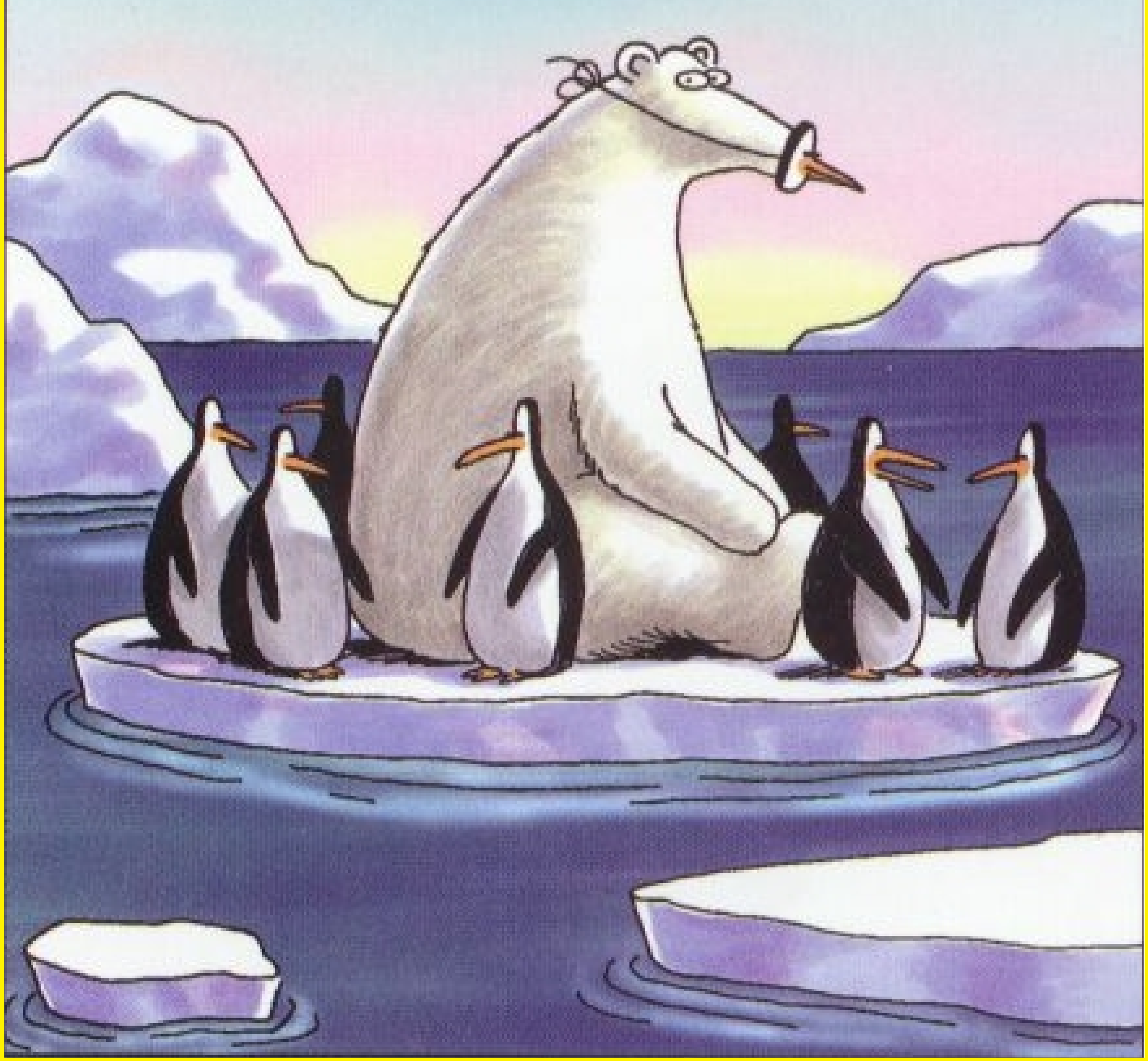
When penguins and polar bears meet ...

(the occurrence of global ice ages)



INTERNATIONAL STRATIGRAPHIC CHART

ICS

IUGS International Union of Geological Sciences

International Commission on Stratigraphy

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP
Phanerozoic	Cenozoic	Neogene	Holocene		0.0115	
			Pleistocene	Upper	0.126	
				Middle	0.781	
				Lower	1.806	
			Pliocene	Gelasian	2.588	
				Piacenzian	3.600	
				Zanclean	5.332	
			Miocene	Messinian	7.246	
				Tortonian	11.608	
				Serravallian	13.65	
				Langhian	15.97	
				Burdigalian	20.43	
				Aquitanian	23.03	
		Paleogene	Oligocene	Chattian	28.4 ±0.1	
				Rupelian	33.9 ±0.1	
			Eocene	Priabonian	37.2 ±0.1	
				Bartonian	40.4 ±0.2	
				Lutetian	48.6 ±0.2	
				Ypresian	55.8 ±0.2	
			Paleocene	Thanetian	58.7 ±0.2	
				Selandian	61.7 ±0.2	
				Danian	65.5 ±0.3	
	Mesozoic	Cretaceous	Upper	Maastrichtian	70.6 ±0.6	
				Campanian	83.5 ±0.7	
				Santonian	85.8 ±0.7	
				Coniacian	89.3 ±1.0	
				Turonian	93.5 ±0.8	
				Cenomanian	99.6 ±0.9	
			Lower	Albian	112.0 ±1.0	
				Aptian	125.0 ±1.0	
				Barremian	130.0 ±1.5	
				Hauterivian	136.4 ±2.0	
				Valanginian	140.2 ±3.0	
				Berriasian	145.5 ±4.0	

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP
					145.5 ±4.0	
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian	150.8 ±4.0	
				Kimmeridgian	155.0 ±4.0	
				Oxfordian	161.2 ±4.0	
			Middle	Callovian	164.7 ±4.0	
				Bathonian	167.7 ±3.5	
				Bajocian	171.6 ±3.0	
				Aalenian	175.6 ±2.0	
			Lower	Toarcian	183.0 ±1.5	
				Pliensbachian	189.6 ±1.5	
				Sinemurian	196.5 ±1.0	
				Hettangian	199.6 ±0.6	
		Triassic	Upper	Rhaetian	203.6 ±1.5	
				Norian	216.5 ±2.0	
				Carnian	228.0 ±2.0	
			Middle	Ladinian	237.0 ±2.0	
				Anisian	245.0 ±1.5	
			Lower	Olenekian	249.7 ±0.7	
				Induan	251.0 ±0.4	
	Paleozoic	Permian	Lopingian	Changhsingian	253.8 ±0.7	
				Wuchiapingian	260.4 ±0.7	
			Guadalupian	Capitanian	265.8 ±0.7	
				Wordian	268.0 ±0.7	
				Roadian	270.6 ±0.7	
			Cisuralian	Kungurian	275.6 ±0.7	
				Artinskian	284.4 ±0.7	
				Sakmarian	294.6 ±0.8	
				Asselian	299.0 ±0.8	
		Carboniferous	Pennsylvanian Upper	Gzhelian	303.9 ±0.9	
				Kasimovian	306.5 ±1.0	
			Pennsylvanian Middle	Moscovian	311.7 ±1.1	
			Pennsylvanian Lower	Bashkirian	318.1 ±1.3	
			Mississippian Upper	Serpukhovian	326.4 ±1.6	
			Mississippian Middle	Visean	345.3 ±2.1	
			Mississippian Lower	Tournaisian	359.2 ±2.5	

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP
					359.2 ±2.5	
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	374.5 ±2.6	
				Frasnian	385.3 ±2.6	
			Middle	Givetian	391.8 ±2.7	
				Eifelian	397.5 ±2.7	
			Lower	Emsian	407.0 ±2.8	
				Pragian	411.2 ±2.8	
				Lochkovian	416.0 ±2.8	
		Silurian	Pridoli		418.7 ±2.7	
			Ludlow	Ludfordian	421.3 ±2.6	
				Gorstian	422.9 ±2.5	
			Wenlock	Homerian	426.2 ±2.4	
				Sheinwoodian	428.2 ±2.3	
			Llandovery	Telychian	436.0 ±1.9	
				Aeronian	439.0 ±1.8	
				Rhuddanian	443.7 ±1.5	
		Ordovician	Upper	Hirnantian	445.6 ±1.6	
					455.8 ±1.6	
					460.9 ±1.6	
			Middle	Darriwilian	468.1 ±1.6	
					471.8 ±1.6	
			Lower		478.6 ±1.7	
				Tremadocian	488.3 ±1.7	
		Cambrian	Furongian			
				Paibian	501.0 ±2.0	
			Middle			
					513.0 ±2.0	
			Lower			
					542.0 ±1.0	

Eonothem Eon	Erathem Era	System Period	Age Ma	GSSP GSSA
			542	
Precambrian	Proterozoic	Neoproterozoic: Ediacaran	600	
		Cryogenian	850	
		Tonian	1000	
		Mesoproterozoic: Stenian	1200	
		Ectasian	1400	
		Calymmian	1600	
		Paleoproterozoic: Statherian	1800	
		Orosirian	2050	
		Rhyacian	2300	
		Siderian	2500	
	Archean	Neoarchean	2800	
		Mesoarchean	3200	
		Paleoarchean	3600	
		Eoarchean	Lower limit is not defined	

Subdivisions of the global geologic record are formally defined by their lower boundary. Each unit of the Phanerozoic interval (~542 Ma to Present) and the base of the Ediacaran is defined by a Global Standard Section and Point (GSSP) at its base, whereas the Precambrian Interval is formally subdivided by absolute age, Global Standard Stratigraphic Age (GSSA).

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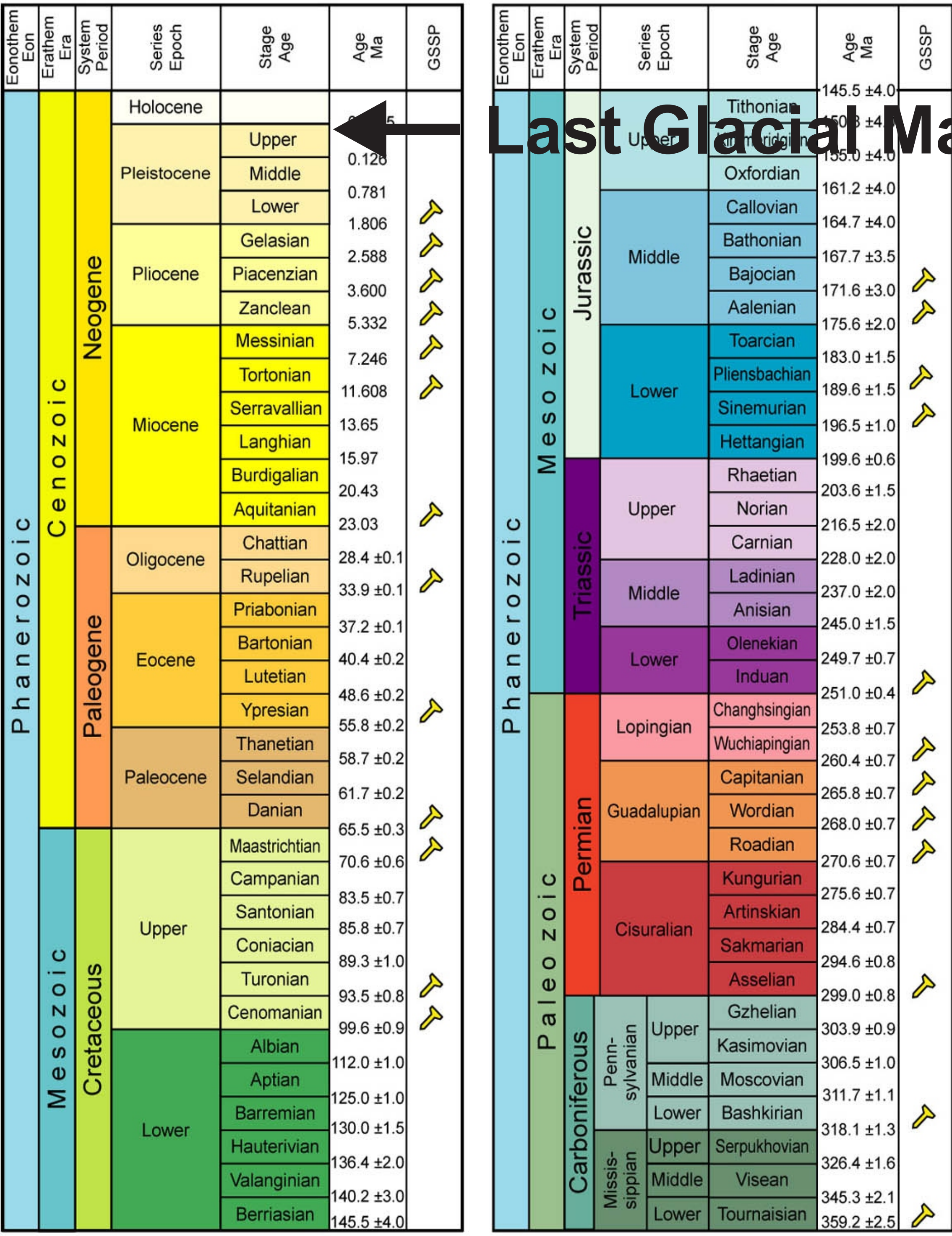
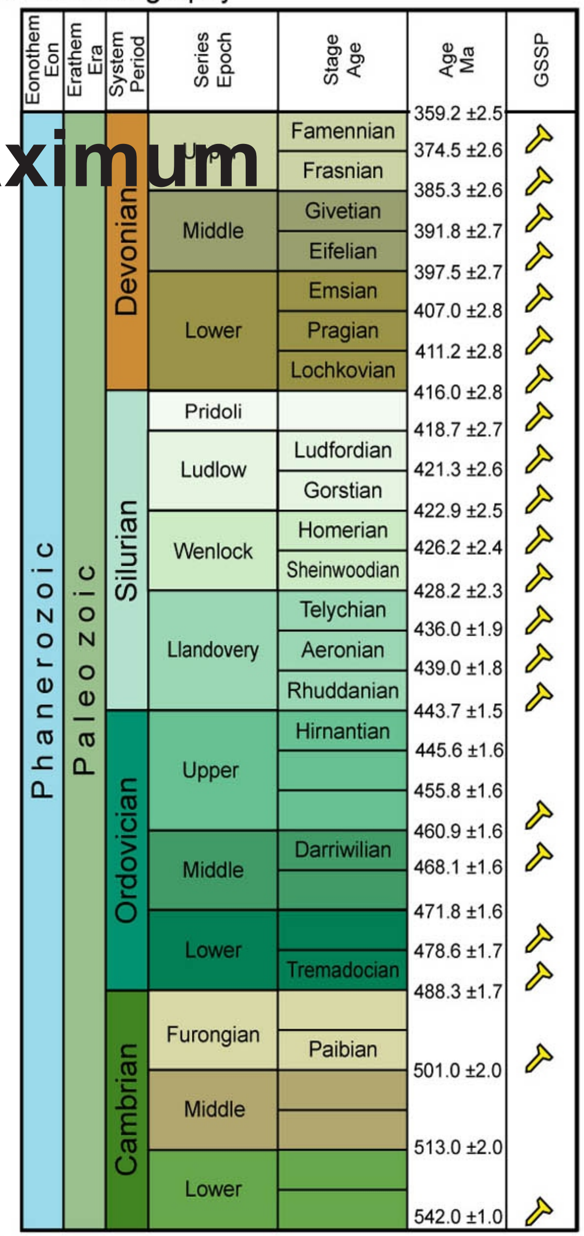
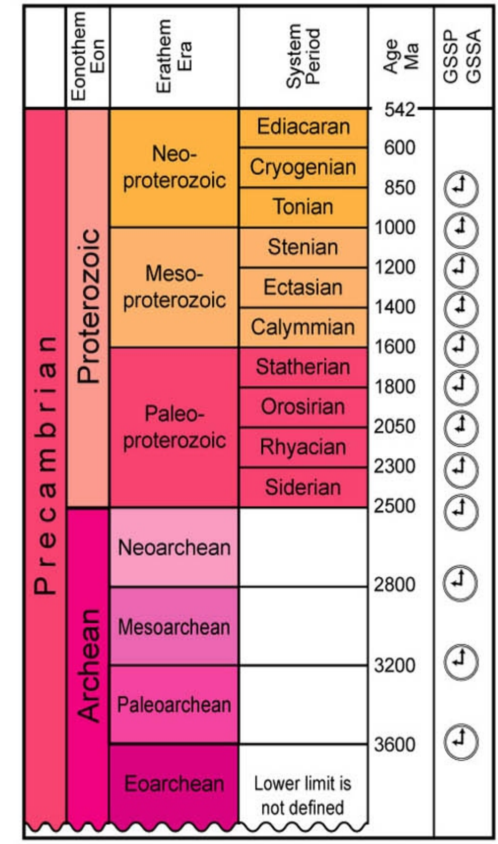
INTERNATIONAL STRATIGRAPHIC CHART

