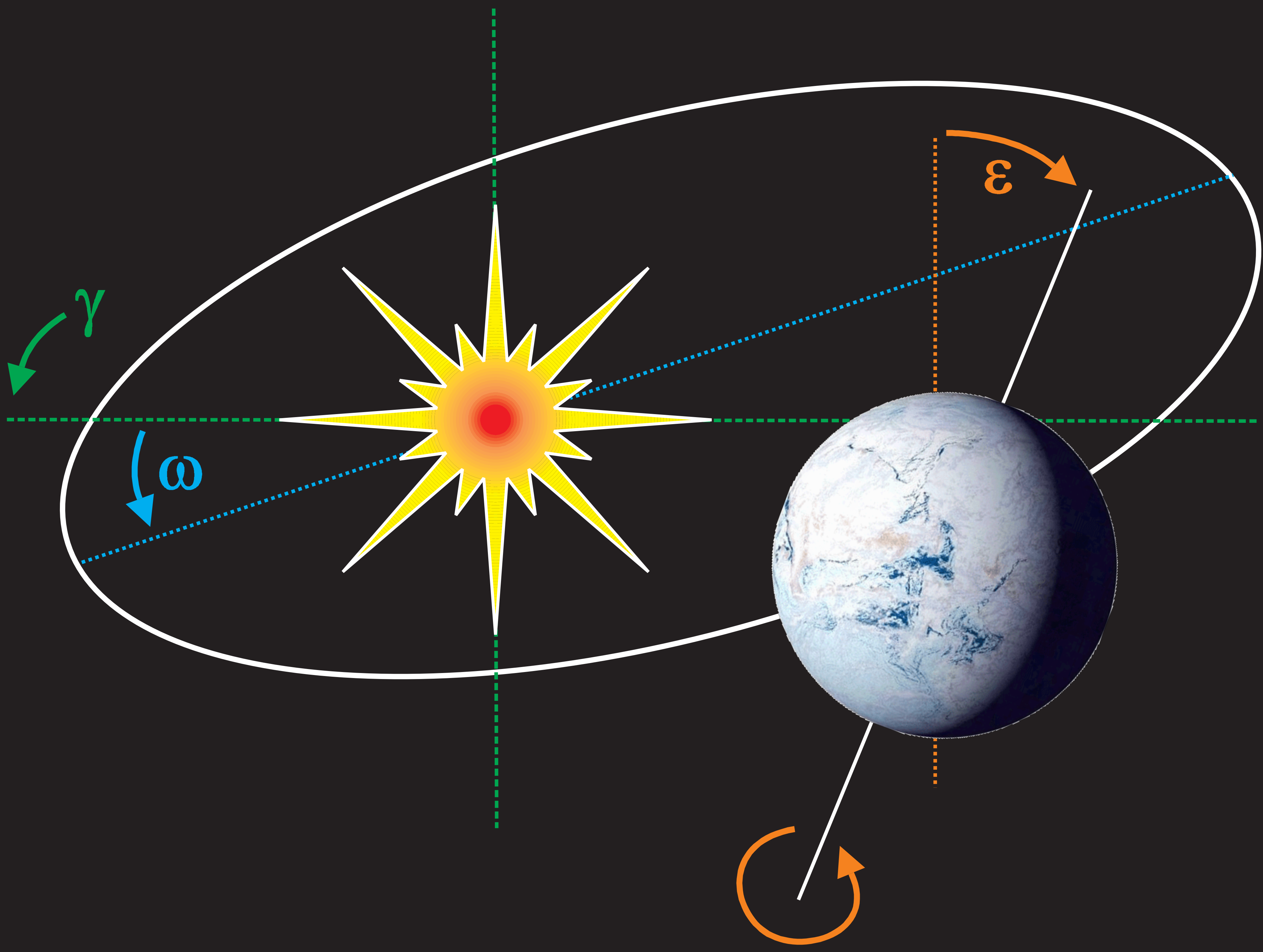
Snowball Earth



Suggested reading

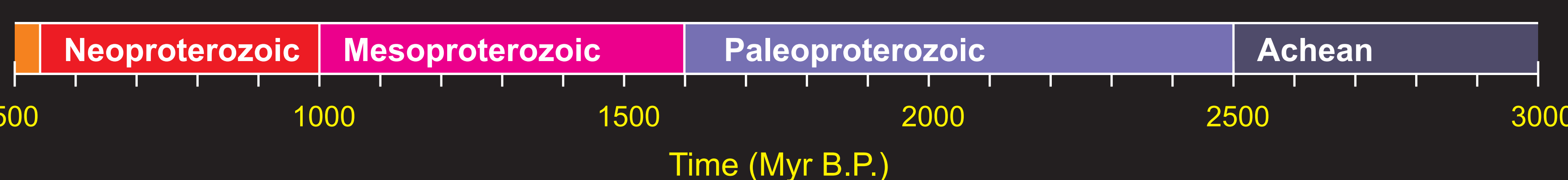
Fairchild and Kennedy [2007] (more recent and slightly more neutral/contrarian review)

Hoffman and Schrag [2002] ('pro' snowball Earth hypothesis review)

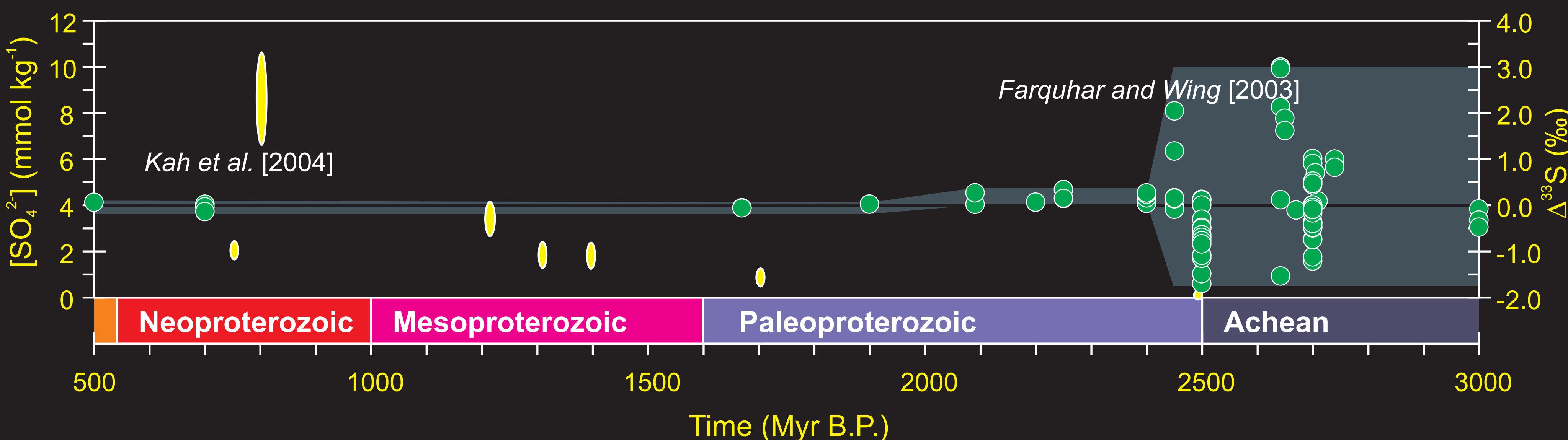
Ridgwell and Kennedy [2004] (a different and more carbon cycle focussed view-point)

Background

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



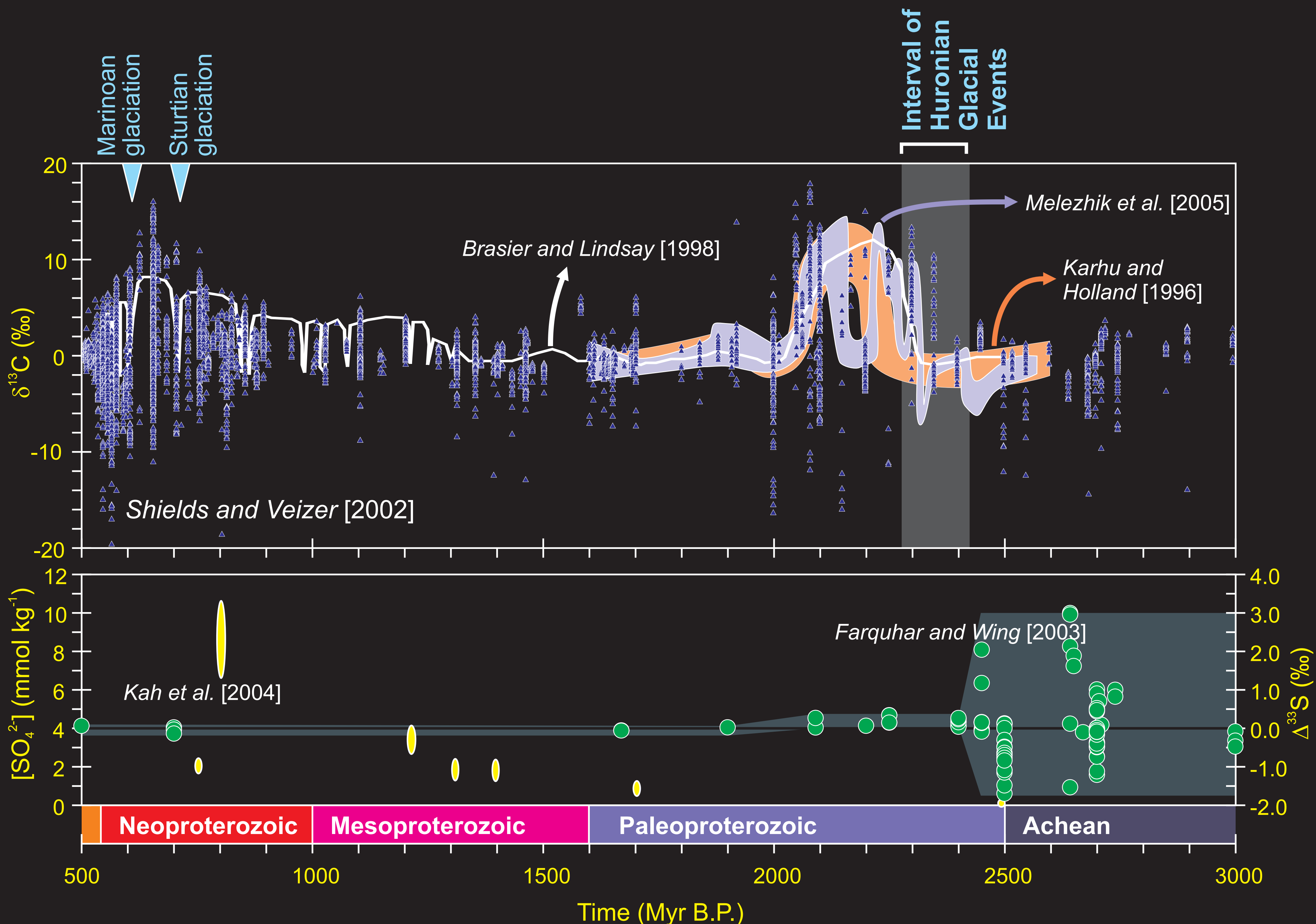
Background



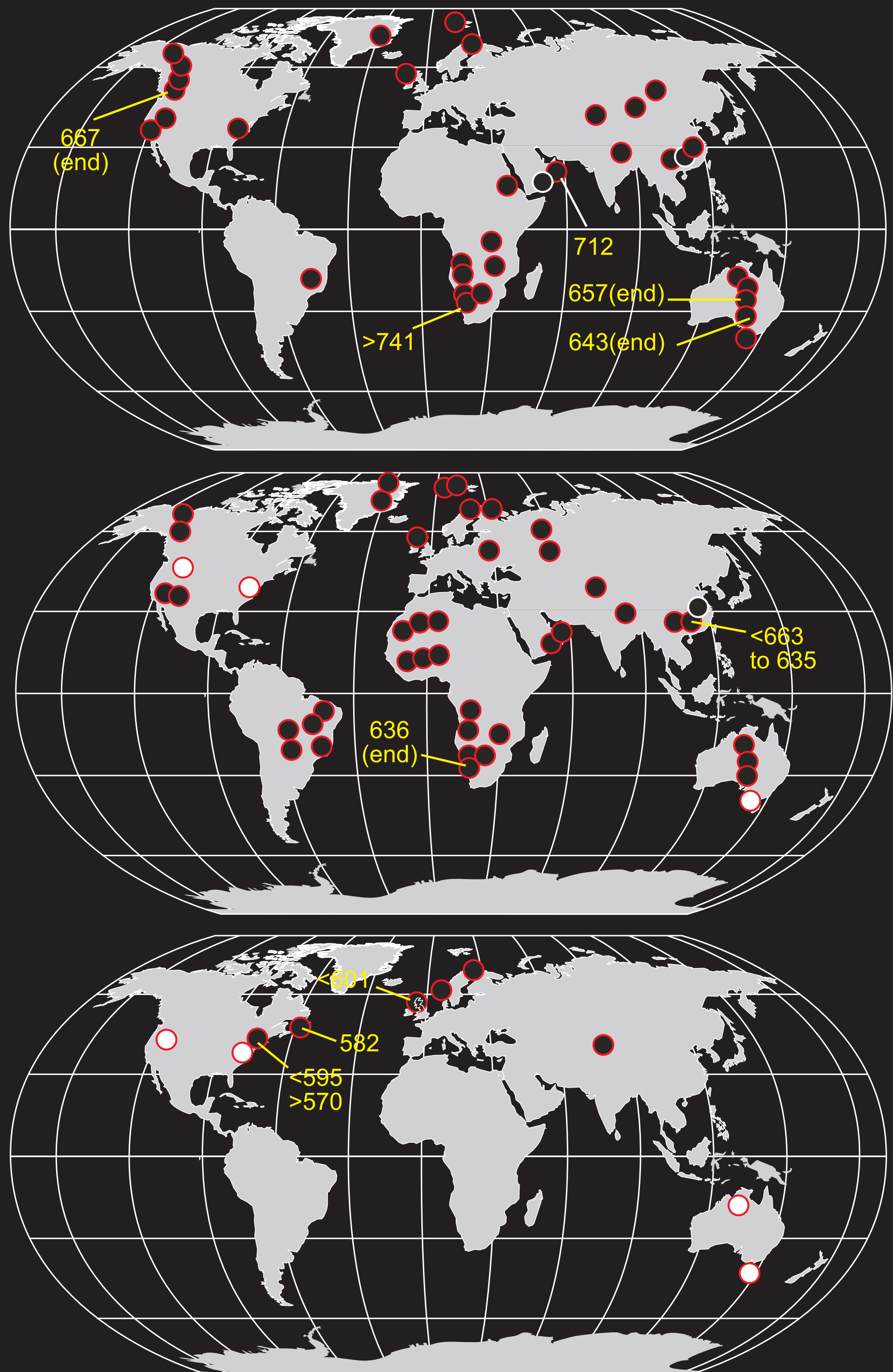
12
10
8
6
4
2
0
[SO4 2-] (mmol kg-1)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
Δ33S (‰)
Kah et al. [2004]
Farquhar and Wing [2003]
Neoproterozoic
Mesoproterozoic
Paleoproterozoic
Achean
500
1000
1500
2000
2500
3000
Time (Myr B.P.)

Background

Snowball Earth



Background – evidence for glaciation

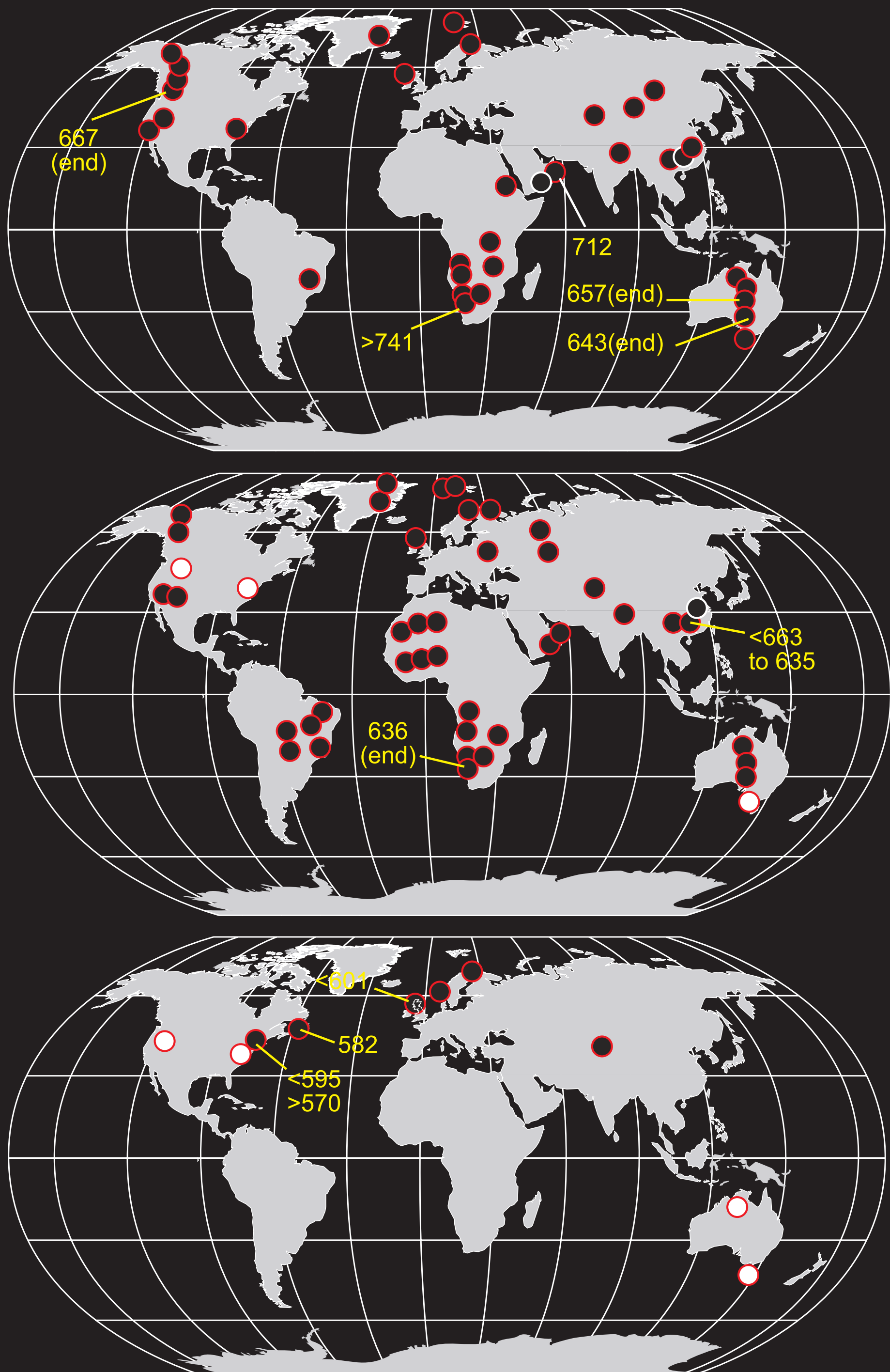


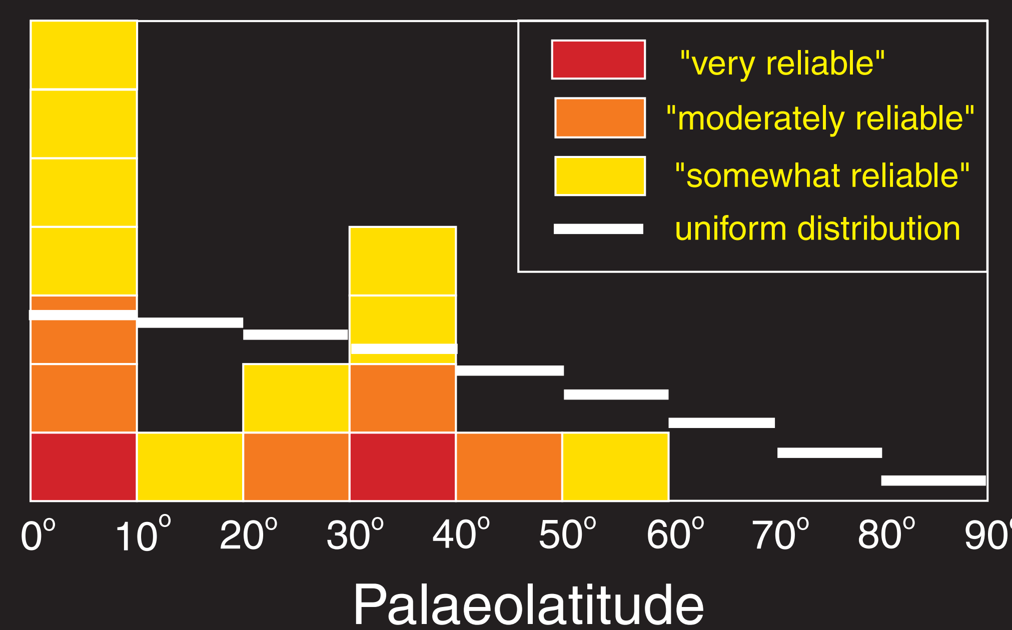
From: *Fairchild and Kennedy* [2007]

From: *Hoffman and Schrag* [2002]

