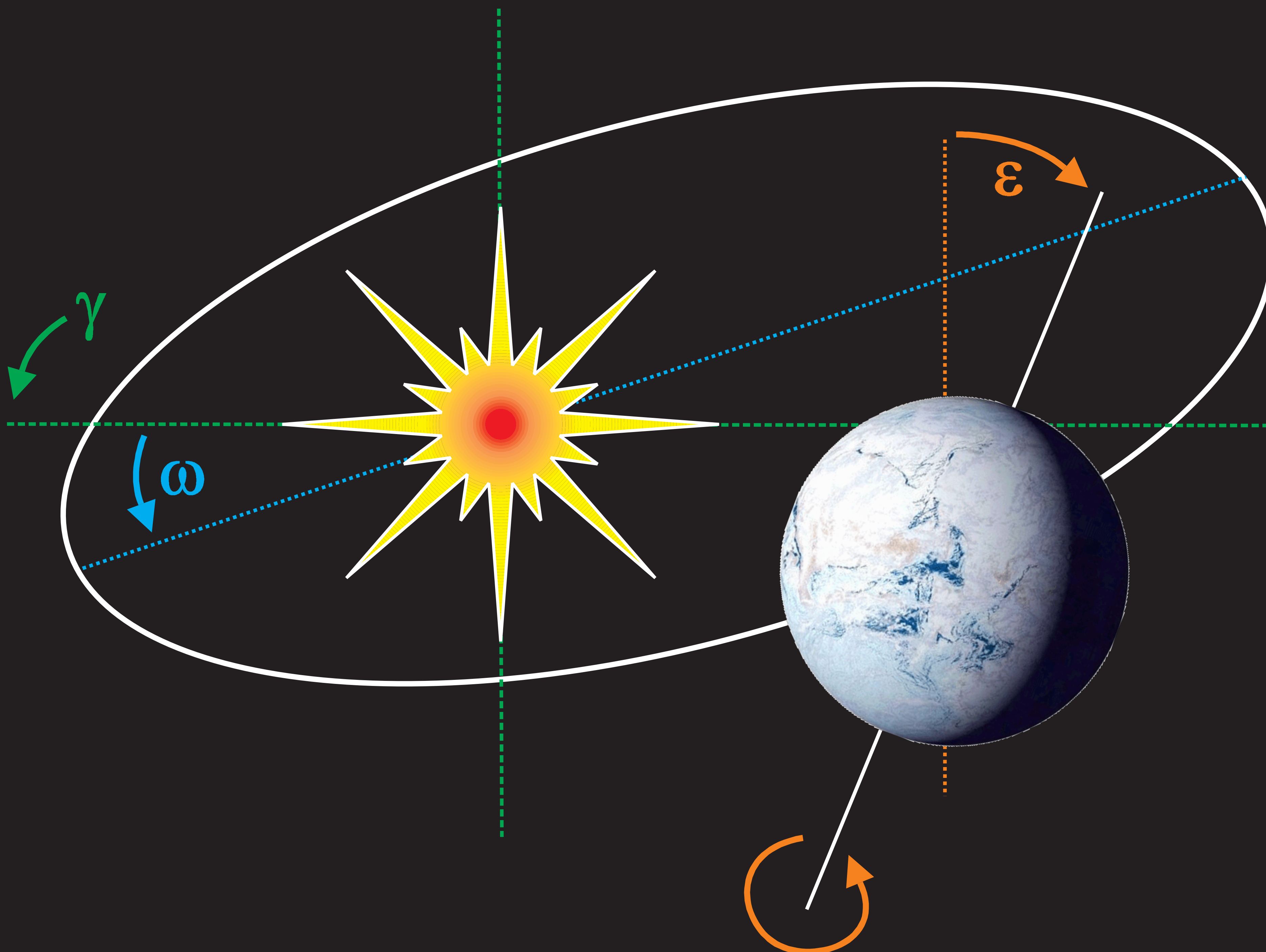
Snowball Earth



The Neoproterozoic: Gateway to a metazoan-dominated, oxygenated, ‘modern-like’ biosphere?

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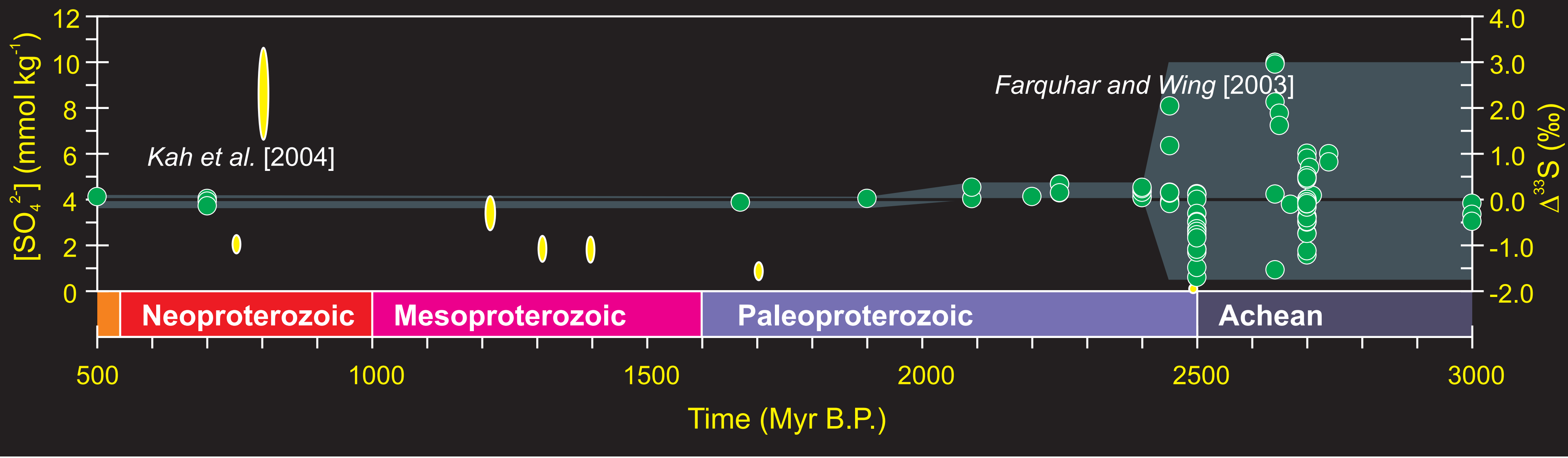
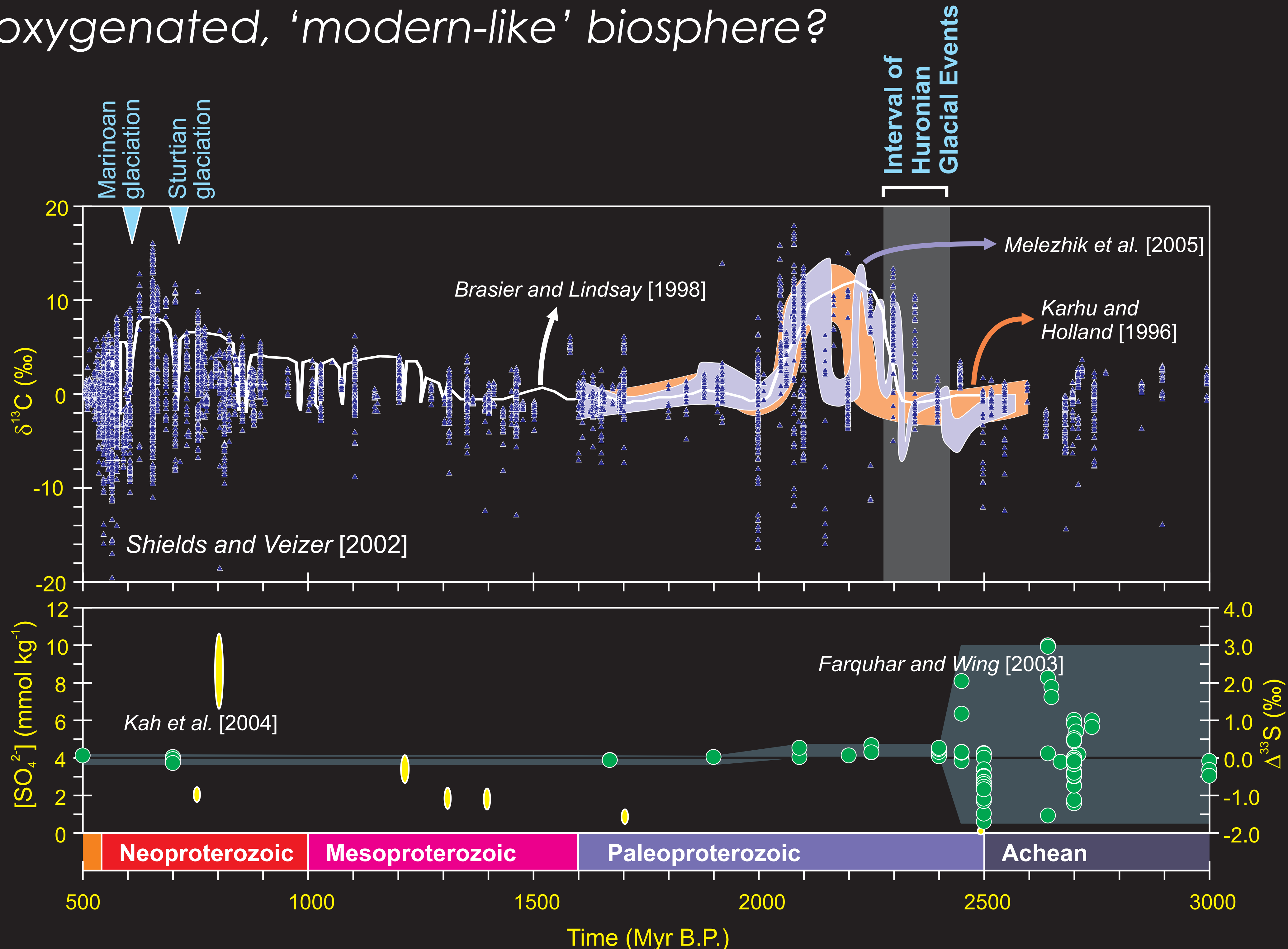
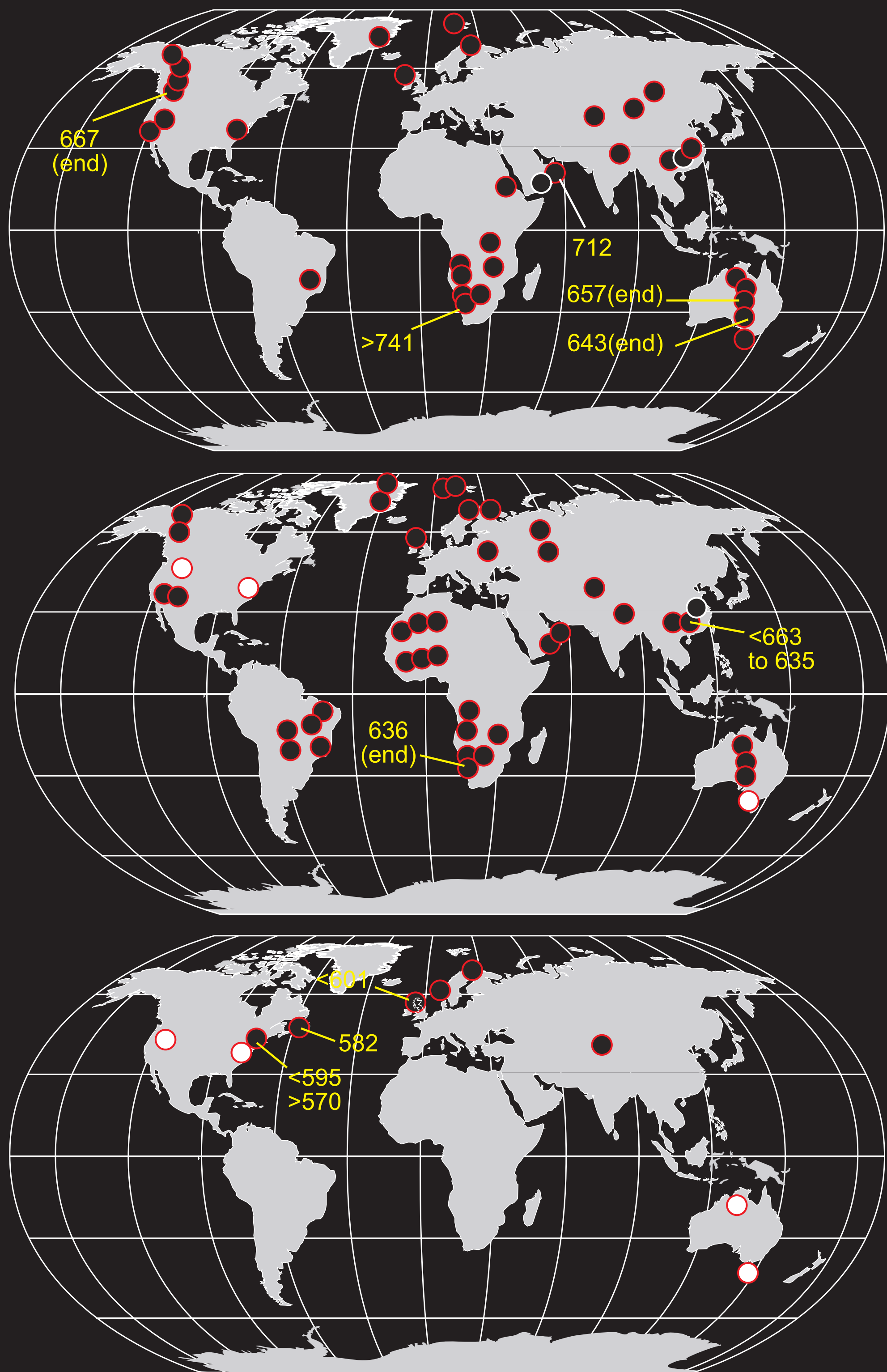


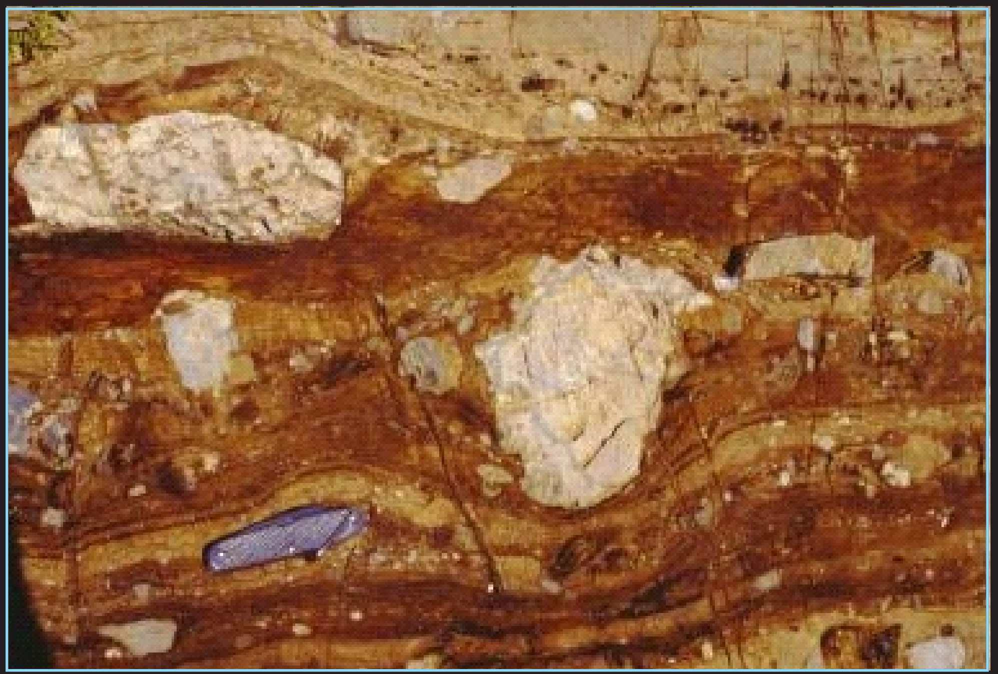
The Neoproterozoic: Gateway to a metazoan-dominated, oxygenated, 'modern-like' biosphere?



Evidence for glaciation



From: *Fairchild and Kennedy* [2007]



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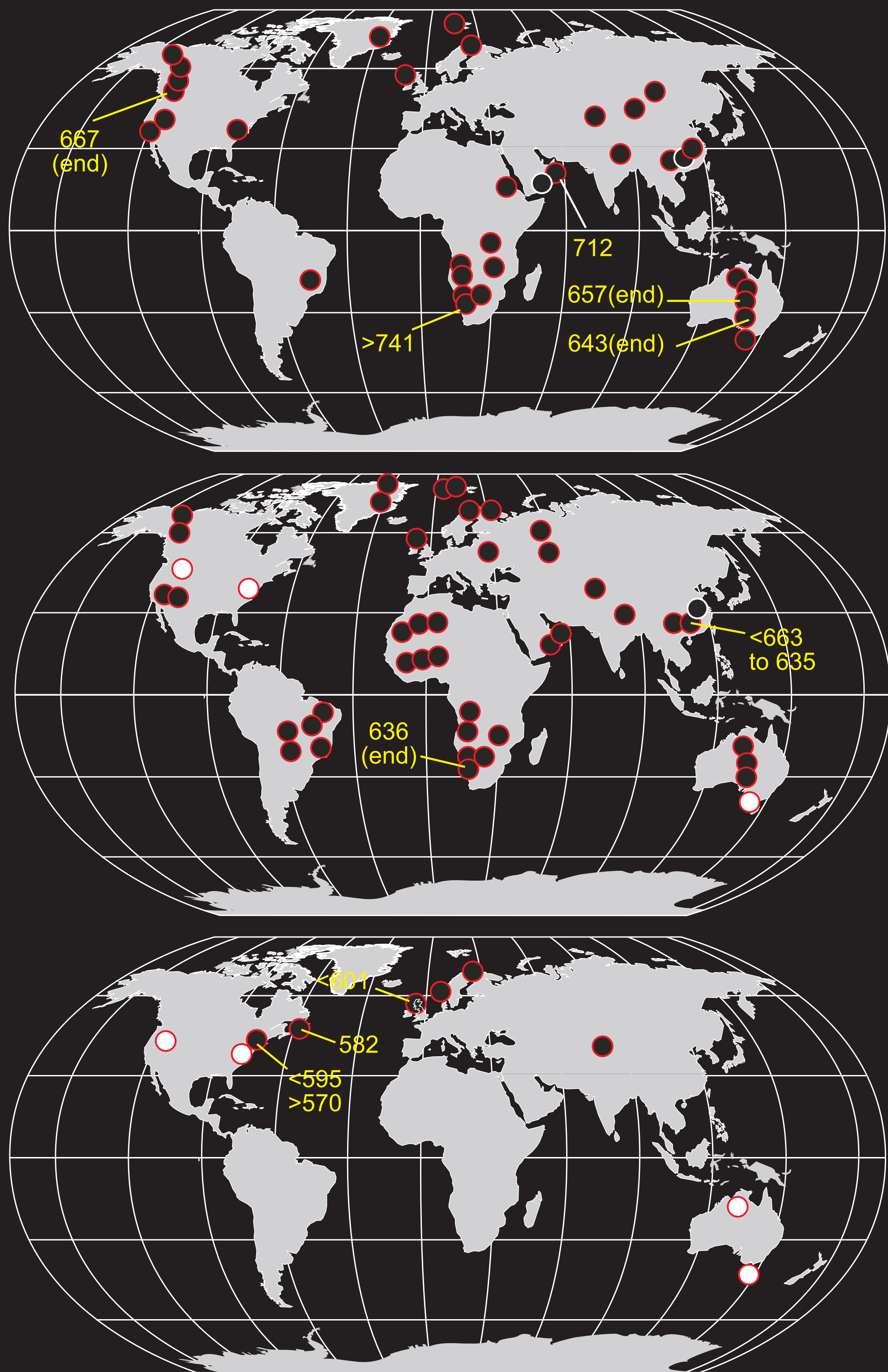
Evidence for glaciation



