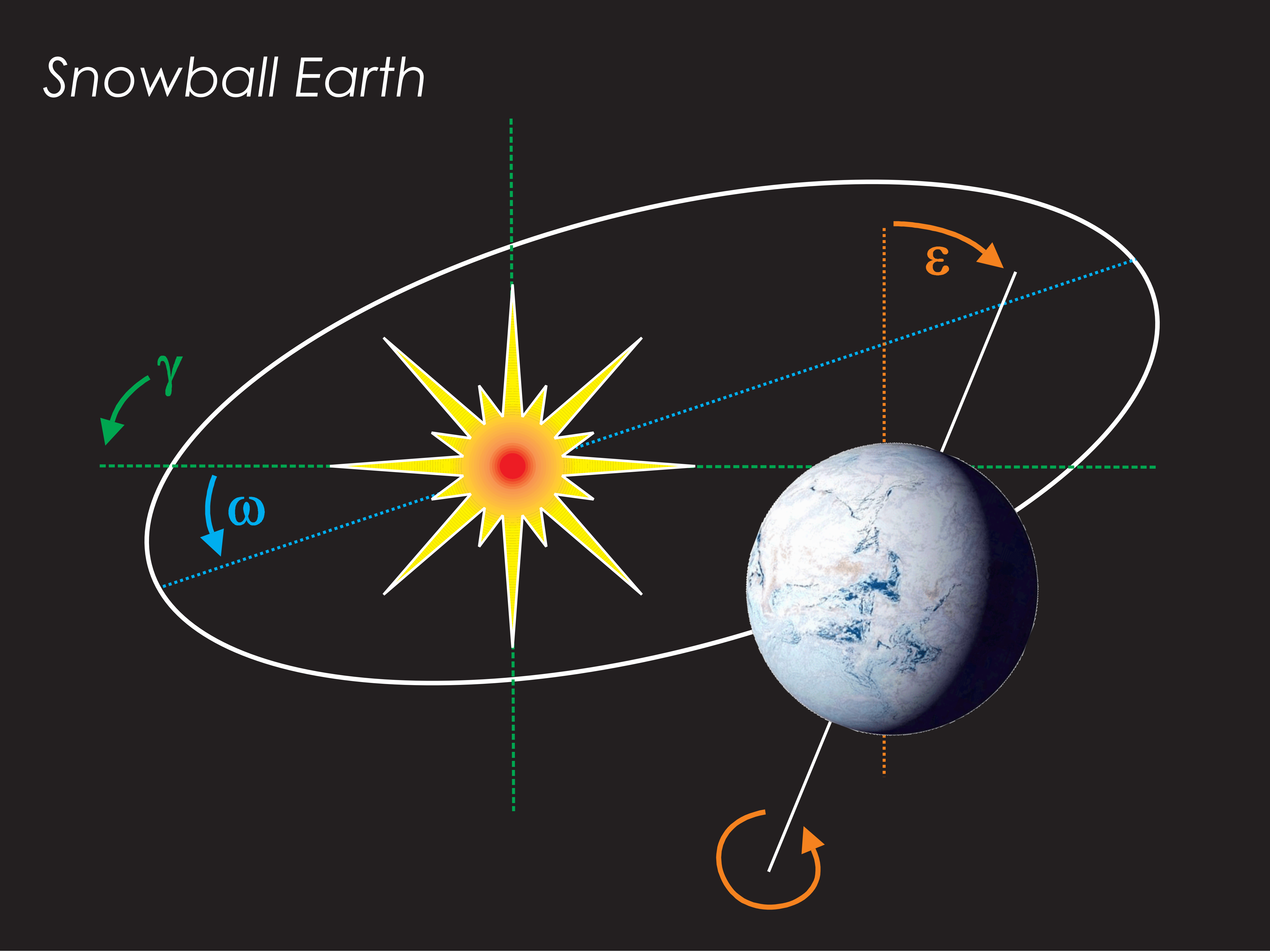
Snowball Earth
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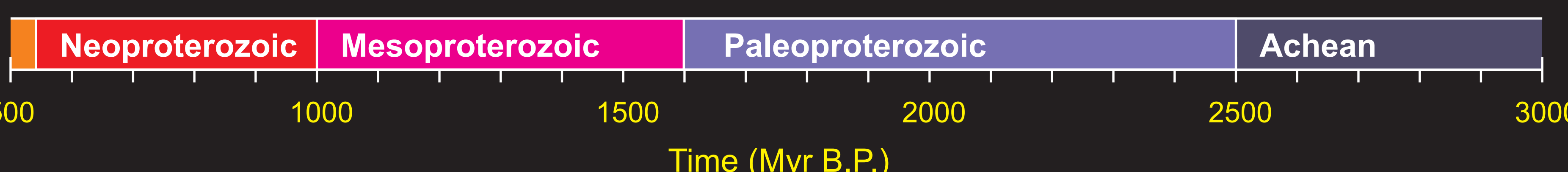
The Neoproterozoic: Gateway to a metazoan-dominated, oxygenated, 'modern-like' biosphere?



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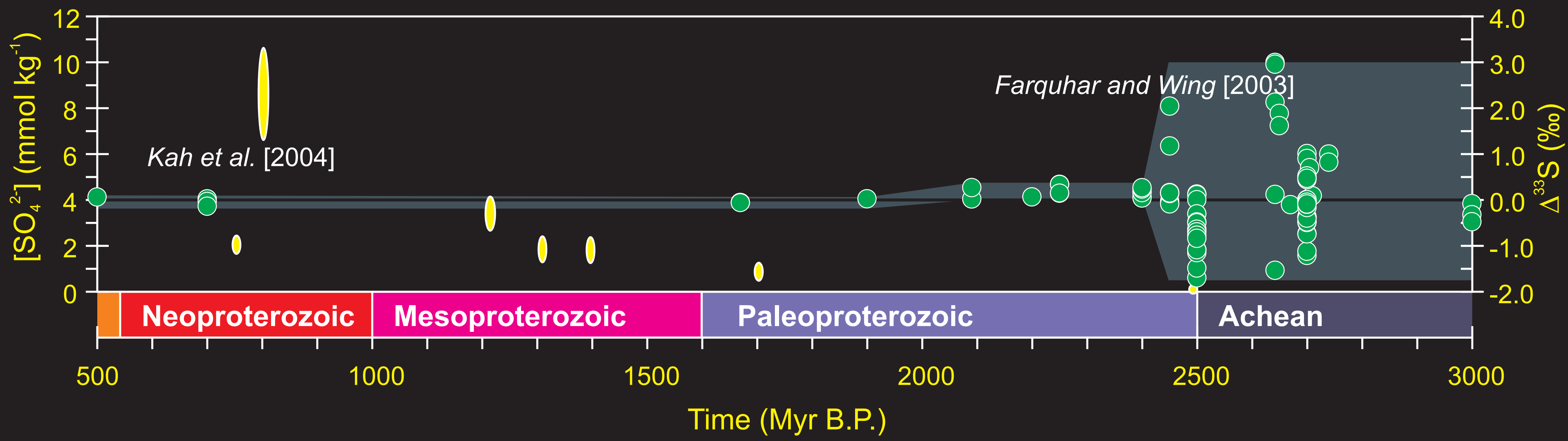

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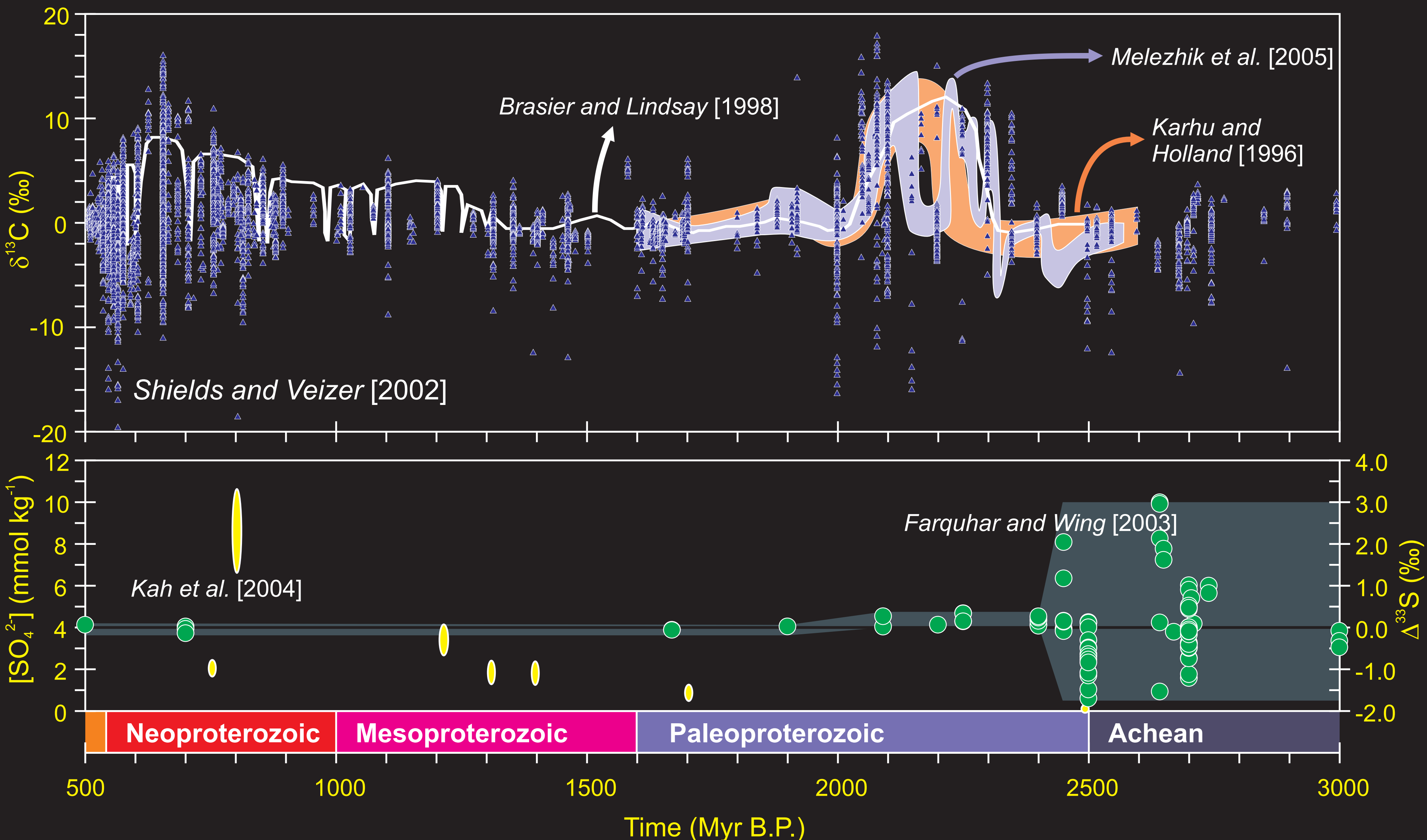

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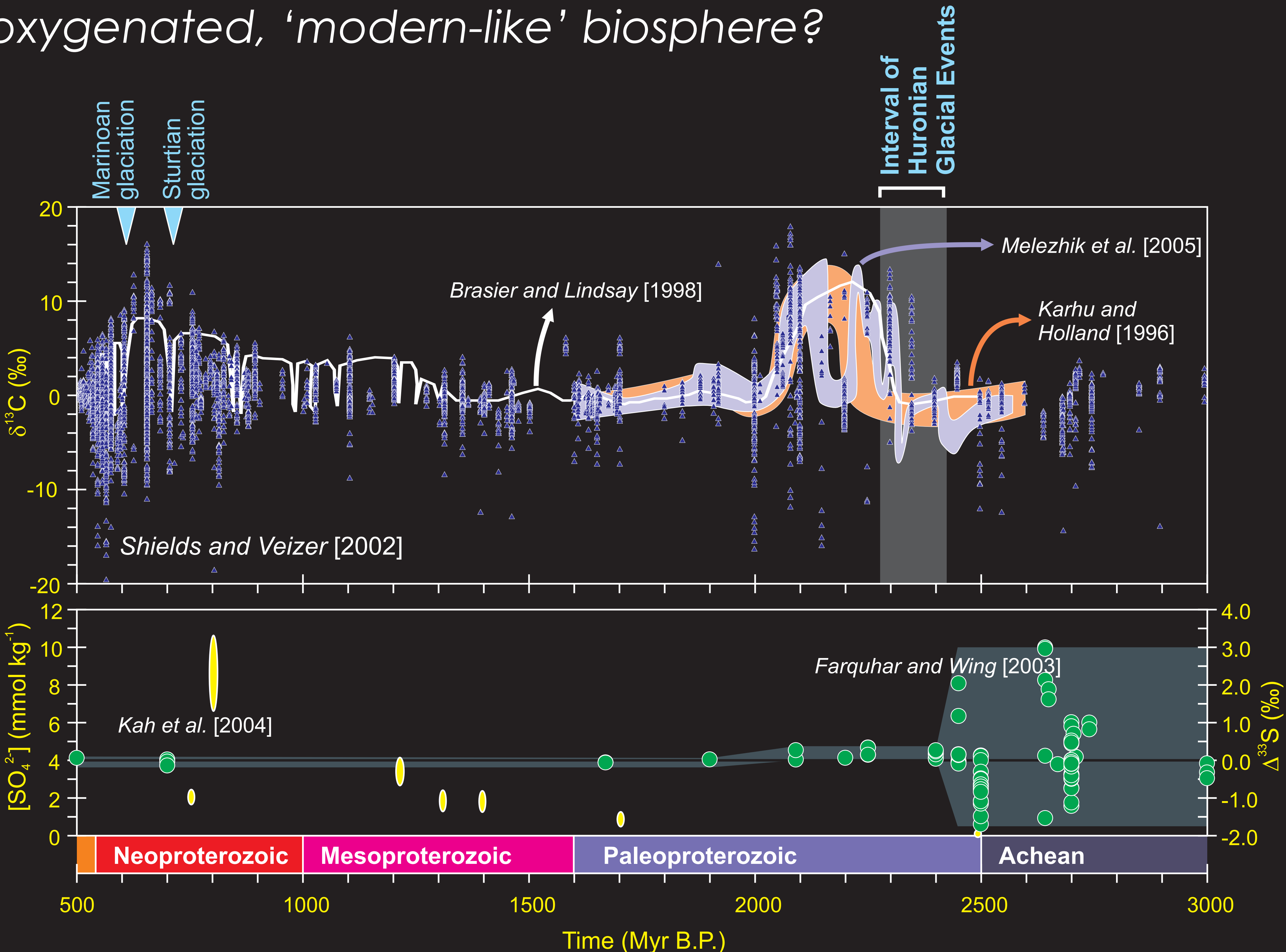
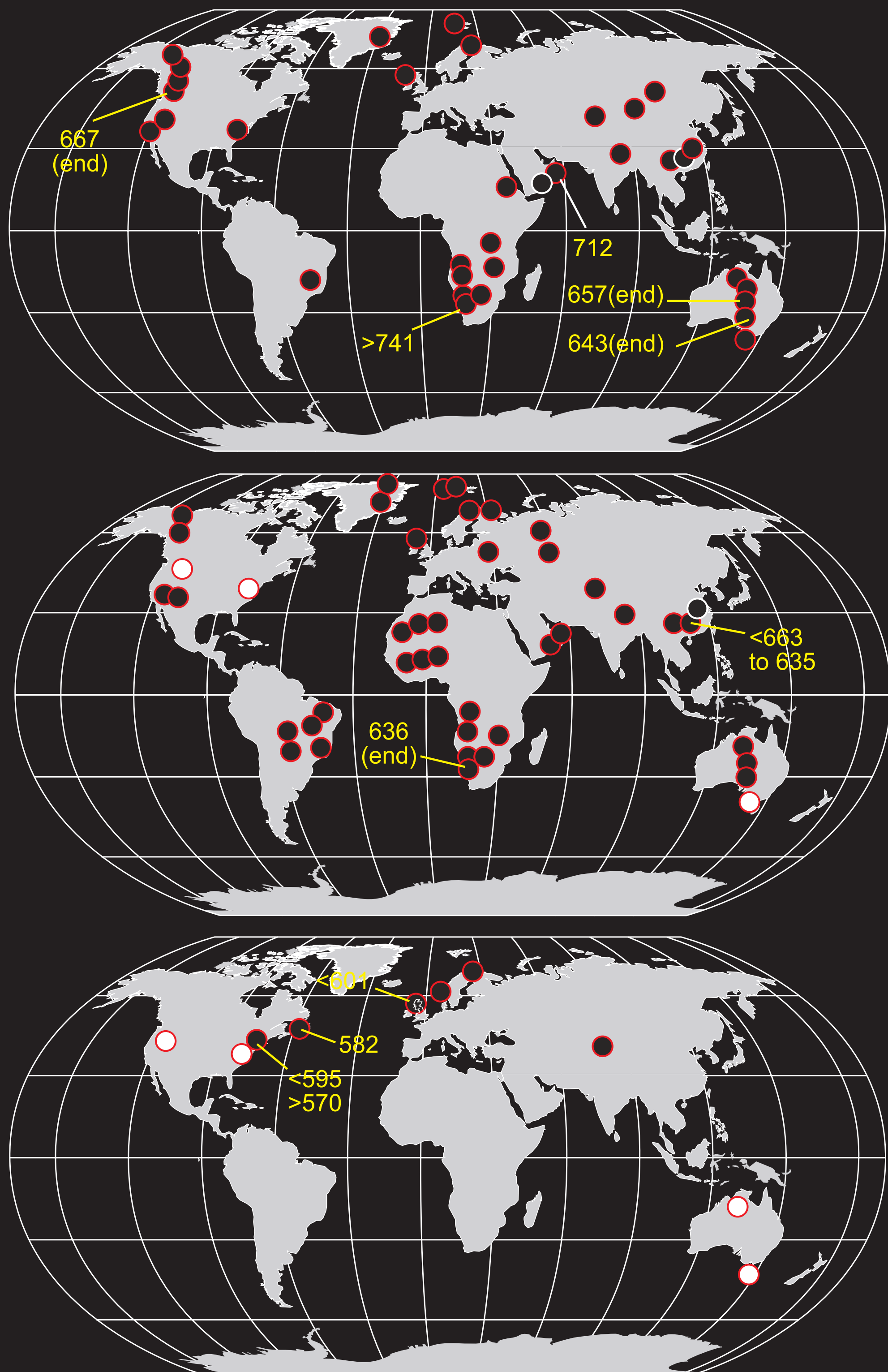


Evidence for glaciation



From: *Fairchild and Kennedy* [2007]

From: *Hoffman and Schrag* [2002]