International Commission on Stratigraphy







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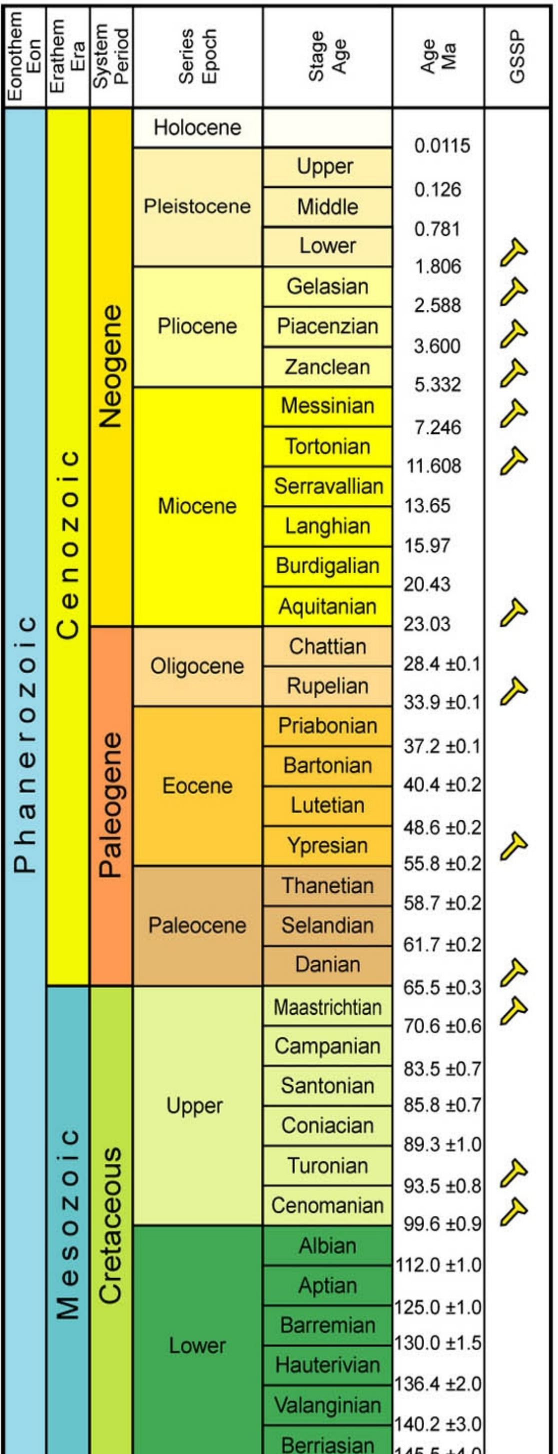

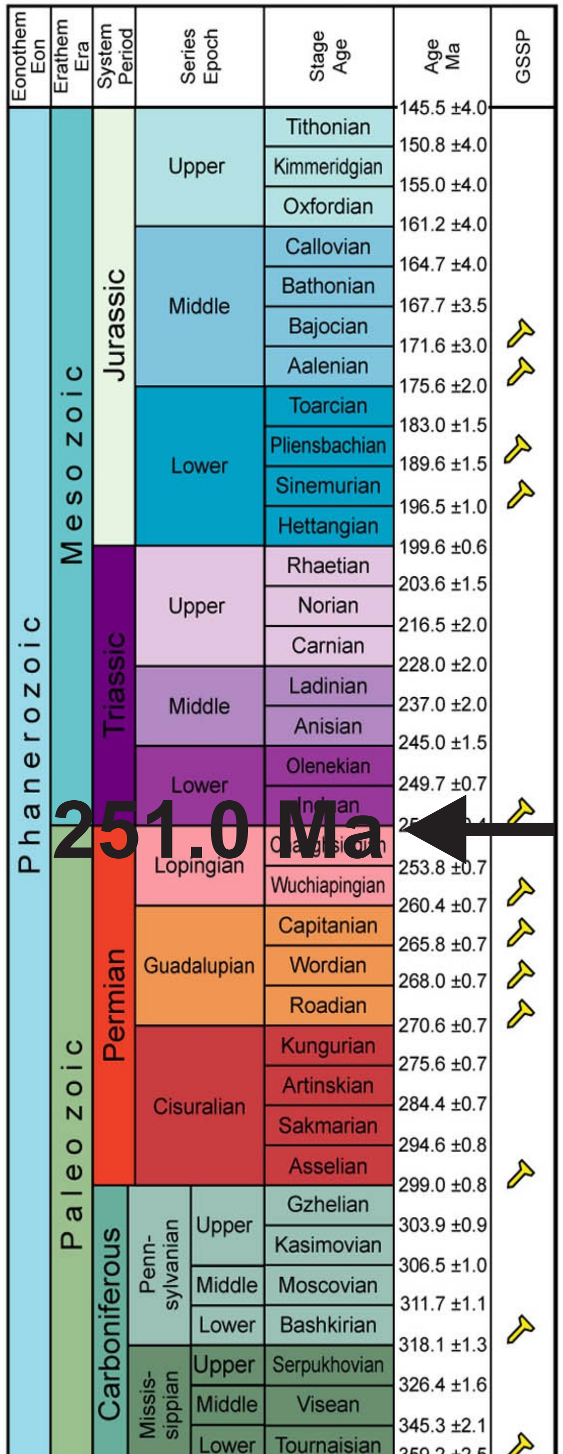

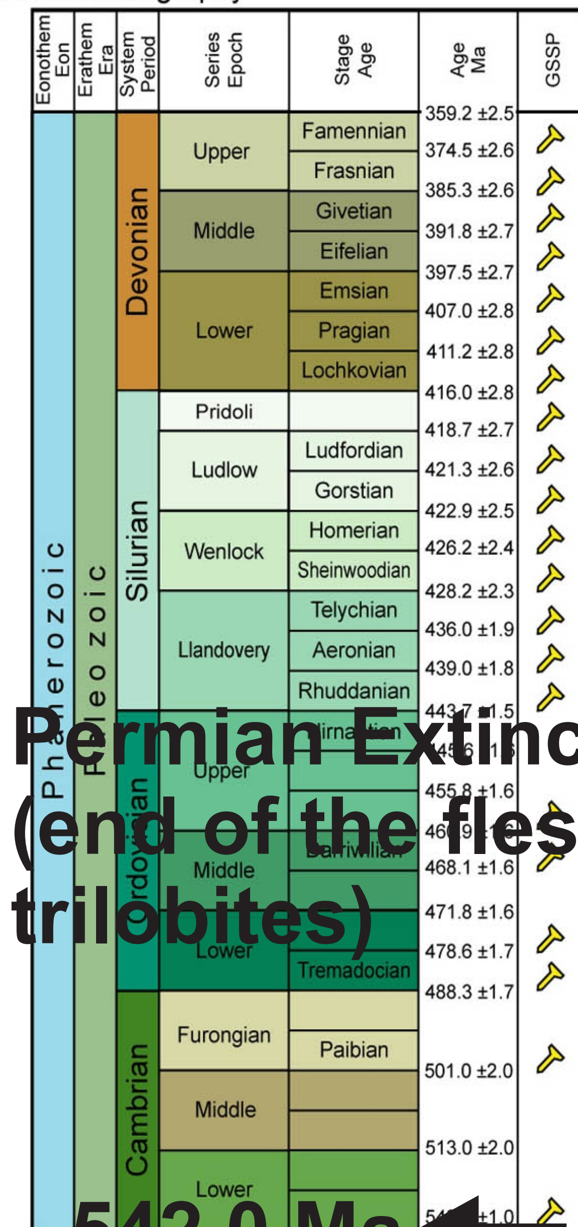

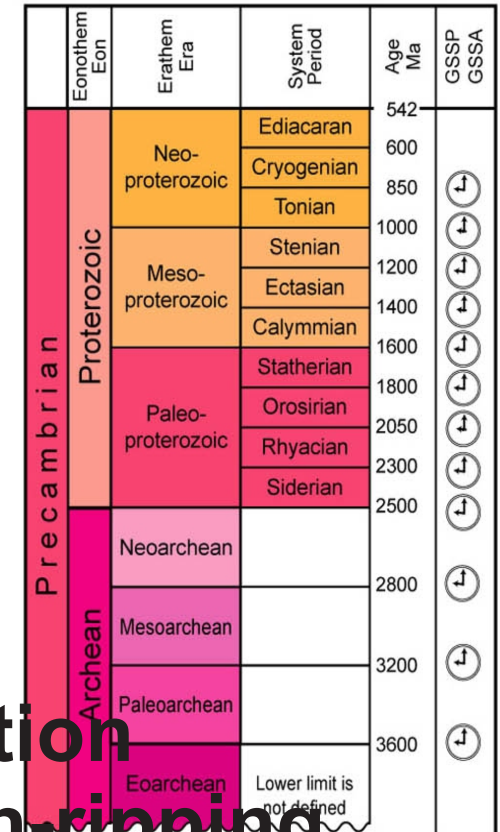

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'Cambrian explosion'

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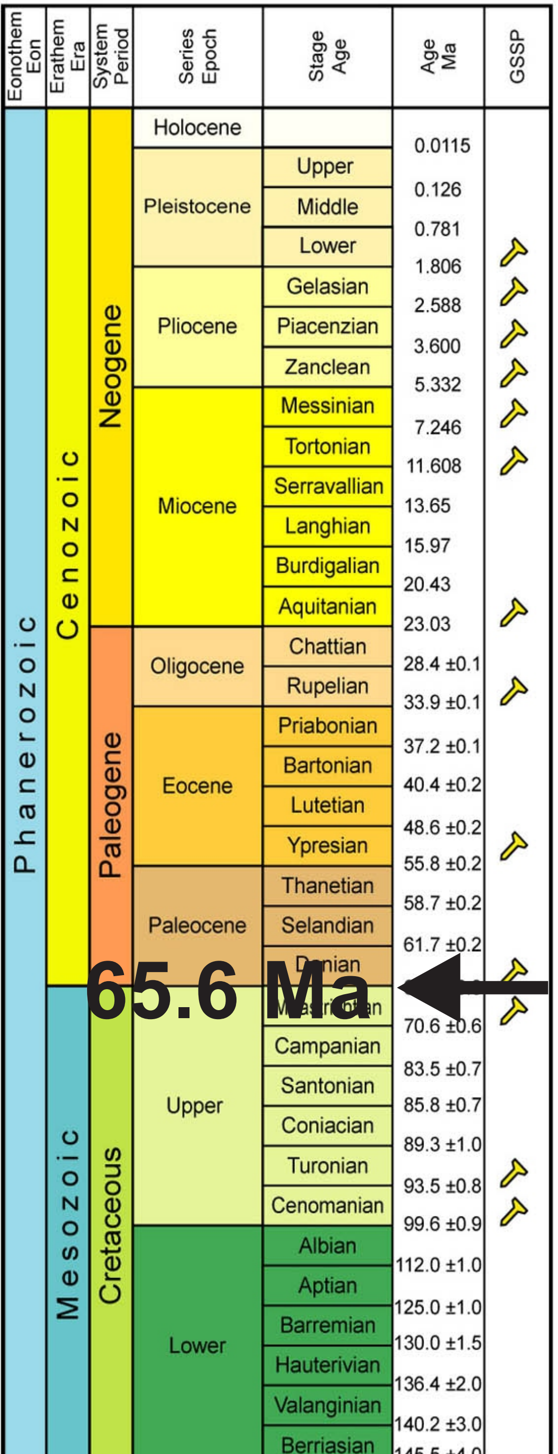

