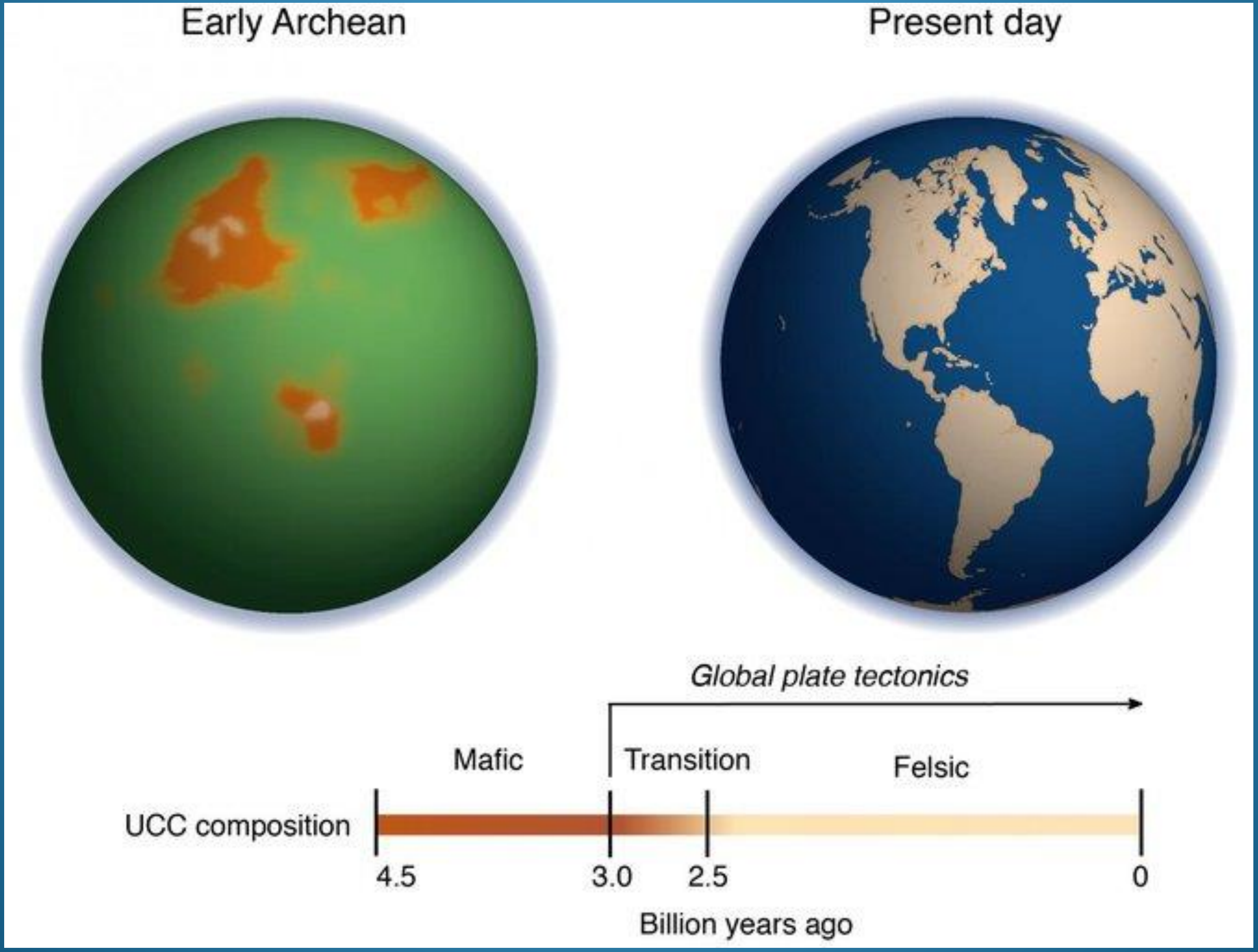
Lecture 10 - Earth's Climate History



Today’s Learning Outcomes

1. Know how to read a geologic time scale
2. Be able to explain how the planet escaped the “Snowball Earth” events
3. Know what the relationship between the direction and rate of climate change are with mass extinction events

INTERNATIONAL CHRONOSTRATIGRAPHIC CHART

IUGS

www.stratigraphy.org

International Commission on Stratigraphy

v 2024/12

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch		Stage / Age	numerical age (Ma)
						present
Phanerozoic	Cenozoic	Quaternary	Holocene	U/L	Meghalayan	0.0042
				M	Northgrippian	0.0082
				L/E	Greenlandian	0.0117
			Pleistocene	U/L	*Upper*	0.129
				M	Chibanian	0.774
				L/E	Calabrian	1.80
					Gelasian	2.58
		Neogene	Pliocene	U/L	Piacenzian	3.600
				L/E	Zanclean	5.333
			Miocene	U/L	Messinian	7.246
					Tortonian	11.63
				M	Serravallian	13.82
					Langhian	15.98
				L/E	Burdigalian	20.45
					Aquitanian	23.04
		Paleogene	Oligocene		Chattian	27.30
					Rupelian	33.9
			Eocene		Priabonian	37.71
					Bartonian	41.03
					Lutetian	48.07
					Ypresian	56.00
			Paleocene		Thanetian	59.24
					Selandian	61.66
					Danian	66.00
	Mesozoic	Cretaceous	Upper		Maastrichtian	72.2 ±0.2
					Campanian	83.6 ±0.2
					Santonian	85.7 ±0.2
					Coniacian	89.8 ±0.3
					Turonian	93.9 ±0.2
					Cenomanian	100.5 ±0.1
			Lower		Albian	113.2 ±0.3
					Aptian	121.4 ±0.6
					Barremian	125.77
					Hauterivian	132.6 ±0.6
					Valanginian	137.05 ±0.2
					Berriasian	143.1 ±0.6

Eonothem / Eon	Erathem / Era	System / Period		Series / Epoch	Stage / Age	numerical age (Ma)
						143.1 ±0.6
Phanerozoic	Mesozoic	Jurassic		Upper	Tithonian	149.2 ±0.7
					Kimmeridgian	154.8 ±0.8
					Oxfordian	161.5 ±1.0
				Middle	Callovian	165.3 ±1.1
					Bathonian	168.2 ±1.2
					Bajocian	170.9 ±0.8
					Aalenian	174.7 ±0.8
				Lower	Toarcian	184.2 ±0.3
					Pliensbachian	192.9 ±0.3
					Sinemurian	199.5 ±0.3
					Hettangian	201.4 ±0.2
		Triassic		Upper	Rhaetian	~ 205.7
					Norian	~ 227.3
					Carnian	~ 237
				Middle	Ladinian	241.464 ±0.28
					Anisian	246.7
				Lower	Olenekian	249.9
					Induan	251.902 ±0.024
	Paleozoic	Permian		Lopingian	Changhsingian	254.14 ±0.07
					Wuchiapingian	259.51 ±0.21
				Guadalupian	Capitanian	264.28 ±0.16
					Wordian	266.9 ±0.4
					Roadian	274.4 ±0.4
				Cisuralian	Kungurian	283.3 ±0.4
					Artinskian	290.1 ±0.26
					Sakmarian	293.52 ±0.17
					Asselian	298.9 ±0.15
		Carboniferous	Pennsylvanian	Upper	Gzhelian	303.7 ±0.1
					Kasimovian	307.0 ±0.1
				Middle	Moscovian	315.2 ±0.2
				Lower	Bashkirian	323.4 ±0.4
			Mississippian	Upper	Serpukhovian	330.3 ±0.4
				Middle	Visean	346.7 ±0.4
				Lower	Tournaisian	358.86 ±0.19

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	numerical age (Ma)
					358.86 ±0.19
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	372.15 ±0.46
				Frasnian	382.31 ±1.36
			Middle	Givetian	387.95 ±1.04
				Eifelian	393.47 ±0.99
			Lower	Emsian	410.62 ±1.95
				Pragian	413.02 ±1.91
				Lochkovian	419.62 ±1.36
		Silurian	Pridoli		422.7 ±1.6
			Ludlow	Ludfordian	425.0 ±1.5
				Gorstian	426.7 ±1.5
			Wenlock	Homerian	430.6 ±1.3
				Sheinwoodian	432.9 ±1.2
			Llandovery	Telychian	438.6 ±1.0
				Aeronian	440.5 ±1.0
				Rhuddanian	443.1 ±0.9
		Ordovician	Upper	Hirnantian	445.2 ±0.9
				Katian	452.8 ±0.7
				Sandbian	458.2 ±0.7
			Middle	Darriwilian	469.4 ±0.9
				Dapingian	471.3 ±1.4
			Lower	Floian	477.1 ±1.2
				Tremadocian	486.85 ±1.5
		Cambrian	Furongian	*Stage 10*	~ 491.0
				Jiangshanian	~ 494.2
				Paibian	~ 497.0
			Miaolingian	Guzhangian	~ 500.5
				Drumian	~ 504.5
				Wuliuan	~ 506.5
			Series 2	*Stage 4*	~ 514.5
				Stage 3	~ 521.0
			Terreneuvian	*Stage 2*	~ 529.0
				Fortunian	538.8 ±0.6

Eonothem / Eon		Erathem / Era	System / Period	numerical age (Ma)
				538.8 ±0.6
Precambrian	Proterozoic	Neo-proterozoic	Ediacaran	~ 635
			Cryogenian	~ 720
			Tonian	1000
		Meso-proterozoic	Stenian	1200
			Ectasian	1400
			Calymmian	1600
		Paleo-proterozoic	Statherian	1800
			Orosirian	2050
			Rhyacian	2300
			Siderian	2500
	Archean	Neo-archean		2800
		Meso-archean		3200
		Paleo-archean		3600
		Eo-archean		4031 ± 3
	Hadean			4567

Units of all ranks are in the process of being defined by Global Boundary Stratotype Section and Points (GSSP) for their lower boundaries, including those of the Archean and Proterozoic, long defined by Global Standard Stratigraphic Ages (GSSA). Ratified Subseries/Subepochs are abbreviated as U/L (Upper/Late), M (Middle) and L/E (Lower/Early). Italic fonts indicate informal units and placeholders for unnamed units. Previous versions and detailed information on ratified GSSPs are available at the website http://www.stratigraphy.org. The URL to this chart is provided below.

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Colouring follows the Commission for the Geological Map of the World (www.ccgm.org)

Chart drafted and maintained online by officers K.M. Cohen and N. Car.

The chart is a product of collective work by all ICS members past and present.

URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2024-12.pdf

To cite: Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013; updated) The ICS International Chronostratigraphic Chart. Episodes 36: 199-204

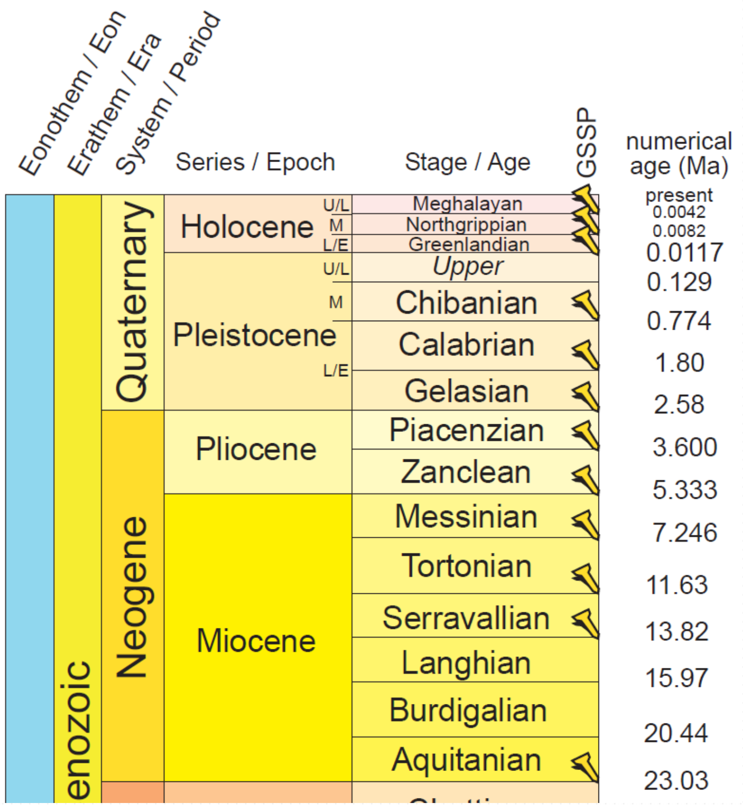
Divisions of the Geologic Time

- Split into a nested hierarchy

Today

- Eon
  - Era
    - Period
      - Epoch
        - Age

- Phanerozoic
  - Cenozoic
    - Quaternary
      - Holocene
        - Recent

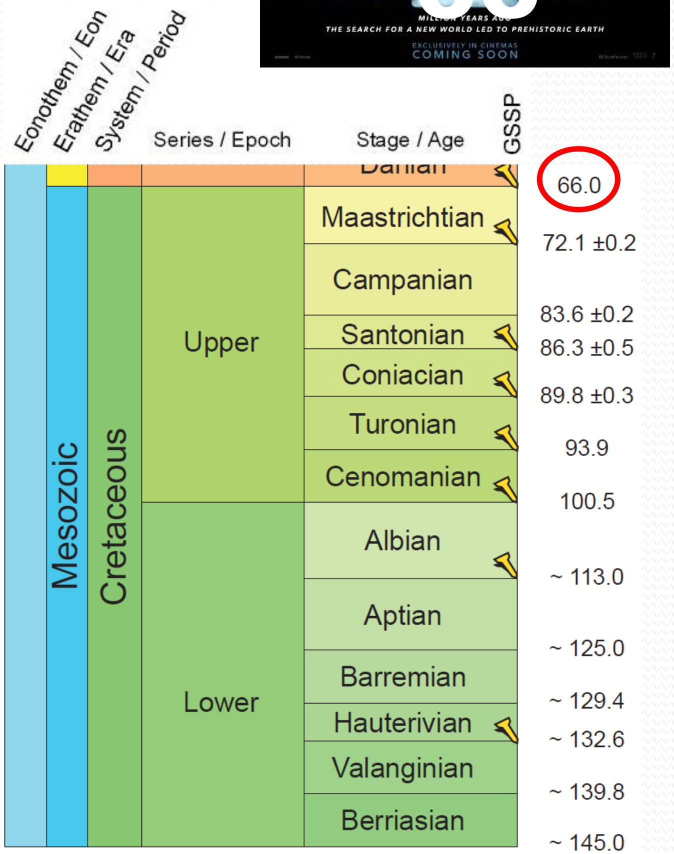


Divisions of the Geologic Time

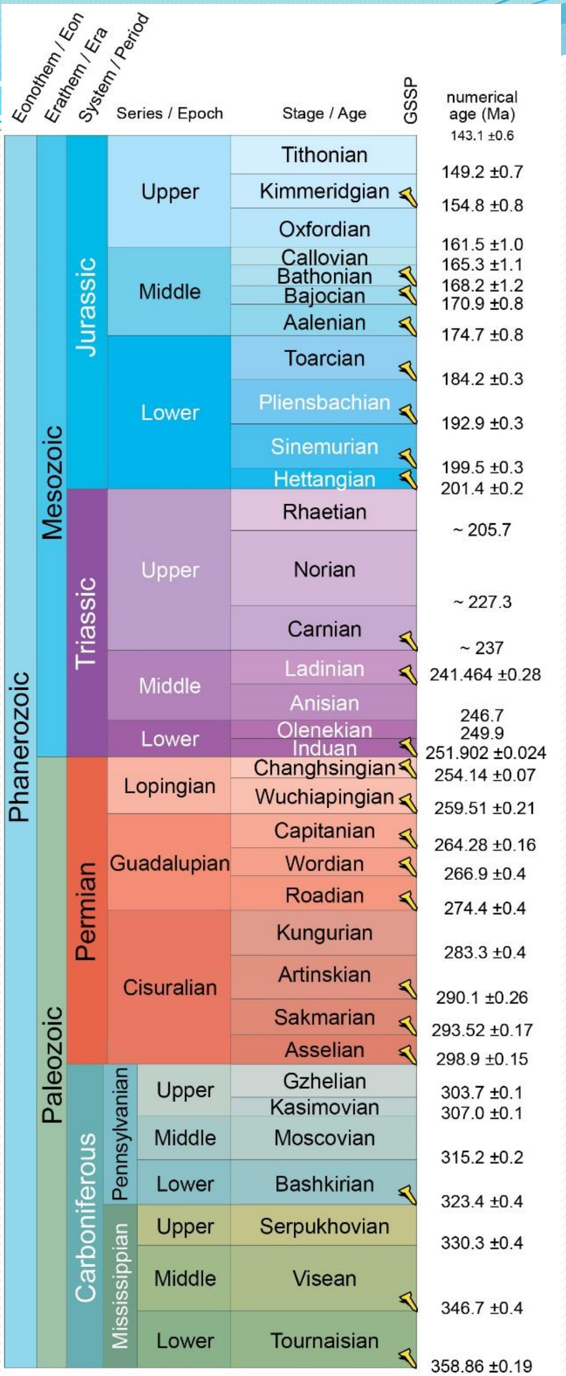
T. Rex roams North America

- Eon
  - Era
    - Period
      - Epoch
        - Age

- Phanerozoic
  - Mesozoic
    - Cretaceous
      - Upper
        - Maastrichtian



- Geological timescale has +/- ranges for most of its boundaries
- Even really precise dates are commonly +/- 0.5 million years
  - 0.2% error at 250 MYA
  - Equivalent time resolution to +/- 3 minutes in a day
- Not unusual to see +/- 2 or 4 million years
  - 1.6% error at 250 MYA
  - +/- 24 minutes in a day



Changing Ages

- The estimated ages of time bins is constantly being updated
- Ordovician Period shrunk ~6 million years in length between the 2009 and 2012 versions
  - Stable from 2012-2024

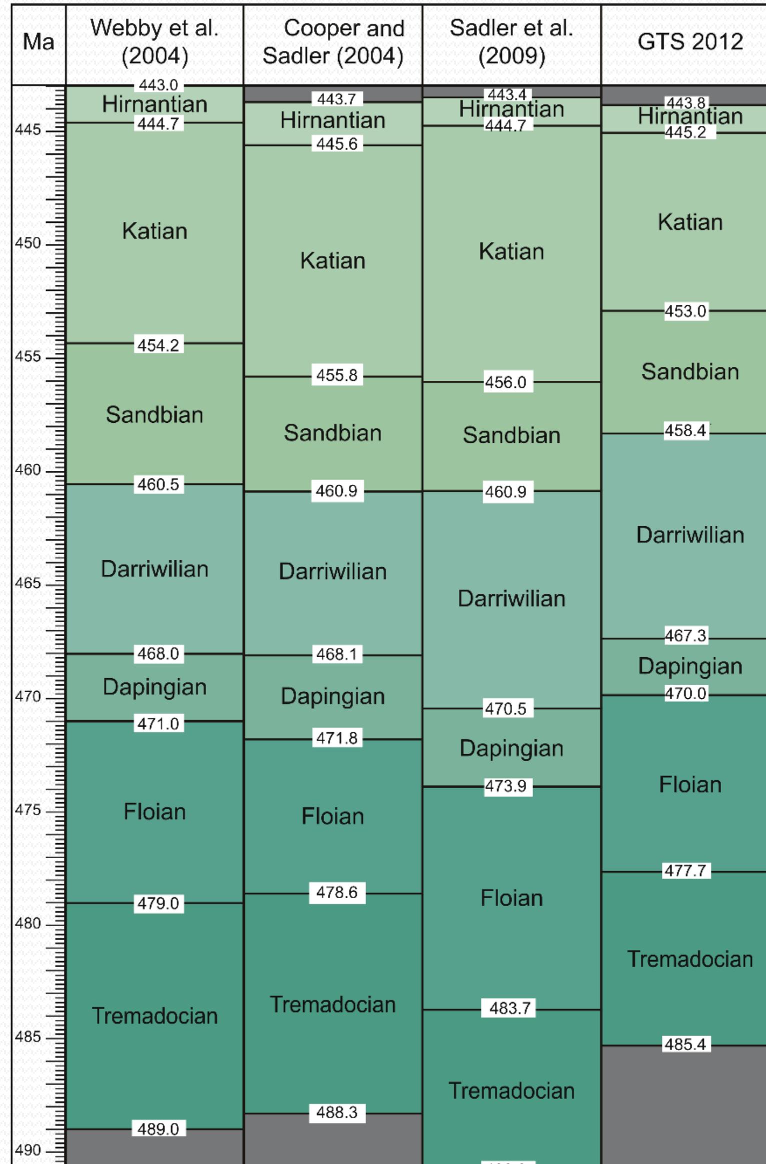


FIGURE 20.14 Comparison of GTS2012 with previous time scales; Cooper and Sadler (2004) is GTS2004 (see text for discussion).

