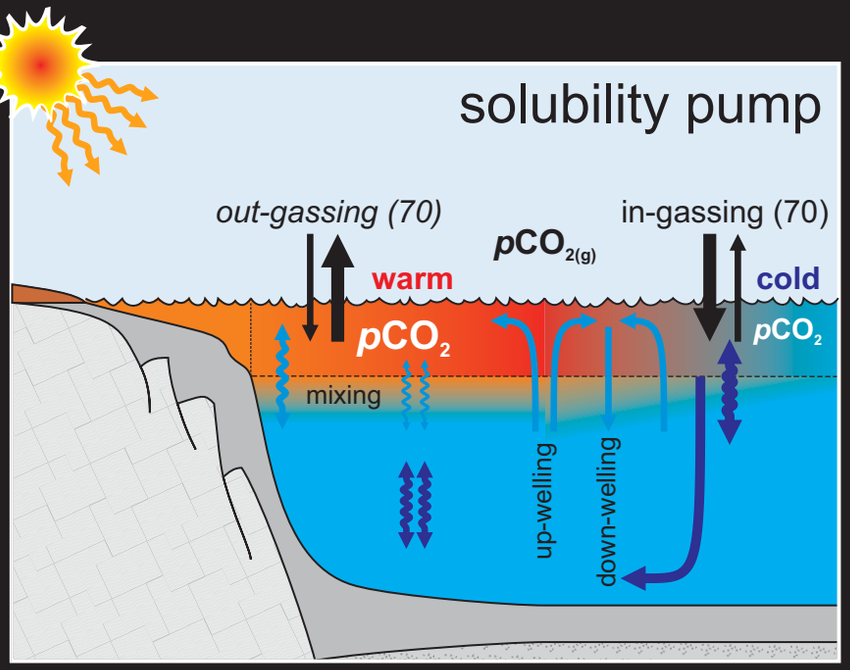




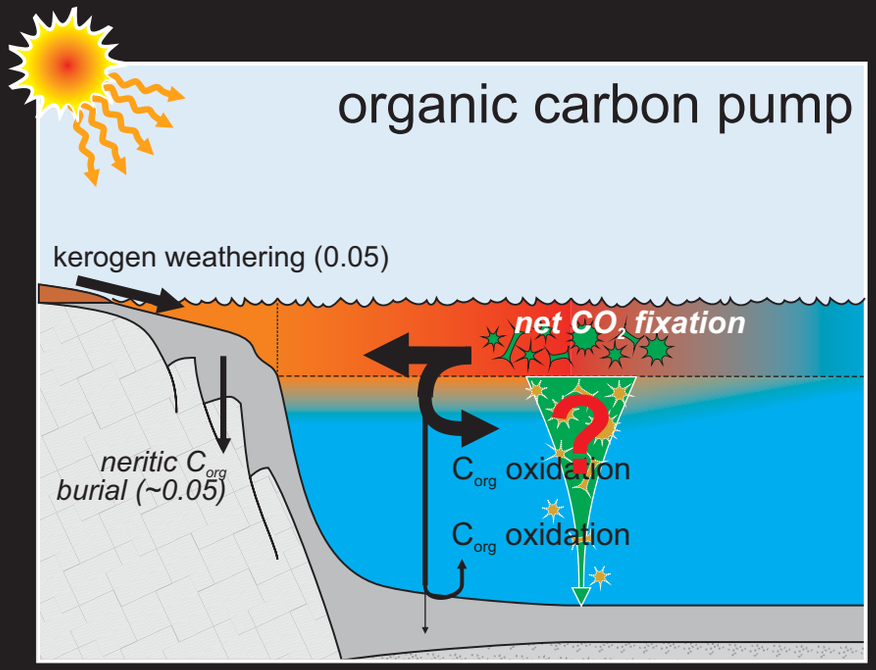


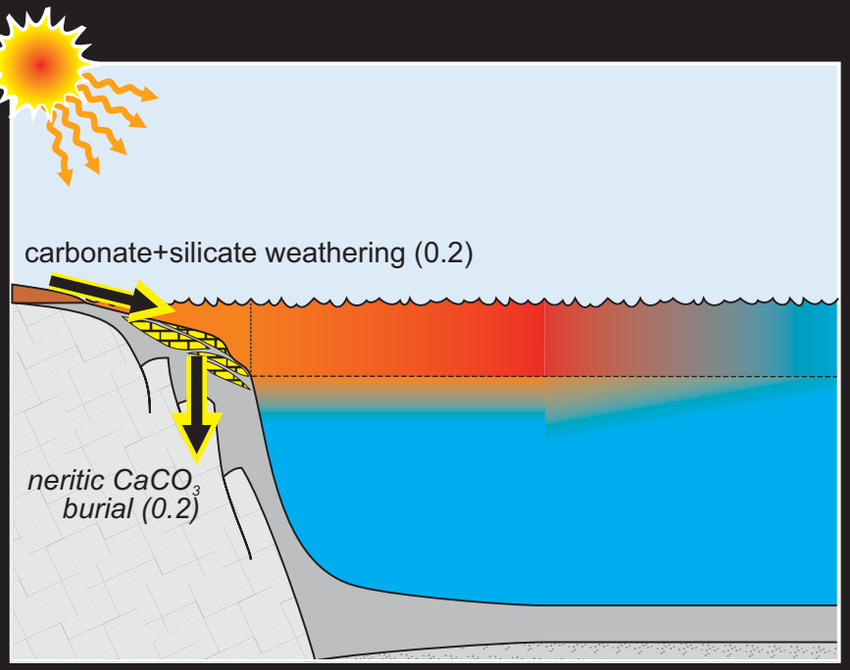
The Force awakens – grazing?