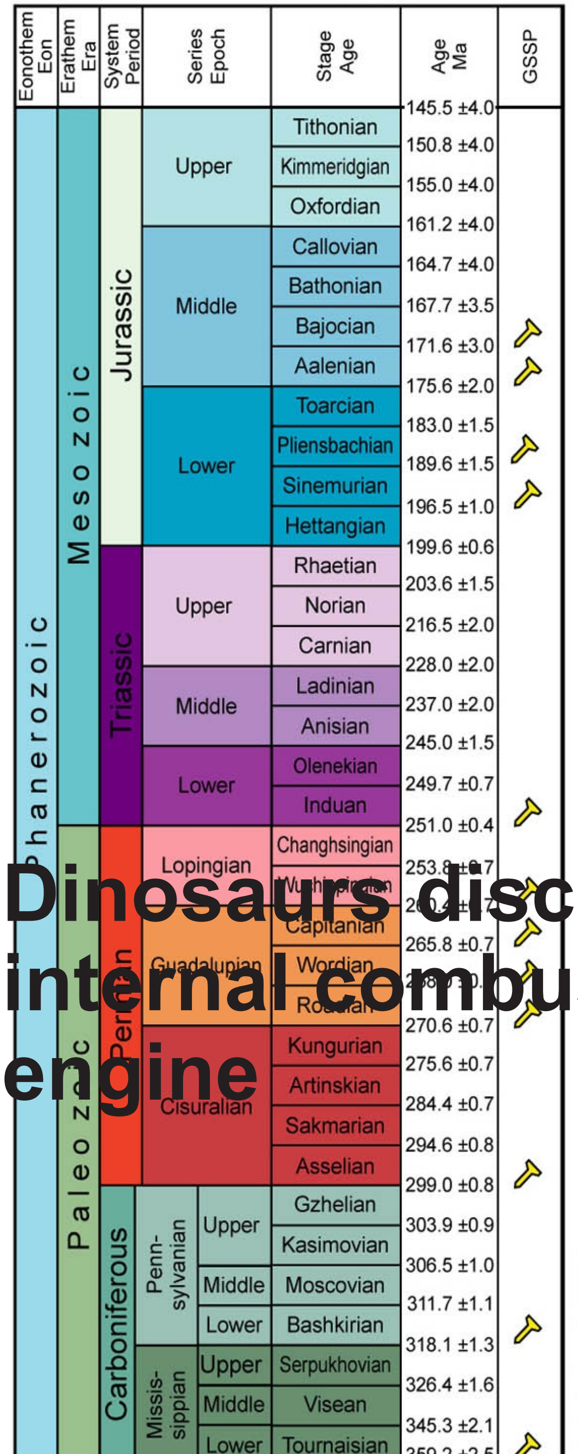

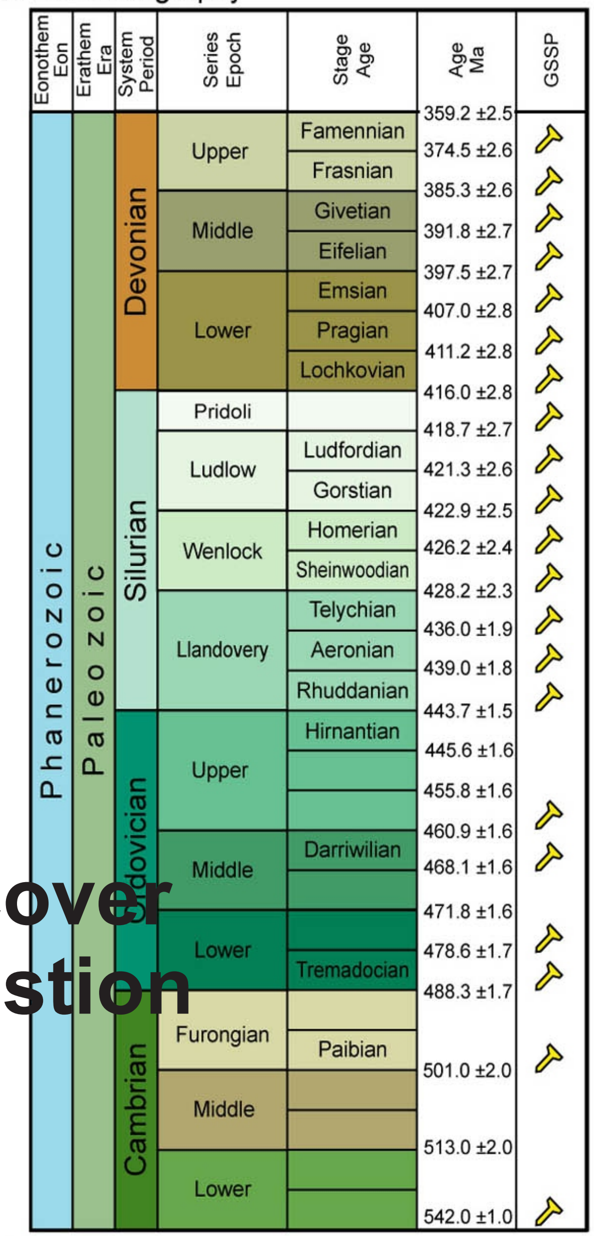

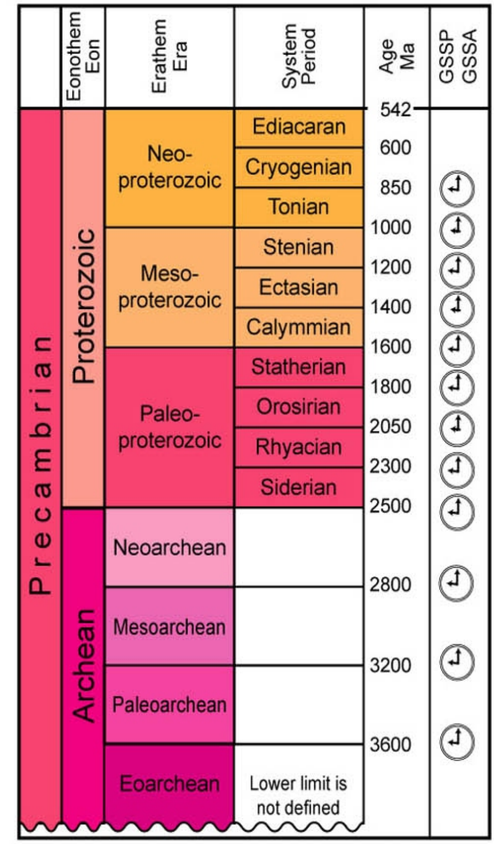

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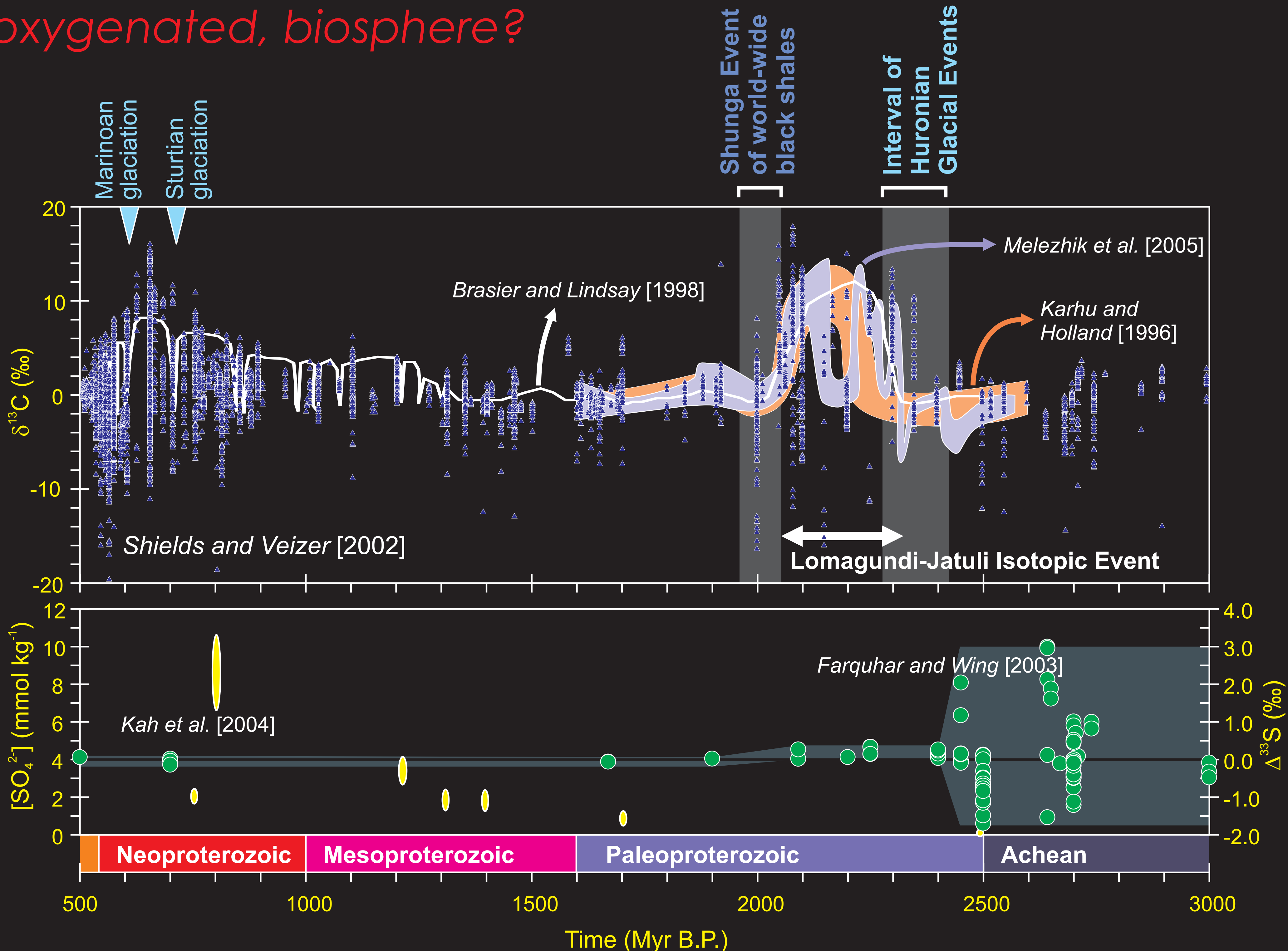
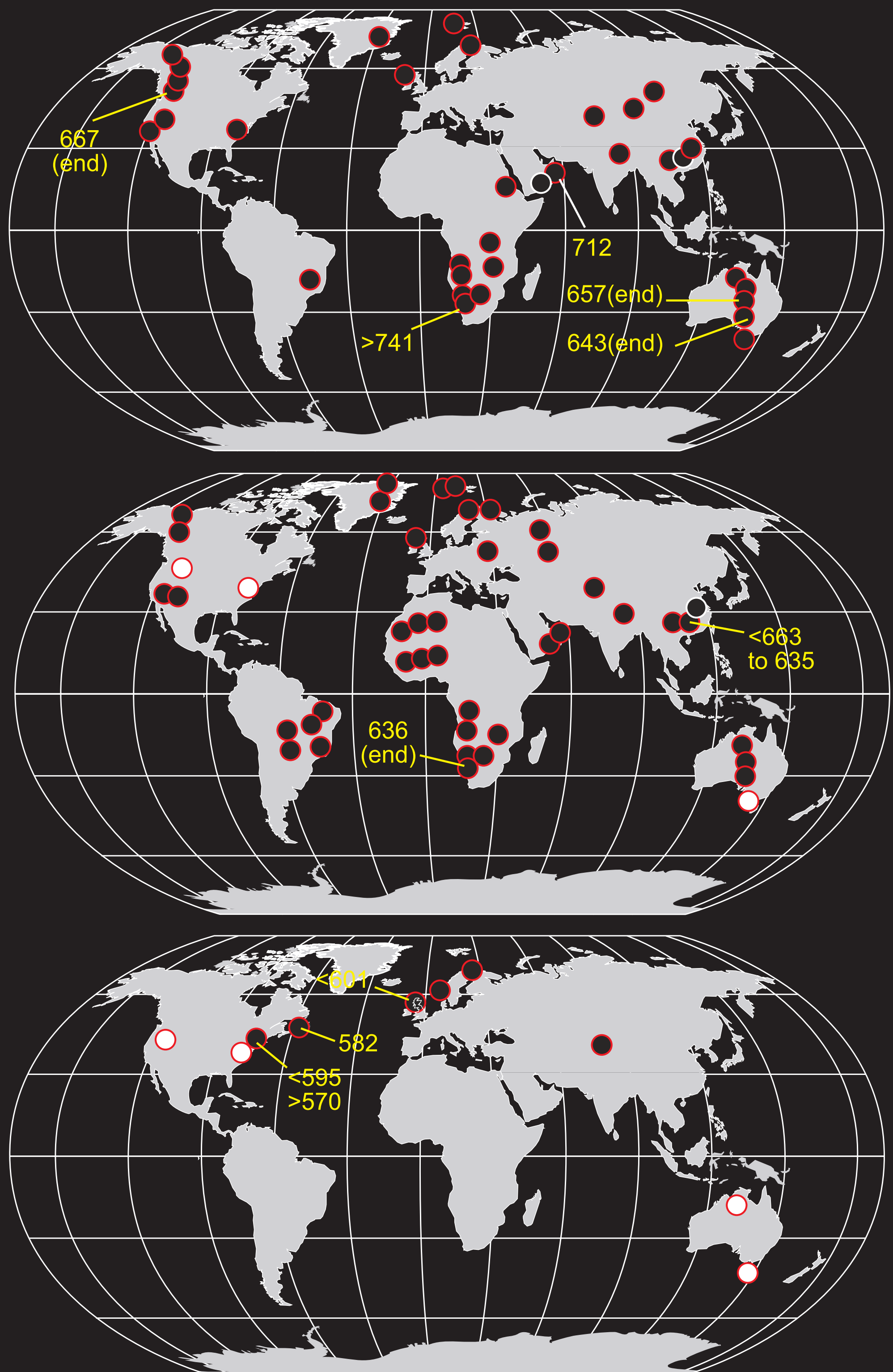
The Proterozoic: Gateway to an metazoan-dominated, oxygenated, biosphere?



