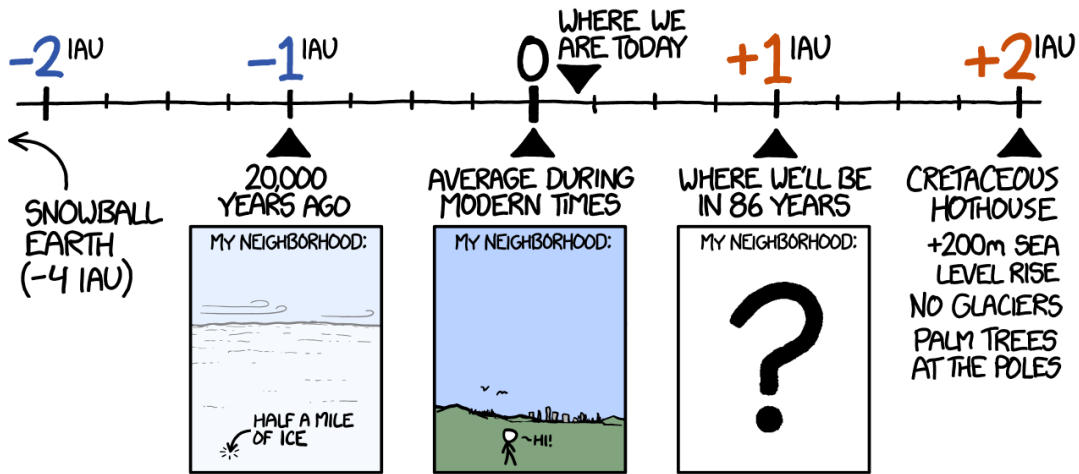


WITHOUT PROMPT, AGGRESSIVE LIMITS ON CO<sub>2</sub> EMISSIONS, THE EARTH WILL LIKELY WARM BY AN AVERAGE OF 4°-5°C BY THE CENTURY'S END.

## HOW BIG A CHANGE IS THAT?

IN THE COLDEST PART OF THE LAST ICE AGE, EARTH'S AVERAGE TEMPERATURE WAS 4.5°C BELOW THE 20<sup>TH</sup> CENTURY NORM. LET'S CALL A 4.5°C DIFFERENCE ONE "ICE AGE UNIT."



## Class 13: Deep Time Paleoclimate

- Greenhouse vs. Icehouse Worlds
- Plate Tectonic Processes & their Effects on Climate
- The Cretaceous Greenhouse World +Dinosaurs!
- Snowball Earth?

## Learning Objectives

1. Describe the characteristics of greenhouse vs. icehouse worlds
2. Understand what geologic processes modulate global climate over long time scales
3. Identify and explain one hypothesis about the cause(s) of hyperthermal events
4. Explain what runaway feedback system may have led to an 'icehouse' world, otherwise known as the Snowball Earth

# Climate in the News

**Climate change**

**Ben Smee**

🐦 @BenSmee

Sun 20 Oct 2019 19:56 EDT



🔗  
602

## Leading Australian engineers turn their backs on new fossil fuel projects

**The Engineers Declare movement pledges to put climate considerations first in evaluating plans**



▲ About 1,000 Australian engineers have signed a declaration calling for projects to be evaluated against climate considerations. Photograph: Raymond Warren/Alamy

# Climate in the News

☰  
BROWSE

**Bloomberg  
Environment**

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Environment & Energy Report

## Can Climate 'Test Cases' Move Forward? It's Up to Supreme Court

Oct. 18, 2019, 5:55 AM



- Oil companies face growing number of nuisance claims from local governments
- Proceedings could continue in state courts if Supreme Court doesn't step in



**Ellen M. Gilmer**  
Reporter



The Supreme Court is set to decide soon whether to greenlight state-court proceedings for several cases in which state and local government officials seek to hold oil companies accountable for their role in climate change.

### Related Articles

[Court Order Opens New Front in SCOTUS](#)

# Climate in the News

Science

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Linda Birnbaum in 2011 SCOTT J. FERRELL/CONGRESSIONAL QUARTERLY/GETTY IMAGES

## Now retired, top U.S. environmental scientist feels free to speak her mind

By Warren Cornwall | Oct. 17, 2019, 2:25 PM

# Review: The Last 50 Million Years

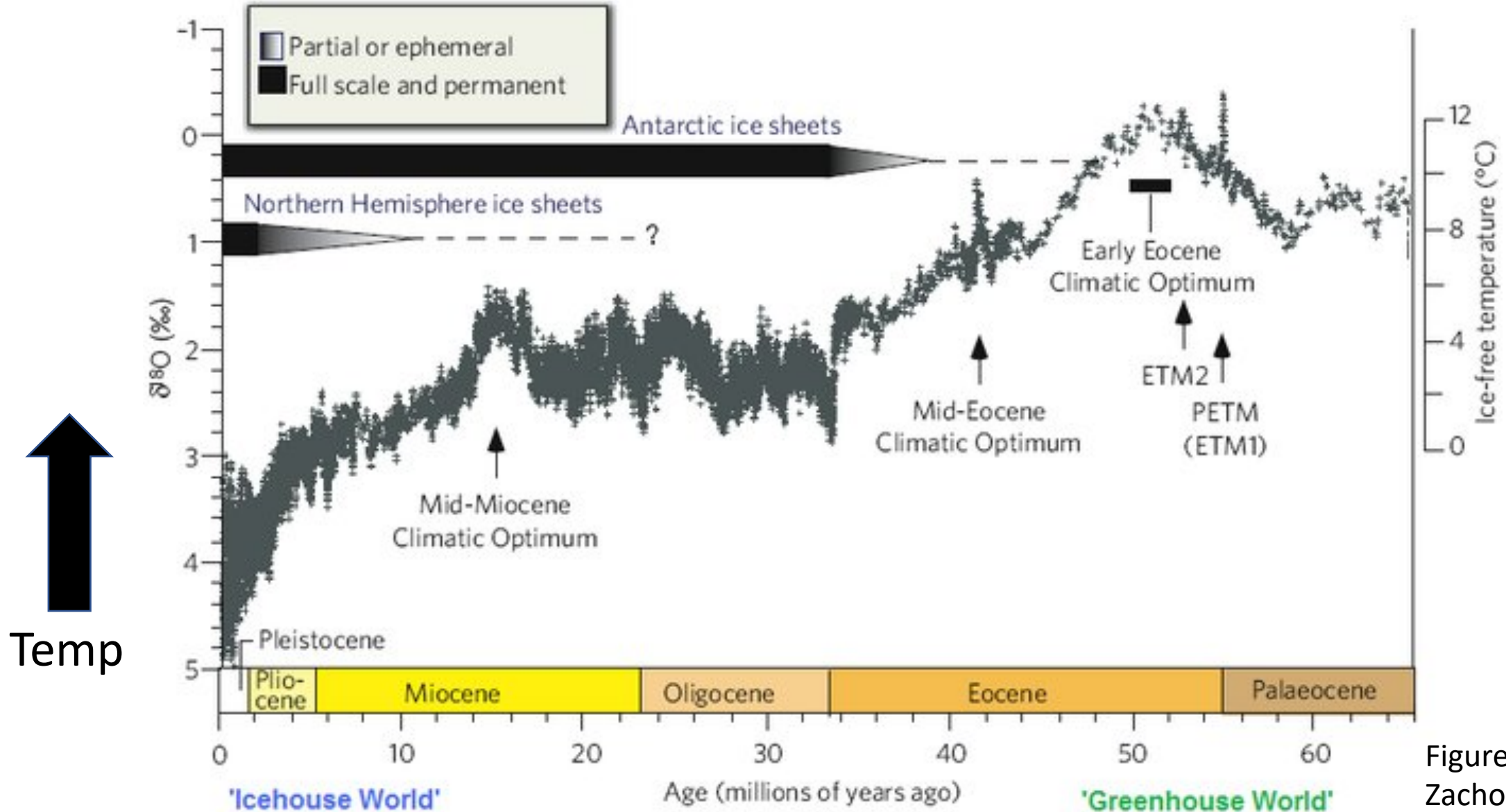
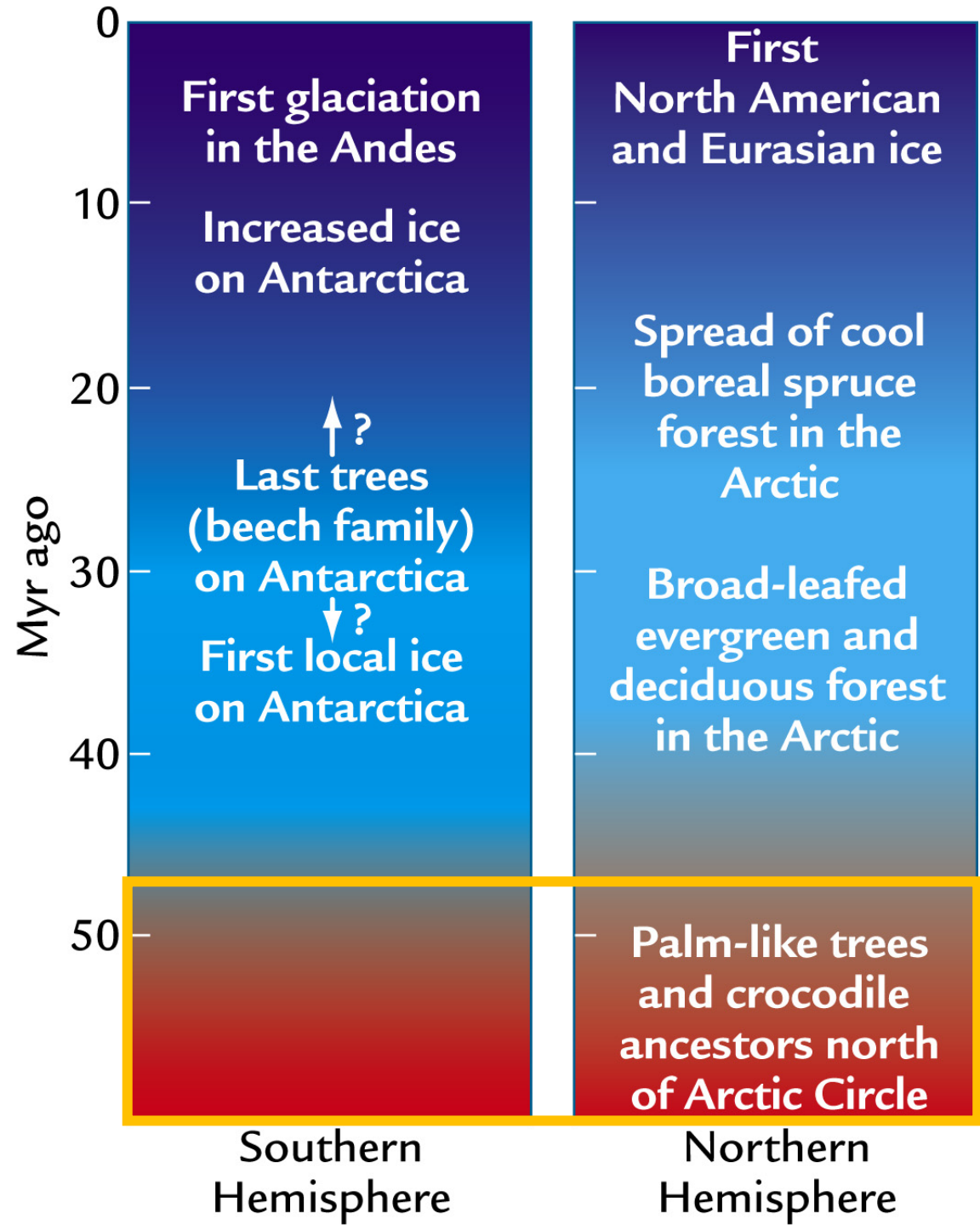
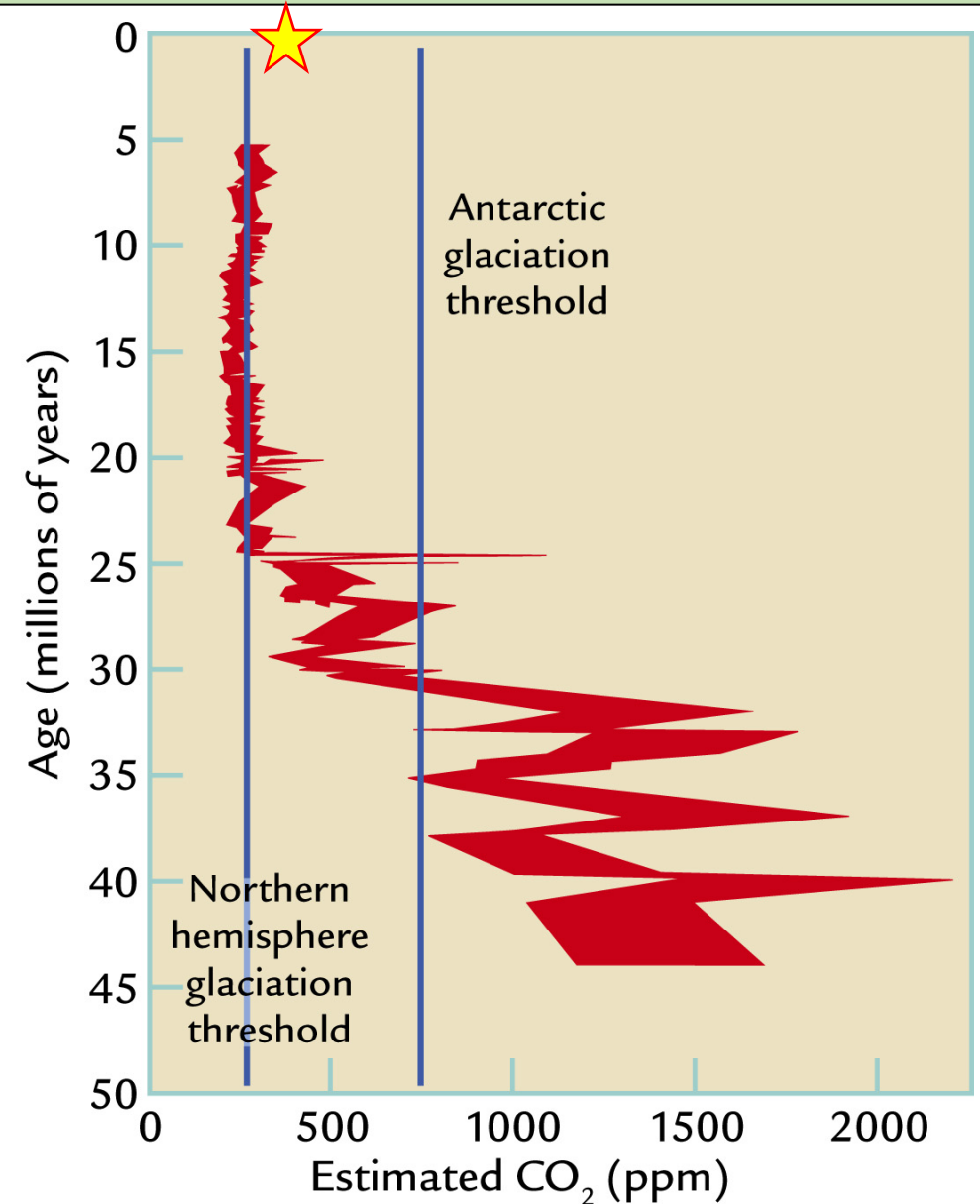