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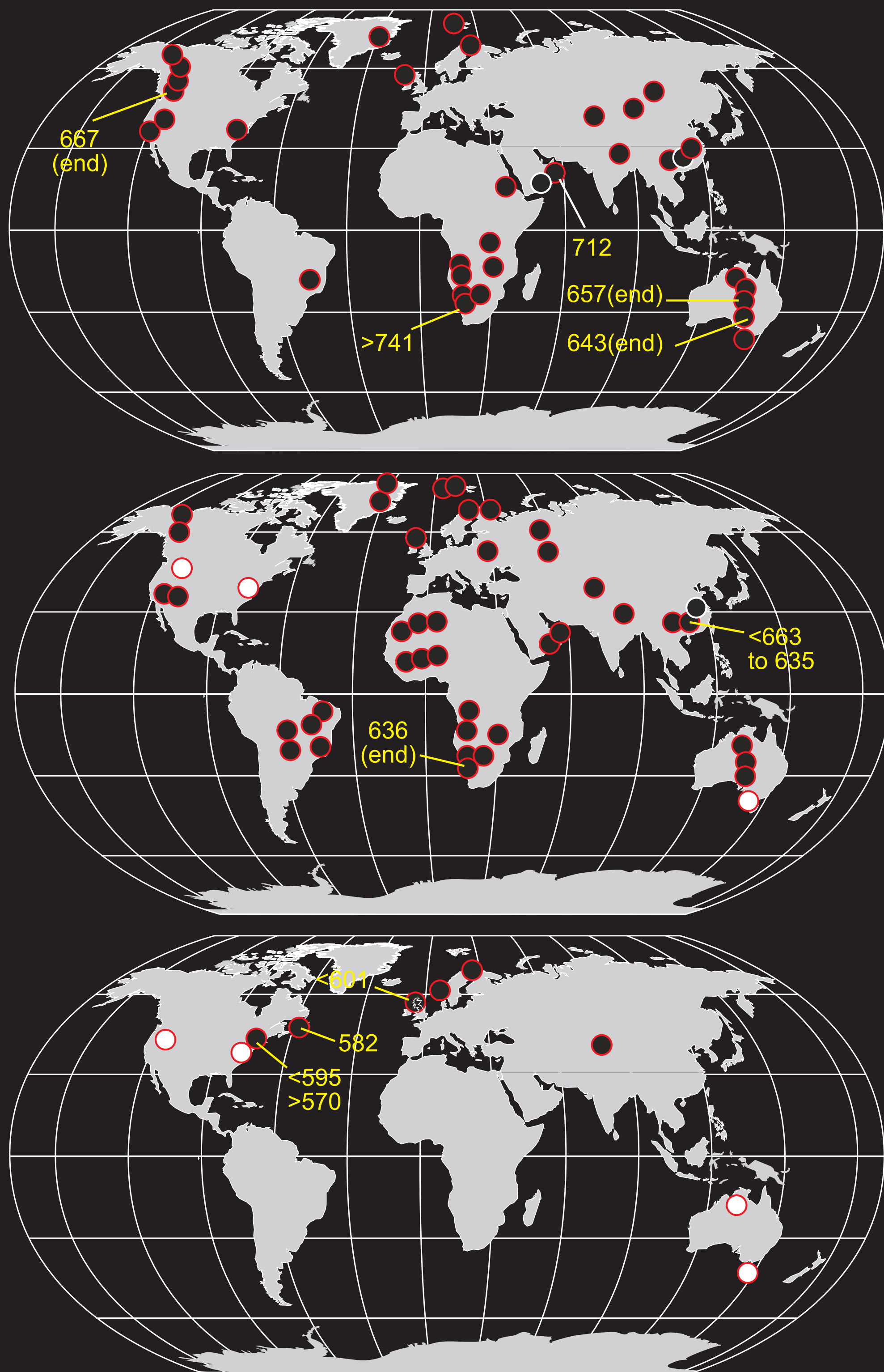

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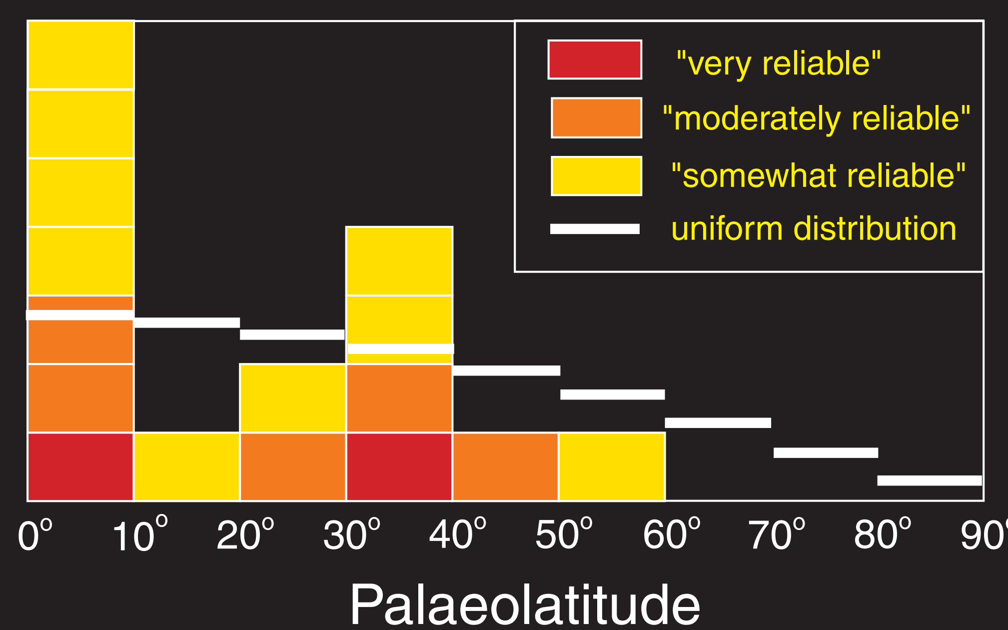

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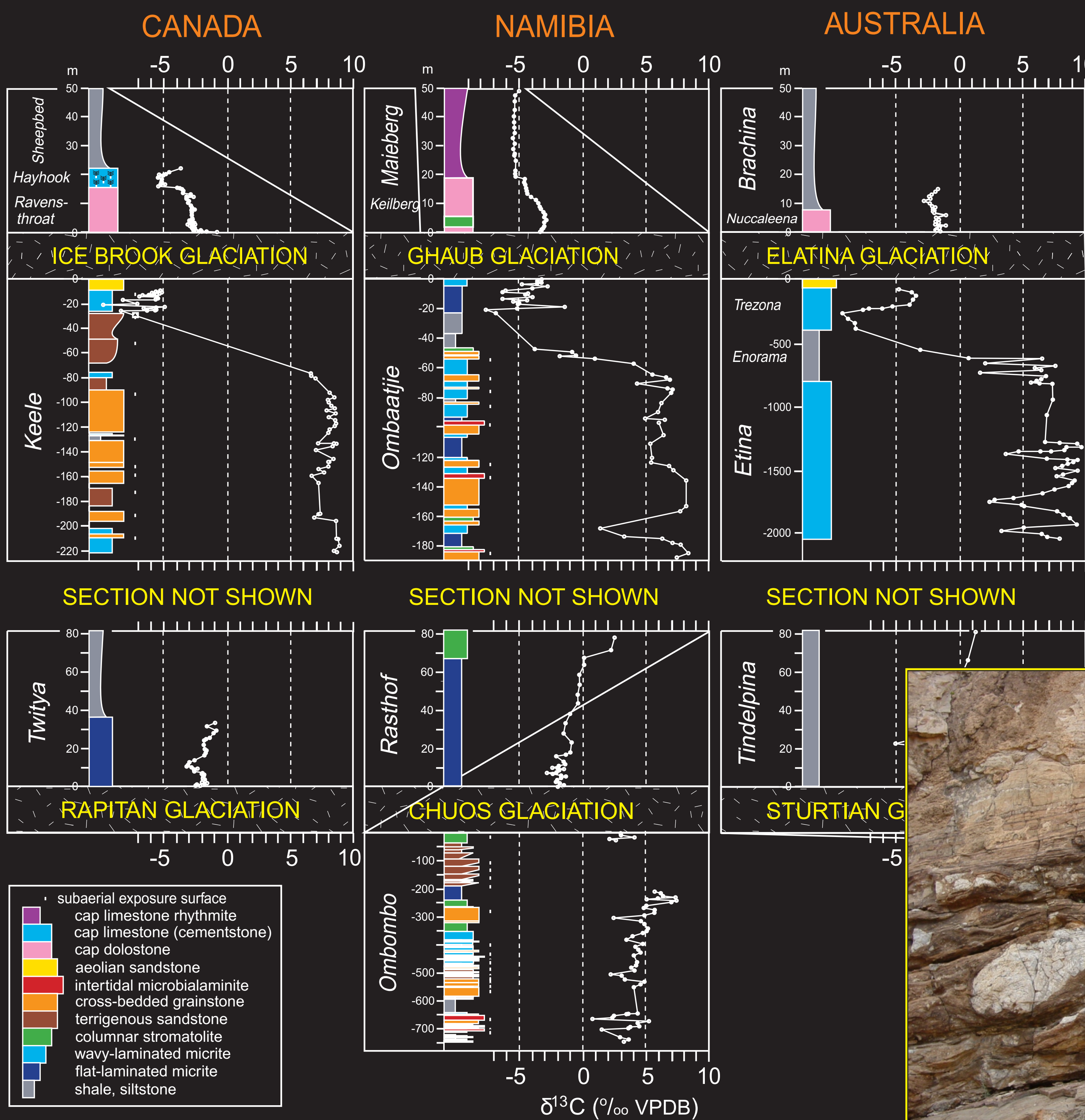
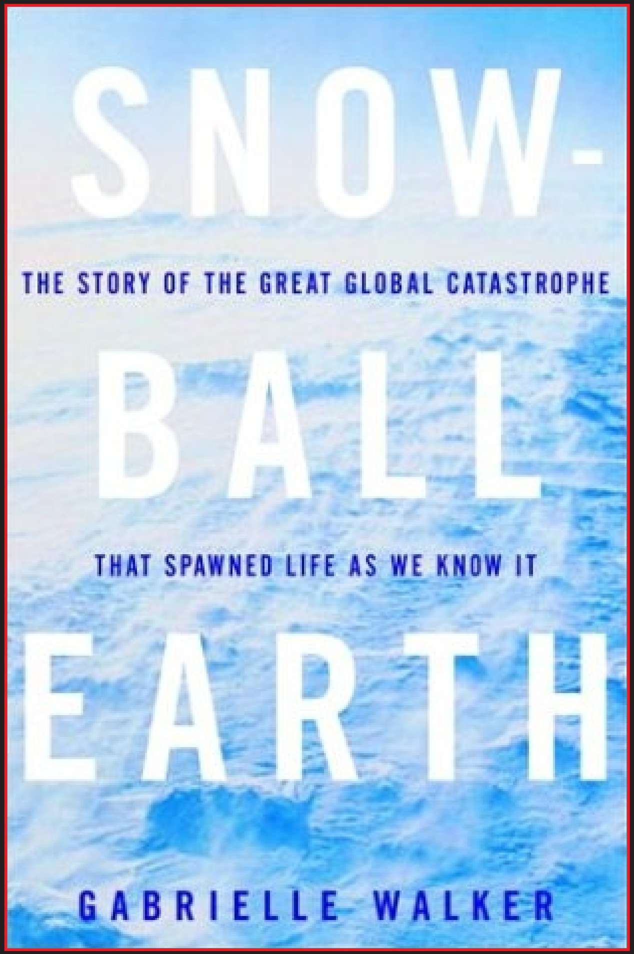


From: *Hoffman and Schrag* [2002]

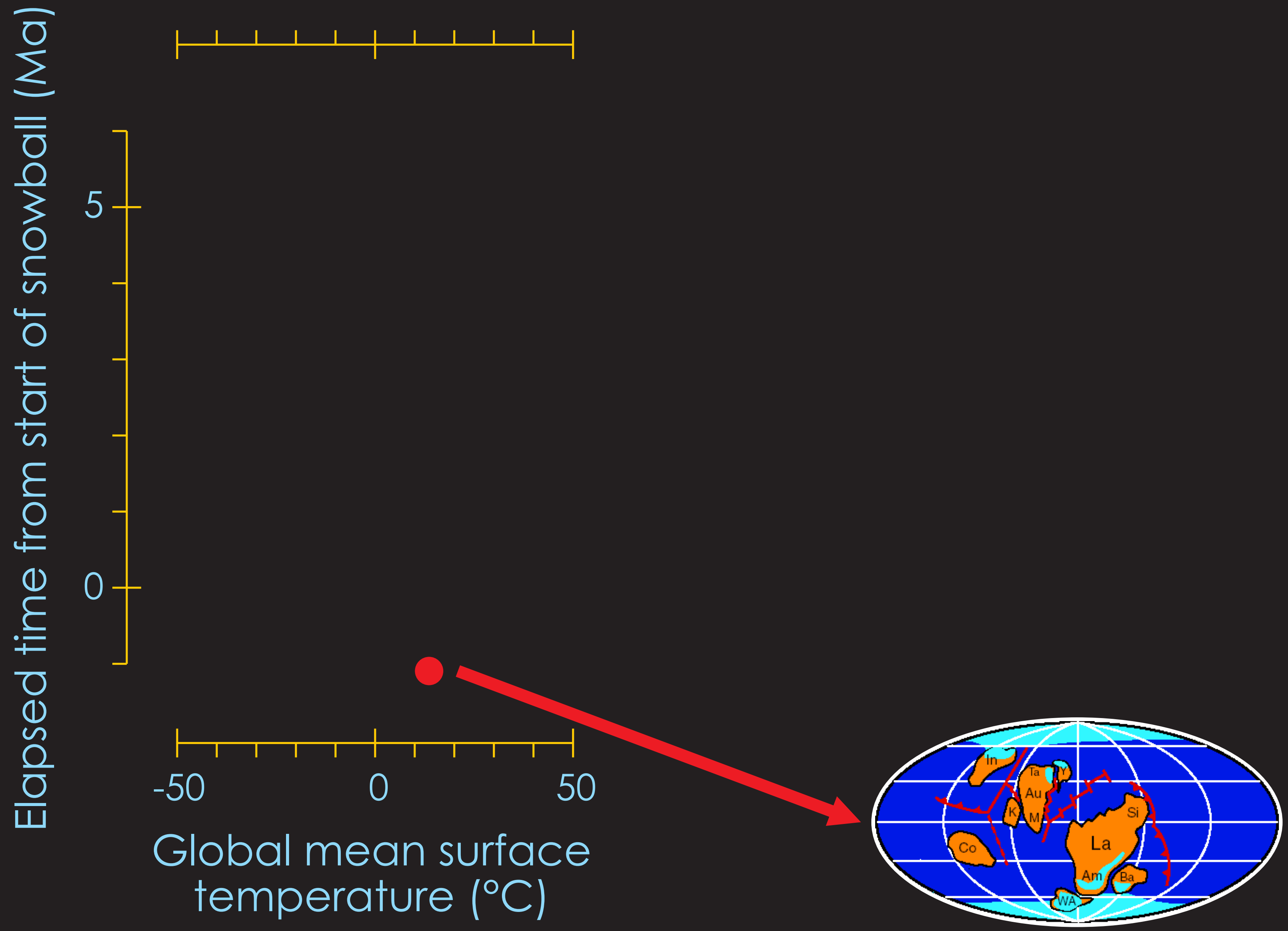
‘snowball Earth’

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

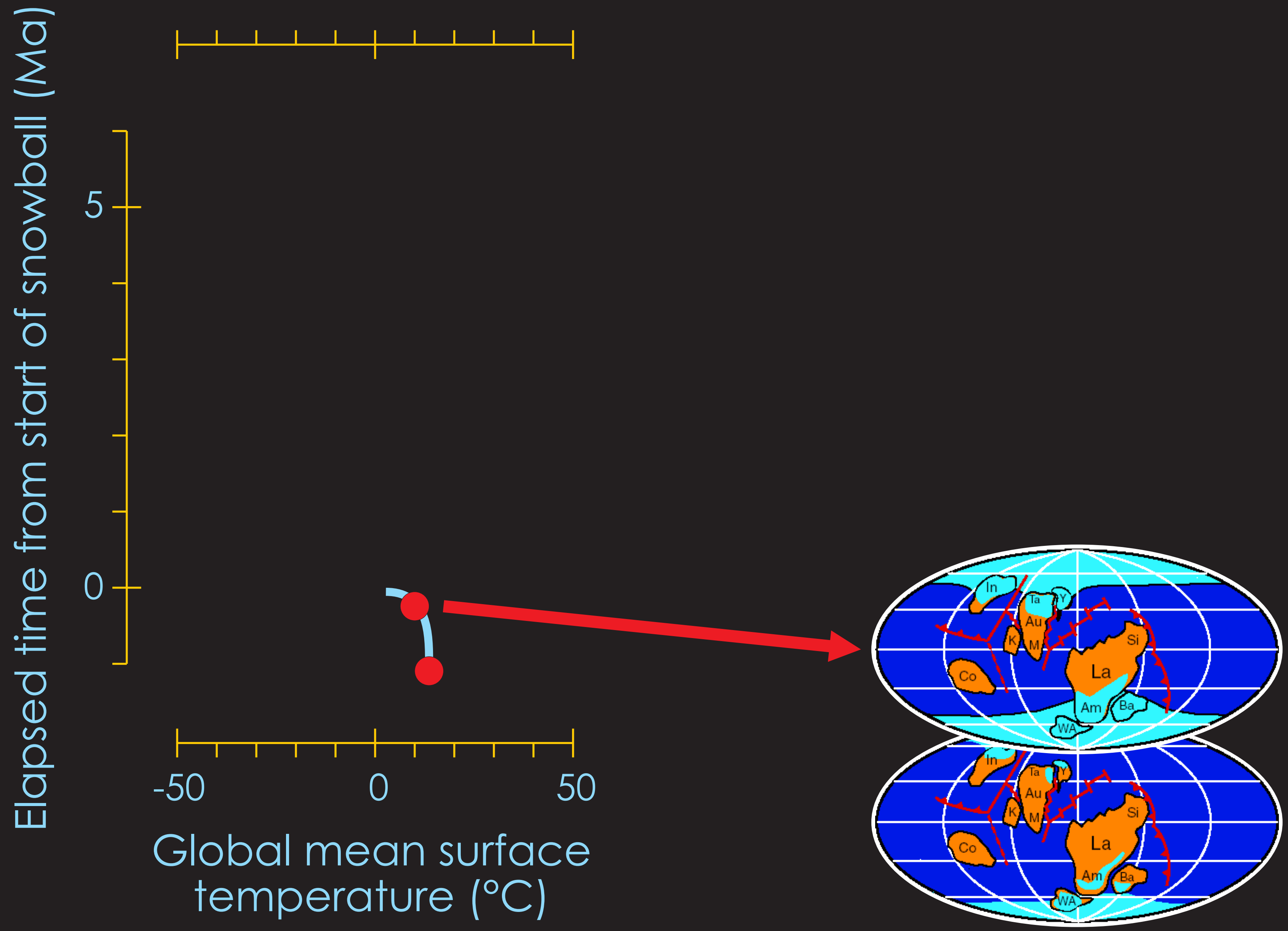


The snowball Earth hypothesis

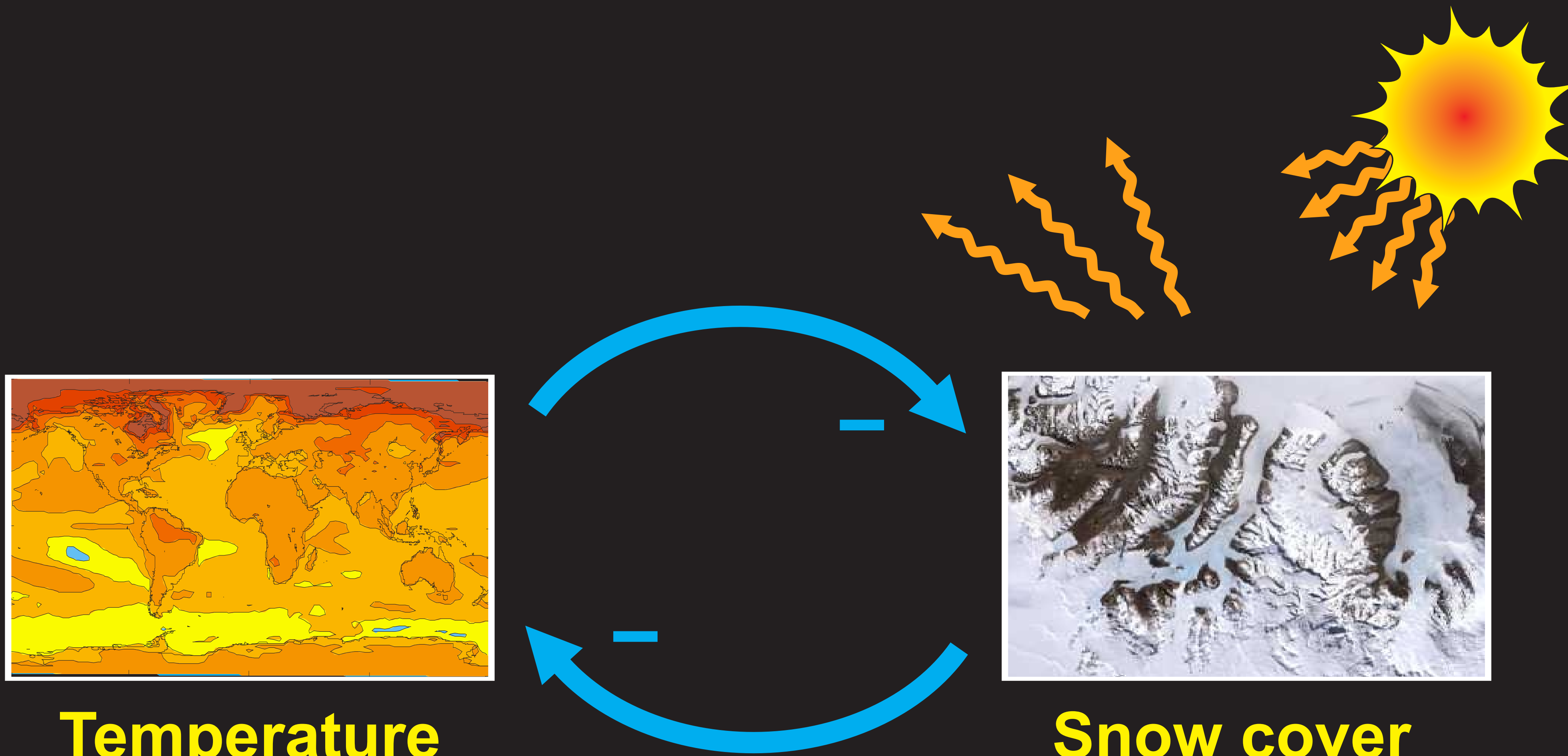
*[Hoffman and Schrag, 2002] (Terra Nova **14**, 129-155)*