Evidence for glaciation



From: *Fairchild and Kennedy* [2007]

From: *Hoffman and Schrag* [2002]

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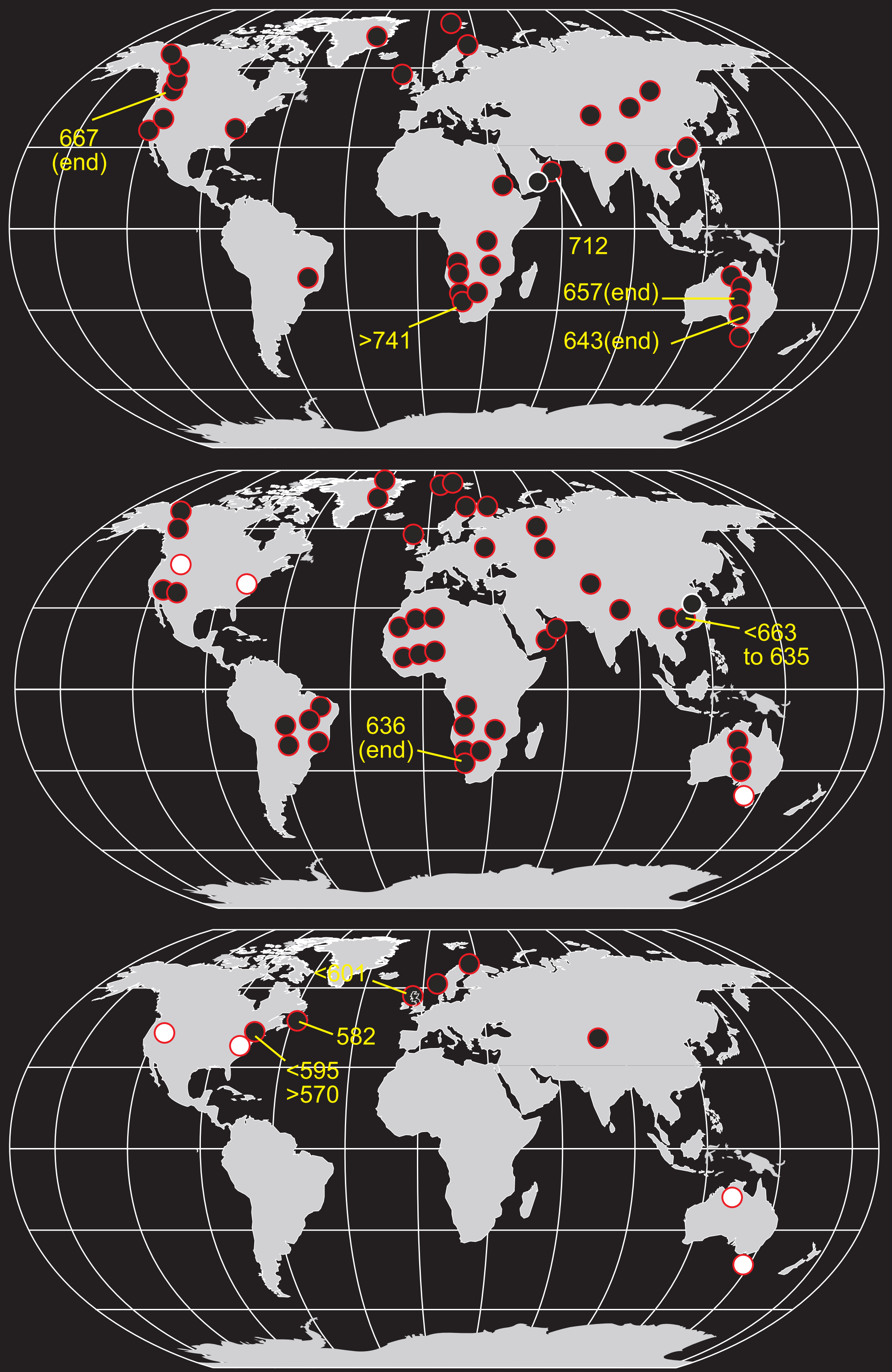

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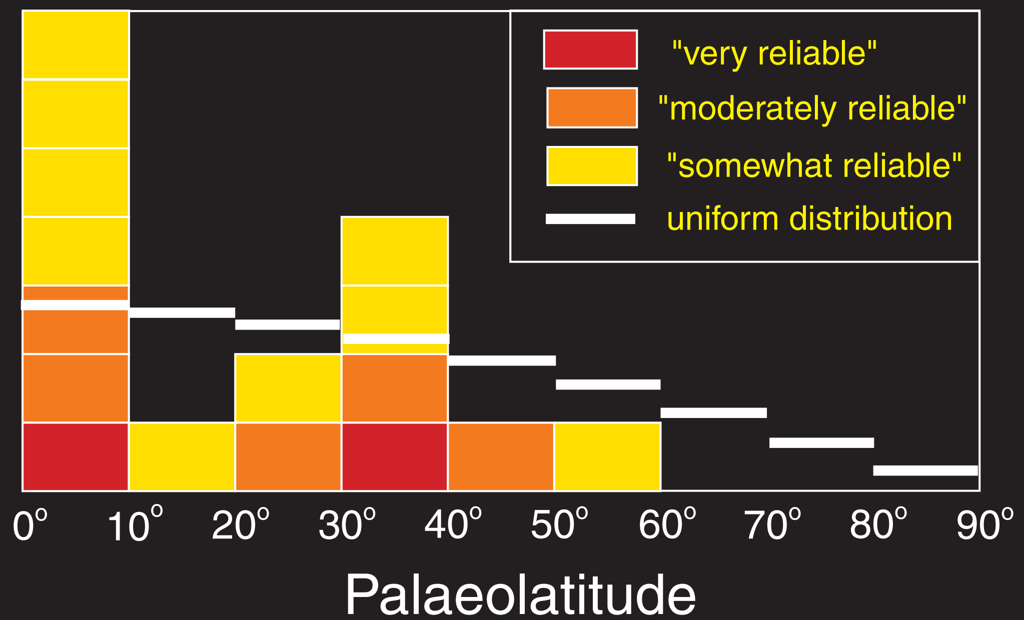

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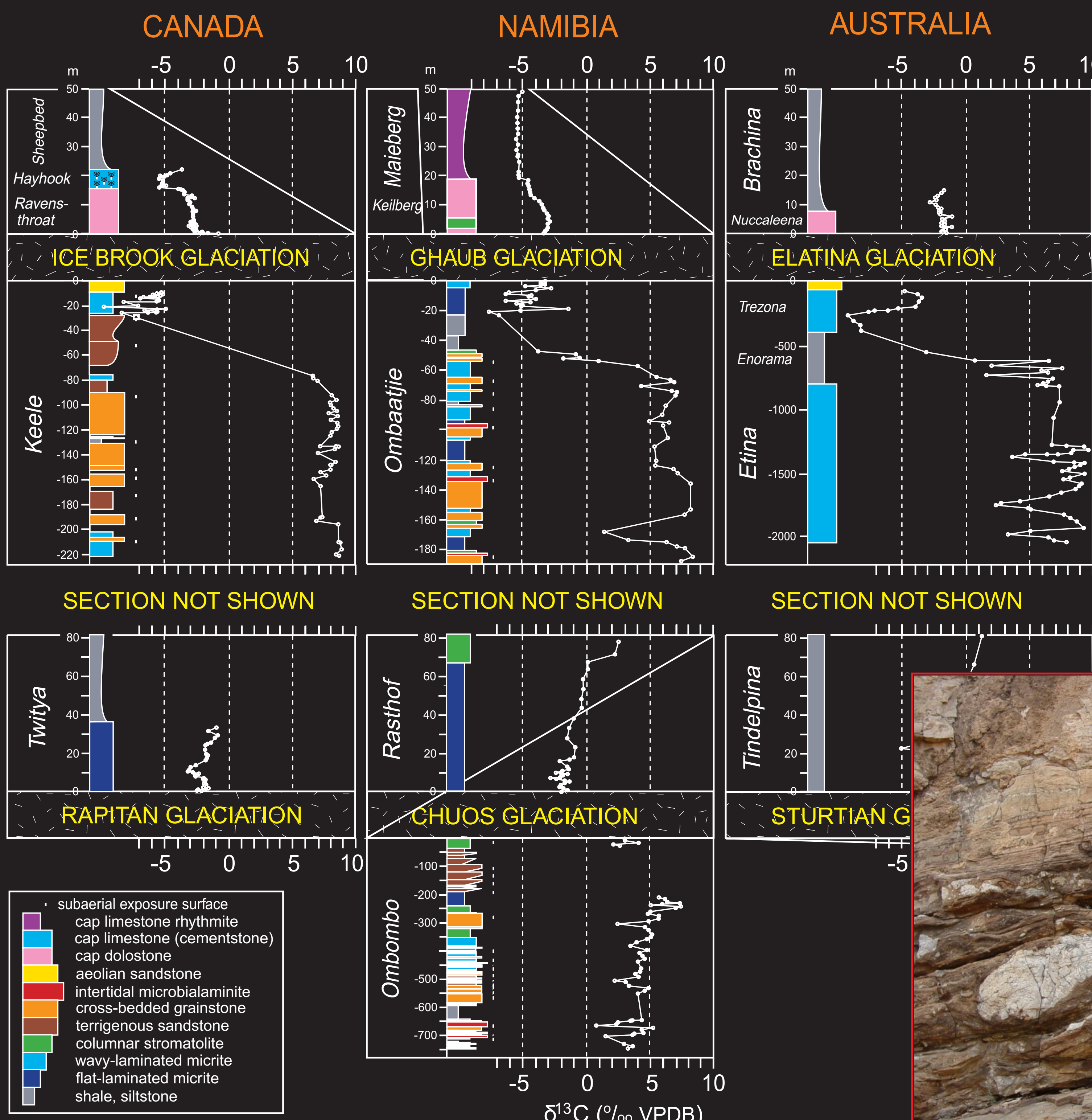
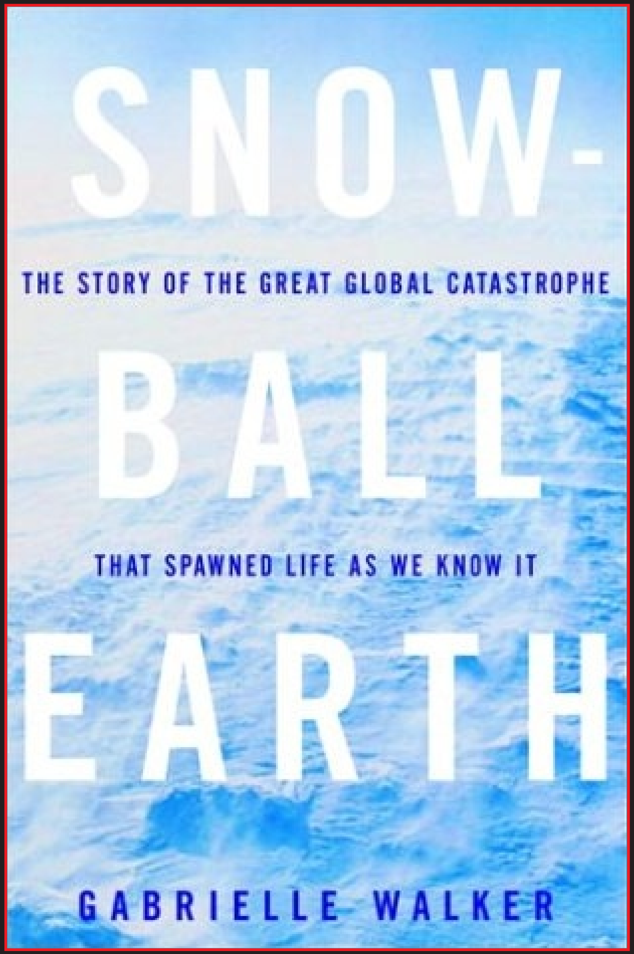


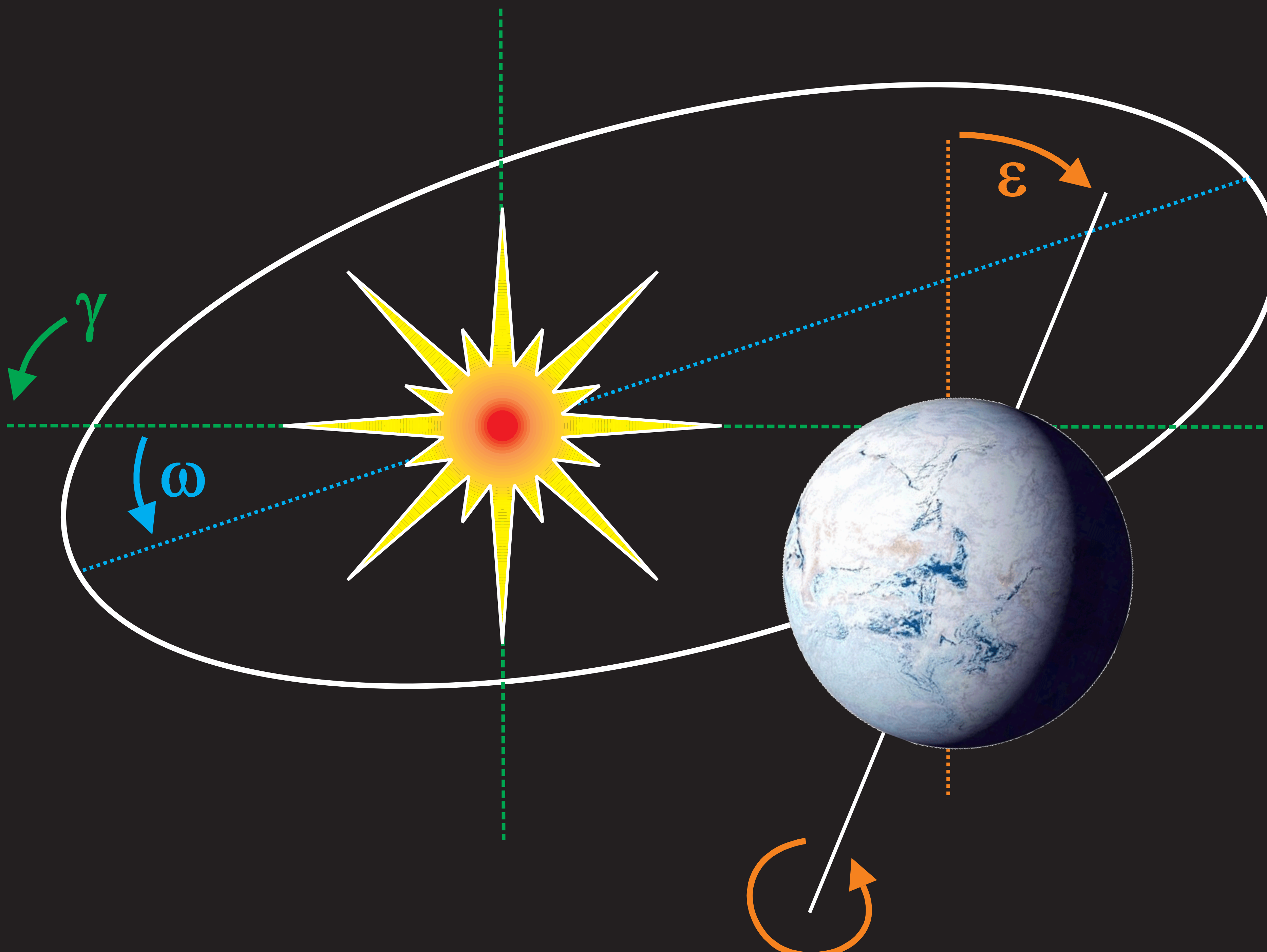
From: *Hoffman and Schrag* [2002]