Figure from Zachos et al. (2008)



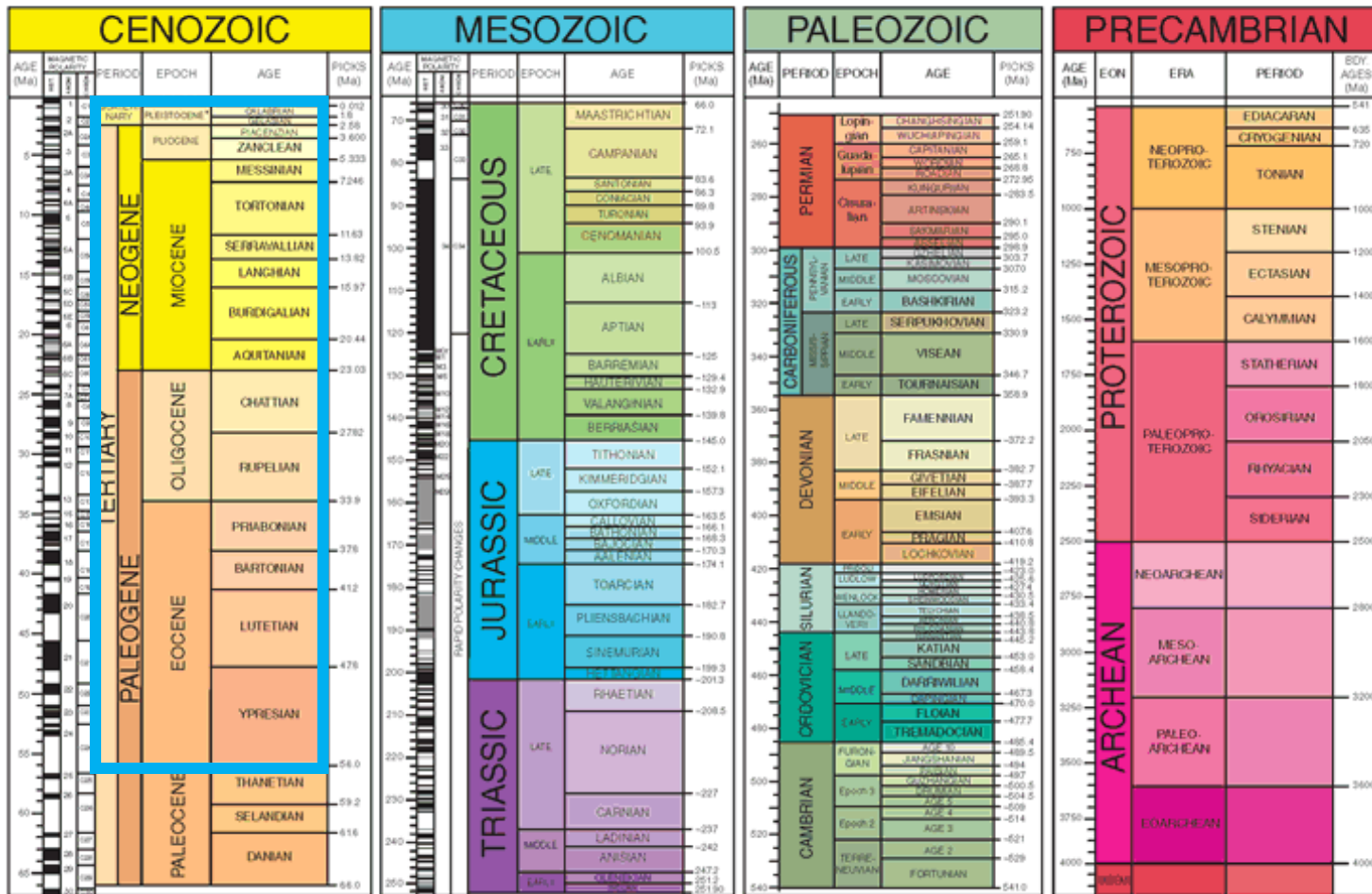
# What explains the cooling?

- Atmospheric CO<sub>2</sub> lowered *a lot*
- Most likely due to a combination of:
  - Reduced Volcanism
  - Increased chemical weathering (due to the formation of the Himalayan Mountains)



# Today's Class – Deep Time Paleoclimate

GSA GEOLOGIC TIME SCALE v. 5.0



So far we've talked about ~50 million years in the Earth's ~4.5 billion year history...