solubility pump

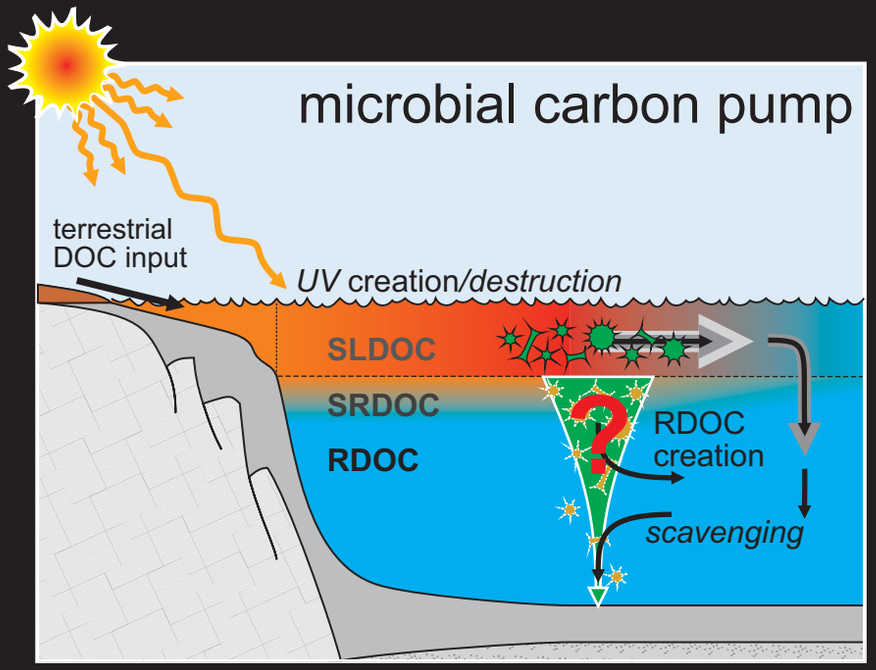


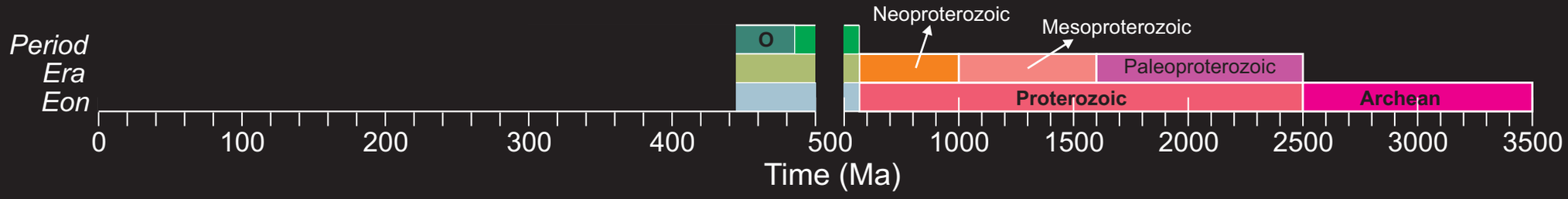
organic carbon pump



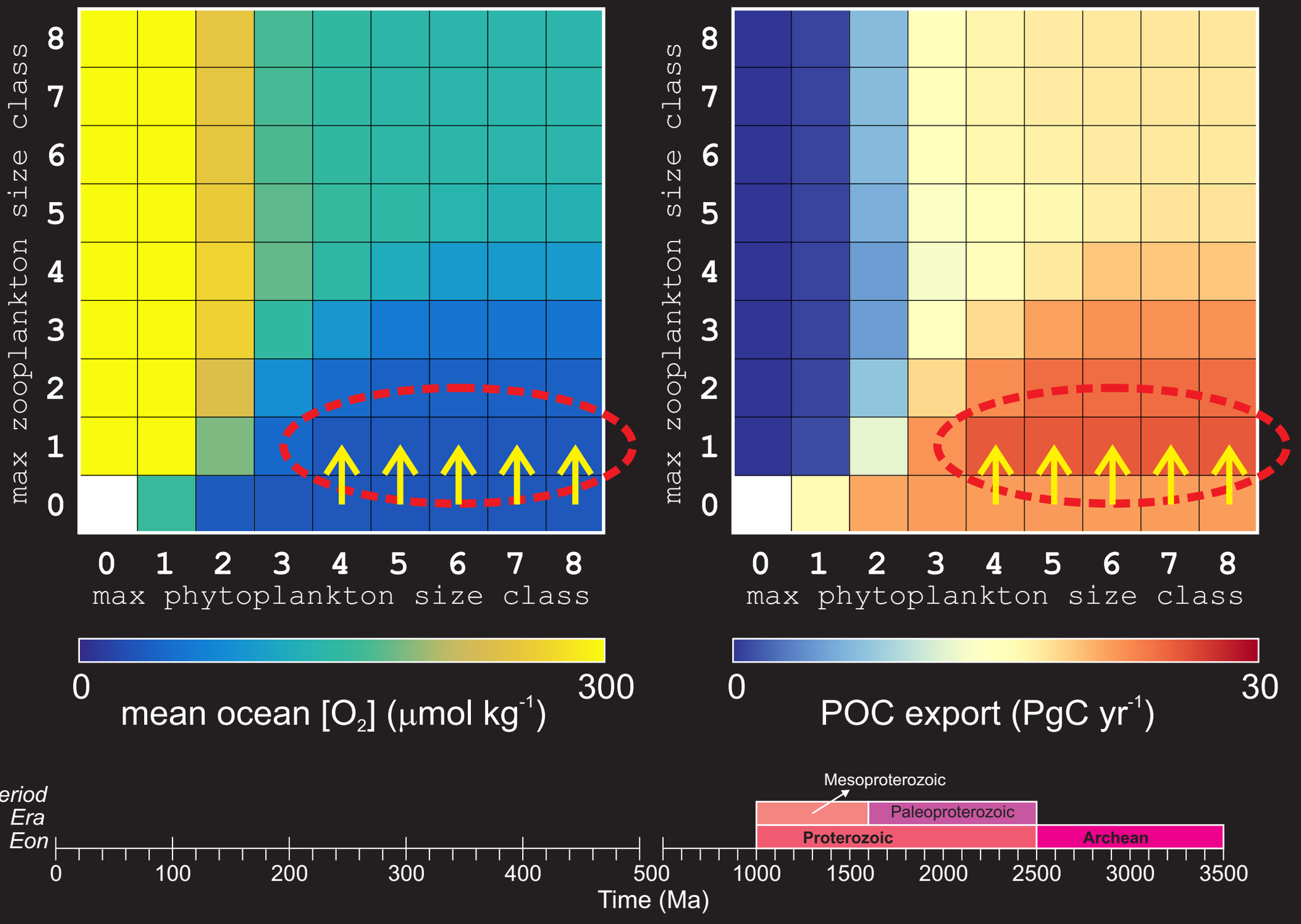


microbial carbon pump

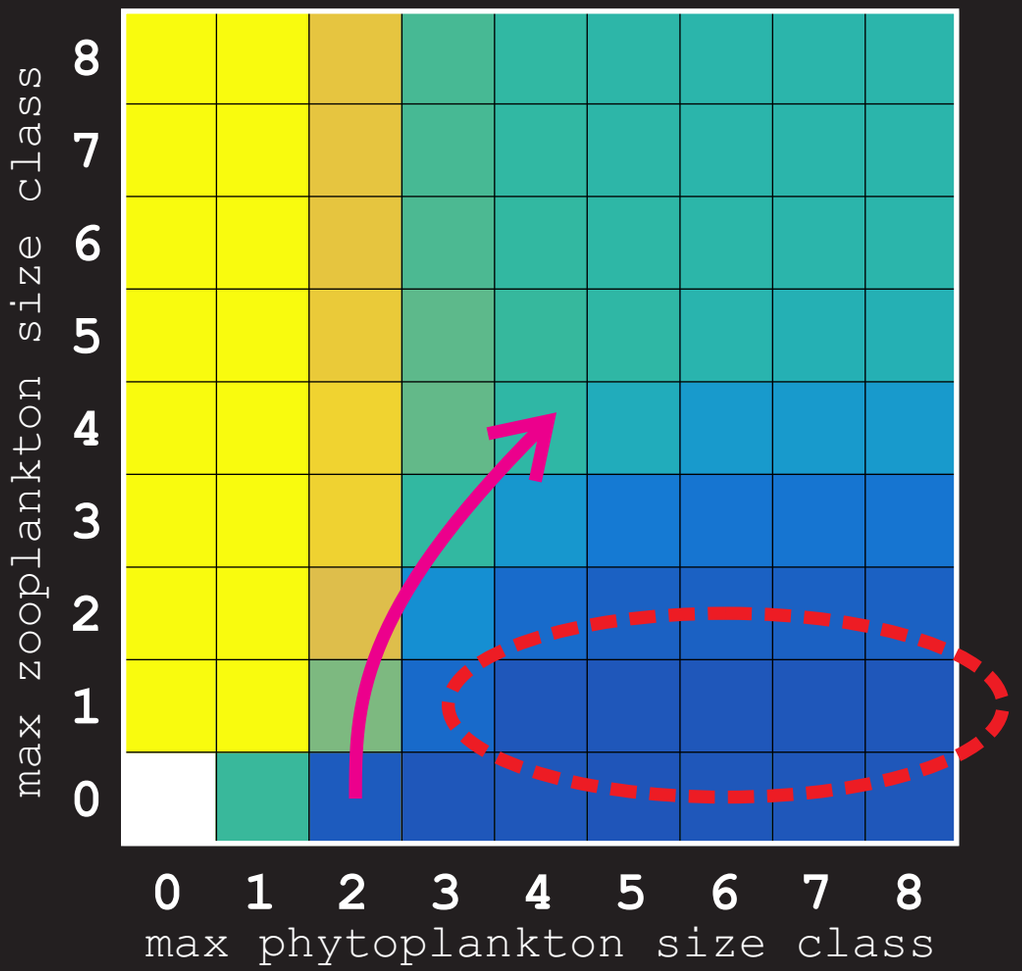


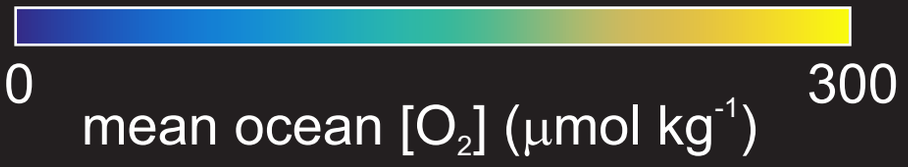


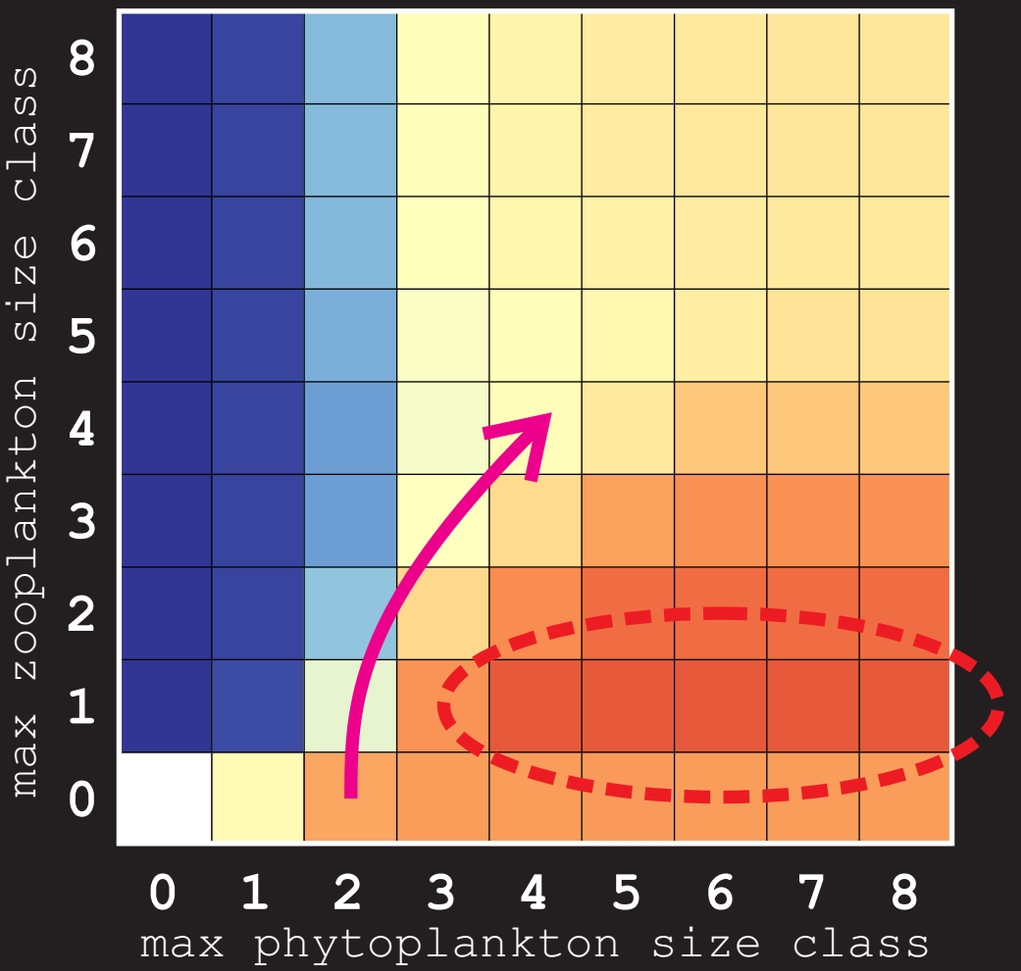
The Force awakens – grazing?



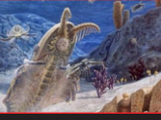
The Force awakens – grazing?