Background – evidence for glaciation

Snowball Earth





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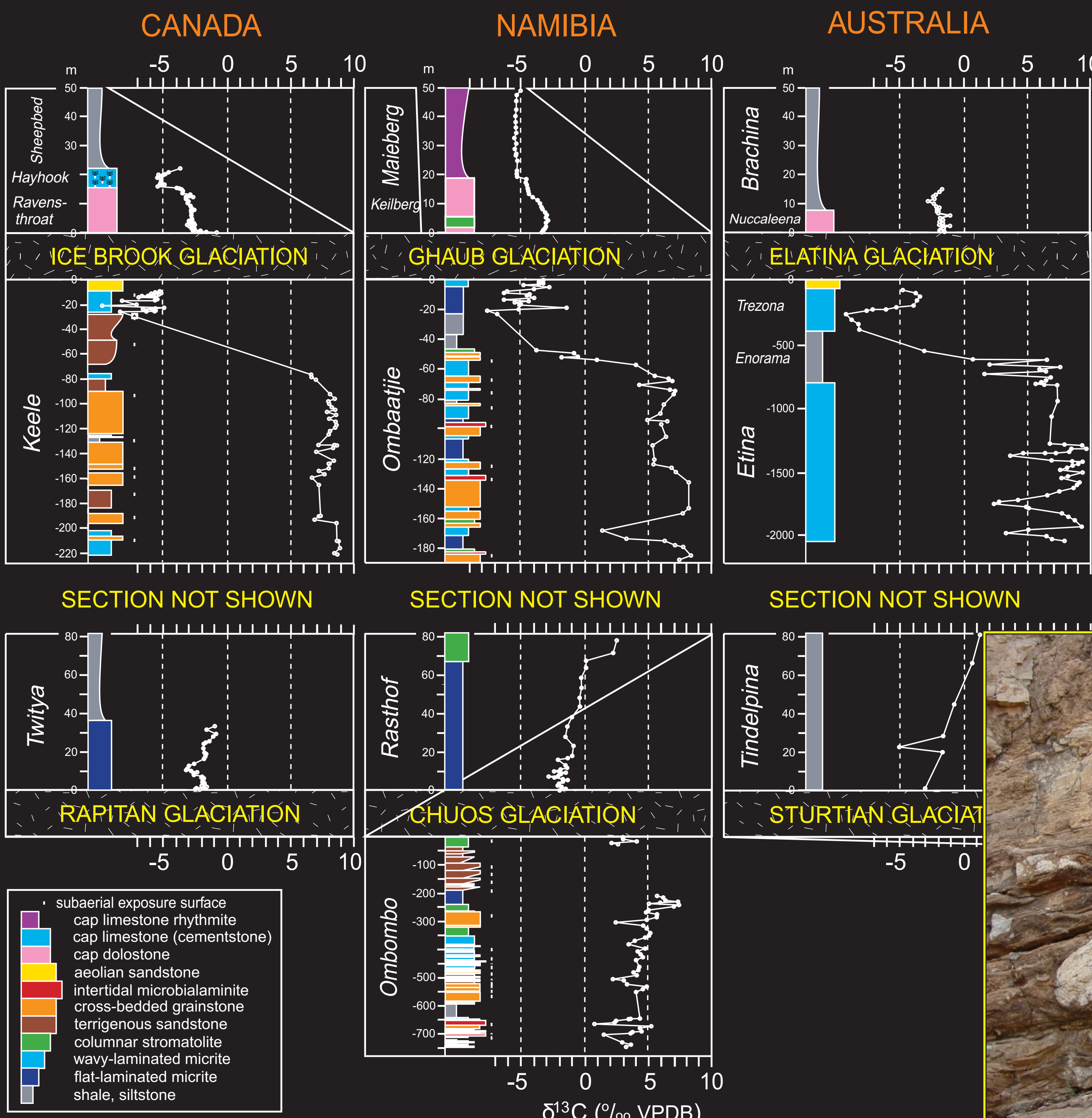
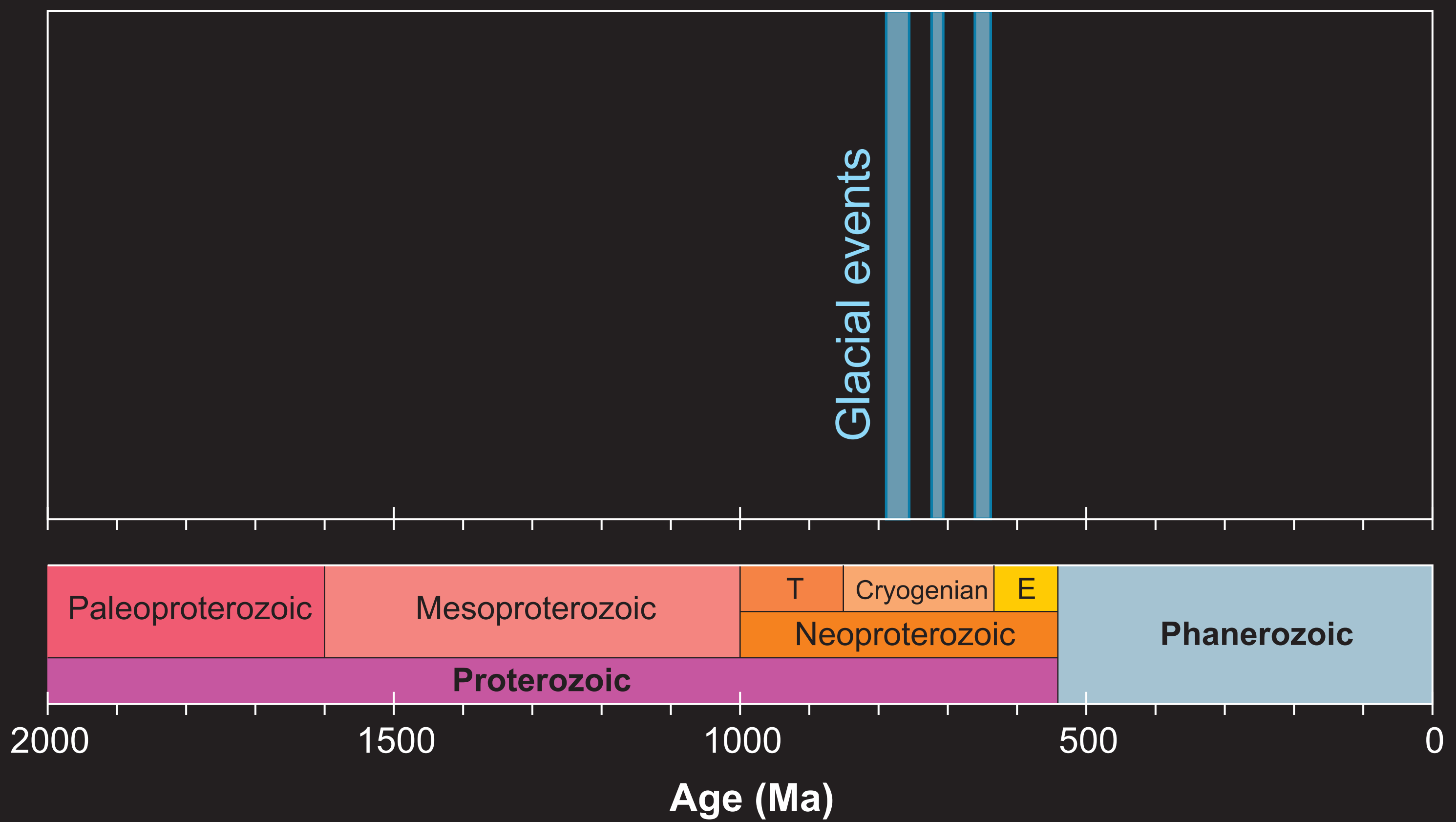


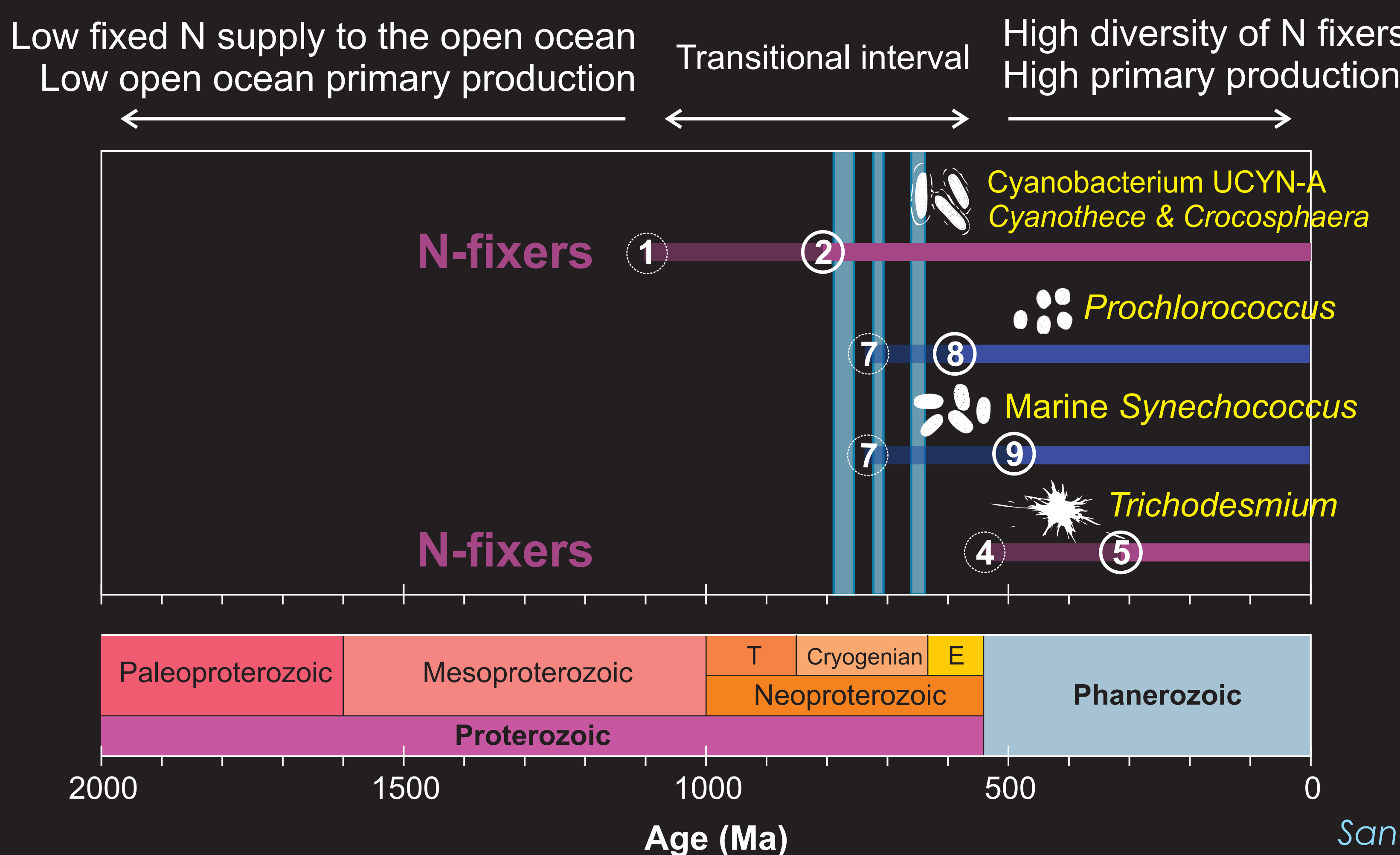
From: *Hoffman and Schrag* [2002]

Background – biotic changes



Sanchez-Baracaldo et al. [2014]

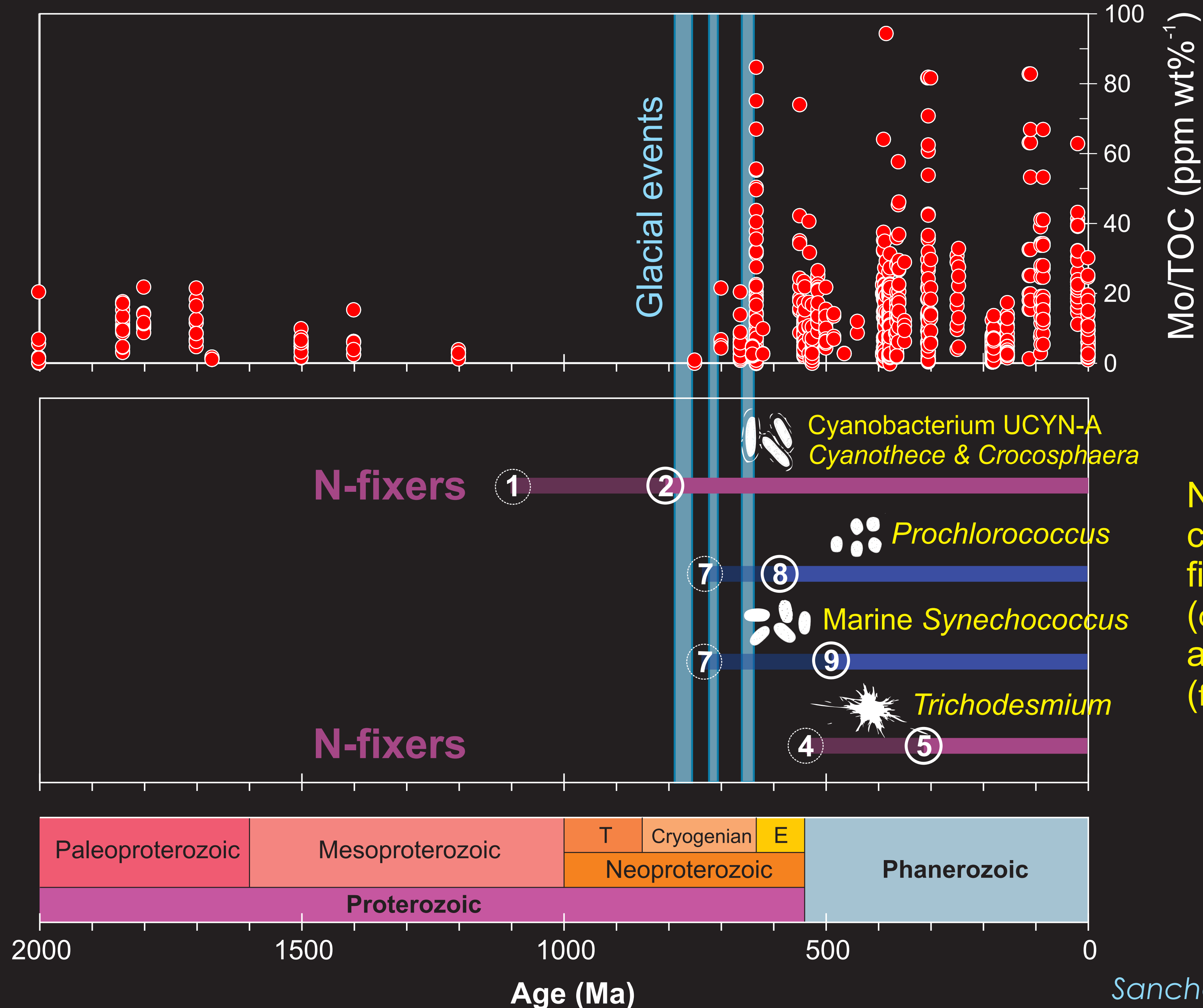
Background – biotic changes



Nodes of planktonic cyanobacteria first occurrence (dashed circle) and divergence (full circle)

Sanchez-Baracaldo et al. [2014]

Background – biotic changes



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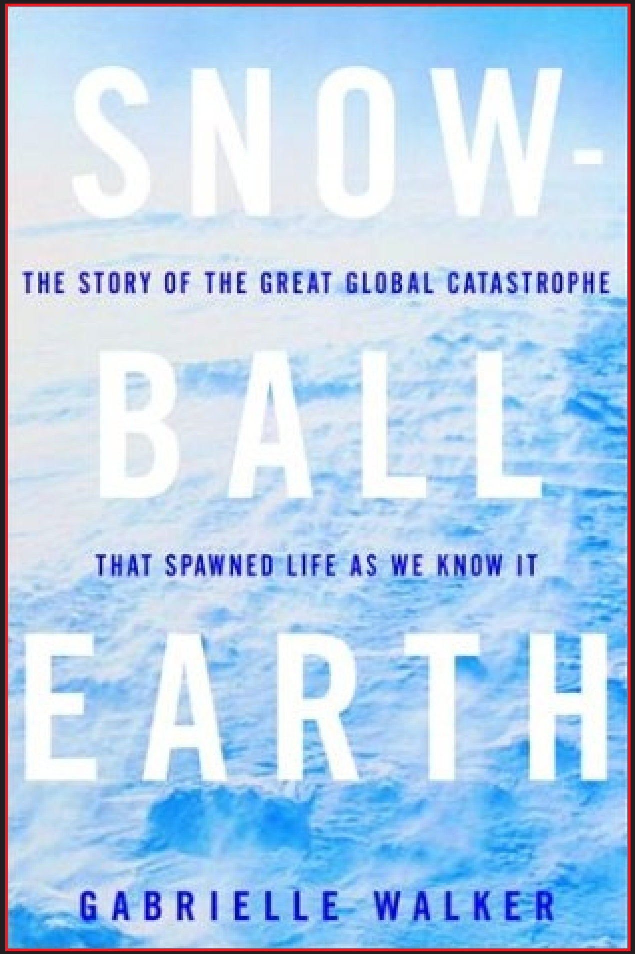
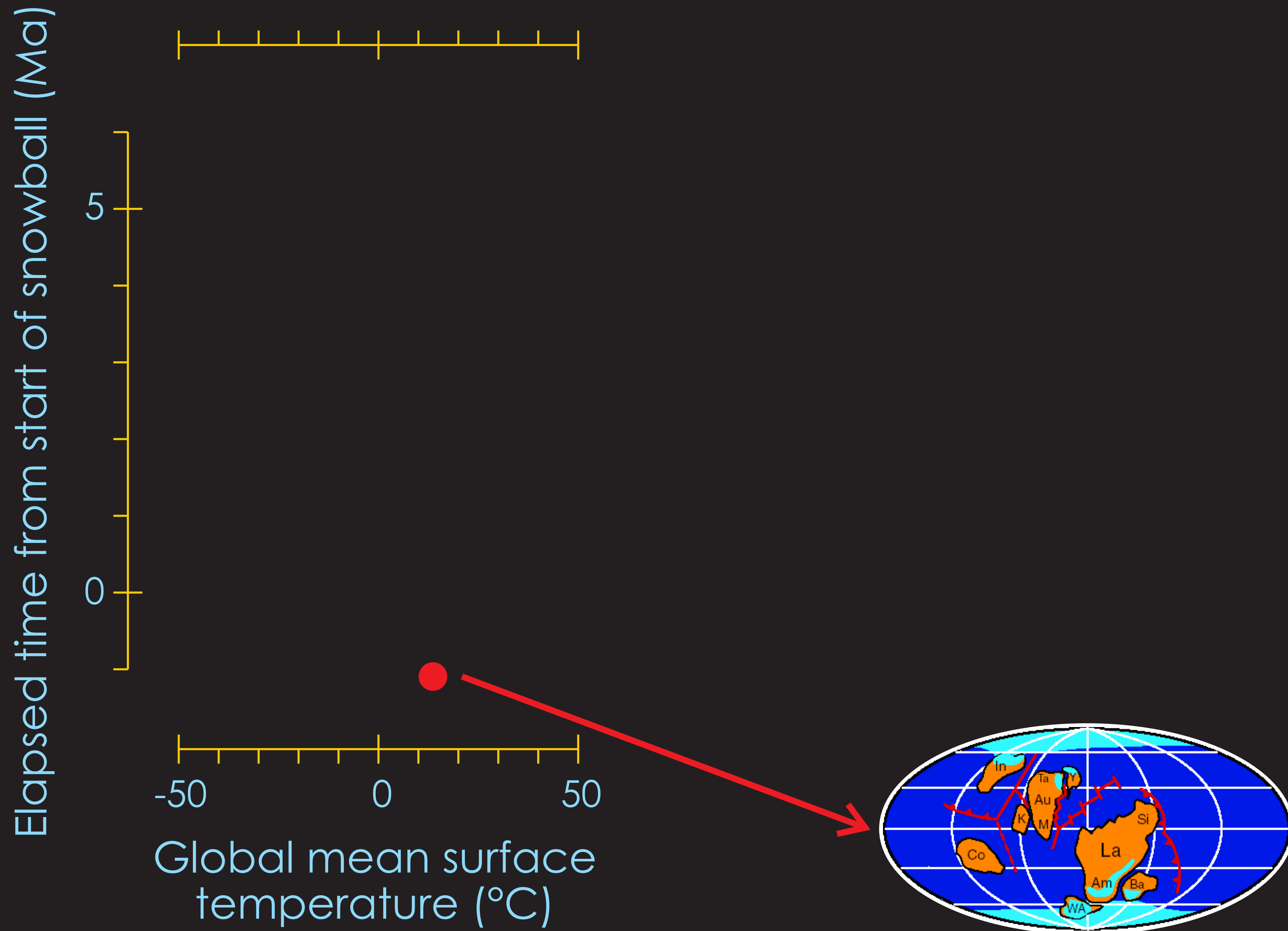
Sanchez-Baracaldo et al. [2014]

The 'snowball Earth' hypothesis

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



The 'snowball Earth' hypothesis



adapted from; *Hoffman and Schrag* [2002]