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	Paleoproterozoic	Statherian	1800
		Orosirian	2050
		Rhyacian	2300
		Siderian	2500
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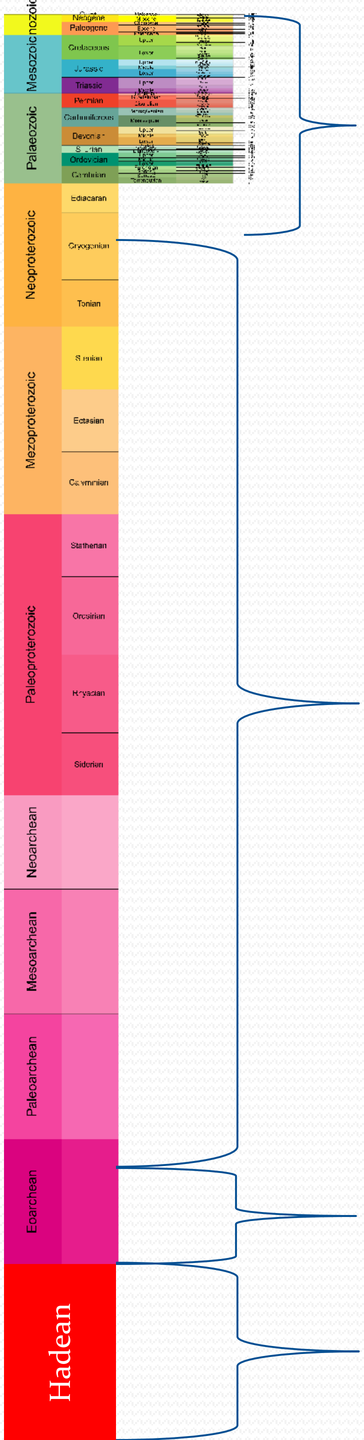
Geological ages scaled linearly



Animal life

Single-celled life, no animals

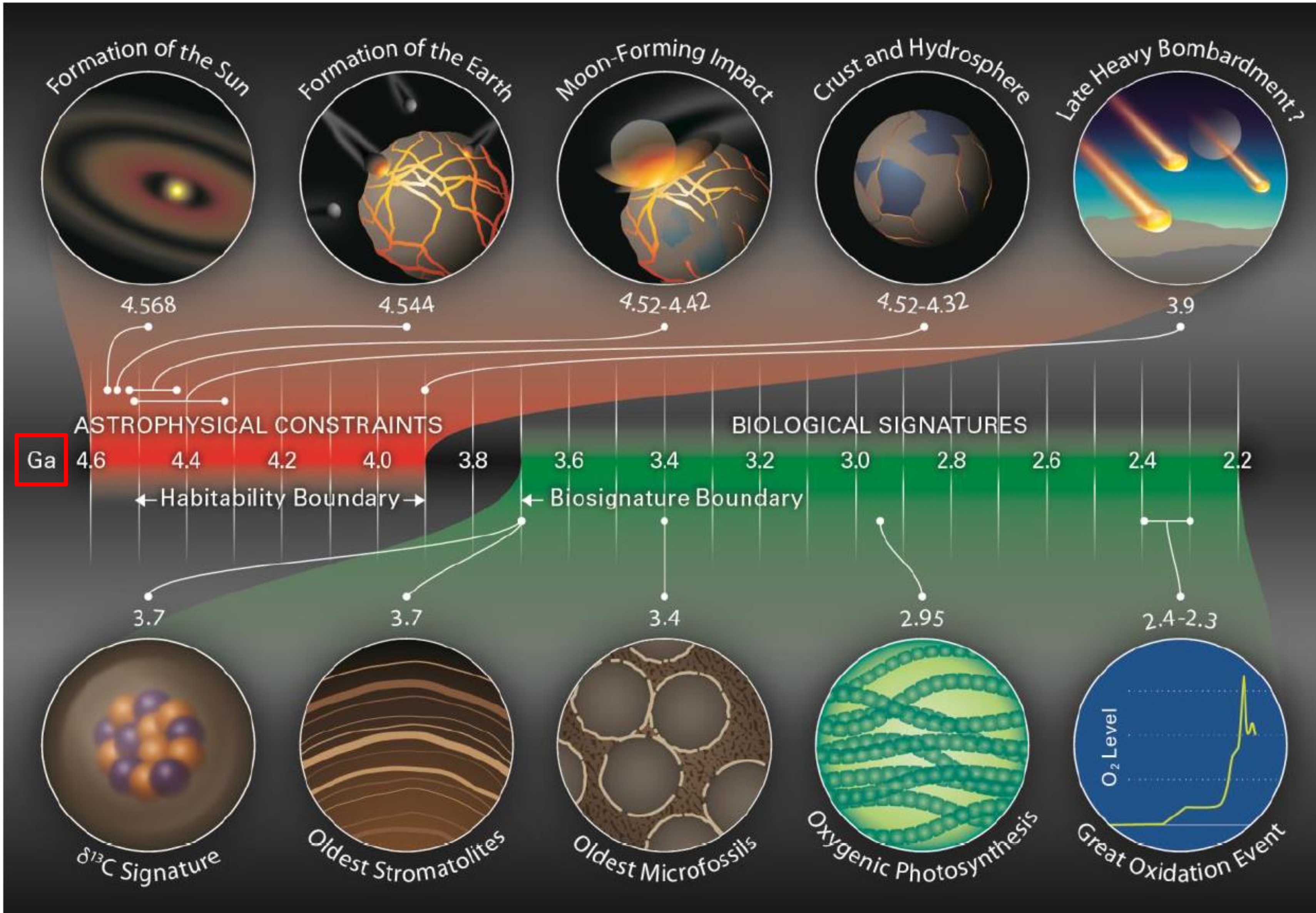
Rocks, but no life

No rocks survive from this time, just grains

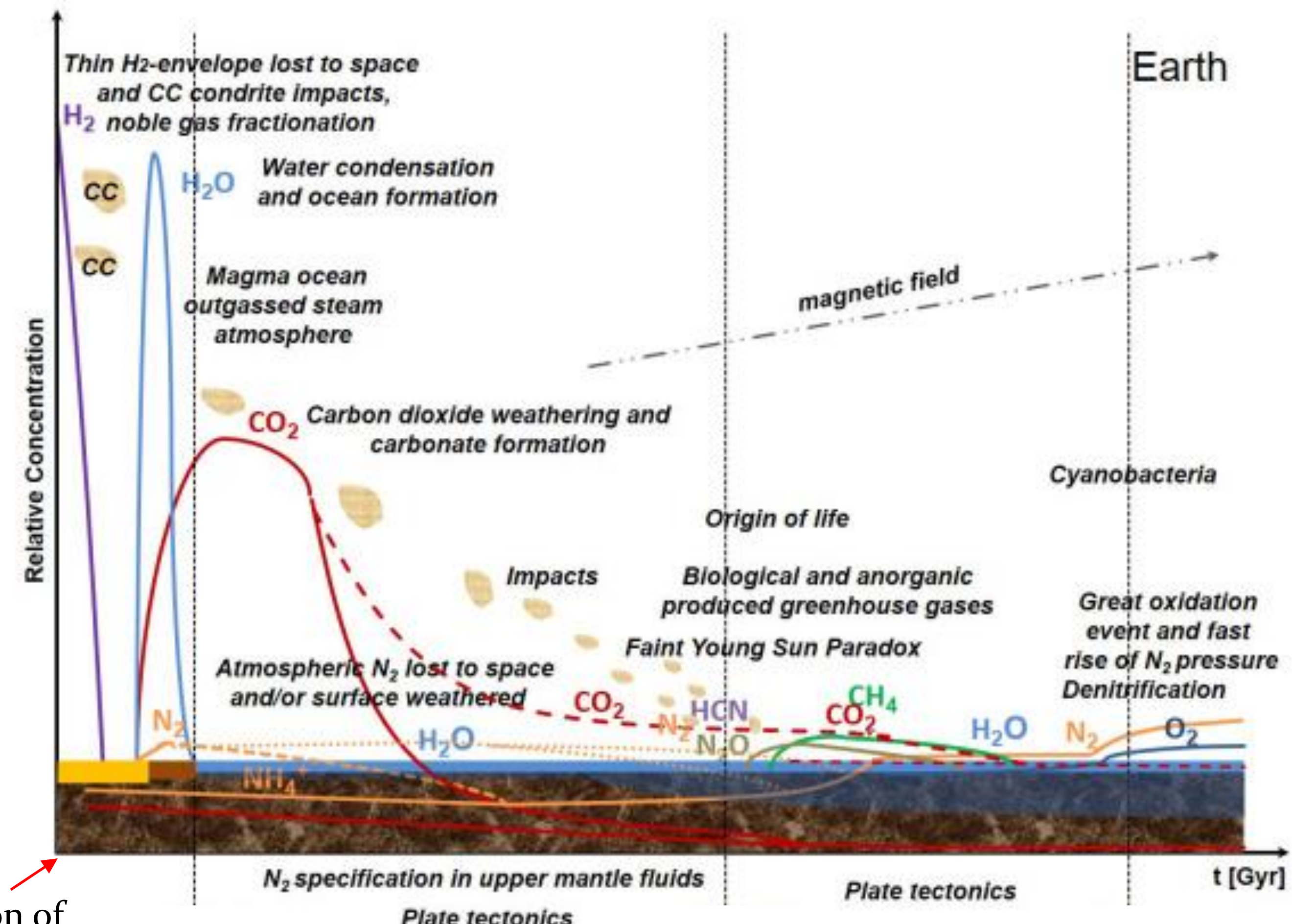
Units of time

Ma = mega-annum = millions of years ago

Ga = giga-annum = billions of years ago


Formation of the Sun
Formation of the Earth
Moon-Forming Impact
Crust and Hydrosphere
Late Heavy Bombardment?
4.568
4.544
4.52-4.42
4.52-4.32
3.9
ASTROPHYSICAL CONSTRAINTS
BIOLOGICAL SIGNATURES
Ga
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
Habitability Boundary
Biosignature Boundary
3.7
3.7
3.4
2.95
2.4-2.3
δ13C Signature
Oldest Stromatolites
Oldest Microfossils
Oxygenic Photosynthesis
O2 Level
Great Oxidation Event

Earth's Atmospheric History



Formation of Earth = 4.54

≈ 4.4 Ga

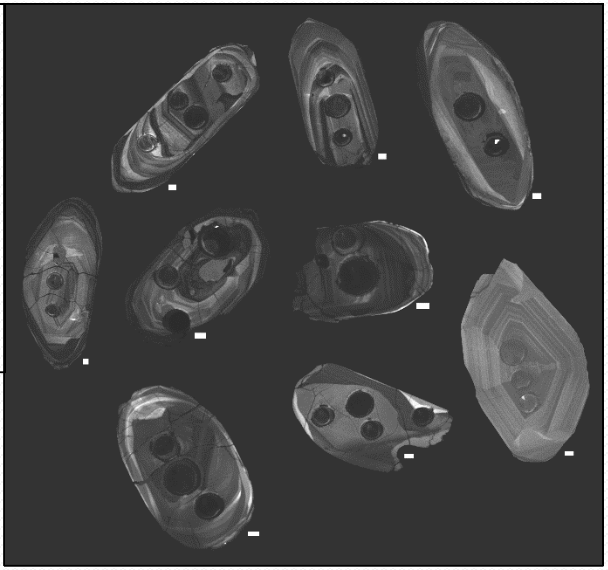
≈ 3.9 Ga

≈ 2.5 Ga

Hadean Eon (4-4.54 Ga)