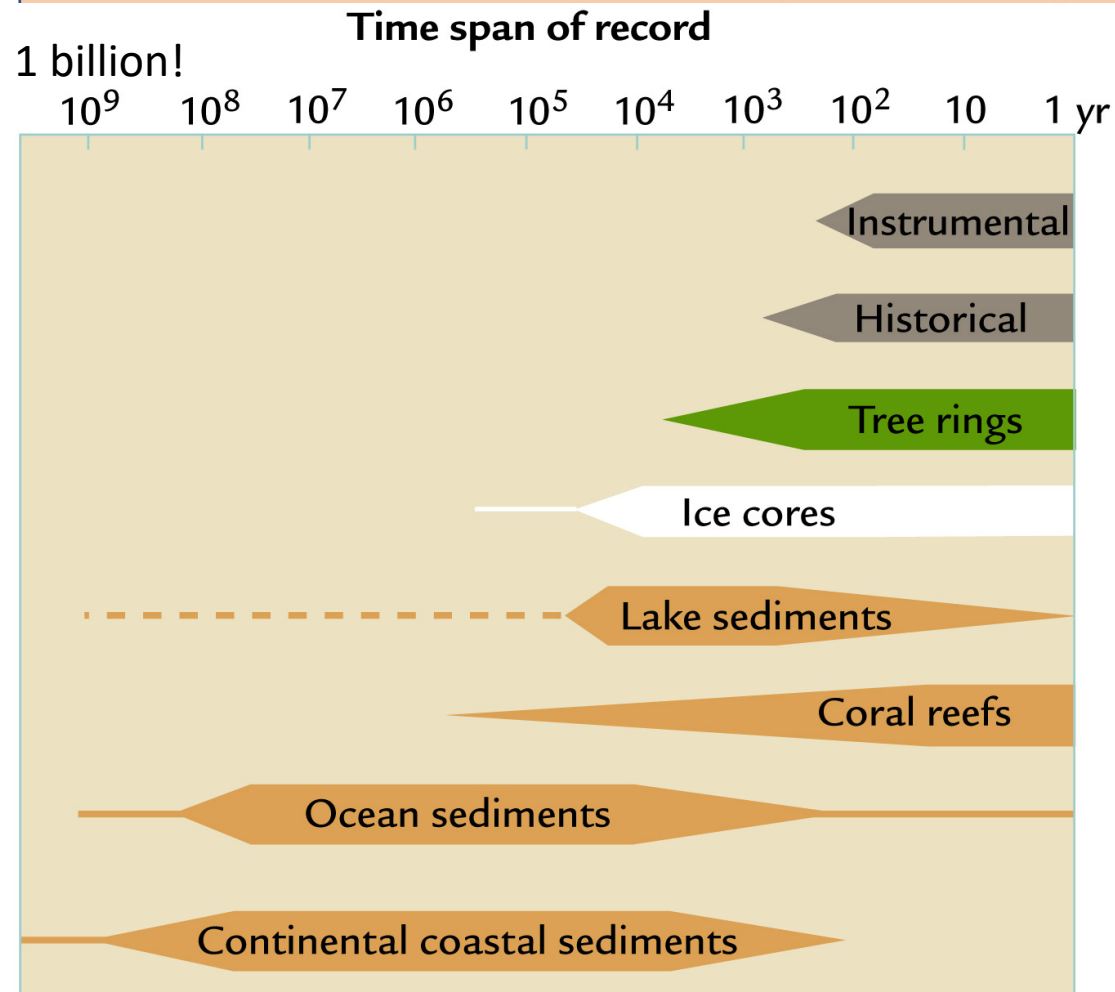
What happened in the rest of it?

Walker, J.D., Geissman, J.W., Bowering, S.A., and Babcock, L.E., compilers, 2016, Geologic Time Scale v. 5.0, Geological Society of America, <https://doi.org/10.1130/2015.CS0059DC>. ©2016 The Geological Society of America  
 \*The Proterozoic is divided into four ages, but only two are shown here. What is shown as Cambrian is actually three ages—Cambrian from 1.80 to 0.781 Ma, Middle from 0.781 to 0.126 Ma, and Late from 0.126 to 0.0117 Ma.  
 The Cenozoic, Mesozoic, and Paleozoic are the Eras of the Phanerozoic Eon. Names of units and age boundaries usually follow the Gradstein et al. (2012), Cohen et al. (2012), and Cohen et al. (2013, updated) compilations. Numerical age estimates and picks of boundaries usually follow the Cohen et al. (2013, updated) compilation. The numbered epochs and ages of the Cambrian are provisional. A "-" before a numerical age estimate typically indicates an associated error of ±0.4 to over 1.6 Ma.  
 REFERENCES CITED  
 Cohen, K.M., Finney, S., and Gibbard, P.L., 2012, International Chronostratigraphic Chart: International Commission on Stratigraphy, [www.stratigraphy.org](http://www.stratigraphy.org) (accessed May 2012). (Chart reproduced for the 34th International Geological Congress, Brisbane, Australia, 5-10 August 2012.)  
 Cohen, K.M., Finney, S.L., Gibbard, P.L., and Fan, J.-X., 2013, The ICS International Chronostratigraphic Chart: Episodes v. 36, no. 3, p. 199-204 [updated 2017, v. 2, <http://www.stratigraphy.org/index.php/ics-chart-timescale>, accessed May 2015].  
 Gradstein, F.M., Ogg, J.G., Schmitz, M.D., et al., 2012, The Geologic Time Scale 2012, Boston, USA, Elsevier, <https://doi.org/10.1016/B978-0-444-59425-9.00004-4>.  
 Previous versions of the time scale and previously published papers about the time scale and its evolution are posted at <http://www.geosociety.org/timescale>.



# How Do We Know About Deep Time Paleoclimate?

## 1. Some Paleoclimate Archives



## 2. Rocks From the Past—the Geologic Record

## 3. Life from the Past — The Fossil Record

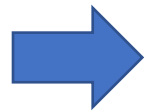


# Today's Class – Deep Time Paleoclimate

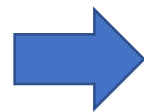
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4. Explain what runaway feedback system may have led to an 'icehouse' world, otherwise known as the Snowball Earth

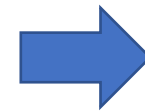
Greenhouse  
vs. Icehouse  
Climates



CO<sub>2</sub> and Plate  
Tectonics



Greenhouse  
World  
example: the  
Cretaceous



Icehouse  
World  
Example:  
Snowball  
Earth

# Greenhouse vs. Icehouse Worlds



**Greenhouse World**— Times when no ice sheets are present on Earth



**Icehouse World**— Times when ice sheets are present on Earth

# Think Pair Share...Greenhouse vs. Icehouse Worlds

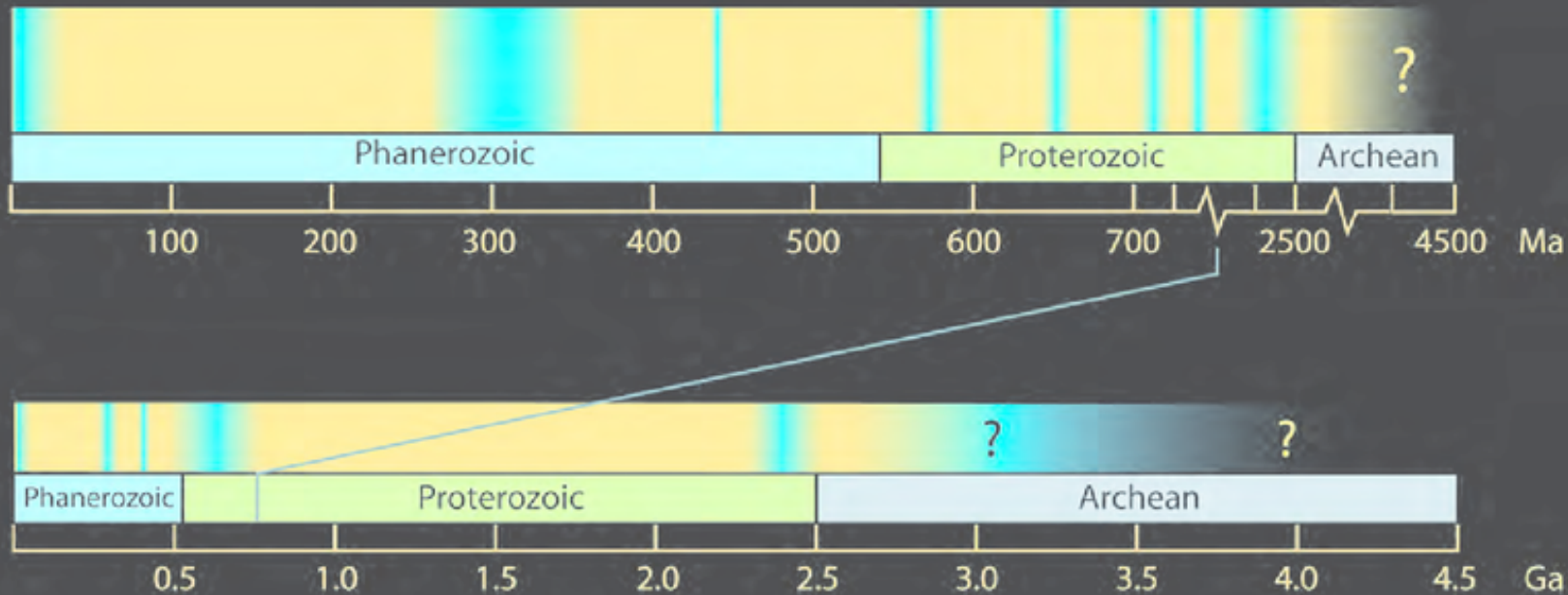


Figure from Parrish and Soreghan, 2013

Blue = icehouse world

Tan = greenhouse world

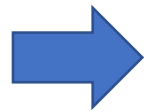
What observations can you make about the frequency and duration of greenhouse vs. icehouse climate conditions in Earth's history?

# Today's Class – Deep Time Paleoclimate

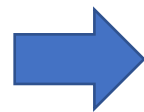
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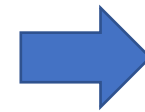
Greenhouse  
vs. Icehouse  
Climates