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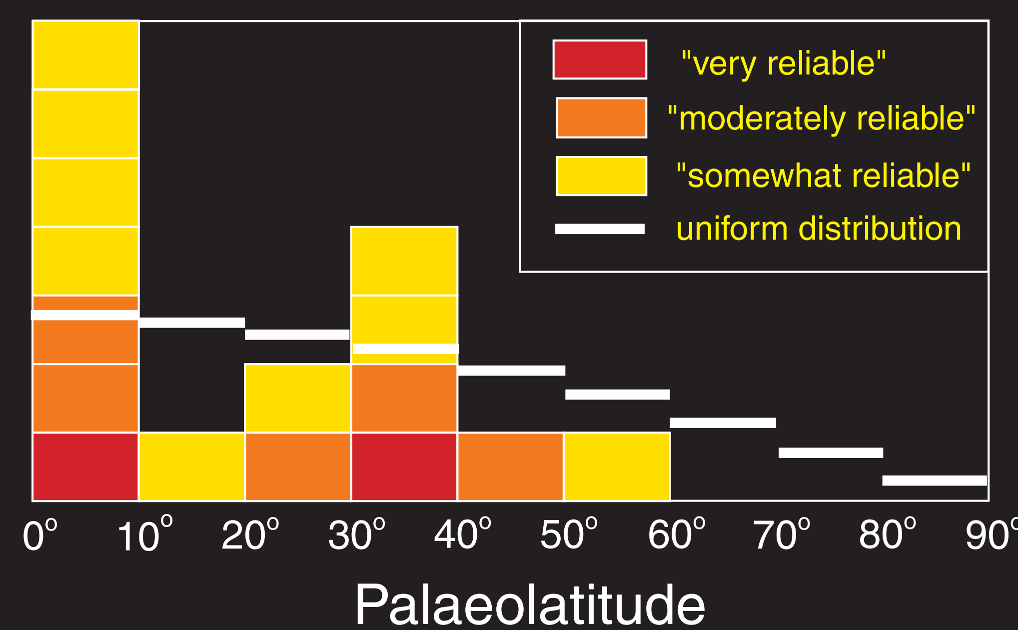
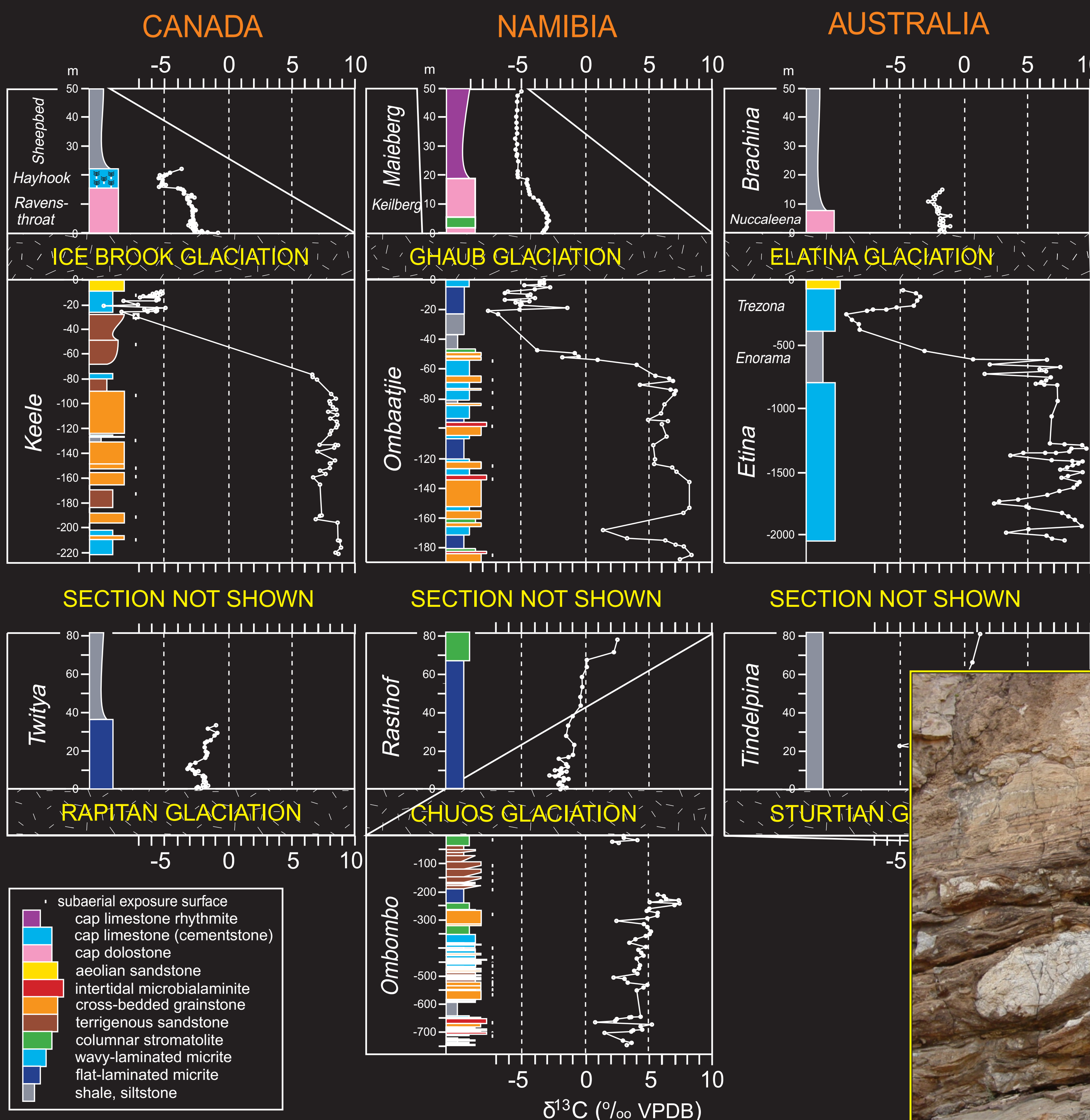


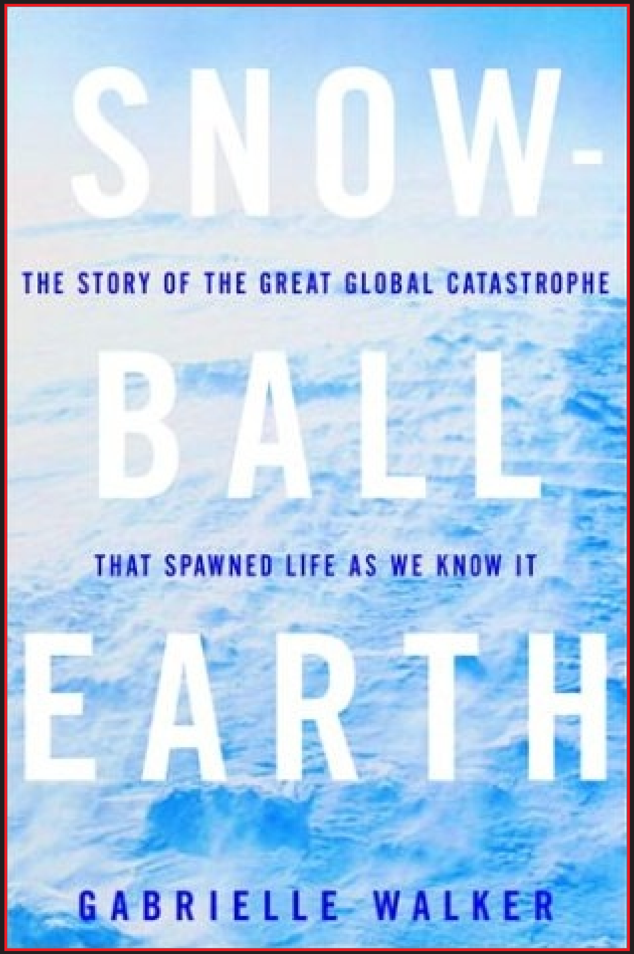
From: *Hoffman and Schrag* [2002]



From: *Hoffman and Schrag* [2002]

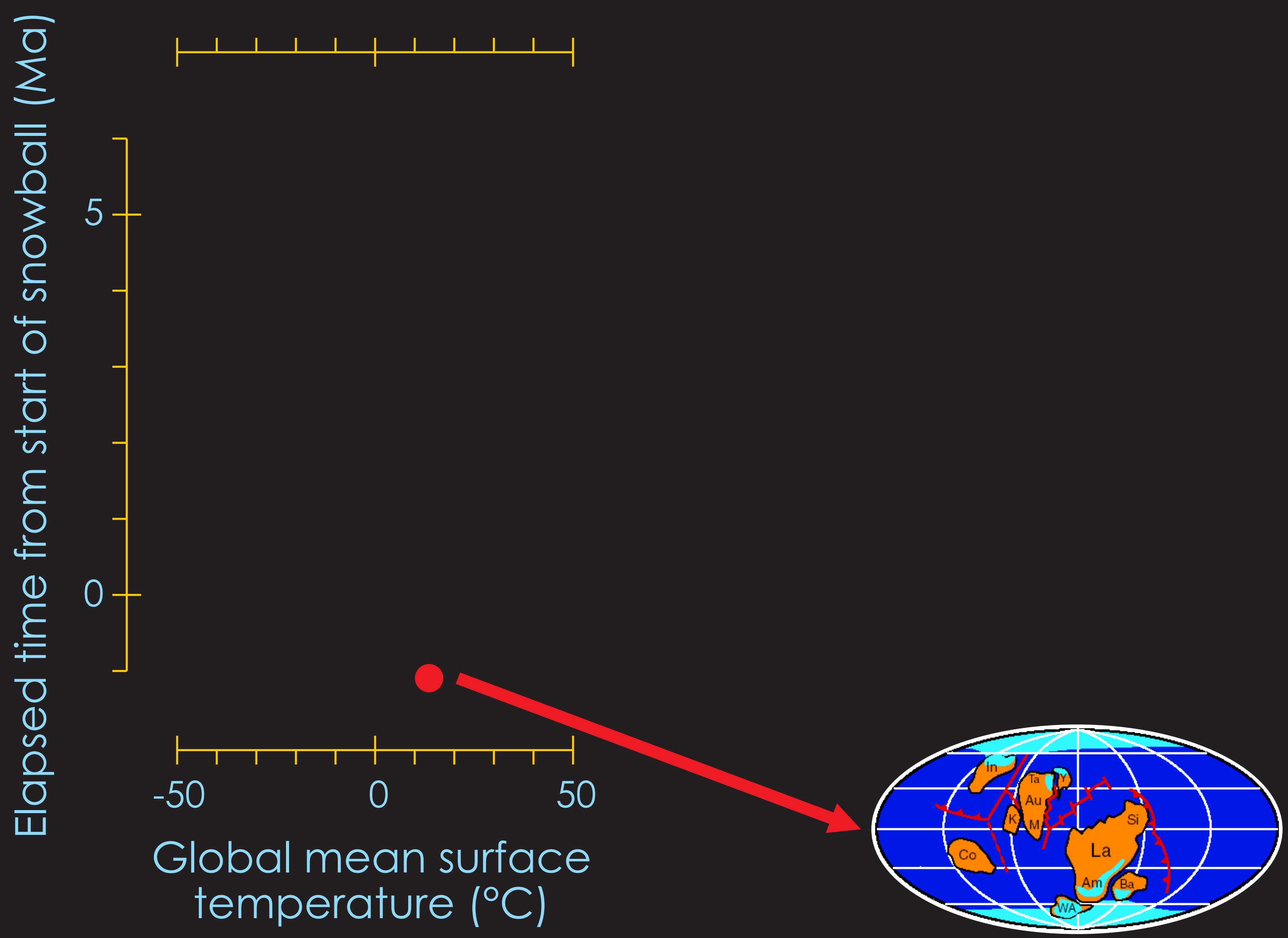
'snowball Earth'

Hoffman et al. [1998] (*Science* **281**)

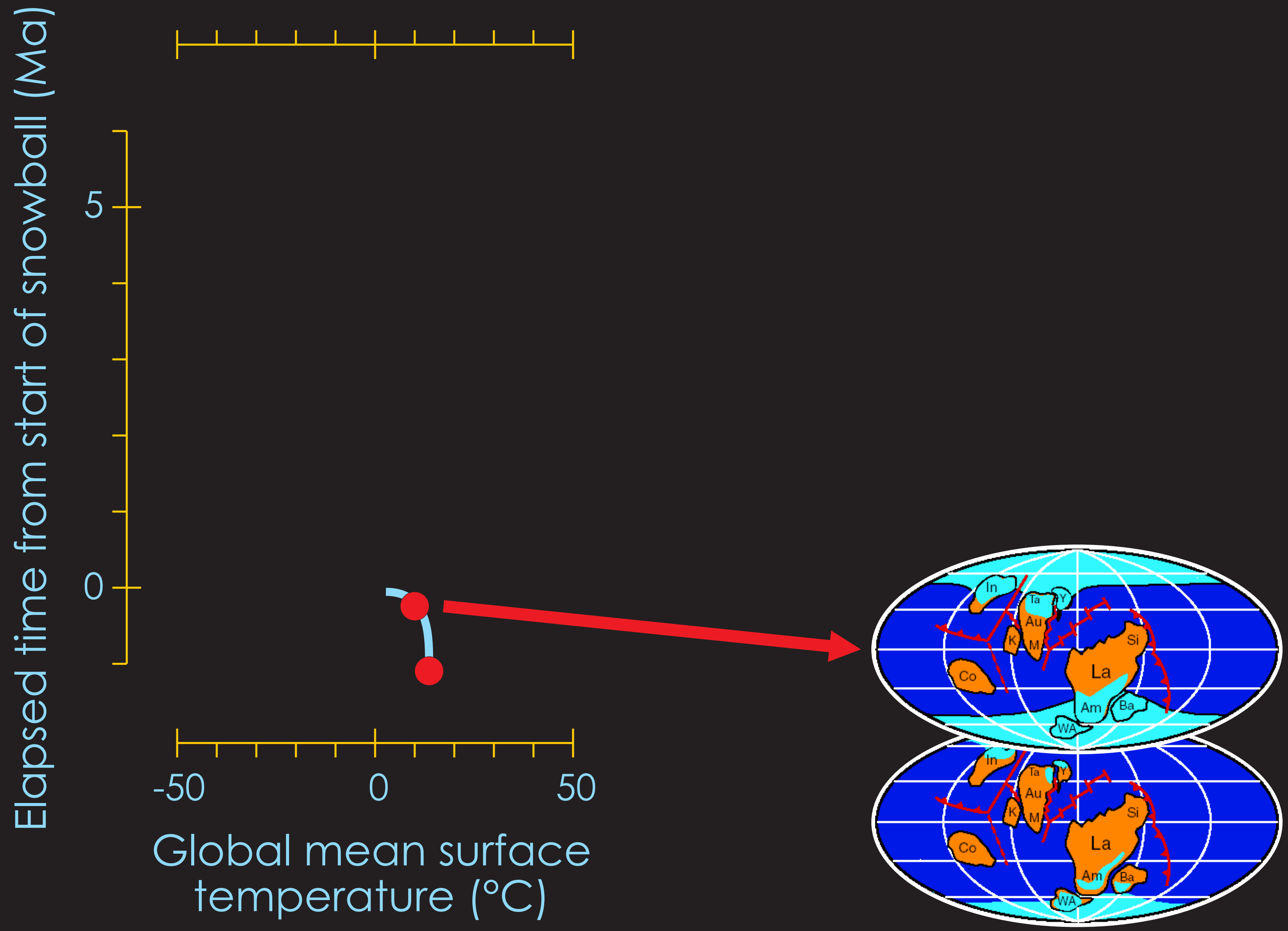


The snowball Earth hypothesis

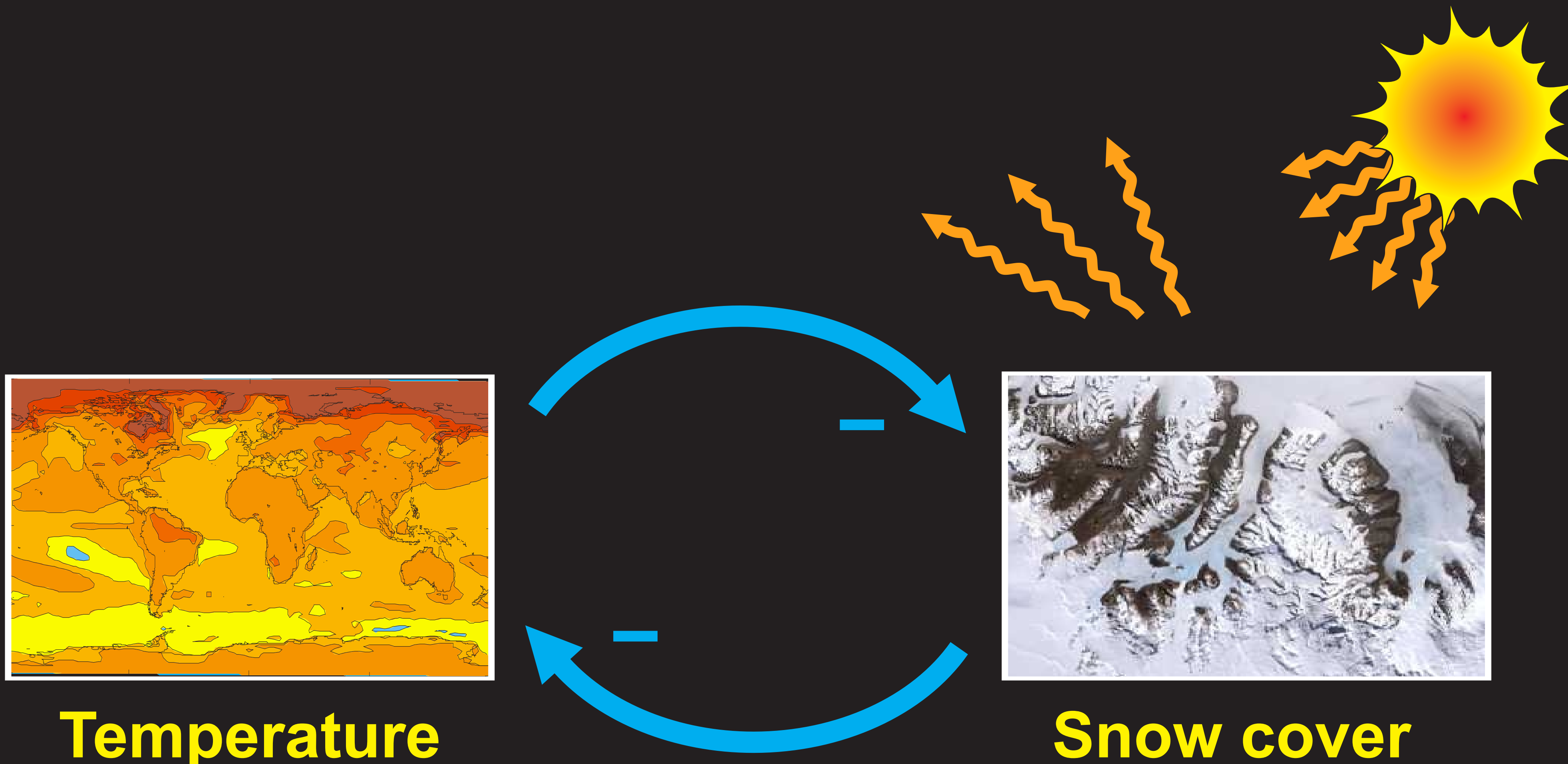
*[Hoffman and Schrag, 2002] (Terra Nova **14**, 129-155)*



The snowball Earth hypothesis

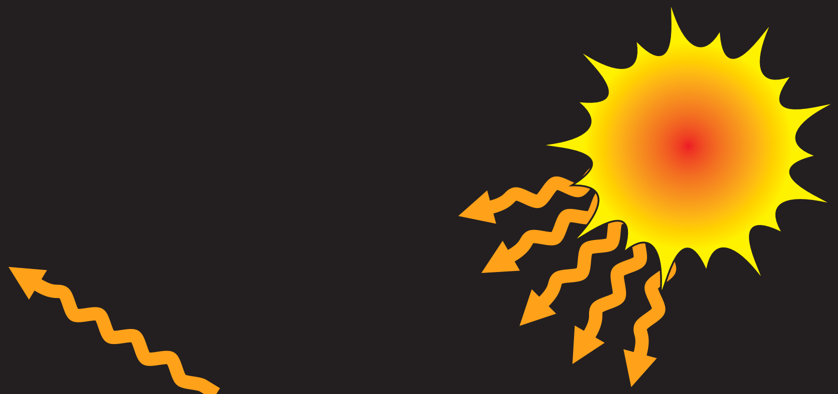


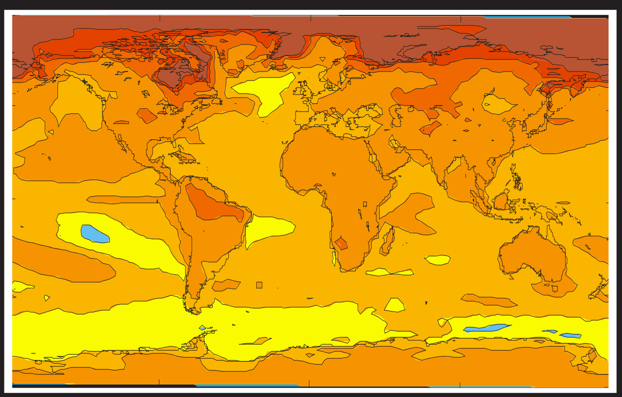
‘Feedbacks’



positive “ice-albedo” feedback

‘Feedbacks’