The Force awakens – animals (larger grazers)



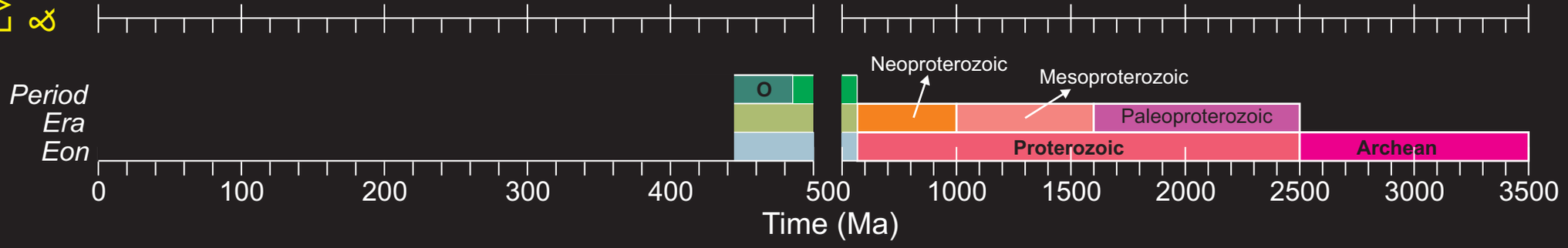
Evolutionary innovations & plankton assemblage

Animals! (metzoans)

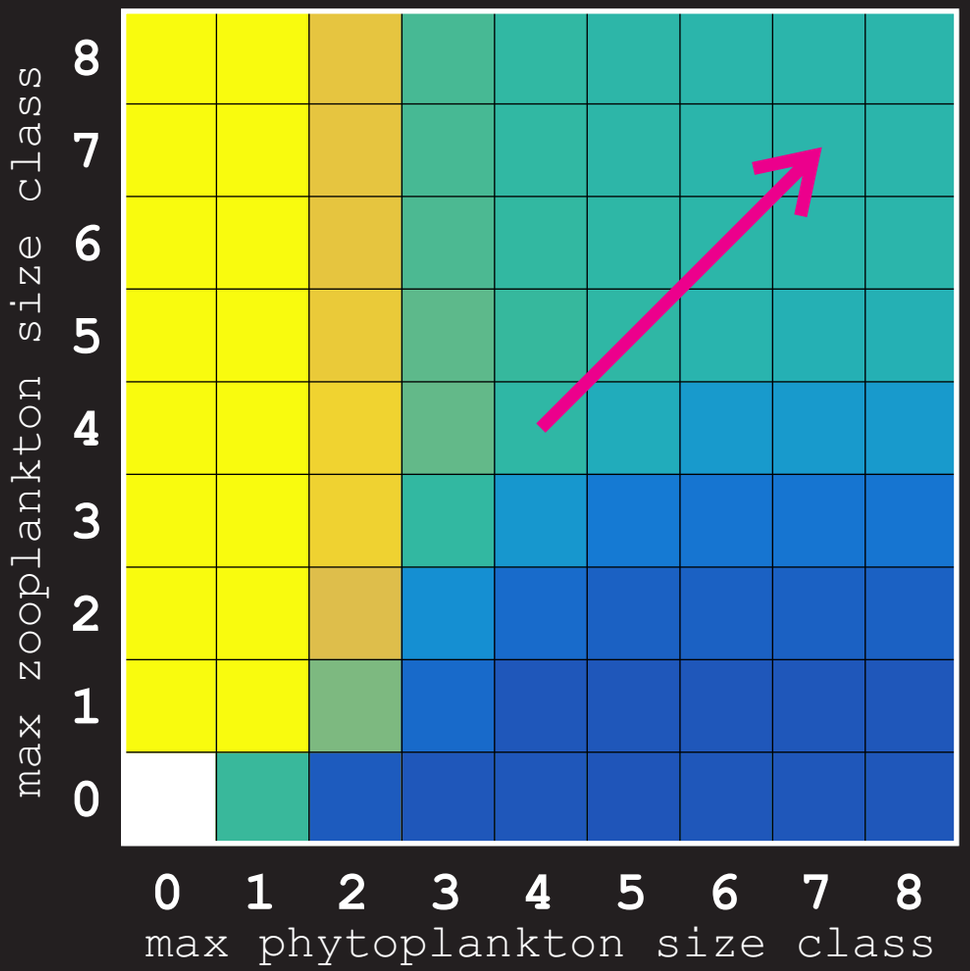
Eurkaryotes [*Knoll*, 2014]

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

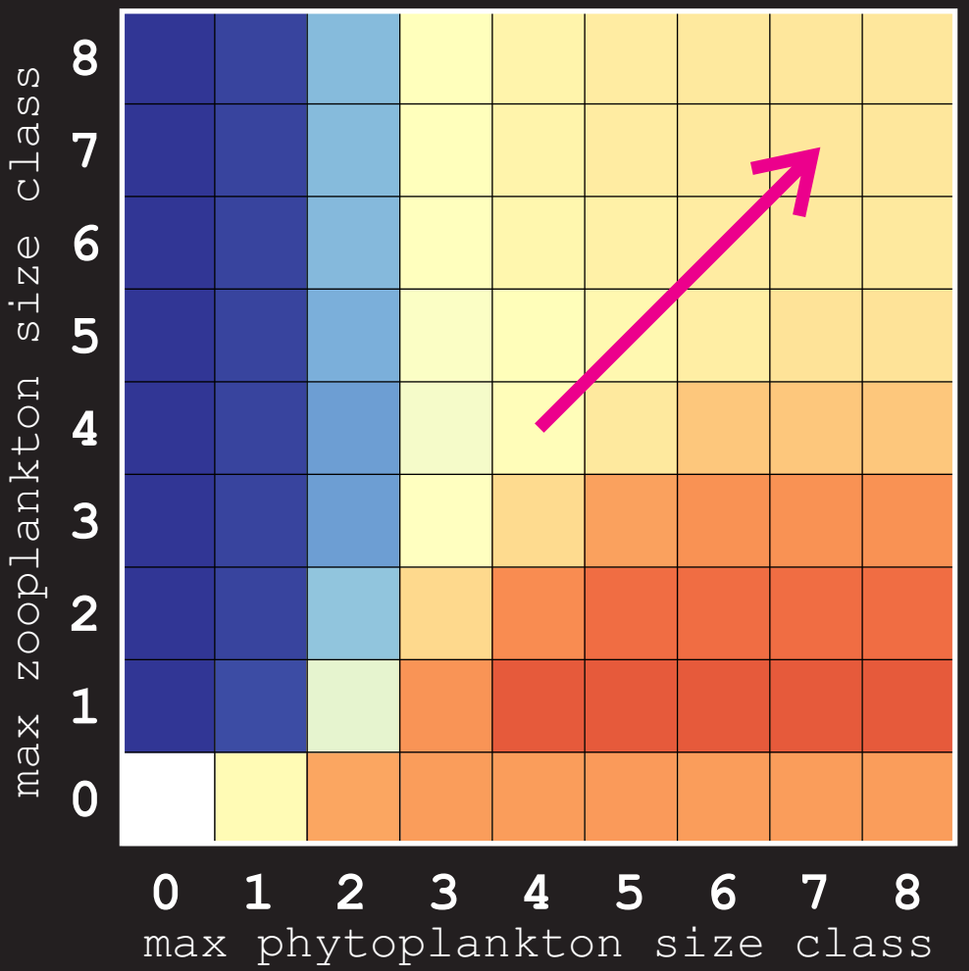
Cyanobacteria (benthic) [*Sánchez-Baracaldo*, 2015]



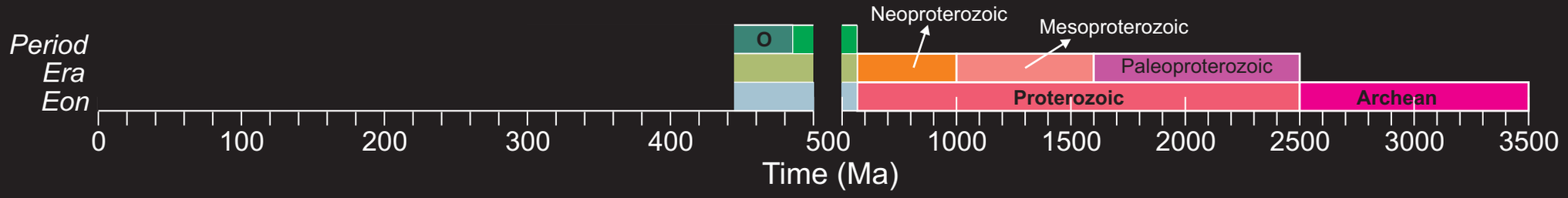
The Force awakens – animals (larger grazers)



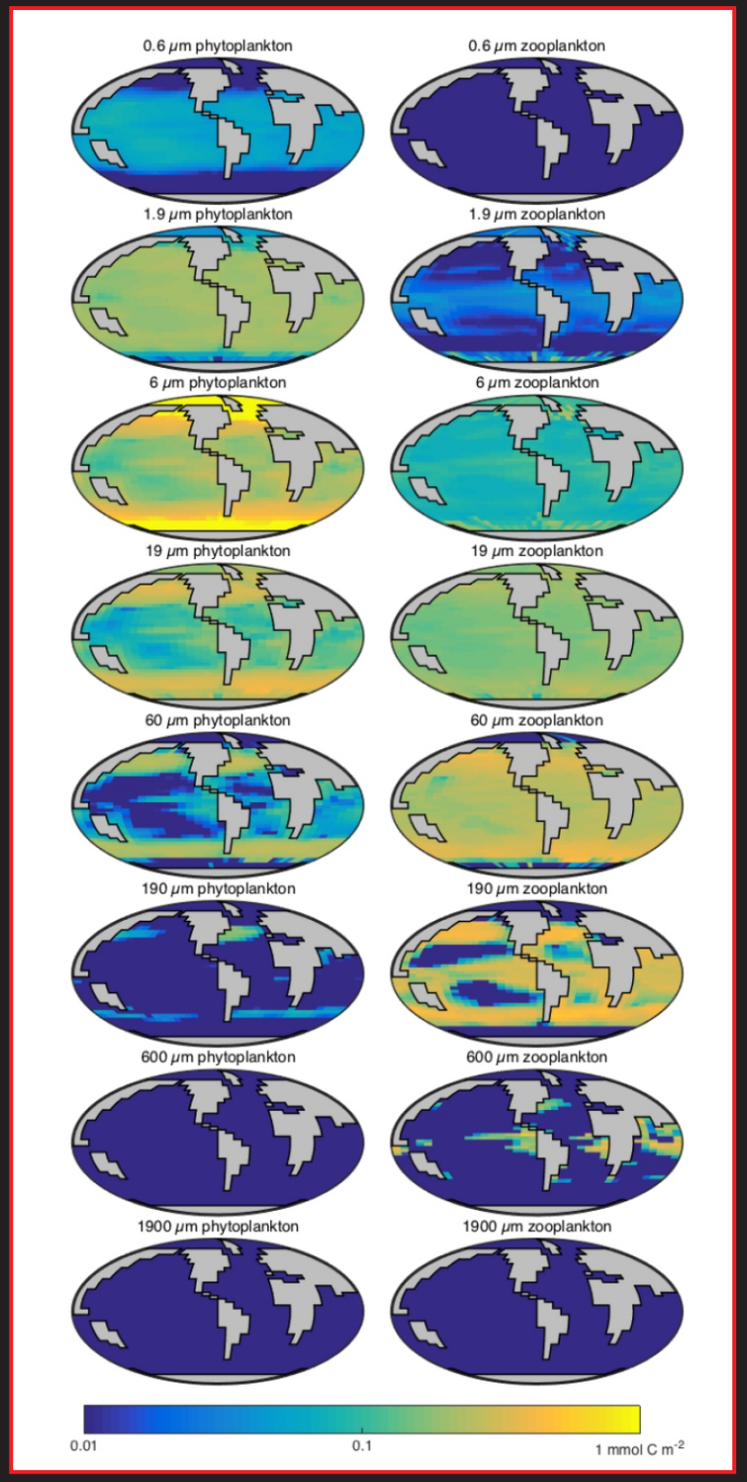
mean ocean [O_2] (μmol kg^{-1})