CO<sub>2</sub> and Plate  
Tectonics



Greenhouse  
World  
example: the  
Cretaceous

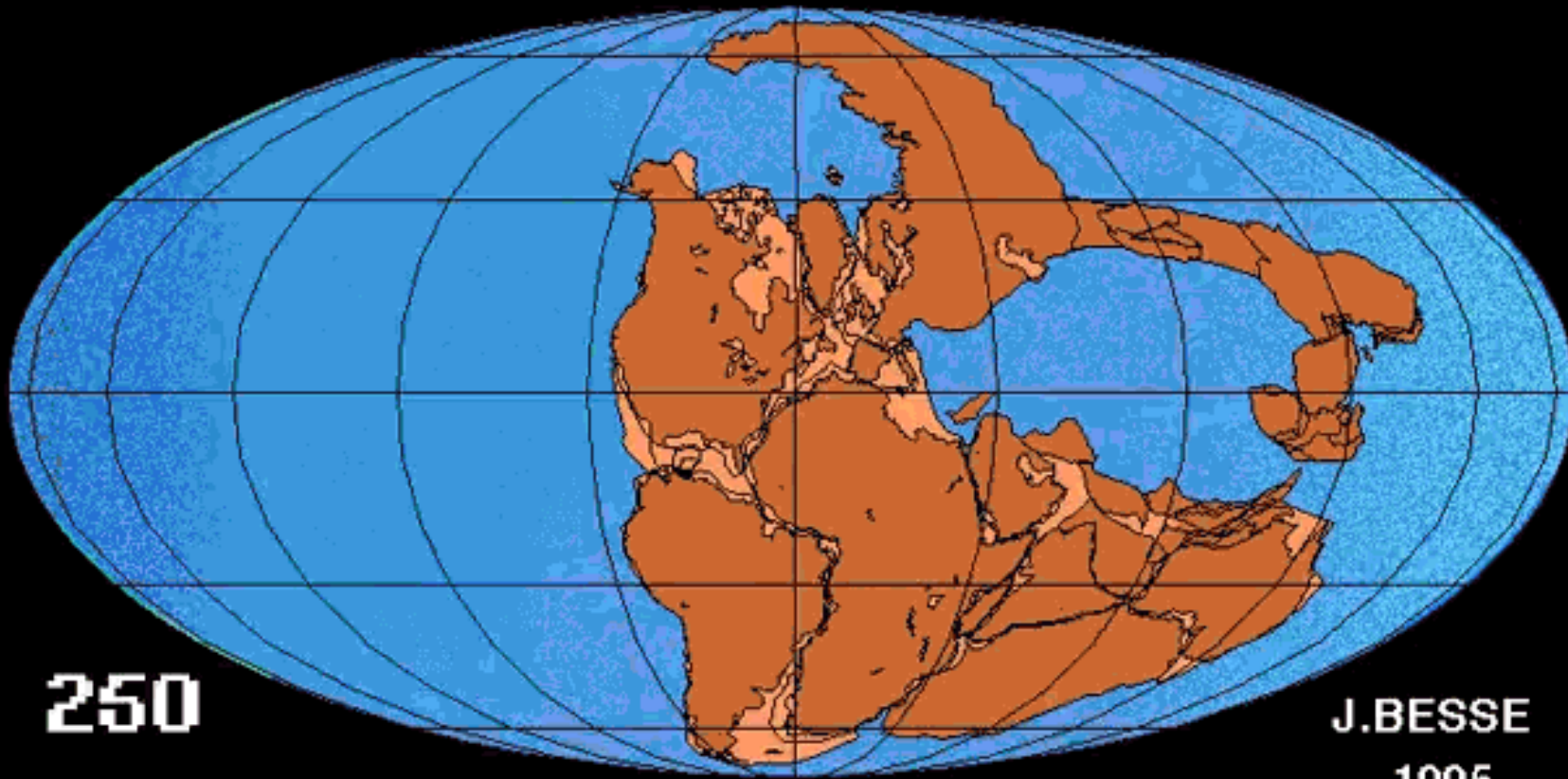


Icehouse  
World  
Example:  
Snowball  
Earth

# What Causes Changes in Temperature over Deep Time?



# What Causes Changes in CO<sub>2</sub>?



250

J.BESSE  
1995

Spreading plates =  
more volcanism =  
more CO<sub>2</sub> in the  
atmosphere

Colliding plates =  
mountain building =  
increased chemical  
weathering = less CO<sub>2</sub>  
in the atmosphere

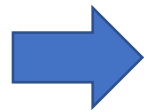
Position of the  
continents also plays  
a role in climate

# Today's Class – Deep Time Paleoclimate

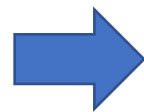
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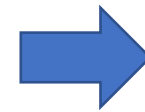
Greenhouse  
vs. Icehouse  
Climates