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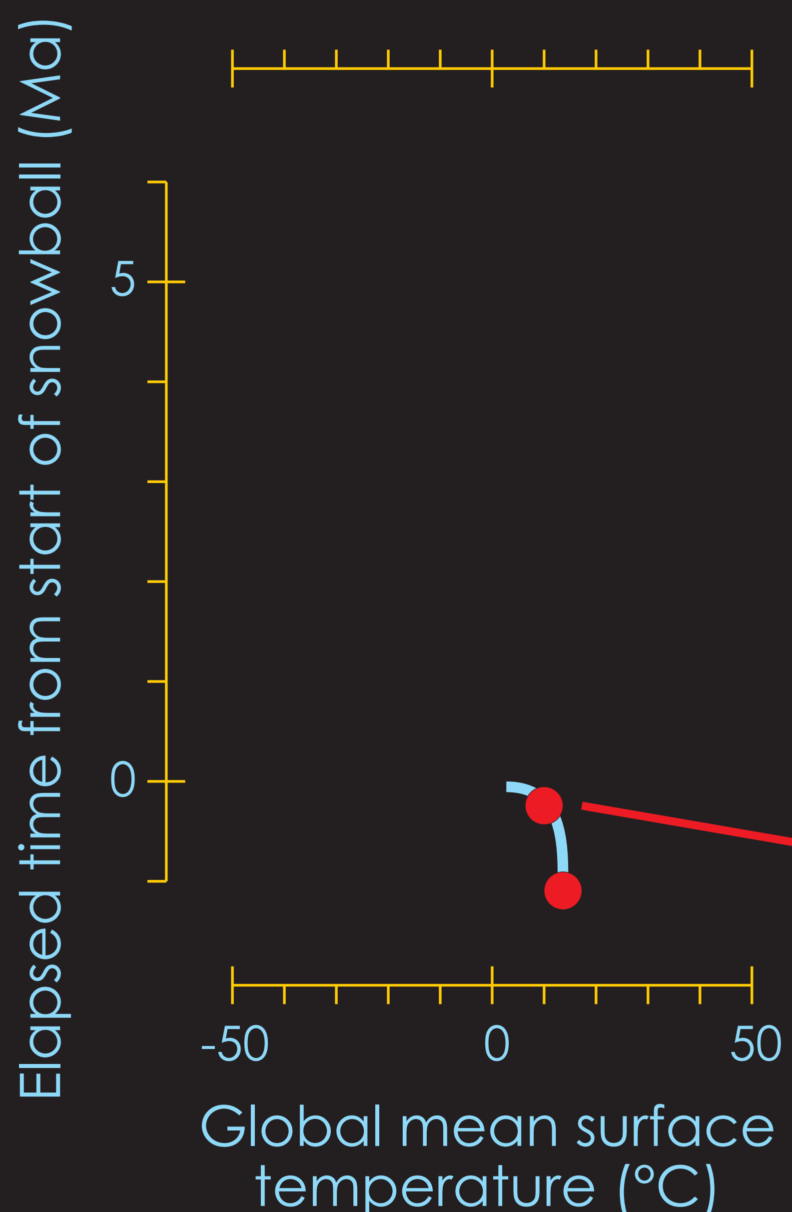
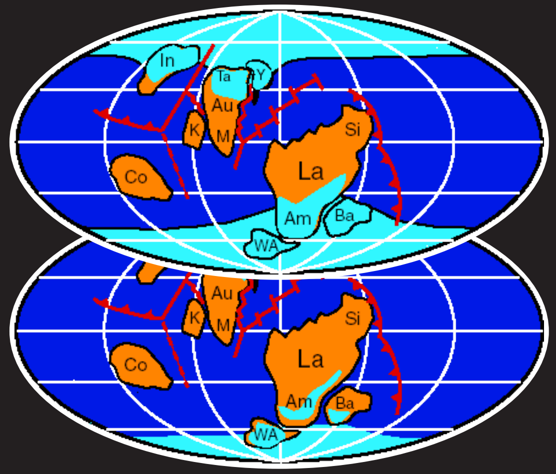
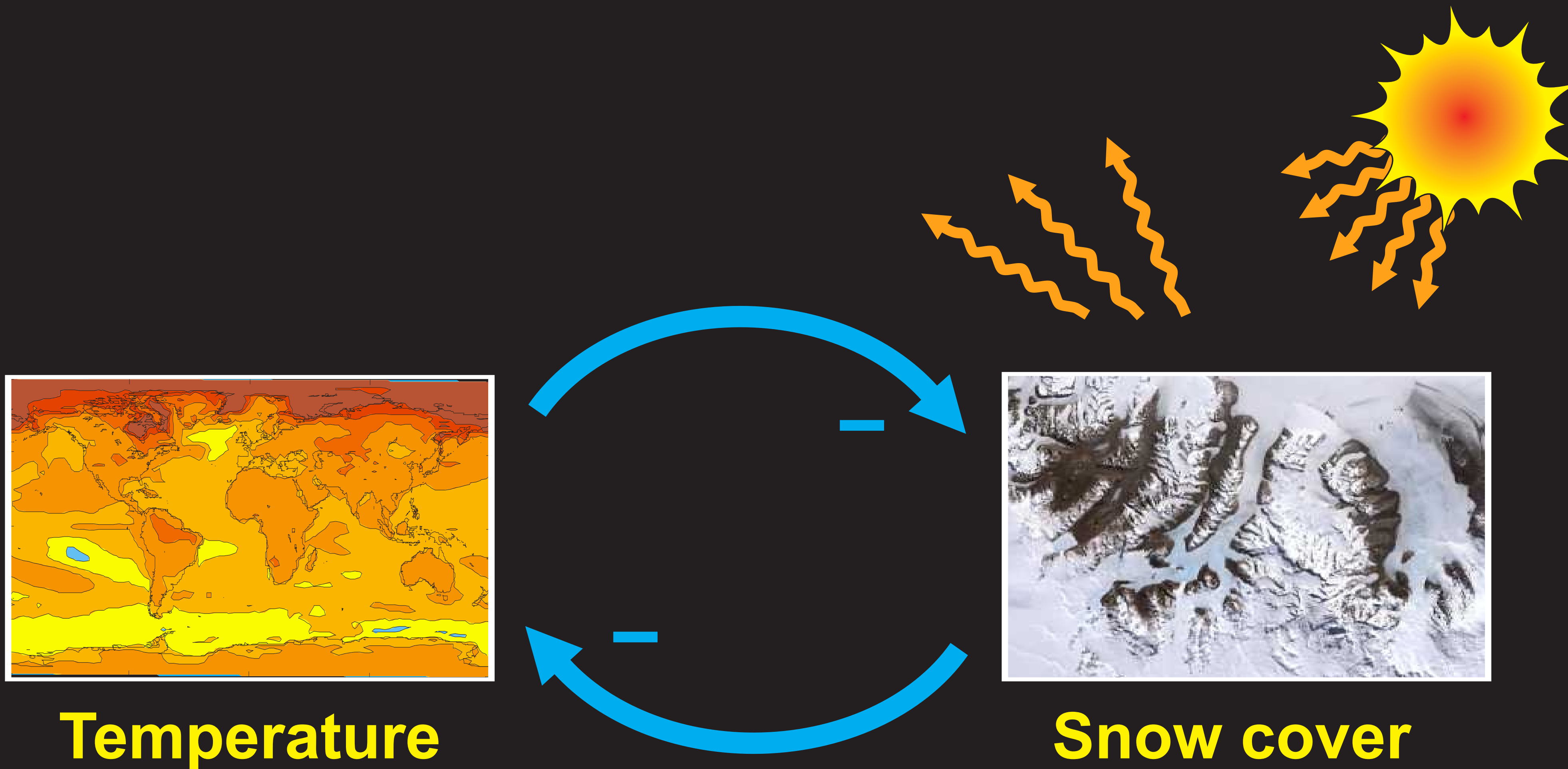




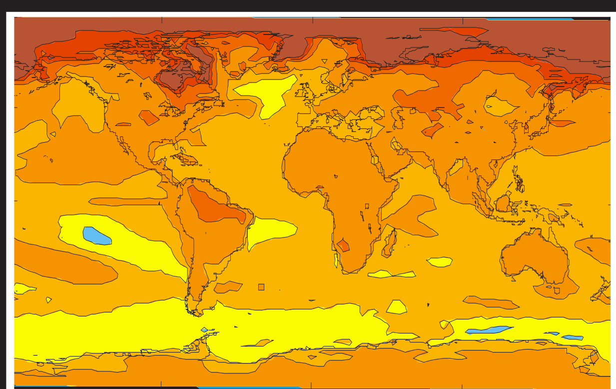
adapted from; *Hoffman and Schrag* [2002]

The ‘snowball Earth’ hypothesis – ‘feedbacks’



positive “ice-albedo” feedback

The ‘snowball Earth’ hypothesis – ‘feedbacks’



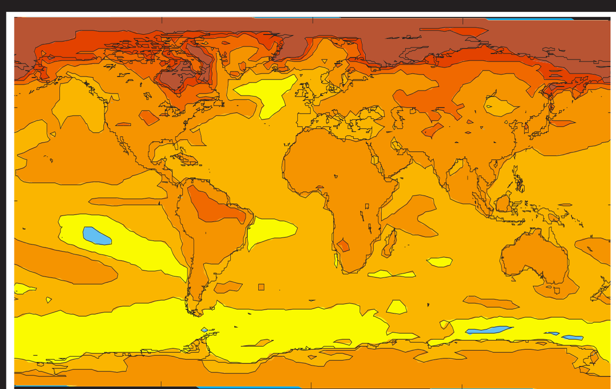
Temperature

–

Snow cover

= -1/2°C

The 'snowball Earth' hypothesis – 'feedbacks'



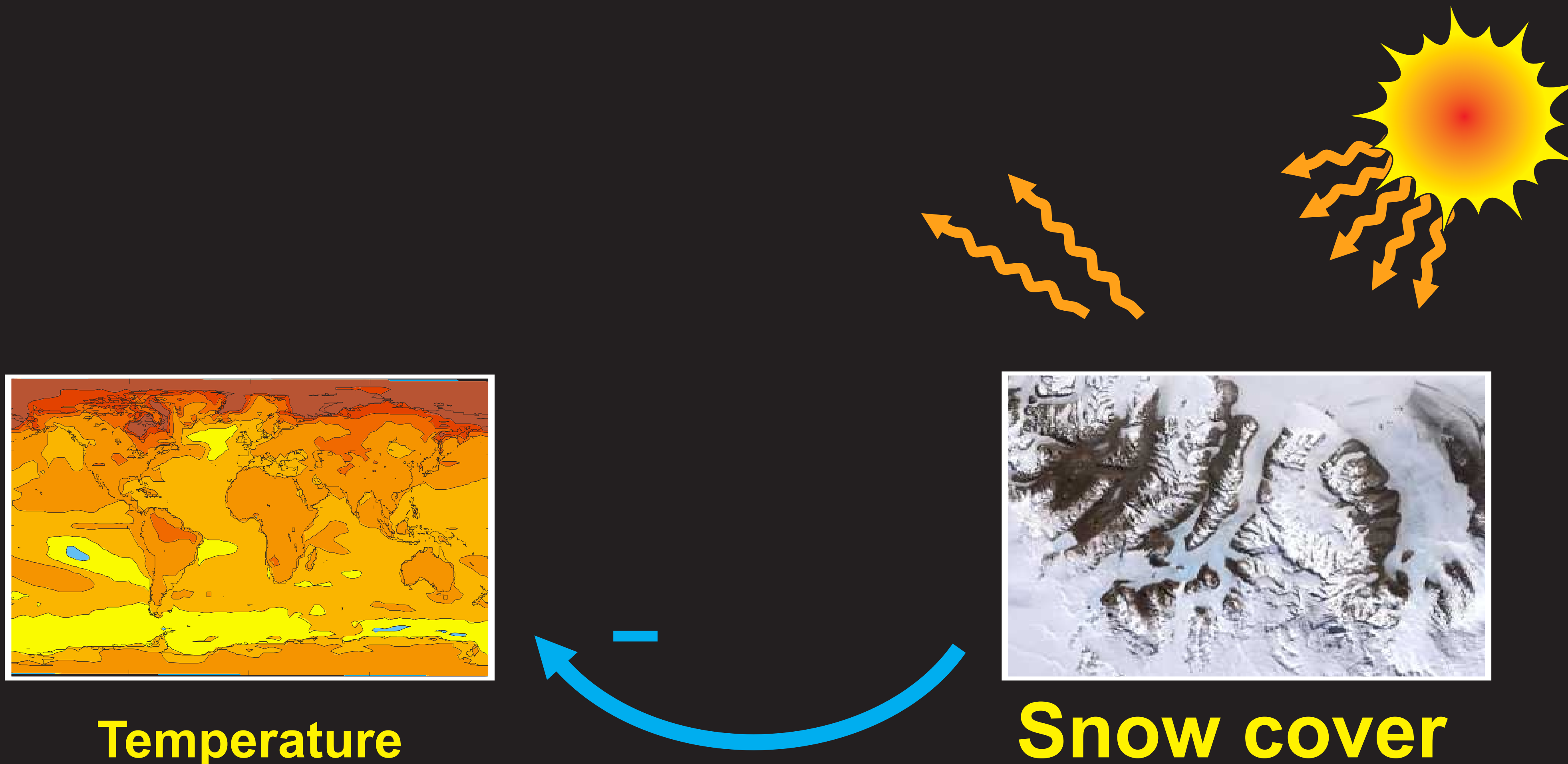
Temperature

–

Snow cover

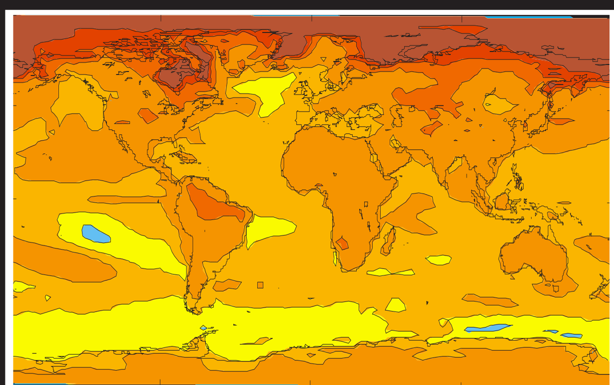
TOTAL CHANGE = -1/2°C

The ‘snowball Earth’ hypothesis – ‘feedbacks’



TOTAL CHANGE = $-1/2°C - 1/4°C$

The ‘snowball Earth’ hypothesis – ‘feedbacks’



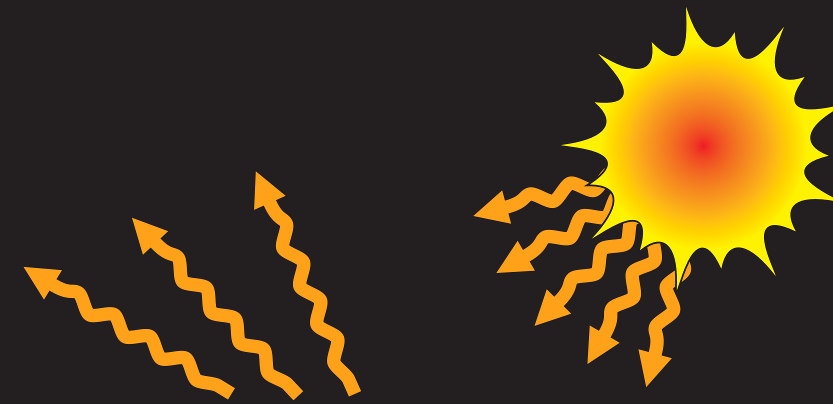
Temperature

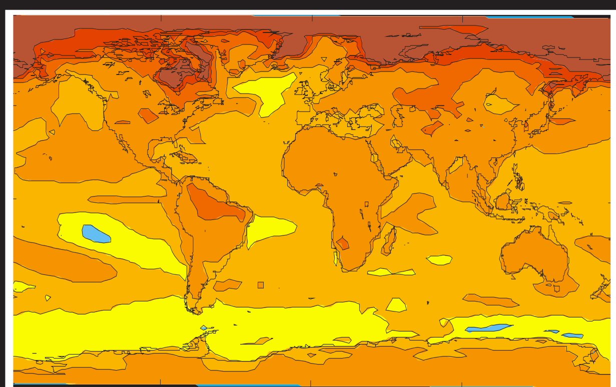
–

Snow cover

```
TOTAL CHANGE = -1/2°C - 1/4°C
```

The 'snowball Earth' hypothesis – 'feedbacks'





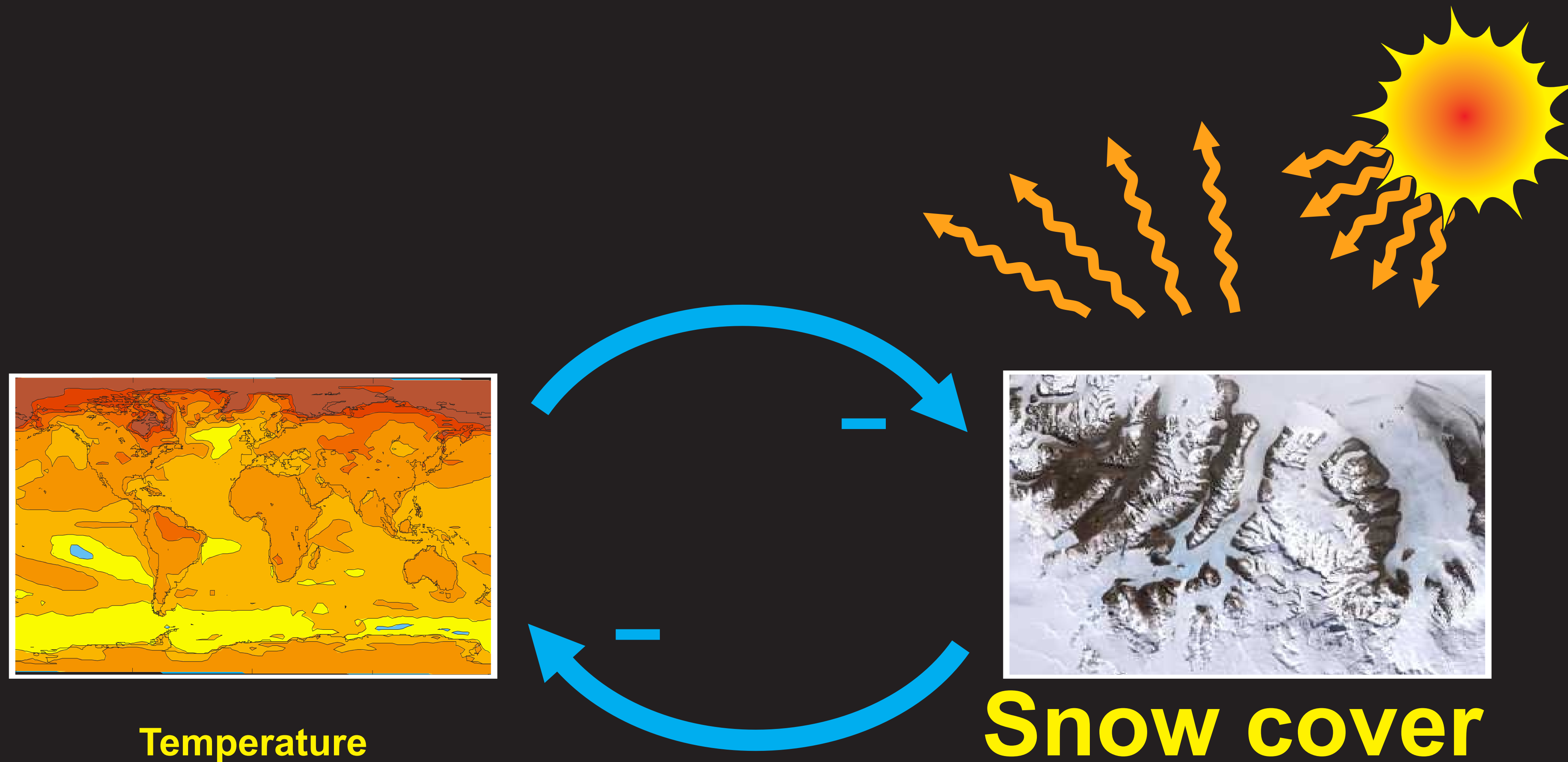
Temperature

–

Snow cover

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

The 'snowball Earth' hypothesis – 'feedbacks'

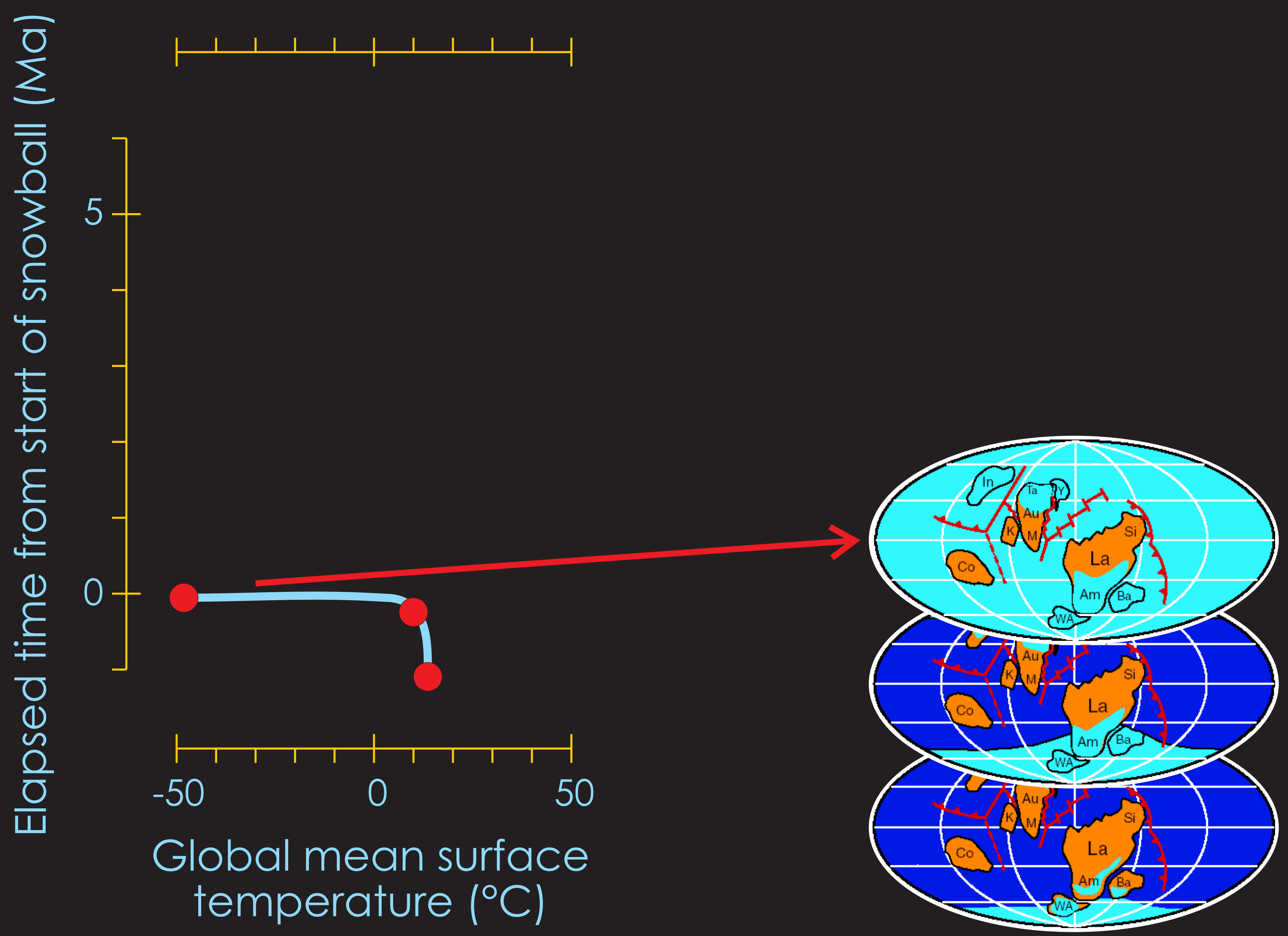


TOTAL CHANGE = -1/2°C - 1/4°C - 1/8°C - 1/16° - ....