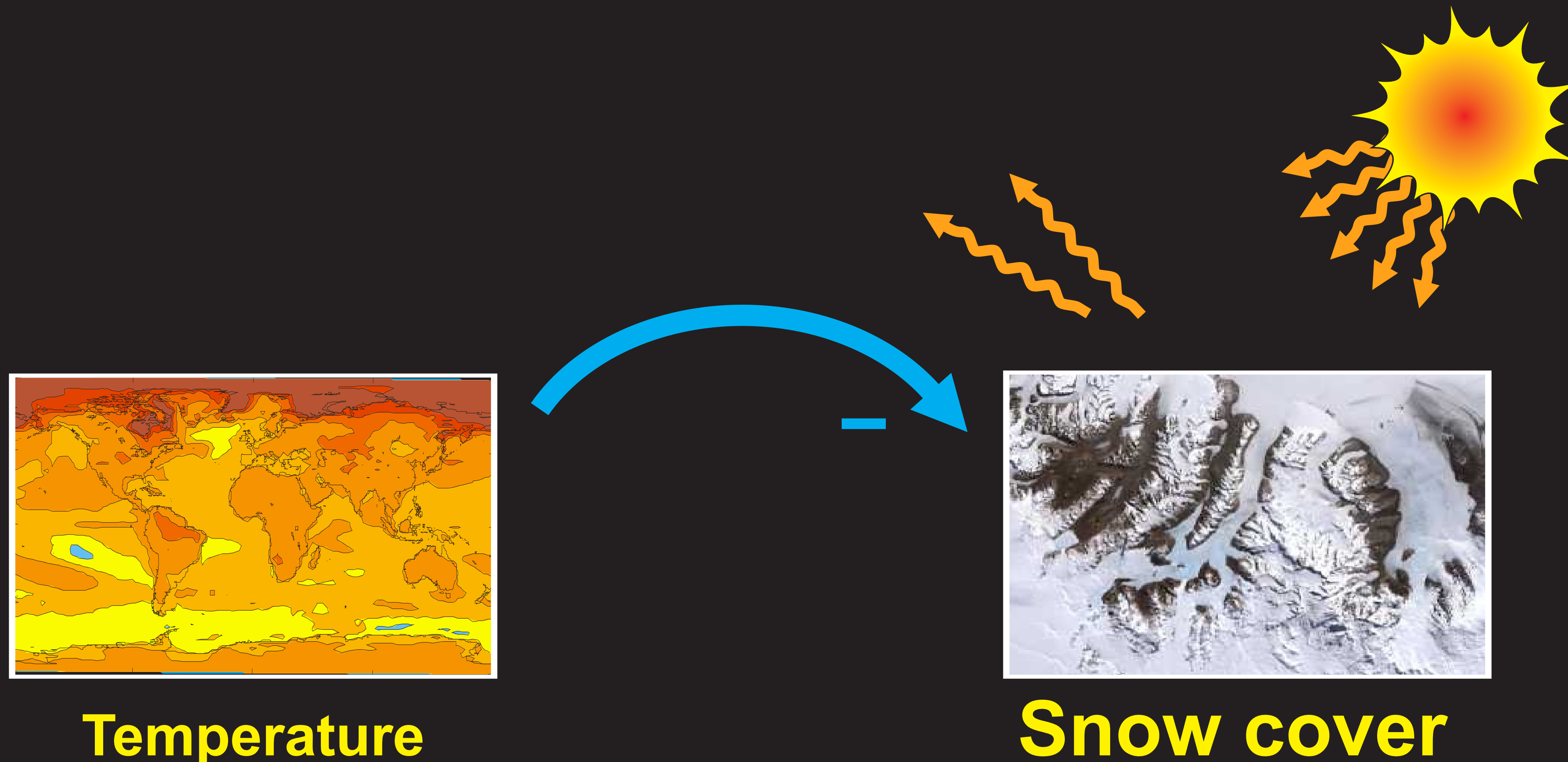
Temperature

−

Snow cover

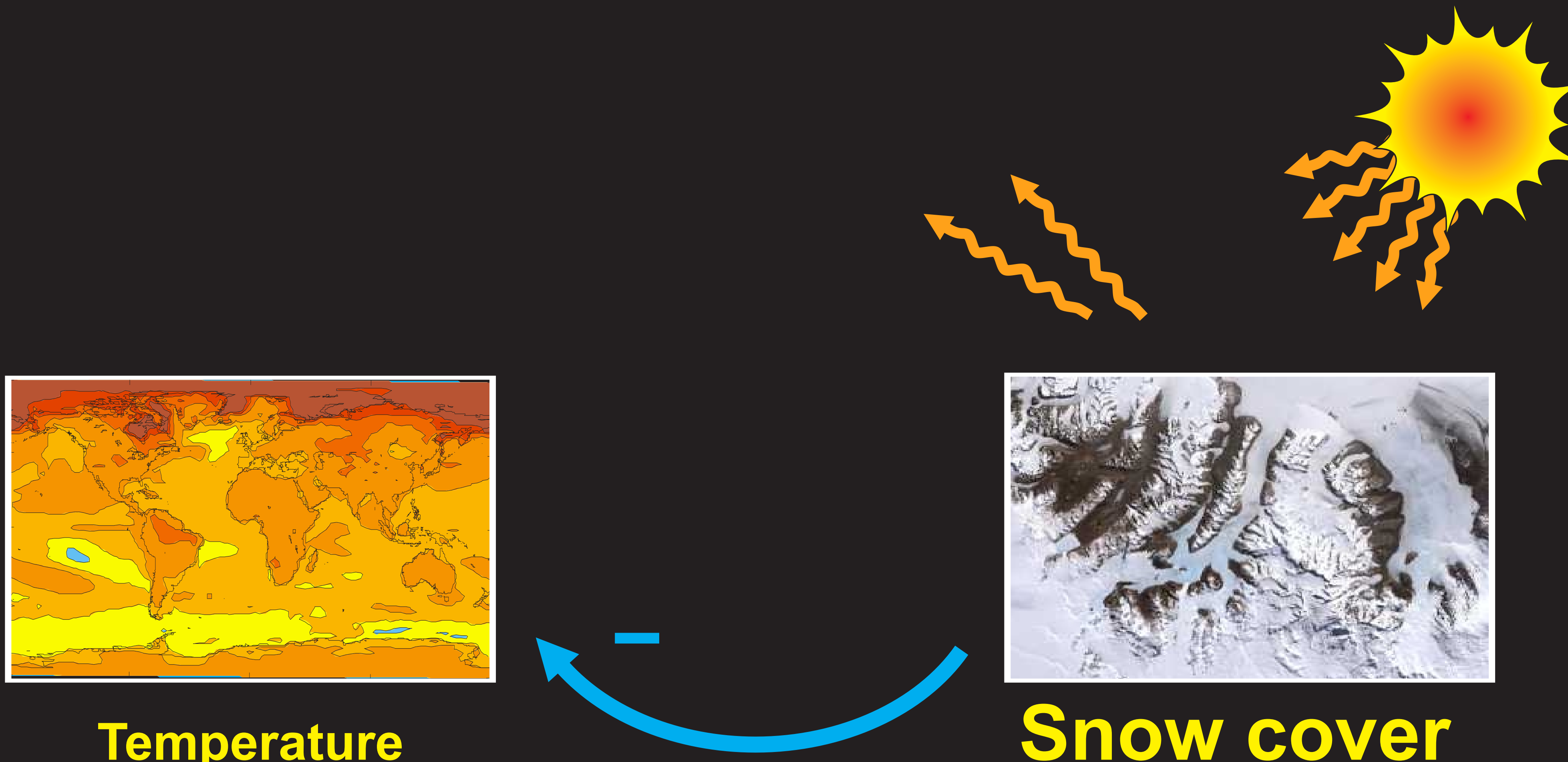
= -1/2°C

‘Feedbacks’



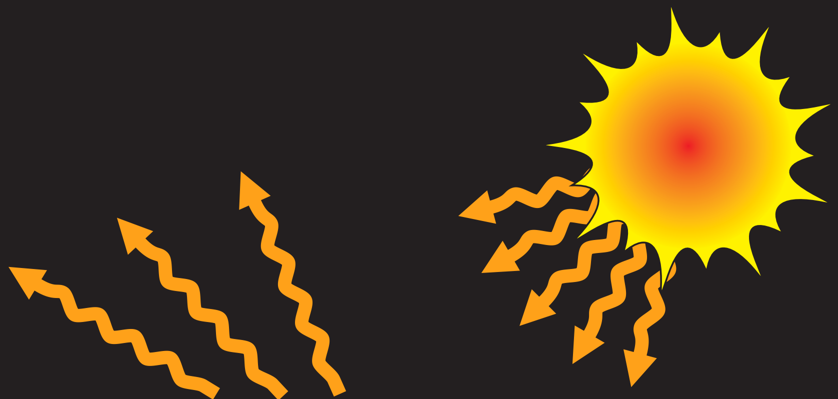
TOTAL CHANGE = -1/2°C

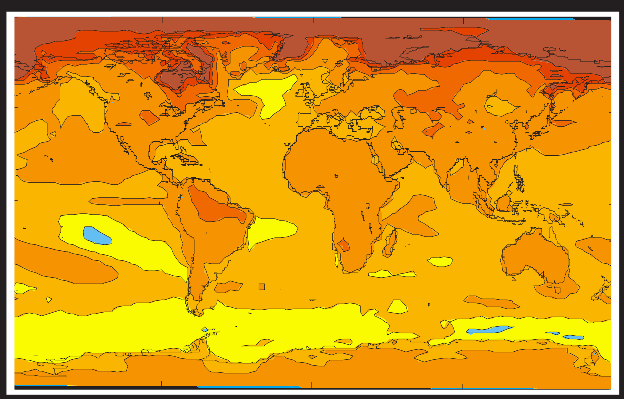
‘Feedbacks’



TOTAL CHANGE = -1/2°C - 1/4°C

‘Feedbacks’





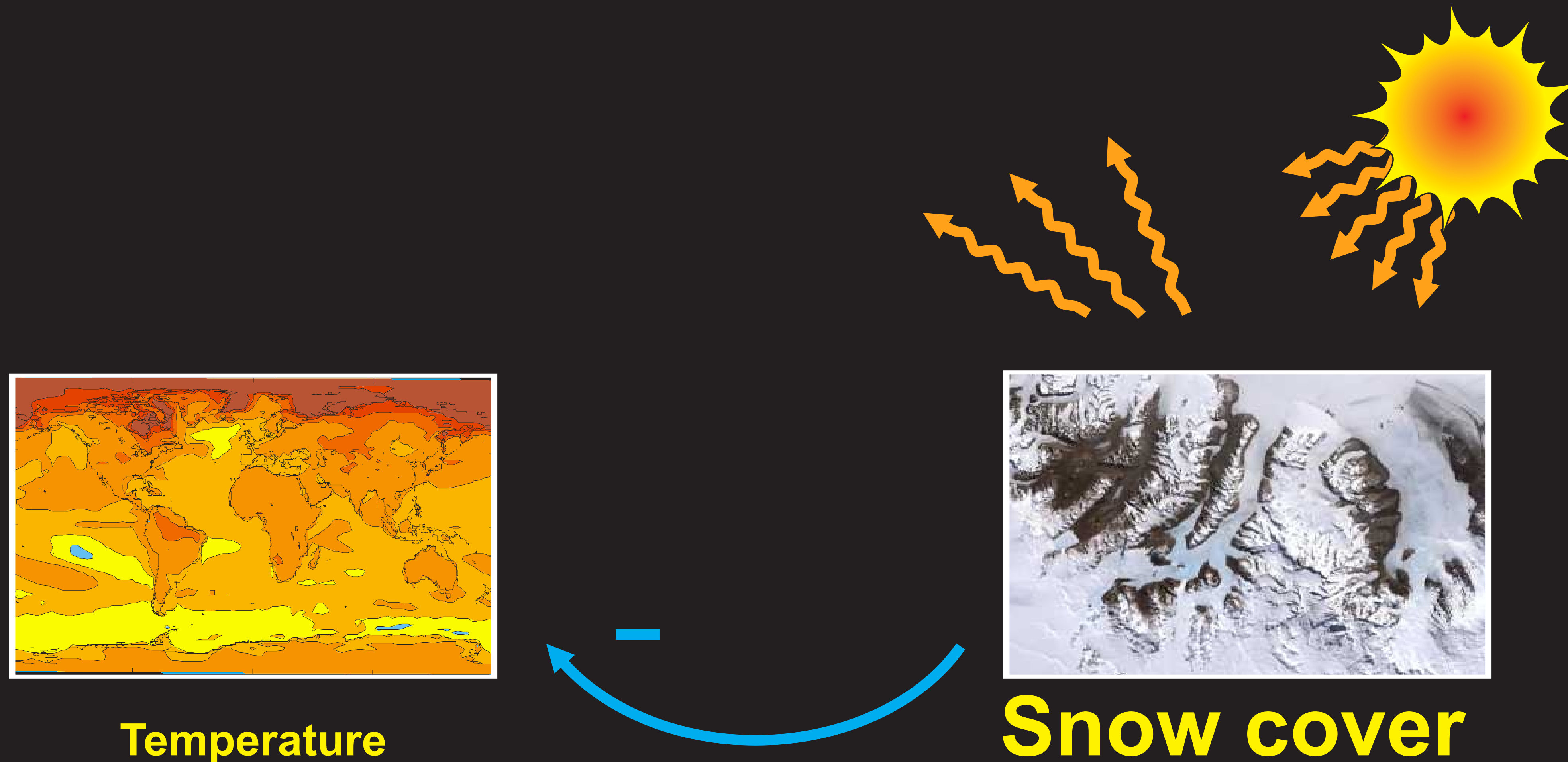
Temperature

–

Snow cover

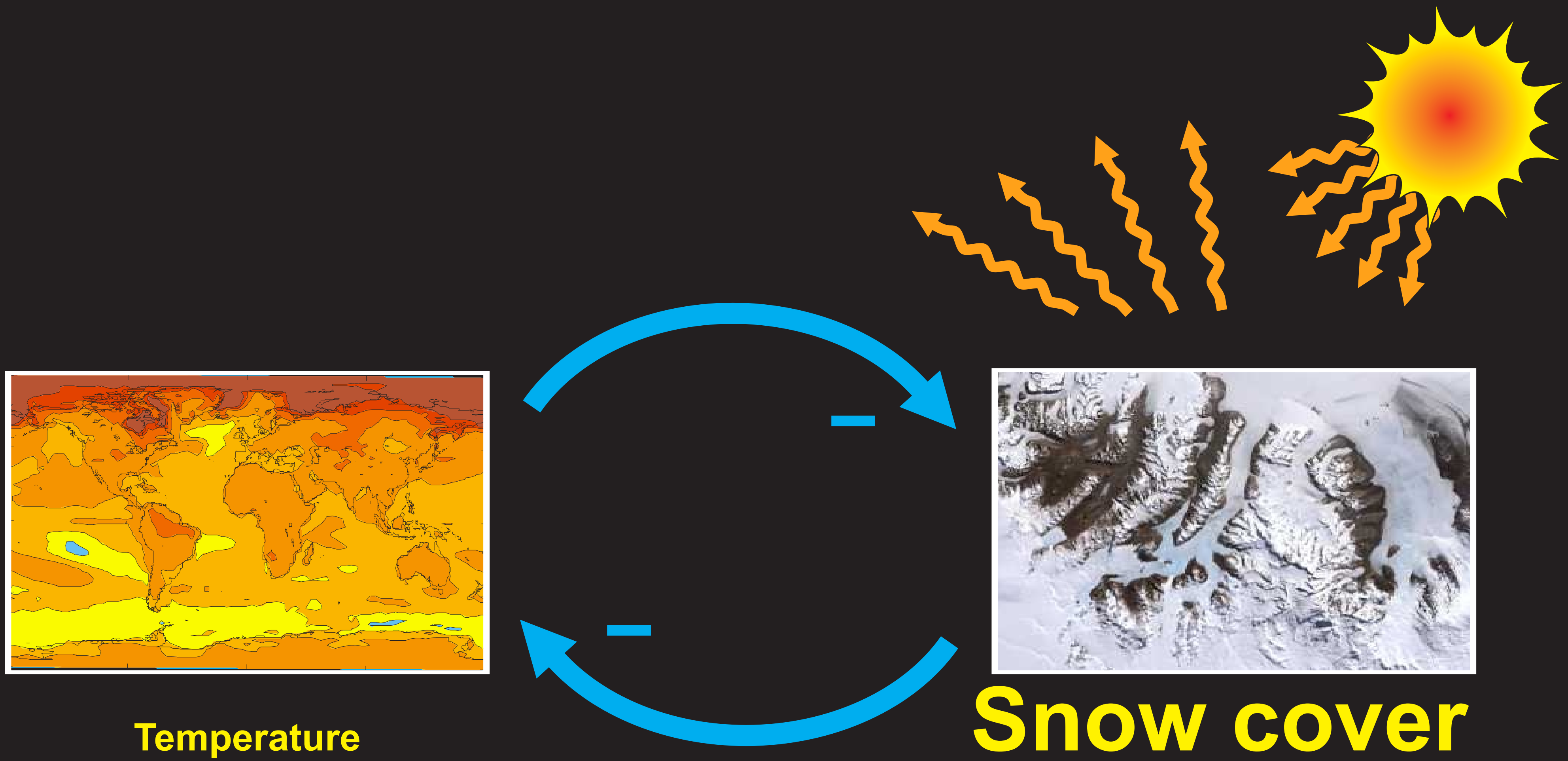
TOTAL CHANGE = -1/2°C - 1/4°C

‘Feedbacks’



TOTAL CHANGE = -1/2°C - 1/4°C - 1/8°C

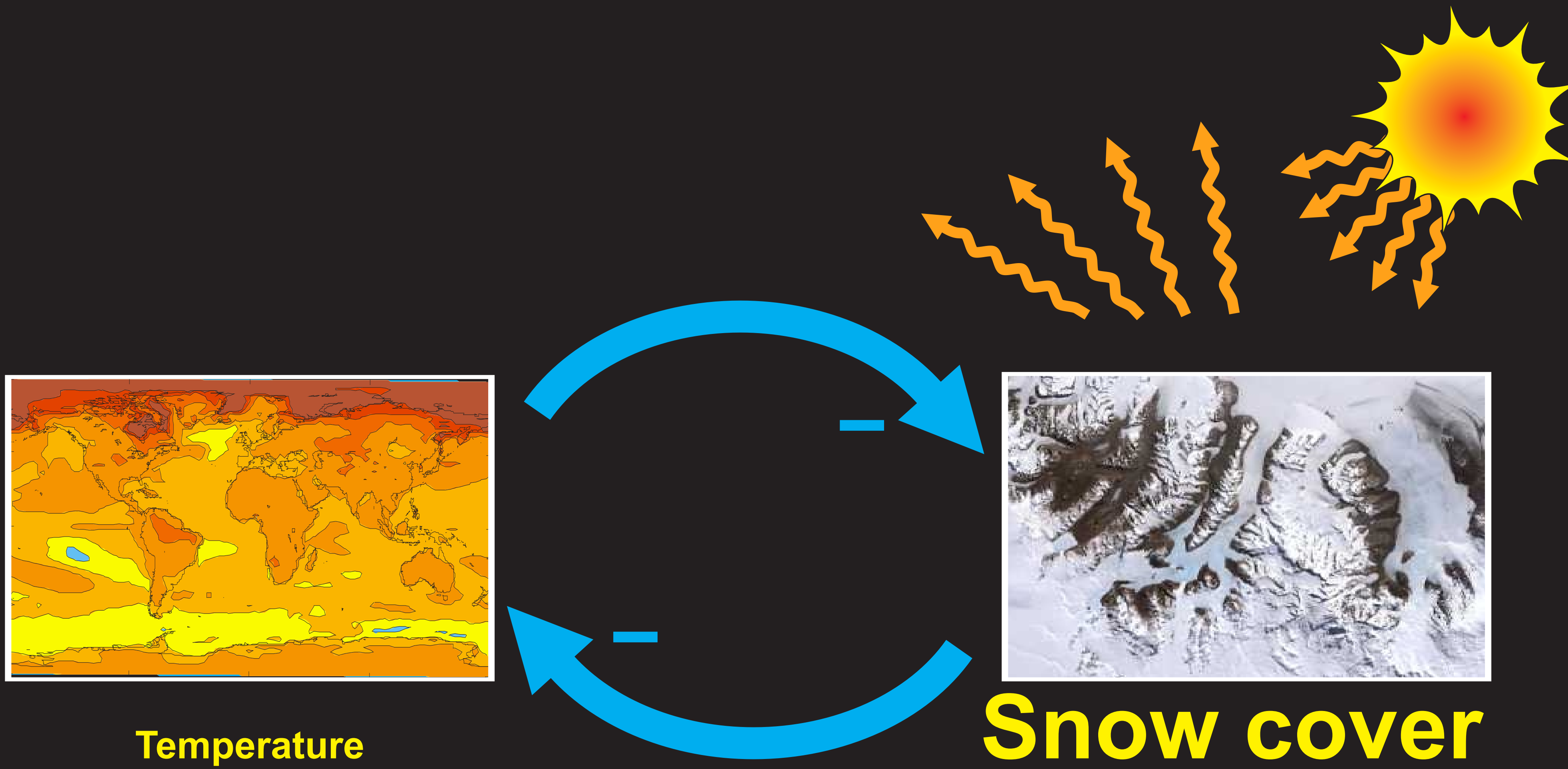
‘Feedbacks’



TOTAL CHANGE = -1/2°C - 1/4°C - 1/8°C - 1/16°

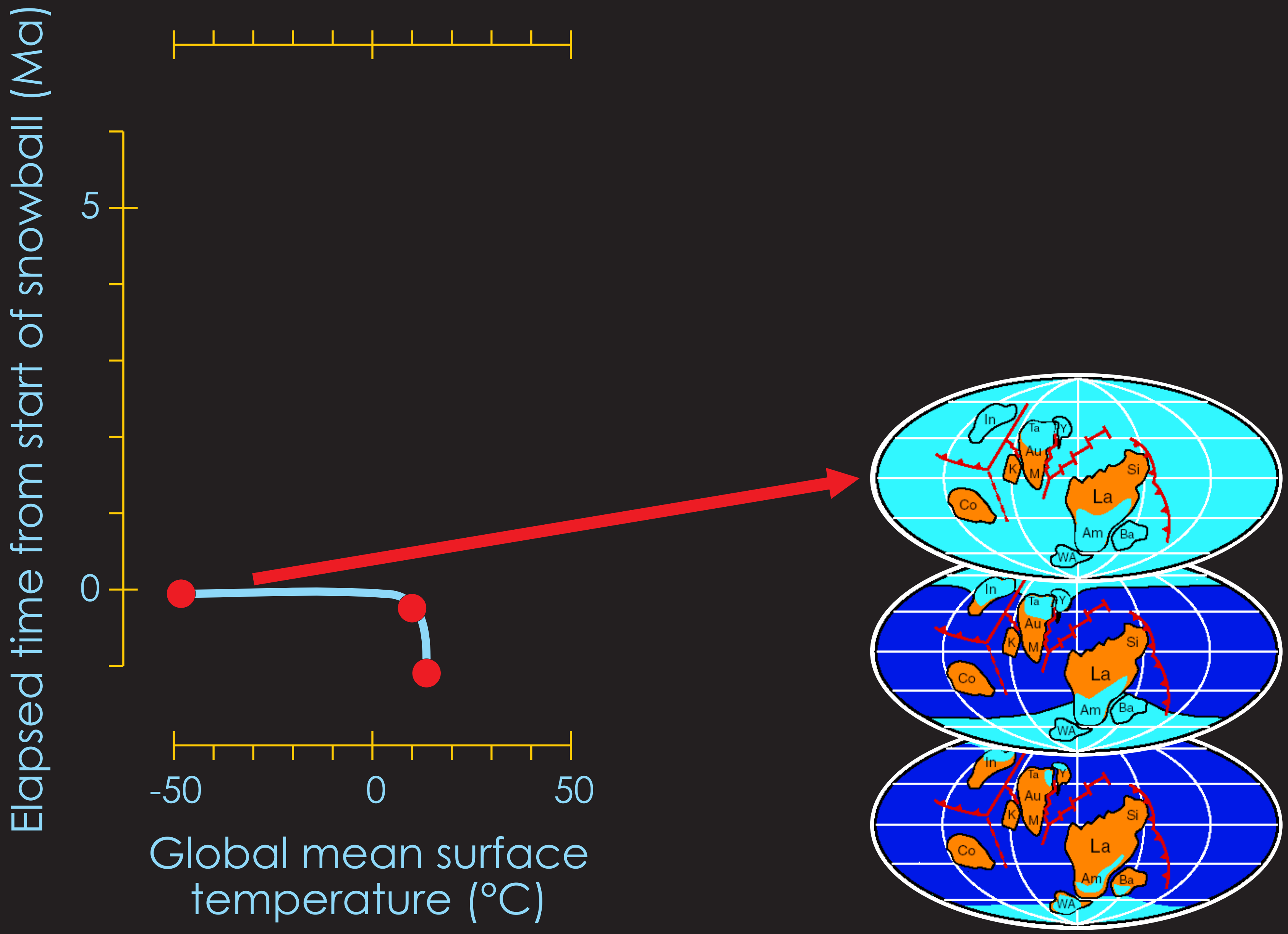
- ....