CO<sub>2</sub> and Plate  
Tectonics



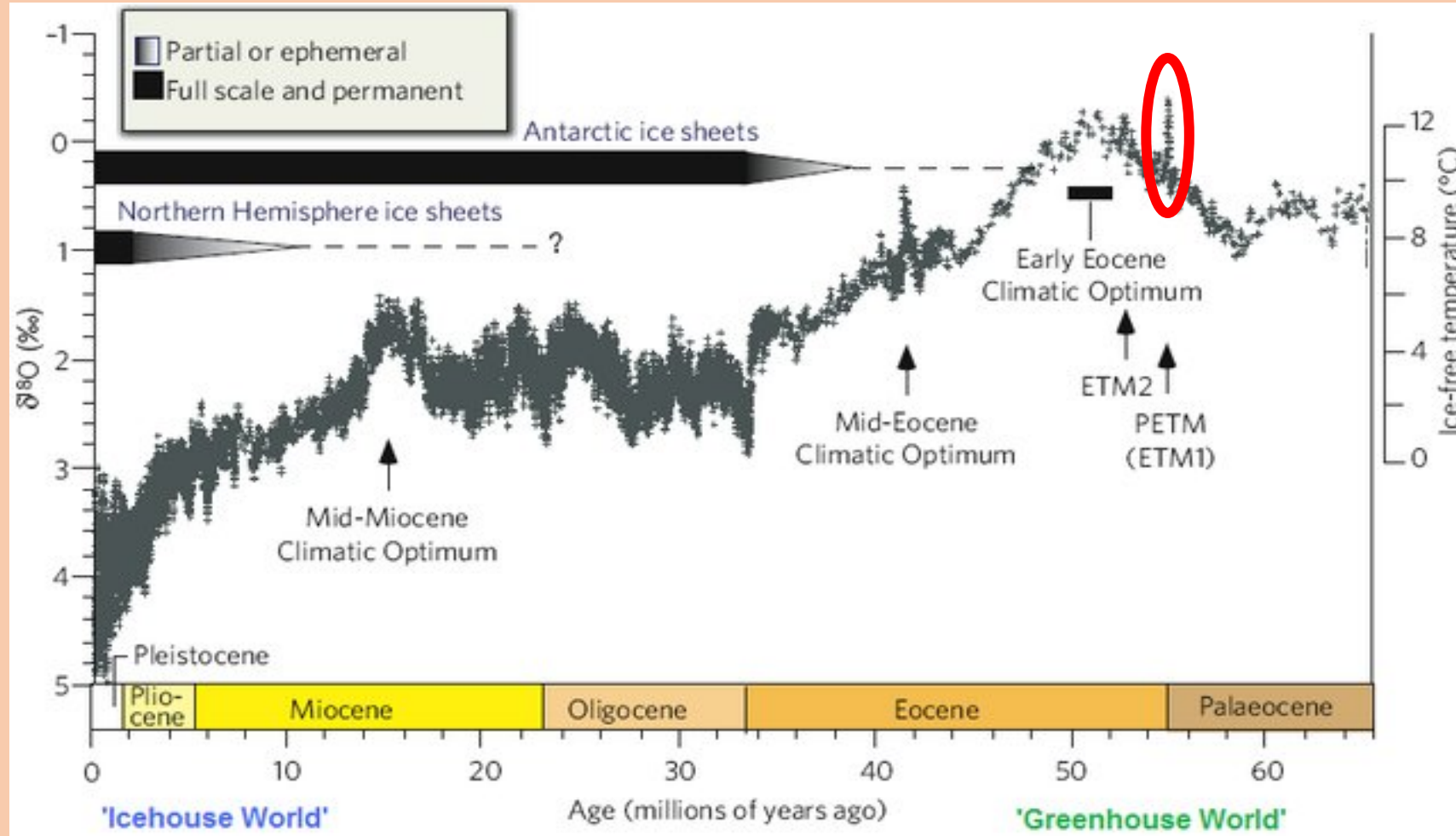
Hyperthermal  
events



Greenhouse  
and Icehouse  
World  
Examples



# Hyperthermals

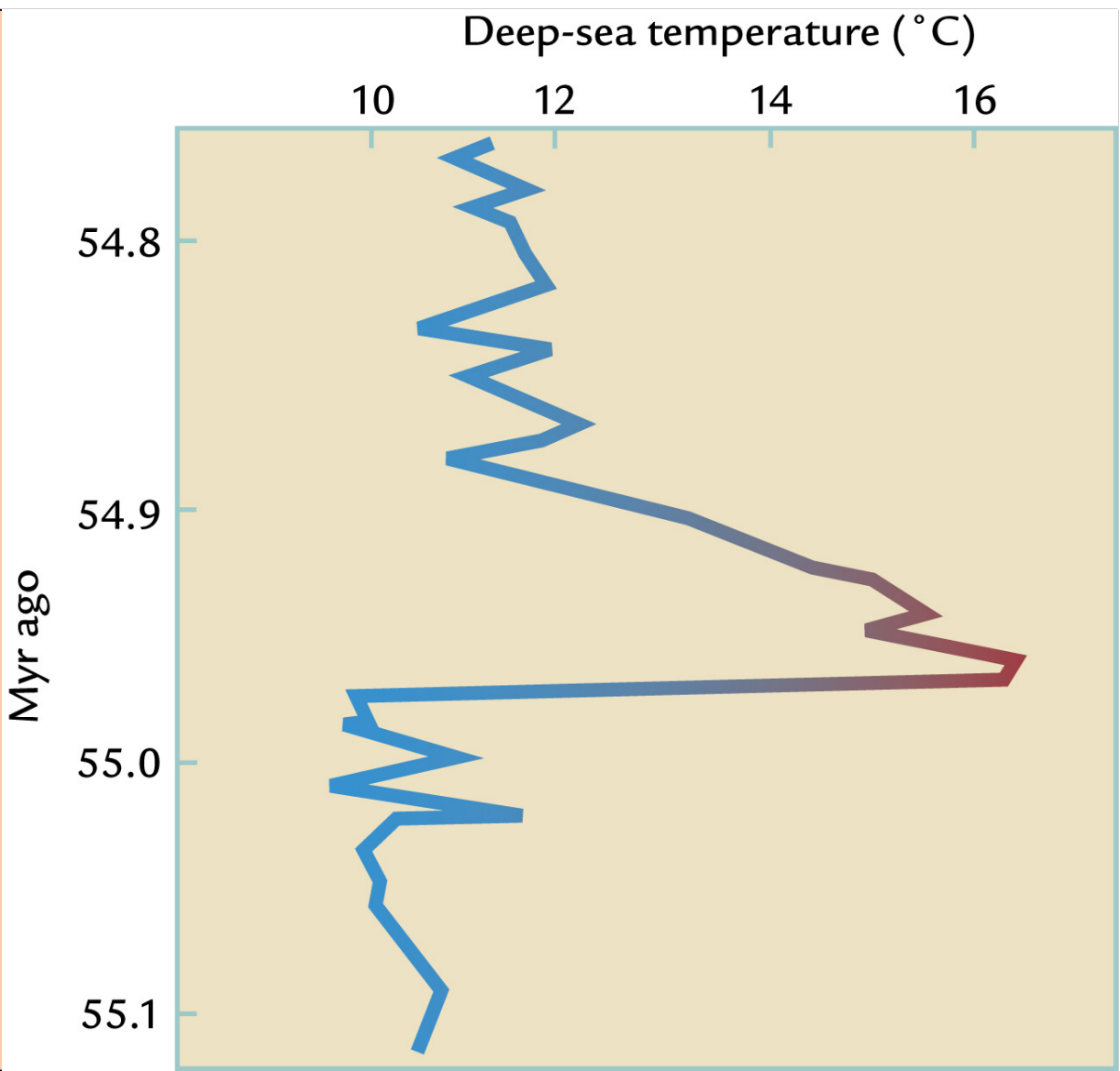


**Hyperthermals:** Times when the climate is *really* warm!

# Hyperthermals

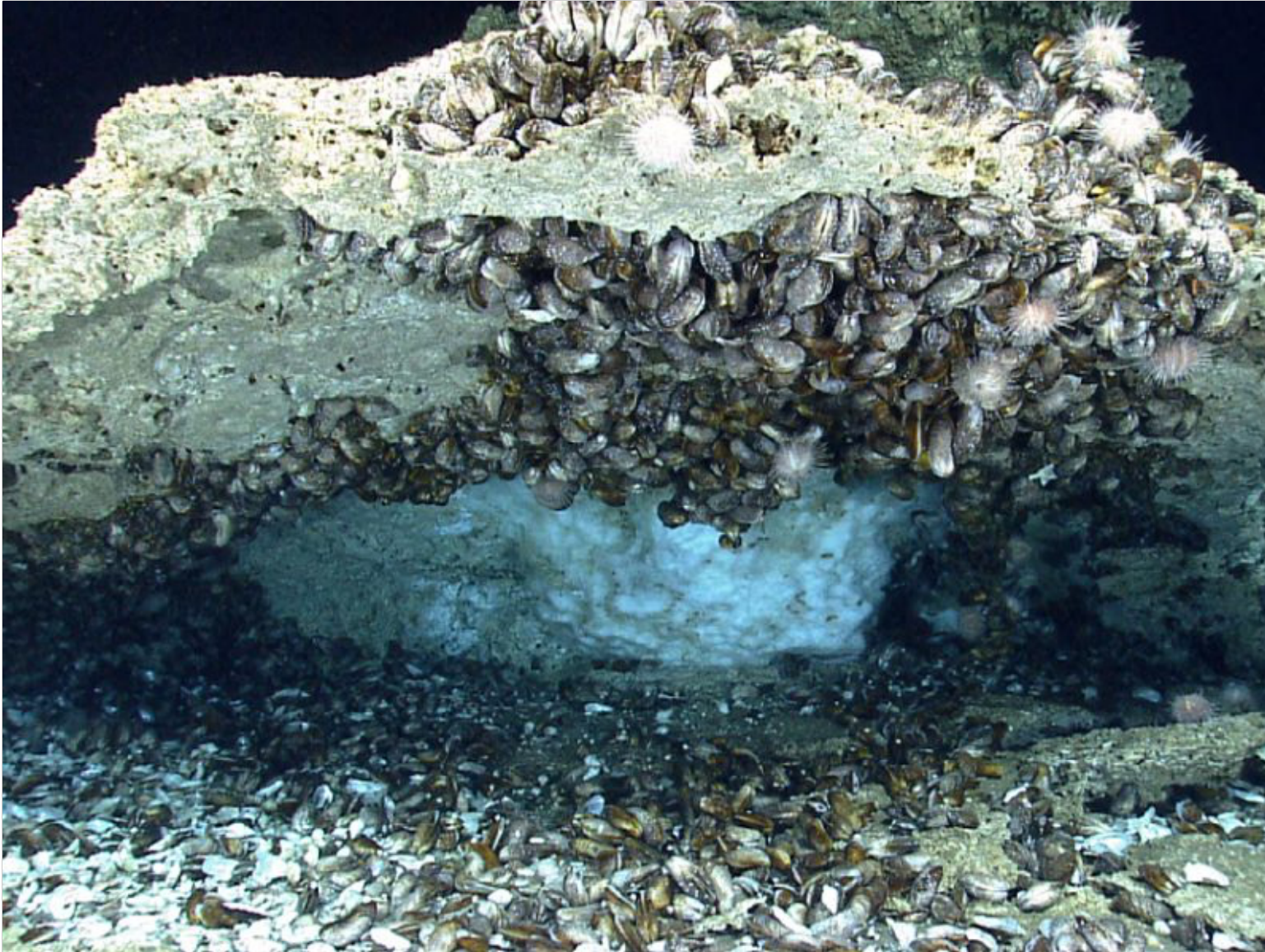
EONOTHEM / EON	ERATHEM / ERA	SYSTEM, SUBSYSTEM / PERIOD, SUBPERIOD	SERIES / EPOCH	Age estimates of boundaries in mega-annum (Ma) unless otherwise noted	
Phanerozoic	Cenozoic (Cz)	Quaternary (Q)	Holocene	11,700 ±99 yr*	
			Pleistocene		
		Tertiary (T)	Neogene (N)	Pliocene	2.588*
				Miocene	5.332 ±0.005
				Oligocene	23.03 ±0.05
			Paleogene (Pt)	Eocene	33.9 ±0.1
				<b>Paleocene</b>	55.8 ±0.2
				Paleocene	65.5 ±0.3
				Upper / Late	

The Paleocene-Eocene Thermal Maximum





# The PETM—An Analog to Current Warming?



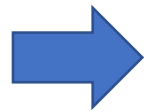
- The release of methane from the deep ocean is something scientists are concerned about with human-induced warming

# Today's Class – Deep Time Paleoclimate

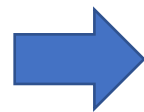
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4. Explain what runaway feedback system may have led to an 'icehouse' world, otherwise known as the Snowball Earth