The 'snowball Earth' hypothesis – 'feedbacks'

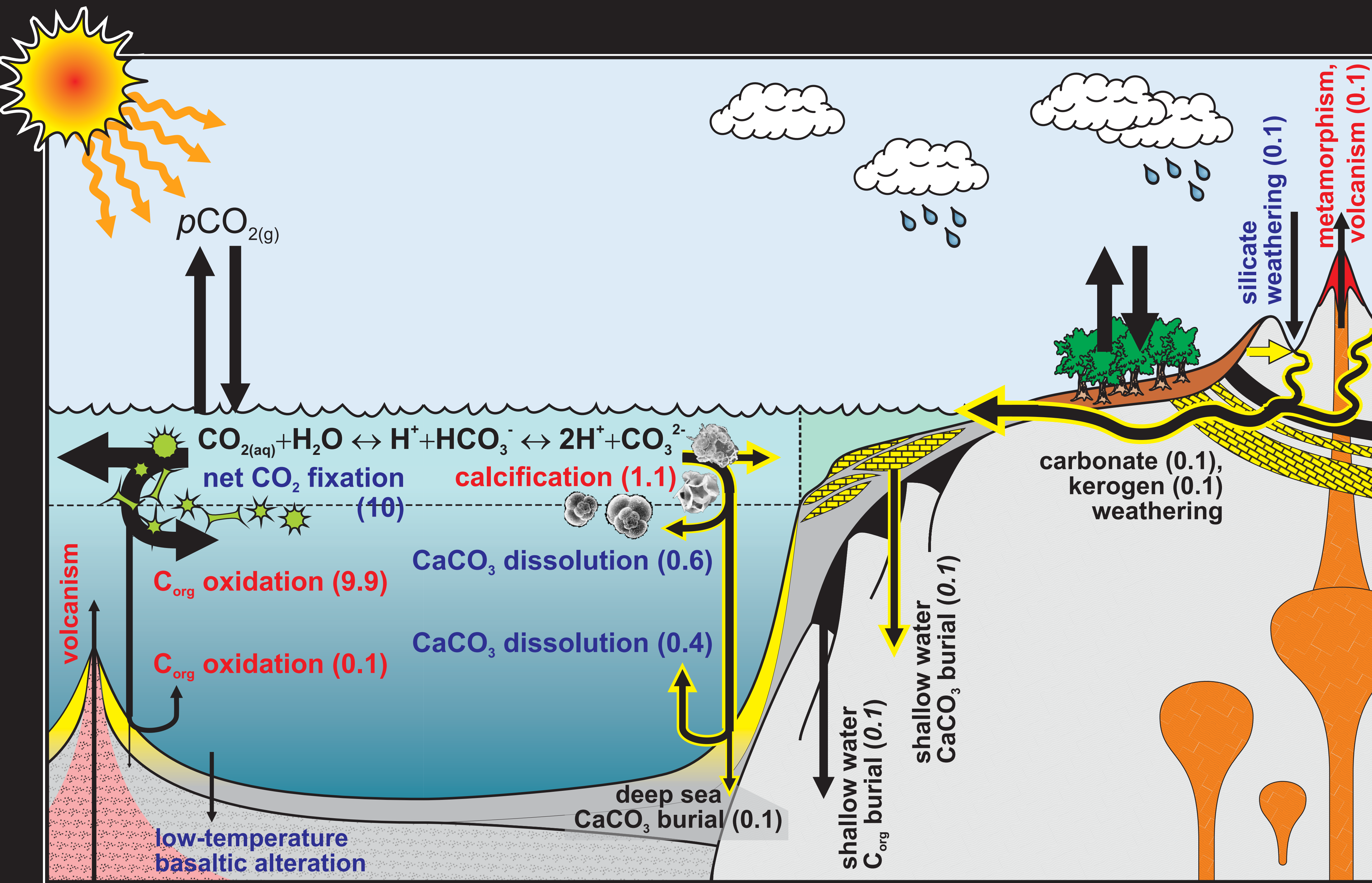
TOTAL CHANGE = -1°C - 2°C - 4°C - 8°C - ....

The ‘snowball Earth’ hypothesis



adapted from; *Hoffman and Schrag* [2002]

Global carbon cycling (modern)



Global carbon cycling (long-term controls)

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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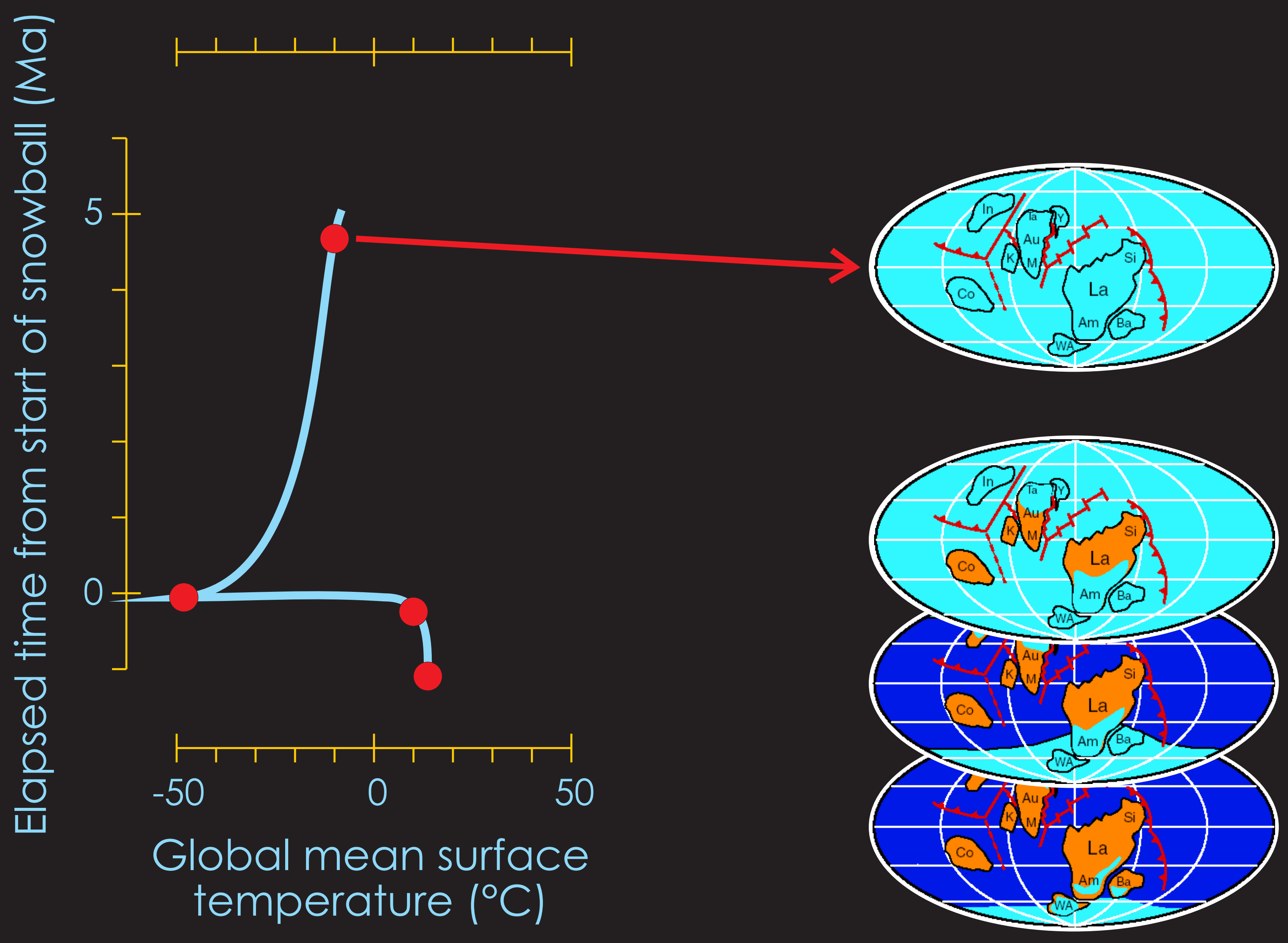
The 'snowball Earth' hypothesis



adapted from; *Hoffman and Schrag* [2002]

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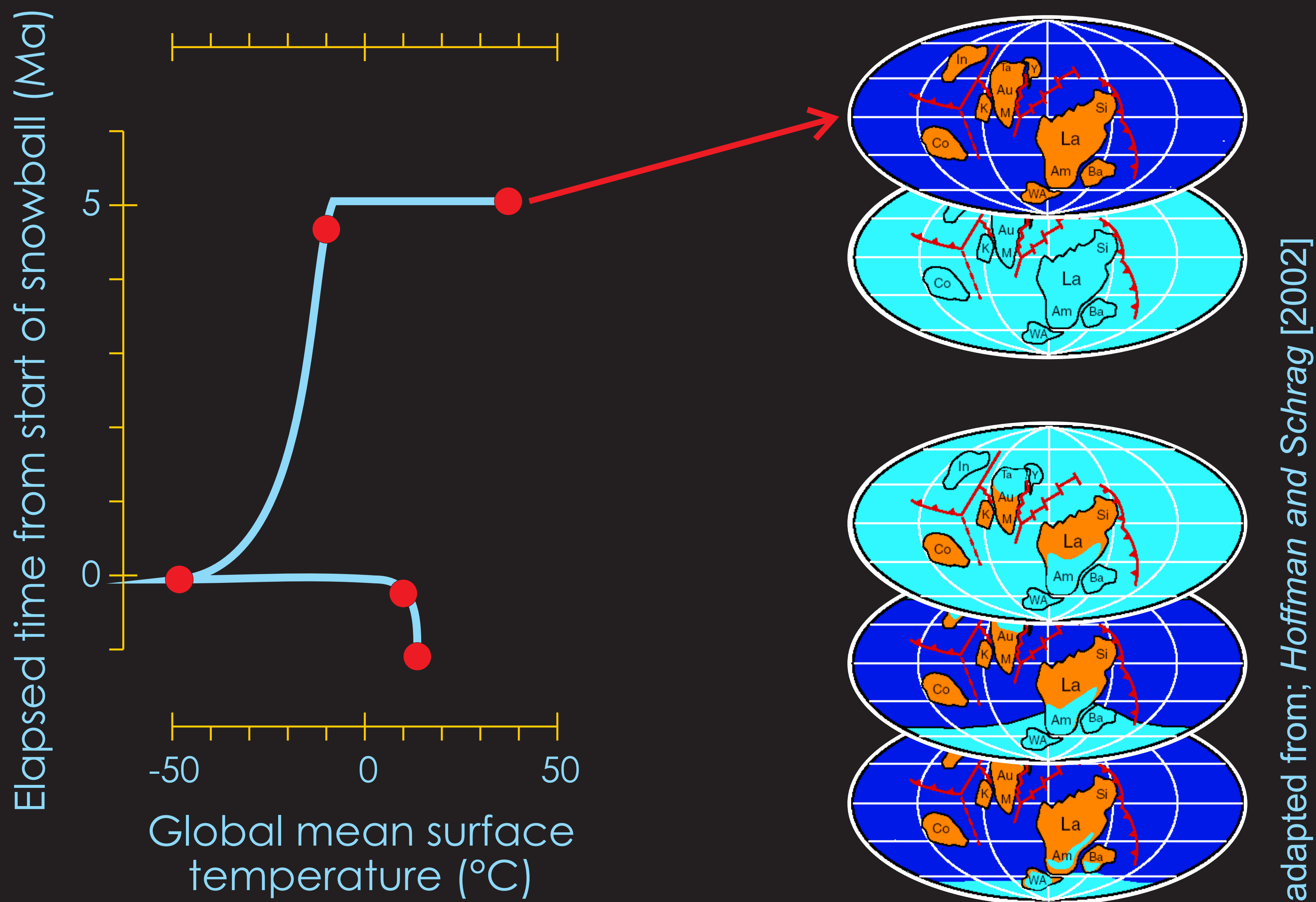

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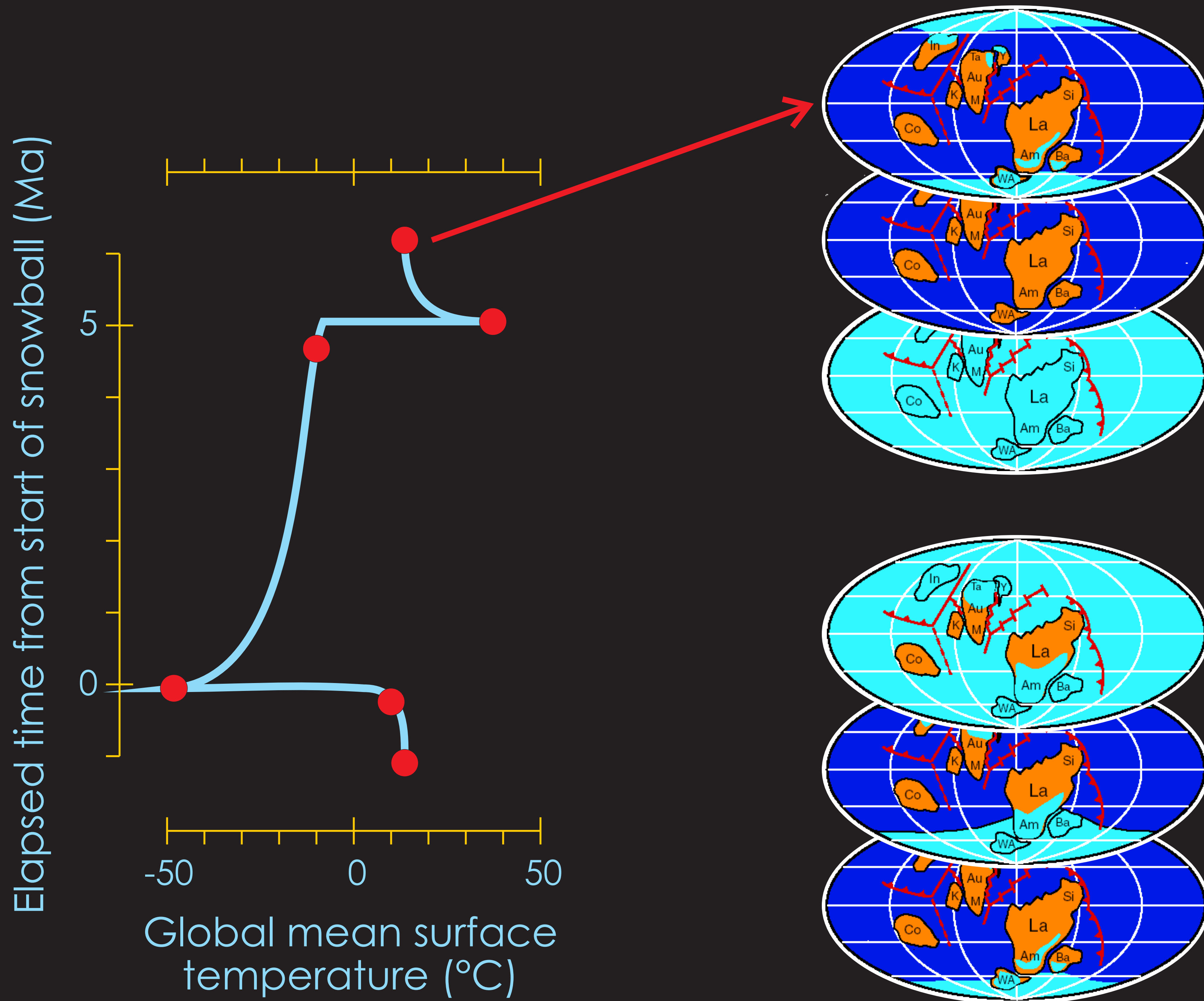

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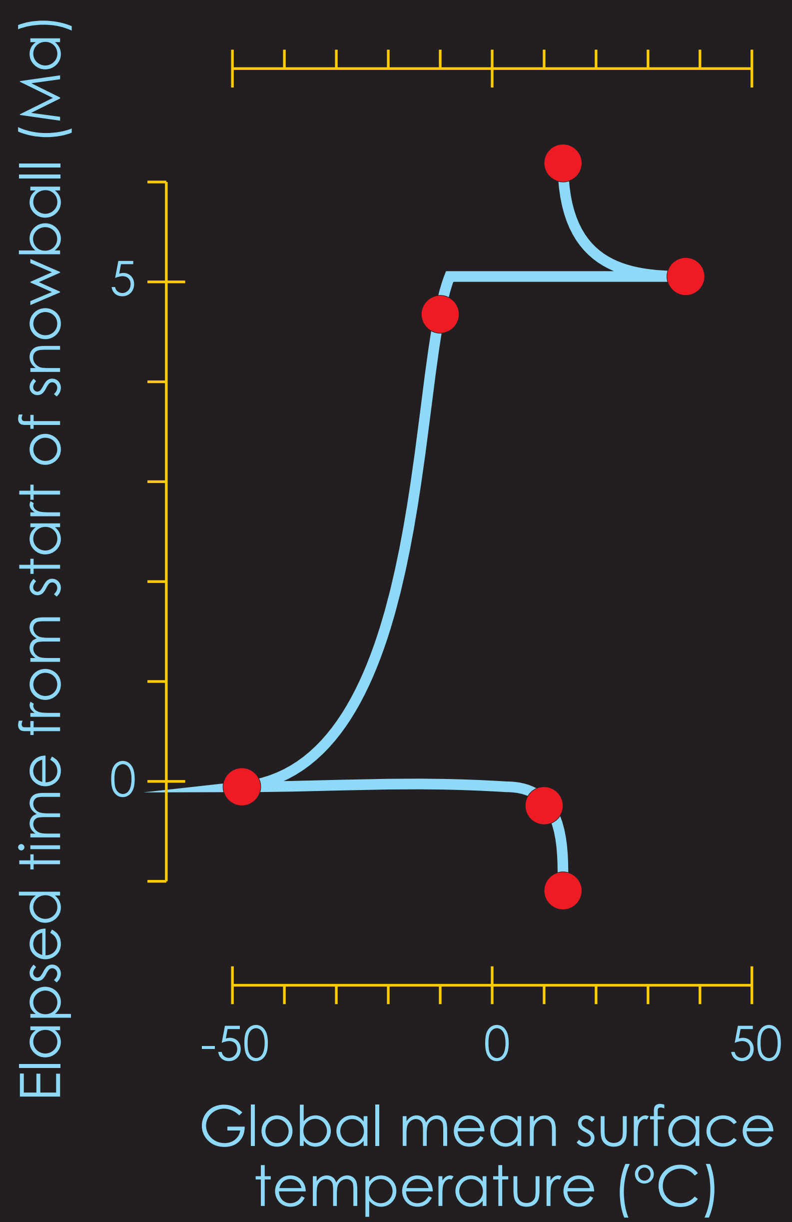
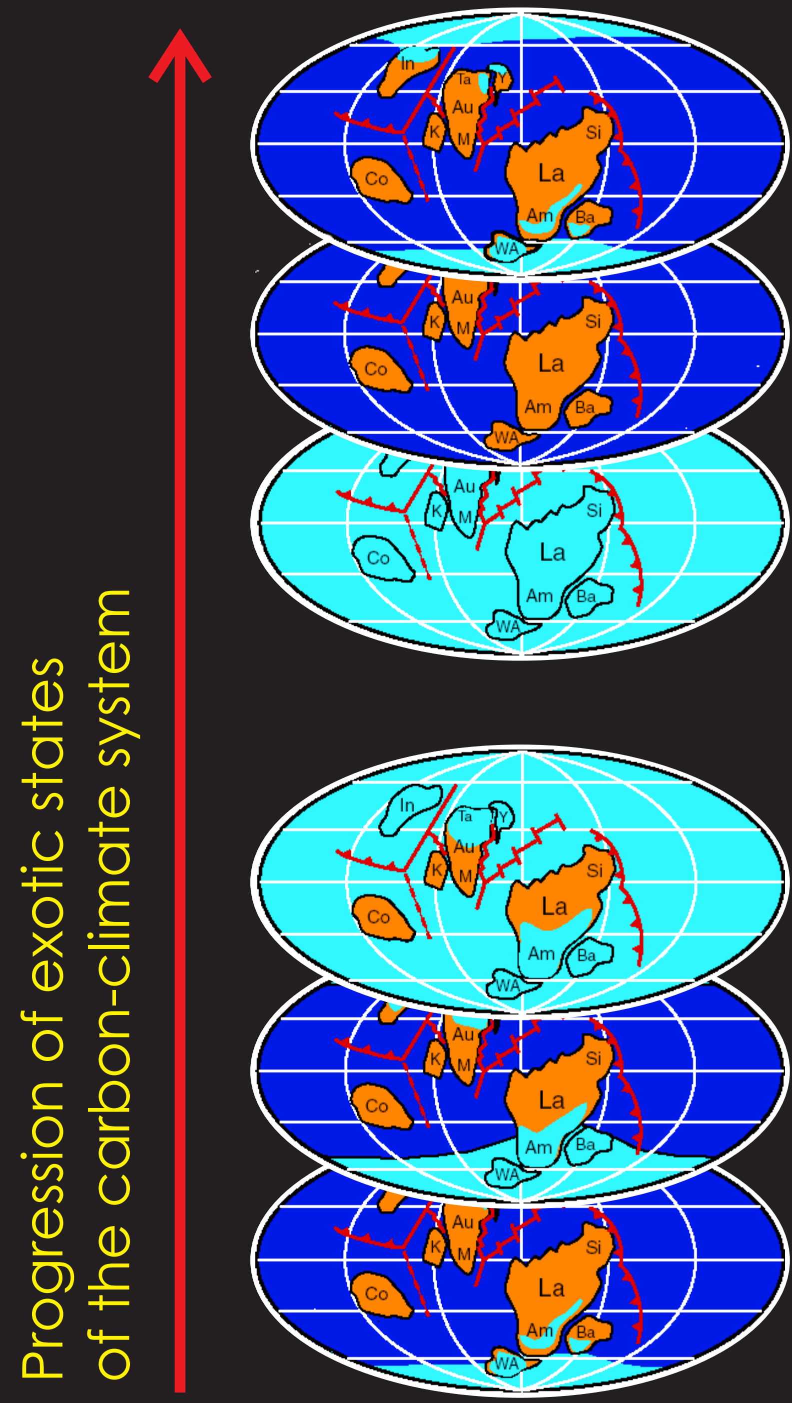
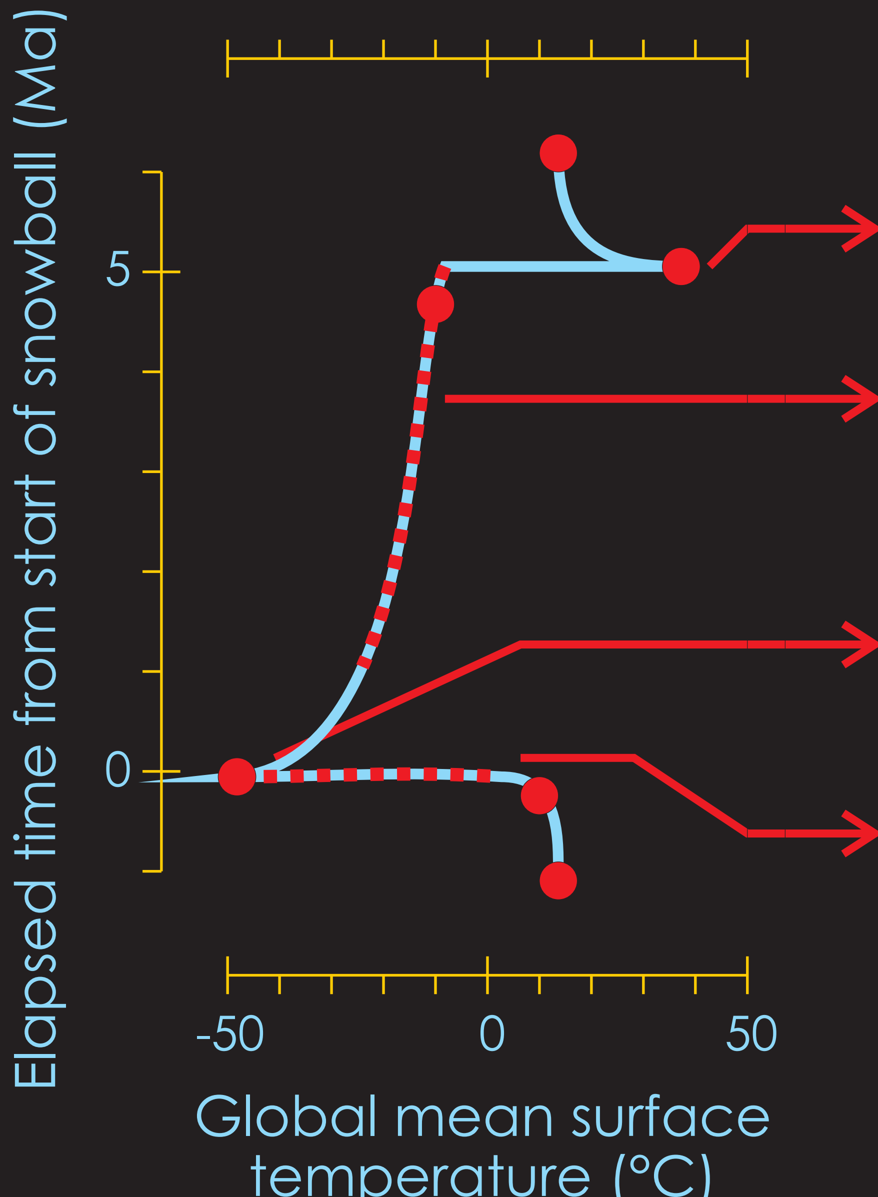




adapted from; *Hoffman and Schrag* [2002]

The 'snowball Earth' hypothesis

All very well, but ...