‘Feedbacks’ (’runaway’)

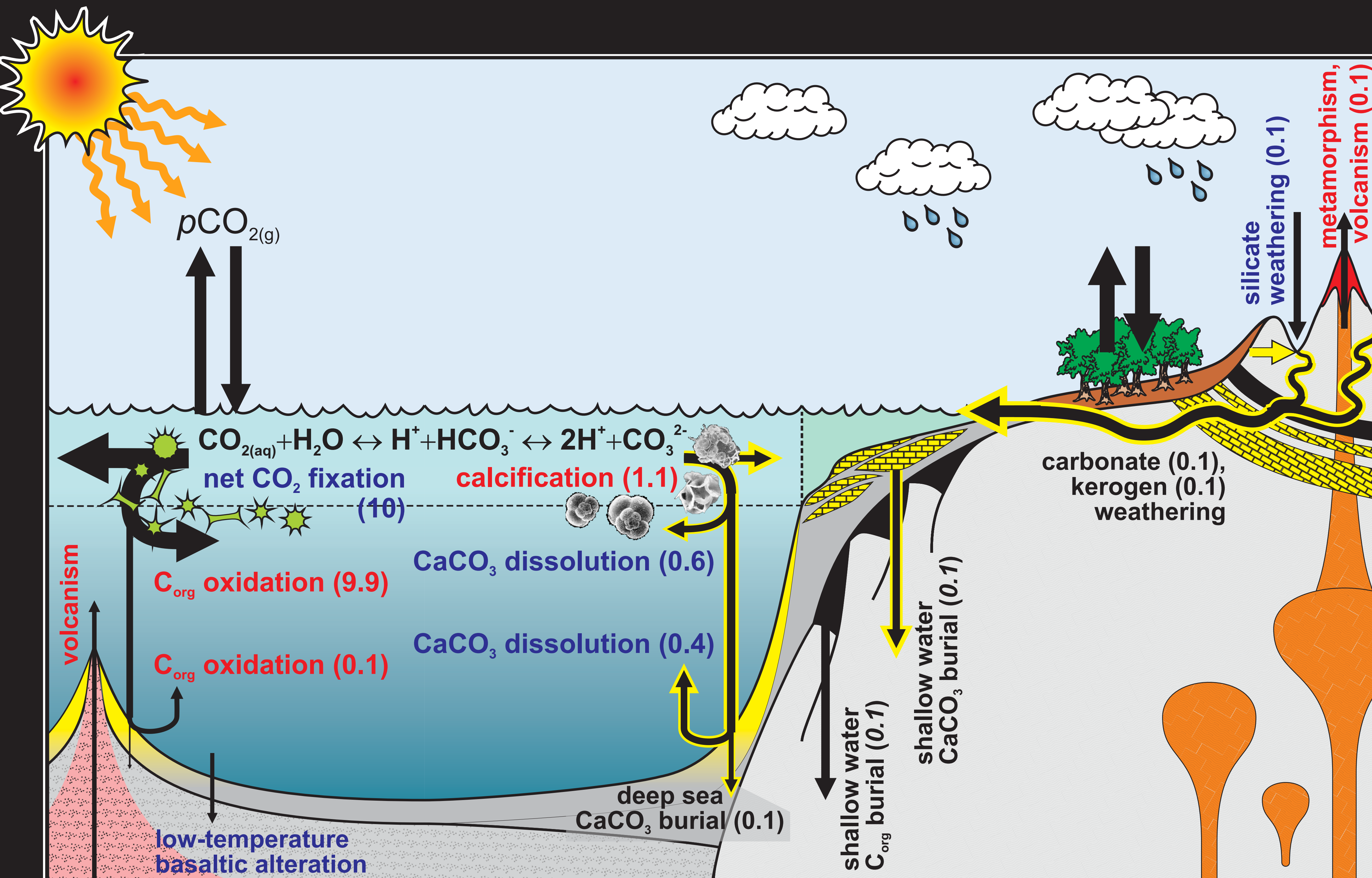


TOTAL CHANGE = -1°C - 2°C - 4°C - 8°C
- ....

The snowball Earth hypothesis



The global carbon cycle (modern)



Long-term controls on atmospheric pCO_2

Terrestrial weathering can be (approximately equally) divided into carbonate ($CaCO_3$) and calcium-silicate ('$CaSiO_3$') weathering:

(1) $2CO_{2(aq)} + H_2O + CaSiO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$

(2) $CO_{2(aq)} + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$

Ultimately, the (alkalinity: Ca^{2+}) weathering products must be removed through carbonate precipitation and burial in marine sediments:

(3) $Ca^{2+} + 2HCO_3^- \rightarrow CO_{2(aq)} + H_2O + CaCO_3$

It can be seen that in (2) + (3), that the CO_2 removed (from the atmosphere) during weathering, is returned upon carbonate precipitation (and burial). In (1) + (3) (silicate weathering) CO_2 is permanently removed to the geological reservoir. This CO_2 must be balanced by mantle (/volcanic) out-gassing on the very long term.

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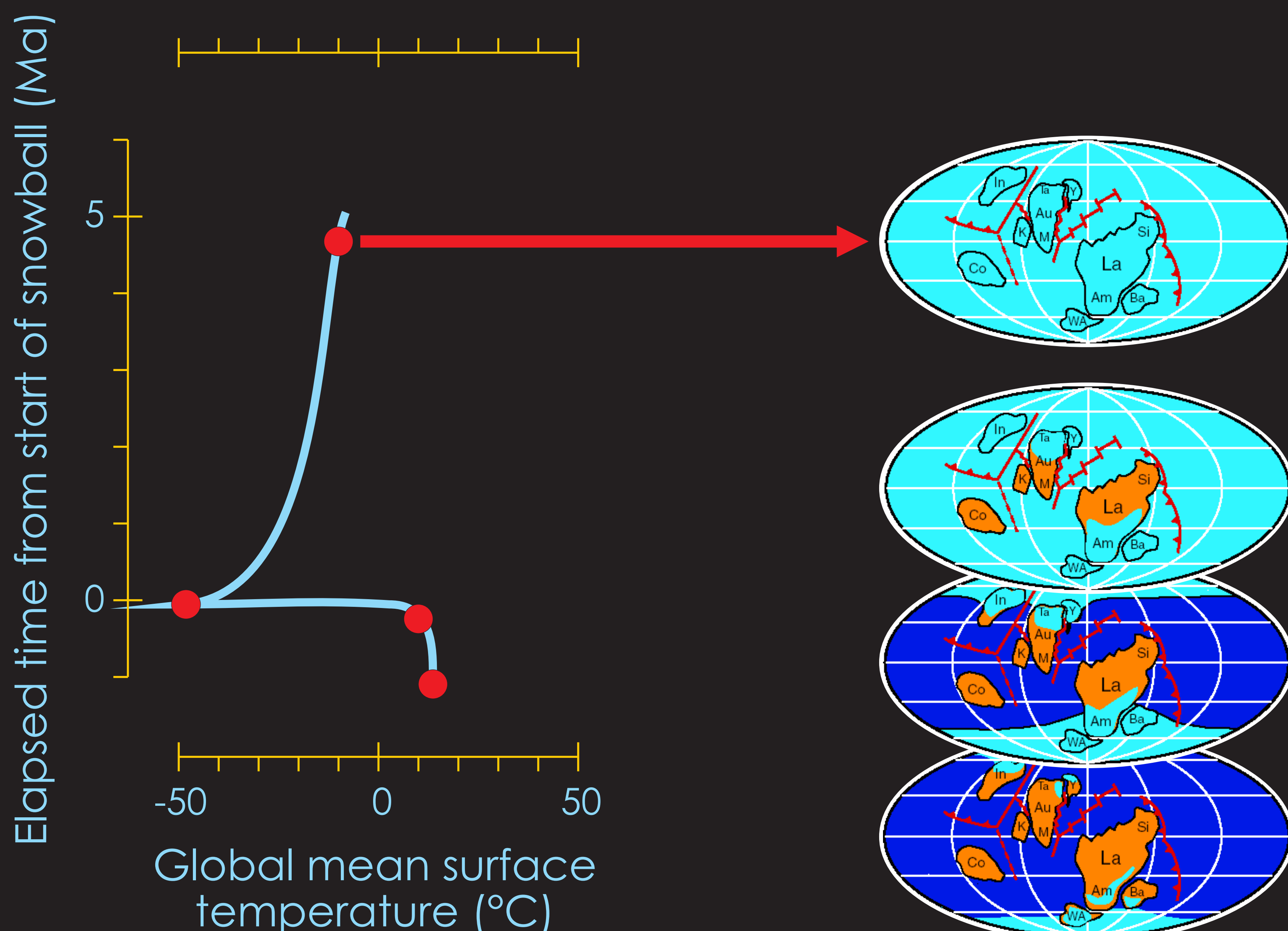

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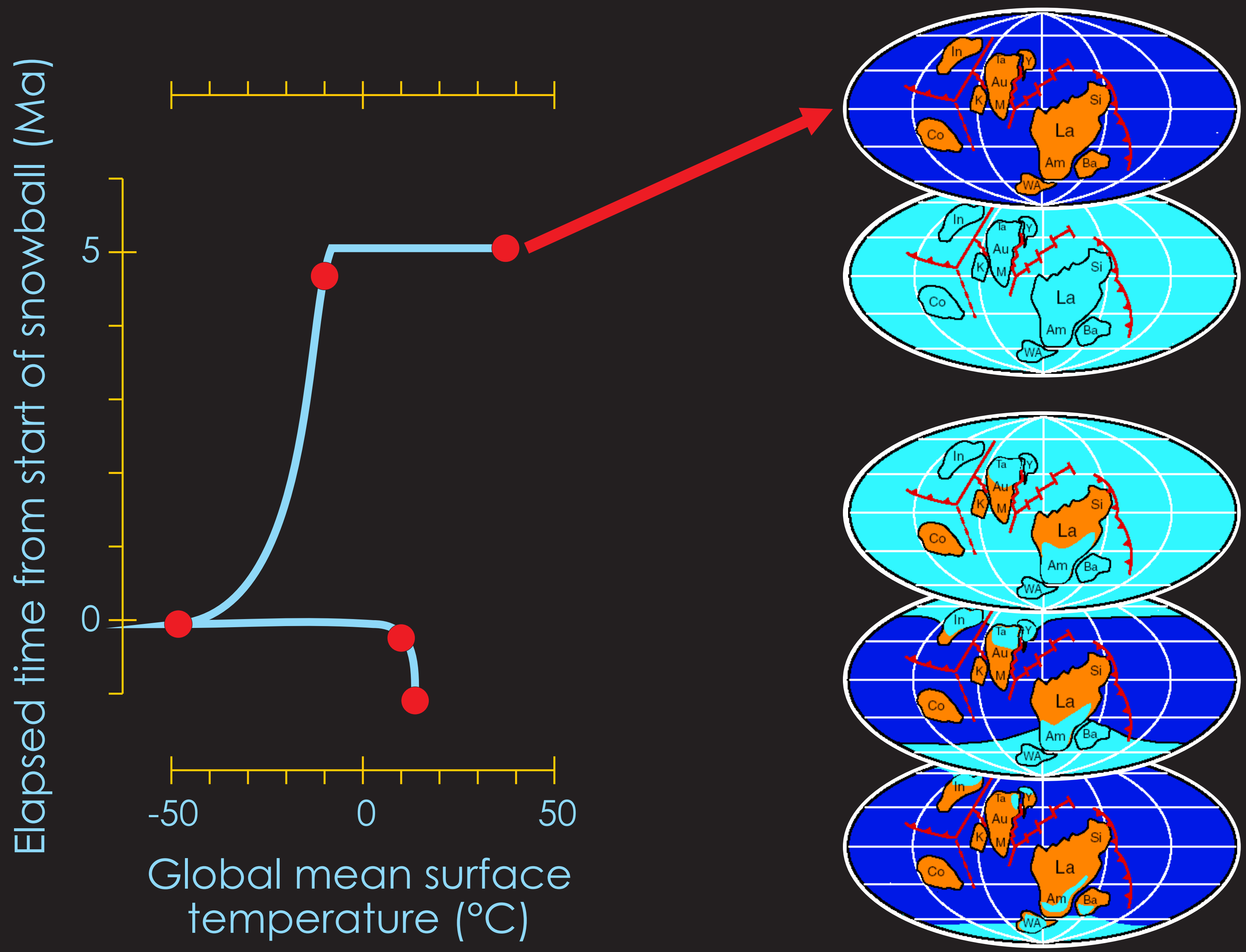

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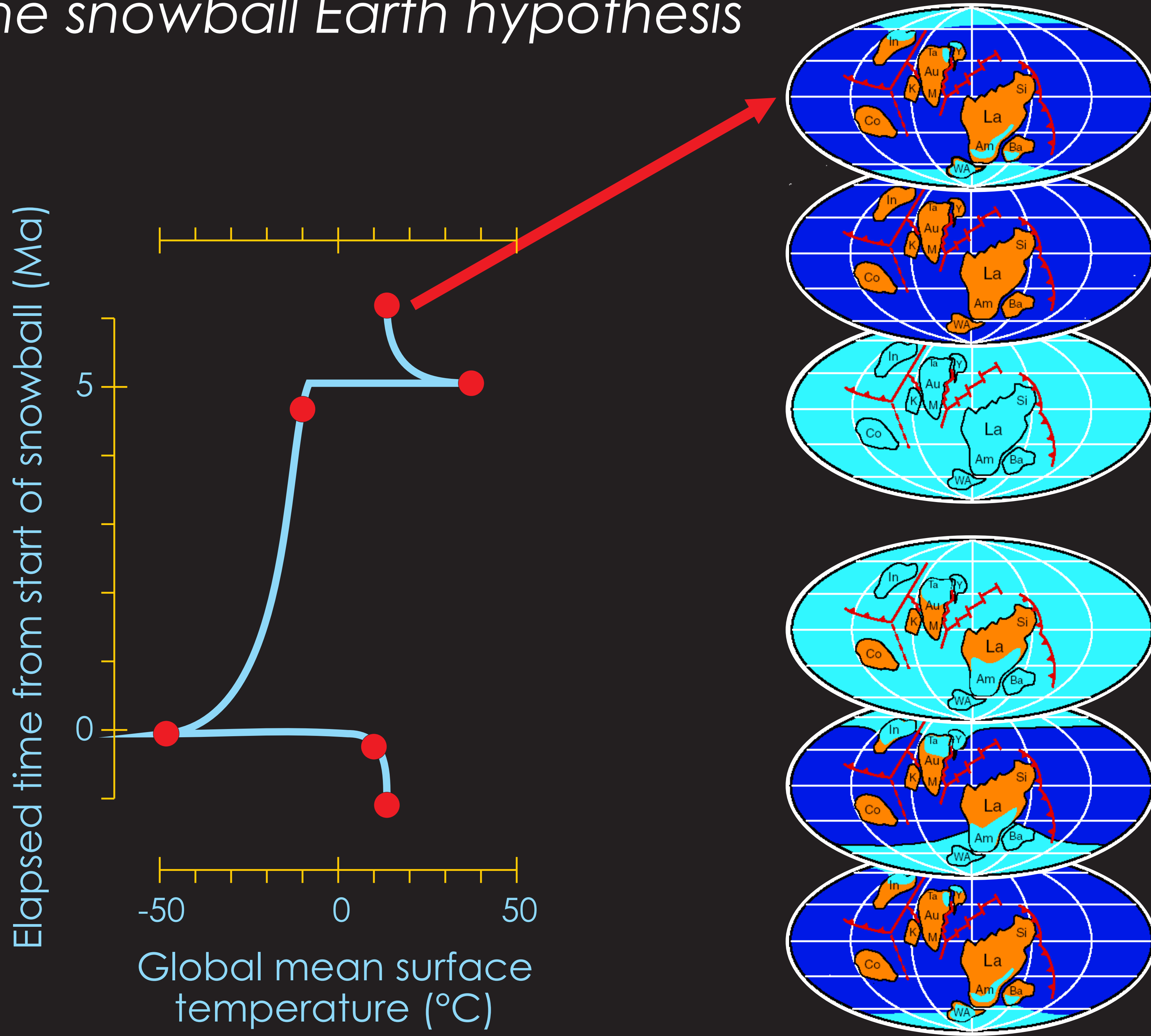
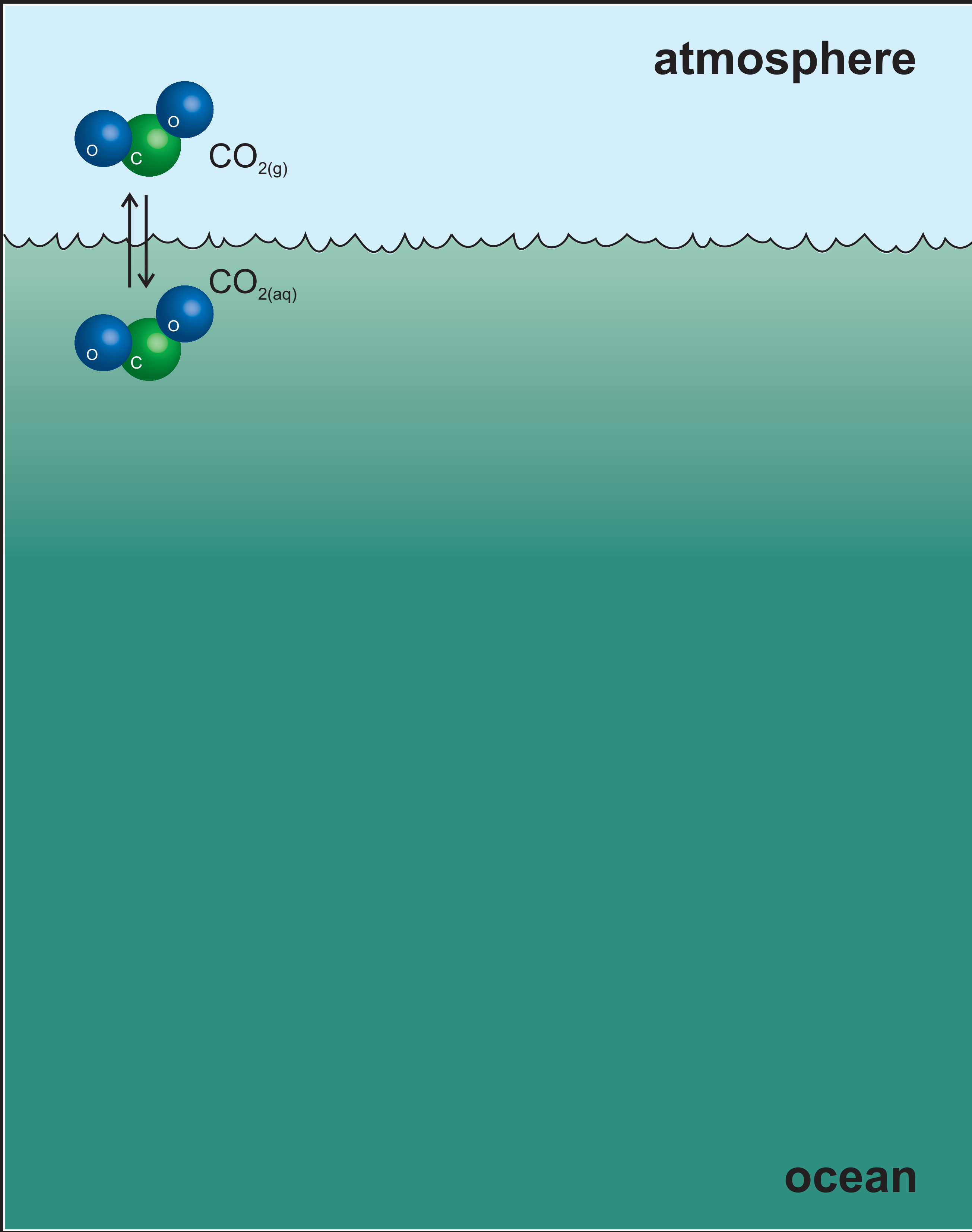


adapted from: *Hoffman and Schrag* [2002]

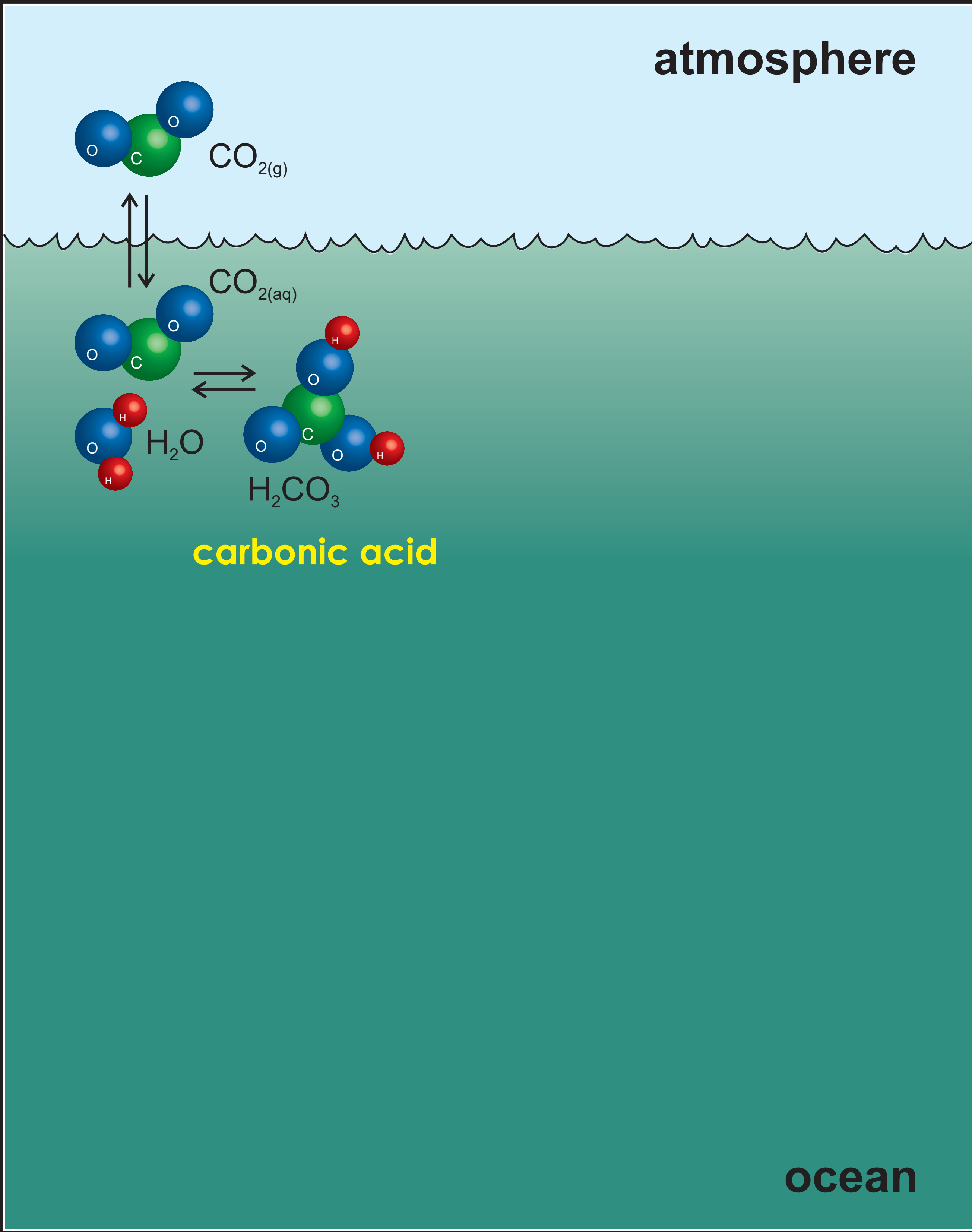
The enigma of the 'cap carbonates'