The snowball Earth hypothesis



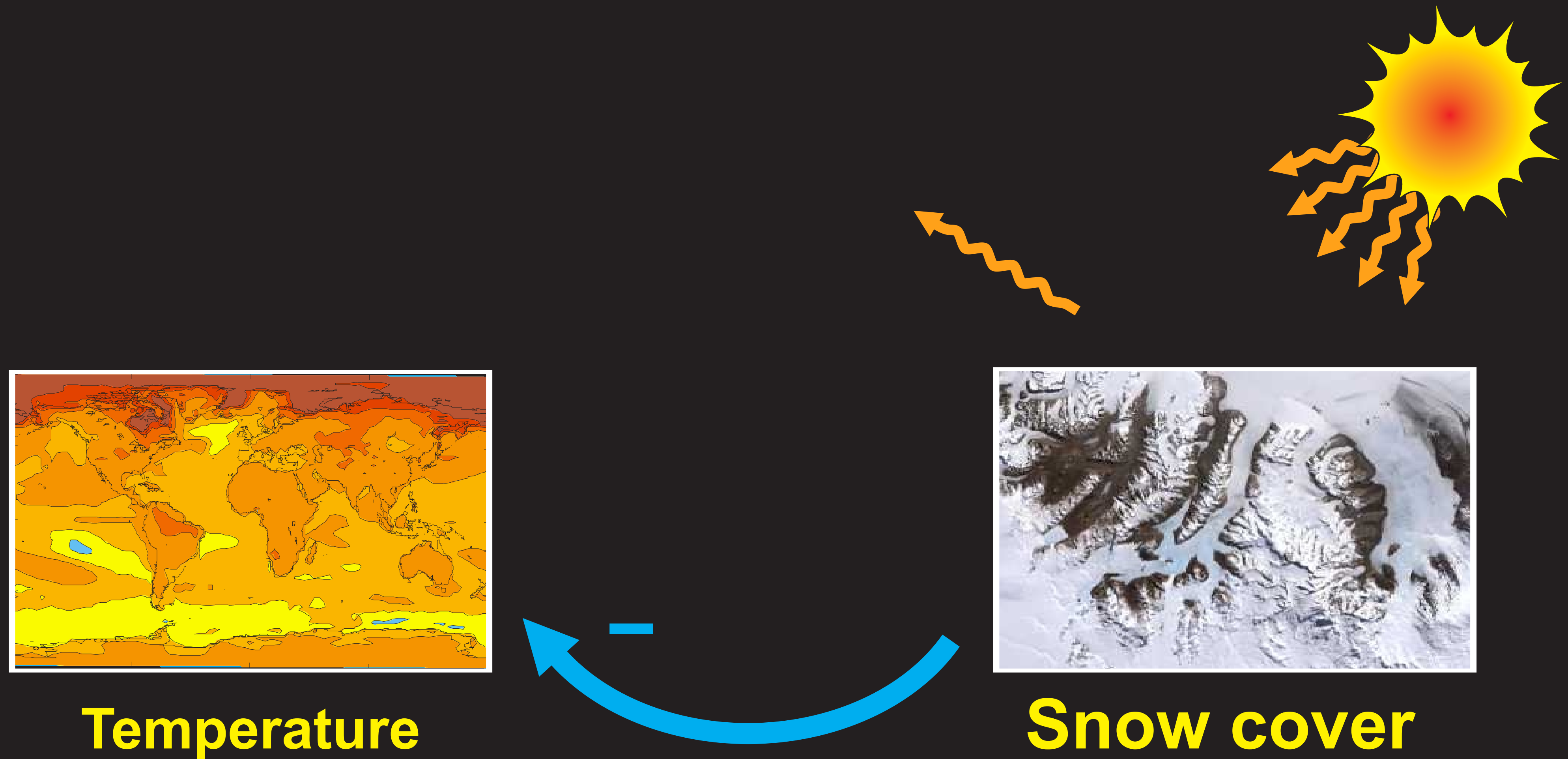
‘Feedbacks’



Temperature **Snow cover**

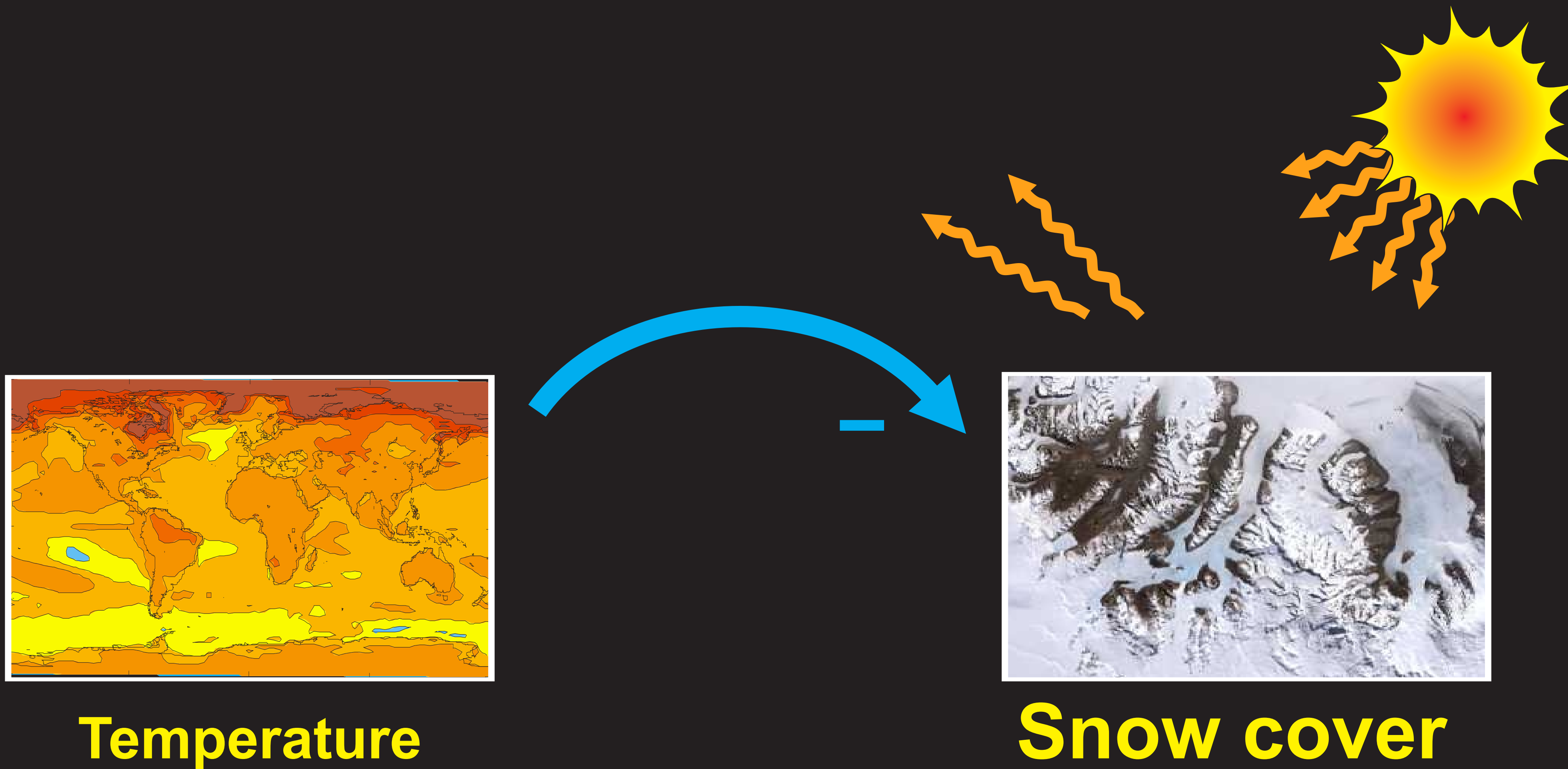
positive “ice-albedo” feedback

‘Feedbacks’



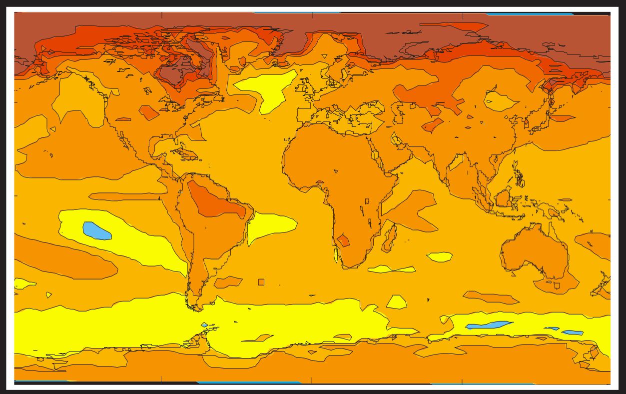
= −1/2°C

‘Feedbacks’



TOTAL CHANGE = $-1/2$°C

‘Feedbacks’



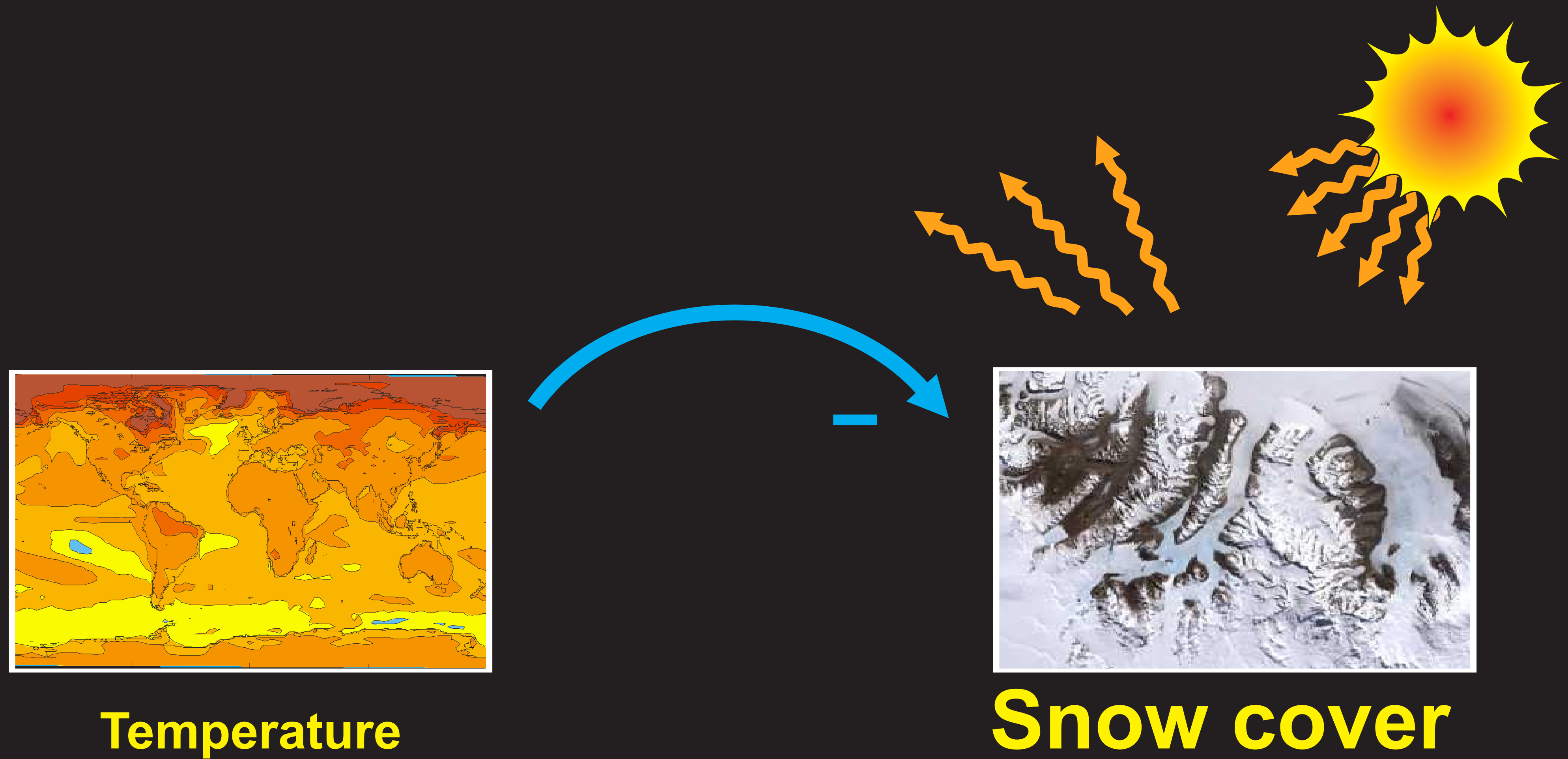
Temperature

–

Snow cover

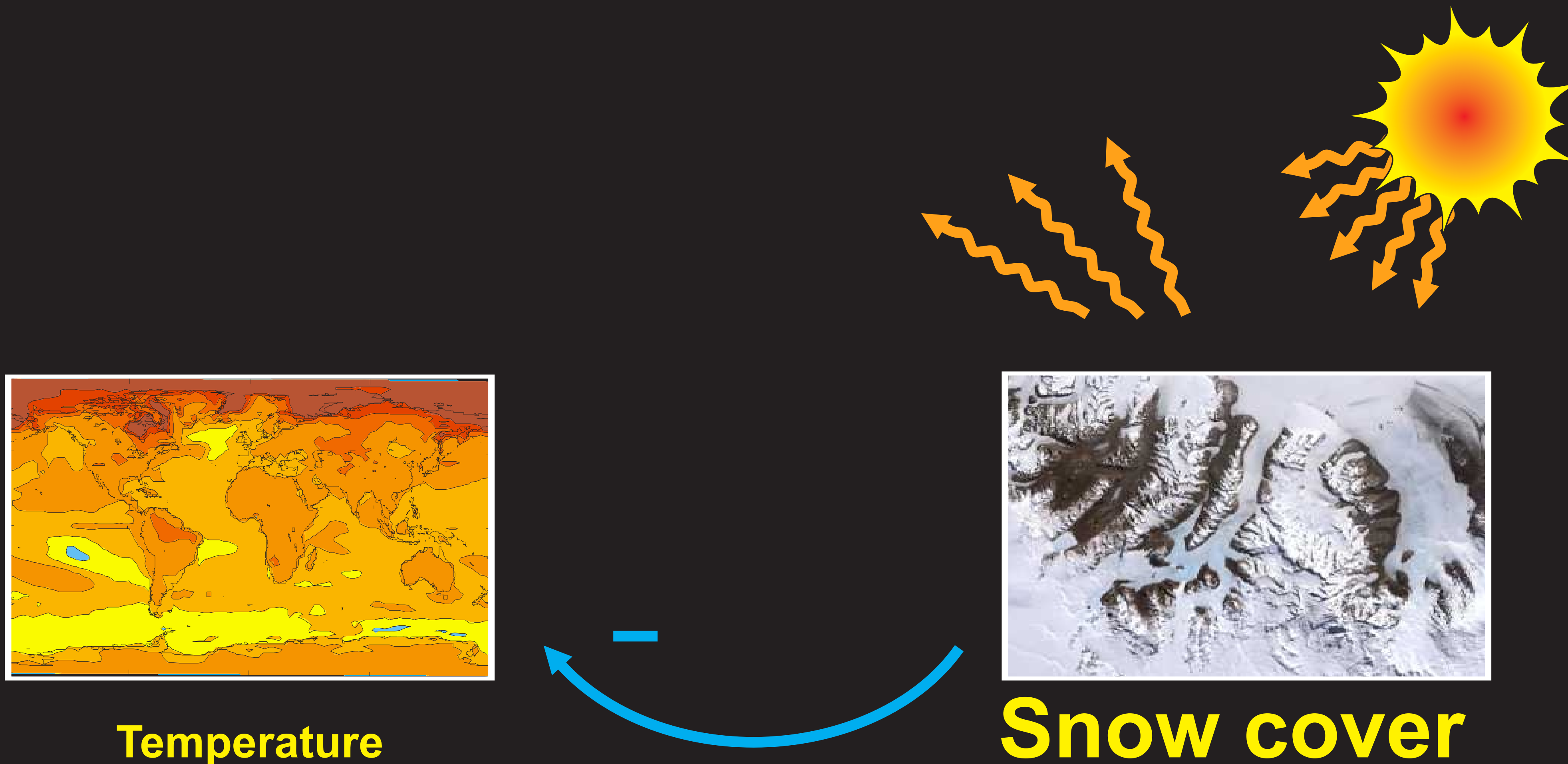
TOTAL CHANGE = -1/2°C - 1/4°C

‘Feedbacks’



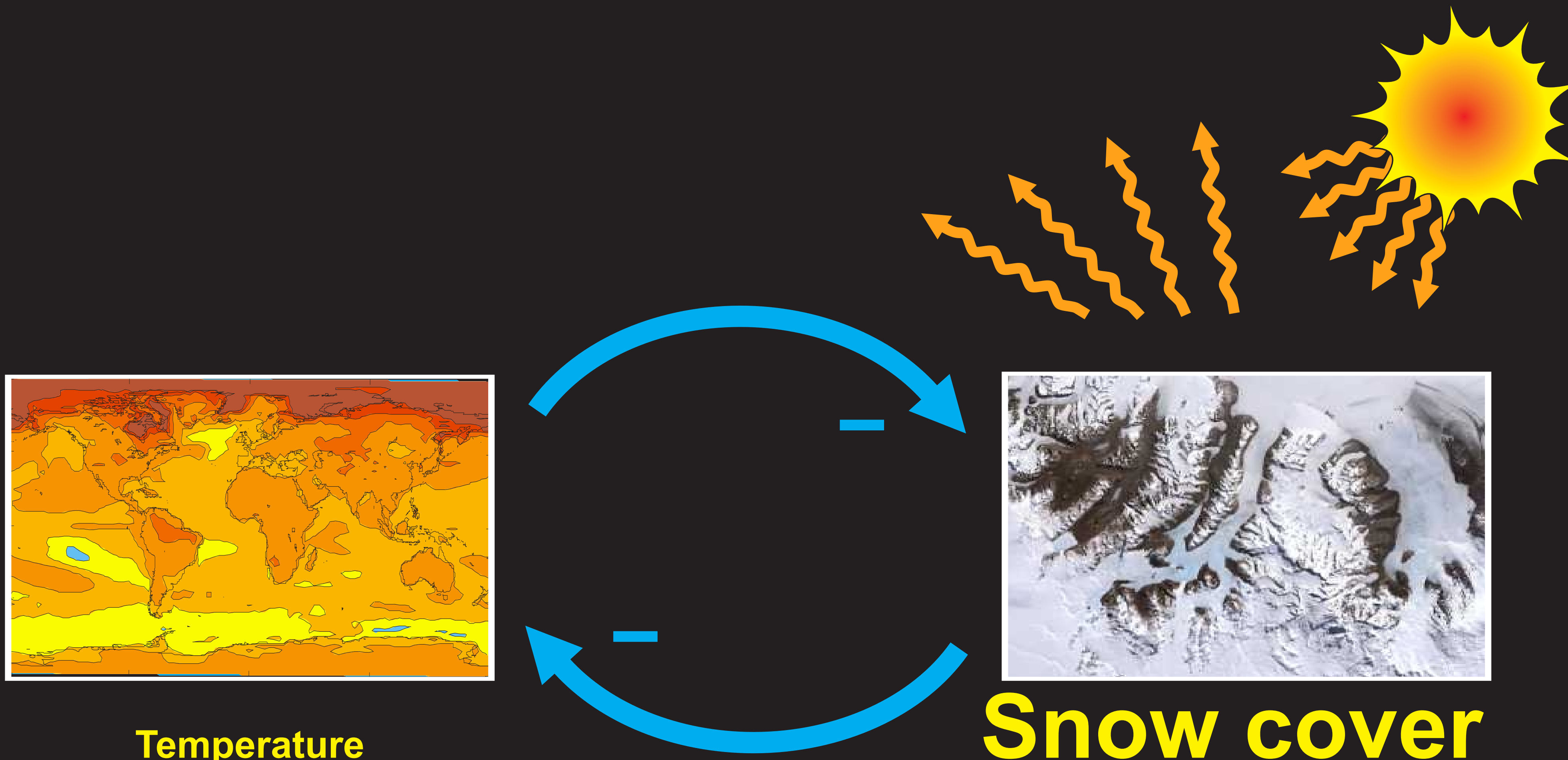
TOTAL CHANGE = -1/2°C - 1/4°C

‘Feedbacks’