‘snowball Earth’

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

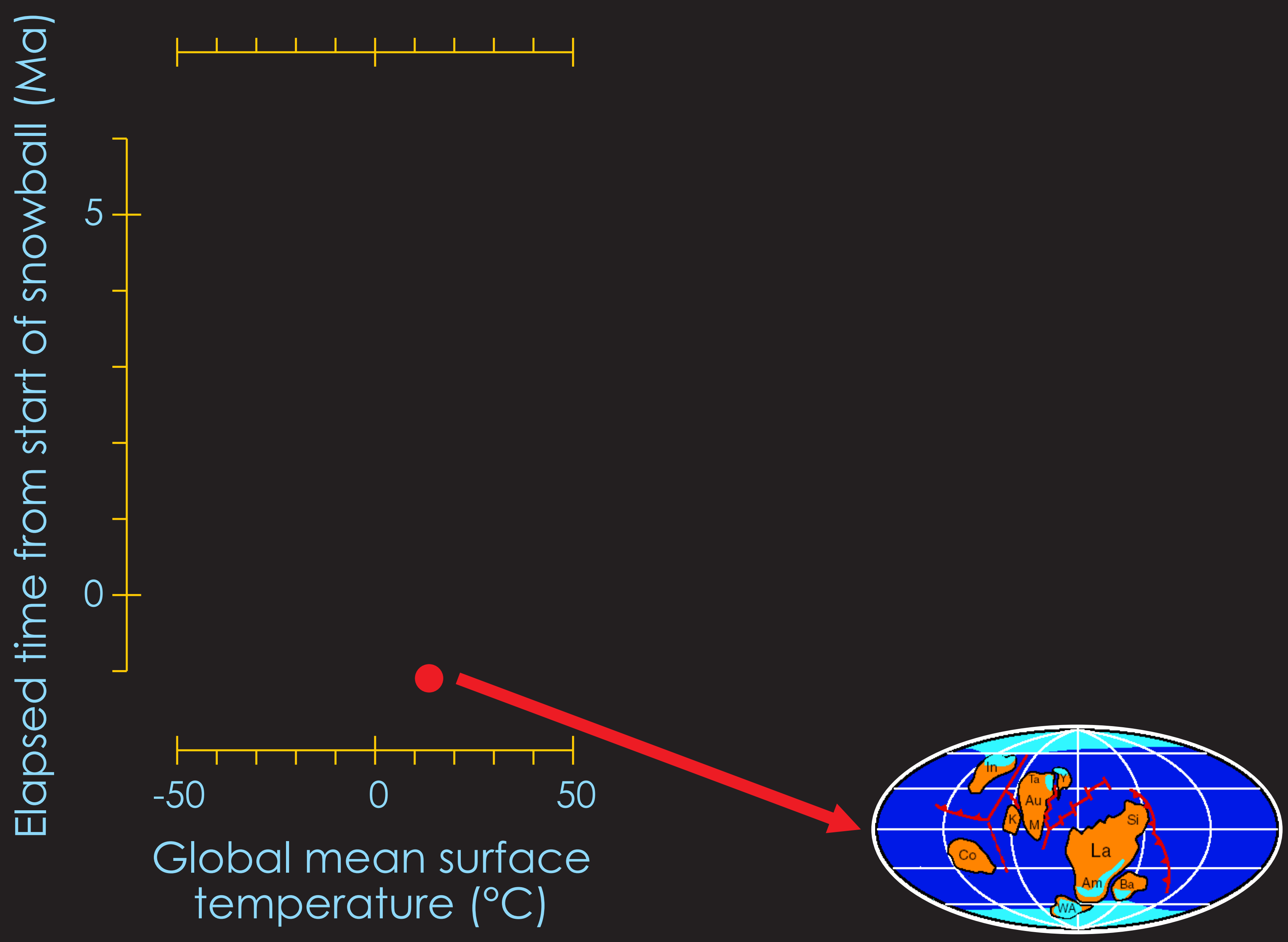


'snowball Earth'



The snowball Earth hypothesis

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



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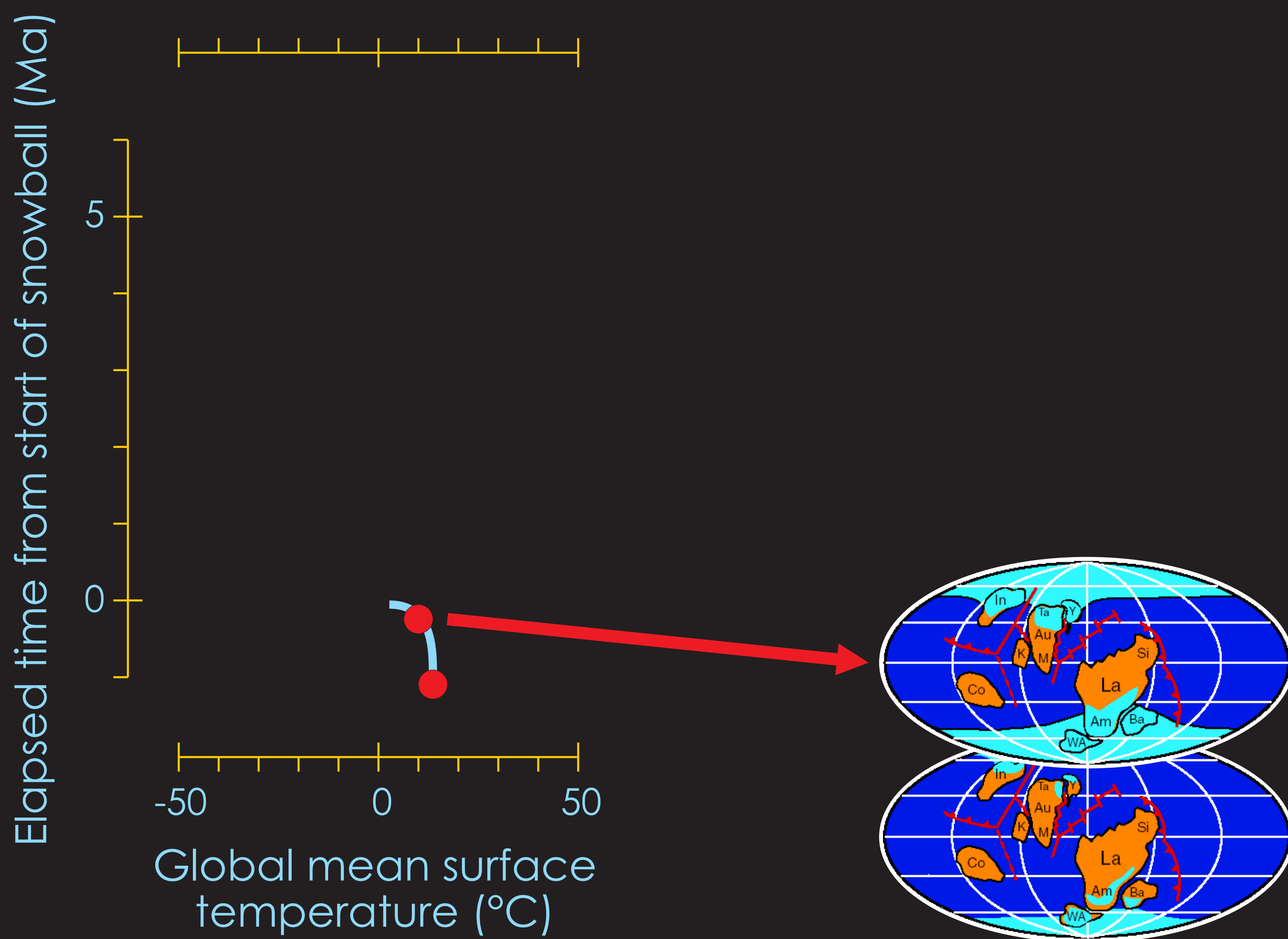
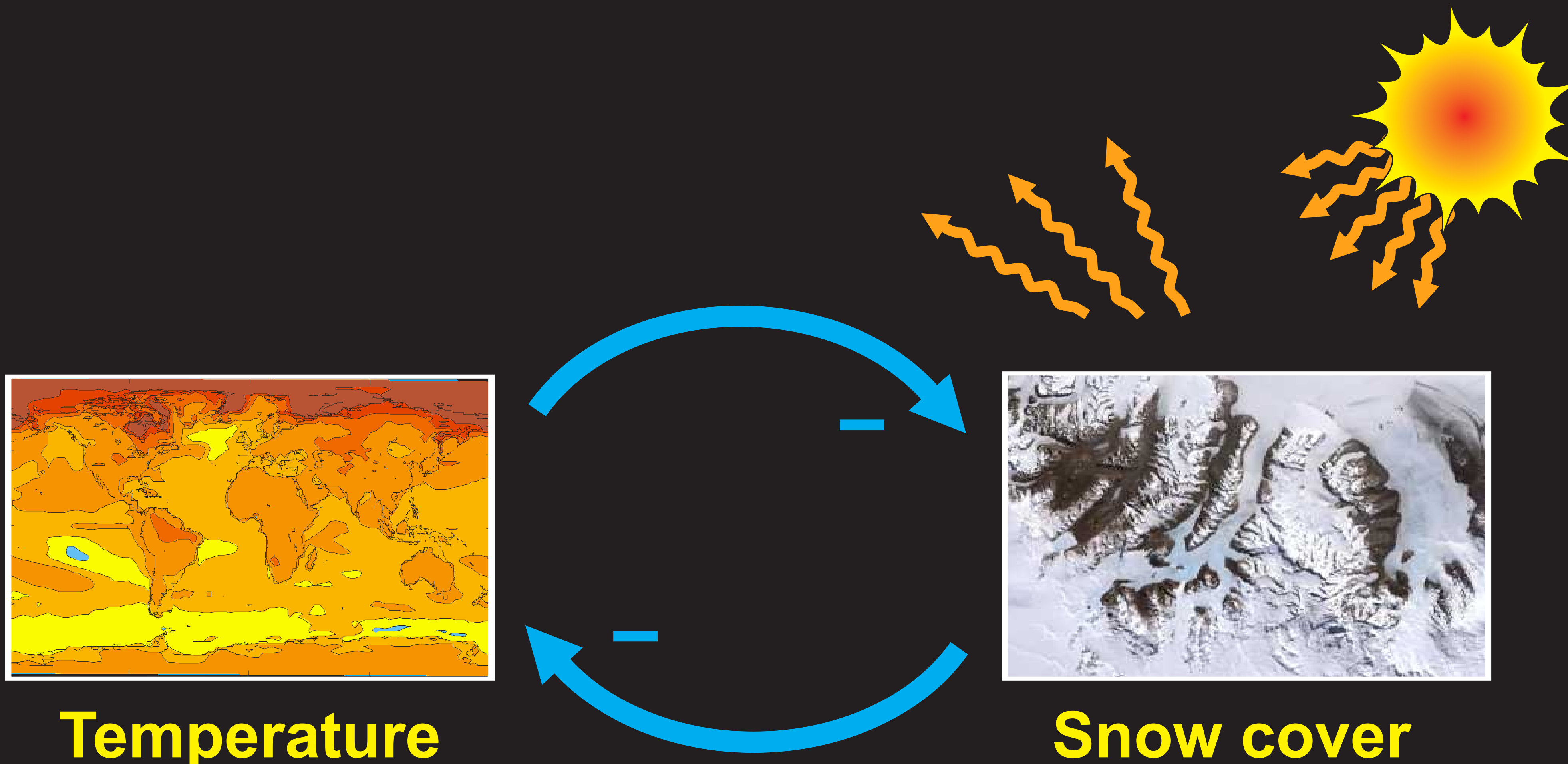
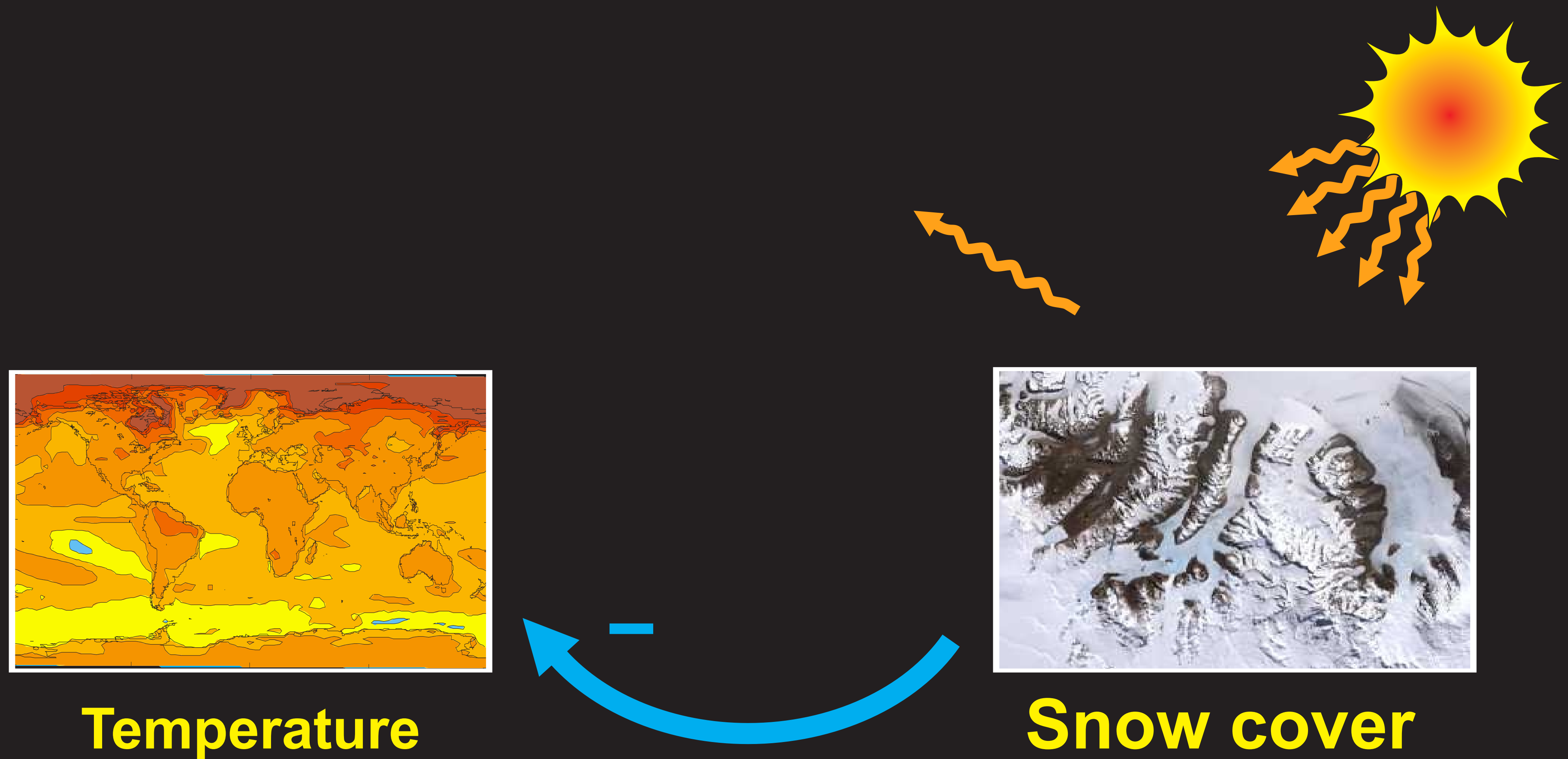