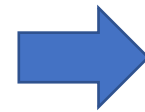
Greenhouse  
vs. Icehouse  
Climates



CO<sub>2</sub> and Plate  
Tectonics

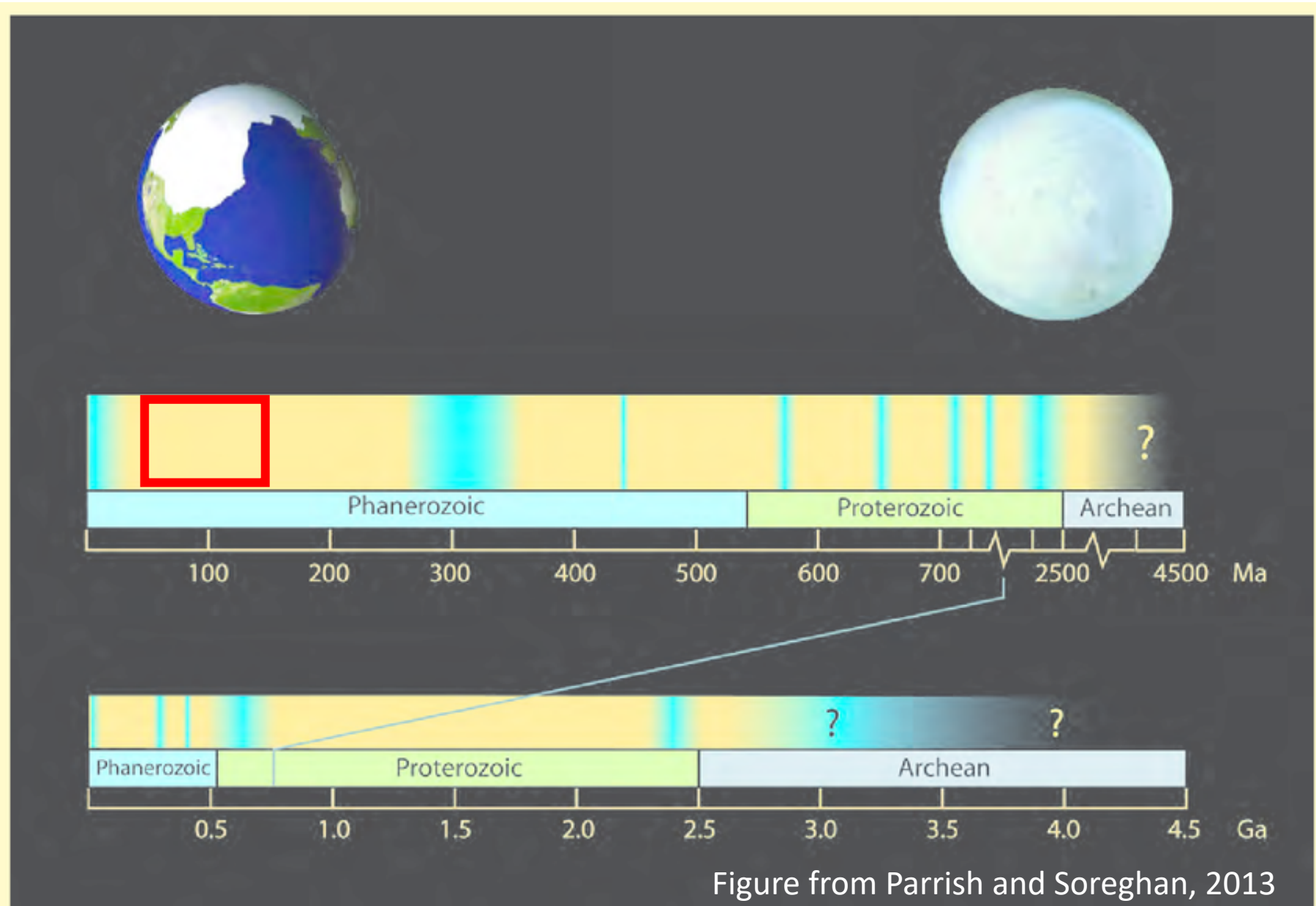


Hyperthermal  
events



Greenhouse  
and Icehouse  
World  
Examples

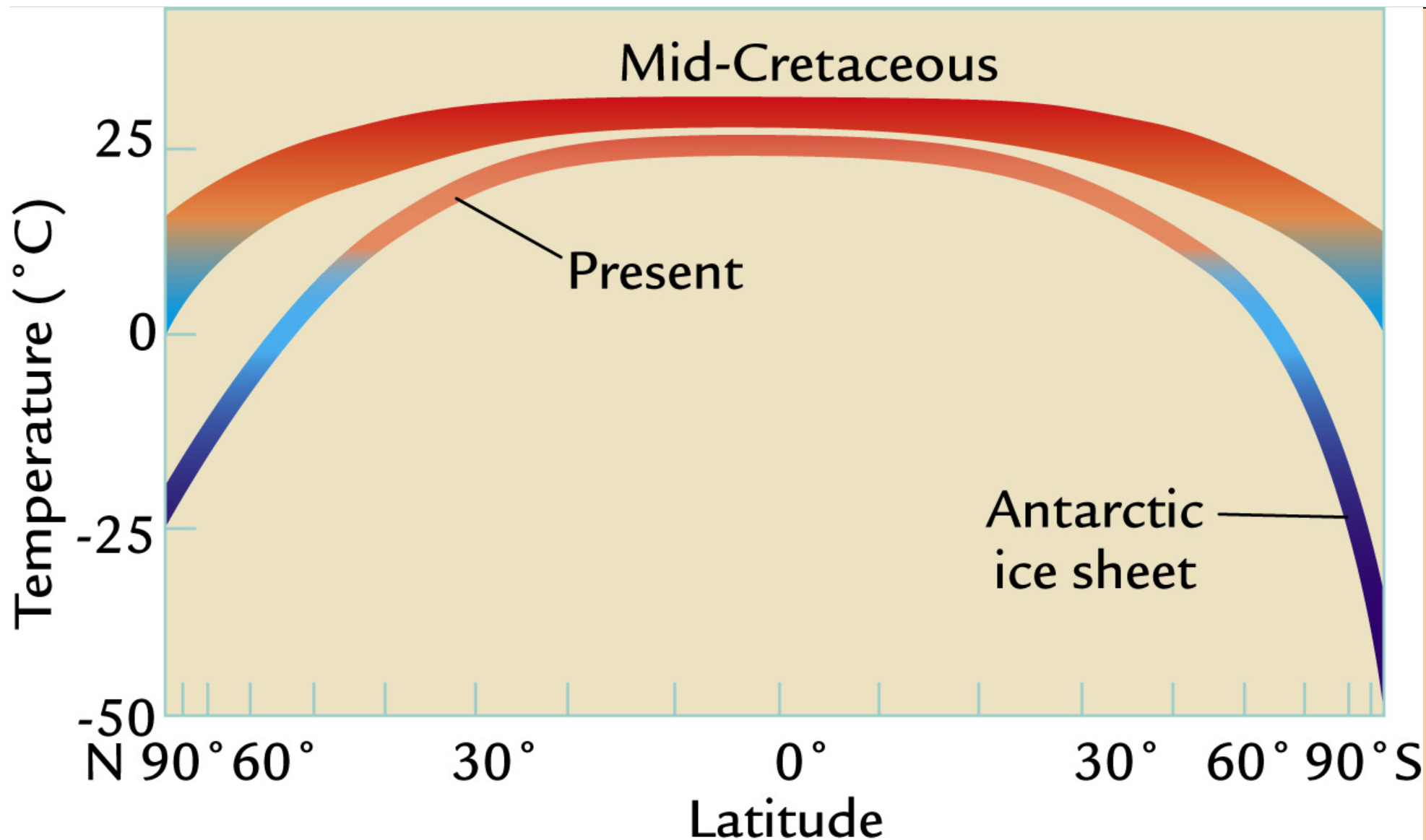
# Another Warm Time—the Cretaceous



# The Cretaceous



# The Cretaceous

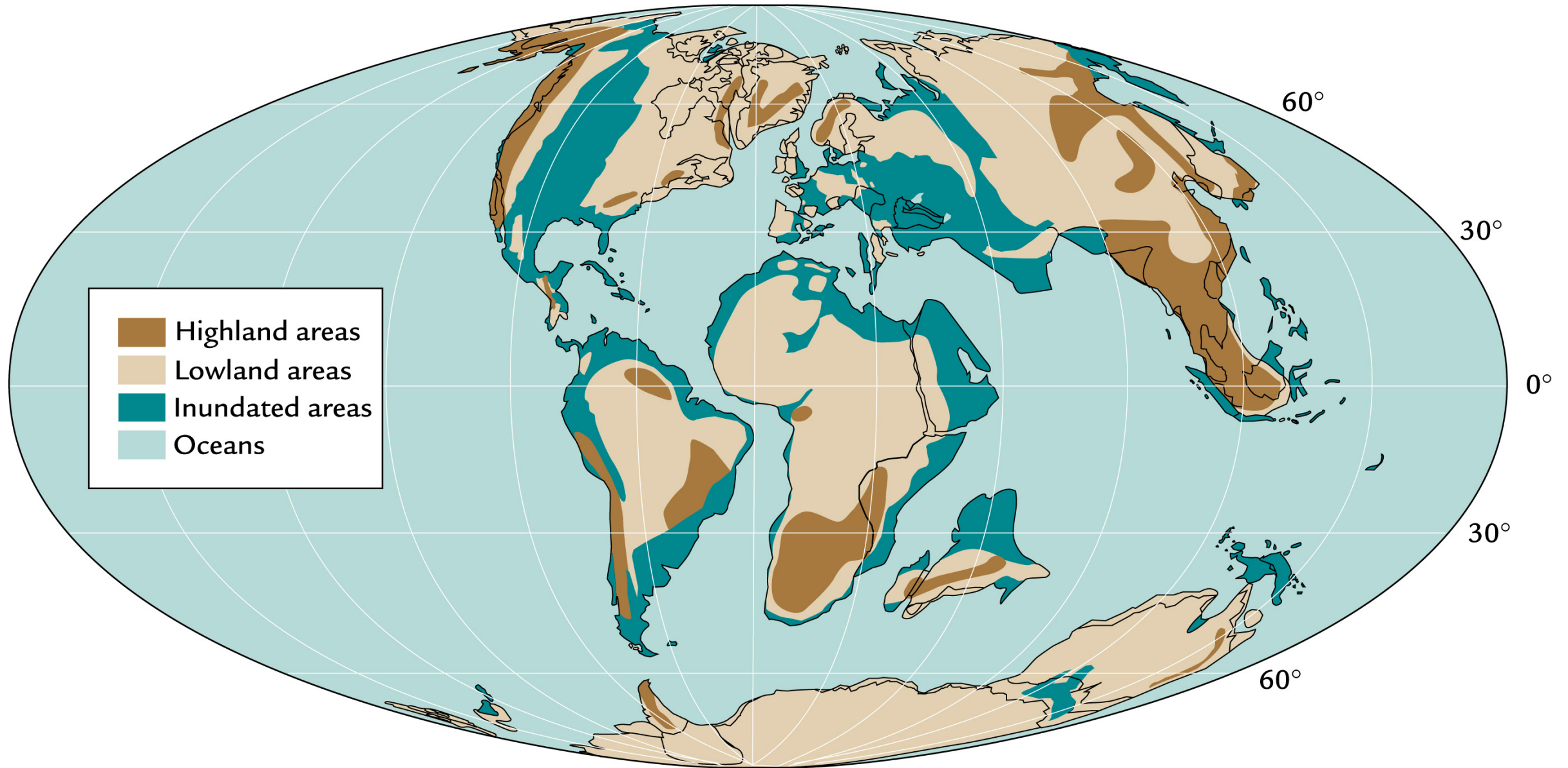


CO<sub>2</sub> levels were 4x higher than preindustrial levels

Polar temperatures were much warmer—no ice sheets



# The Cretaceous

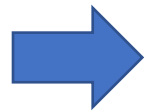


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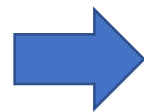
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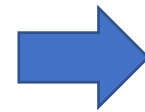
Greenhouse  
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CO<sub>2</sub> and Plate  
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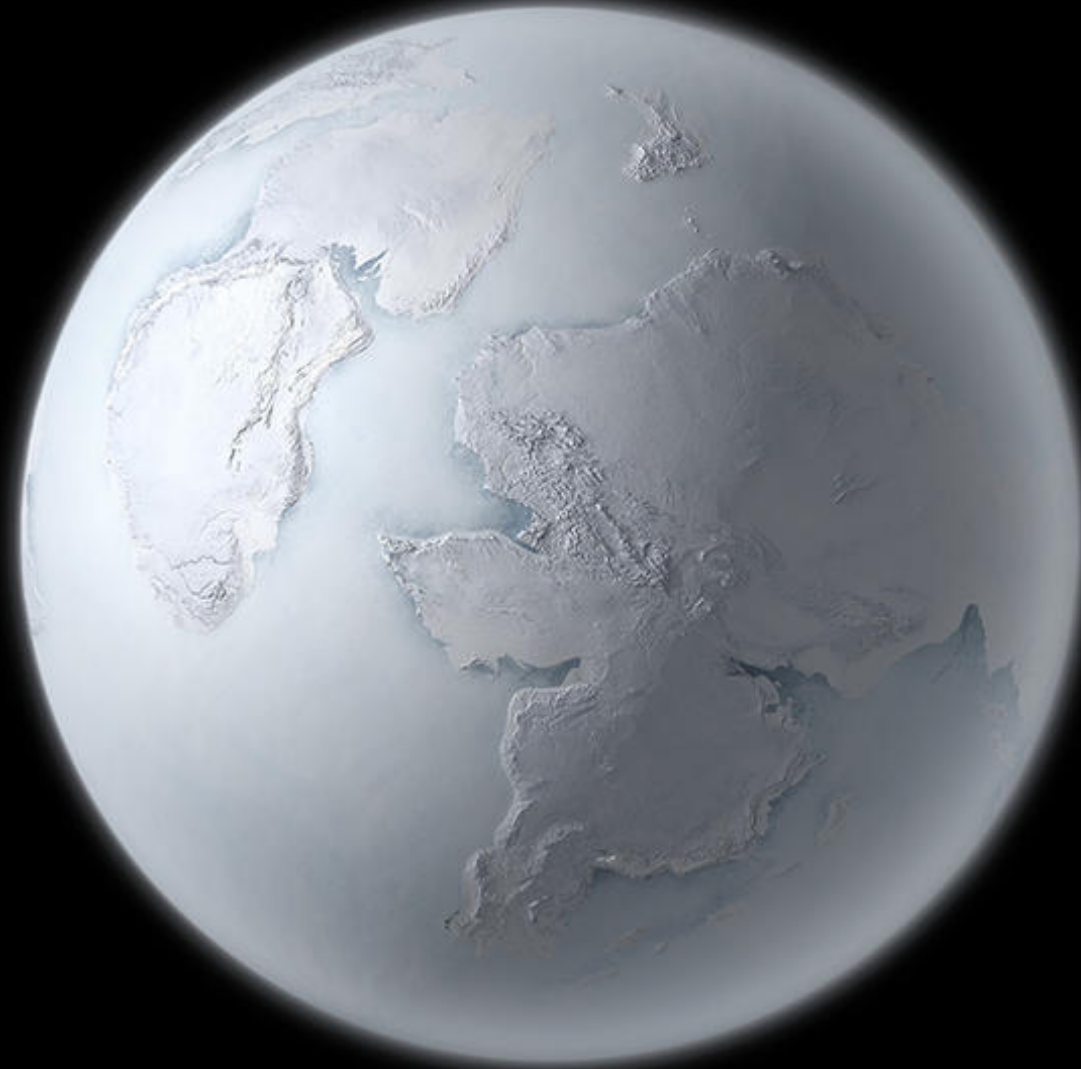