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

'Feedbacks'

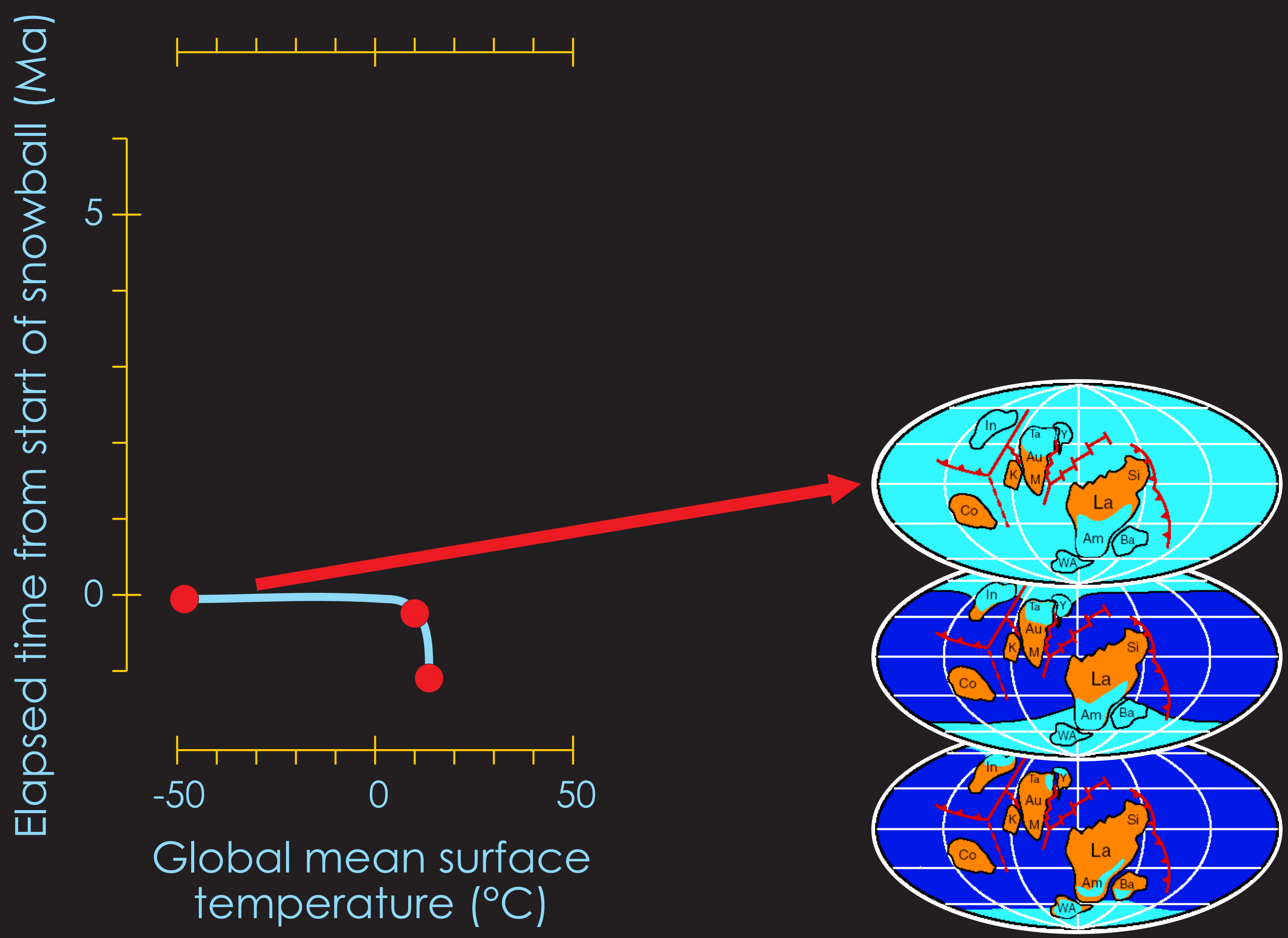


TOTAL CHANGE = -1/2°C - 1/4°C - 1/8°C - 1/16°
- ....

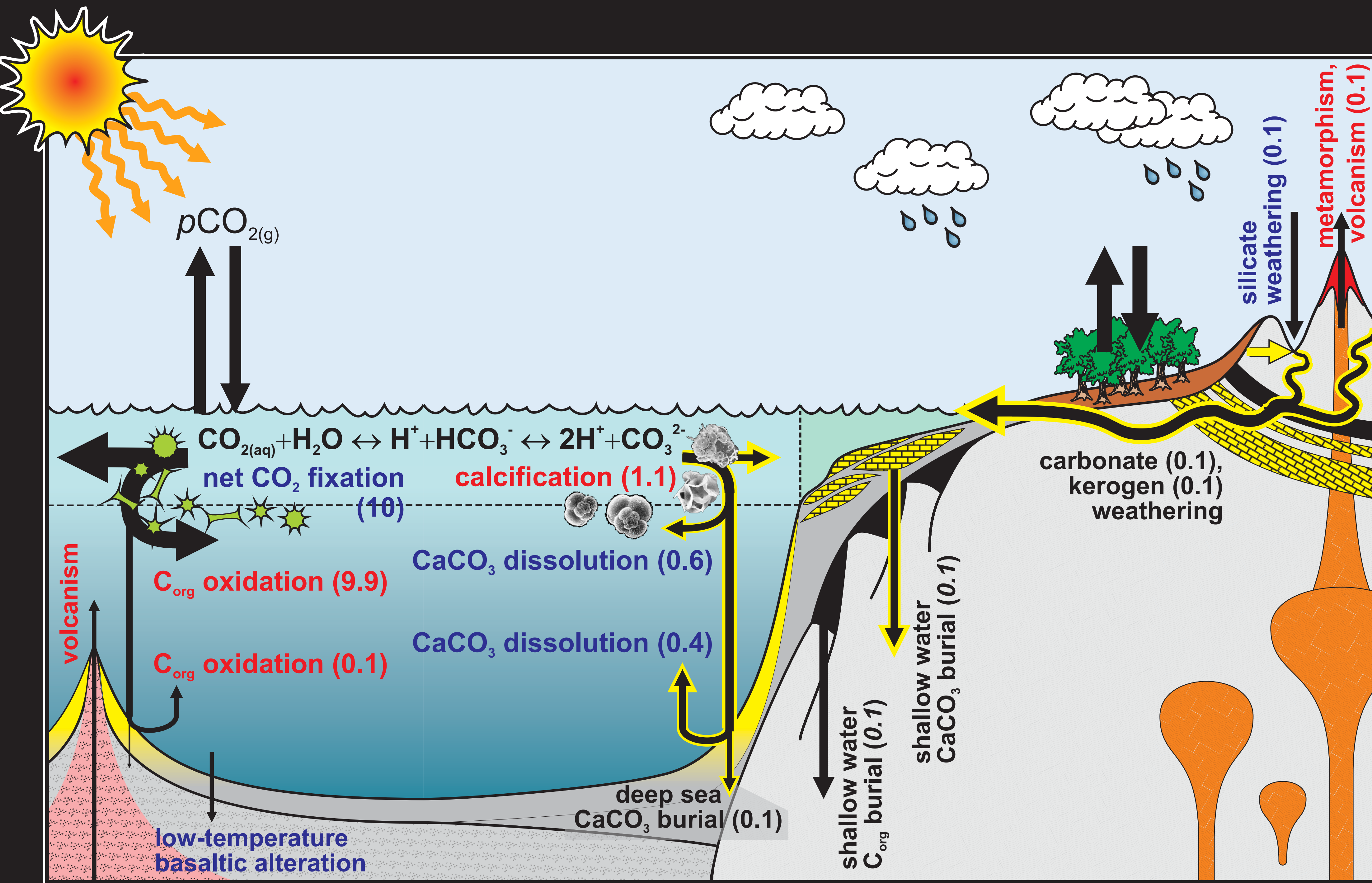
‘Feedbacks’ (’runaway’)

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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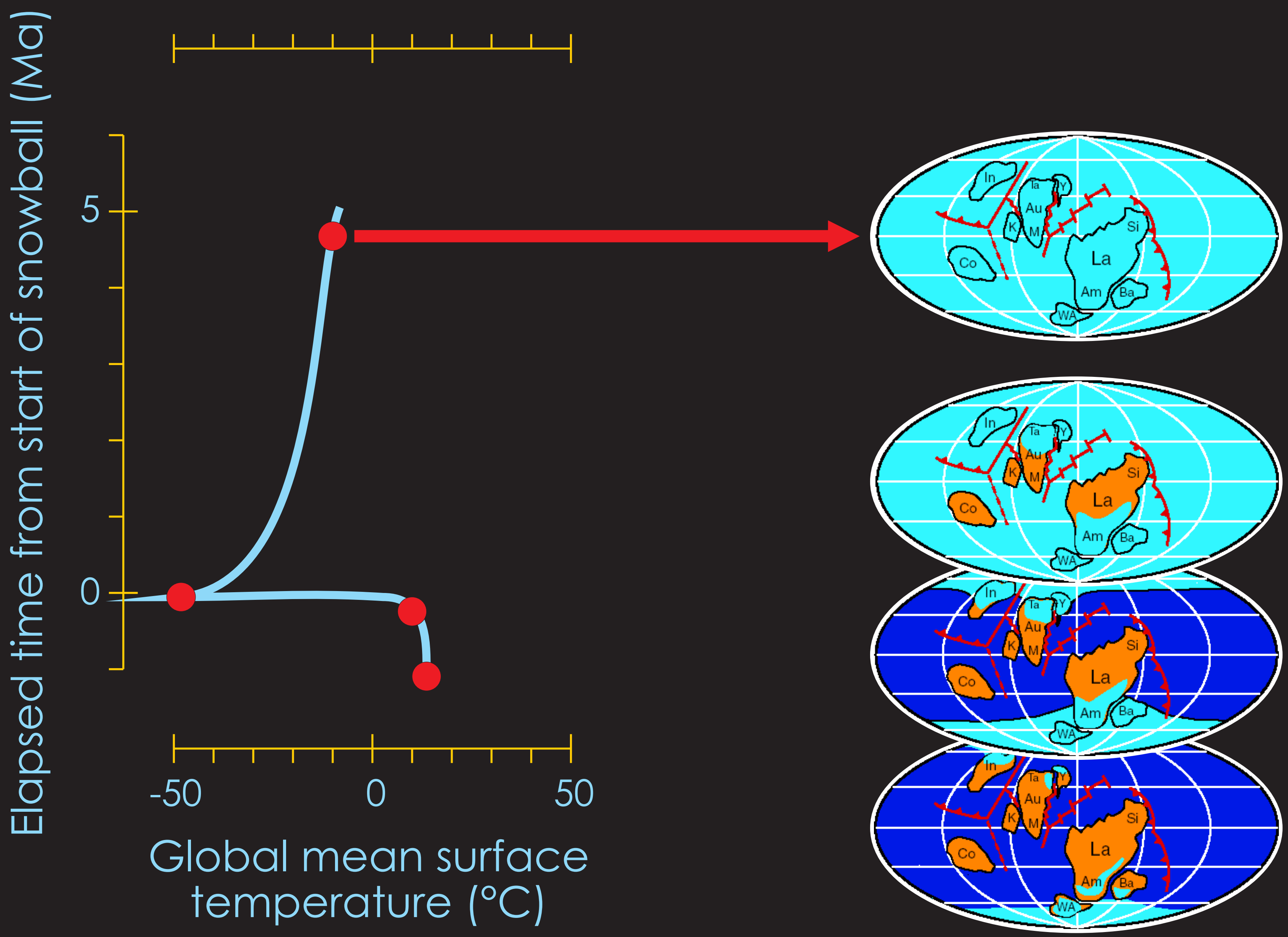

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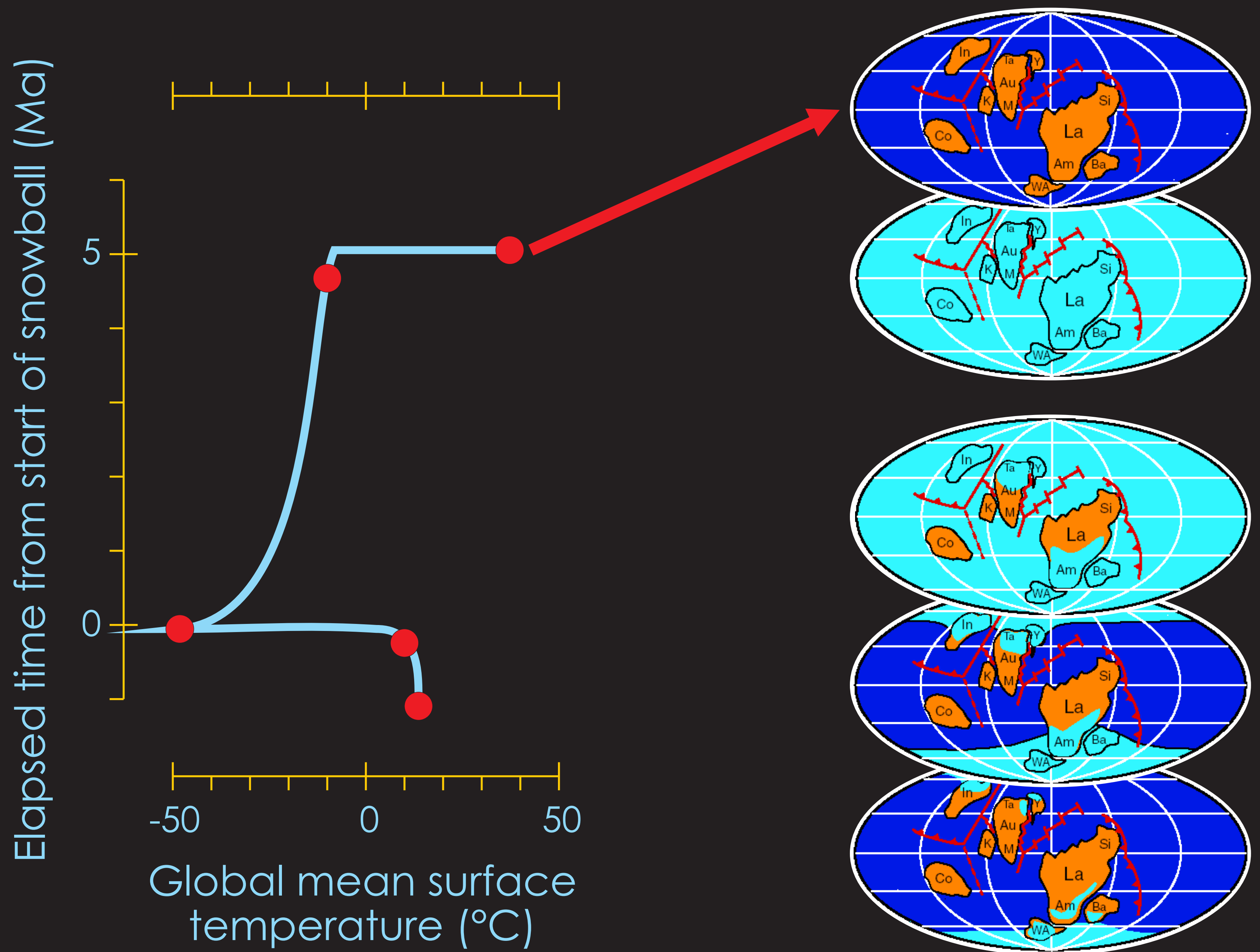

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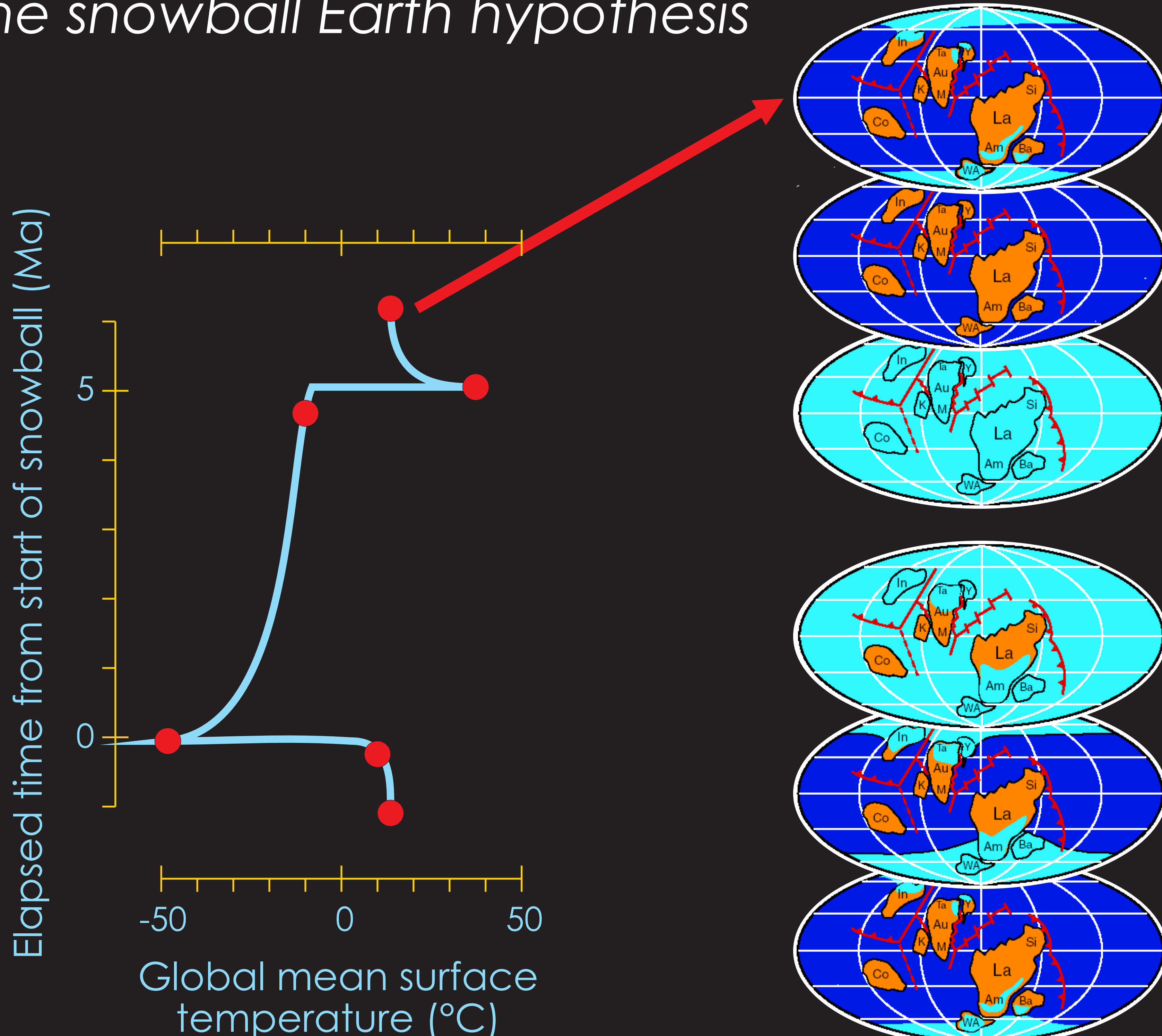


adapted from; *Hoffman and Schrag* [2002]

Snowball or Slushball?