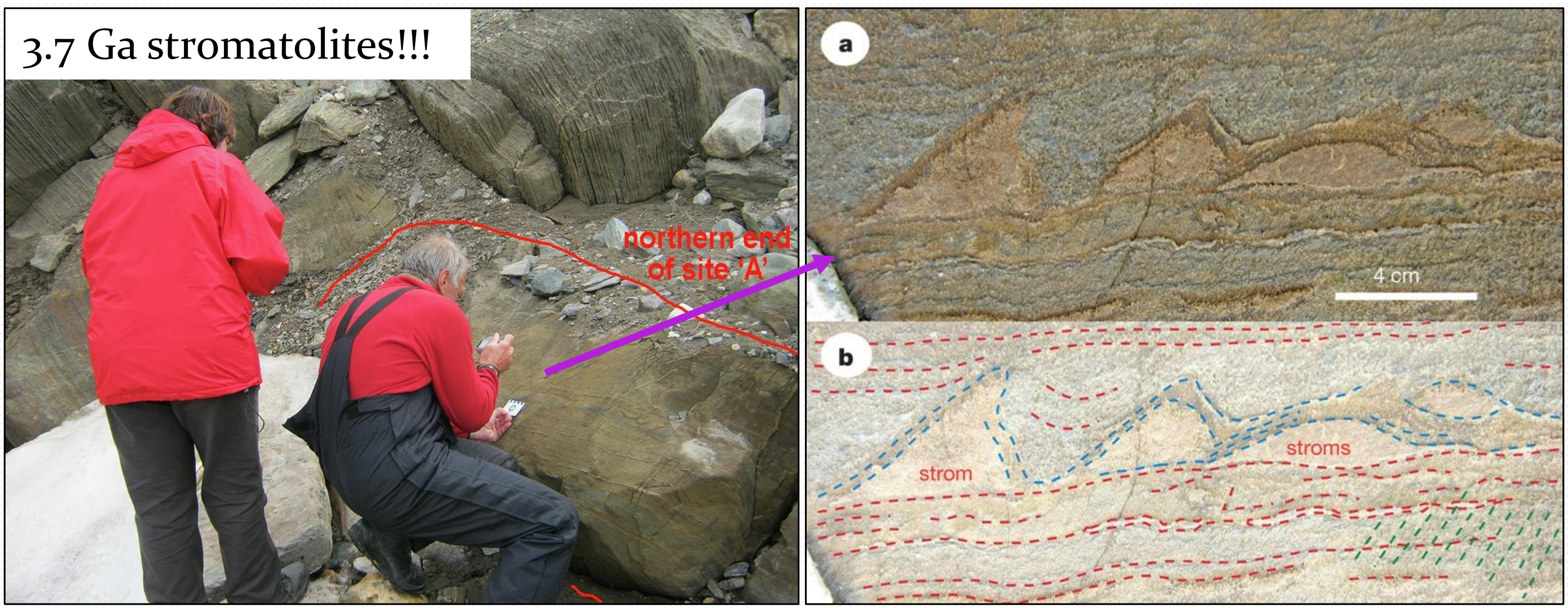
- A lot **more** atmosphere than today (~27x more!)
- Mostly carbon dioxide, nitrogen, water, and methane
- Earth cooled quickly with surface oceans probably present by 4.2 Ga

Zircon grains from Jack Hills, Australia are the oldest dated material on Earth (~4.3 Ga)



Archean Eon (2.5-4 Ga)

- Planet continues to cool, oceans are well-established (absorb CO_2), and life appears for the first time
  - Earliest organisms are chemotrophs which do not use oxygen, instead partially produce methane as waste



Original claim (2016), Claim that it's abiotic (2018, 2020), Original author claims again (2019)

Oxygenic Photosynthesis

- The appearance of photosynthetic organisms 3.2-3.5 (or 3.7) Ga brought the biosphere into play for carbon

- Accelerated the fluxes of carbon at the surface and created an entirely new reservoir of carbon

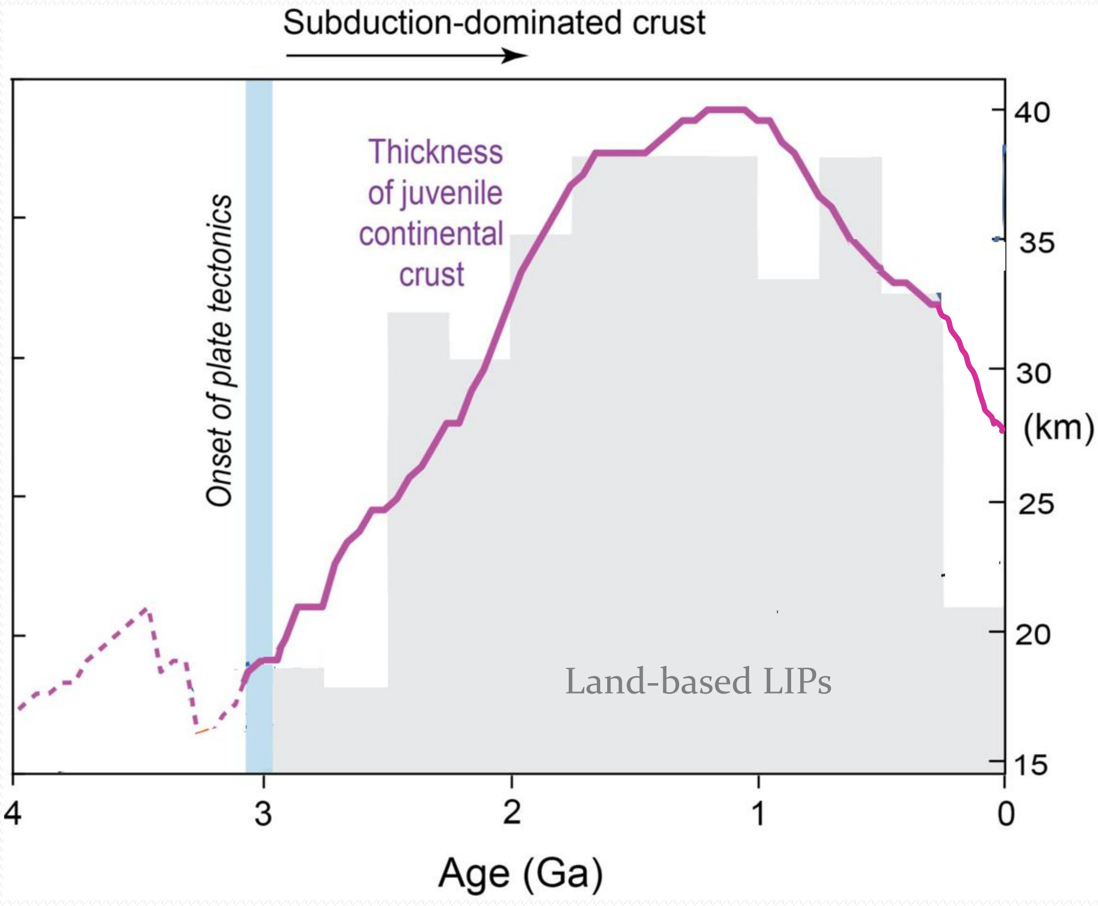
$$6CO_2 + 6H_2O \leftrightarrow C_6H_{12}O_6 + 6O_2$$

- Currently photosynthesis moves…

  ~212 Pg C from atmosphere to biosphere with most then returned within a year

Archean Eon (2.5-4 Ga)

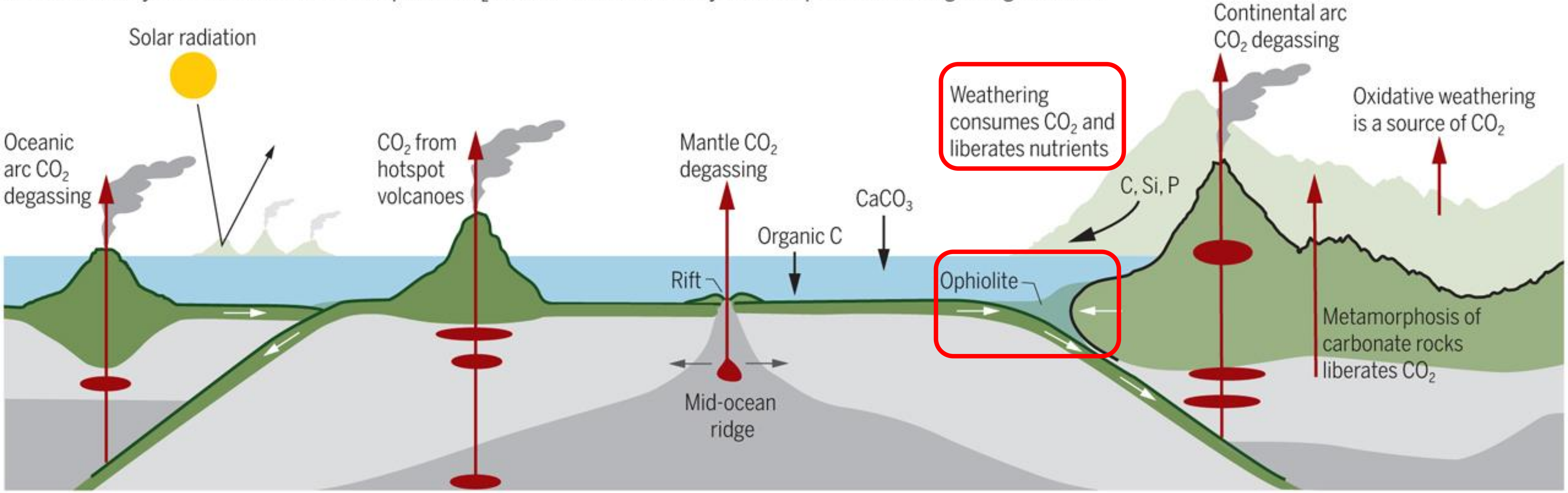
- Planet continues to cool, oceans are well-established, and life appears for the first time
  - Plate tectonics also starts ~3 Ga and ramps up through the end of the Archean Eon
  - Long-term carbon reservoir to buffer Earth's climate



Slow Carbon Cycle (lithosphere)