Hyperthermal  
events

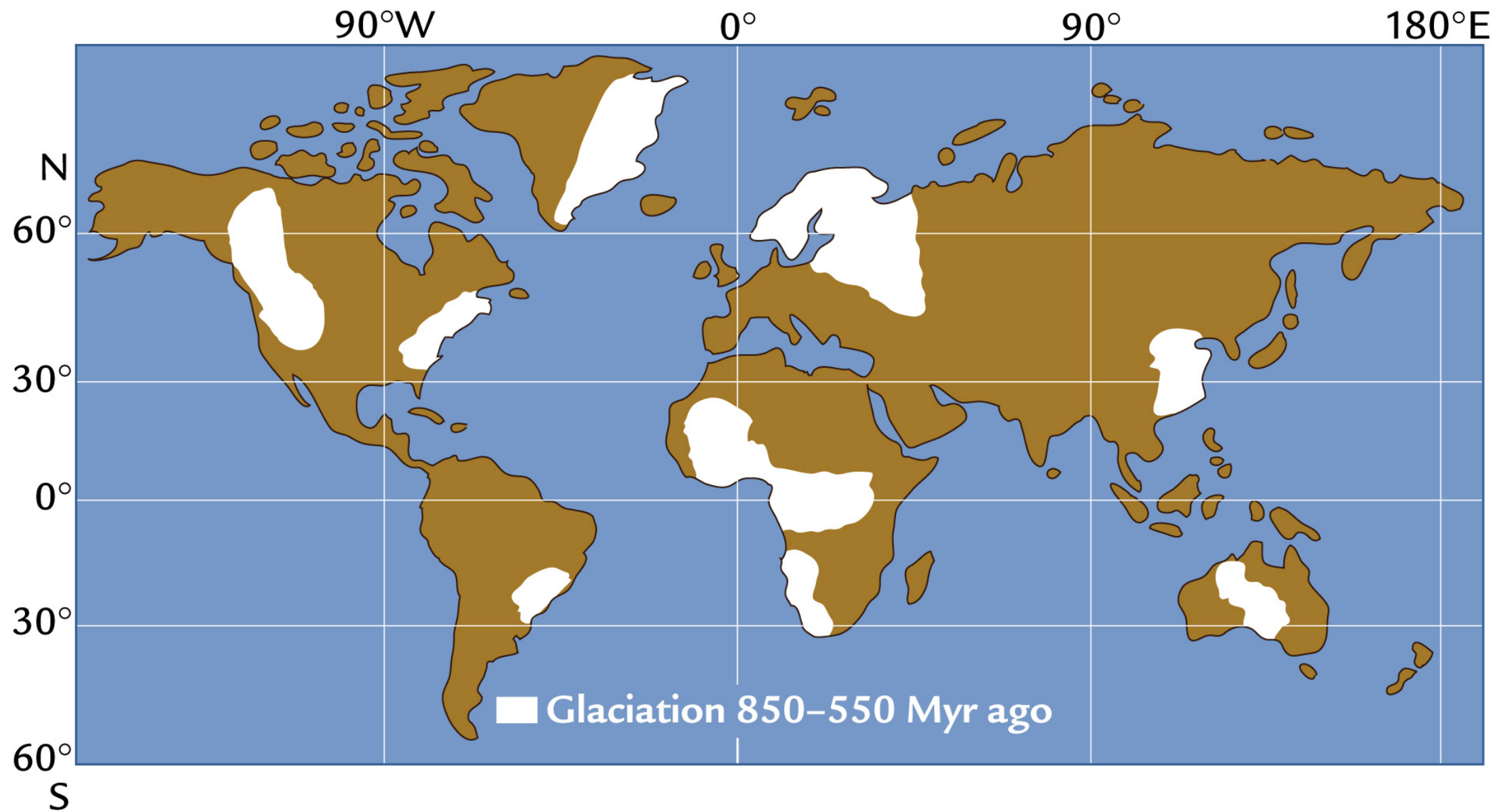


Greenhouse  
and Icehouse  
World  
Examples

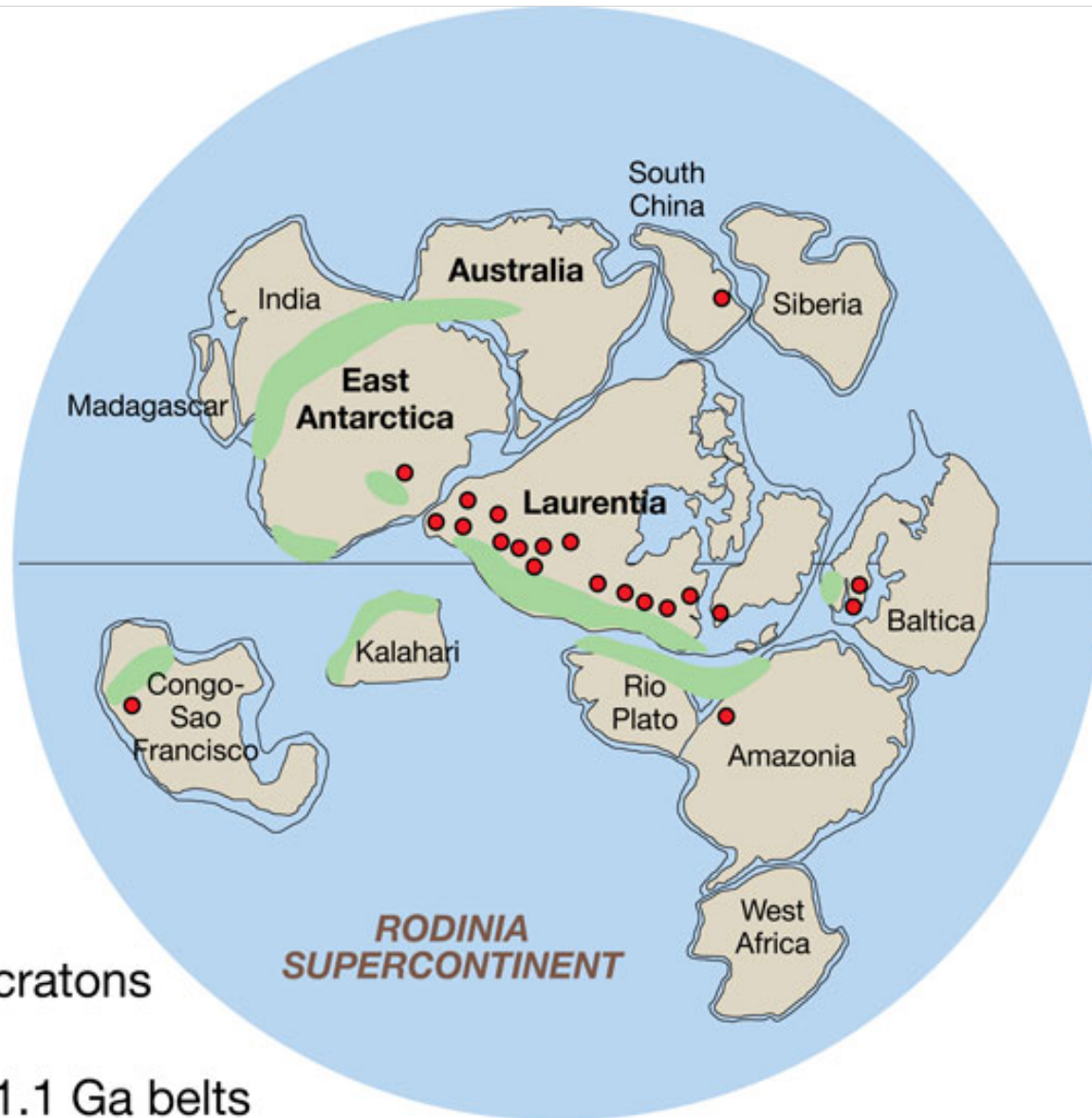
# Snowball Earth



# Snowball Earth



# Snowball Earth



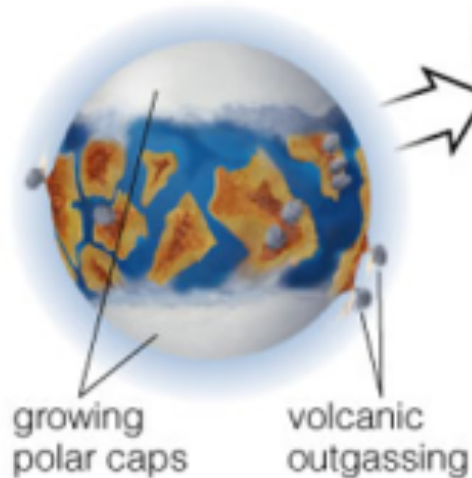
Continents were clustered at the Equator

High rainfall at the equator fell on the continents, causing an immense amount of chemical weathering

Chemical weathering removed a lot of  $\text{CO}_2$  from the atmosphere, causing initial cooling