Let the Battle of the Models commence ...

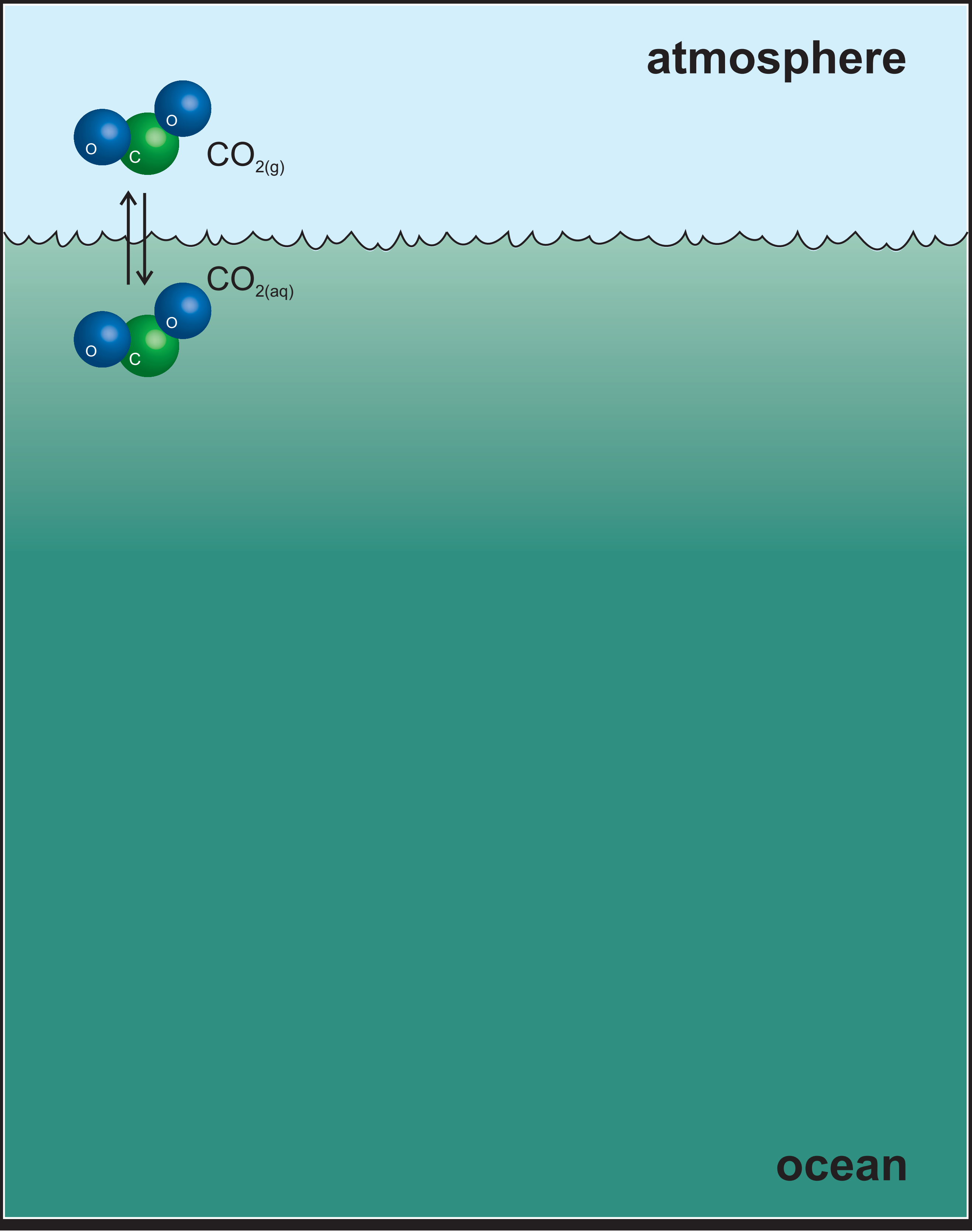
Study	**ATM**	**SEA-ICE**	**OCN**	**ICE-SHT**	***p*CO_2 threshold**	**(conclusions)**
Jenkins and Smith [1999]	ADVANCED	ADVANCED	BASIC		1700 ppm	(snowball)
Chandler and Sohl [2000]	ADVANCED	ADVANCED	INTERMEDIATE		<40 ppm	snowball unlikely
Hyde et al. [2000]; *Crowley et al.* [2001]	INTERMEDIATE	ADVANCED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

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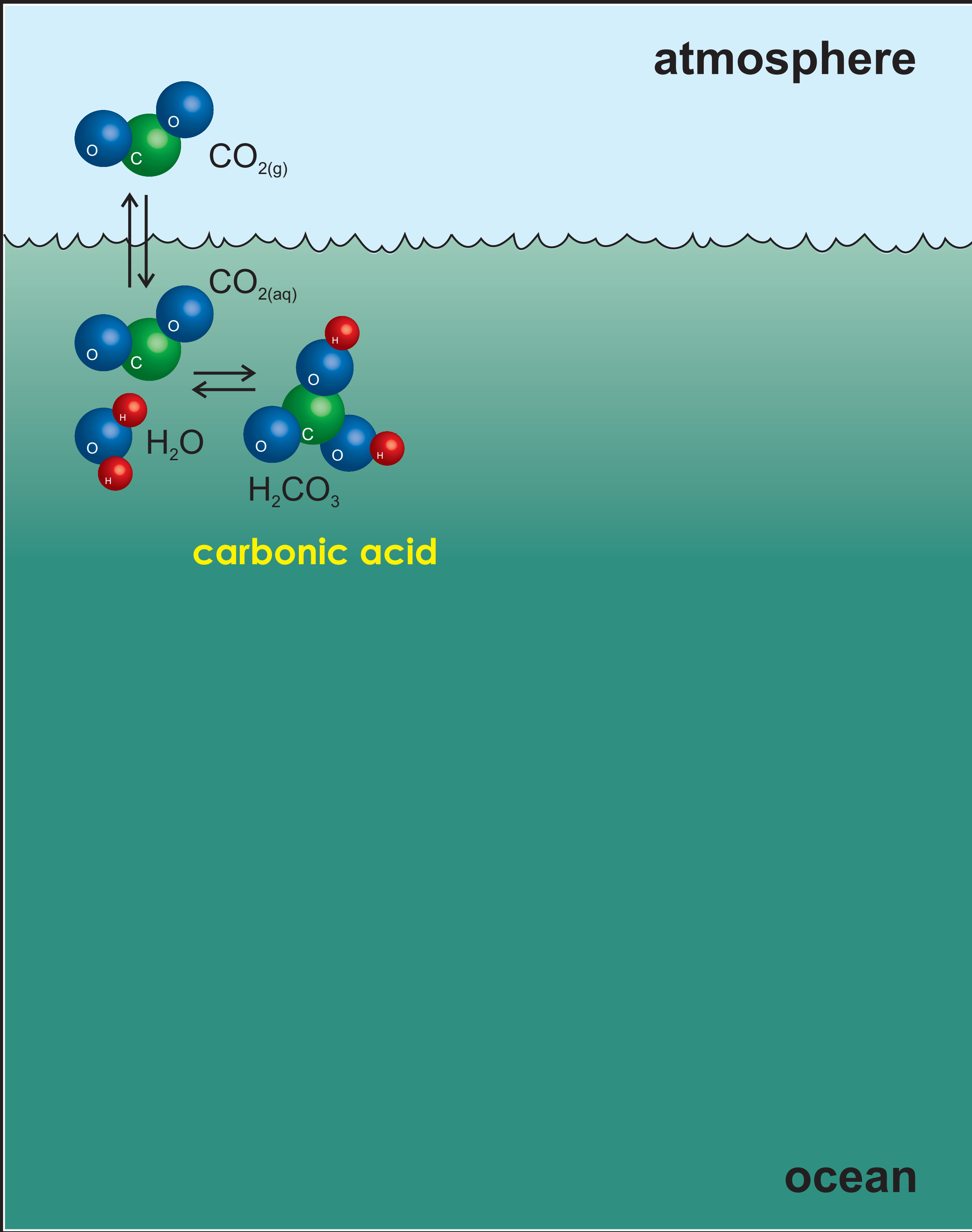

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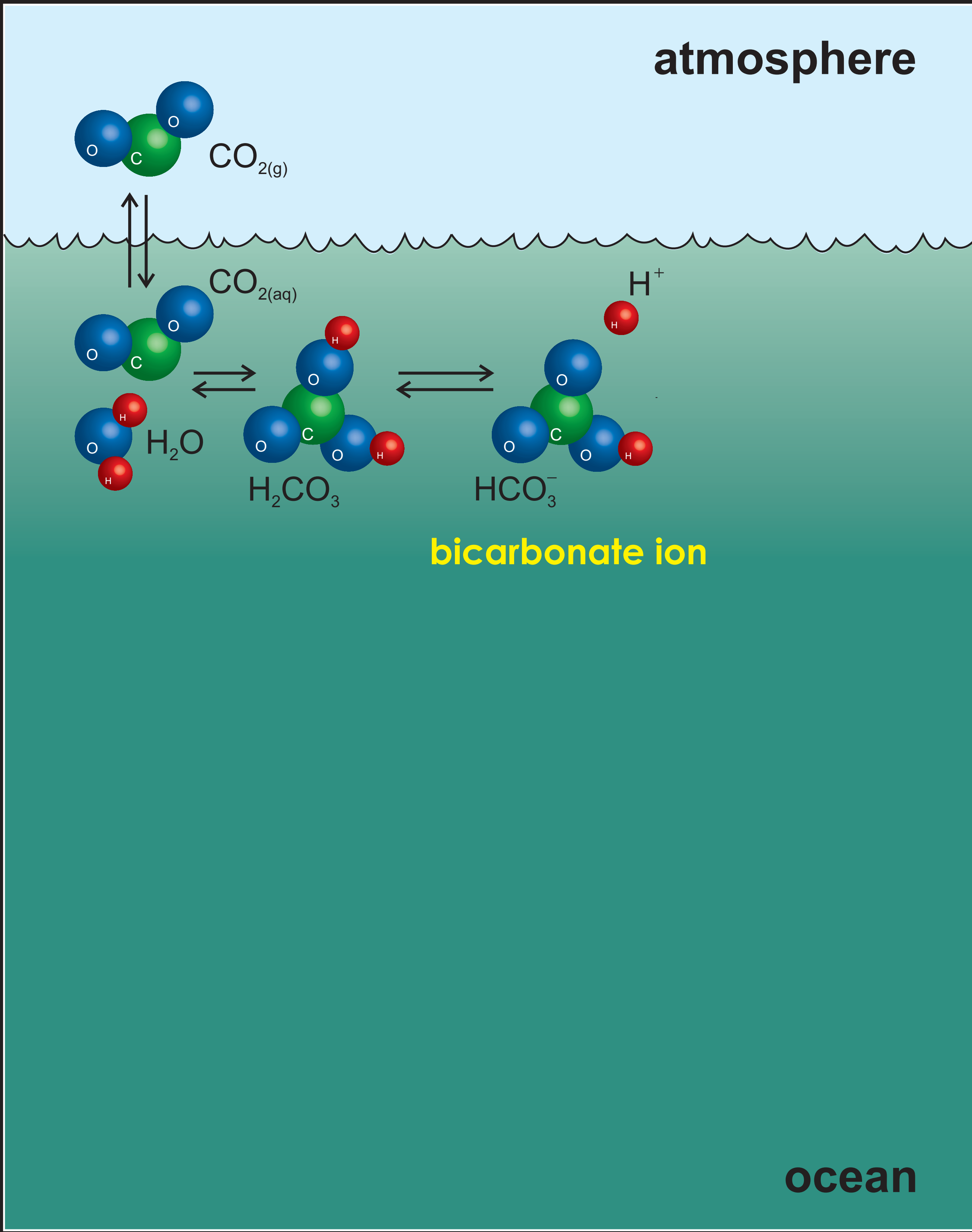

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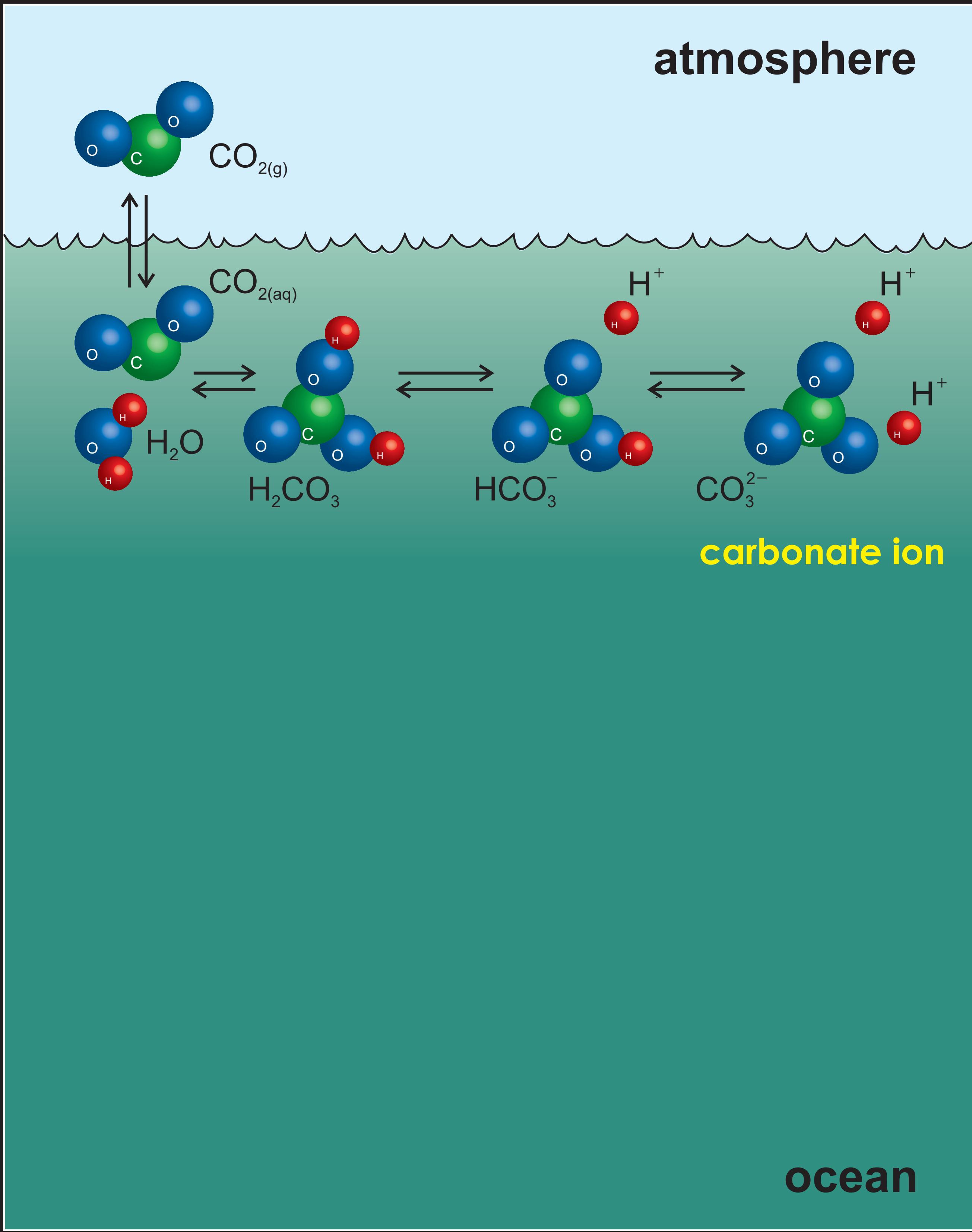
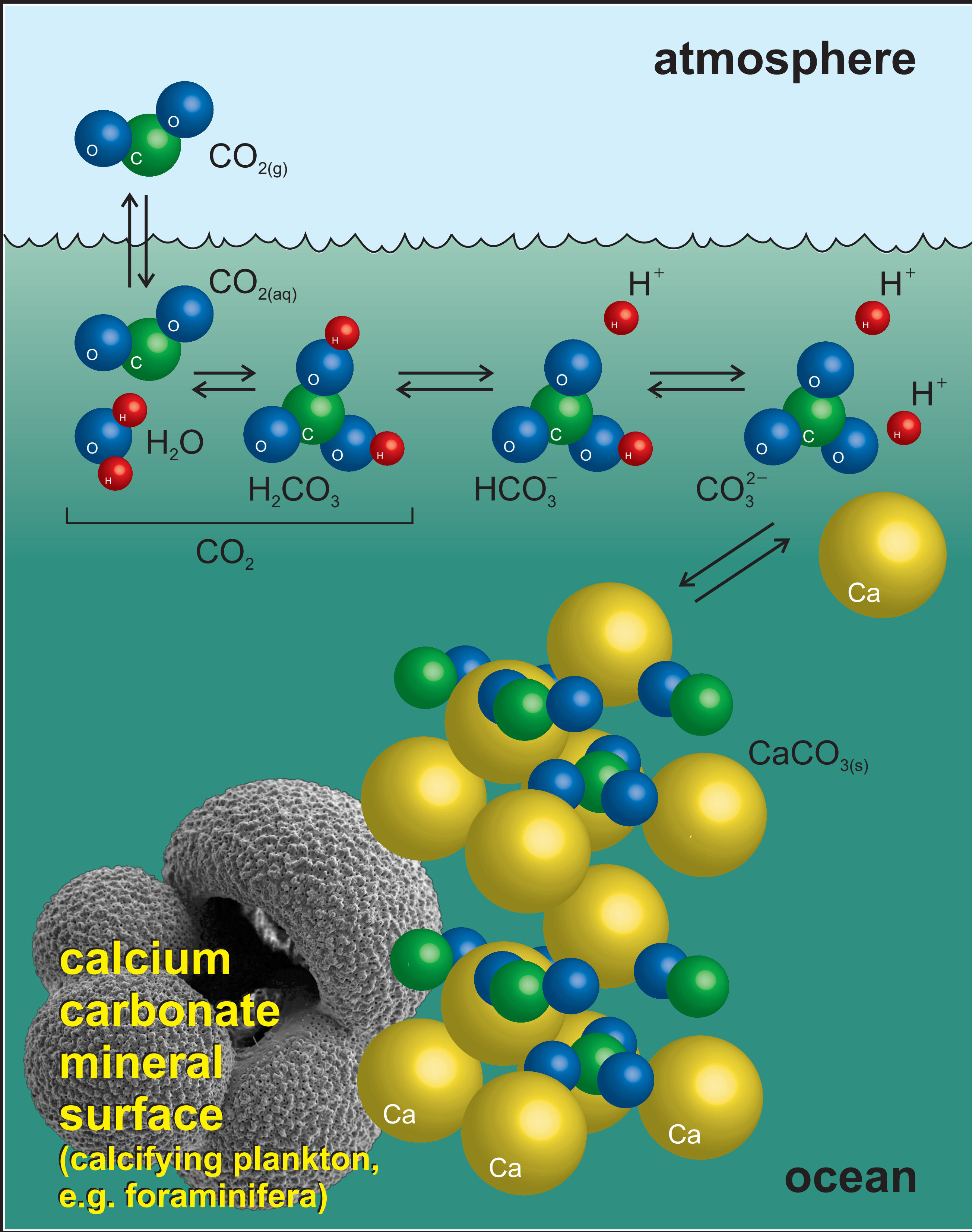
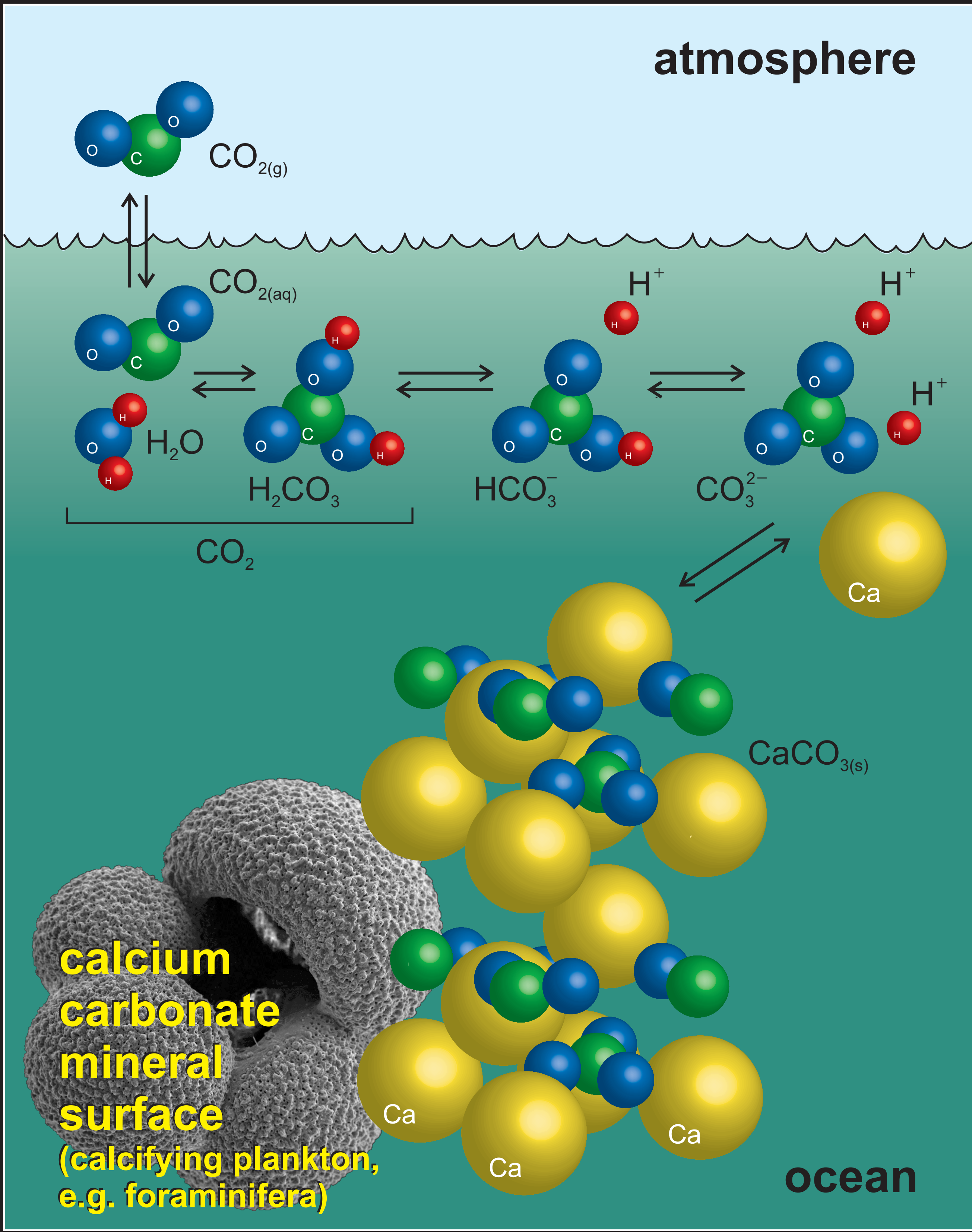