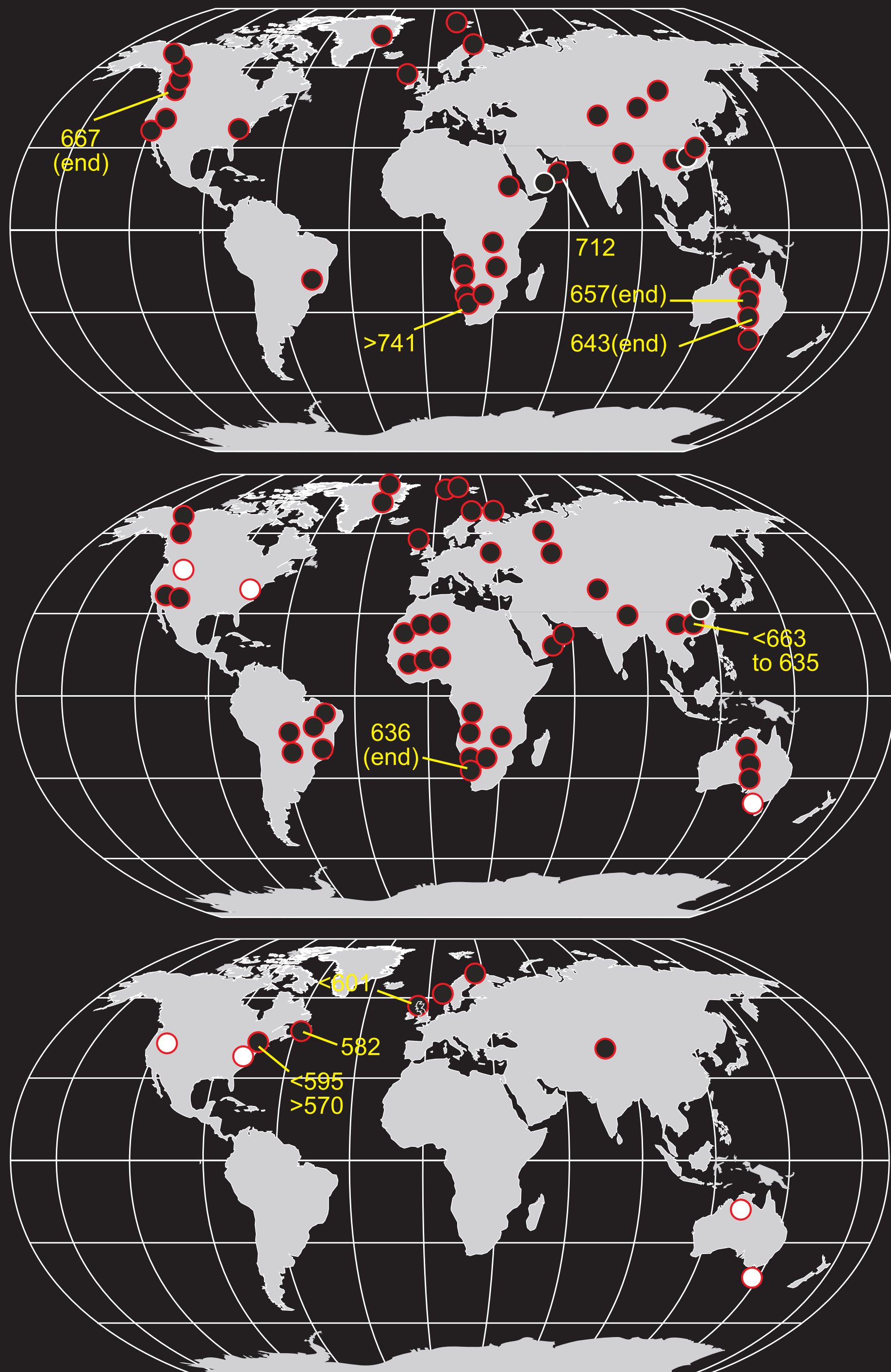
No proxy evidence for: (1) >0.1 bar CO_2 in the atmosphere, (2) the inferred mean global surface temperatures of ca. 50°C, or (3) intense weathering rates in the immediate aftermath of deglaciation.

No proxy evidence of complete cessation of weathering on land (required to build up CO_2 in the atmosphere).

No direct proxy evidence for a completely ice-covered ocean.
How does complex life persist?

Some coupled ocean-atmosphere models do not find an ice-albedo instability.

The ‘snowball Earth’ hypothesis



From: *Fairchild and Kennedy* [2007]

Q ‘snowball’ or ‘slushball’?

i.e., was the equatorial ocean ice-free, or frozen from pole-to-pole during the glacial?

This has profound geochemical and climatic implications, and will constrain the mechanims responsible for going into and coming out of the glaciation.

The 'snowball Earth' hypothesis

All (numerical climate) models are wrong.

Some may be useful.

Study	**ATM**	**SEA-ICE**	**OCN**	**ICE-SHT**	***p*CO_2 threshold**	**(conclusions)**
Jenkins and Smith [1999]					1700 ppm	(snowball)
Chandler and Sohl [2000]					<40 ppm	snowball unlikely
Hyde et al. [2000]; *Crowley et al.* [2001]					130 ppm	slushball probable
Baum and Crowley [2001,2003]					<340 ppm	slushball probable
Poulsen et al. [2001,2]; *Poulsen* [2003]					n/a	no snowball
Bendtsen [2002]					n/a	snowball less likely
Godderis et al. [2003]					130 ppm	(snowball)
Goodman and Pierrehumbert [2003]					130 ppm	snowball more likely
Donnadieu et al. [2003]					500 - 990	slushball unlikely
Lewis et al. [2003,2004]					1800 ppm	(snowball)
Donnadieu et al. [2004a,b]					<149, 250	(snowball)
Edwards and Ridgwell [unpublished]					200 ppm	(snowball)

KEY:

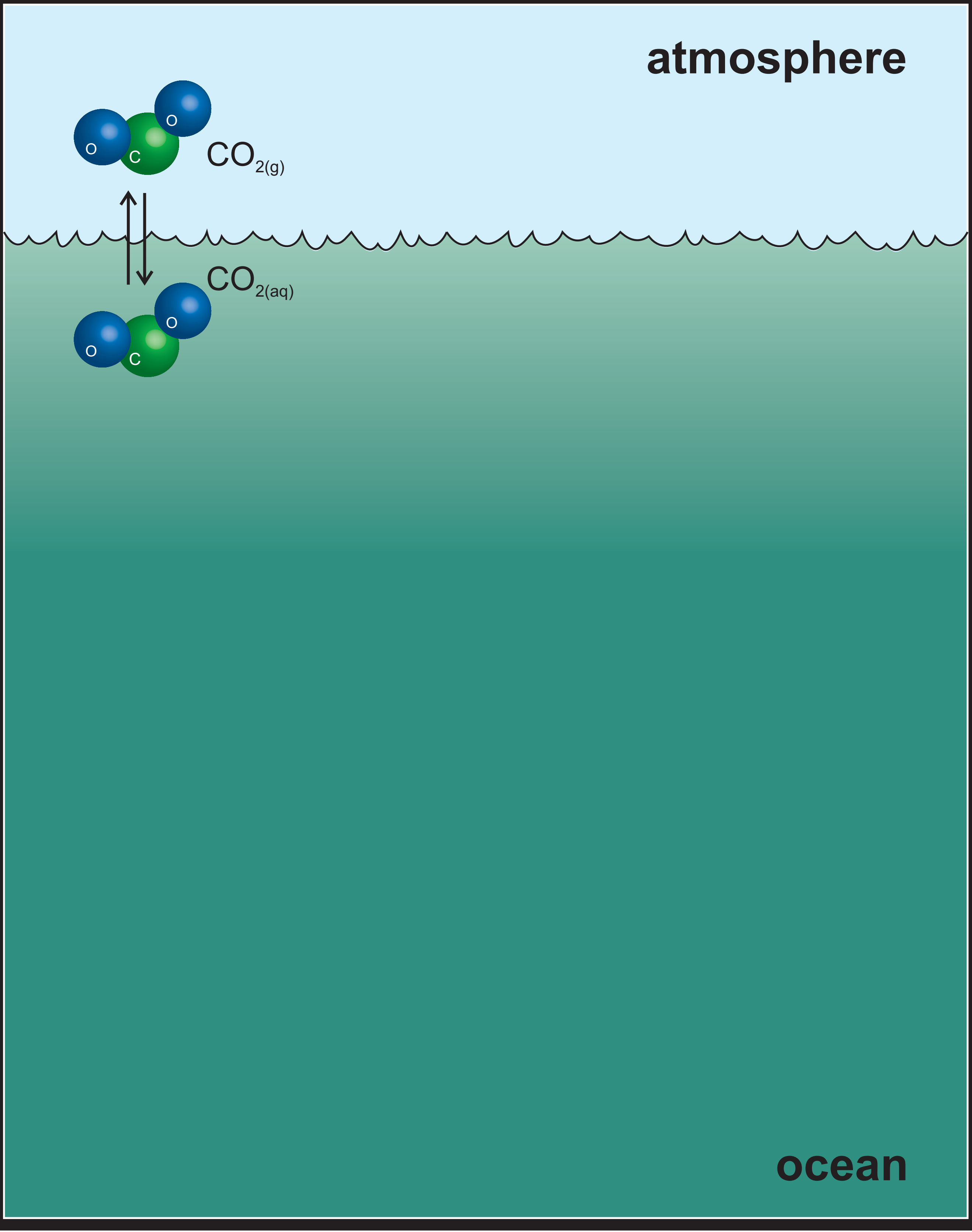
'ADVANCED' e.g. 3D GCM, thermodynamic sea-ice

'INTERMEDIATE' e.g. 2D EBM, seasonal mixed layer ocean

'BASIC' e.g. 1D EBM, slab ocean

DECOUPLED

The enigma of the 'cap carbonates'

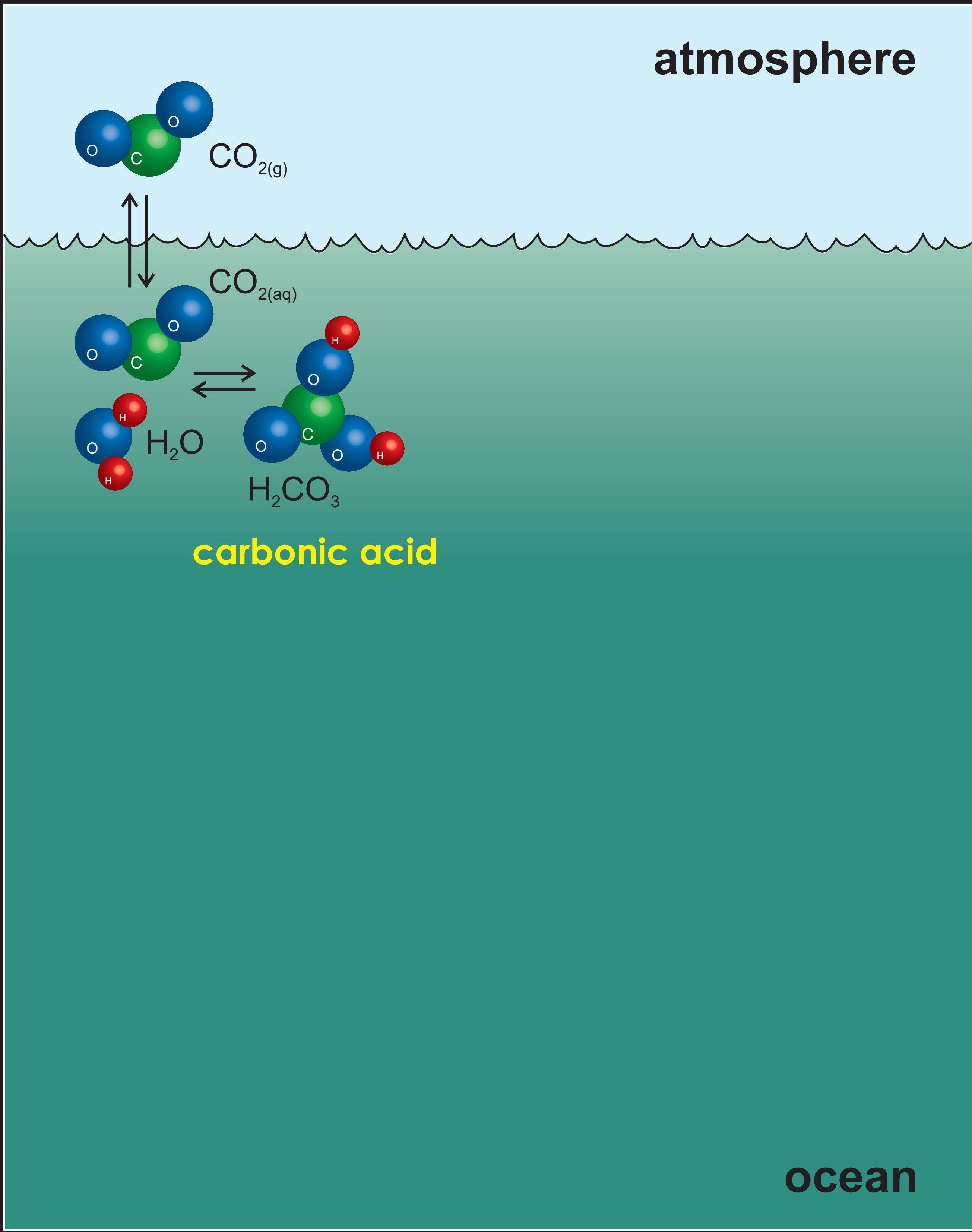


CO_2 chemistry *in seawater*

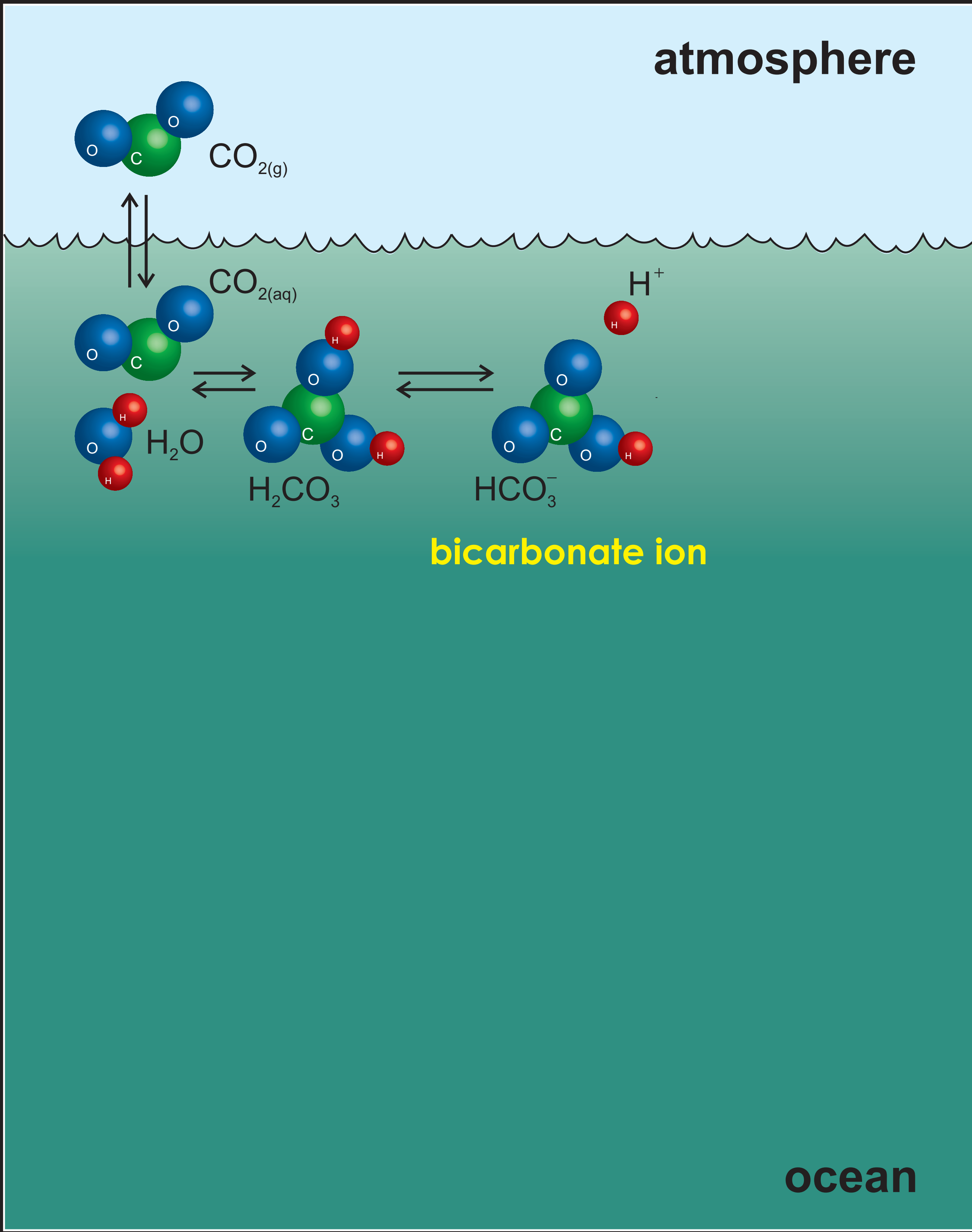
From: *Barker and Ridgwell* [2012]