‘Feedbacks’



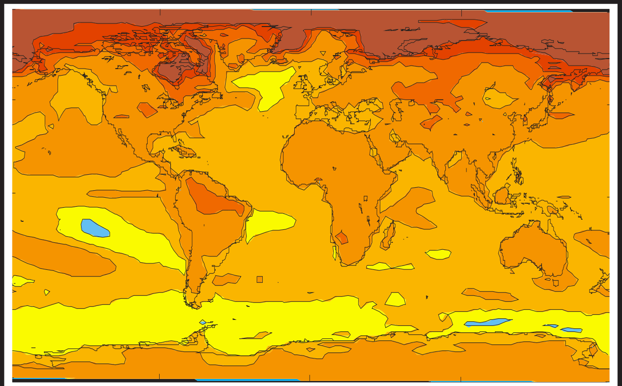
positive “ice-albedo” feedback

‘Feedbacks’



= −1/2°C

‘Feedbacks’



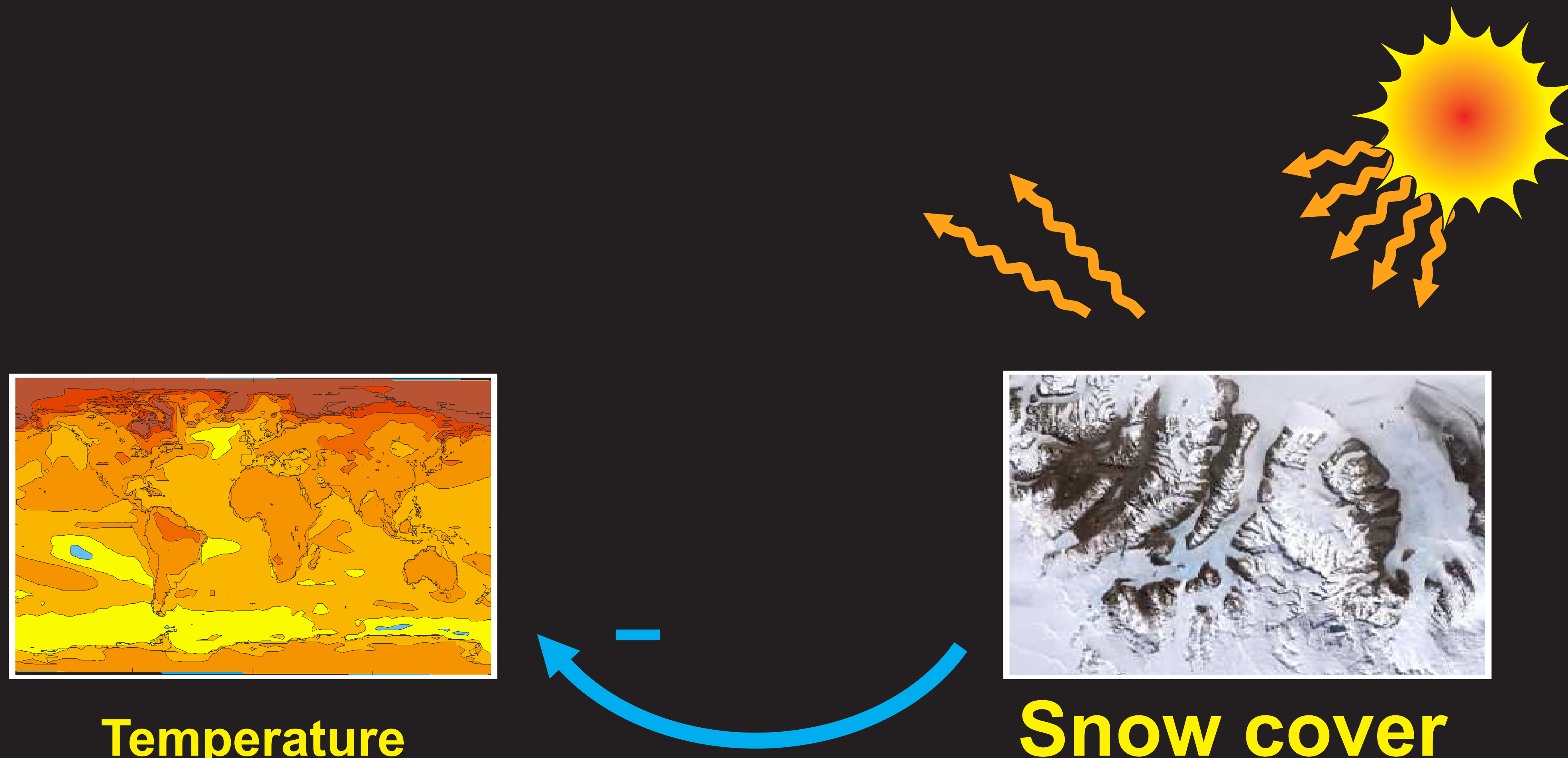
Temperature

–

Snow cover

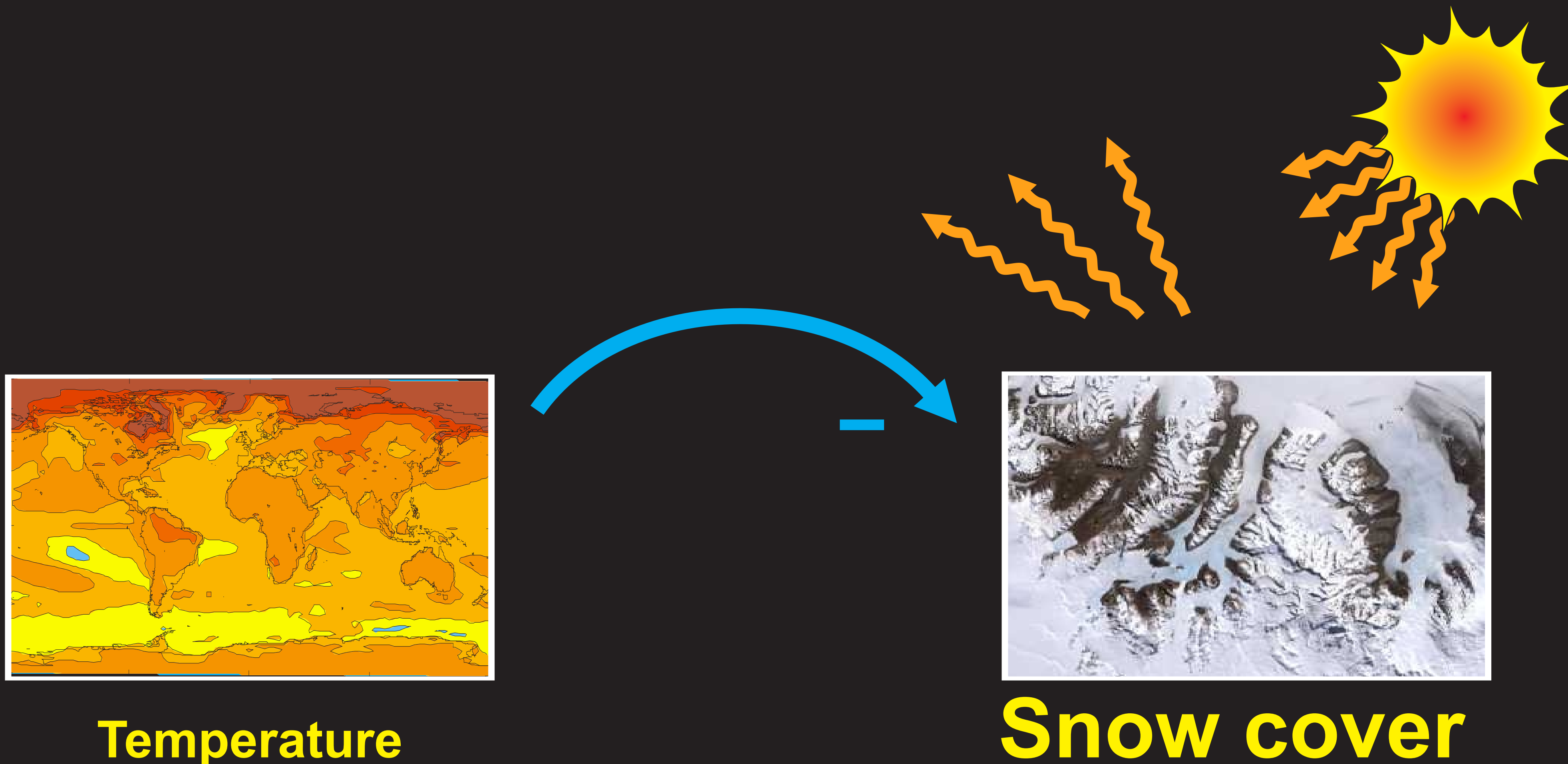
TOTAL CHANGE = -1/2°C

'Feedbacks'



TOTAL CHANGE = $-1/2°C - 1/4°C$

‘Feedbacks’

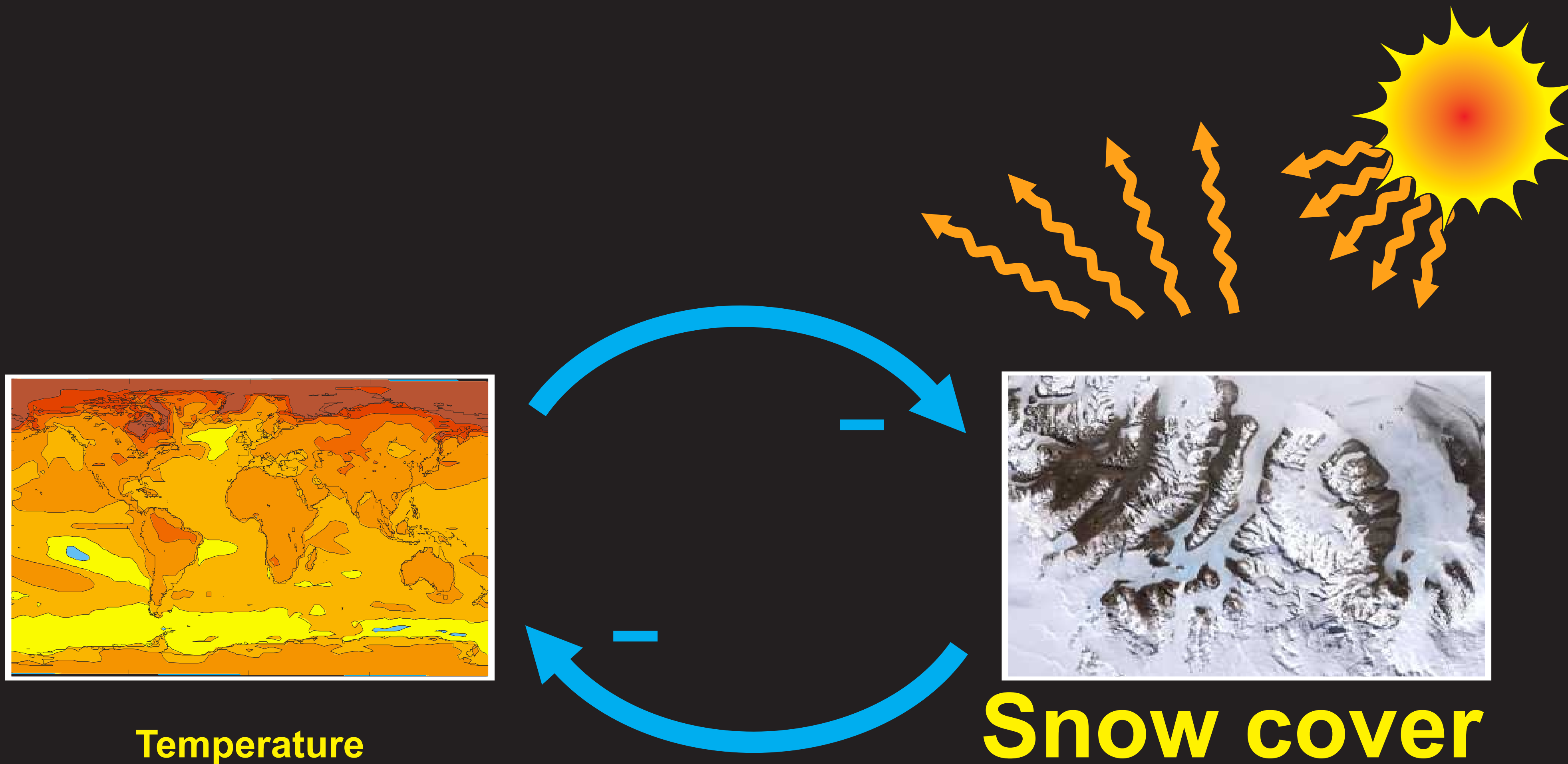


TOTAL CHANGE = -1/2°C - 1/4°C

'Feedbacks'

TOTAL CHANGE = -1/2°C - 1/4°C - 1/8°C

‘Feedbacks’