CO_2 *chemistry in seawater*

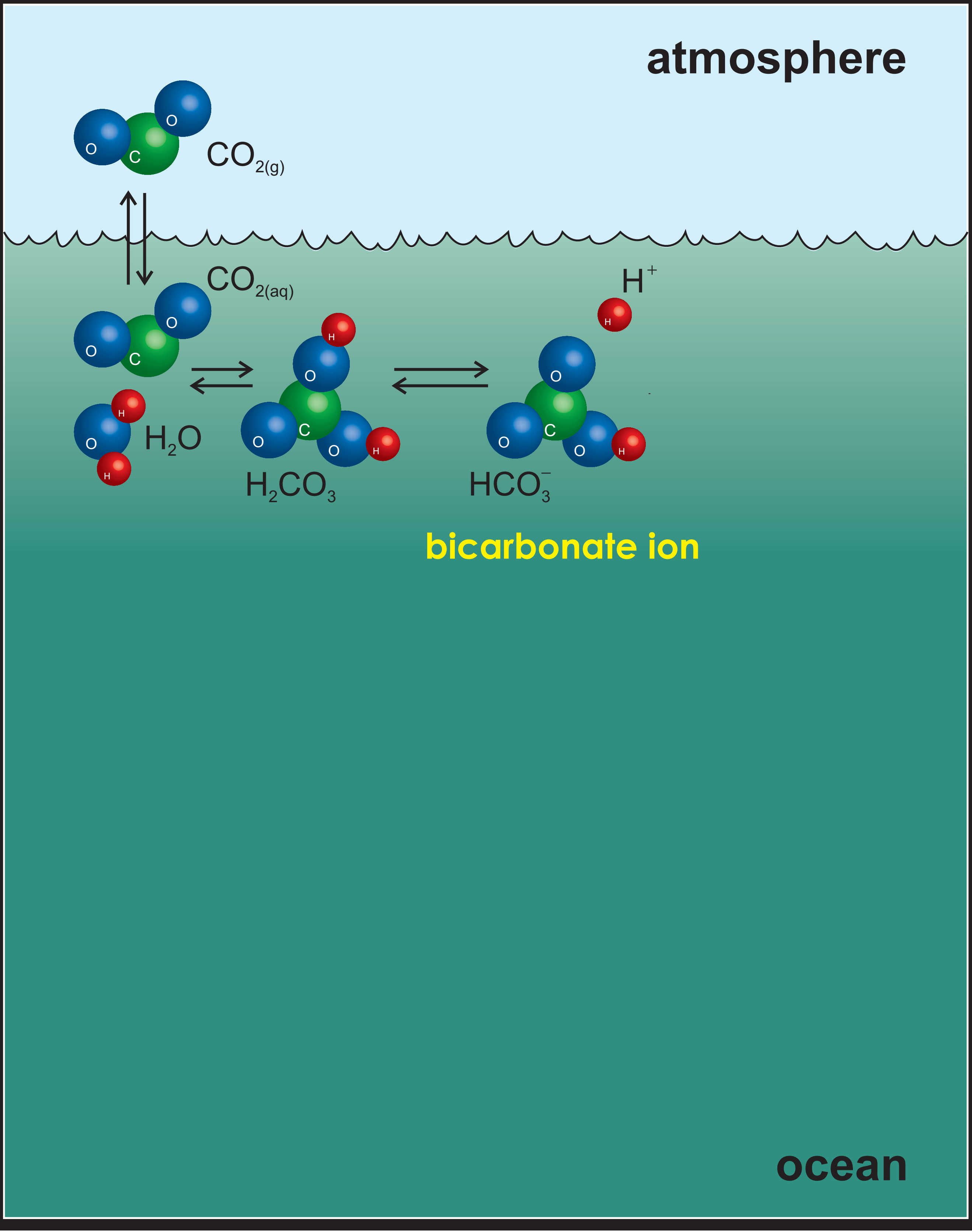


From: *Barker and Ridgwell* [2012]
http://www.nature.com/scitable/knowledge/library/ocean-acidification-25822734

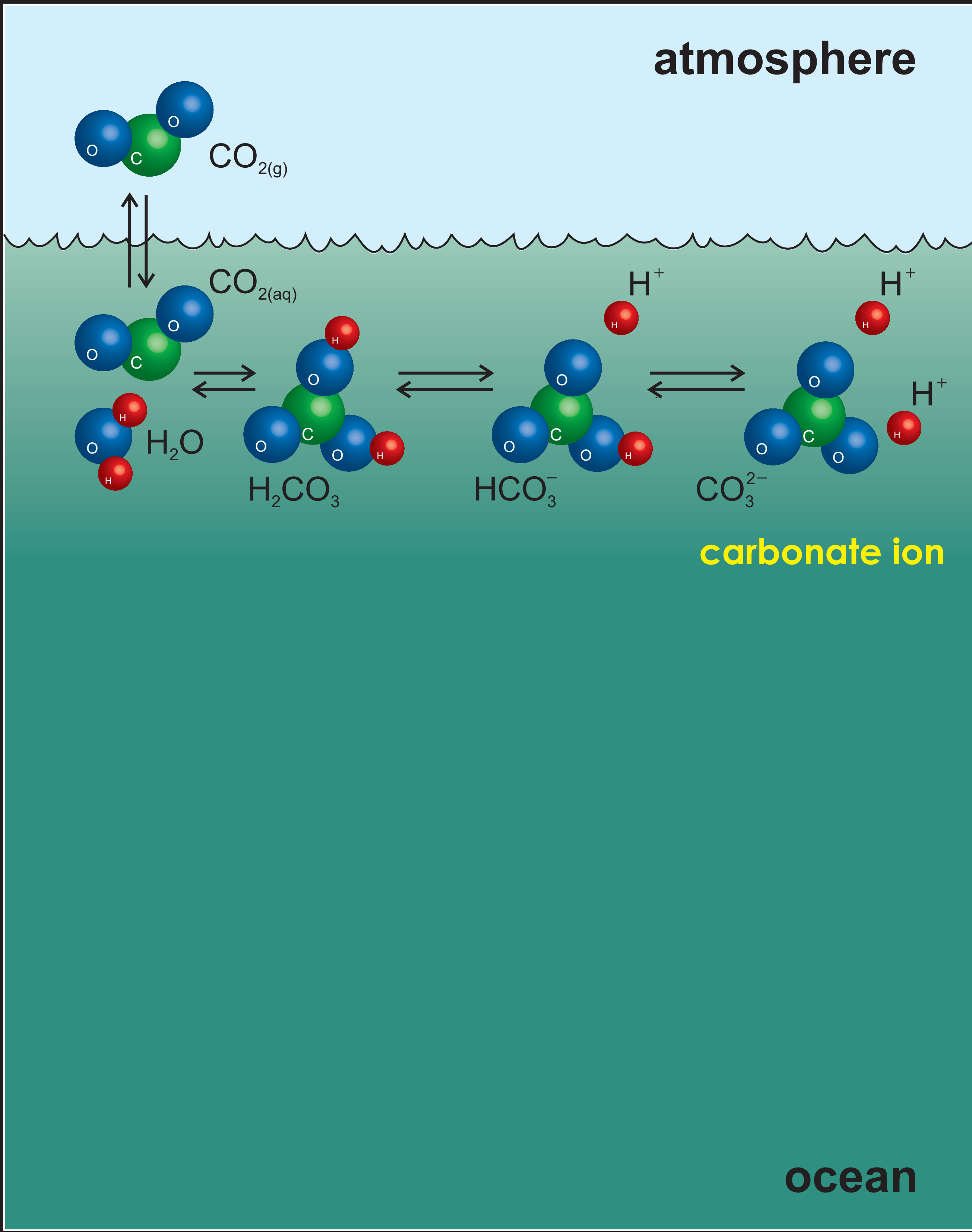
CO_2 chemistry in seawater



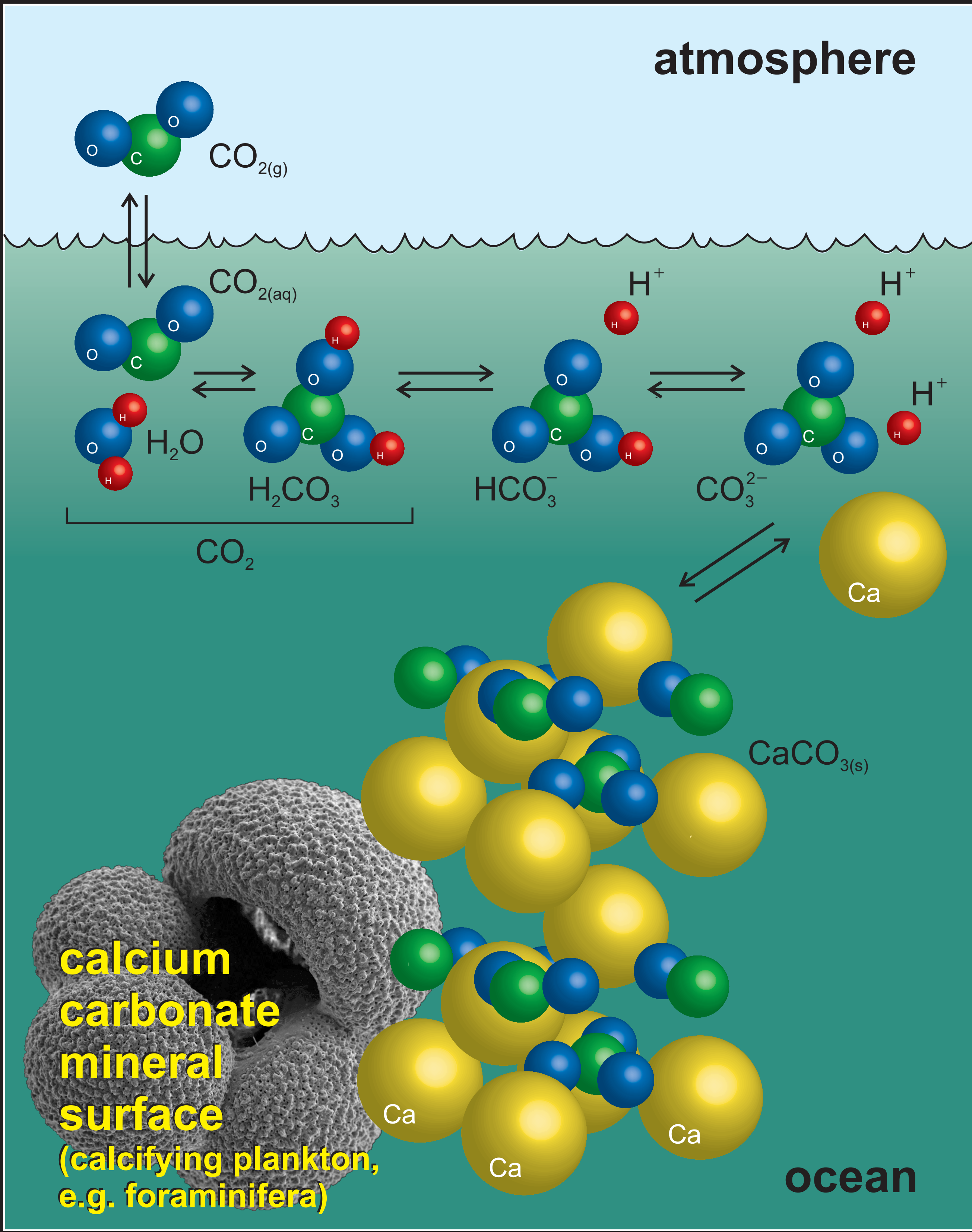
CO_2 chemistry in seawater



CO_2 chemistry in seawater

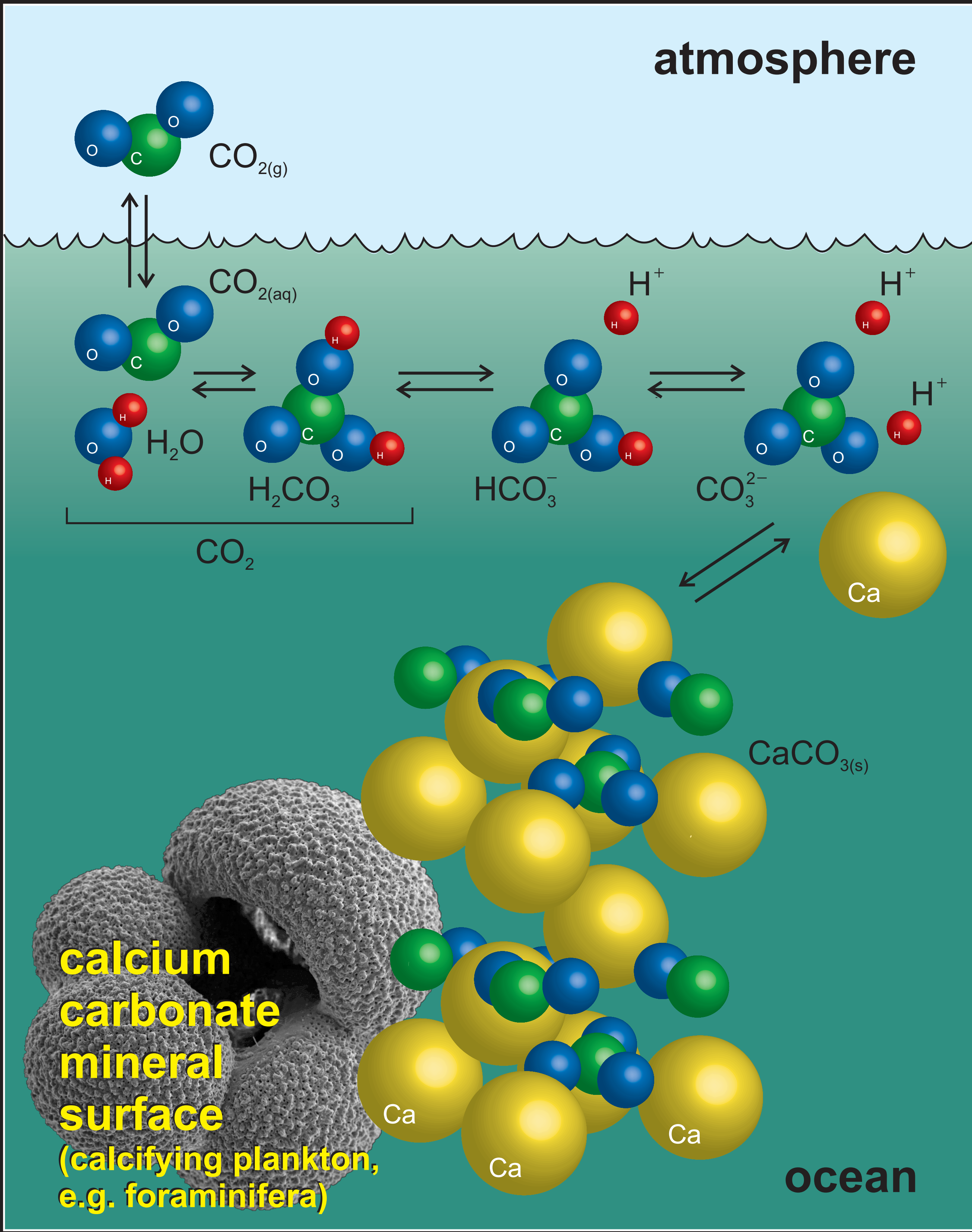


CO_2 chemistry & mineral phases



Aragonite: less stable
orthorhombic polymorph (e.g., many corals, pteropods)

Calcite: more stable
(and more abundant)
trigonal polymorph (e.g., coccolithophorides, foraminifera)



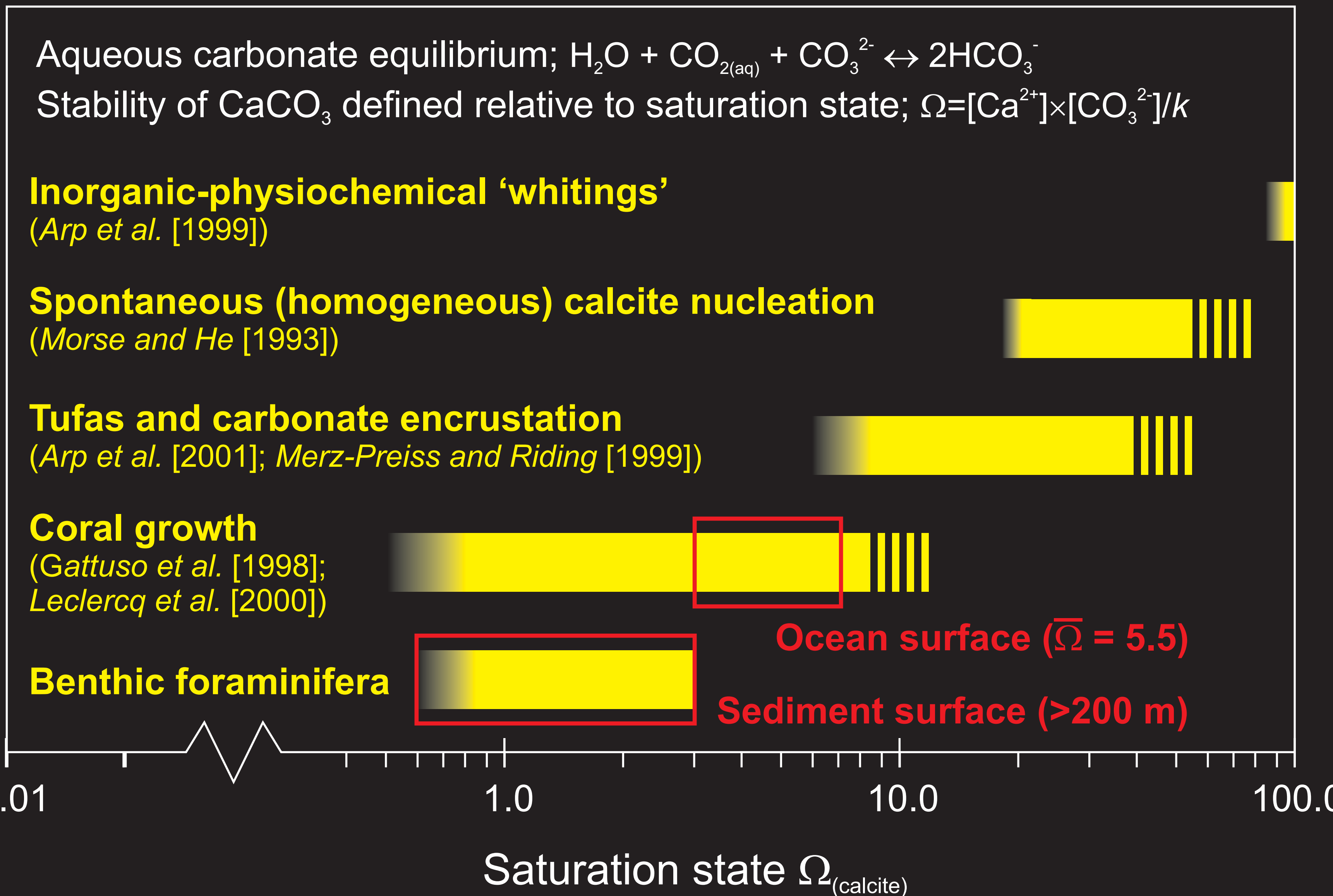
CO_2 chemistry & mineral phases

The addition of CO_2 to seawater results in a decrease in carbonate ion (CO_3^{2-}) concentration and 'ocean acidification'. A decrease in CO_3^{2-}, in turn, suppresses the stability of $CaCO_3$, defined by its *saturation state*:

$$\Omega = [Ca^{2+}] \times [CO_3^{2-}] / k$$

⇒ The thermodynamic efficiency of precipitating $CaCO_3$ is a function of $[CO_3^{2-}]$ (and carbonate 'saturation').