http://www.nature.com/scitable/knowledge/library/ocean-acidification-25822734

CO_2 chemistry in seawater



CO_2 *chemistry in seawater*



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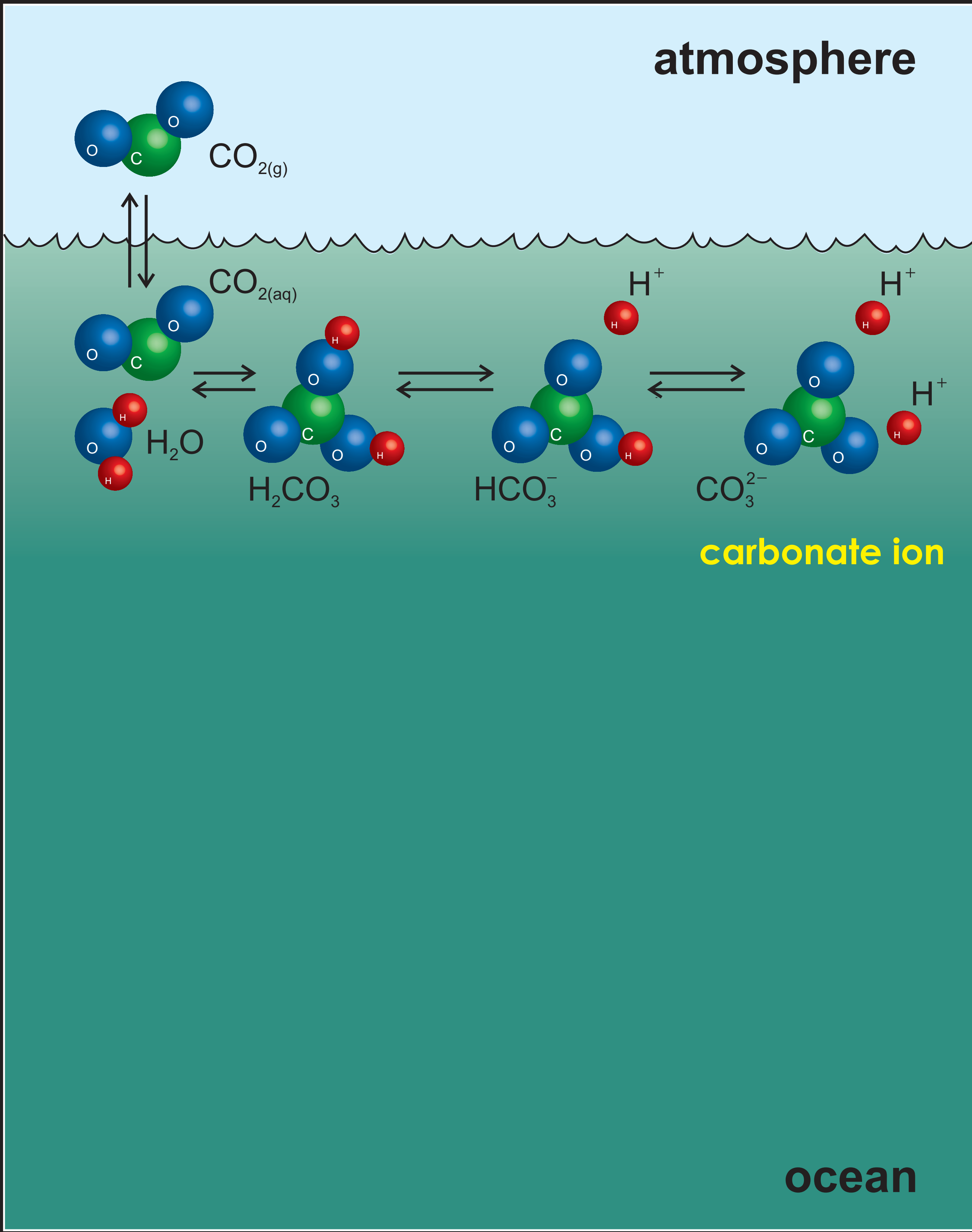
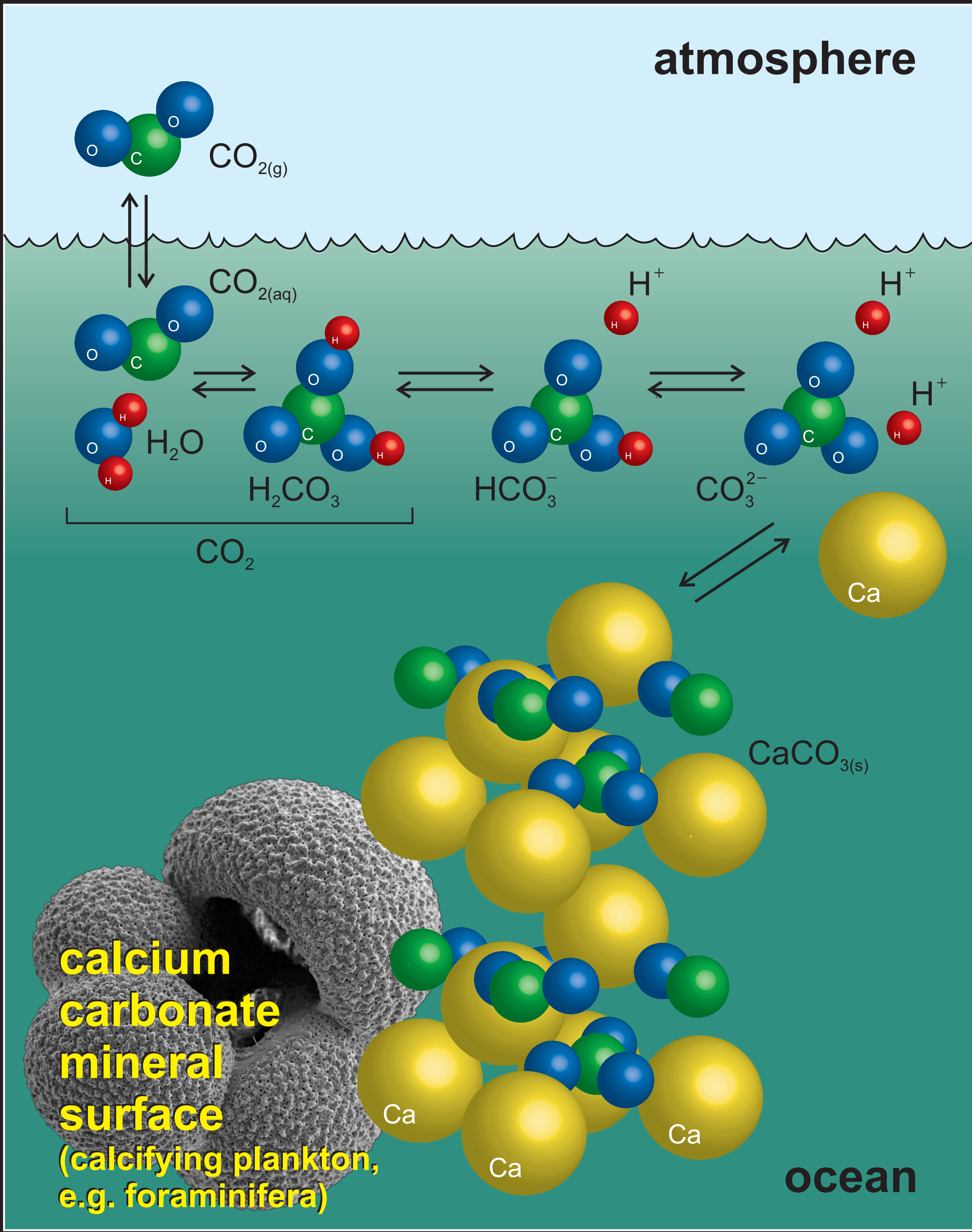
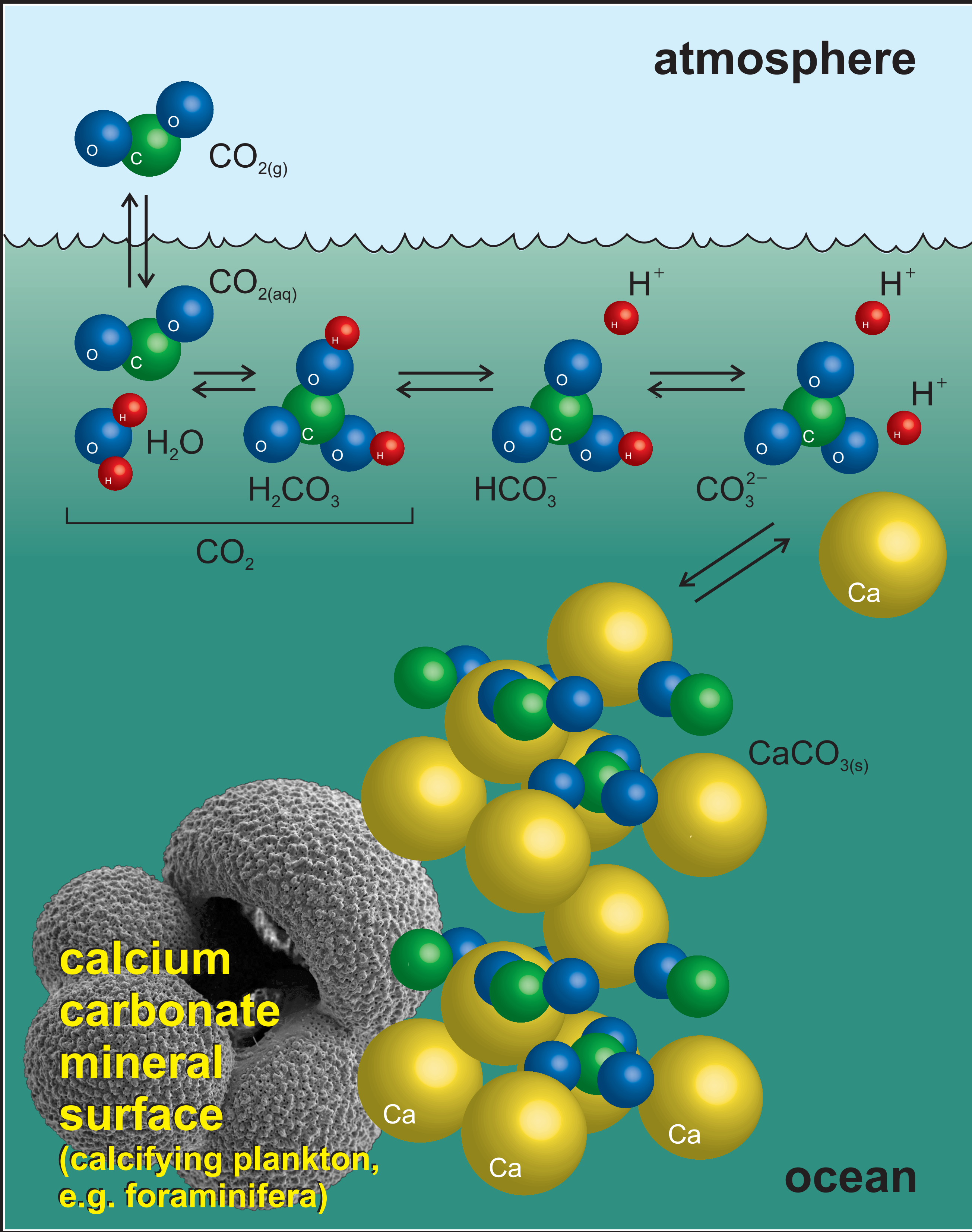


CO_2 chemistry & mineral phases



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*:

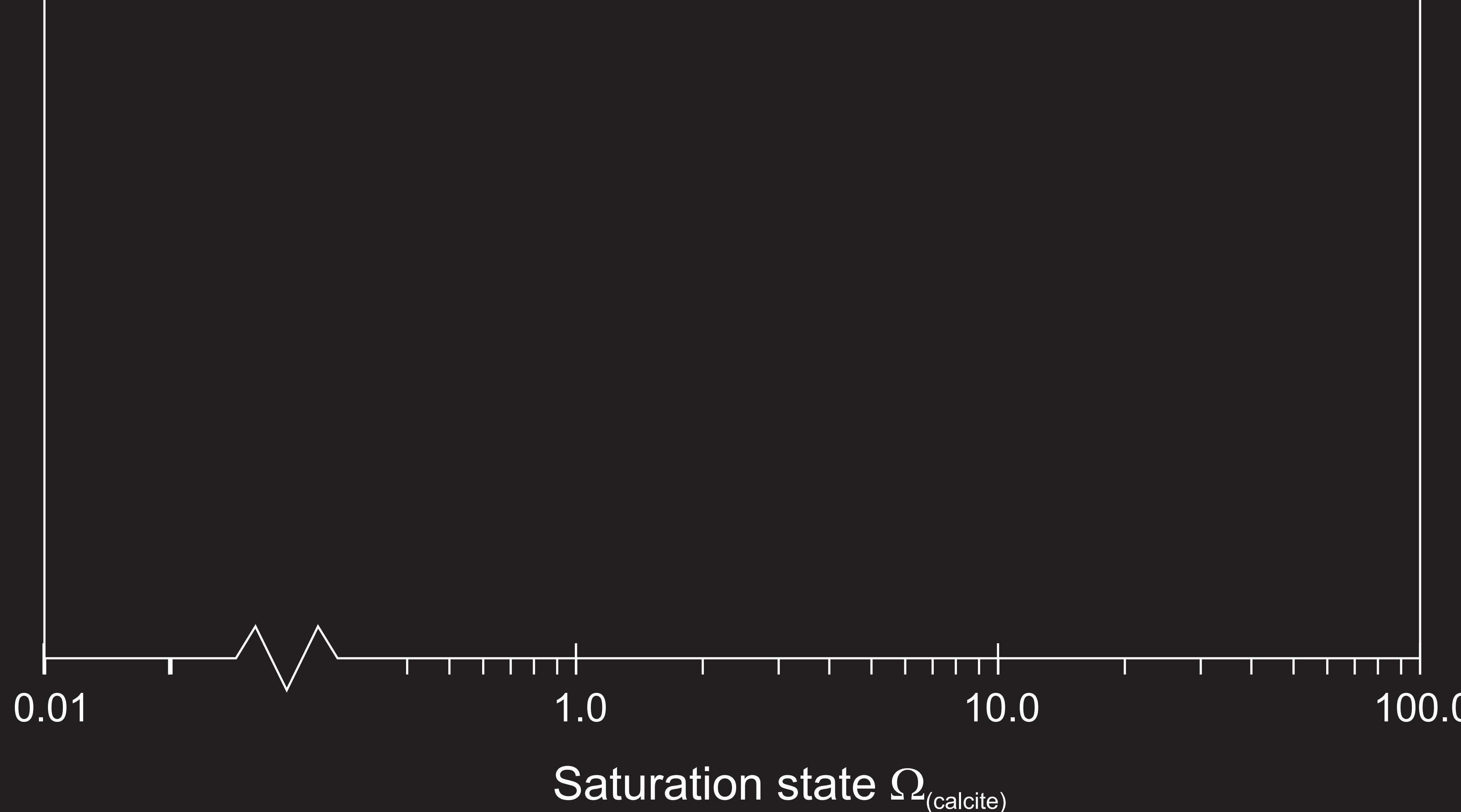
$$\Omega = [Ca^{2+}]\times[CO_3^{2-}]\,/k$$

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

The enigma of the 'cap carbonates'

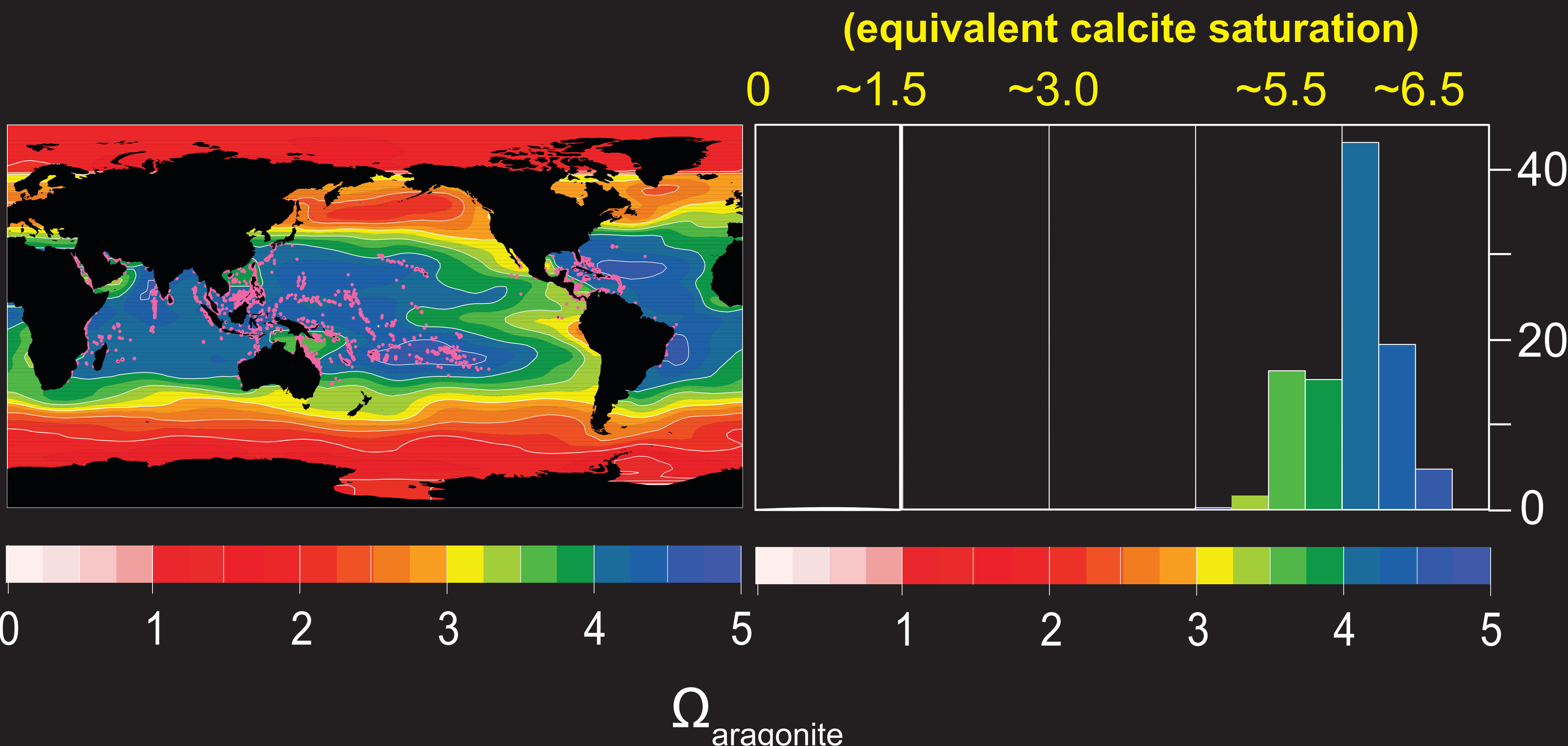
Aqueous carbonate equilibrium; $H_2O + CO_{2(aq)} + CO_3^{2-} \leftrightarrow 2HCO_3^-$

Stability of $CaCO_3$ defined relative to saturation state; $\Omega=[Ca^{2+}]\times[CO_3^{2-}]/k$



The enigma of the 'cap carbonates'

See: GEOG 'World in crisis' lecture on 'Ocean Acidification'
(PDF available from www.seao2.org/teaching.html)



Cao and Caldeira [2008]

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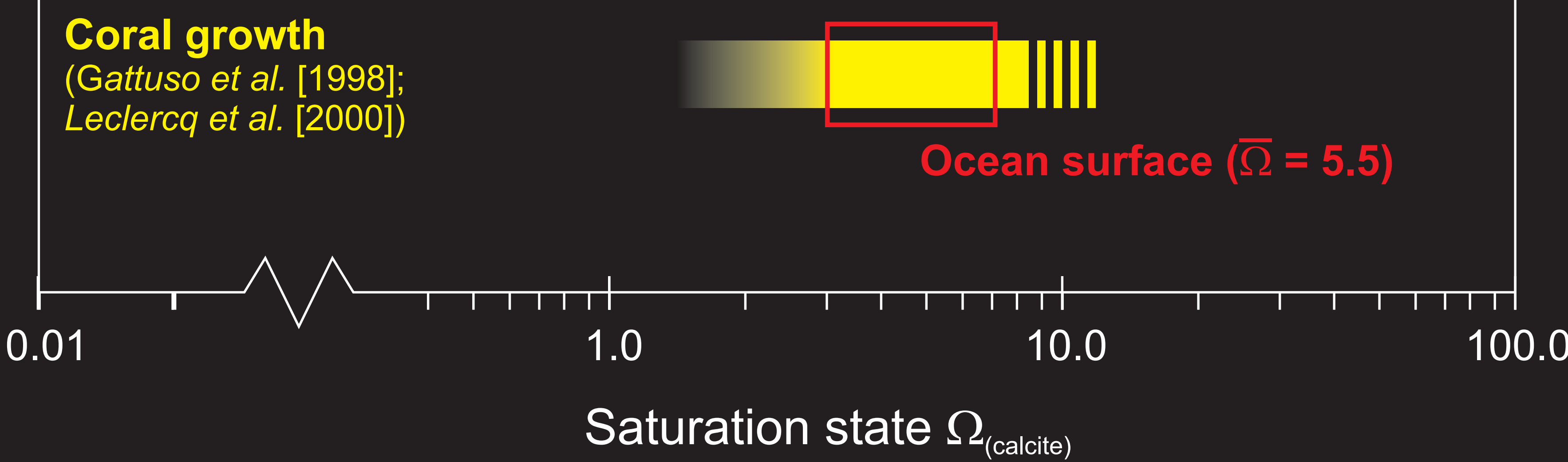

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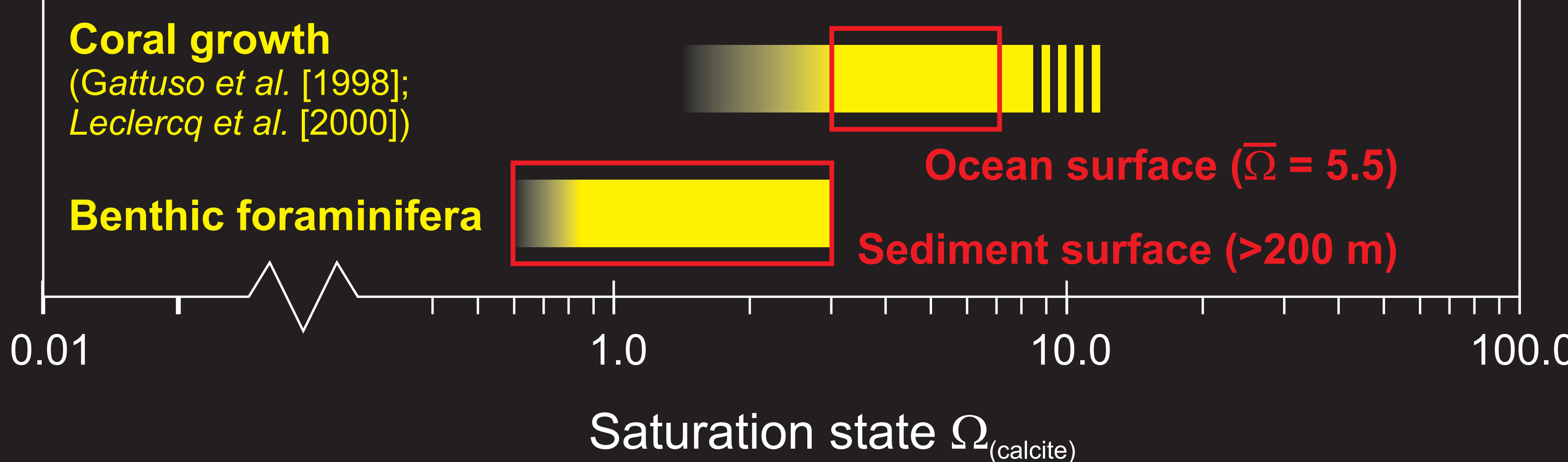

The enigma of the 'cap carbonates'