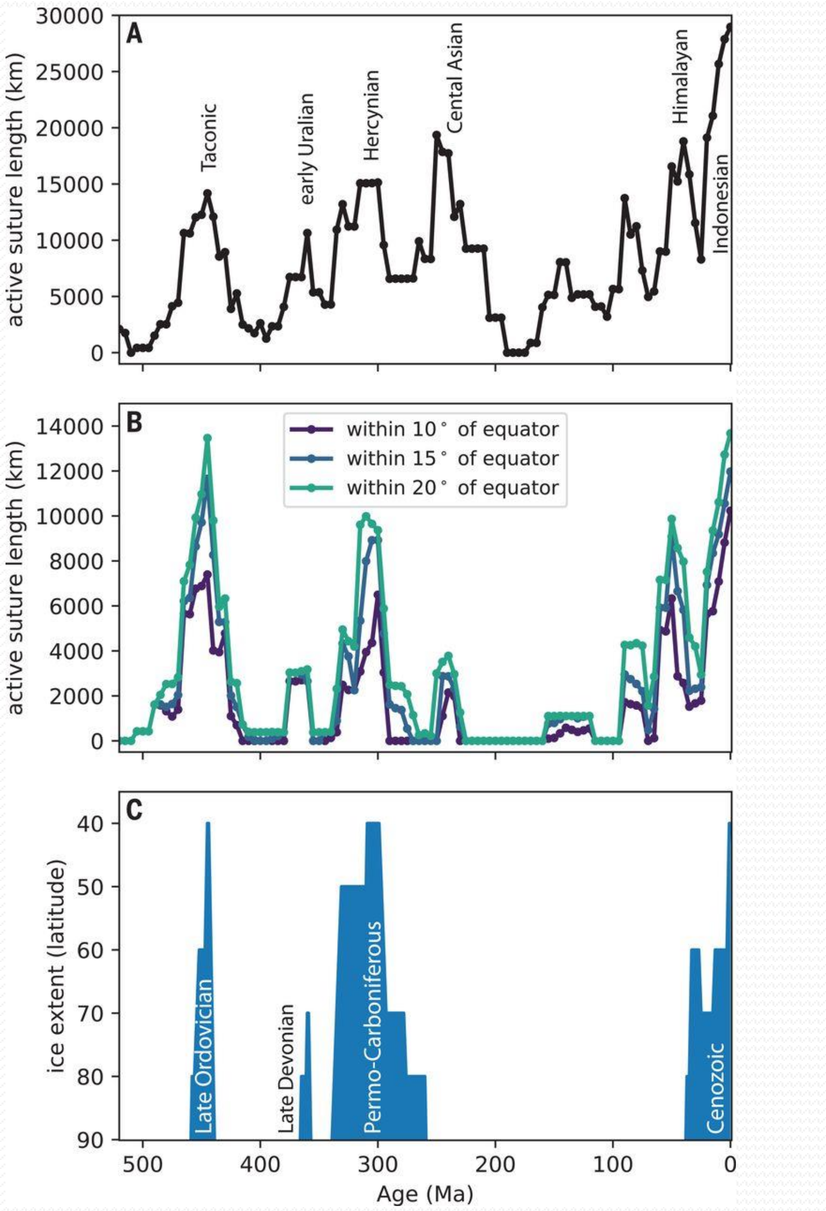
Geological sources and sinks of CO_2

Solar radiation, as well as the differences between sinks and sources of CO_2, contributes to the state of the climate. If a sink term, such as weathering of ophiolite complexes, increases, the system shifts to lower atmospheric CO_2 concentrations. This may lead to a period of cooling with glaciations.



Tectonic Control On Climate

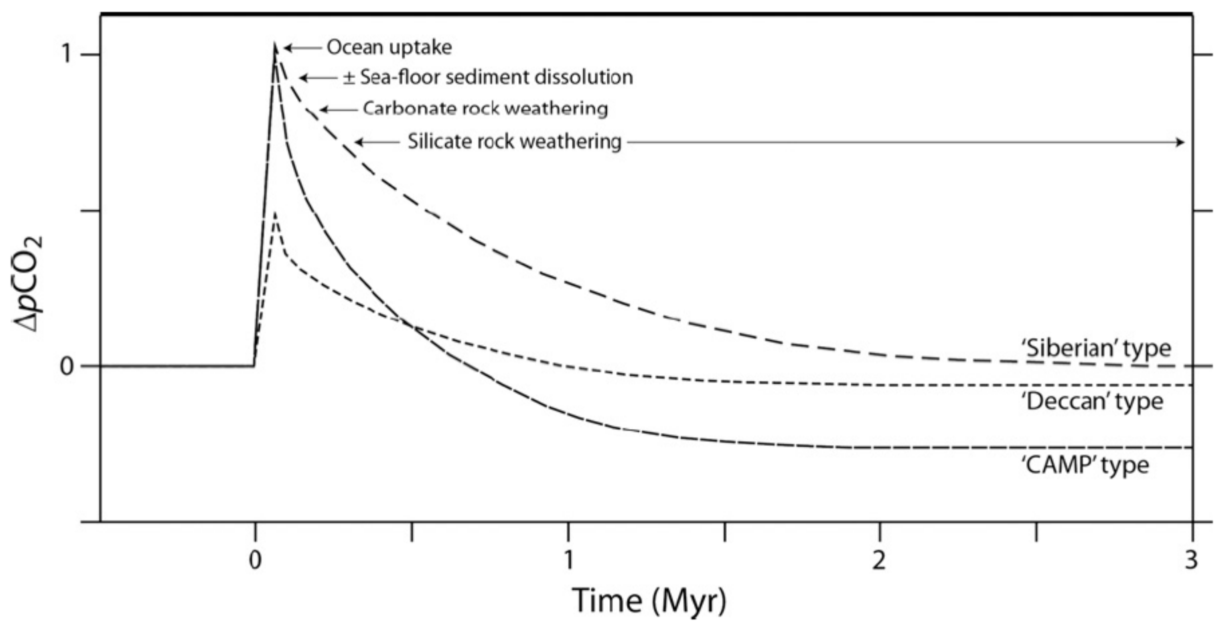
- Silicate weathering increases during times of mountain building
    - Does not match for all glacial periods
- 2019 study suggested tropical continent-continent collision zone orogenies with intense weathering are the answer



Similar Research Now On LIPs

- Difference is that LIPs can give off massive amounts of CO_2 to the atmosphere initially and then, depending on if they are emplaced or move into the tropics can effectively draw down CO_2 levels by weathering

LIP = large igneous province, volcanisms on a continental scale. Has not occurred since humans evolved



Cooling an Archean Earth

- Increased tectonic activity, particularly rifting, sped up silicate weathering drawing down atmospheric CO_2 levels

- Photosynthesis releases O_2 which reacts with methane to produce CO_2

Methane　　　　Carbon Dioxide

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$$

- Overall effect was global cooling
  - Drawing CO_2 out and replacing methane with CO_2

GWP $CO_2 = 1$　　　　GWP methane ≈ 28

Proterozoic Eon (2.5 - 0.541 Ga)

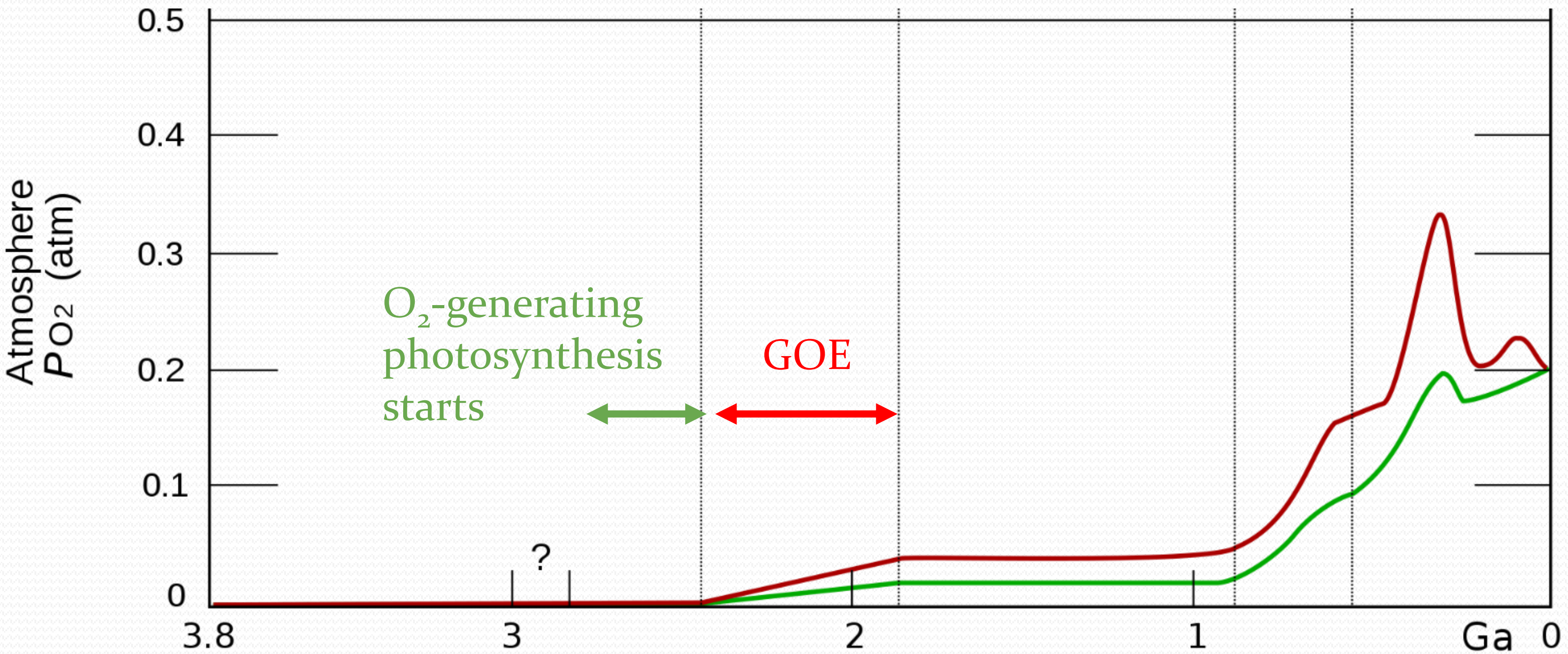
- O_2 produced by photosynthetic algae, but consumed by reaction with iron in ocean water so very little, if any, buildup in the atmosphere
  - Iron + oxygen = rust

Banded Iron Formation

- Eventually iron is low enough for O_2 to accumulate in the surface water and then the atmosphere
  - "Rapid" increase in O_2

The Great Oxidation Event

~2.5-2 Ga BP



Great Oxygenation Event has an Earth with ~3% atmospheric O_2 (present = 21%)

Proterozoic Eon (2.5 - 0.541 Ga)