The enigma of the 'cap carbonates'



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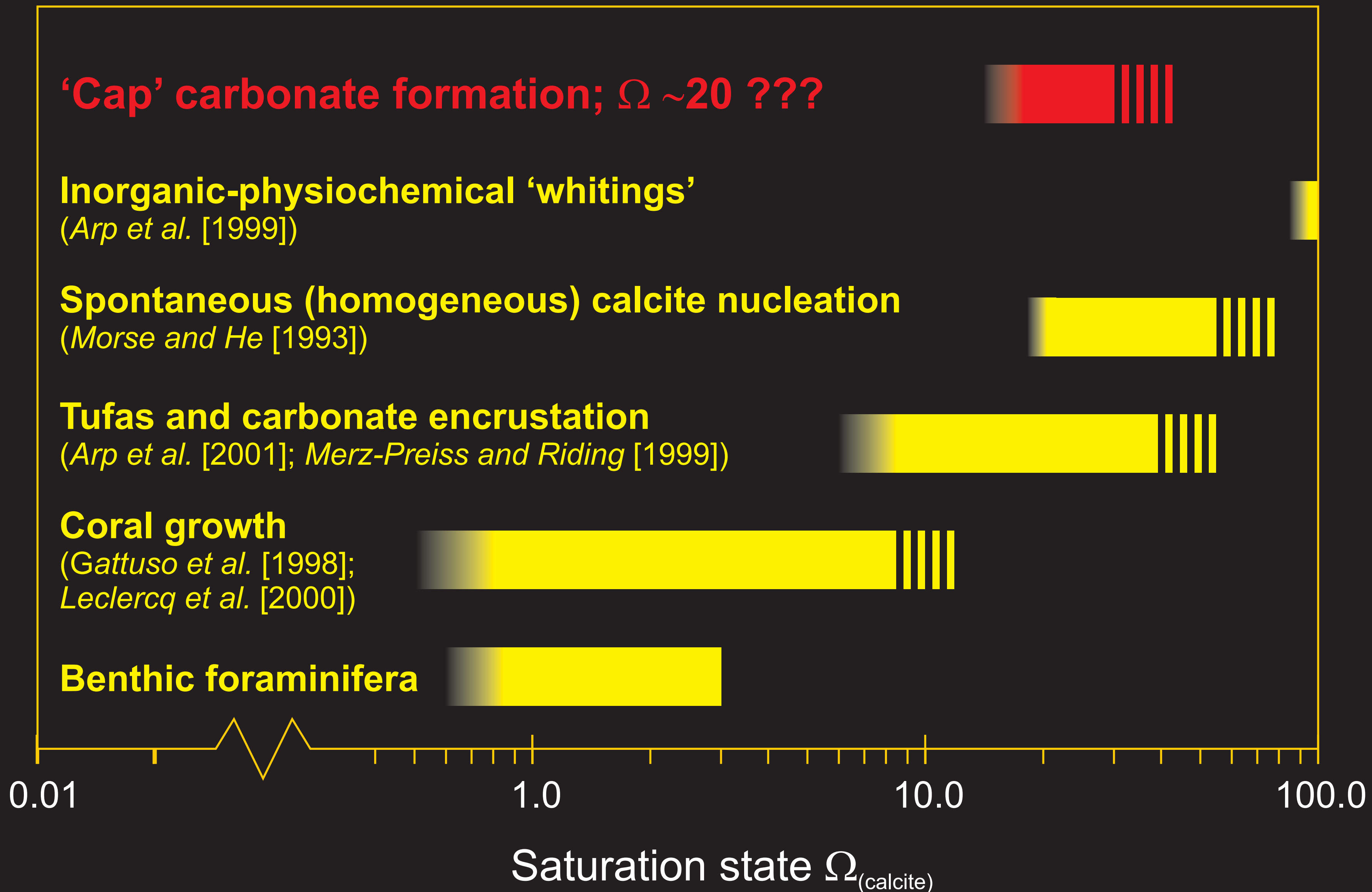
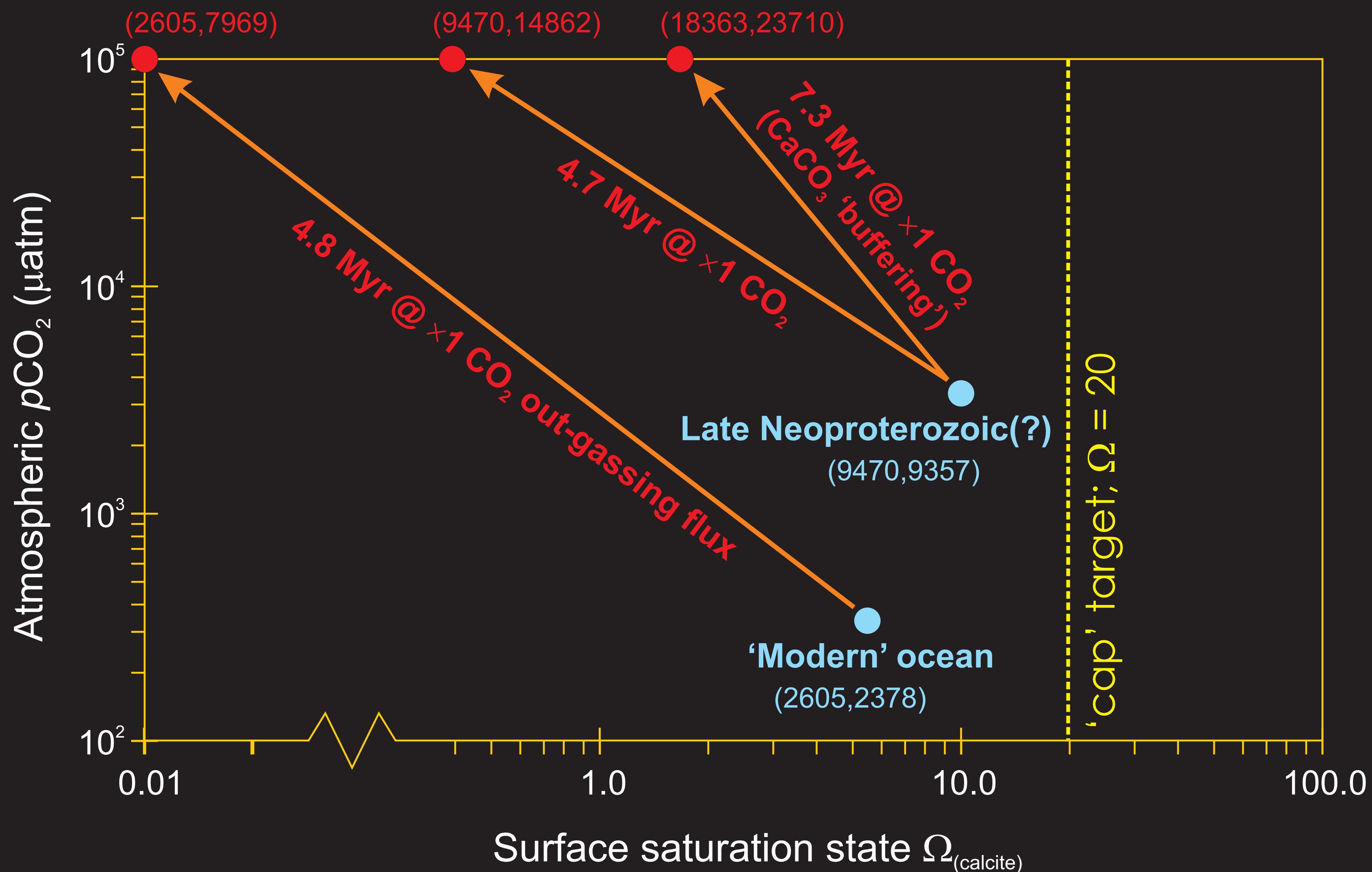


Potential evolution of ocean saturation during a 'snowball'



NOTE: ocean composition format;
[mean alkalinity, mean DIC] (μmol kg^{-1})

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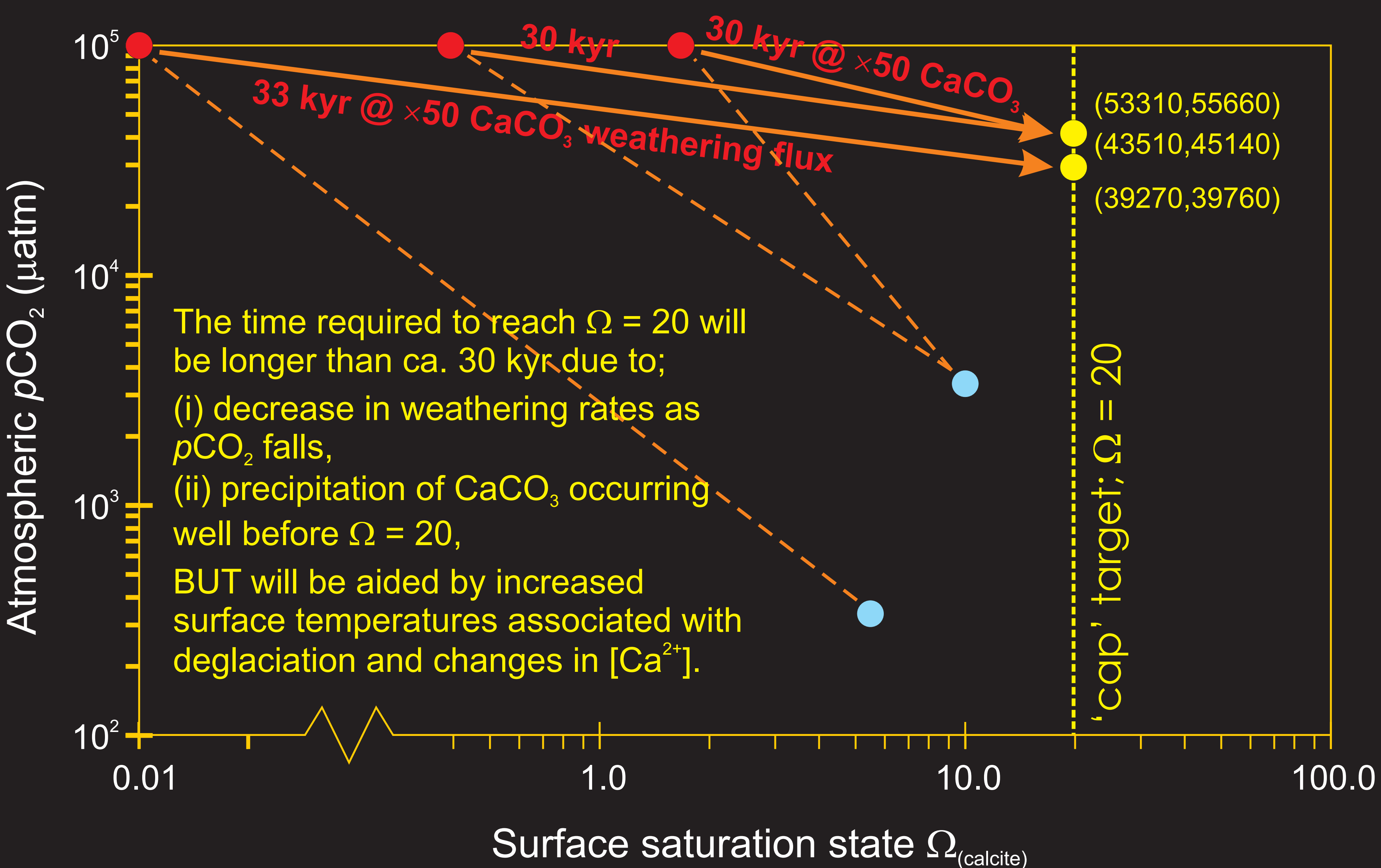

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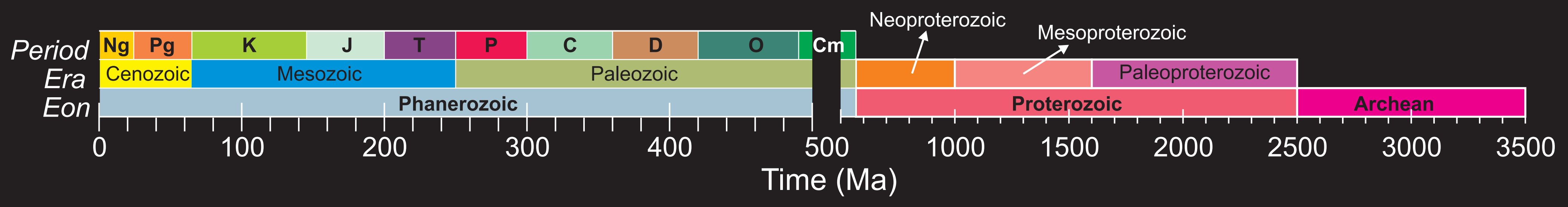
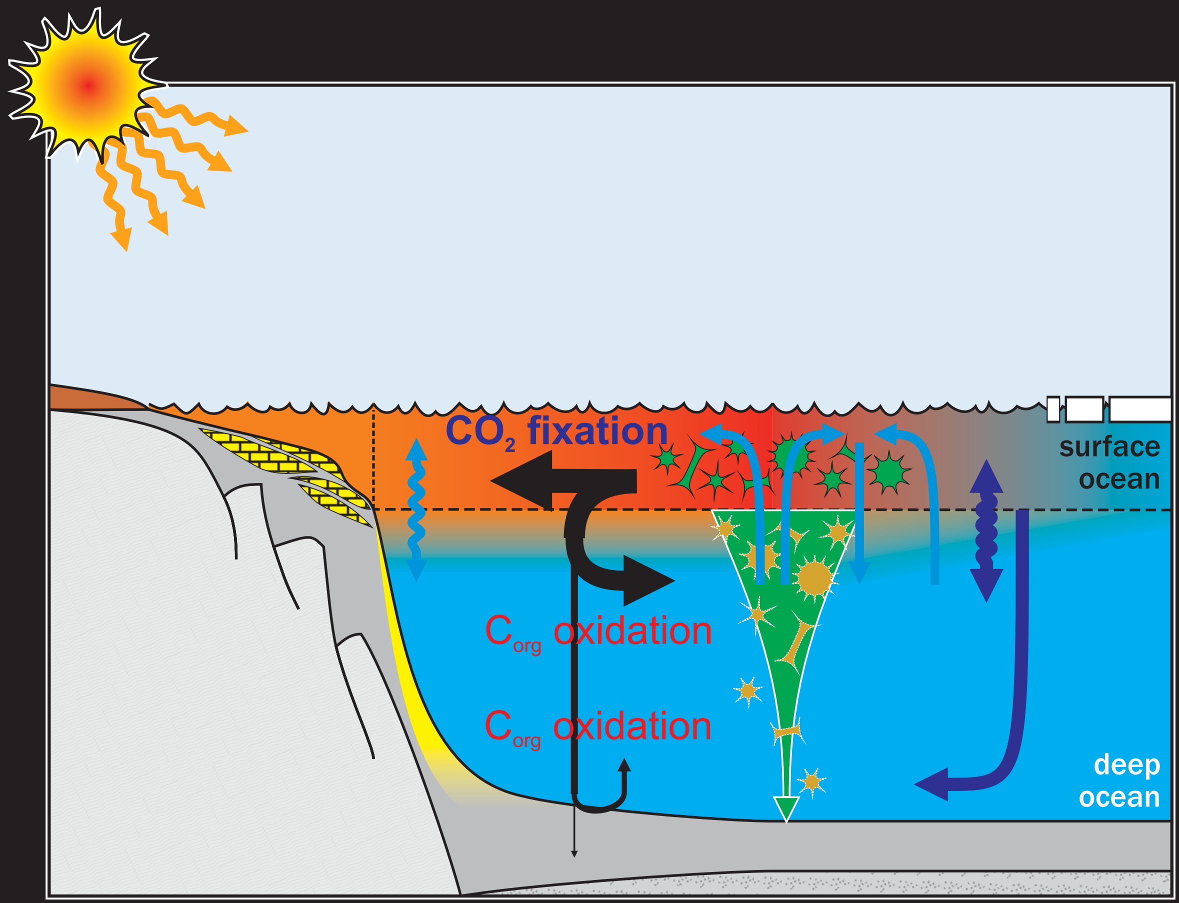
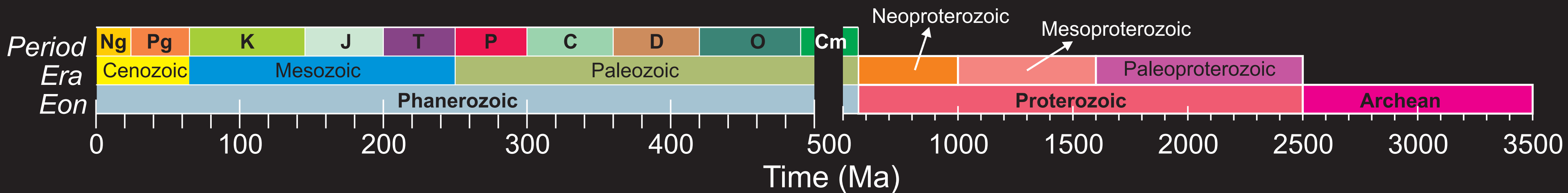
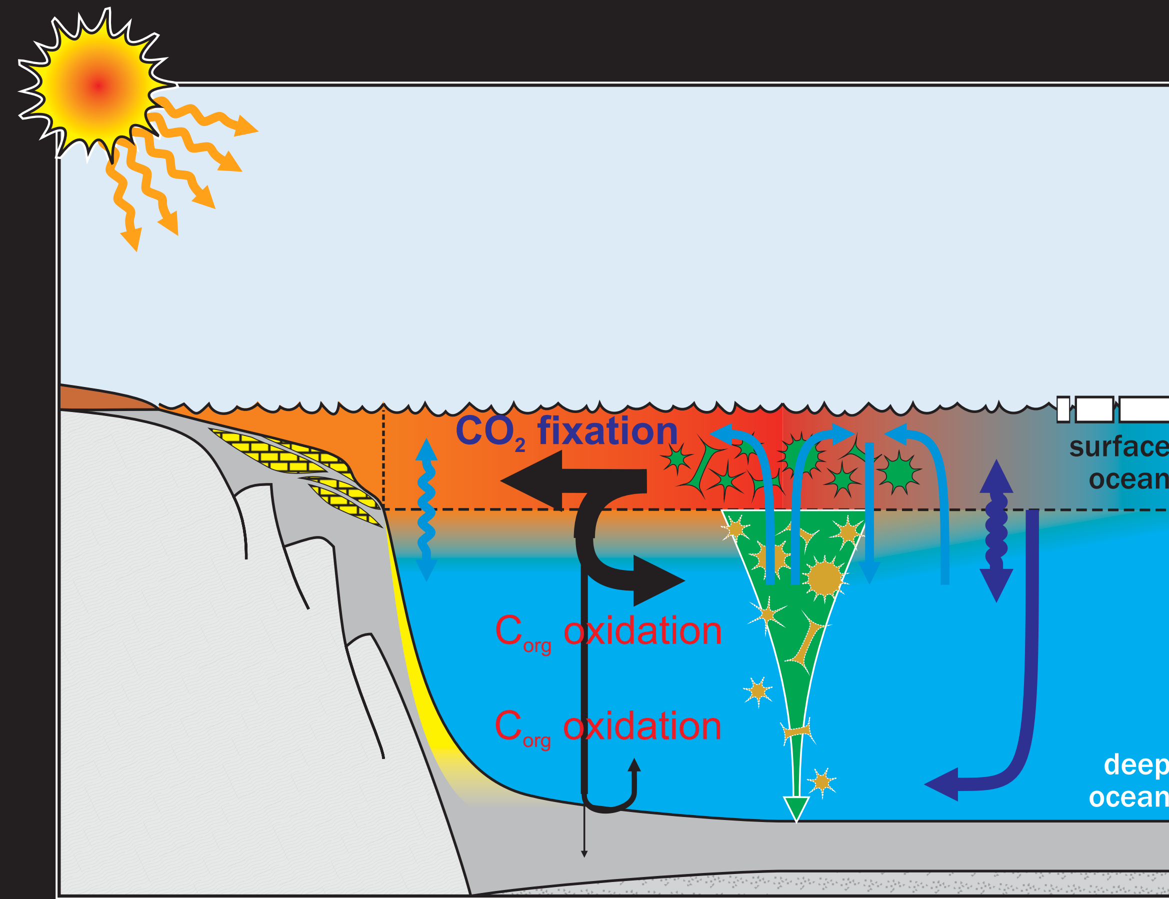
Evolution of the Biological Pump

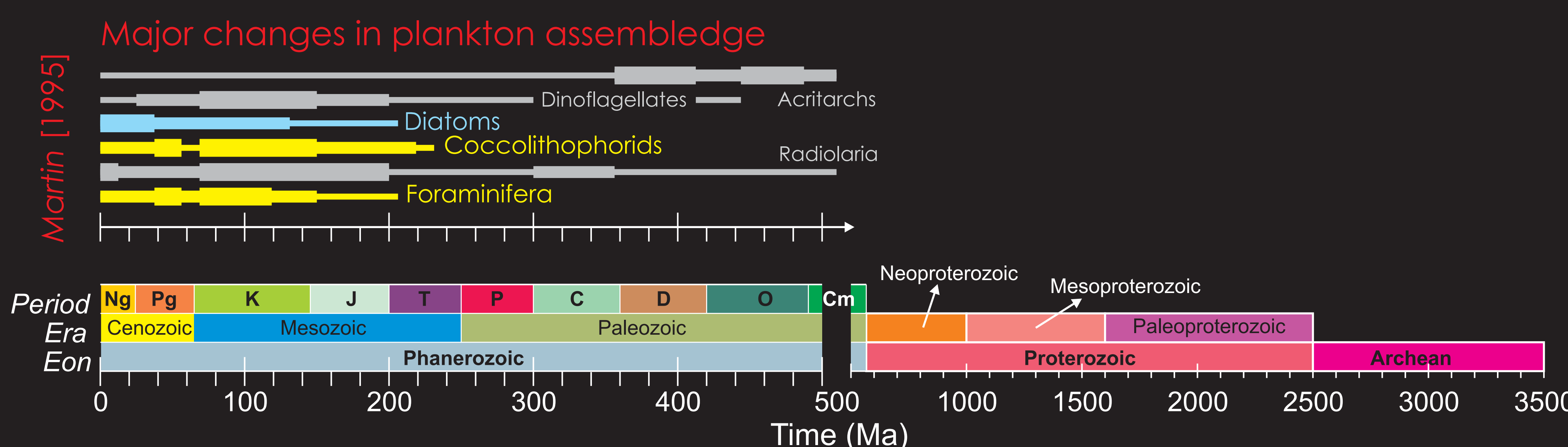



CO2 fixation
surface ocean
Corg oxidation
Corg oxidation
deep ocean


Period
Era
Eon
Ng
Pg
K
J
T
P
C
D
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)