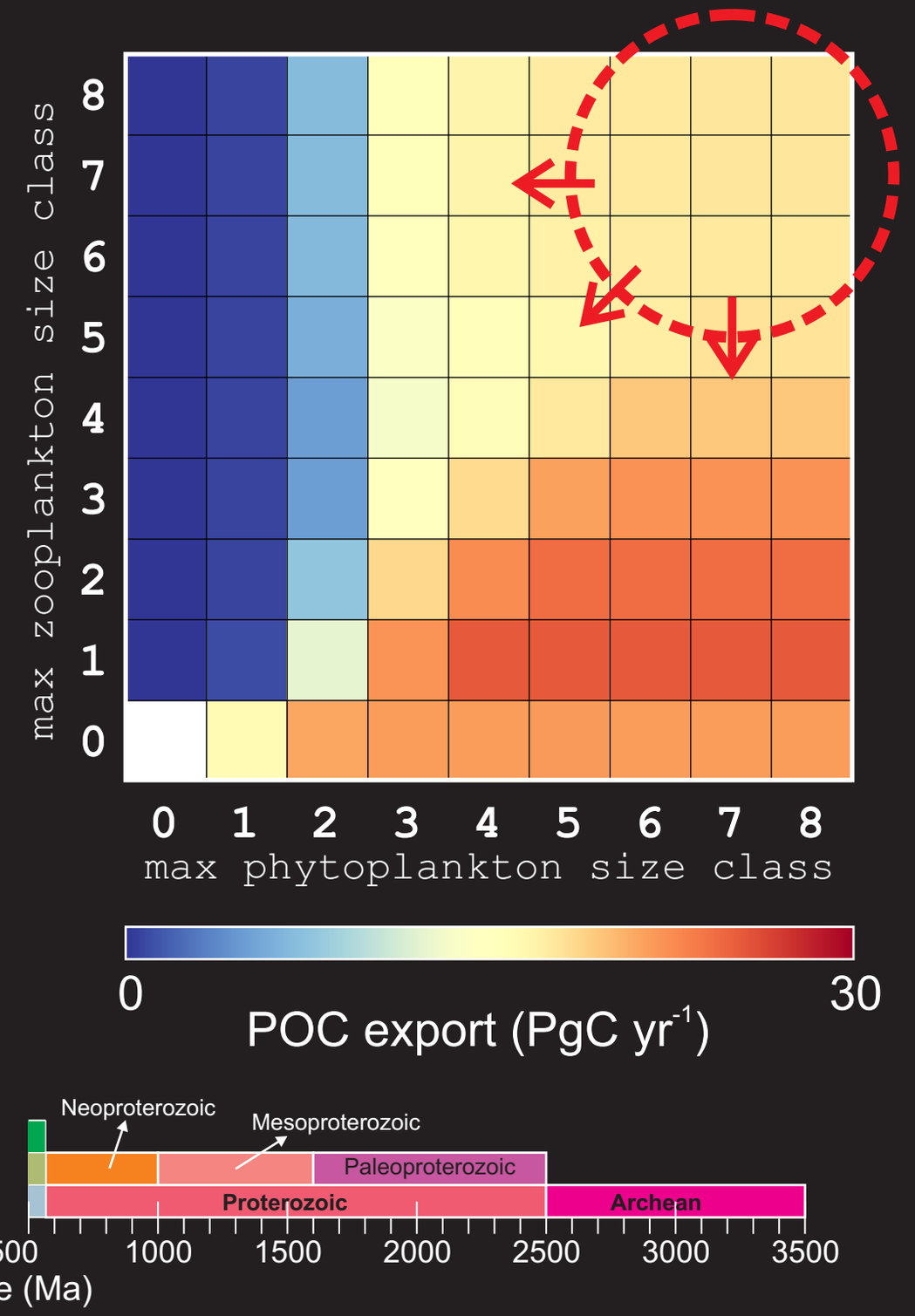


POC export (PgC yr^{-1})

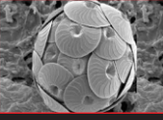


The Force awakens – animals (larger grazers)



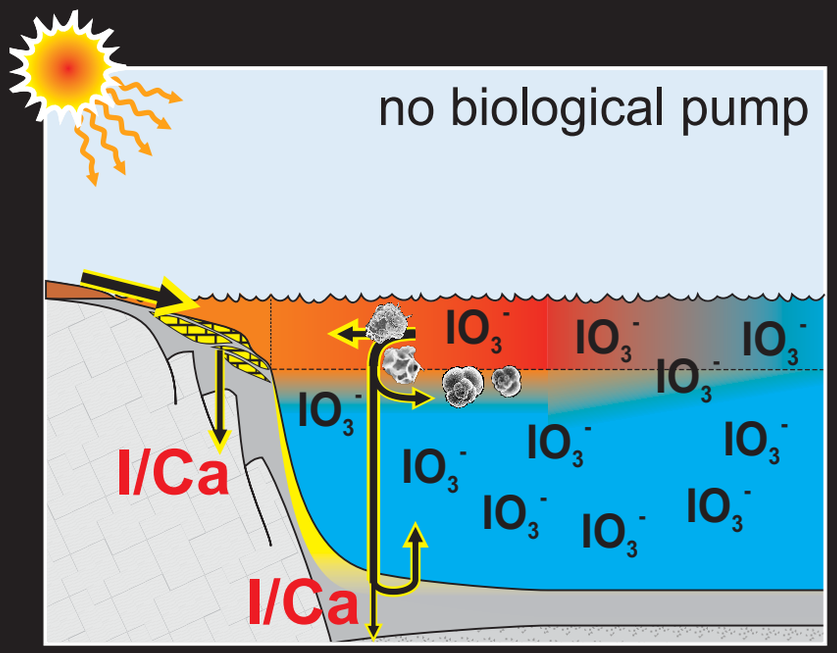


The Force awakens!?



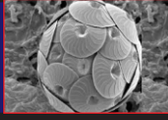
$IO_3^- \rightarrow I^-$ reduction [fast]

$I^- \rightarrow IO_3^-$ reoxidation [slow]



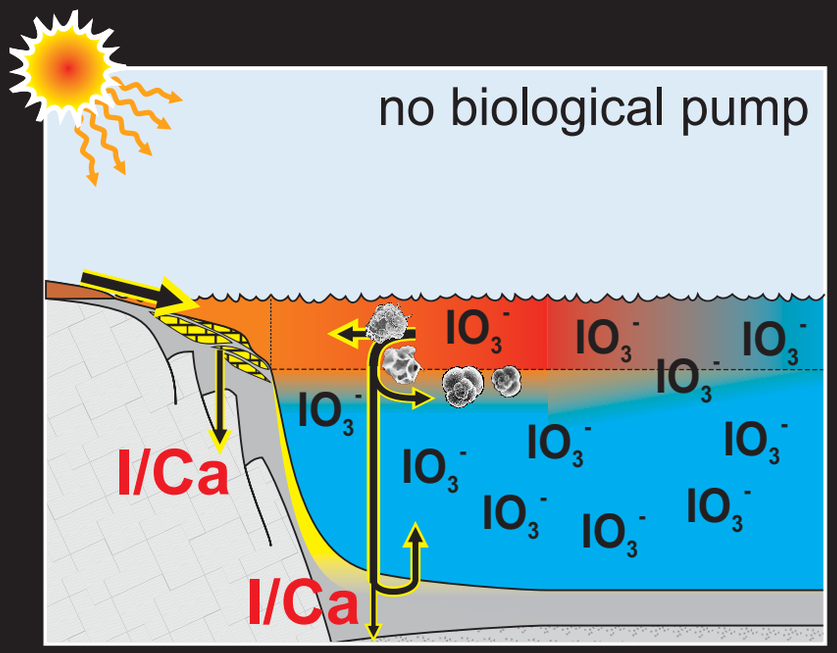
IO_3^- is incorporated into carbonates

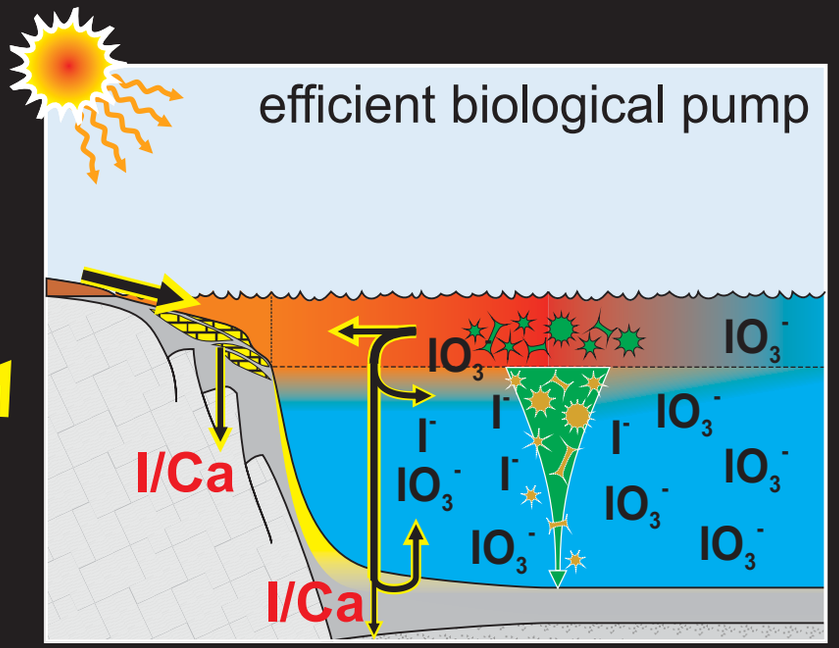
The Force awakens!?