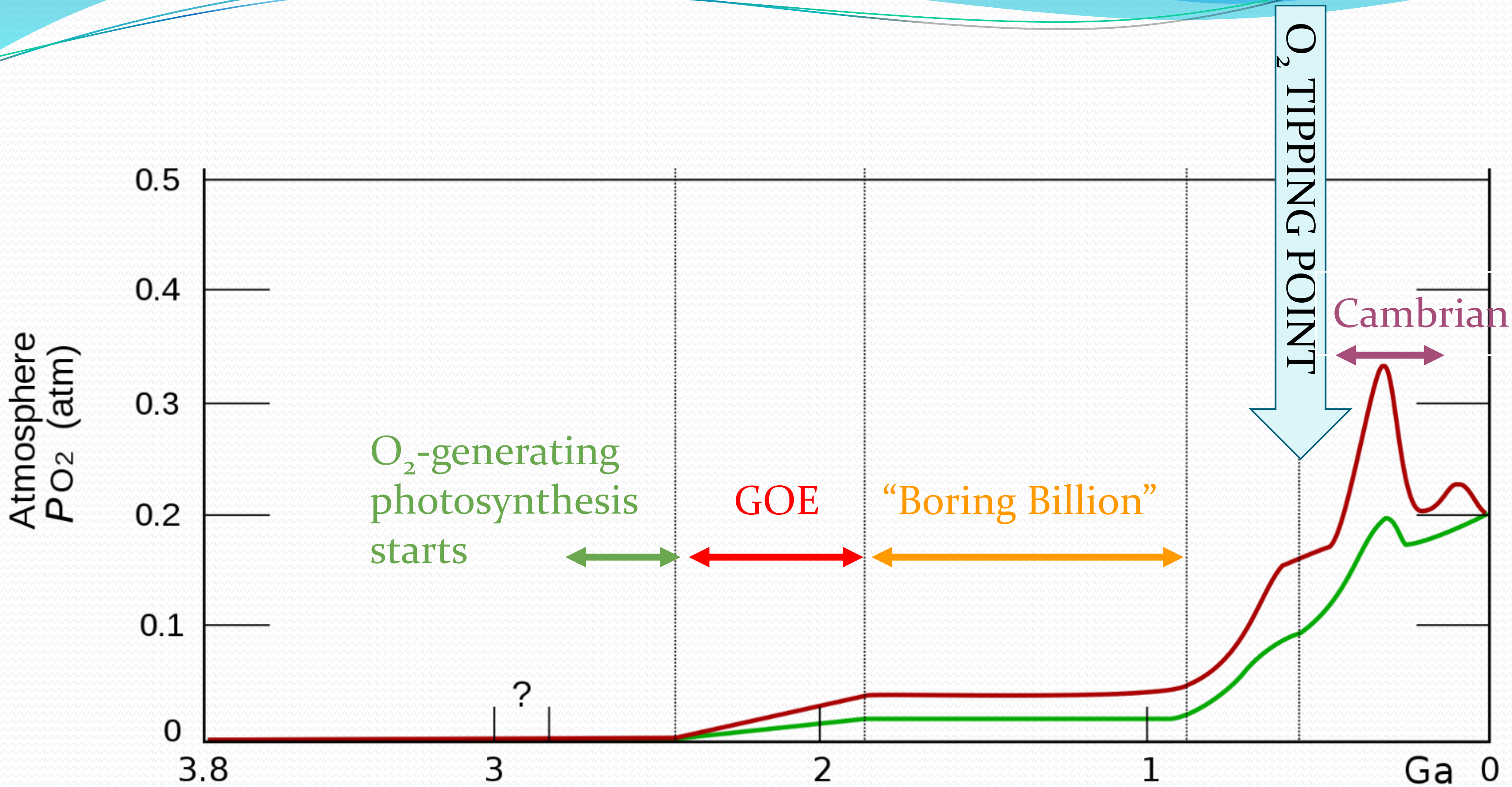
- Drawdown of CO_2 due to photosynthesis, ocean uptake, and weathering continued
  - Triggered the earliest, and most extensive, glaciations in Earth's history
  - Equatorial glaciers

- Snowball Earth
  - Huronian (2.1-2.4 Ga)
  - Sturtian (660-717 Ma)
  - Marinoan (635-640 Ma)

Snowball Earth

- Exact cause unclear but apparent rapid speed of cooling seems to have led to runaway feedback

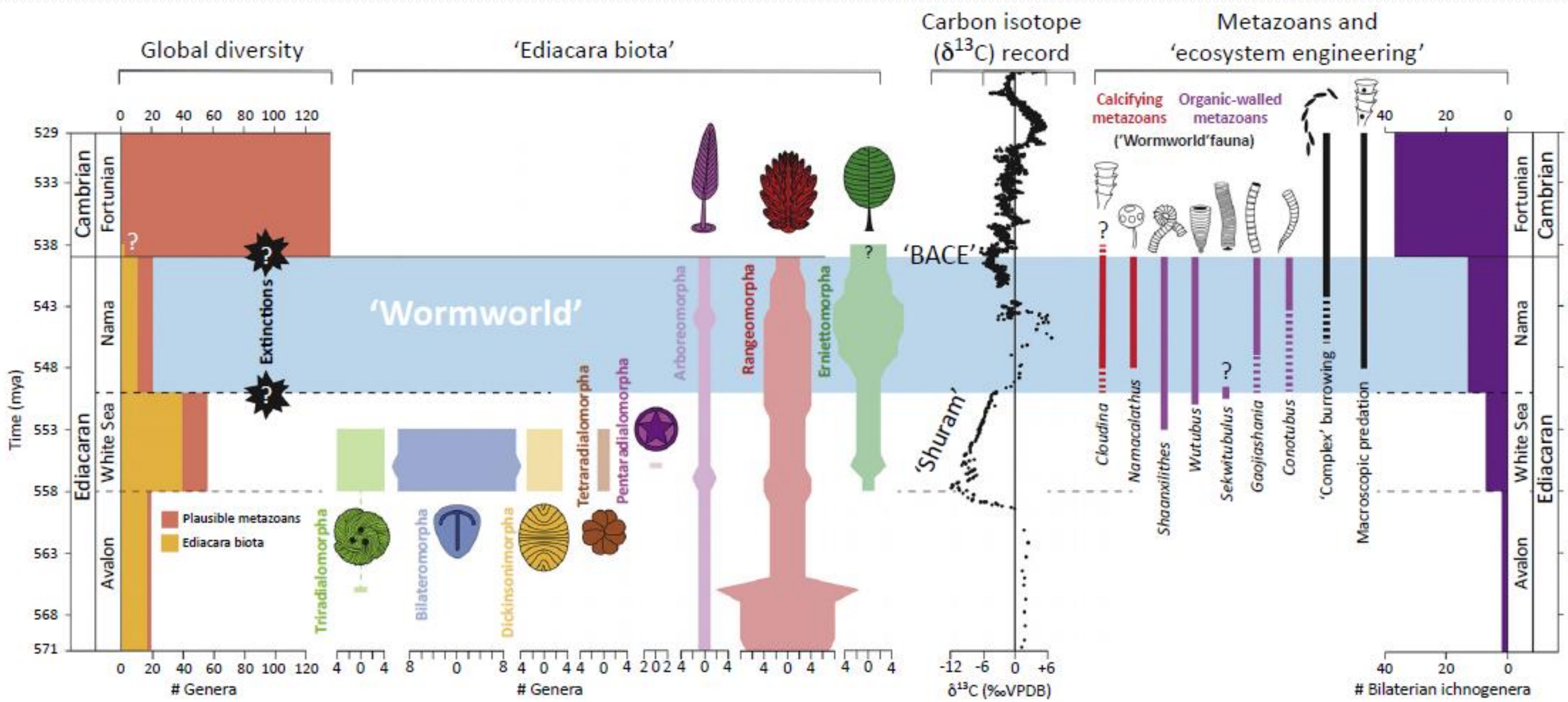
- Escaped due to shutdown of lithosphere carbon sinks while lithosphere carbon emission (volcanism) continued
- Mismatch between response of ice cover and lithosphere



Oceanic and atmospheric levels continue to episodically increase through the Late Proterozoic

Ediacaran Wormworld

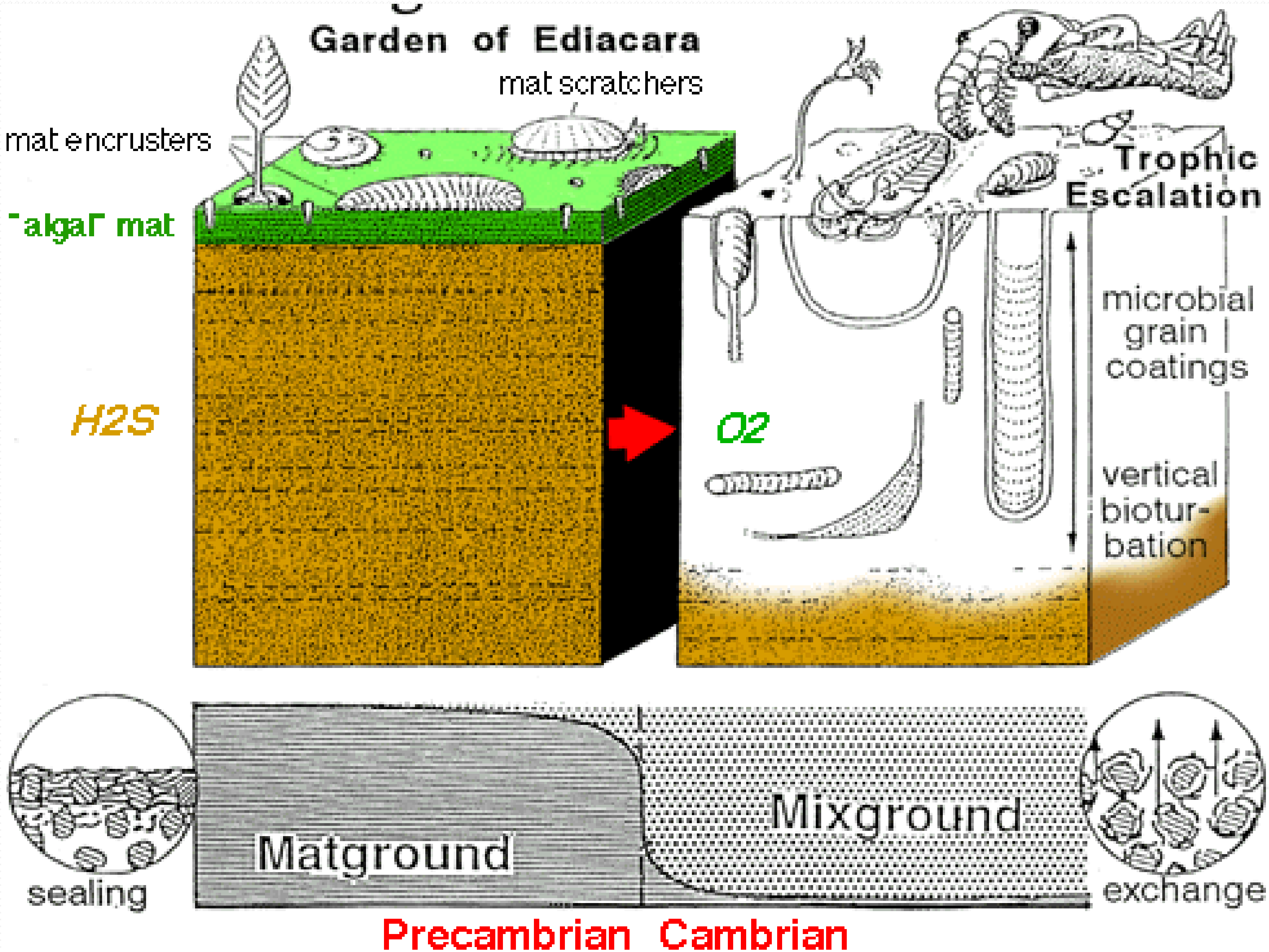
- Evidence of increasingly complex ecosystems in the Late Proterozoic (Ediacaran, 541-635 Ma)