CO_2 chemistry & mineral phases



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

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



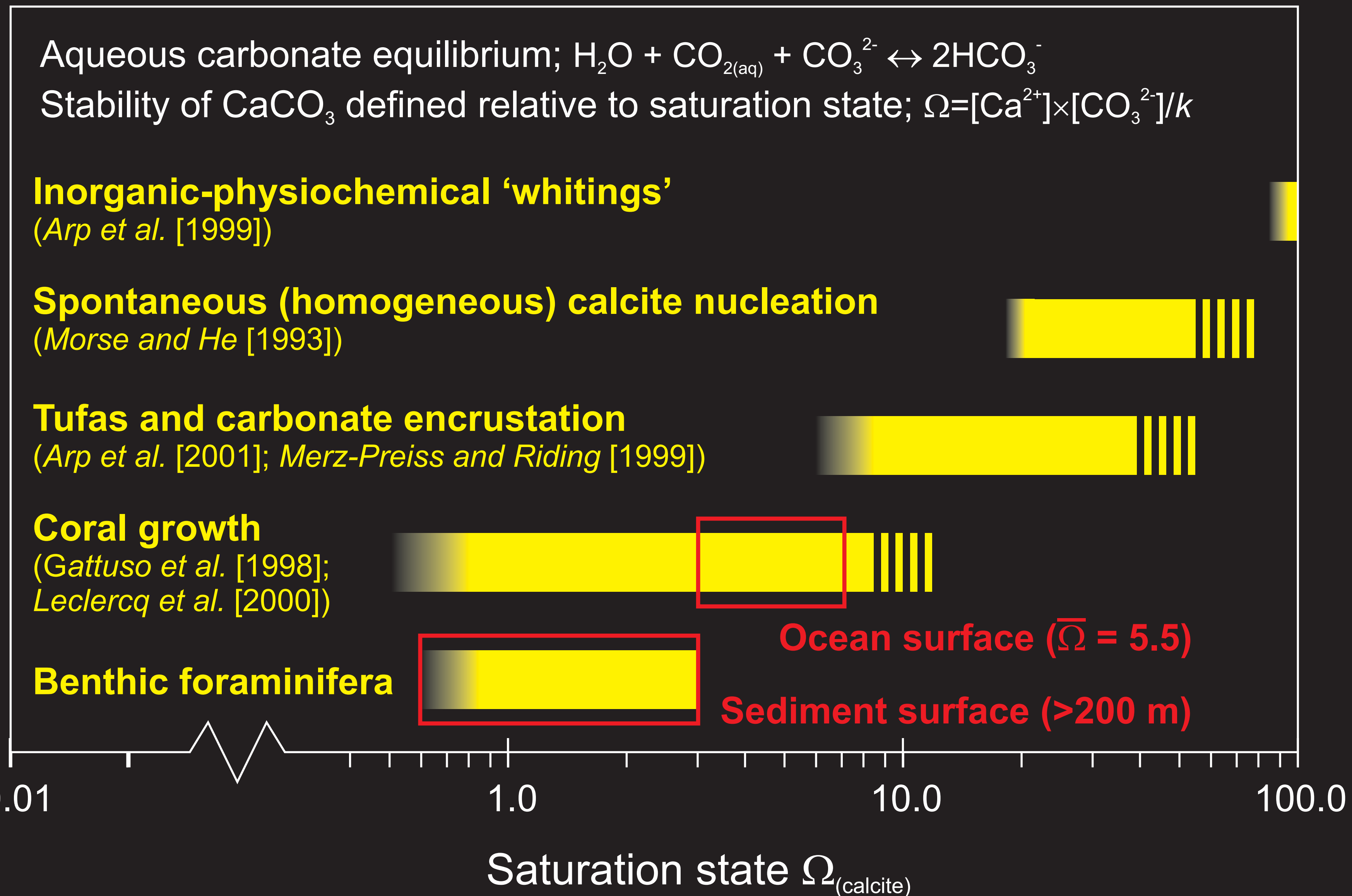
CO_2 chemistry & mineral phases

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'



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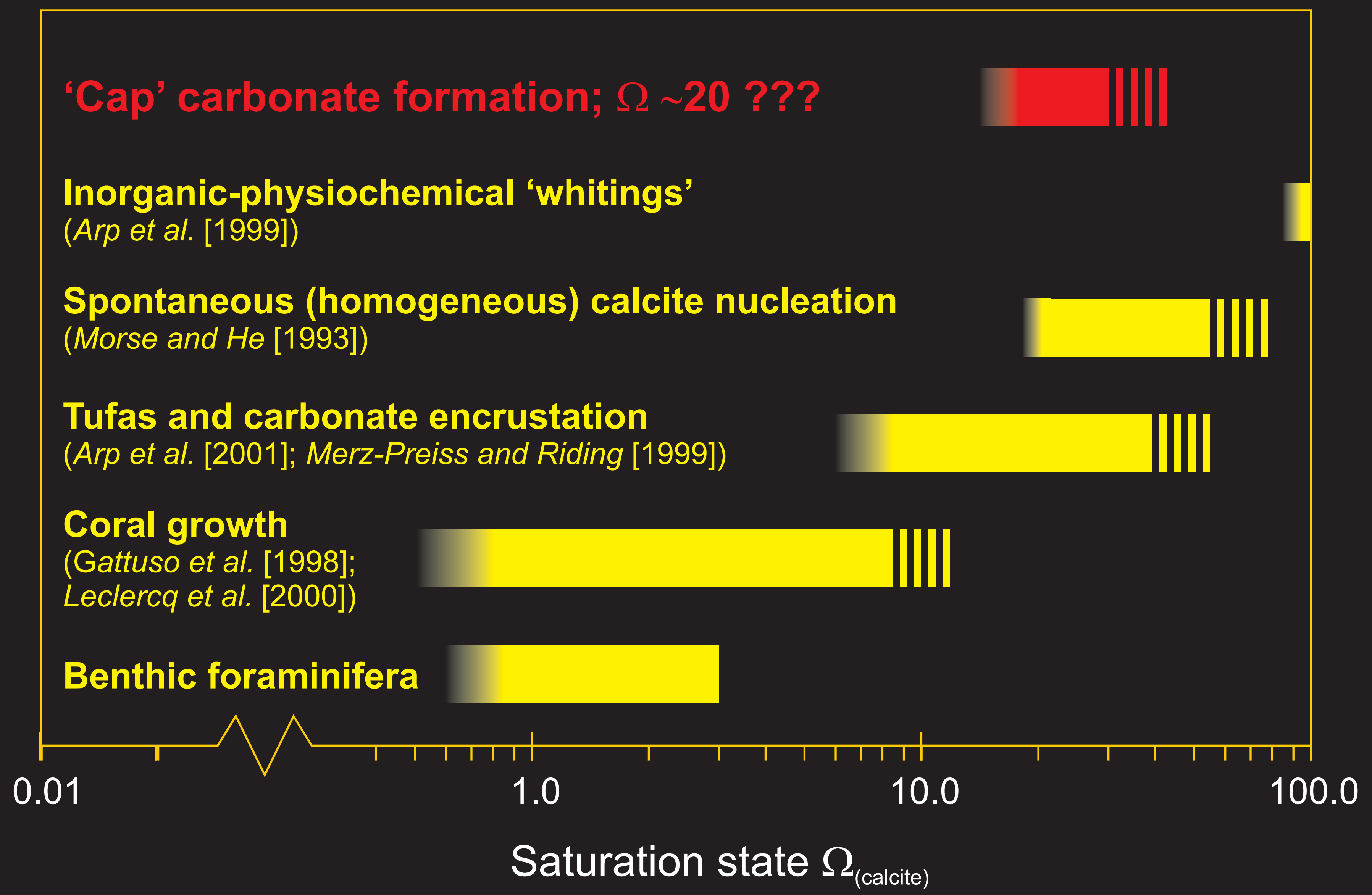
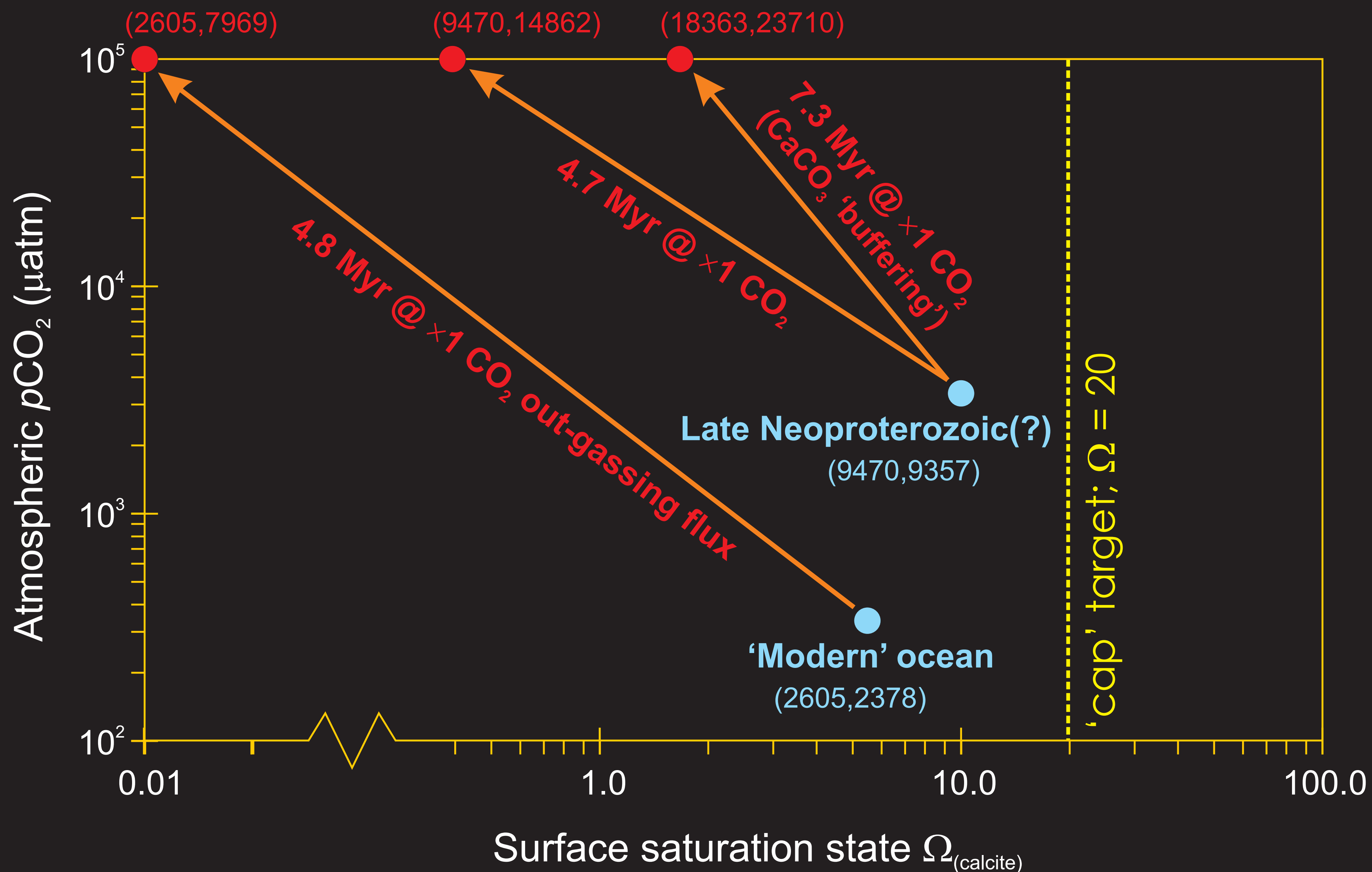


Potential evolution of ocean saturation during a 'snowball'



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

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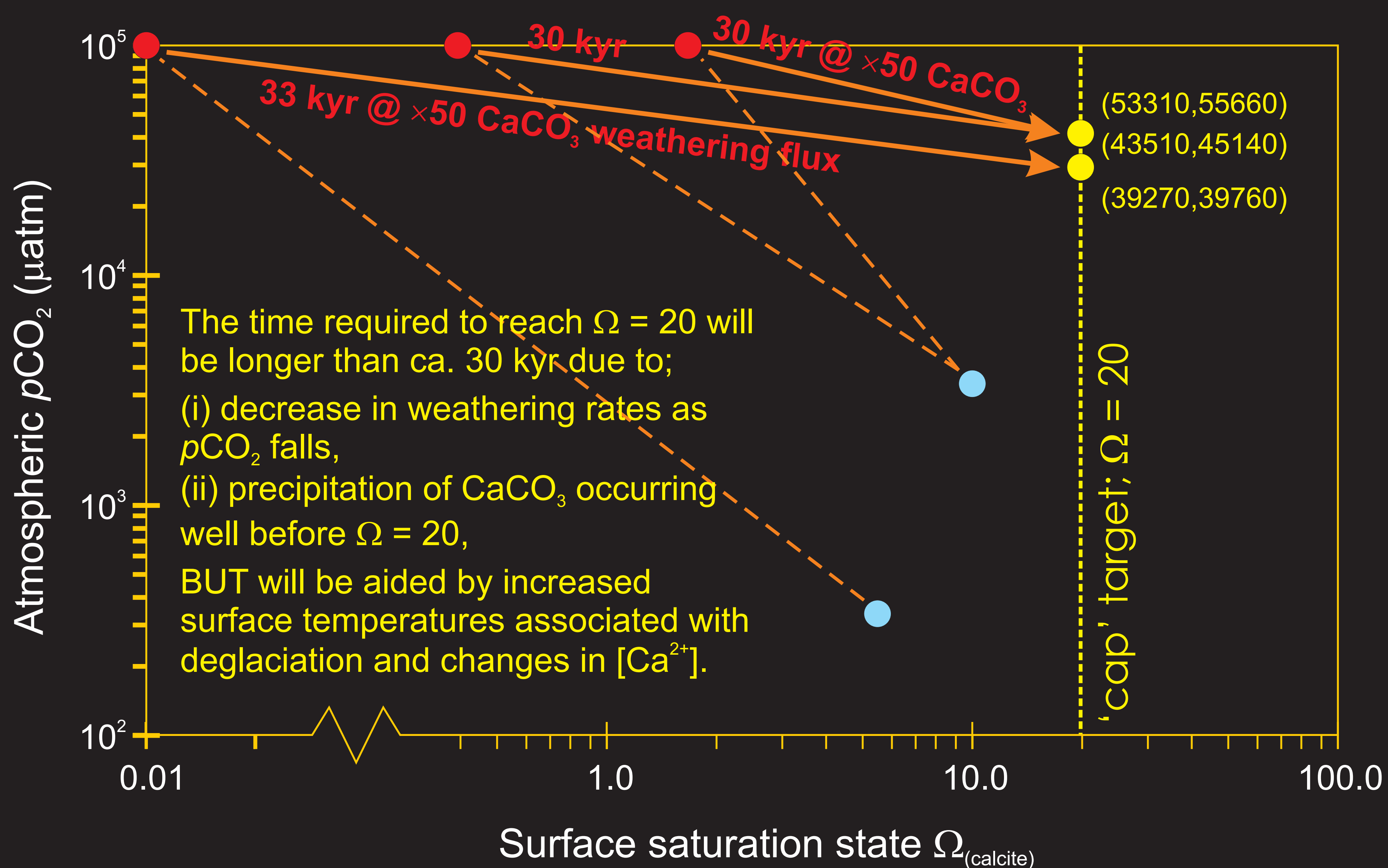