$IO_3^- \rightarrow I^-$ reduction [fast]

$I^- \rightarrow IO_3^-$ reoxidation [slow]



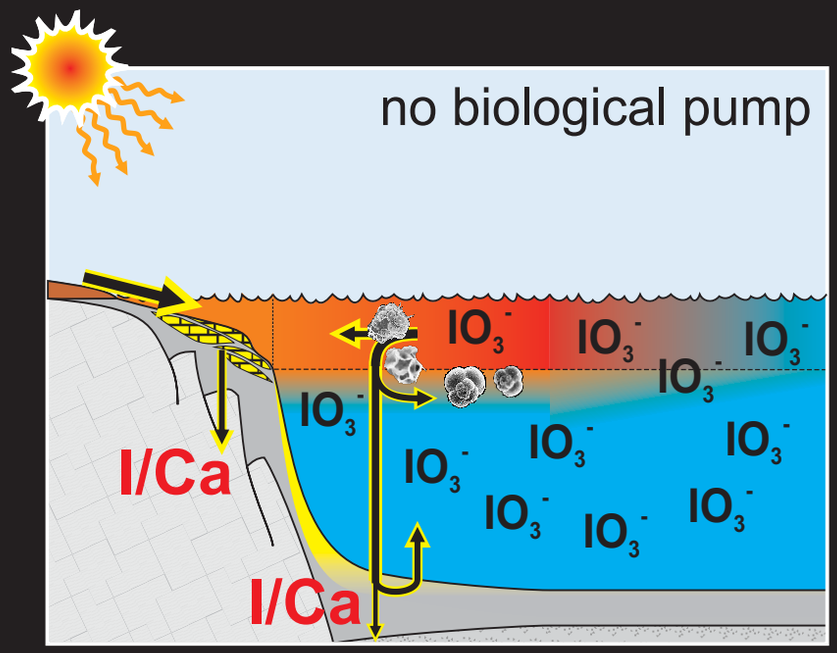


IO_3^- is incorporated into carbonates

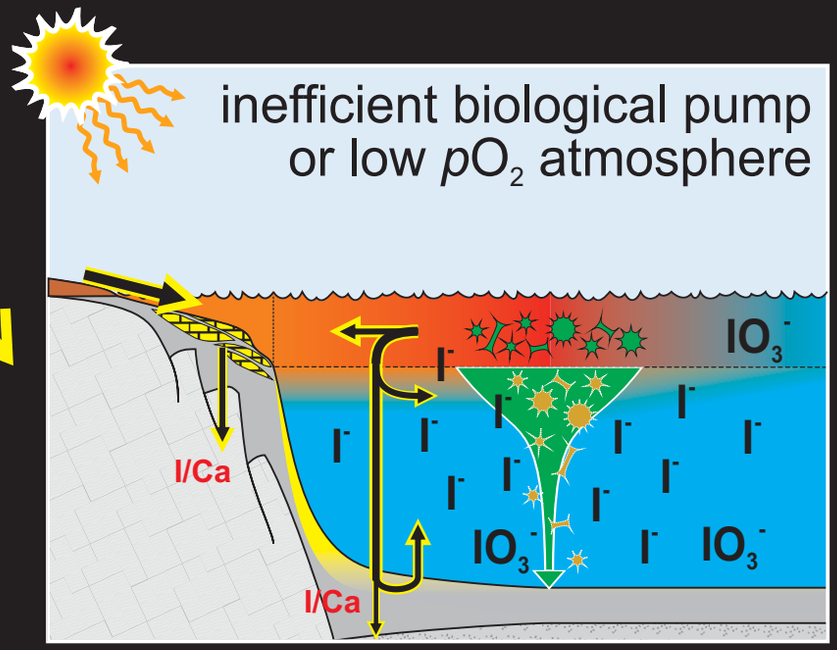
The Force awakens!?

$IO_3^- \rightarrow I^-$ reduction [fast]

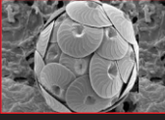
$I^- \rightarrow IO_3^-$ reoxidation [slow]



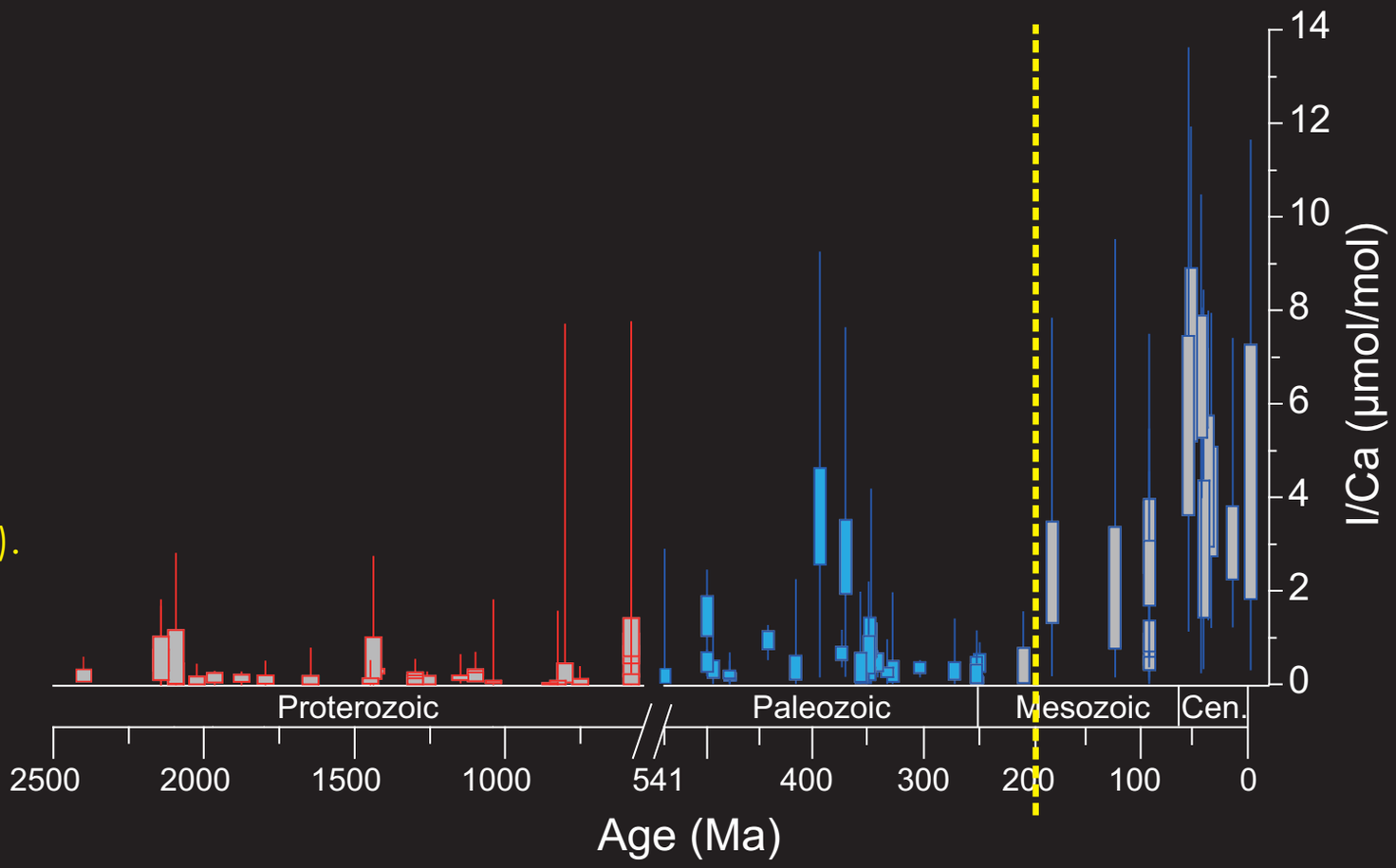
IO_3^- is incorporated into carbonates

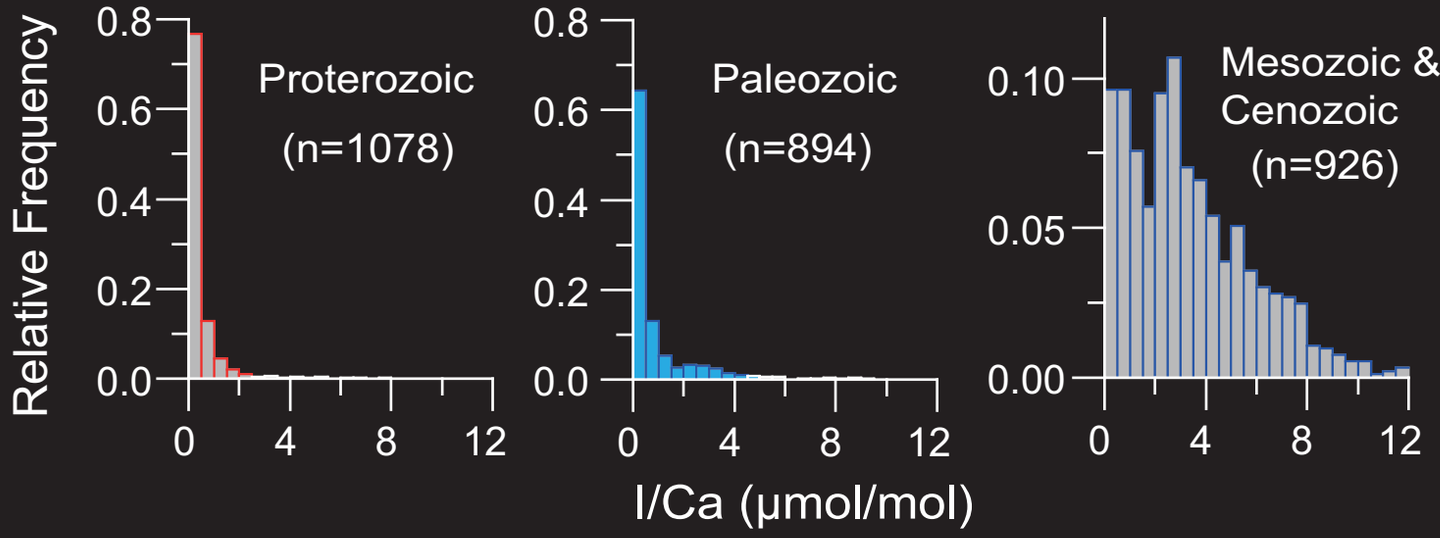


The Force awakens!?