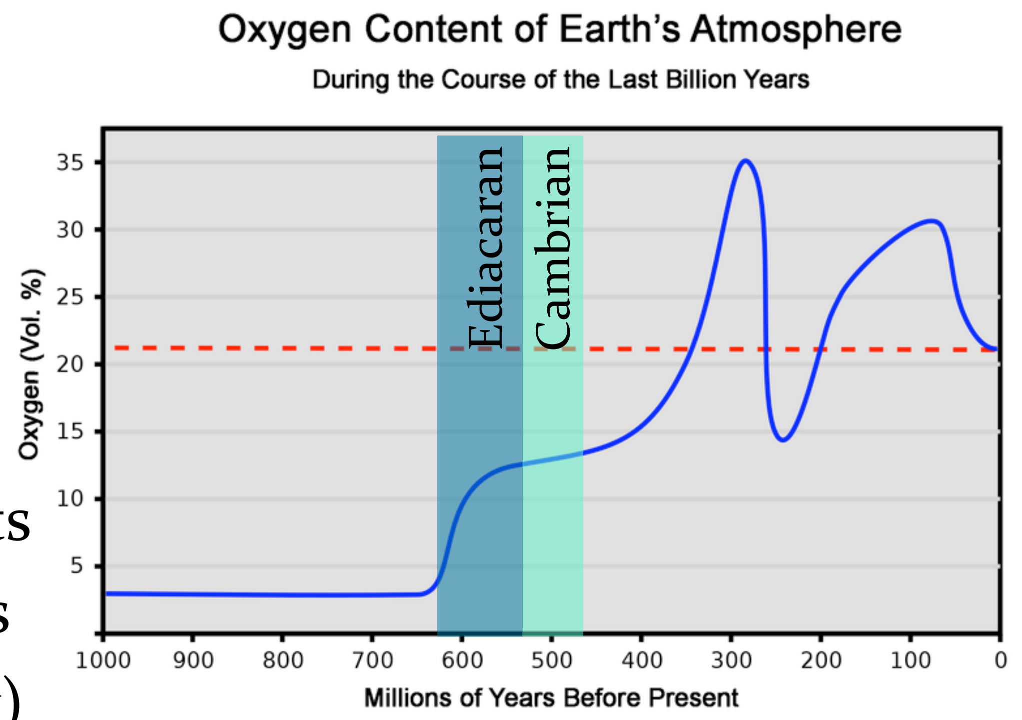
The Substrate Revolution

- Ediacaran Period quiet-water sea floors covered (and sealed) by algal mats
  - Limited carbon cycling through the soils

- Ediacaran-Cambrian boundary marked by rapid diversification of trace fossils and formation of fluid mixed layer at sediment-water interface
  - Further potential for innovation as adaptations to more heterogeneous and mixed substrates

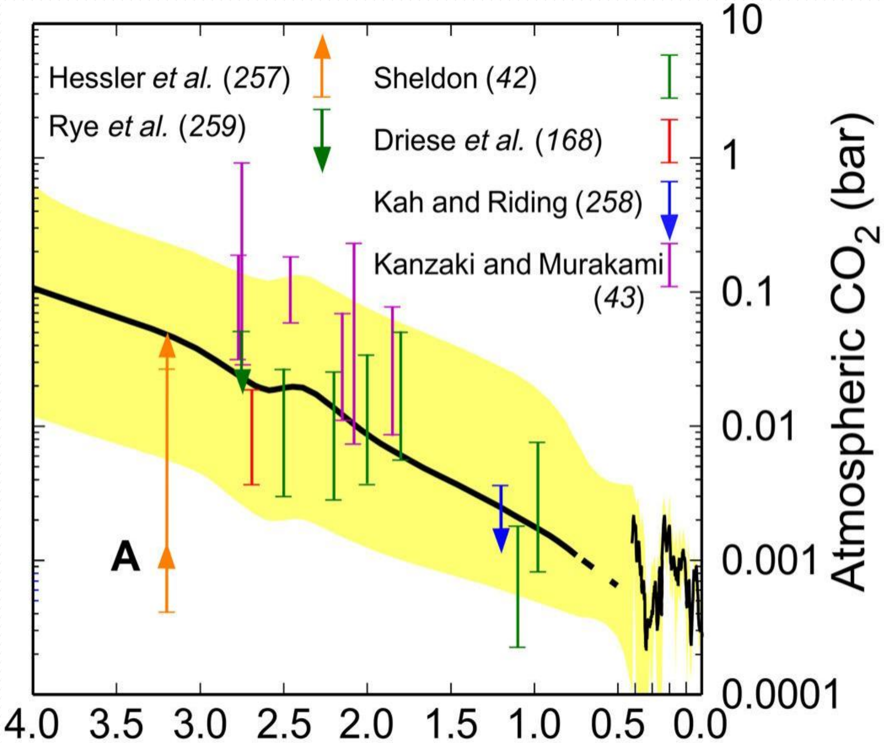

Garden of Ediacara
mat scratchers
mat encrusters
"algal" mat
H2S
O2
Trophic Escalation
microbial grain coatings
vertical biotur-bation
sealing
Matground
Mixground
exchange
Precambrian
Cambrian

Increased Oxygen

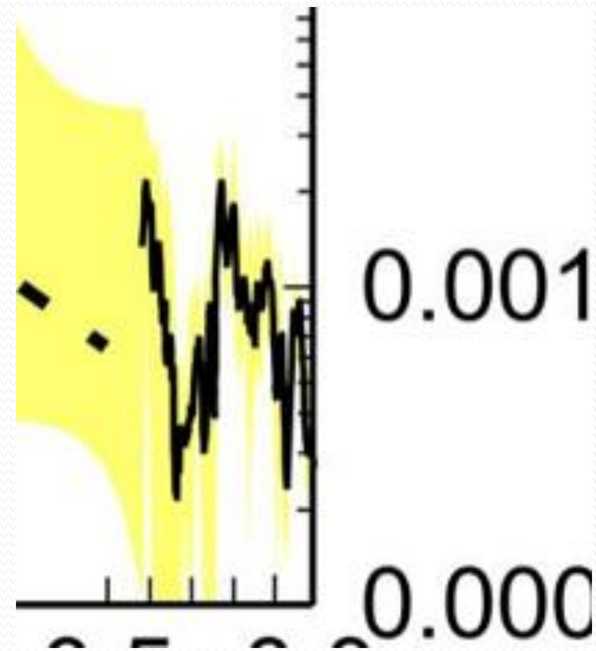


- Increased oxygenation expanded evolutionary opportunities
  - Ventilation of deep shelf expanded habitats
  - Higher metabolic rates possible (more activity)
  - Permitted shells to cover surfaces (broader range of structures, carbonate carbon shells)
  - Larger body size (greater fossilization chance)

Overall trend of decreasing CO_2 and increasing O_2 until ~541 Ma



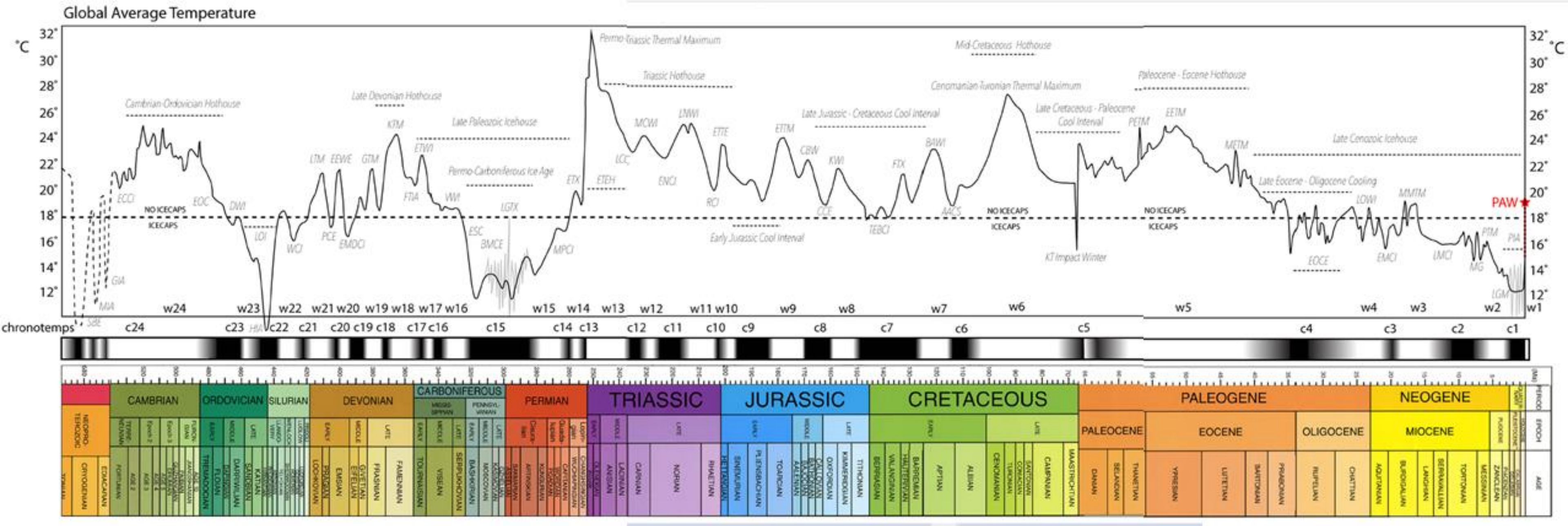
Ga BP



Every animal, every plant, every organism bigger than a single-celled slime has lived in this narrow range of carbon dioxide concentrations, shown at right

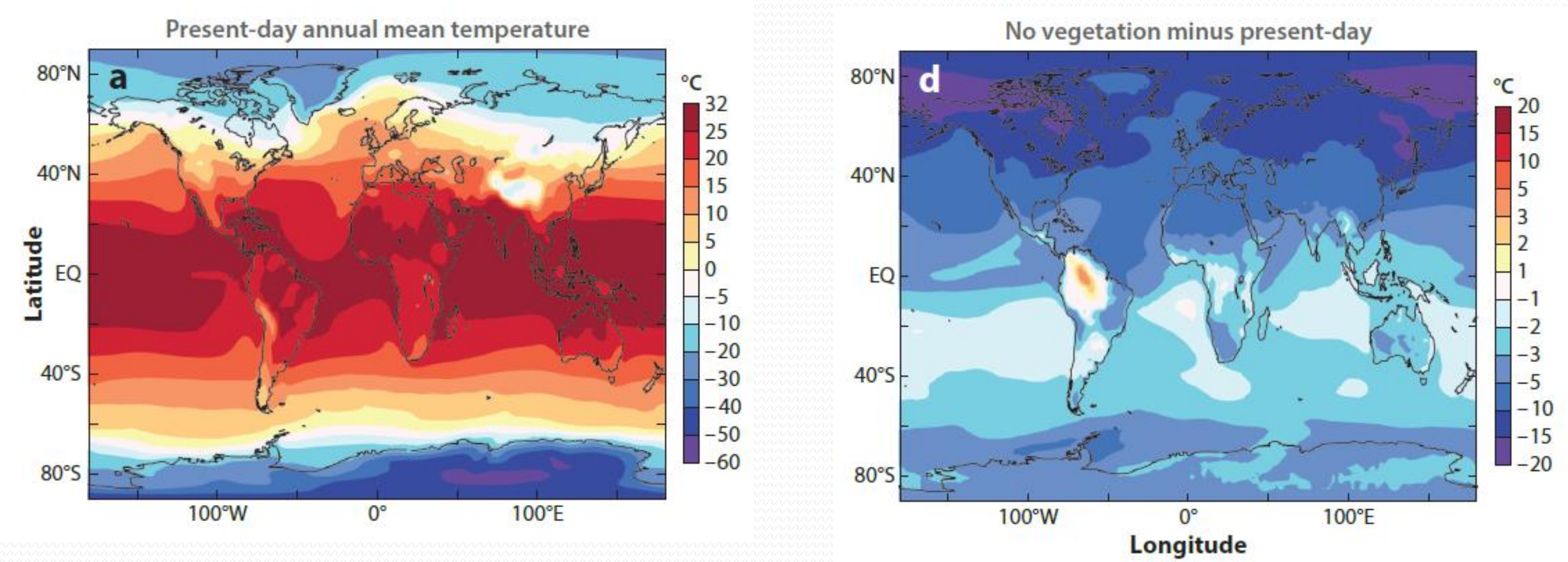
Phanerozoic Eon (0 – 541 Ma)