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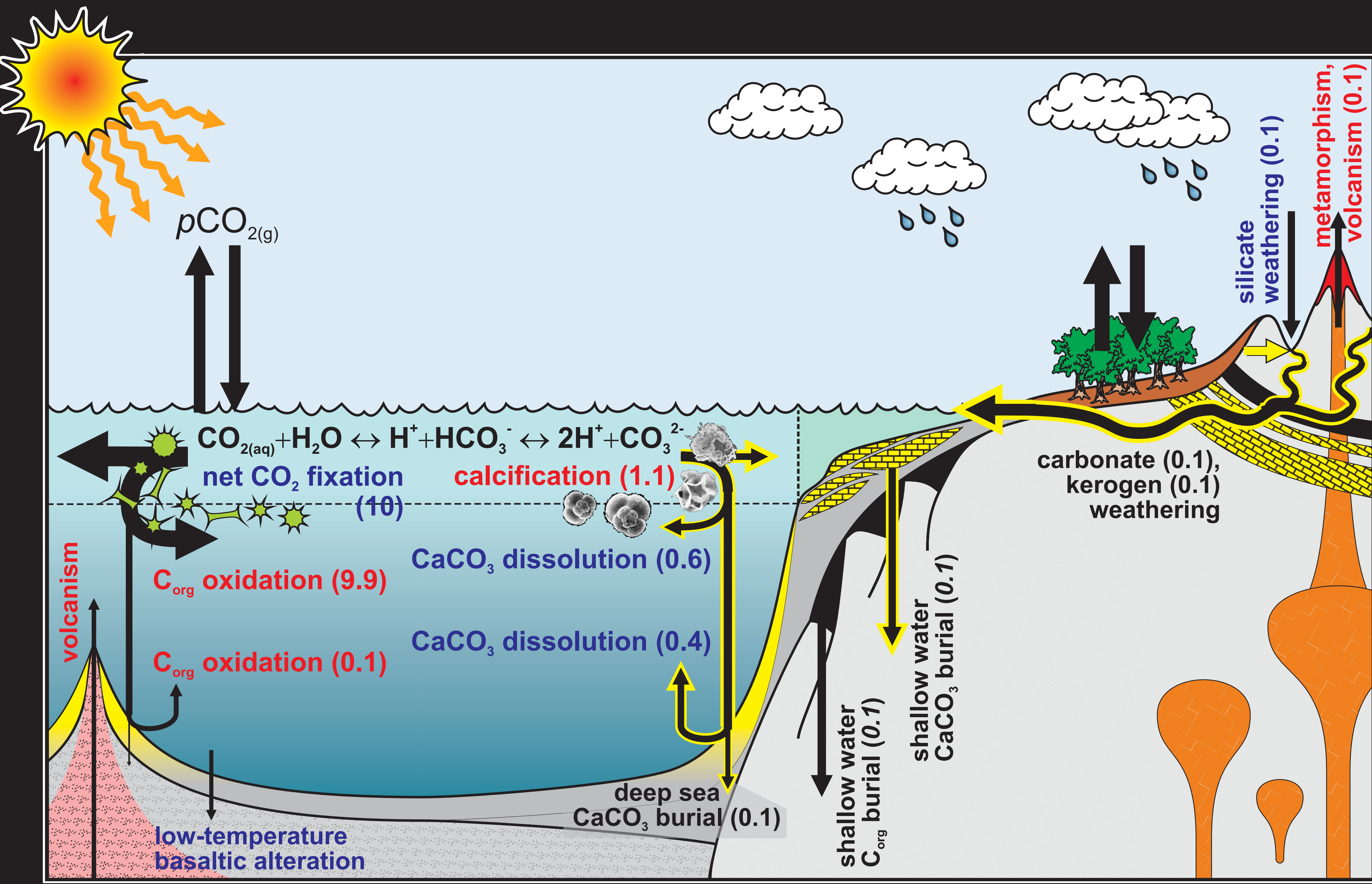
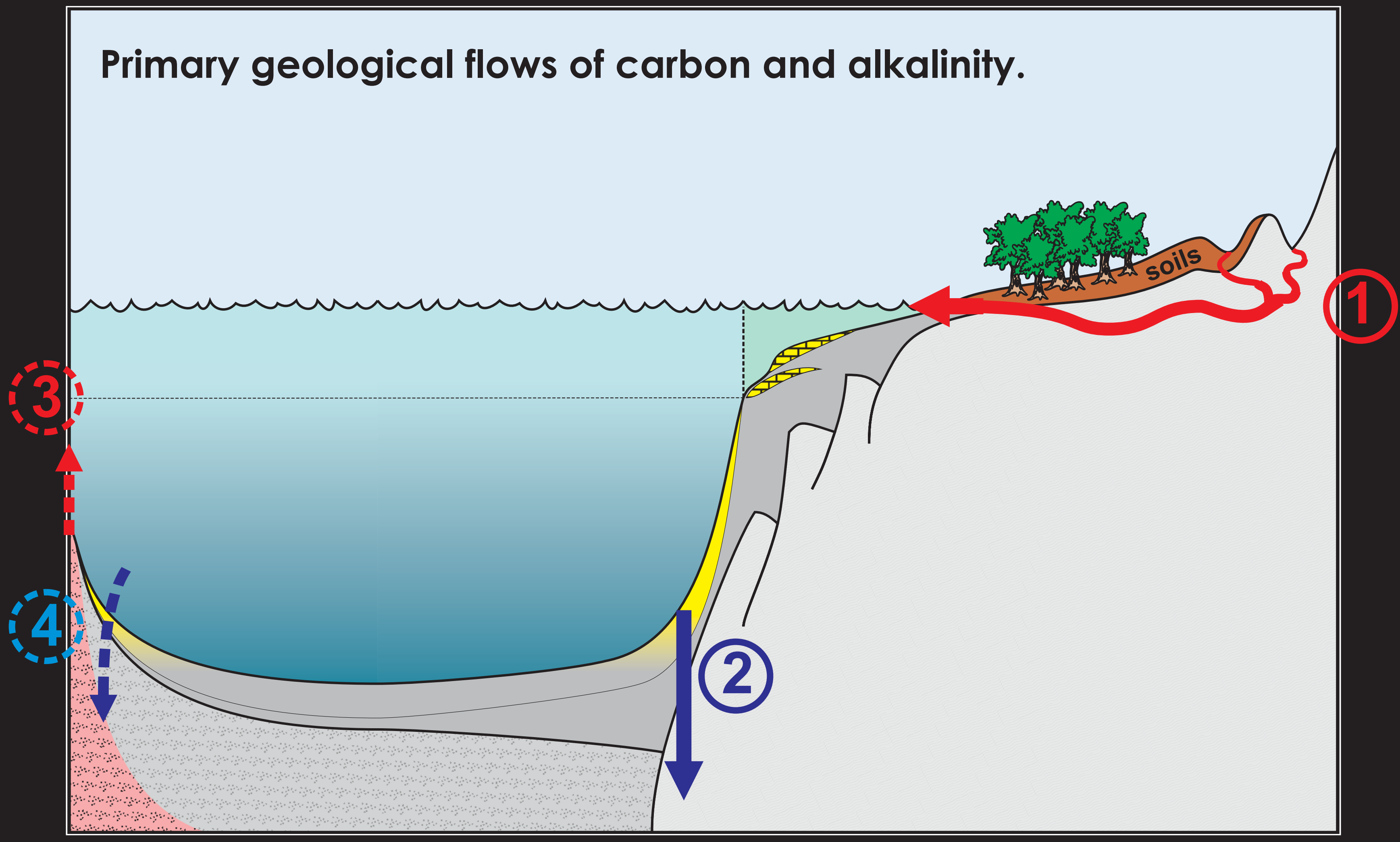
The global carbon cycle (modern)



The signature of extreme weathering

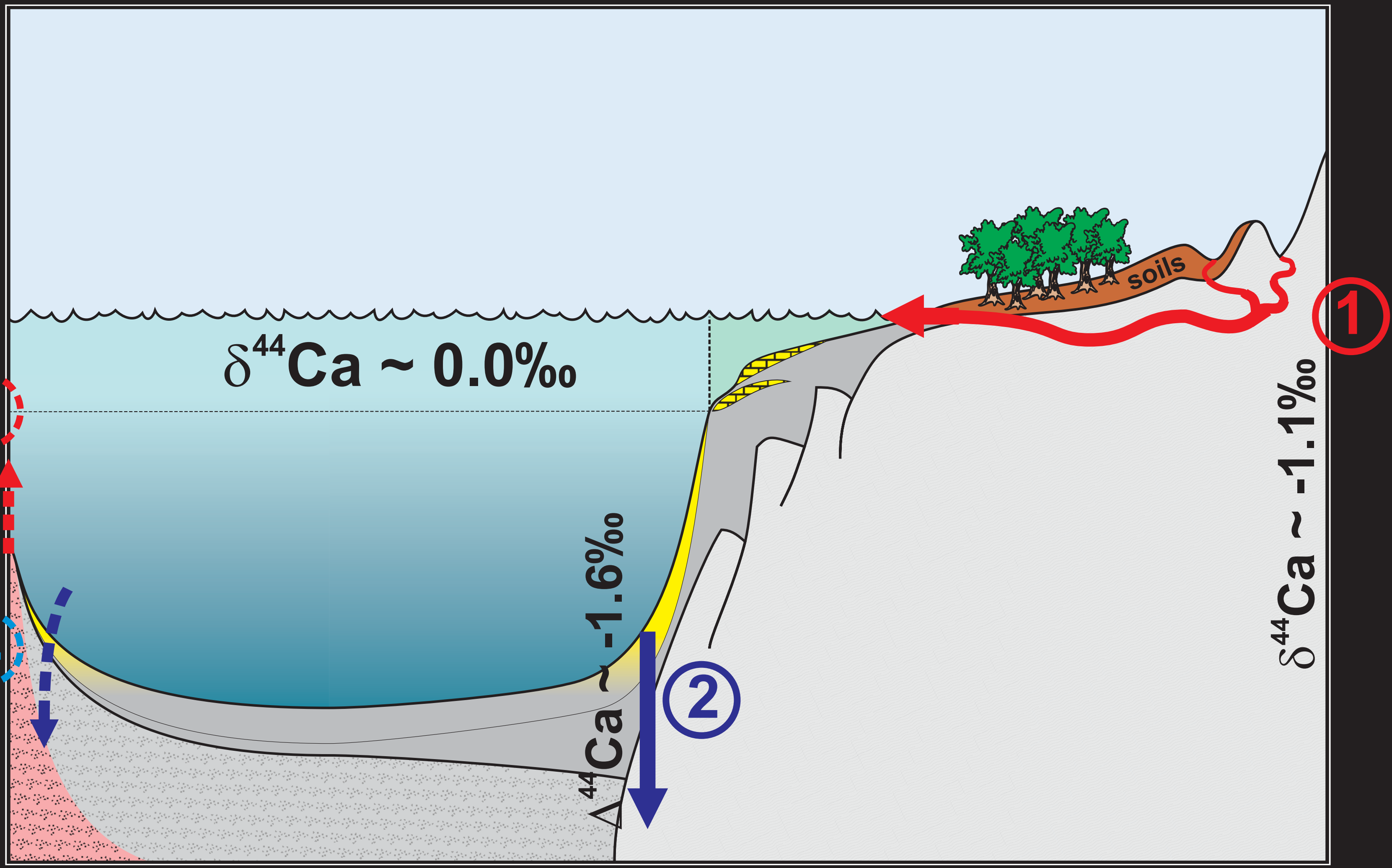


(1) Silicate and carbonate weathering plus volcanic outgassing (source)

(2) Biogenic carbonates (sink)

Ignoring hydrothermal input and low temperature alteration.
Also ... the entire organic carbon sub-cycle ...

The signature of extreme weathering



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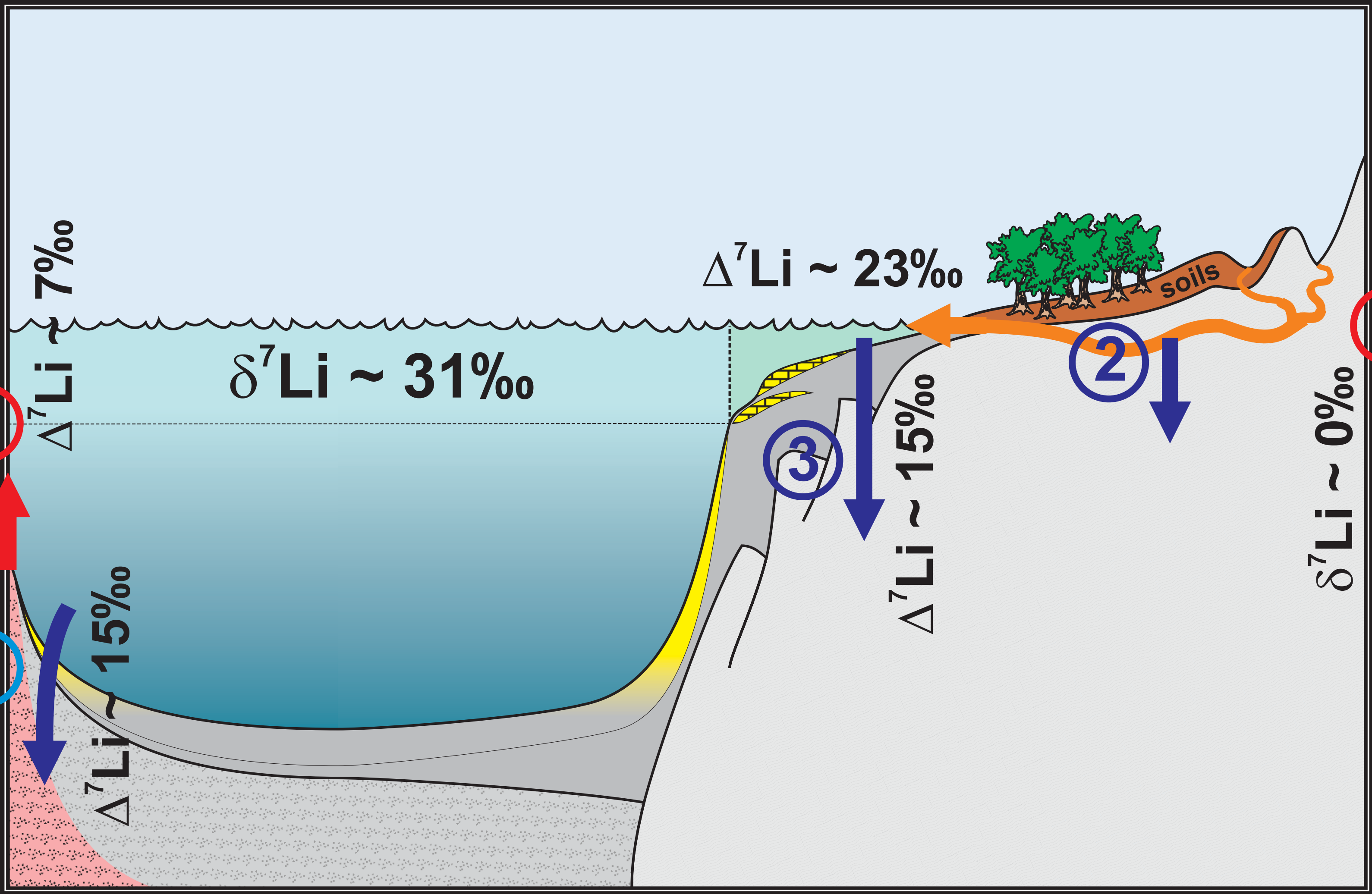

(1) Silicate weathering (source)

(2) Clay sink

(3) Clay (MACC) sink

(4) Hydrothermal input (source)

(5) Low temperature hydrothermal alteration (AOC) sink

Note that biogenic carbonates are only a mass trivial sink, but that the δ^7Li proxy signal is recorded in them.
Values are for the *modern* system.

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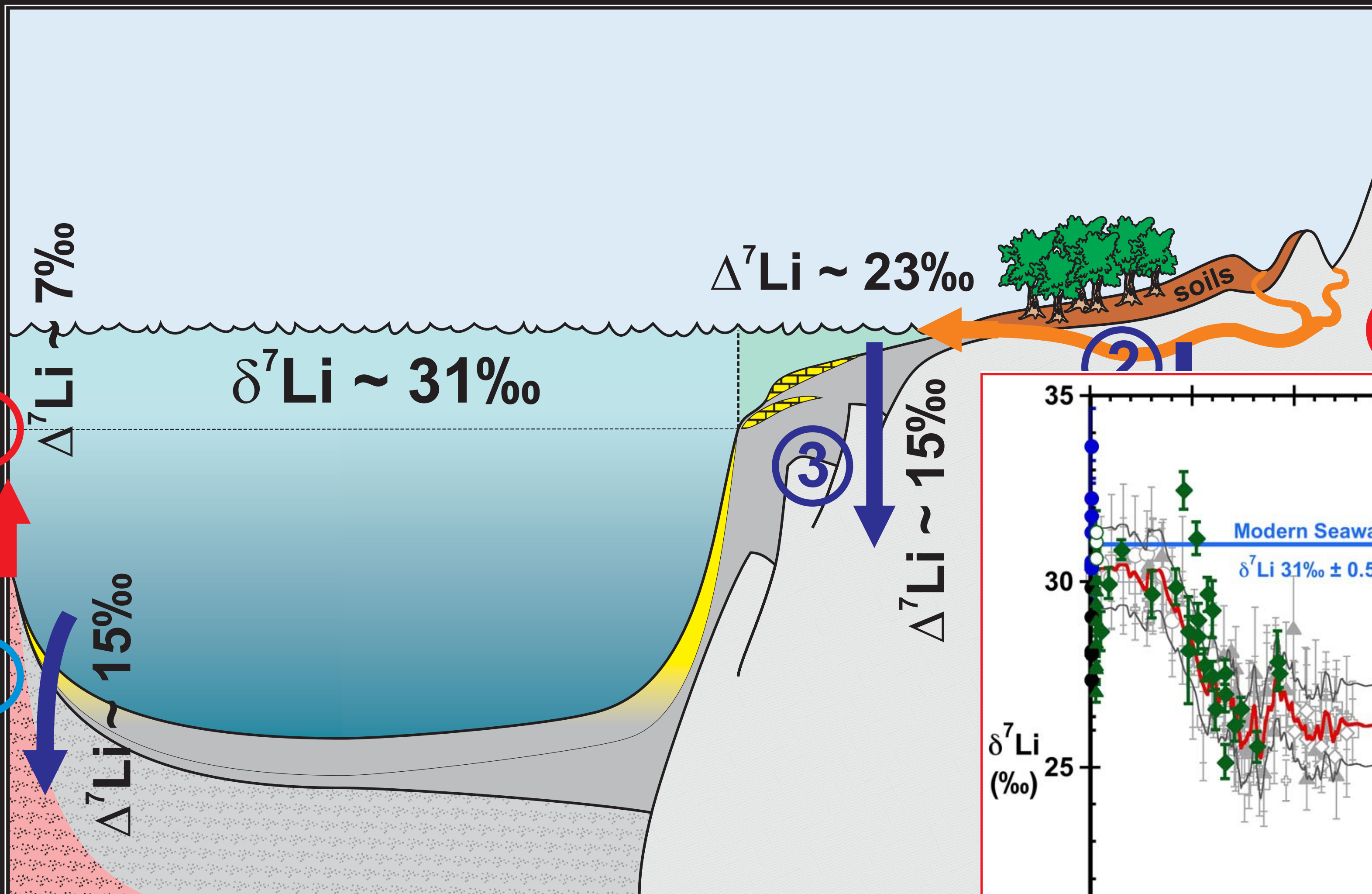