Snowball Earth

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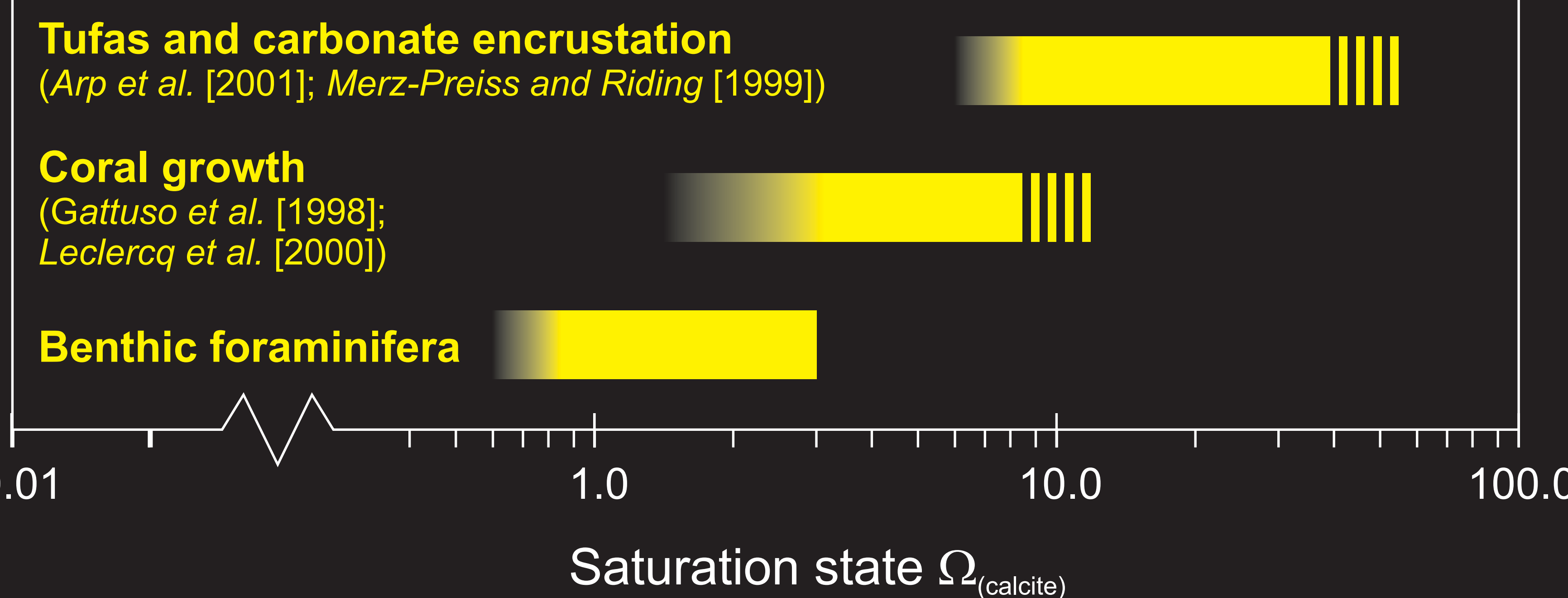

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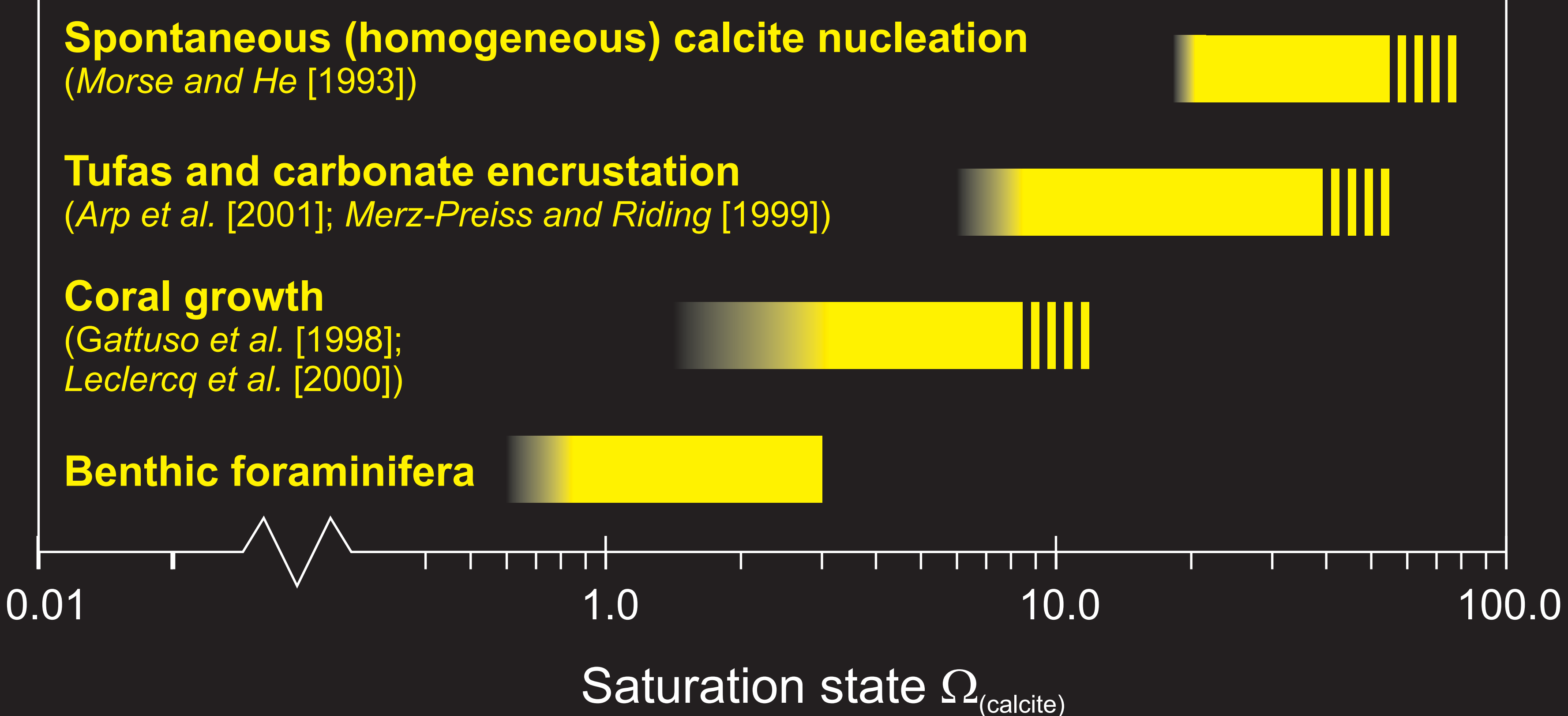

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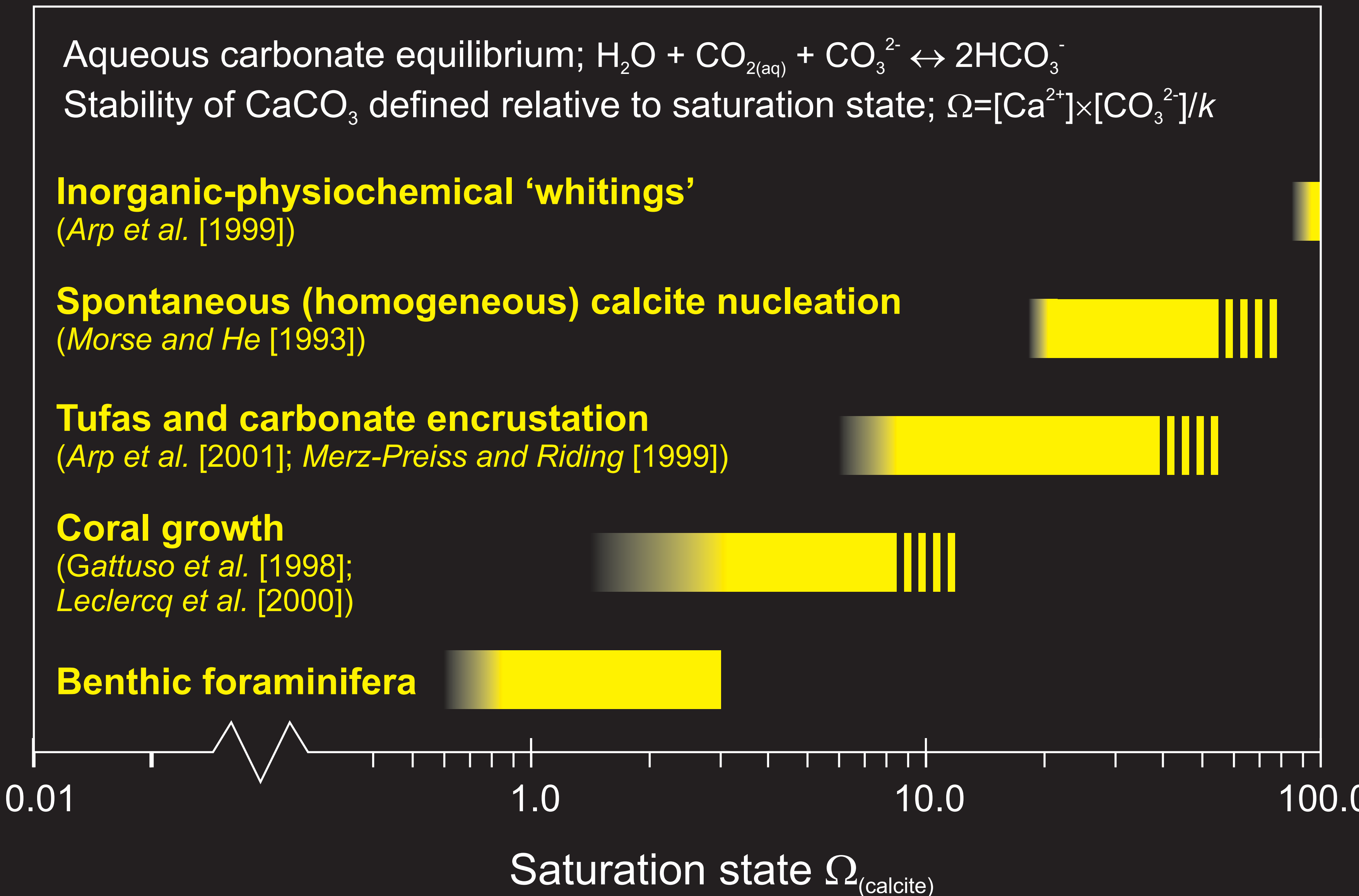

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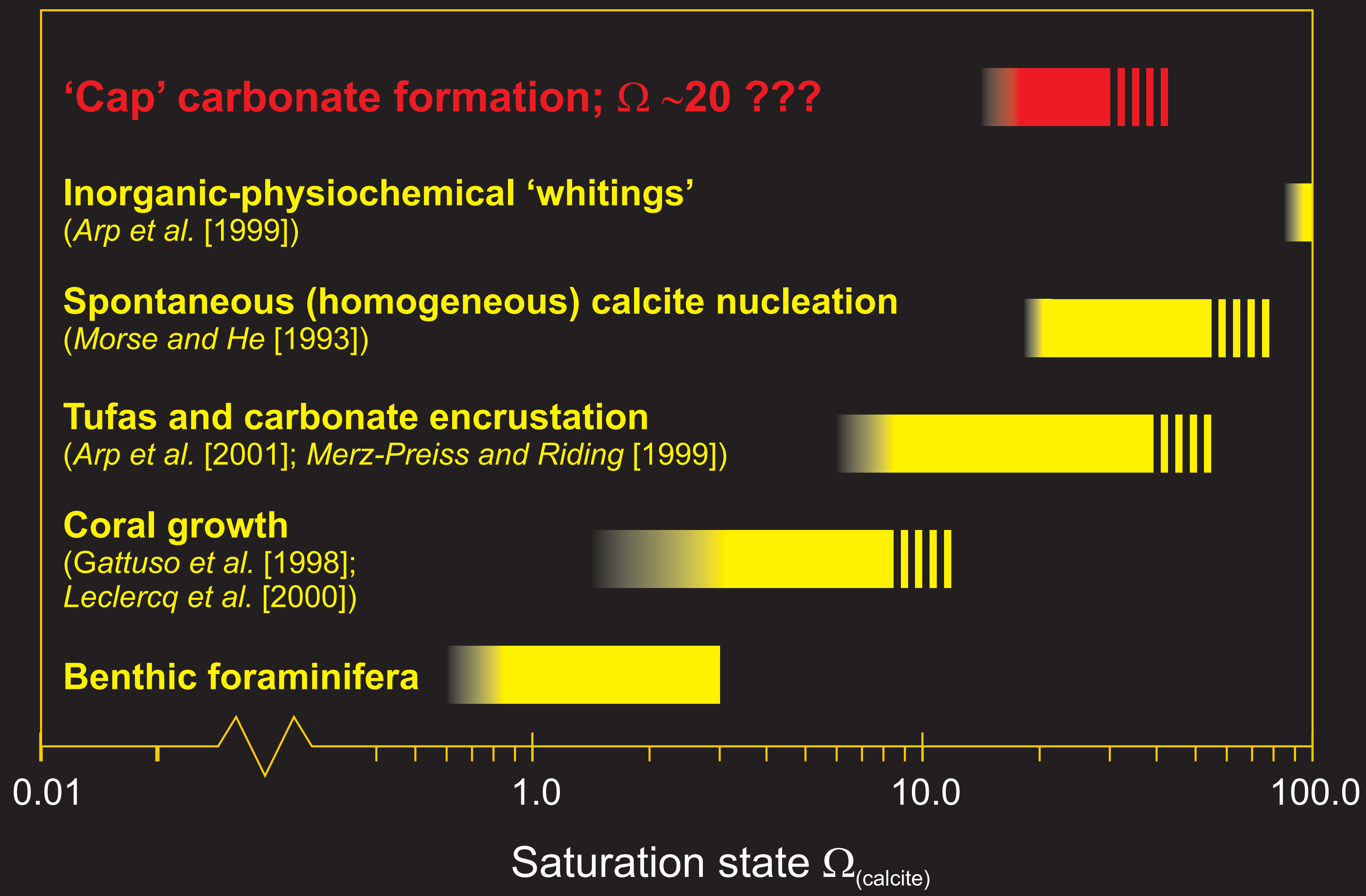
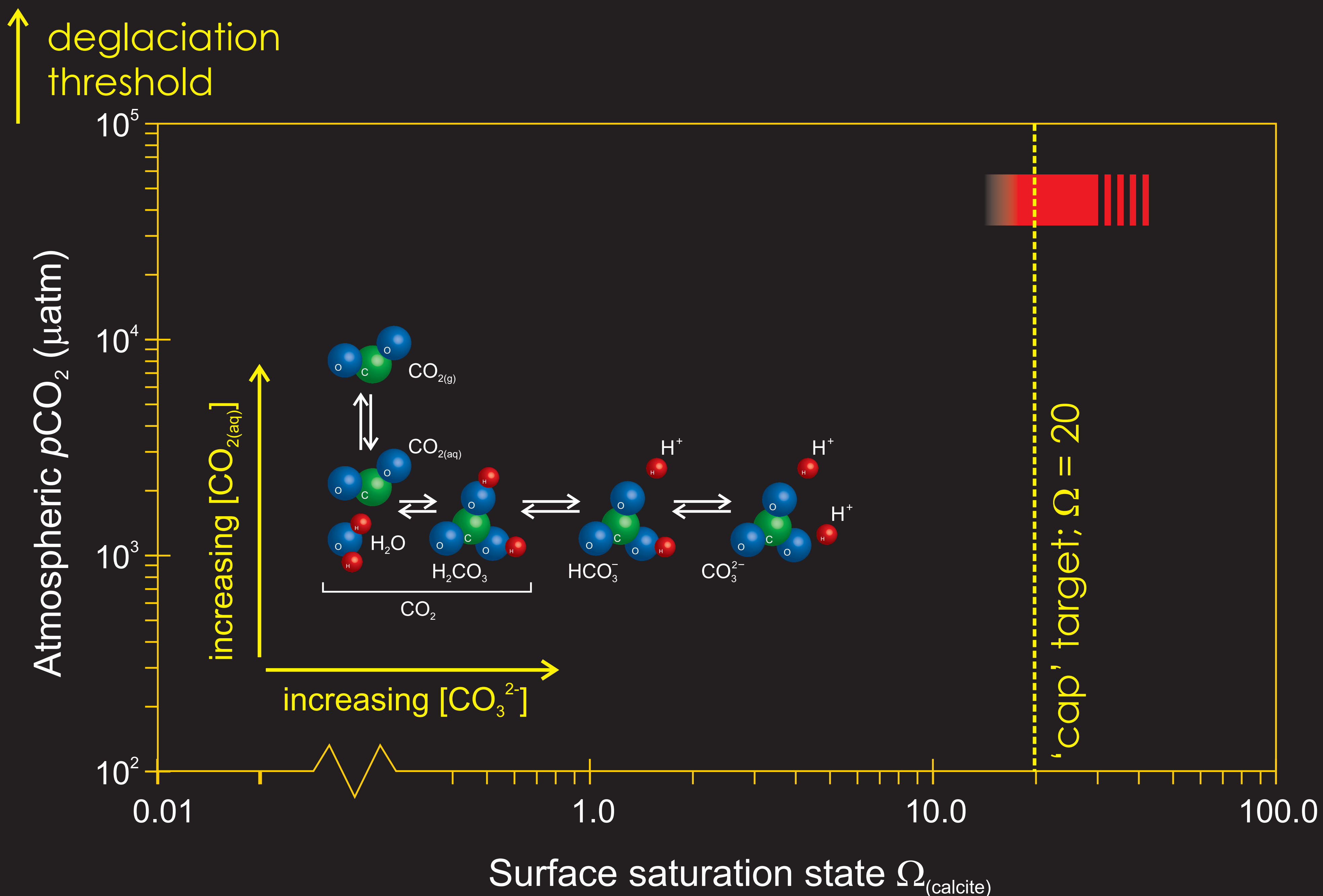
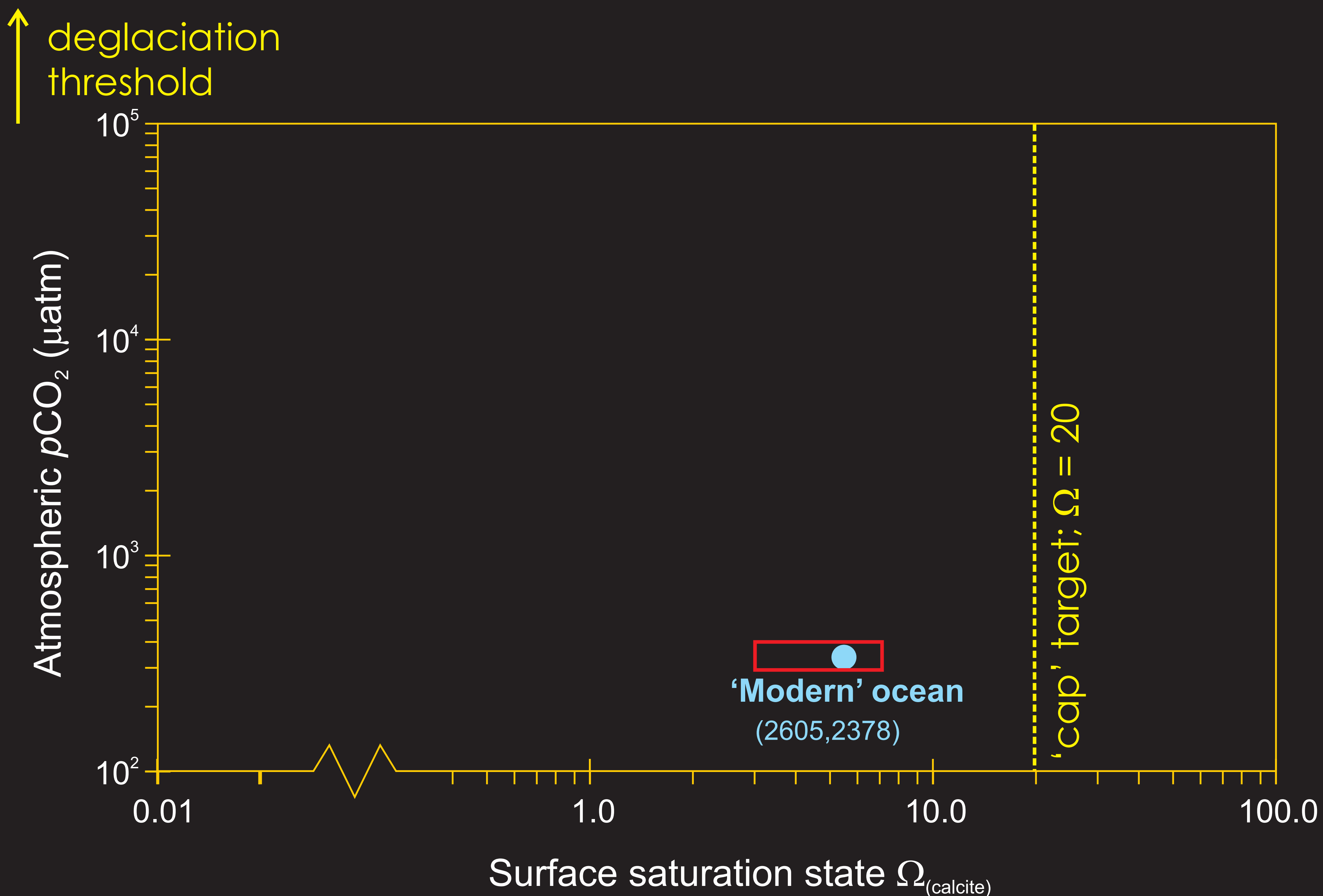


The enigma of the 'cap carbonates'