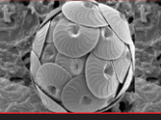


Wanyi, L., A. Ridgwell, E. Thomas, D.S. Hardisty, G. Luo, T.J. Algeo, M.R. Saltzman, B.C. Gill, Y.Shen, H-F. Ling, C.T. Edwards, M.T. Whalen, X. Zhou, K.M. Gutchess, L. Jin, R.E.M. Rickaby, H.C. Jenkyns, T.W. Lyons, T.M. Lenton, L.R. Kump, and Z. Lu1, Late inception of a resiliently oxygenated upper ocean, Science DOI: 10.1126/science.aar5372 (2018).



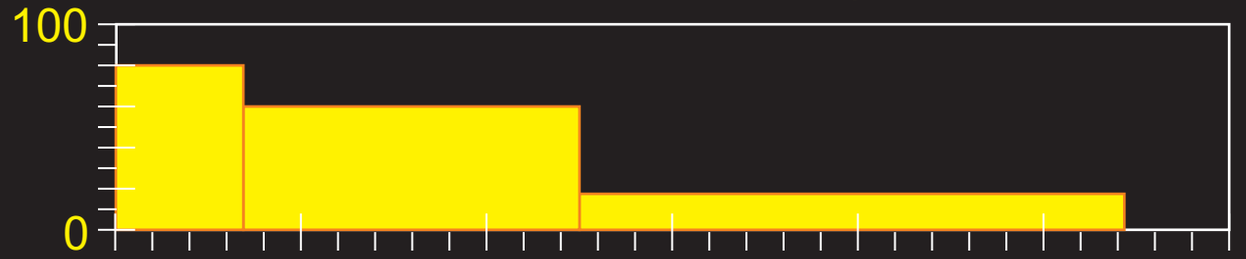


The Force awakens!?



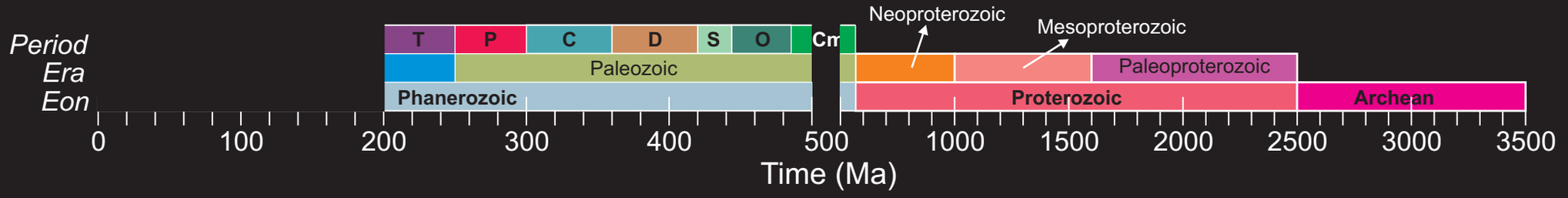
Boss and Wilkinson [1991]

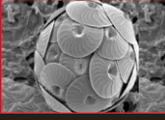
% occurrence of carbonate in ophiolite suites

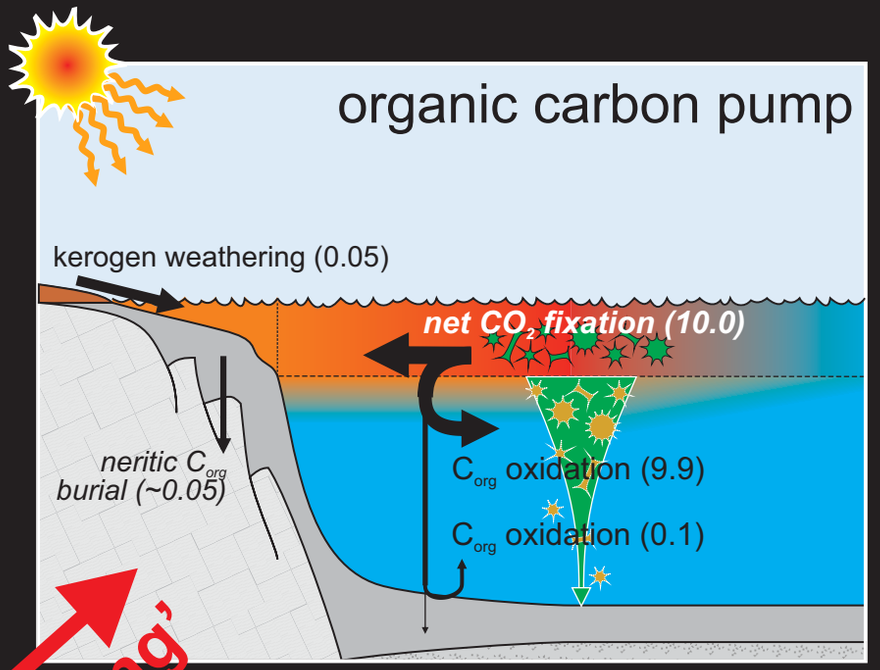


Martin [1995]

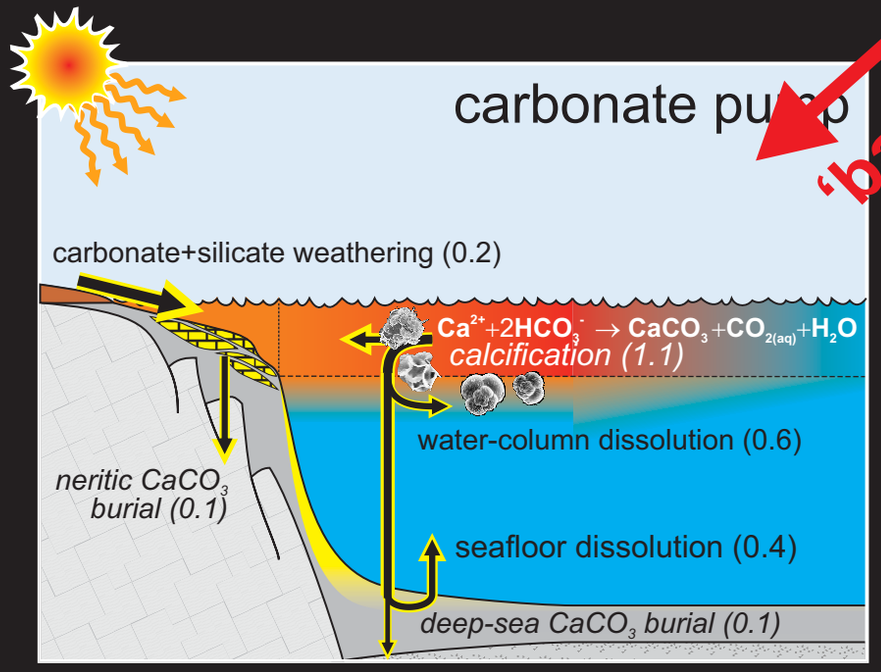
Major changes in plankton assembledge

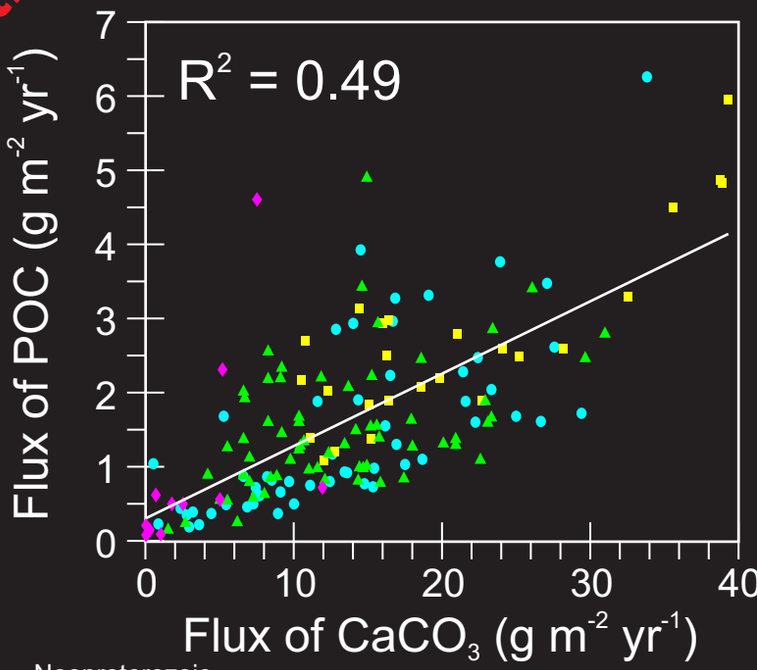


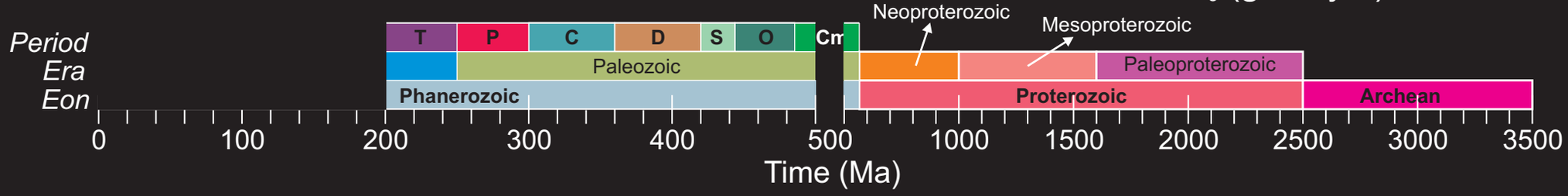



organic carbon pump
kerogen weathering (0.05)
net CO_2 fixation (10.0)
neritic C_{org} burial (~0.05)
C_{org} oxidation (9.9)
C_{org} oxidation (0.1)