- Overall low variability in temperature and CO_2 compared to earlier times as Earth's climate becomes self-buffering
  - Life increasingly influences the climate



Life as a Climate Modifier

- Another major shift occurred when plants invaded land ~390 mya (Middle Devonian)
  - Decreased the planet's albedo (warming effect)
  - Increased silicate weathering (CO_2 decrease, cooling)
  - Transpiration (H_2O to atmosphere, warming effect)



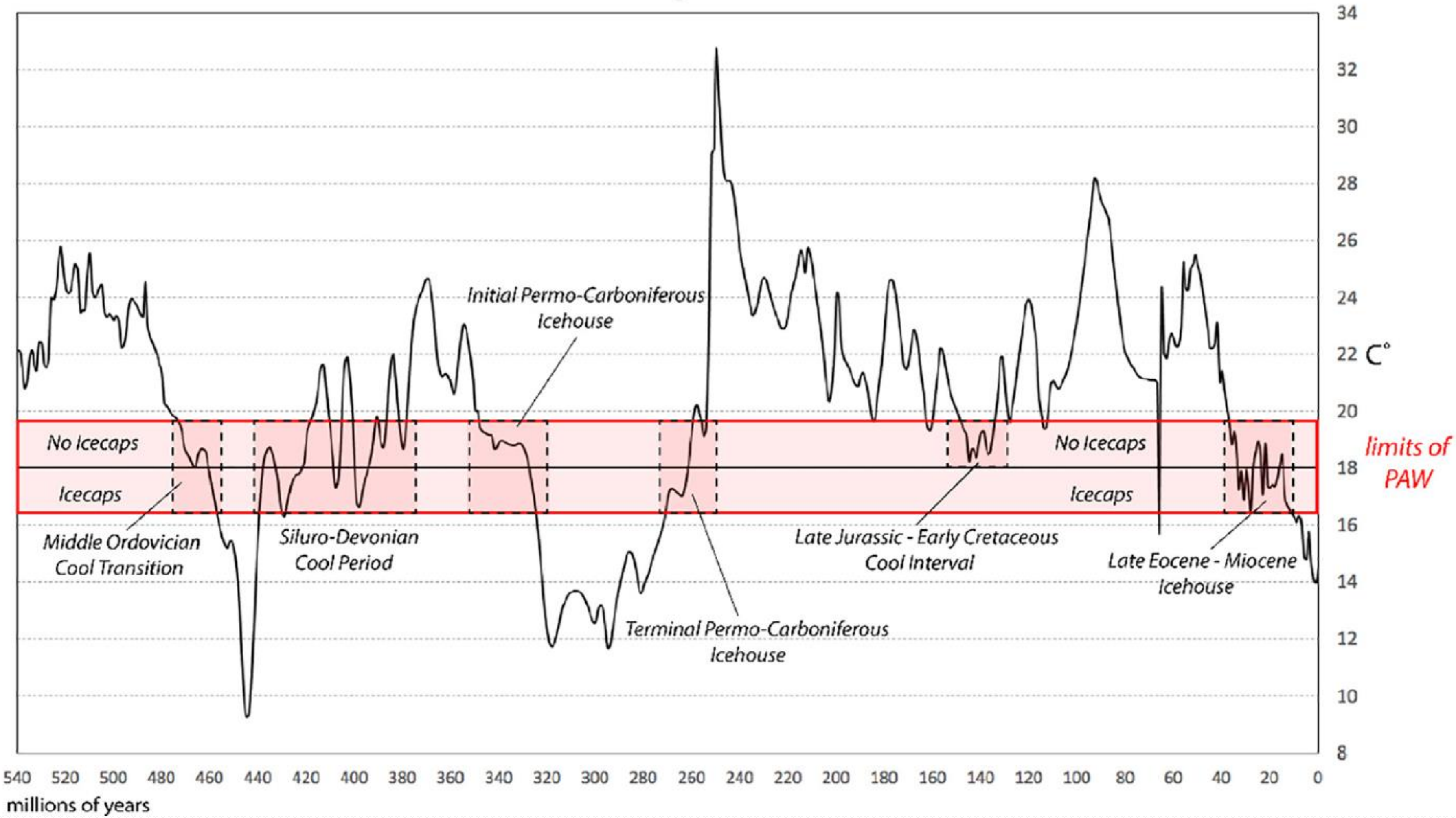
Life Timeline

- 3700 Ma: life arises, probably chemotrophs that produce methane
- 3200-3500 Ma: oxygenic photosynthesis arises, consumes methane and CO_2 while building up O_2
- 2000-2500 Ma: Great oxygenation event
- 541-635 Ma: substrate revolution leading to more active carbon cycling
- 460-491 Ma: Great Ordovician Biodiversity Event [GOBE] colonizing the water column

Life Timeline

- 390-420 Ma: Invasion and establishment of land plants
- 100-145 Ma: flowering plants (i.e. angiosperms) evolve and take over land facilitating soil insects
- 30-45 Ma: evolution and expansion of grasslands
- 0 Ma: human industrialization and fossil fuel release

Post-Anthropogenic Warming

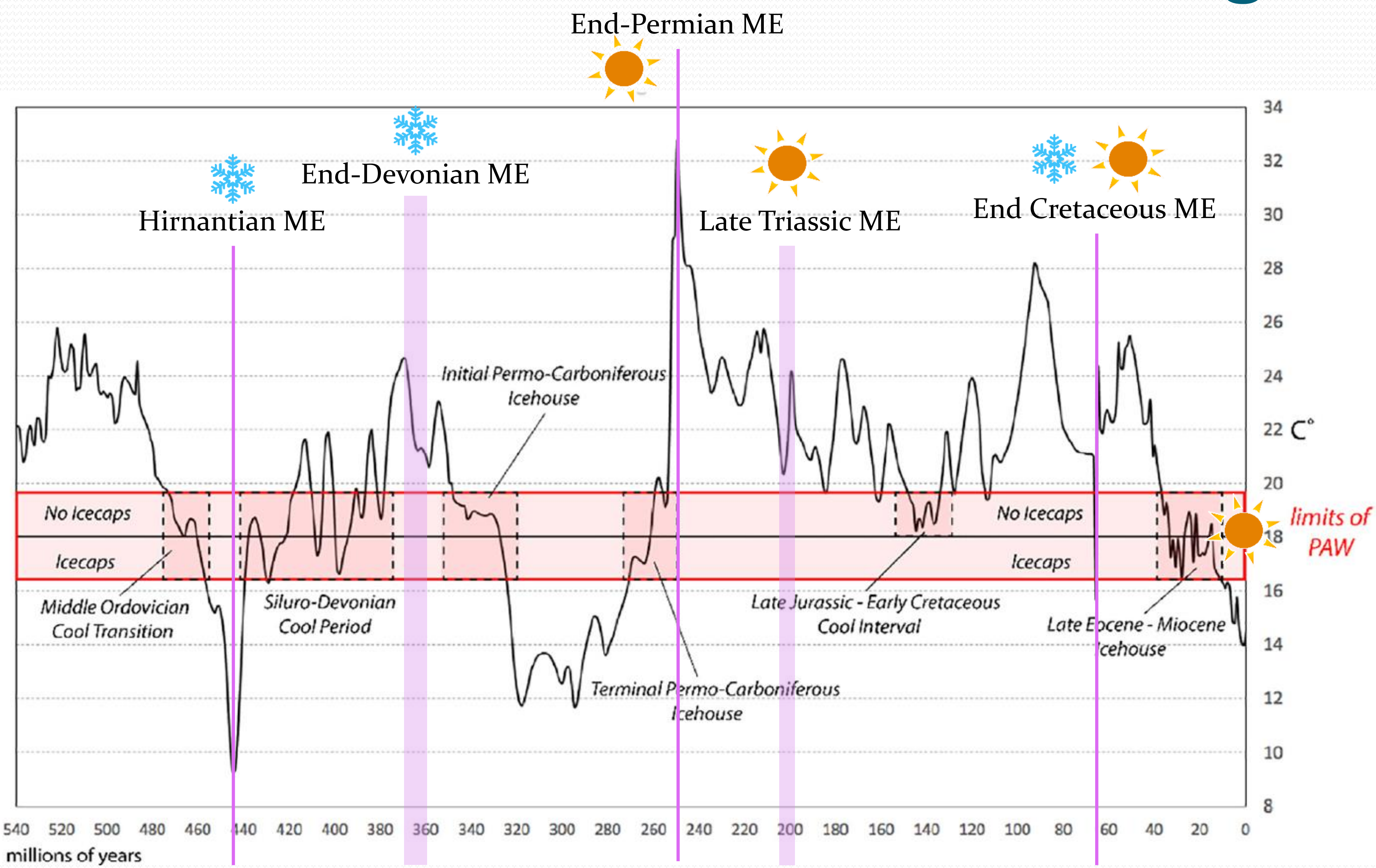


Extinction and Climate

Table 1. Past drivers of extinction in the ocean and current threats[a]

Time period[b]	Drivers and Threats[c]				
	Acidification[d]	Anoxia[e]	Warming	Cooling	Habitat Loss[f]
Ordovician-Silurian (~444 Ma)		○	○	●	●
Late Devonian* (Frasnian-Famennian; ~374 Ma)		●	○	●	●
End Permian* (~251 Ma)	●	●	●	○	●
Early Triassic (~245 Ma)	○	●	○	○	○
Triassic-Jurassic* (~202 Ma)	●		●		
Early Jurassic* (Pliensbachian-Toarcian; ~183 Ma)	●	●	●	●	
Aptian-Albian (~112 Ma)	●	●		○	○
Cenomanian–Turonian (~93.5 Ma)	●	●	○		
Cretaceous–Paleogene (~65.5 Ma)	●		○	●	○
Paleocene–Eocene Thermal Maximum* (~56 Ma)	●	○	●		
Eocene–Oligocene (~34 Ma)				●	○
Mid–Miocene Climatic Optimum (~14.7 Ma)			●		○
Historical (~10 Ka)			○		●
Modern	●	●	●		●

Mass Extinctions & Climate Change



Mass Extinctions & Climate Change

- Both warming and cooling have led to mass extinctions (>50% of species extinct in <1 million years)
  - Cover the bad luck of the end-Hirnantian, end-Permian, and end-Cretaceous next class

- A rapid rate of climate change seems to be more important than the direction of change
  - Rapid change means less time for organisms to move or adapt to the world around them

Today’s Learning Outcomes

1. Know how to read a geologic time scale
2. Be able to explain how the planet escaped the “Snowball Earth” events
3. Know what the relationship between the direction and rate of climate change are with mass extinction events