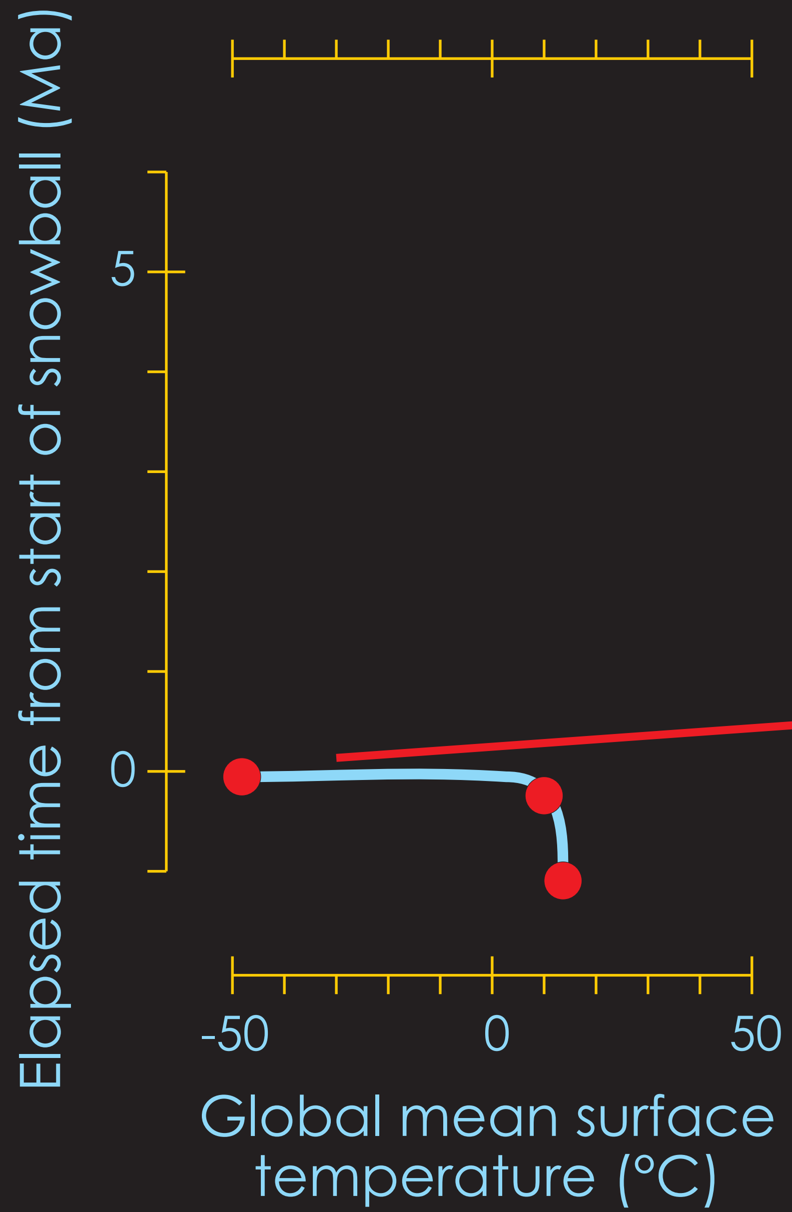
NOTE: ocean composition format;
[mean alkalinity, mean DIC] (μmol kg^{-1})

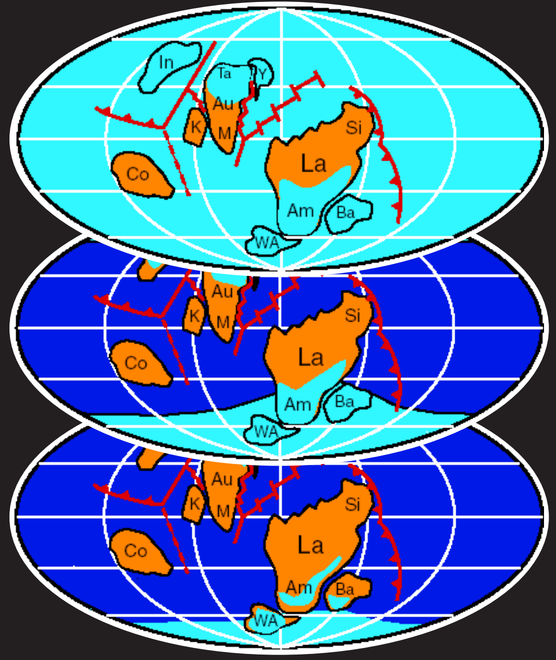
The enigma of the 'cap carbonates'



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

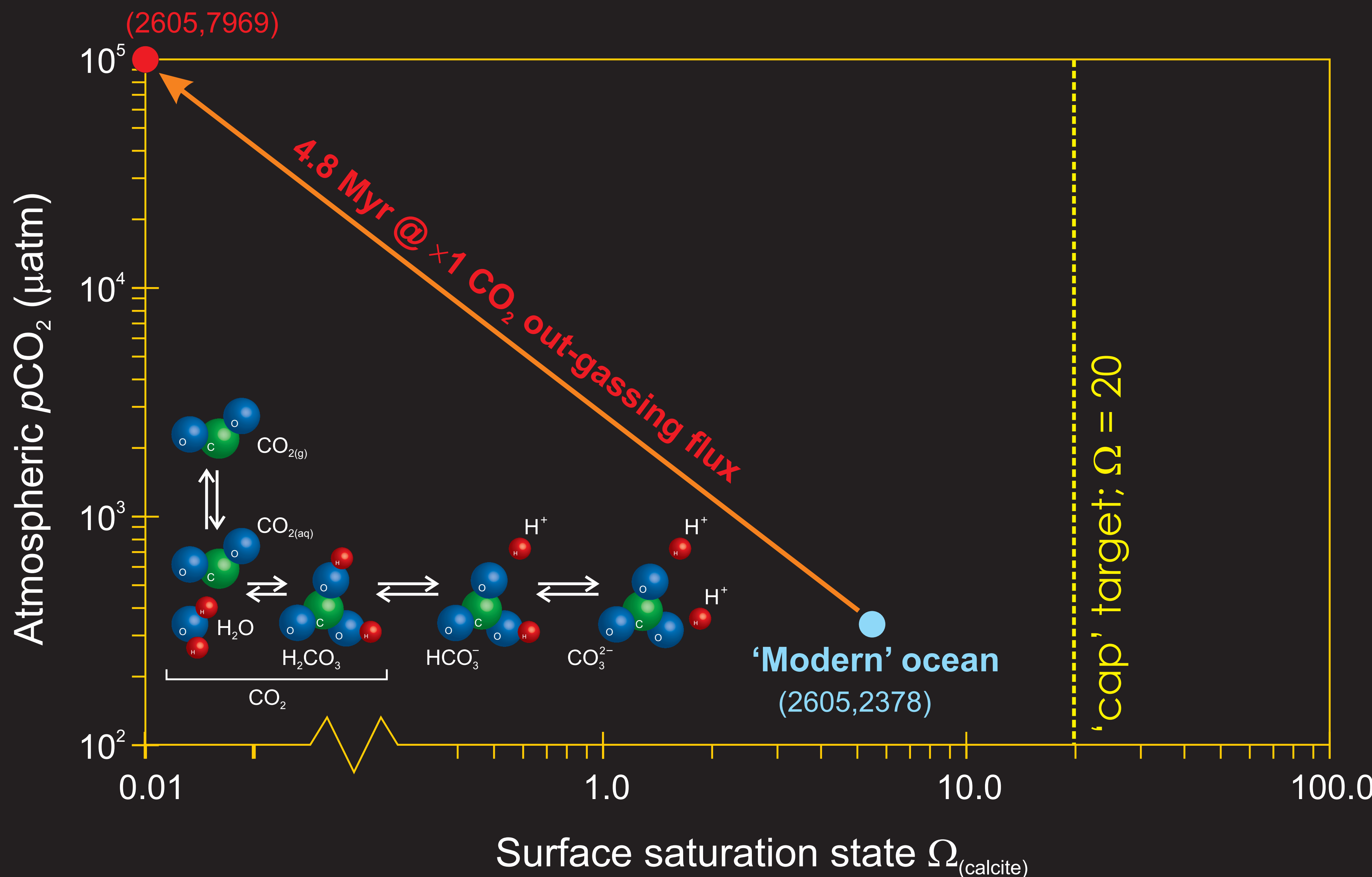
The enigma of the 'cap carbonates'





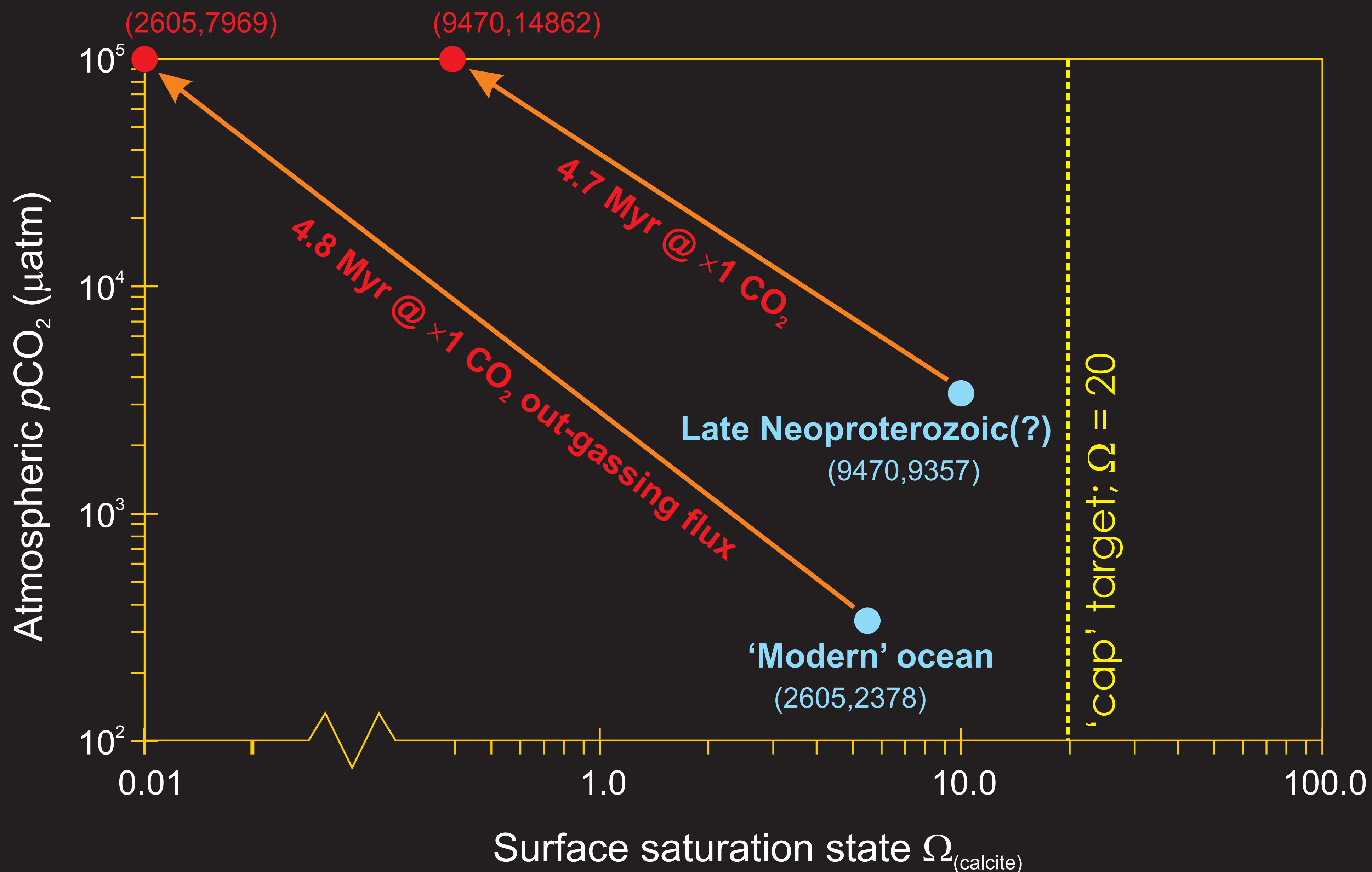
adapted from; *Hoffman and Schrag* [2002]

The enigma of the 'cap carbonates'



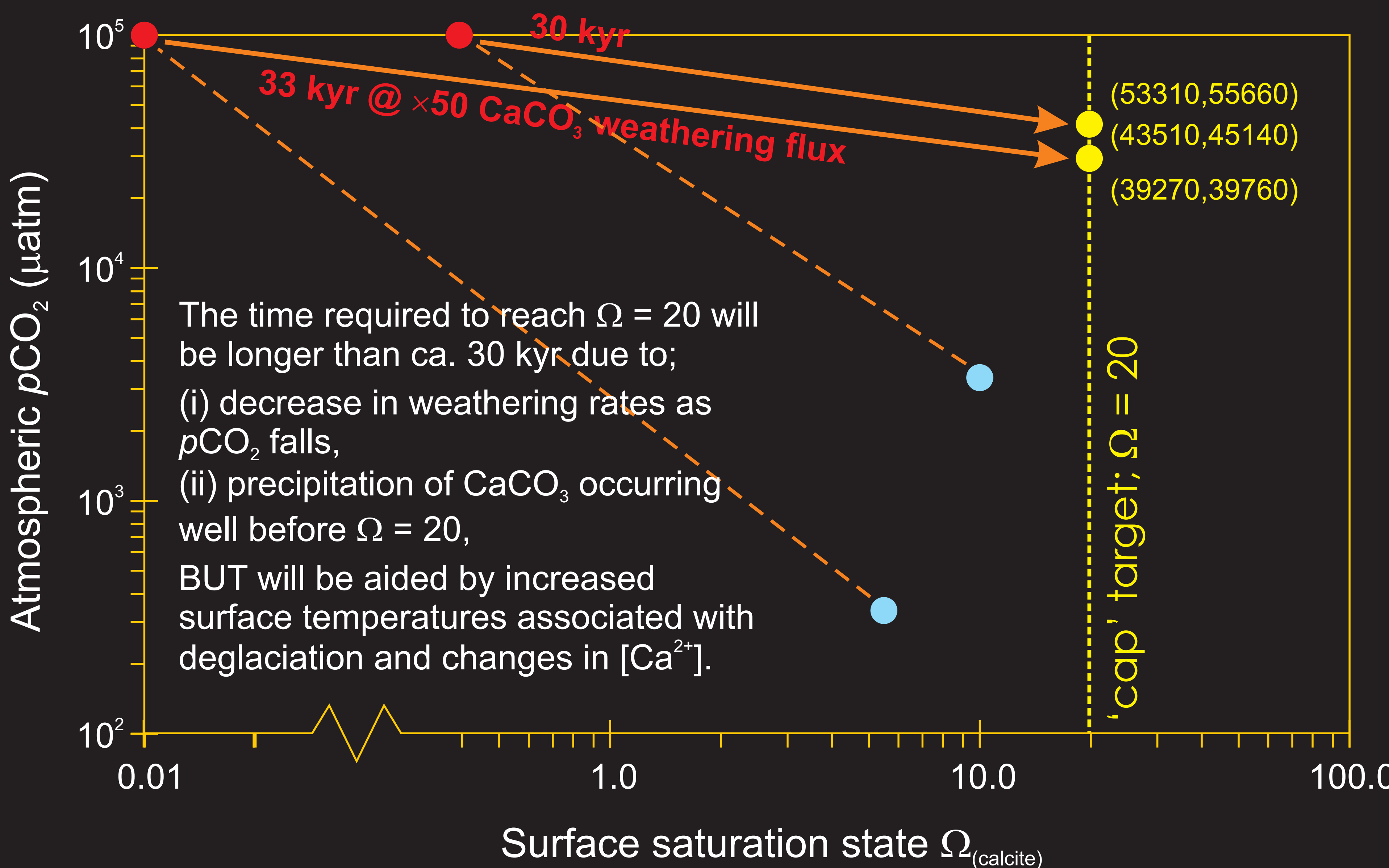
NOTE: ocean composition format;
[mean alkalinity, mean DIC] (μmol kg^{-1})

The enigma of the 'cap carbonates'



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

The enigma of the 'cap carbonates'



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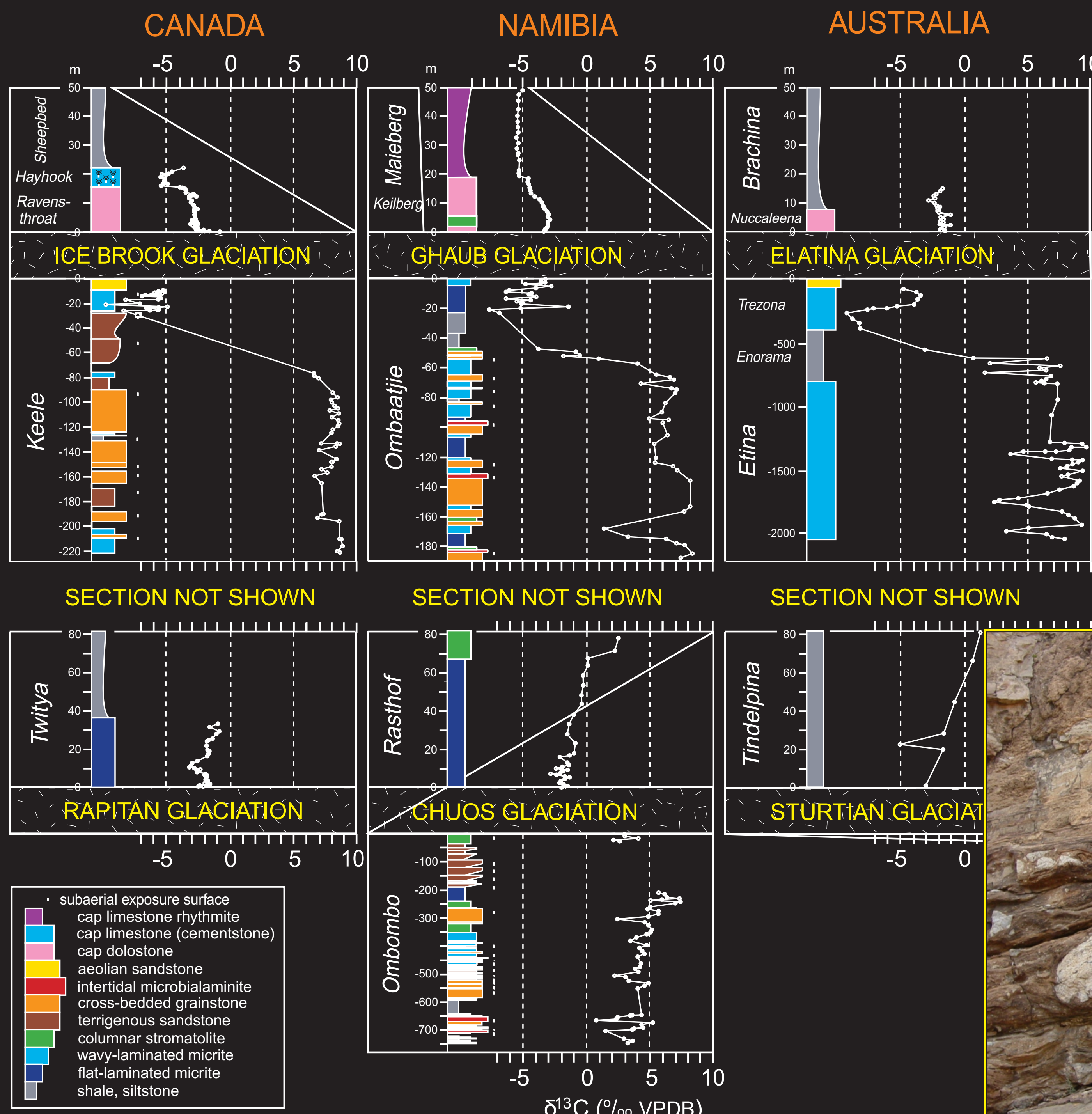
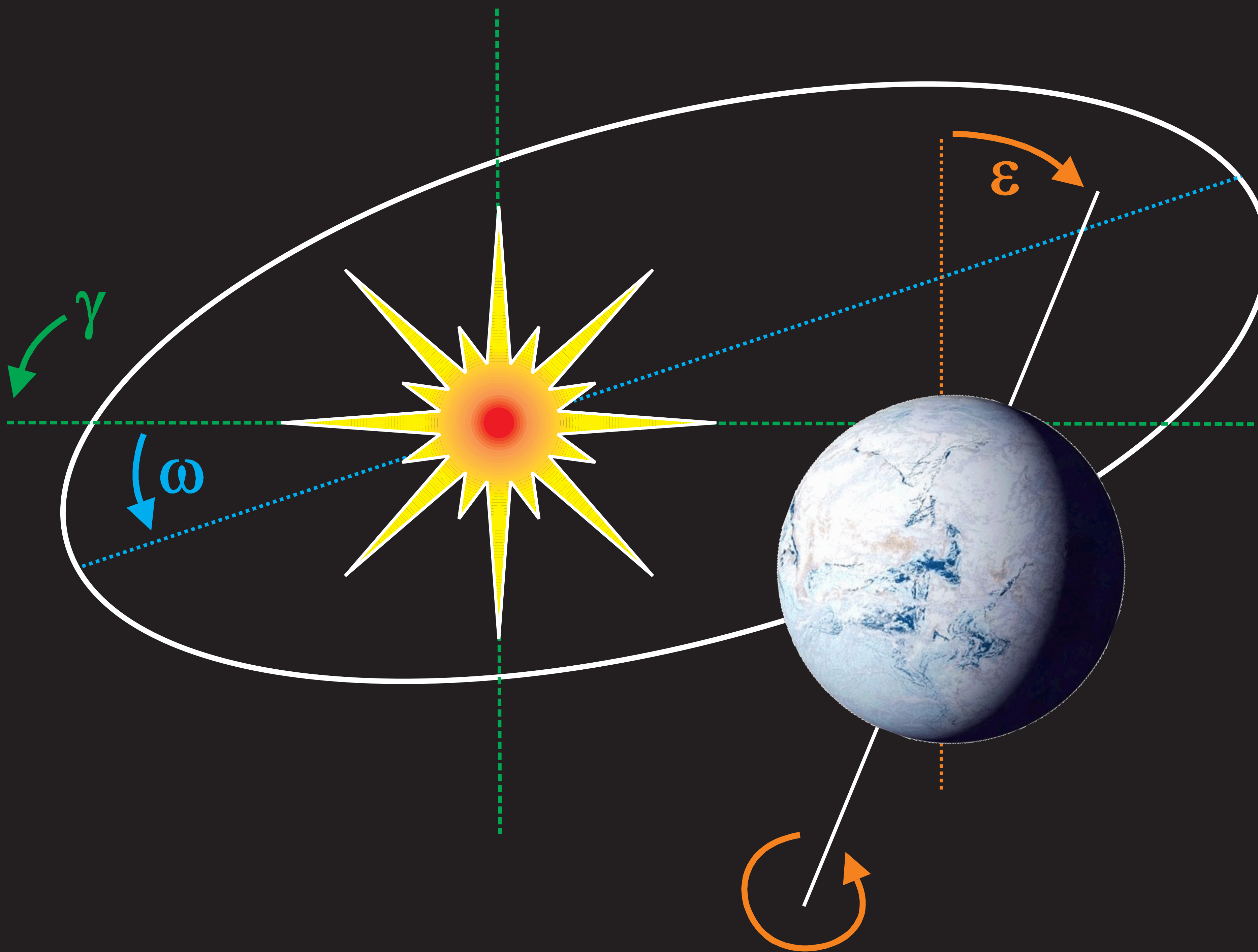
[mean alkalinity, mean DIC] (μmol kg^{-1})

The enigma of the 'cap carbonates'



From: *Hoffman and Schrag* [2002]



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