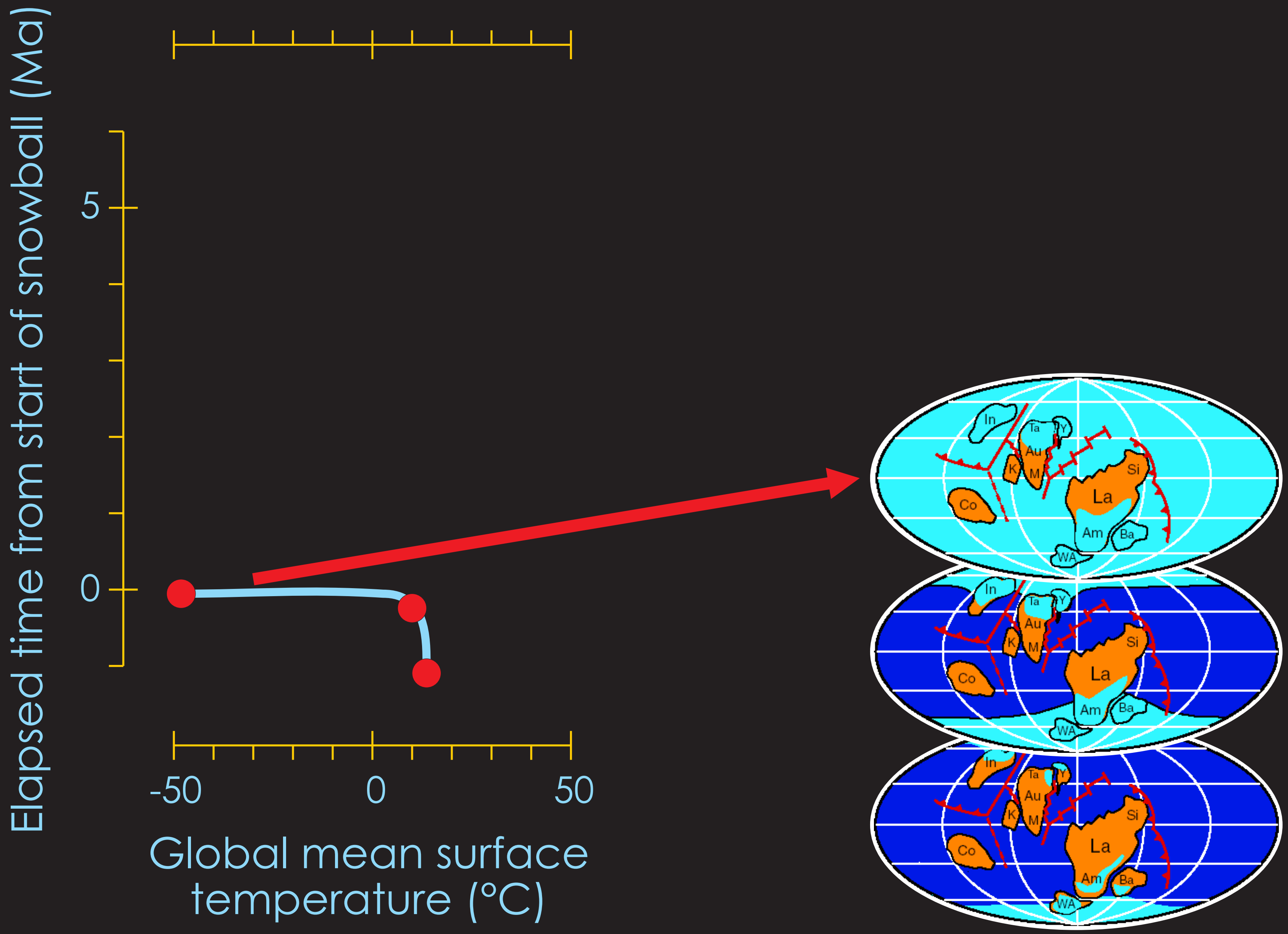


TOTAL CHANGE = -1/2°C - 1/4°C - 1/8°C - 1/16° - ....

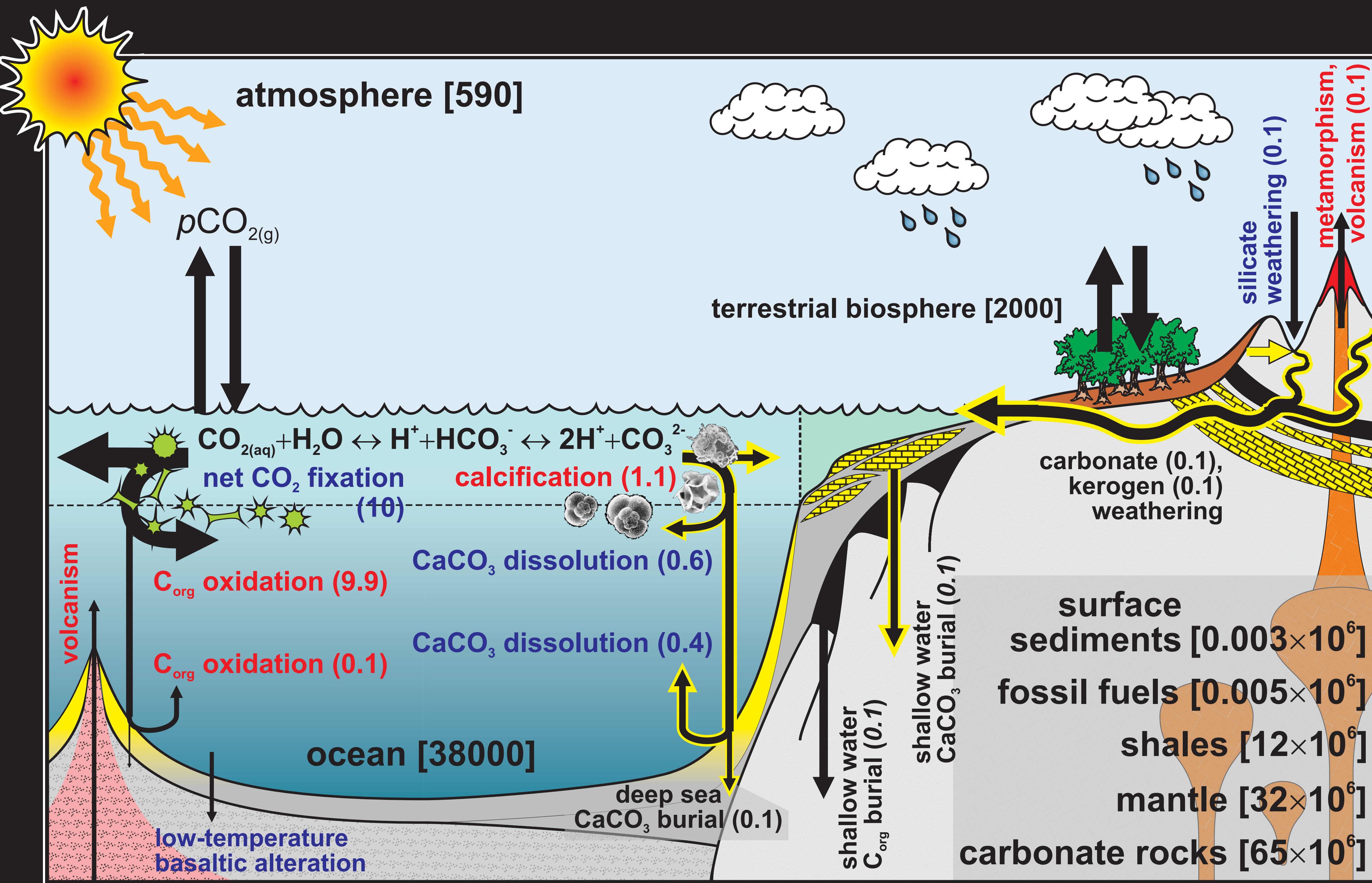
‘Feedbacks’ (’runaway’)

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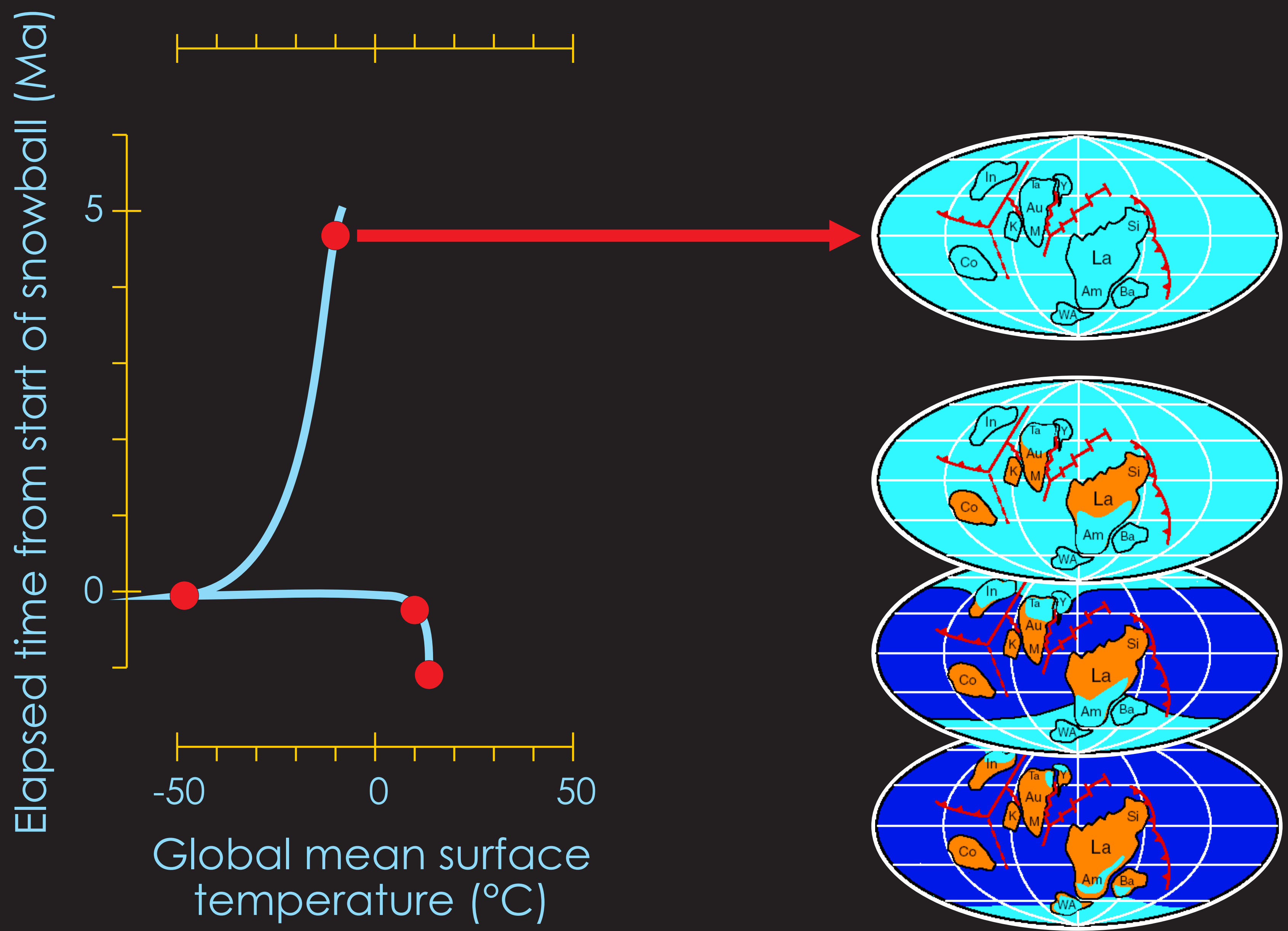
Ultimately, the (alkalinity: Ca^{2+}) weathering products must be removed through carbonate precipitation and burial in marine sediments:

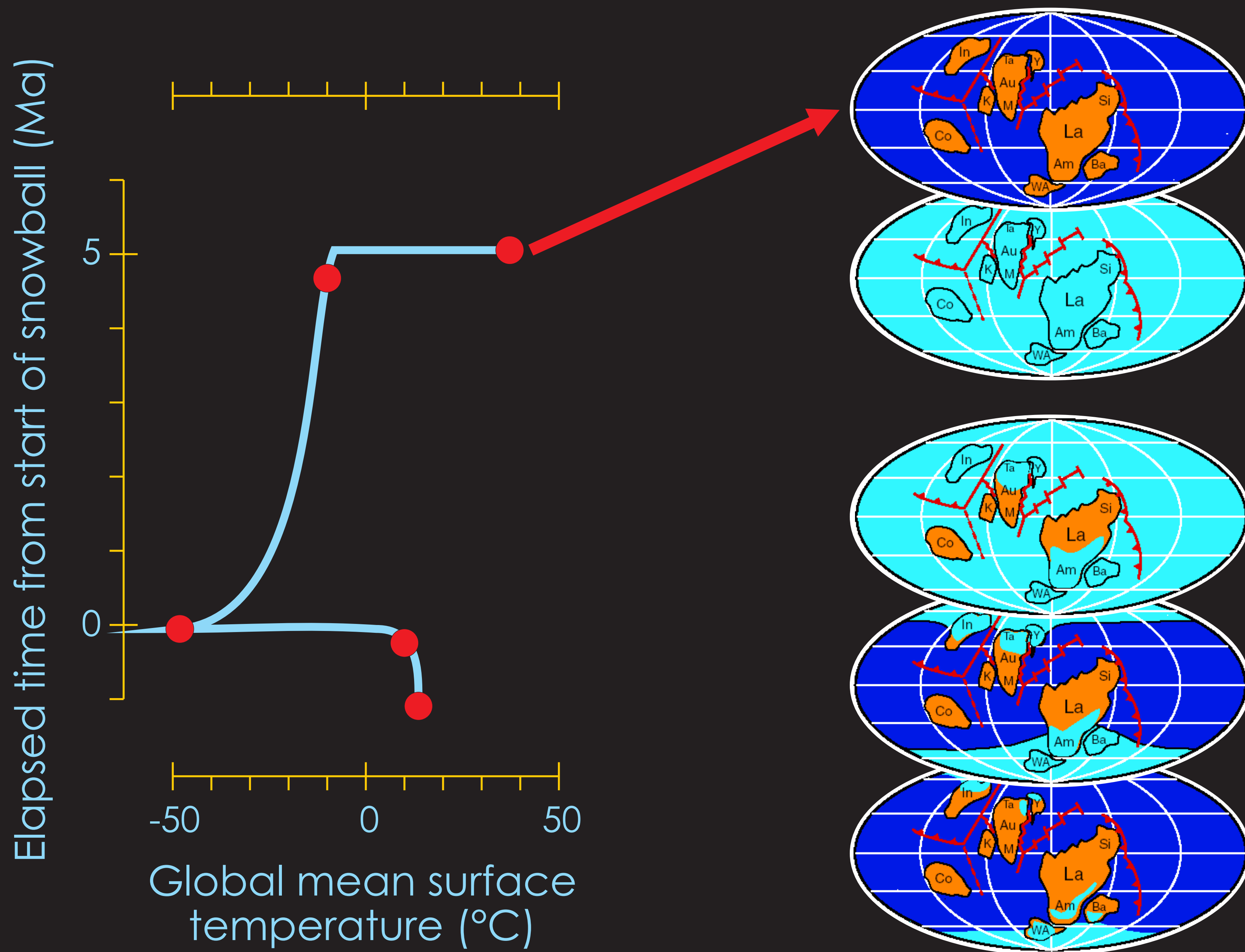
(3) $Ca^{2+} + 2HCO_3^- \rightarrow CO_{2(aq)} + H_2O + CaCO_3$

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.