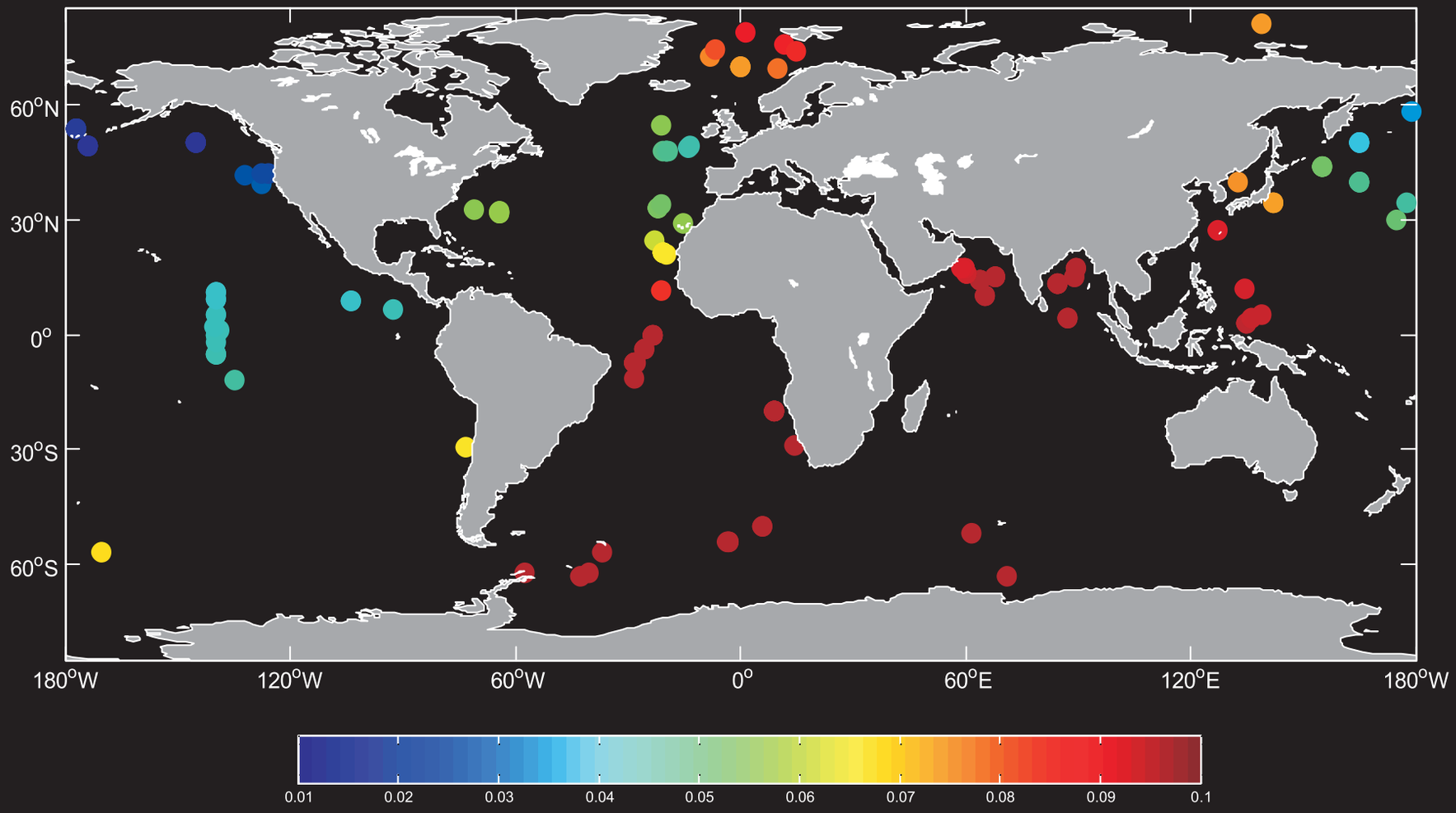
'ballasting'


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
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)

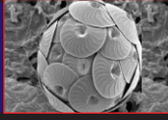
The Force awakens???

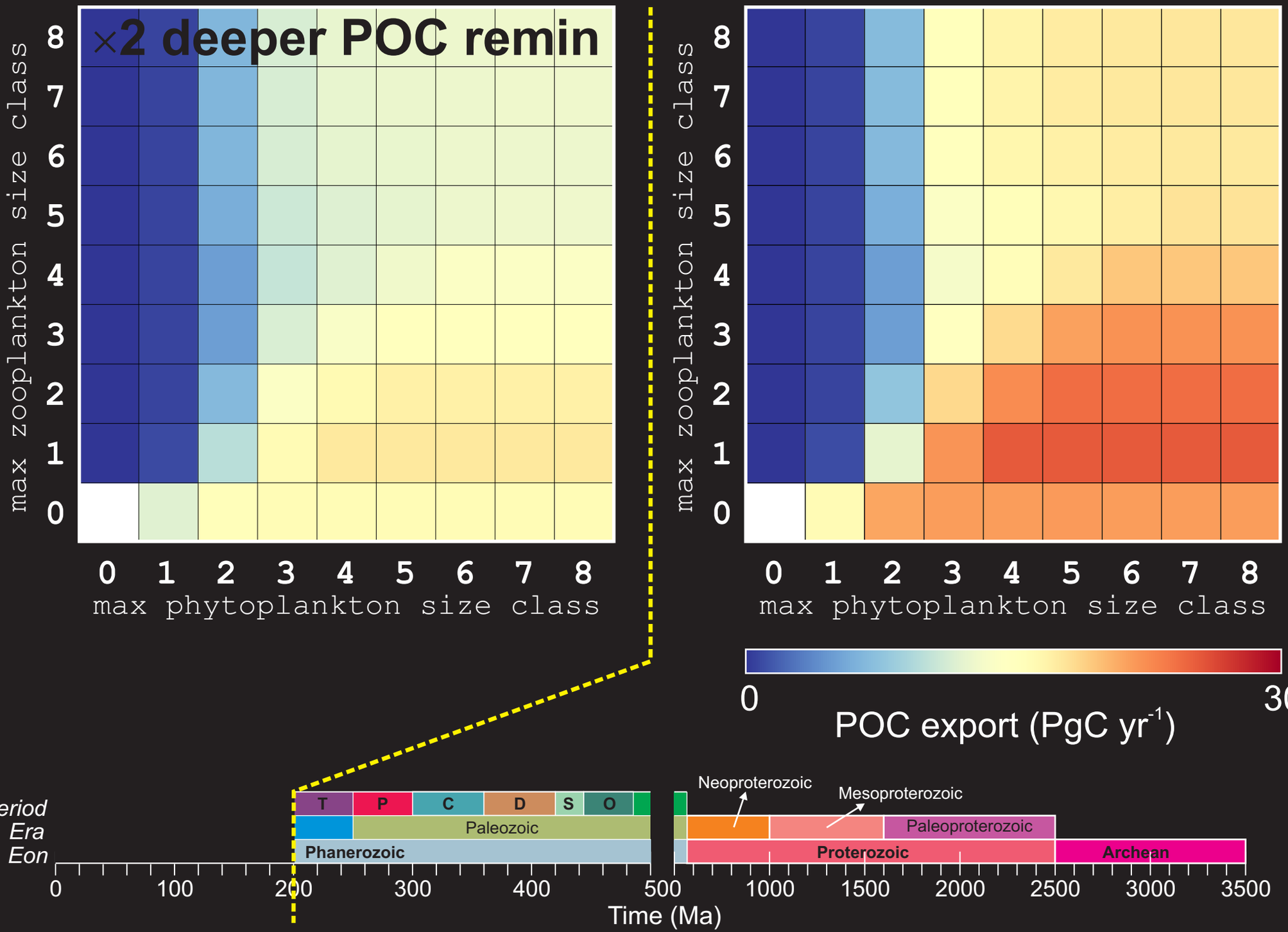


Spatial distribution of carrying capacity (ballasting) coefficients calculated using geographically weighted regression analysis for $CaCO_3$.