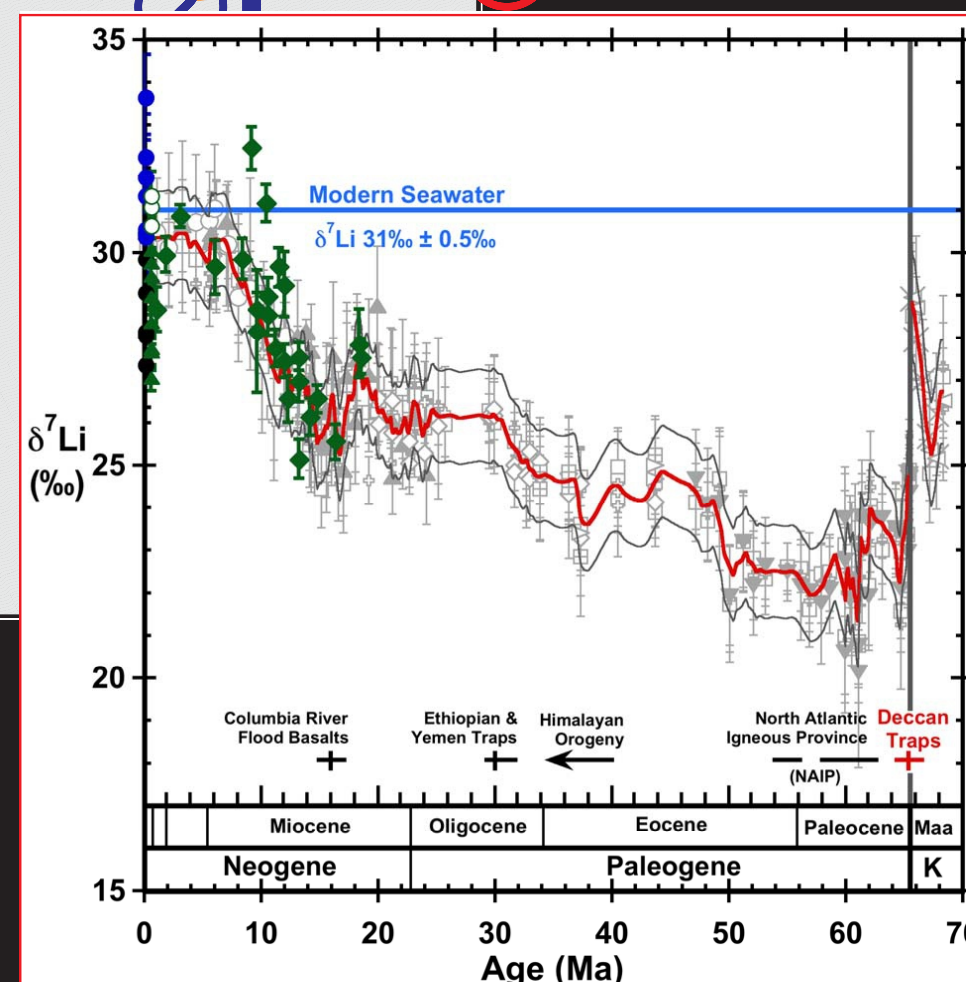

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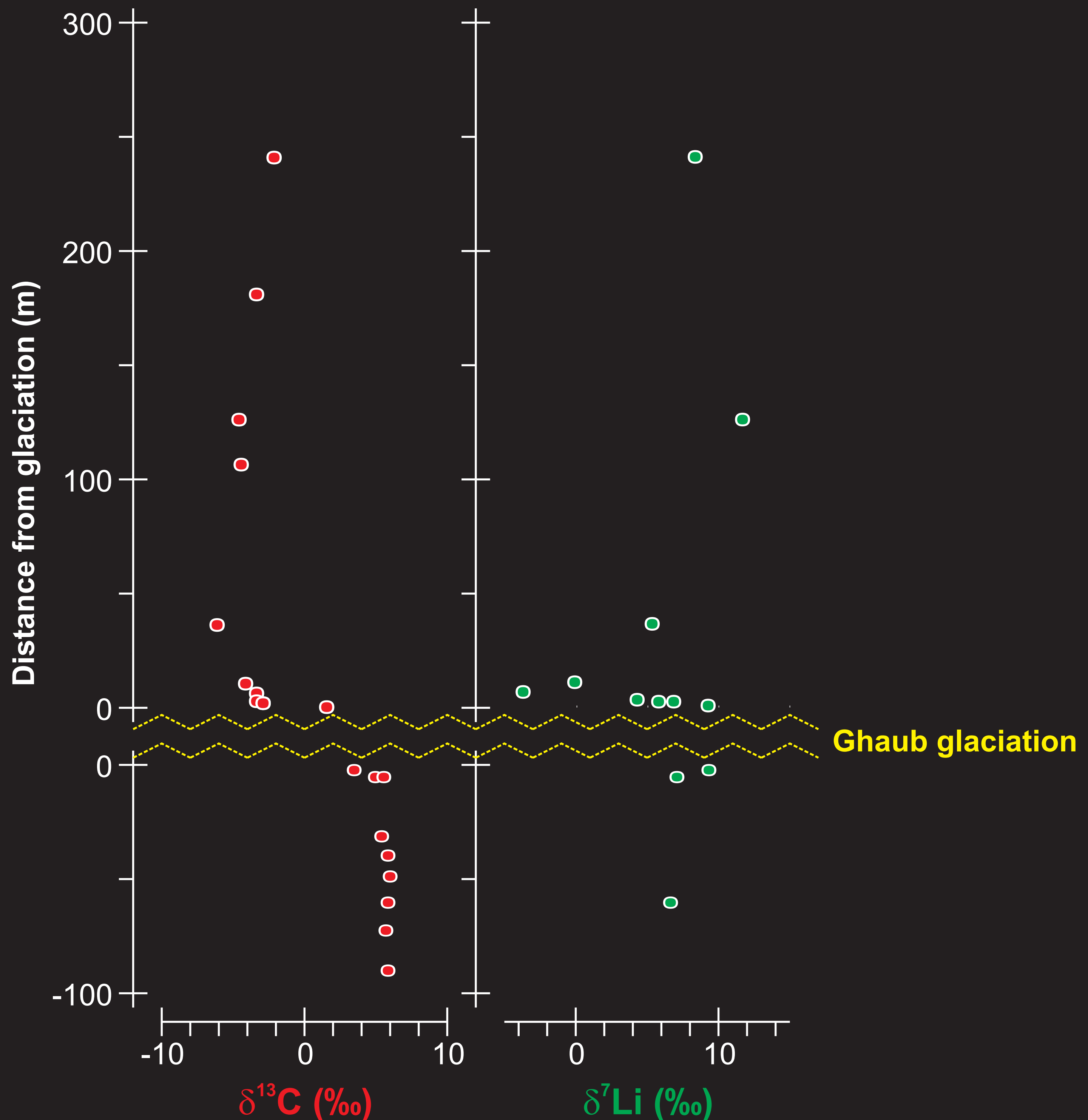

Pogge von Strandmann et al. [in prep]

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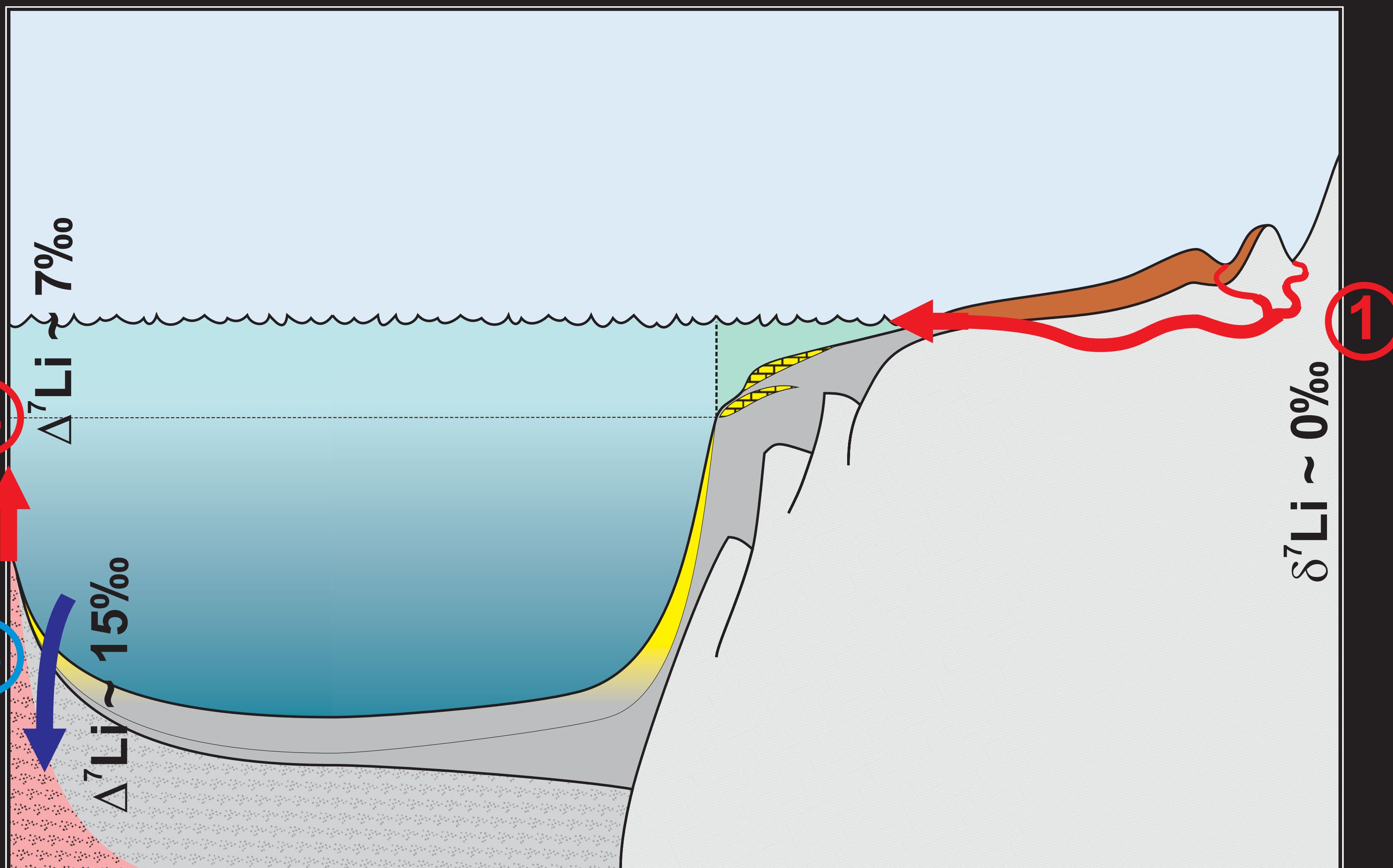

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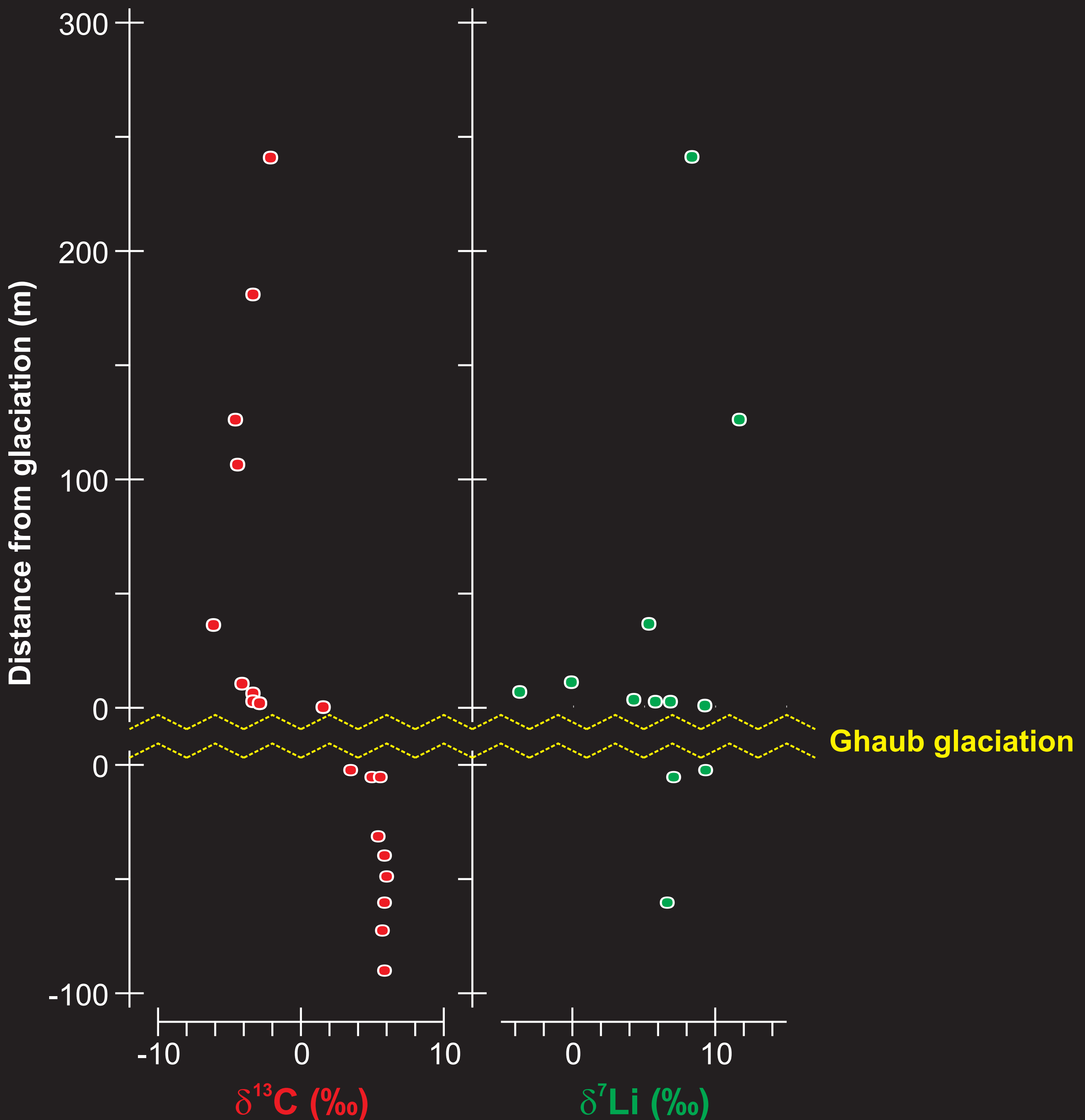

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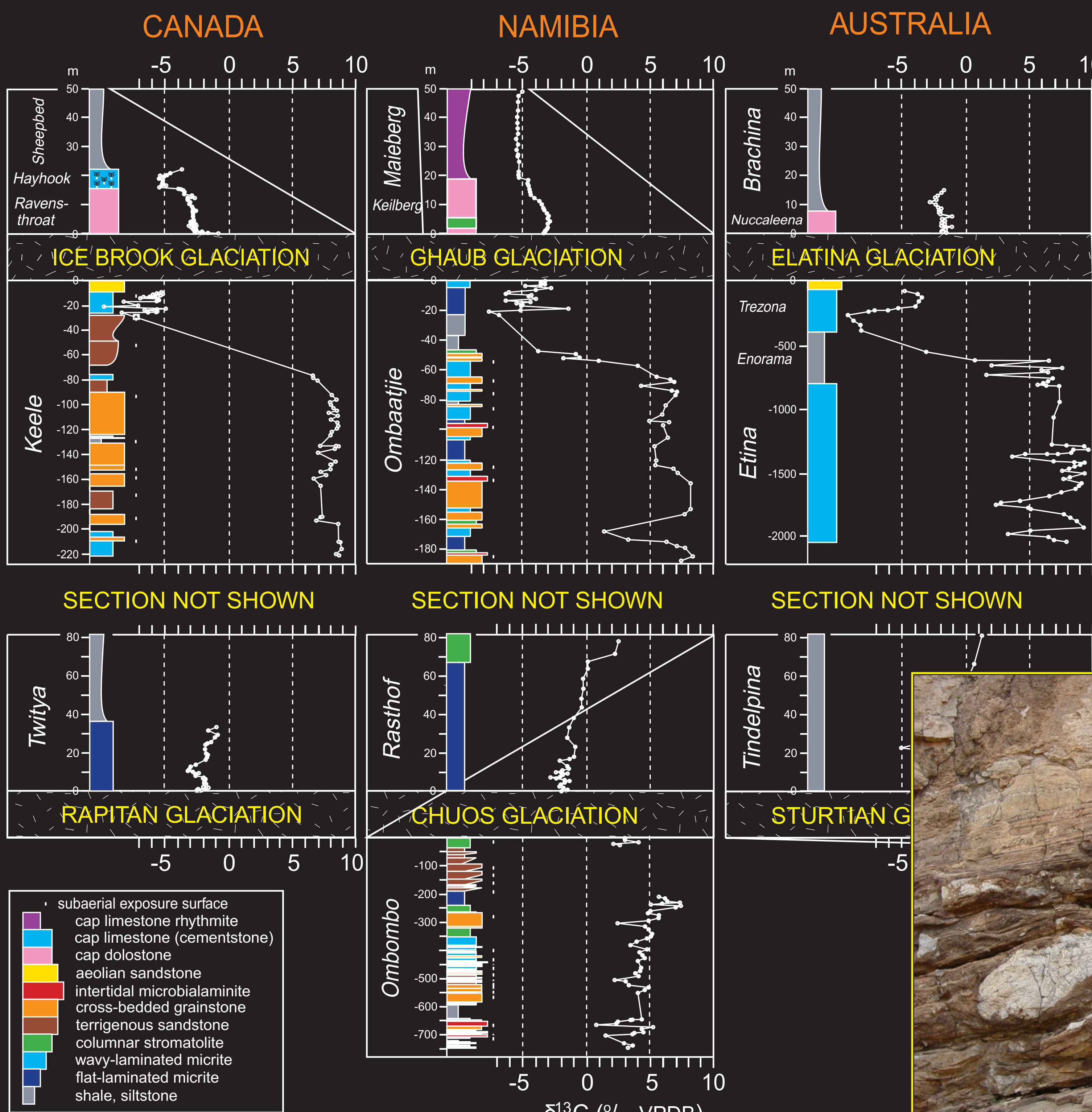
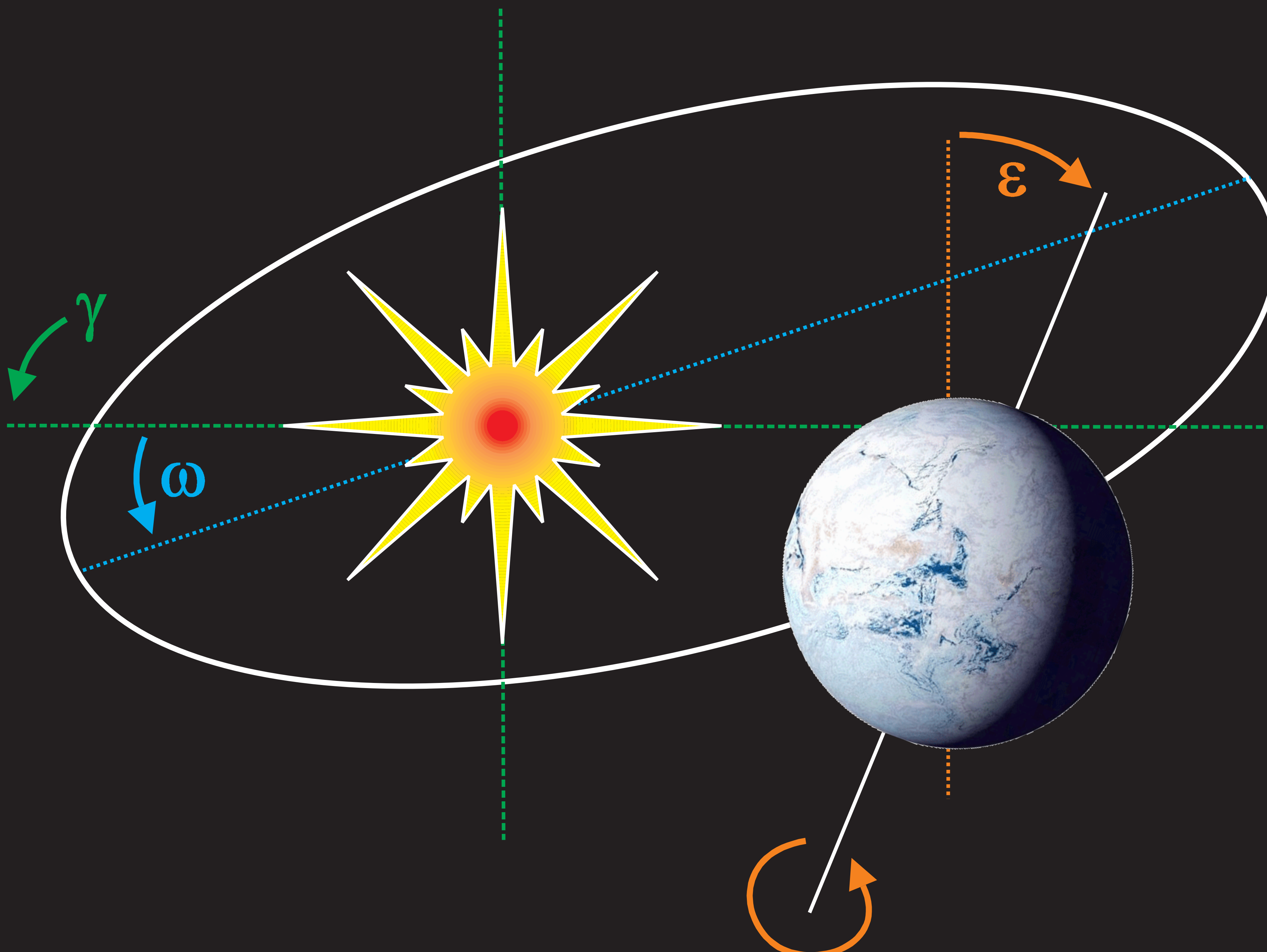


From: *Hoffman and Schrag* [2002]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