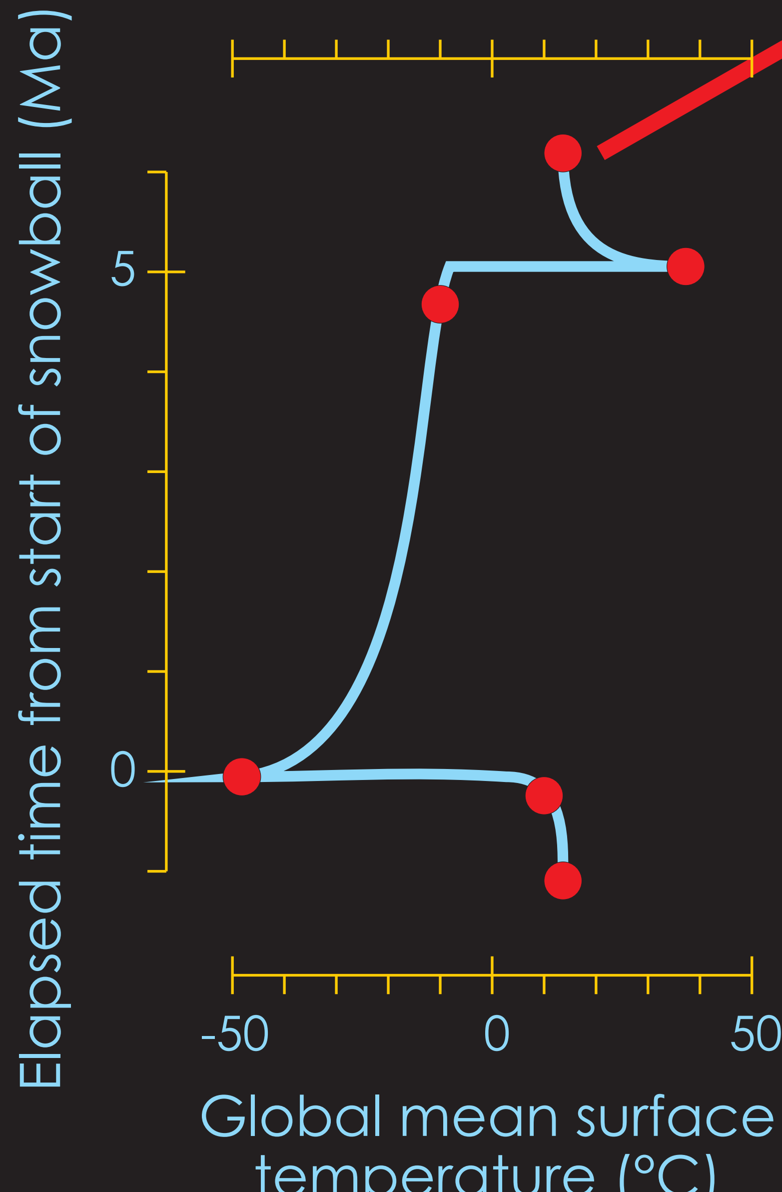
The snowball Earth hypothesis

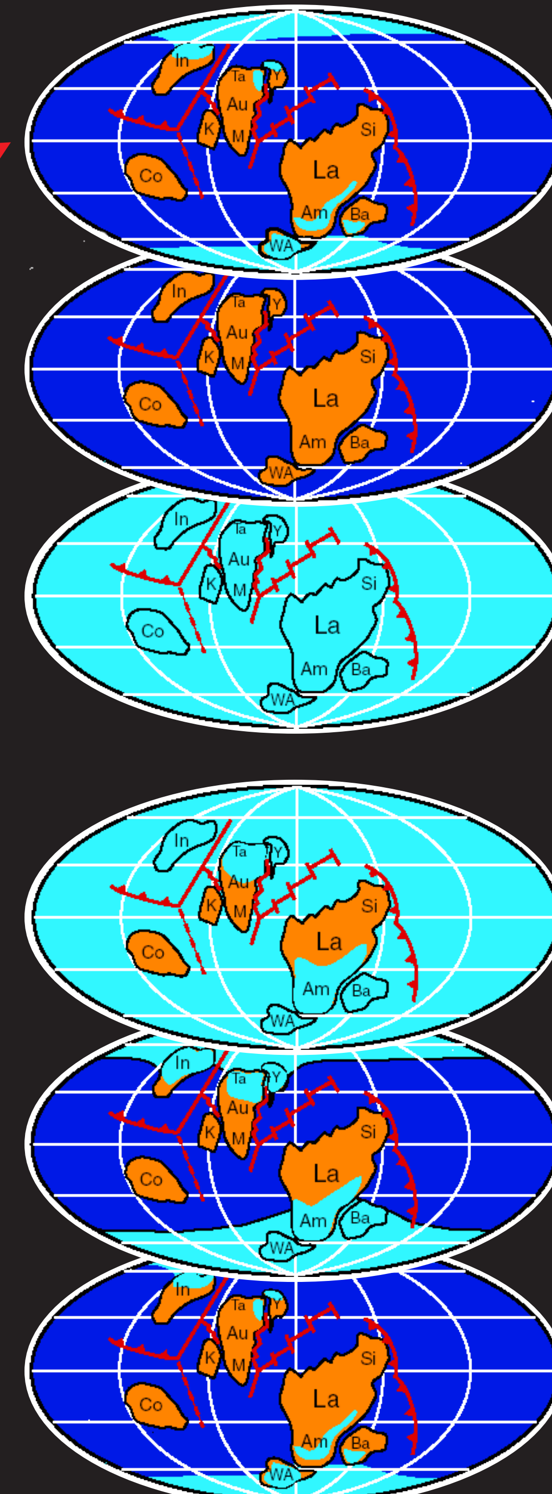


The snowball Earth hypothesis



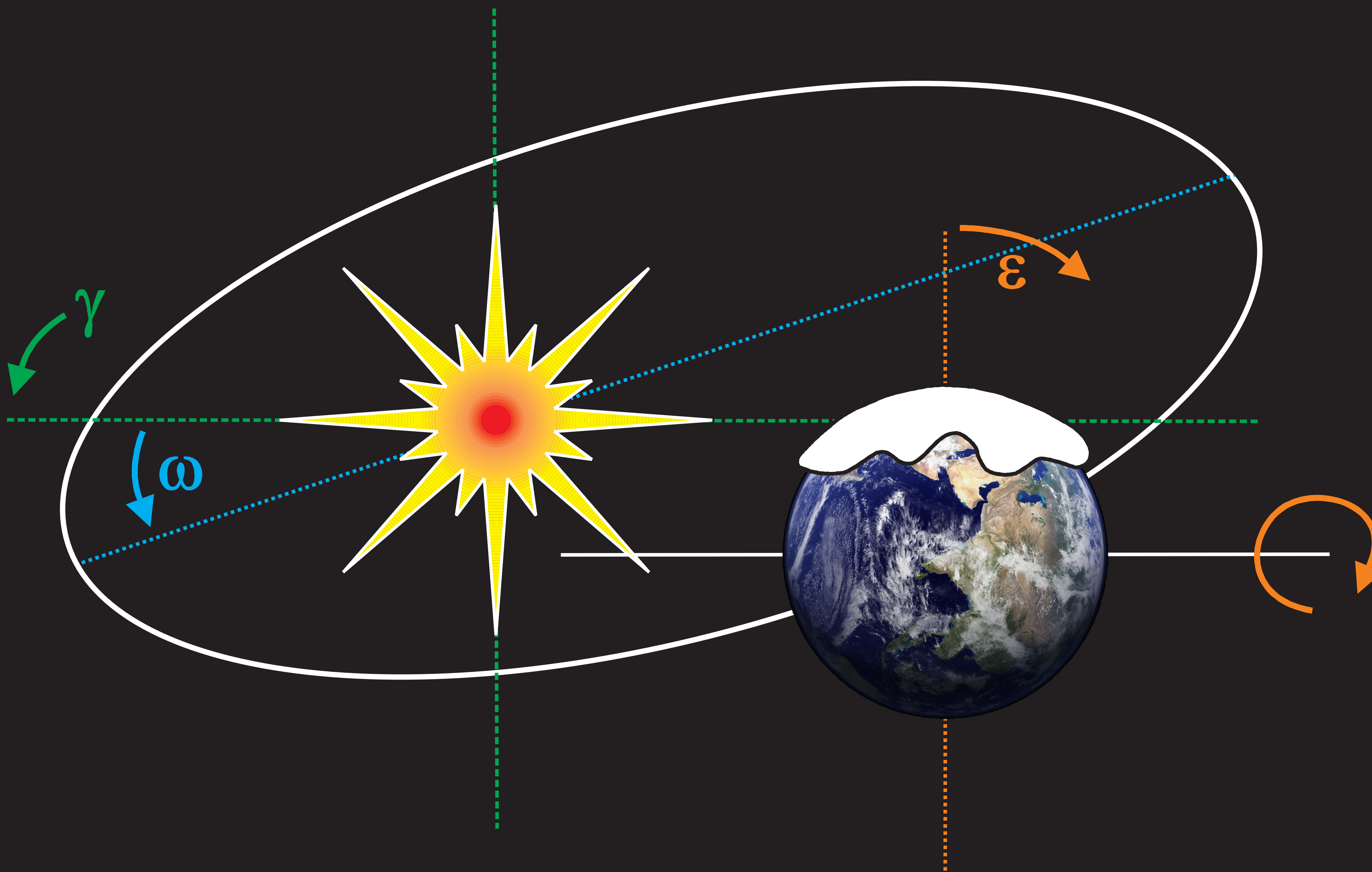
The snowball Earth hypothesis

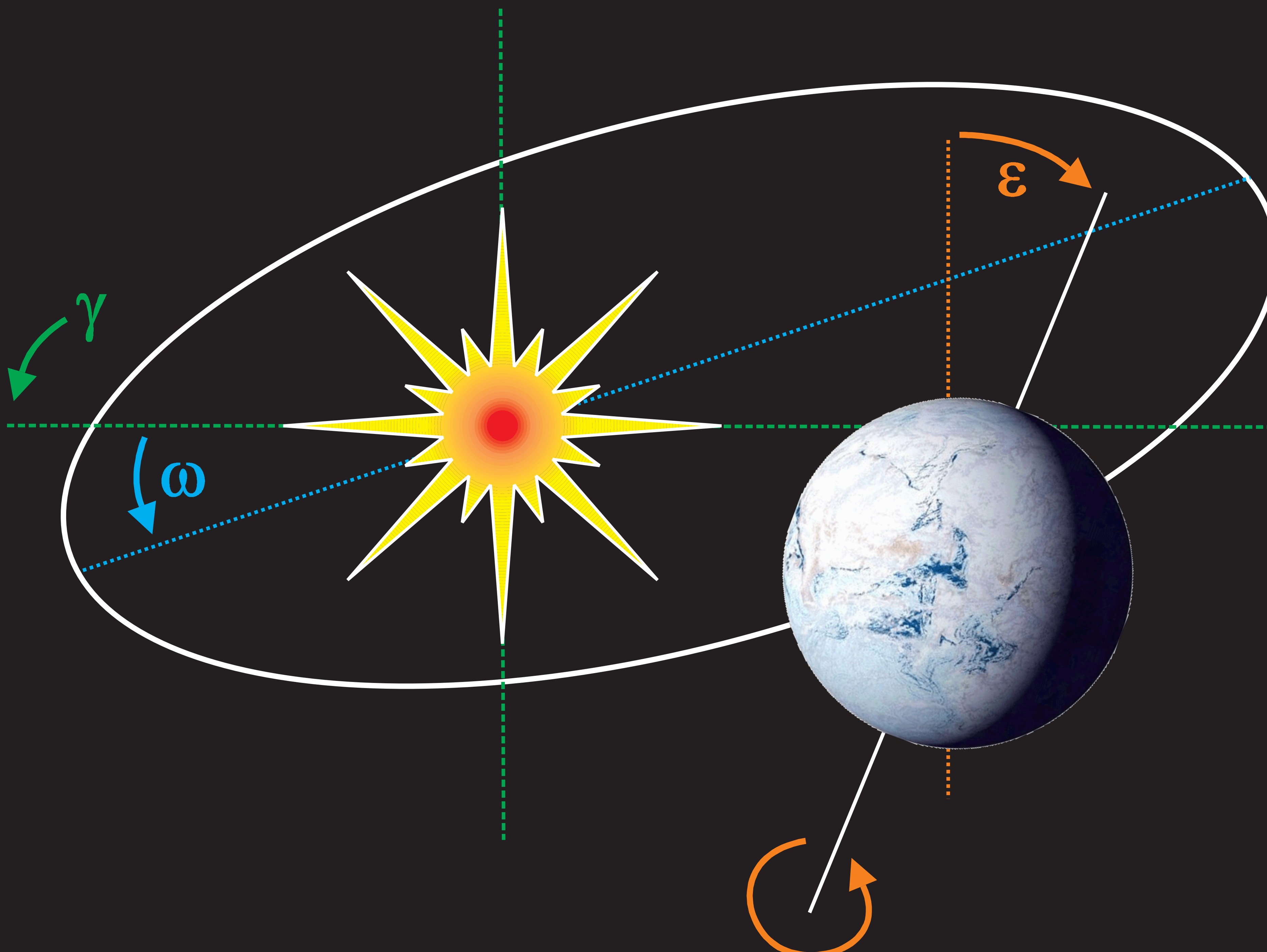




adapted from; *Hoffman and Schrag* [2002]

Alternative explanations for the glacial observations

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