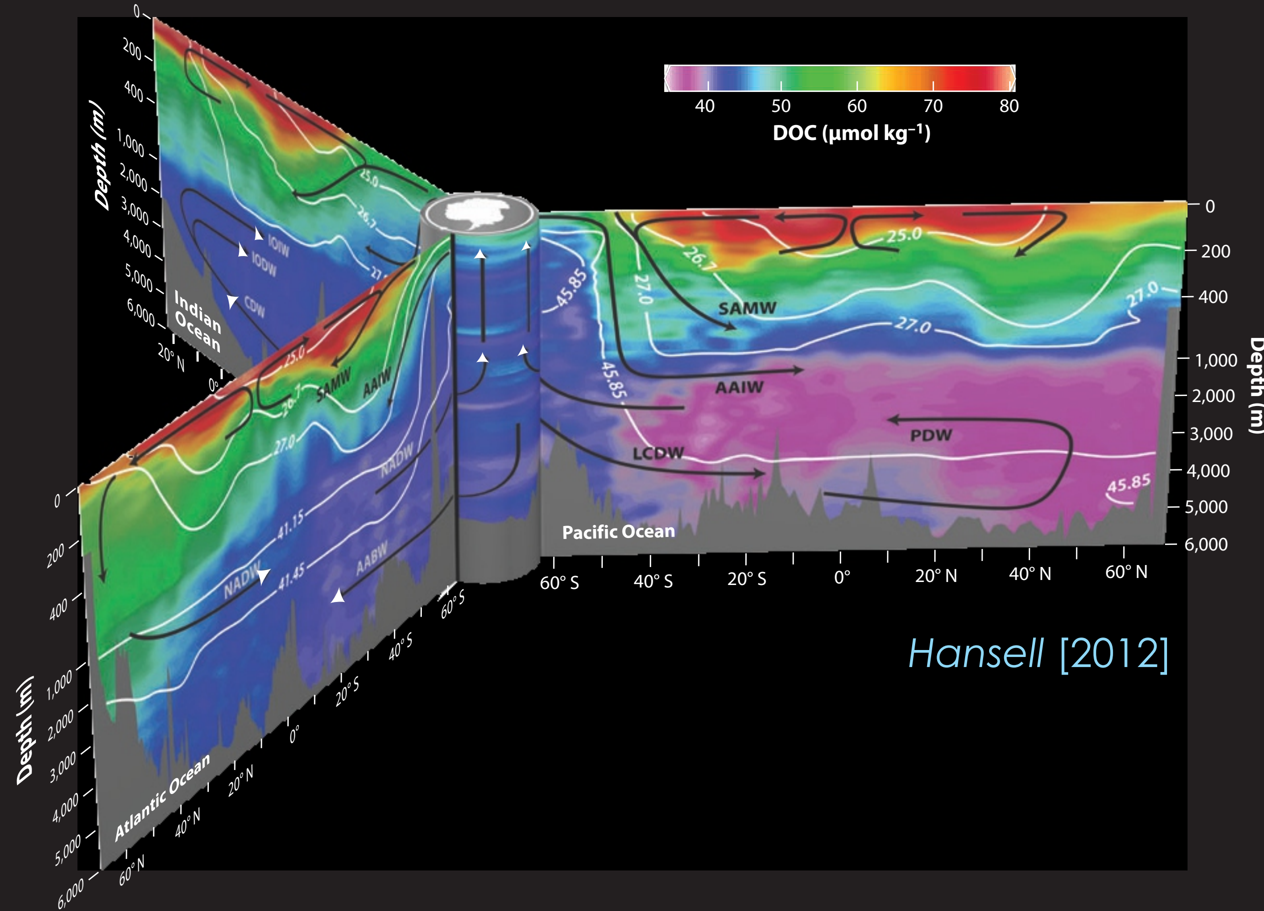
CO_2 fixation
surface ocean
C_{org} oxidation
C_{org} oxidation
deep ocean



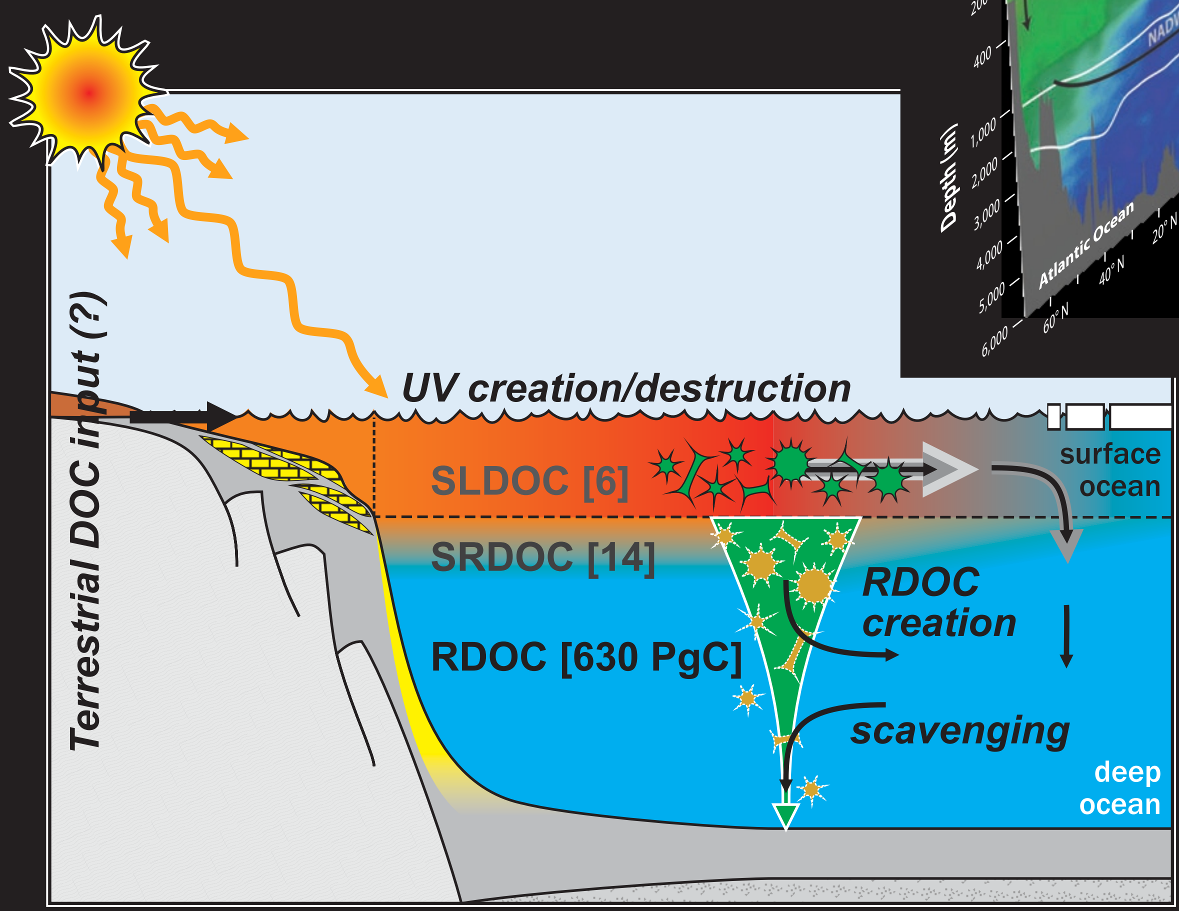
Major changes in plankton assembledge
Martin [1995]
Dinoflagellates
Acritarchs
Diatoms
Coccolithophorids
Radiolaria
Foraminifera
Period
Era
Eon
Ng
Pg
K
J
T
P
C
D
O
Cm
Cenozoic
Mesozoic
Paleozoic
Phanerozoic
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean
0
100
200
300
400
500
1000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

Evolution of the Biological Pump:

Dissolved organic matter



Hansell [2012]



Evolution of the Biological Pump:

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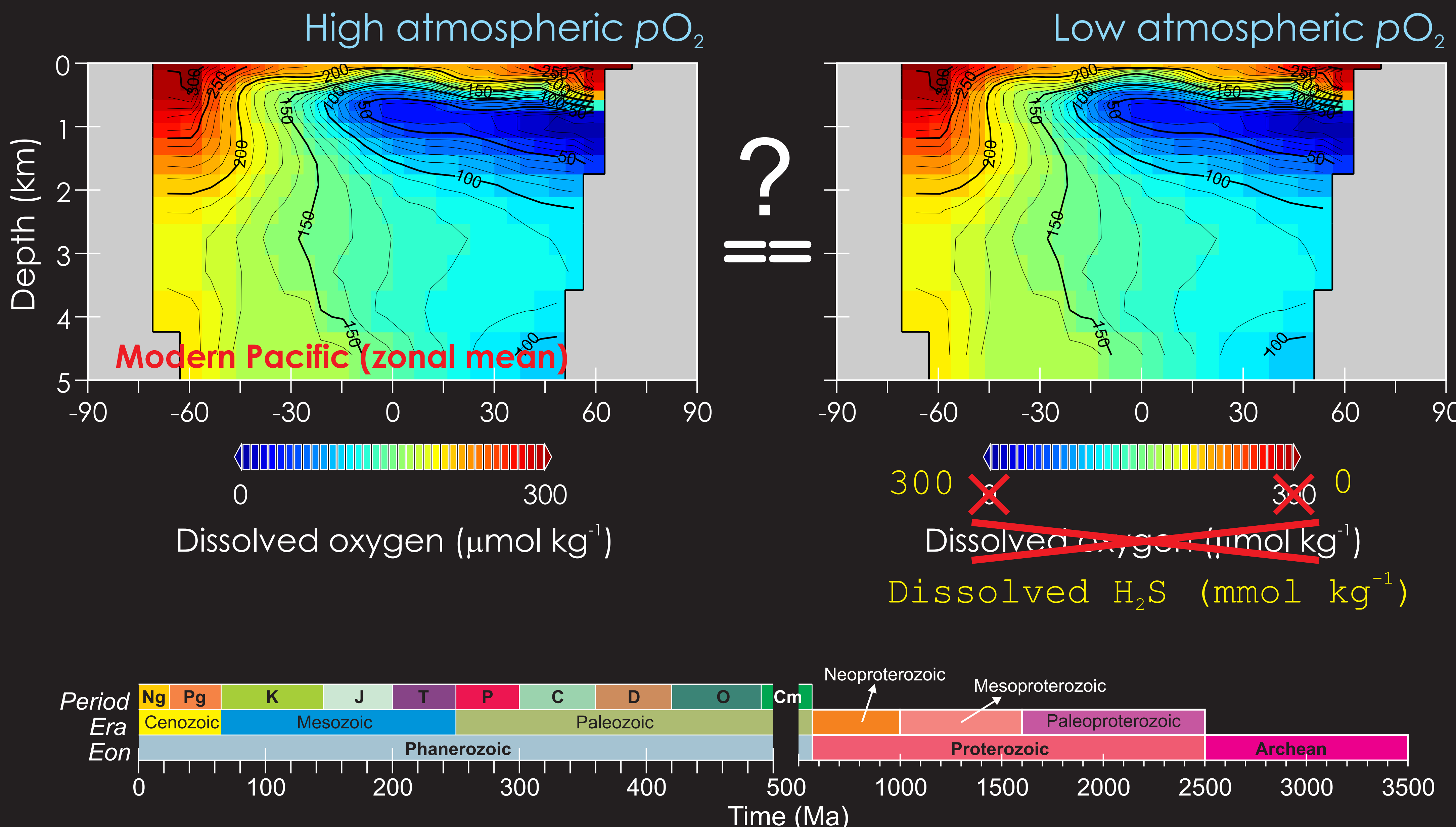

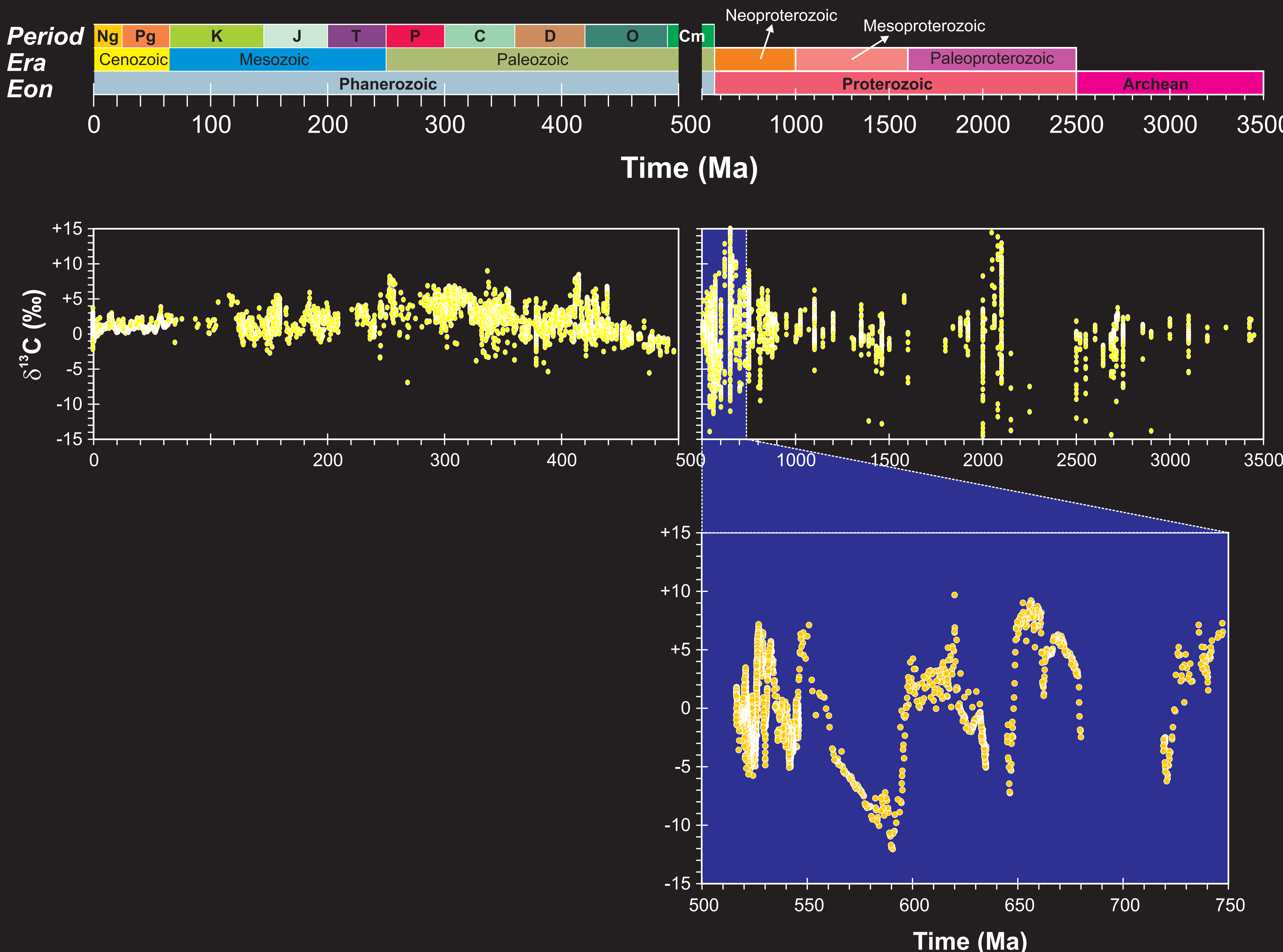

Ridgwell and Arndt [submitted]

Evolution of the Biological Pump:

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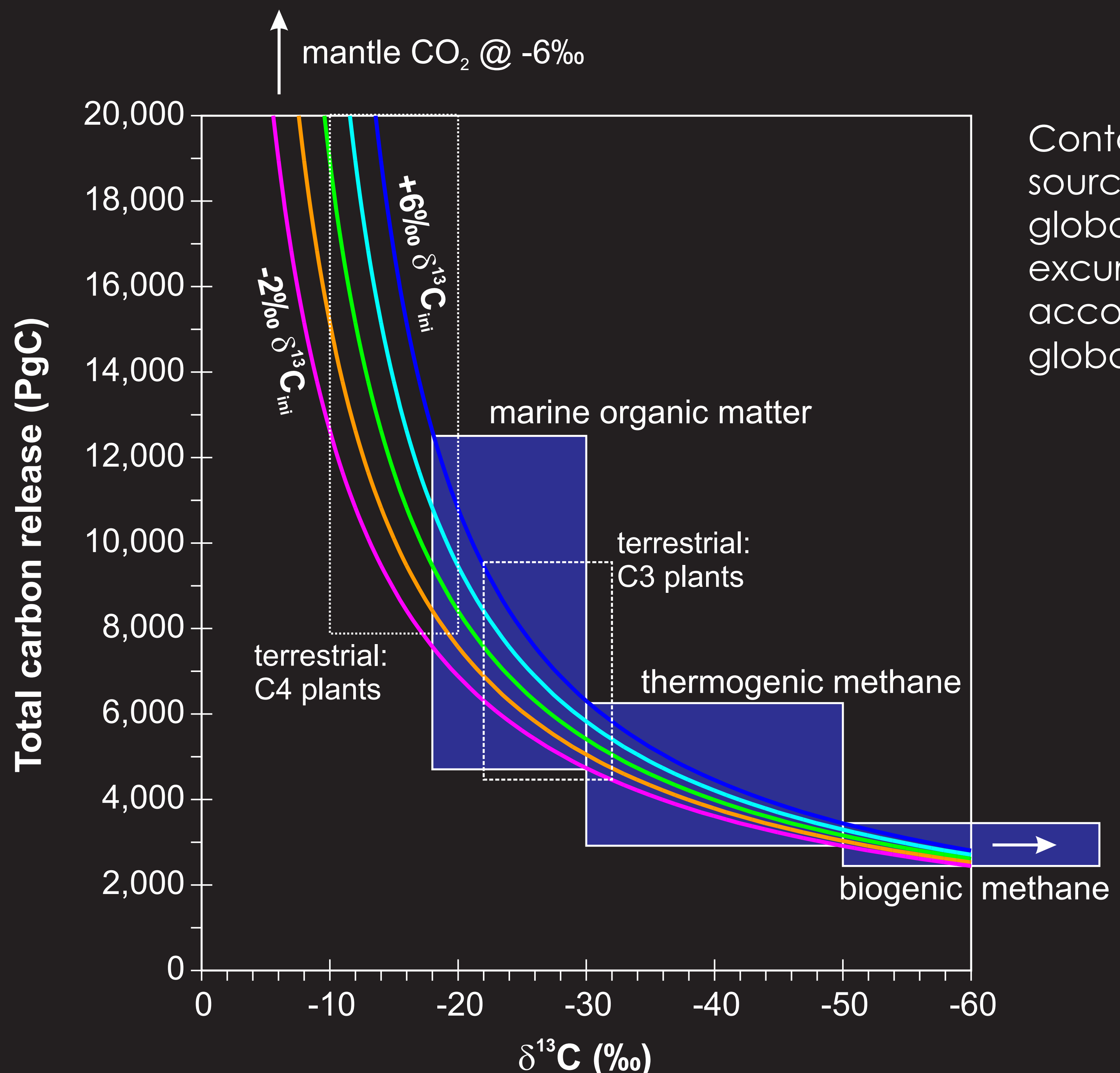
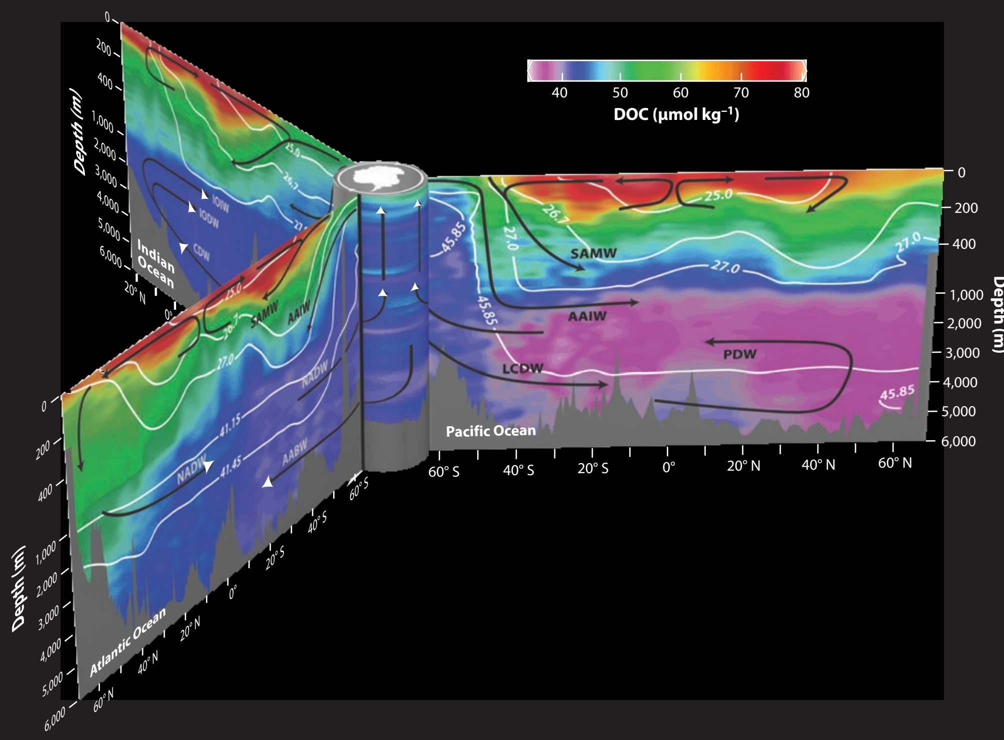


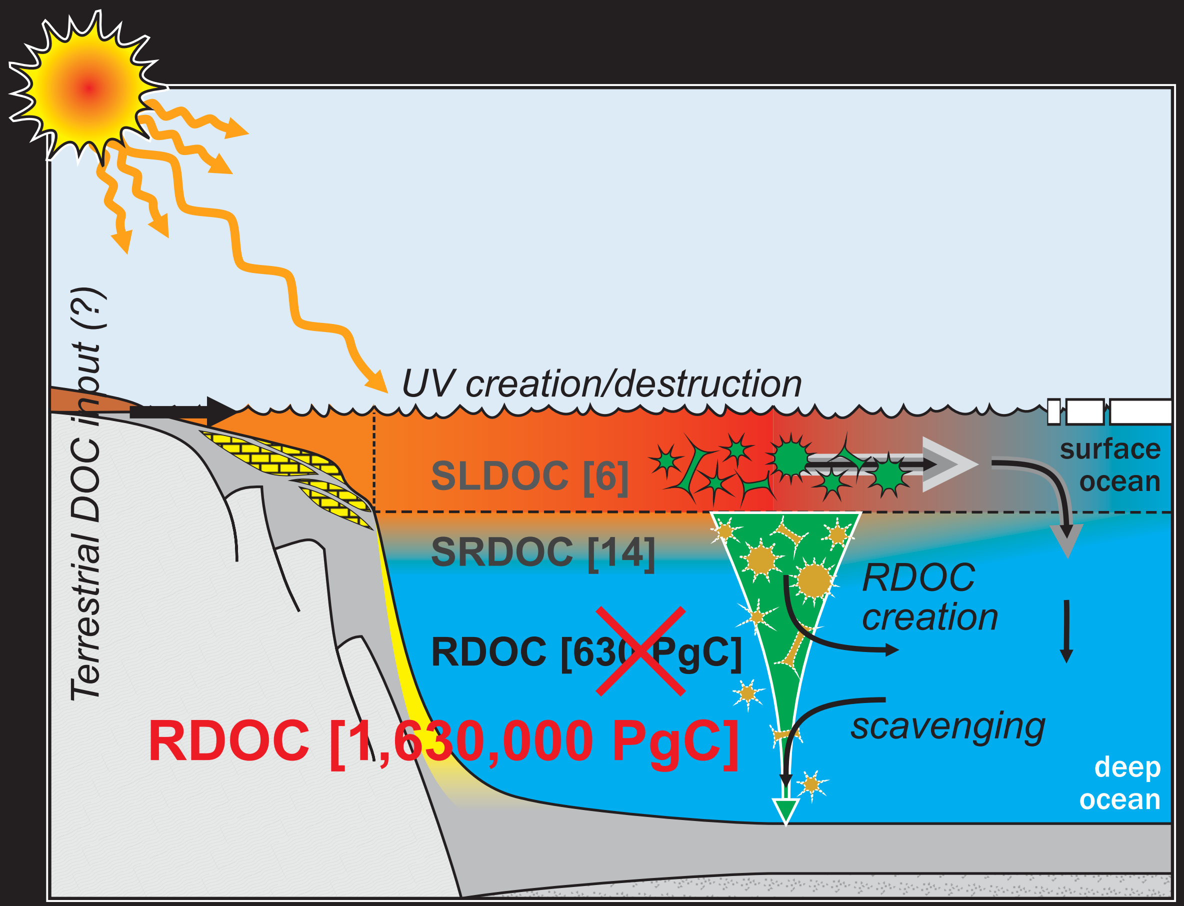
Contours of carbon release vs. source isotopic signature for a global -4‰ carbon isotopic excursion. Contours differ according to the initial mean global $\delta^{13}C$.