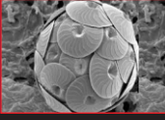
Wilson et al. [2012]

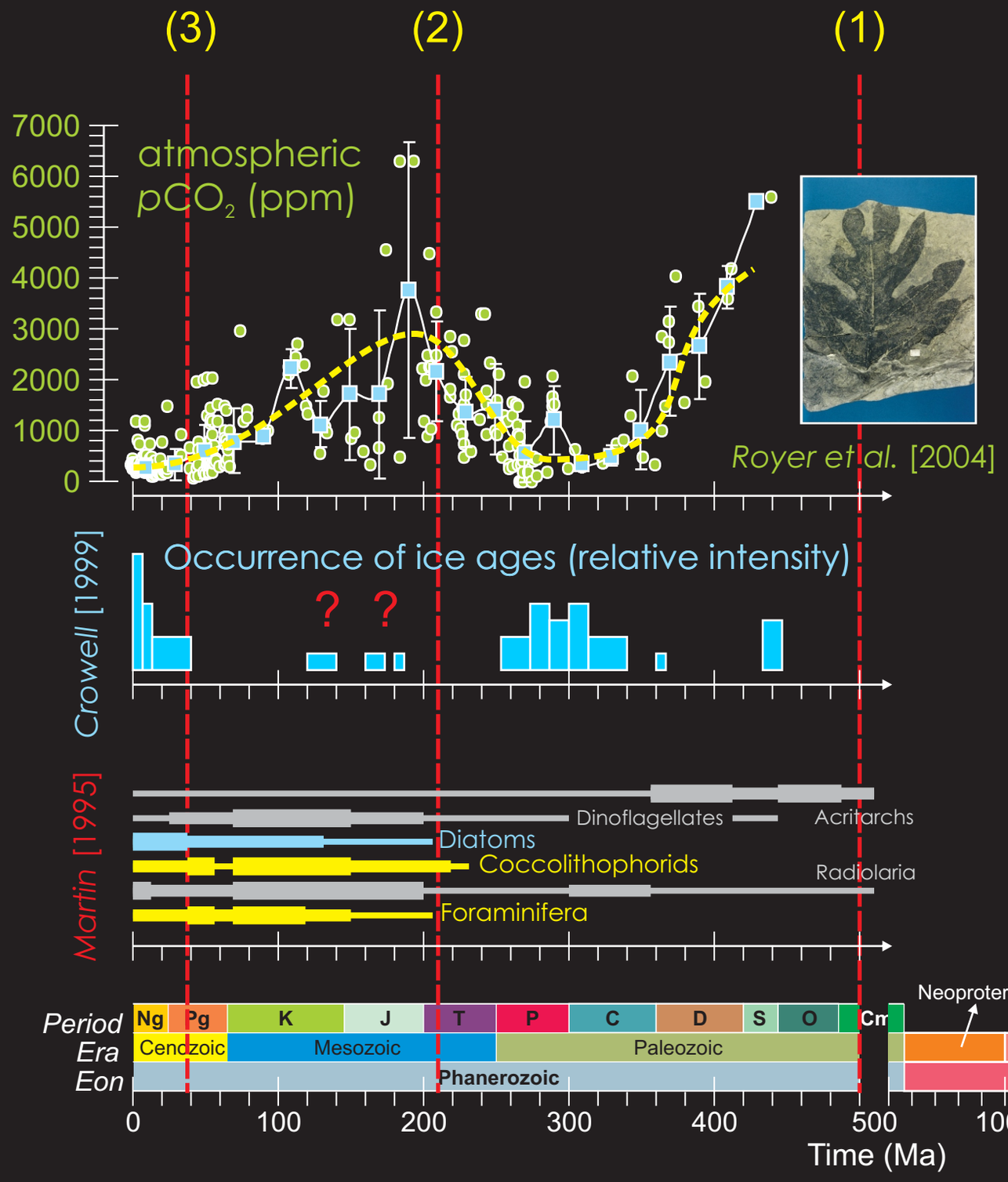
The Force awakens!?





Conclusions/perspectives





What is the relationship between changes in the biological pump and climate? (or controlled by weathering/outgassing?)

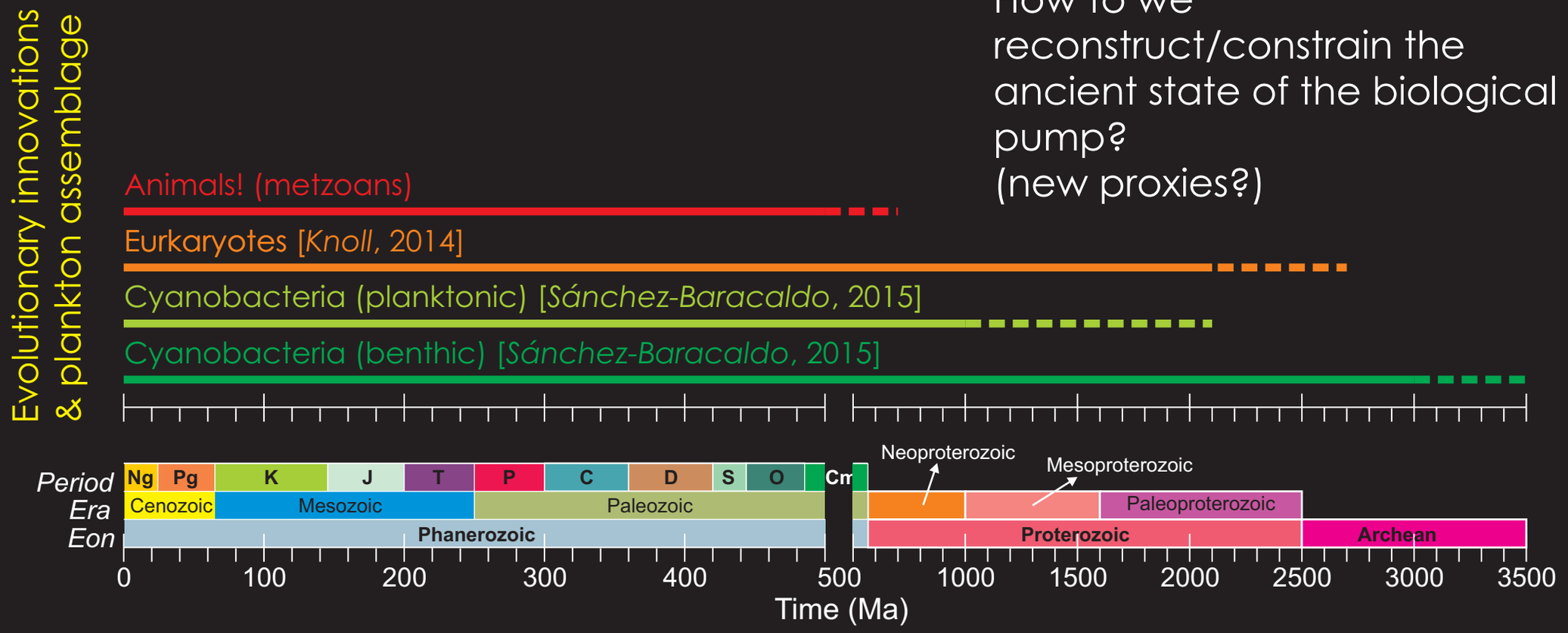
Did changes in the biological pump guide diatom evolution? (or controlled by long-term cooling?)

What can we say about ecosystem stability and resilance, including in the future?

Conclusions/perspectives

Are there, and are there important; feedbacks and interactions between plankton evolution and ecosystem complexity, and the marine environment (esp. nutrient and oxygen cycles)?
('co-evolution of life and the Planet')

How to we reconstruct/constrain the ancient state of the biological pump?
(new proxies?)



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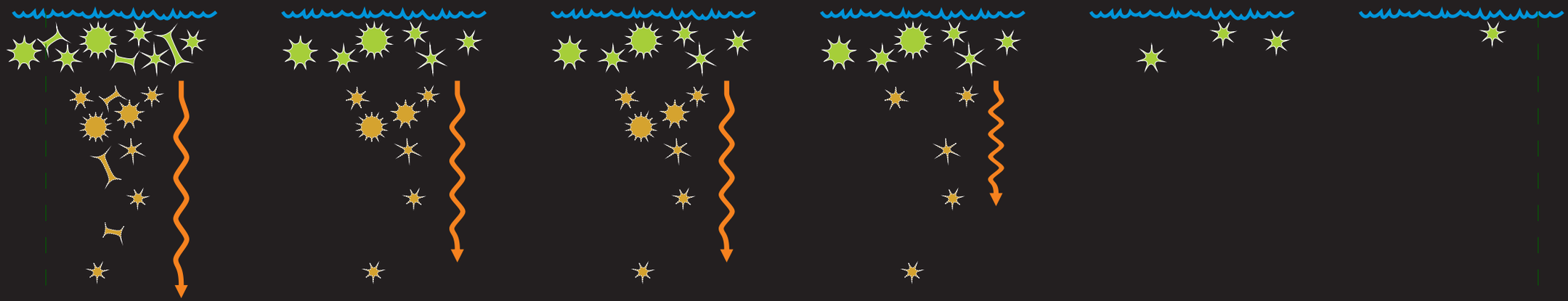
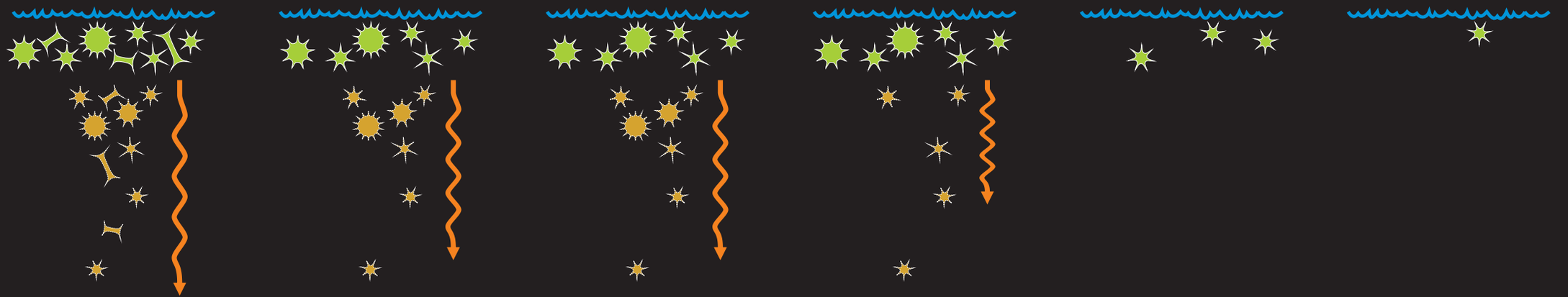


Ng	Pg	K	J	T	P	C	D	S	O	Cm			
Cenozoic		Mesozoic			Paleozoic						Neoprot.	Mesoprot.	Paleoproterozoic
Phanerozoic											Proterozoic		Archean



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

	Neoprot.	Mesoprot.	Paleoproterozoic	
	Proterozoic			Archean