Ridgwell and Arndt [submitted]

Evolution of the Biological Pump:

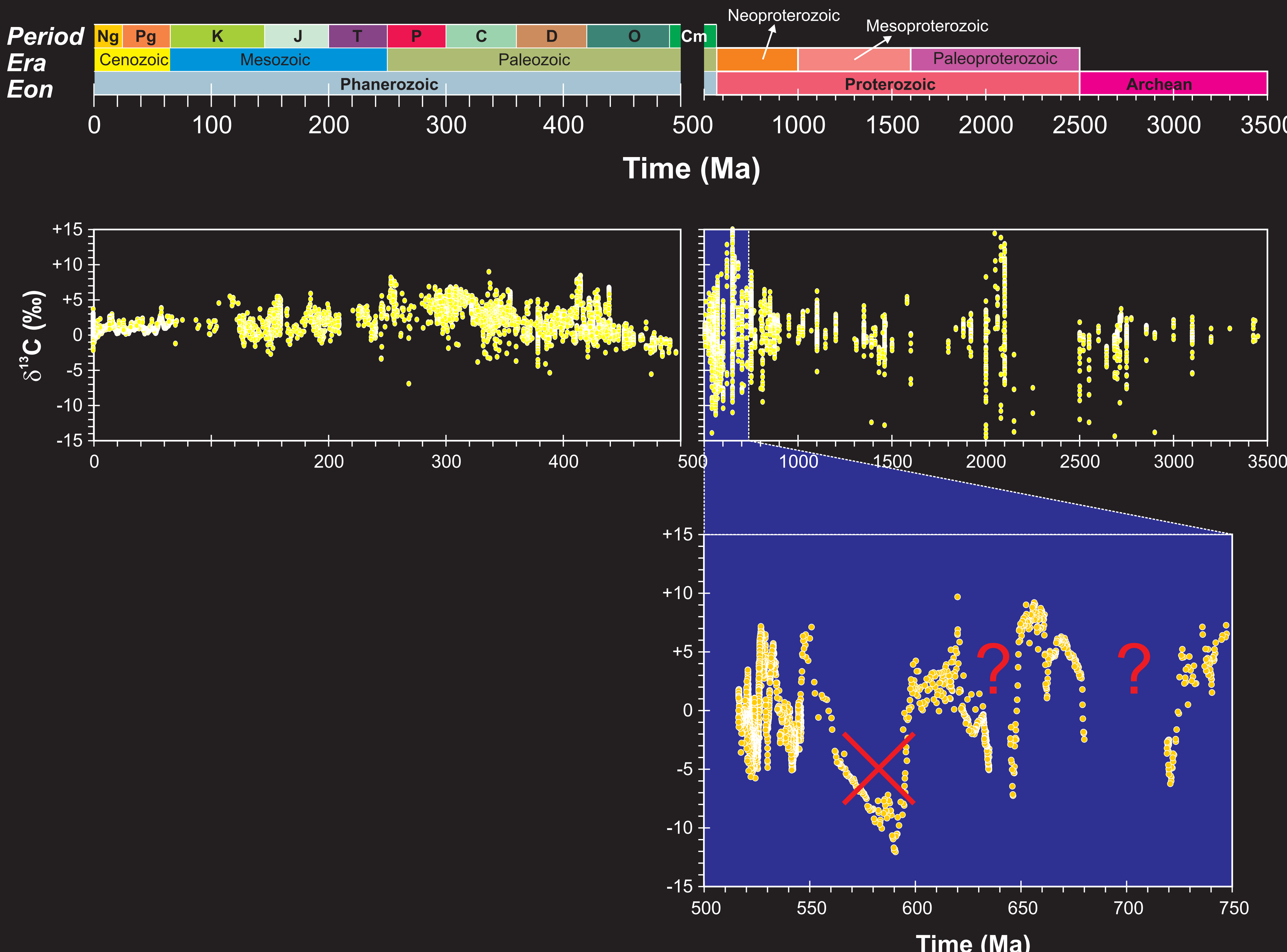
Dissolved organic matter





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^-.

Ridgwell and Arndt [submitted]



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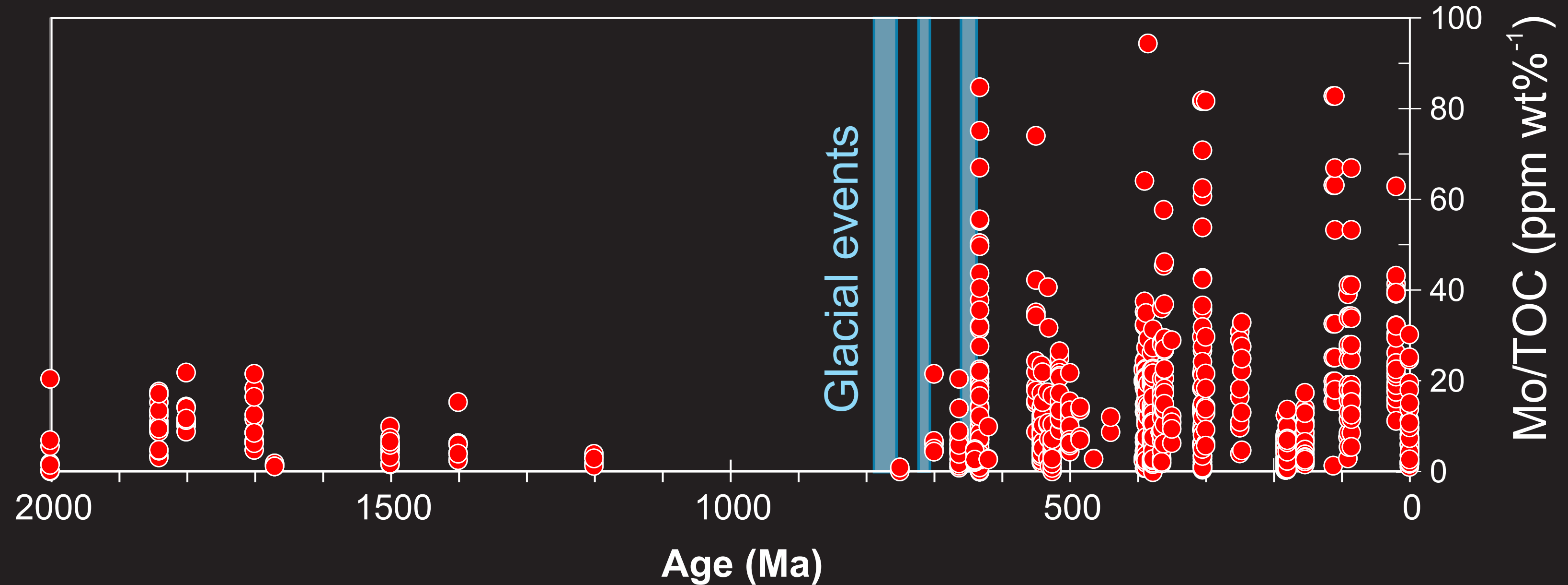
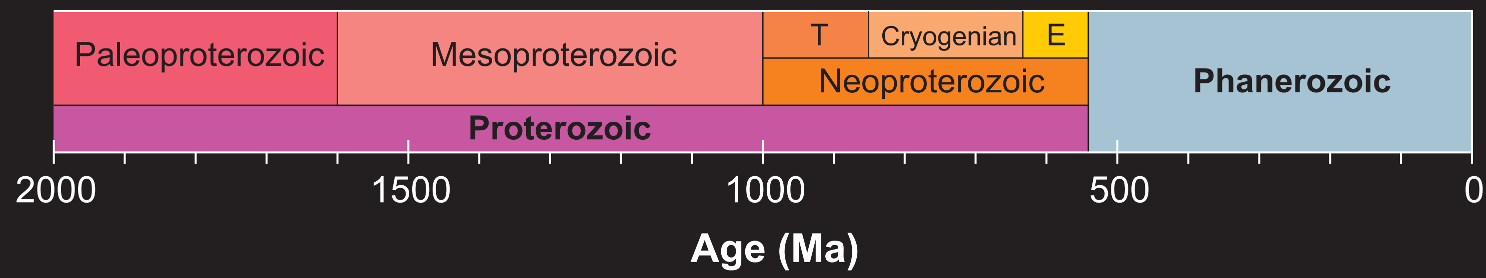
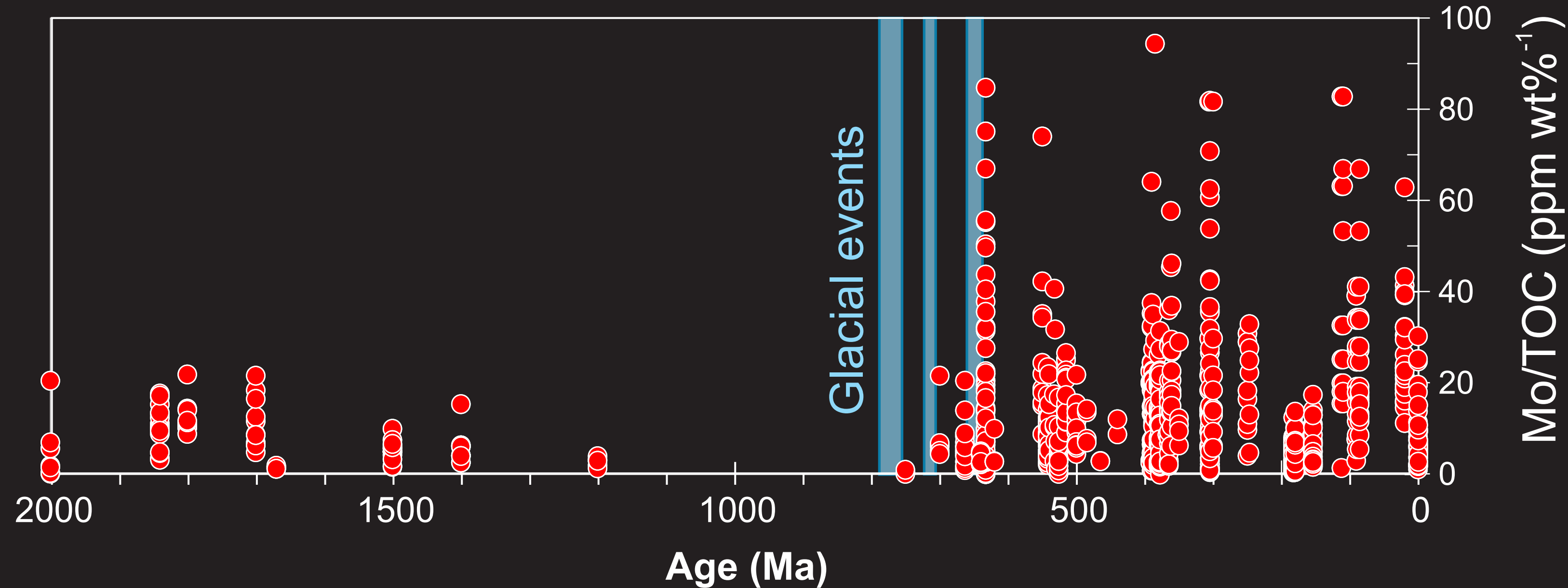
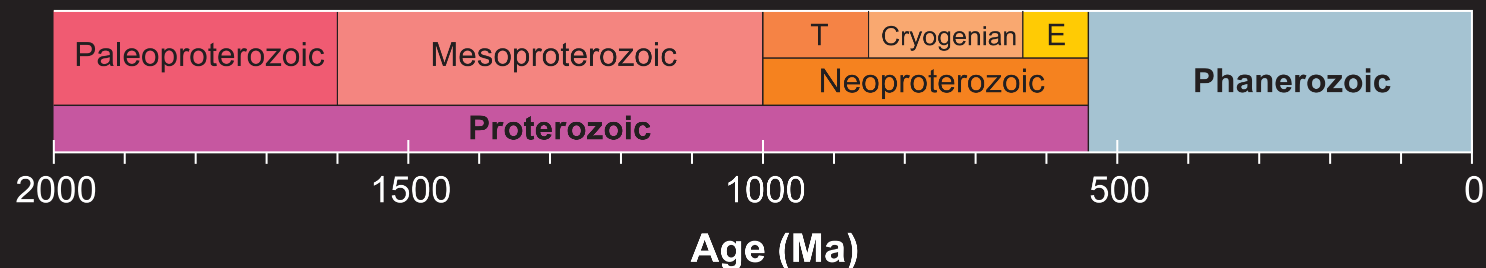




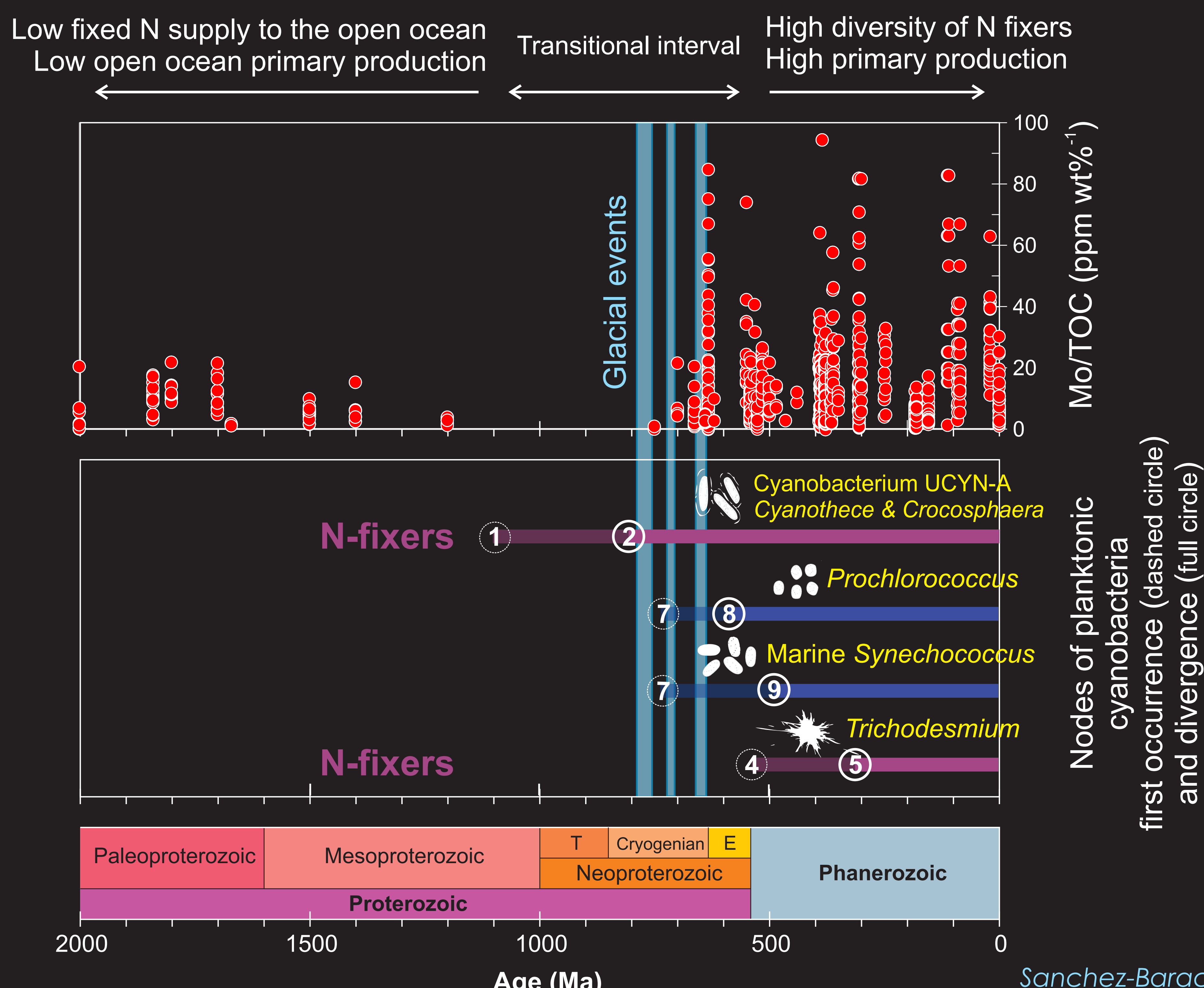
Sanchez-Baracaldo et al. [2014]

Low fixed N supply to the open ocean
Low open ocean primary production

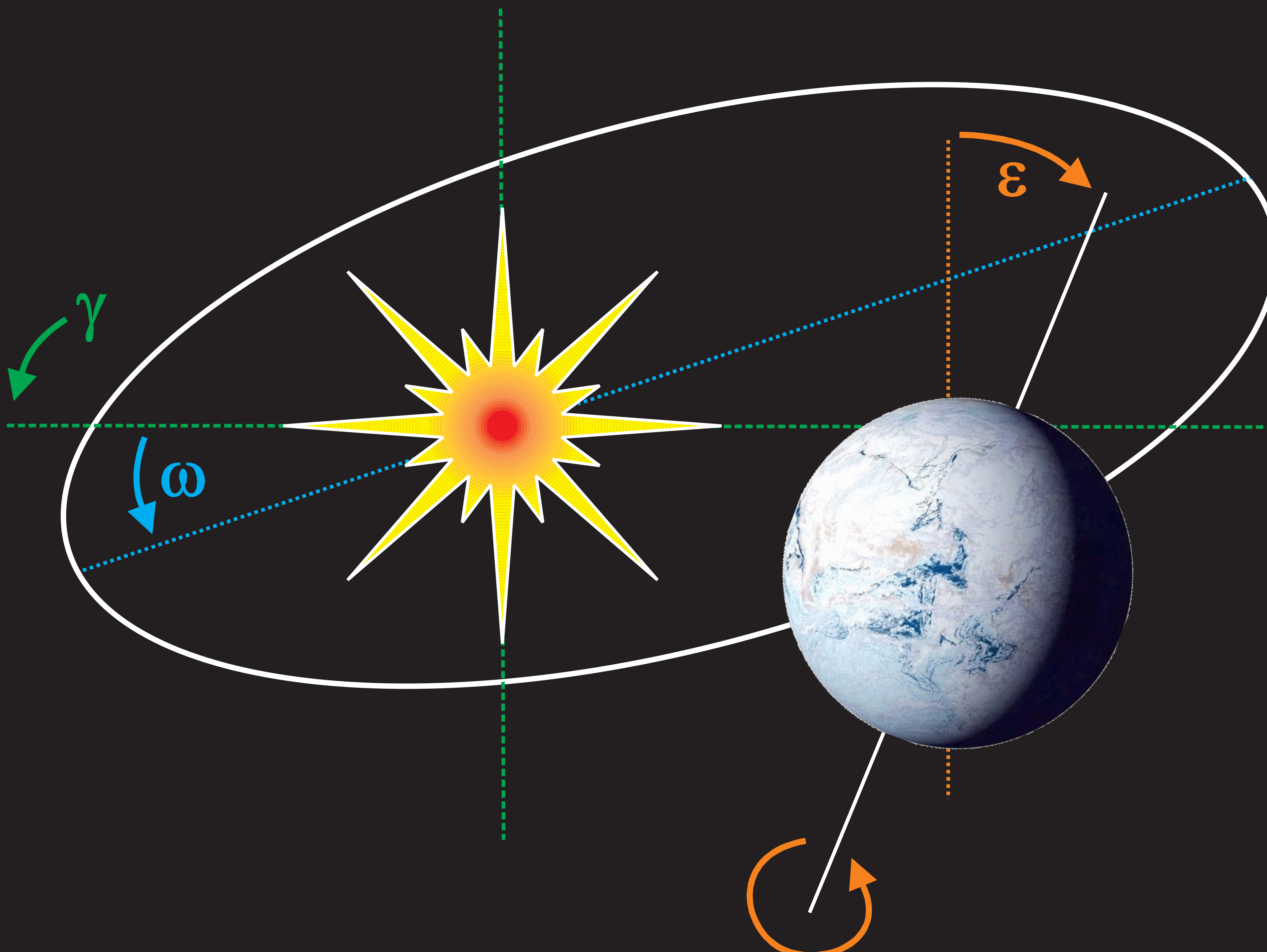




Sanchez-Baracaldo et al. [2014]



Sanchez-Baracaldo et al. [2014]



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