# Snowball Earth

1. Cooler climate = ice sheets grow

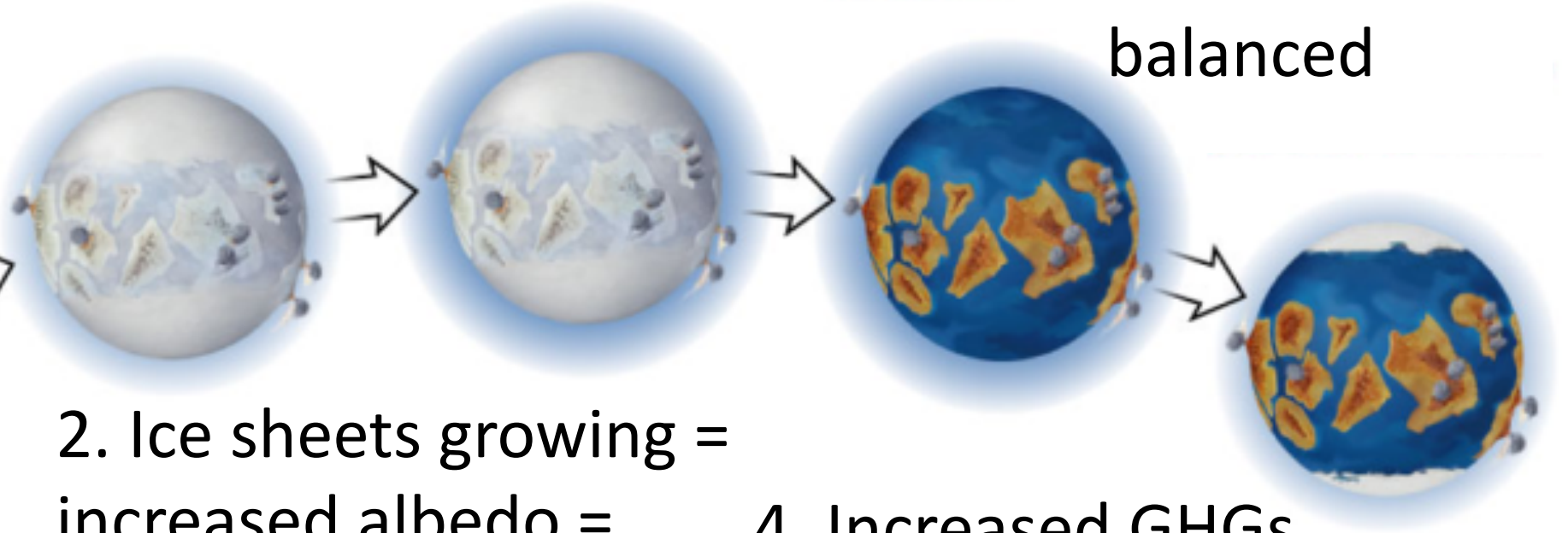


2. Ice sheets growing = increased albedo = bigger ice sheets!

3. Ocean stops storing new carbon, CO<sub>2</sub> builds up in atmosphere

4. Increased GHGs melt the snowball

5. Ocean carbon transport resumes, climate is re-balanced

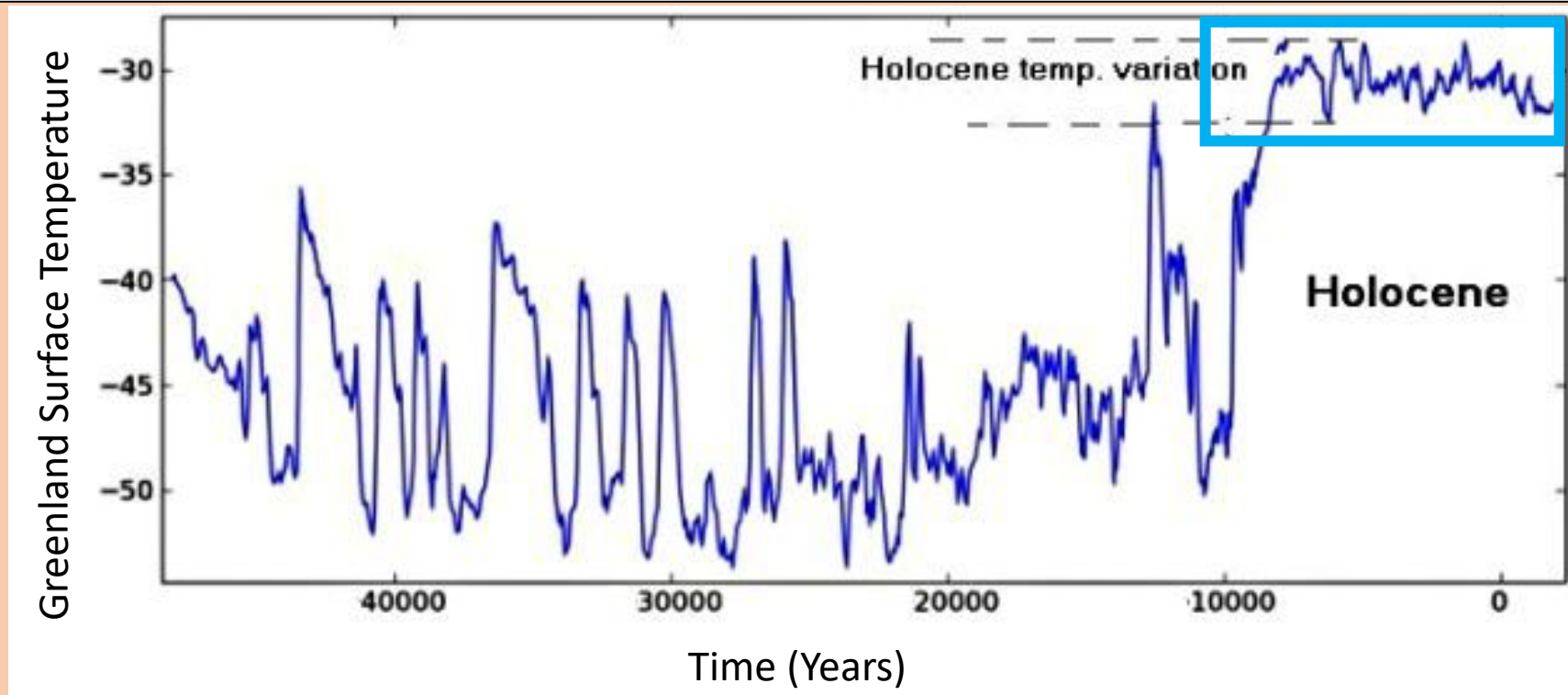


# Summary: Deep Time Paleoclimate

- The Earth's climate has shifted between greenhouse and icehouse conditions numerous times in its history
- Changes in temperature over long timescales are caused by plate tectonic processes that increase or decrease CO<sub>2</sub> in the atmosphere
- Extreme changes in the amount of CO<sub>2</sub> in the atmosphere have caused both extremely warm and extremely cold climate conditions
- Studying these past warm periods can help us learn about changes that may occur as a result of human-caused warming

# Review— The Holocene

EONOTHEM / EON		ERATHEM / ERA		SYSTEM, SUBSYSTEM / PERIOD, SUBPERIOD		SERIES / EPOCH	Age estimates of boundaries in mega-annum (Ma) unless otherwise noted
Phanerozoic	Cenozoic (Cz)	Quaternary (Q)	Holocene		11,700 ±99 yr*		
			Pleistocene		2.588*		
		Tertiary (T)	Neogene (N)	Pliocene		5.332 ±0.005	
				Miocene		23.03 ±0.05	
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				Paleocene		65.5 ±0.3	
				Upper / Late			



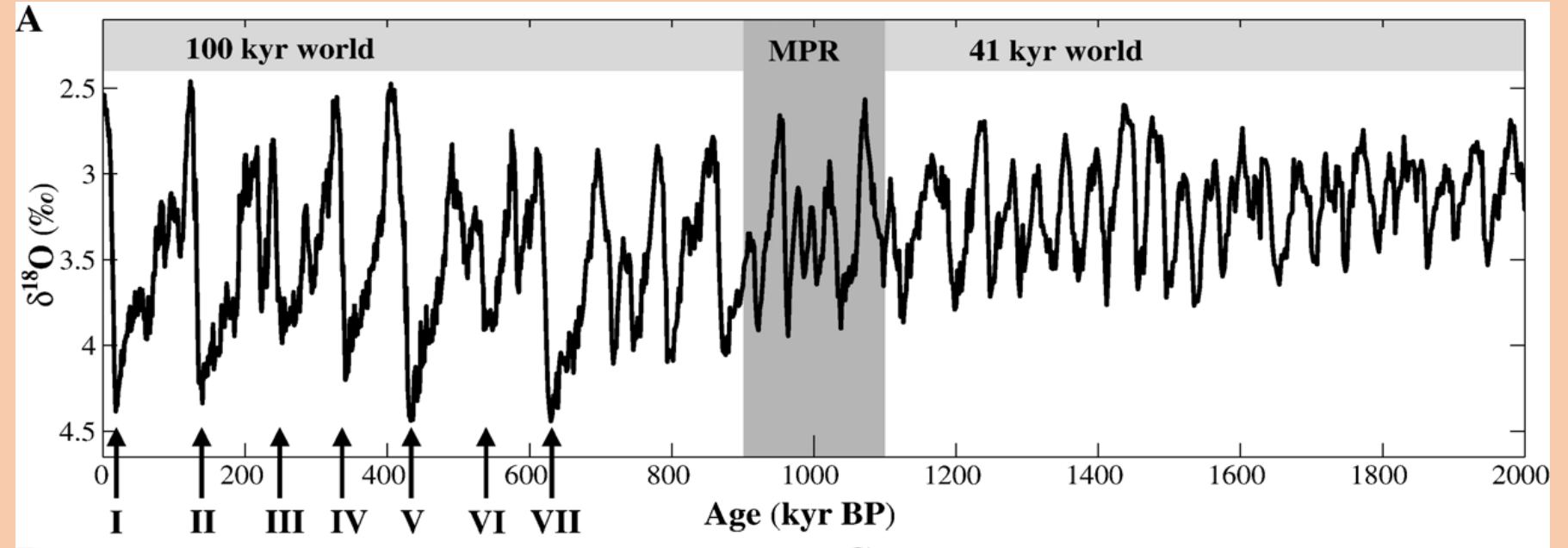
**Holocene:** 11,700 years ago to present

Characterized by stable temperatures, sea levels, and CO<sub>2</sub>



# Review— The Pleistocene

EONOTHEM / EON		ERATHEM / ERA		SYSTEM, SUBSYSTEM / PERIOD, SUBPERIOD		SERIES / EPOCH		Age estimates of boundaries in mega-annum (Ma) unless otherwise noted			
Phanerozoic	Cenozoic (Cz)	Quaternary (Q)	Holocene	11,700 ±99 yr*		Pleistocene		2.588*			
			Pliocene	5.332 ±0.005		Miocene		23.03 ±0.05			
		Neogene (N)	Oligocene	33.9 ±0.1		Eocene		55.8 ±0.2			
			Eocene	55.8 ±0.2		Paleocene		65.5 ±0.3			
			Paleocene	65.5 ±0.3		Upper / Late					
		Tertiary (T)	Paleogene (Pt)								

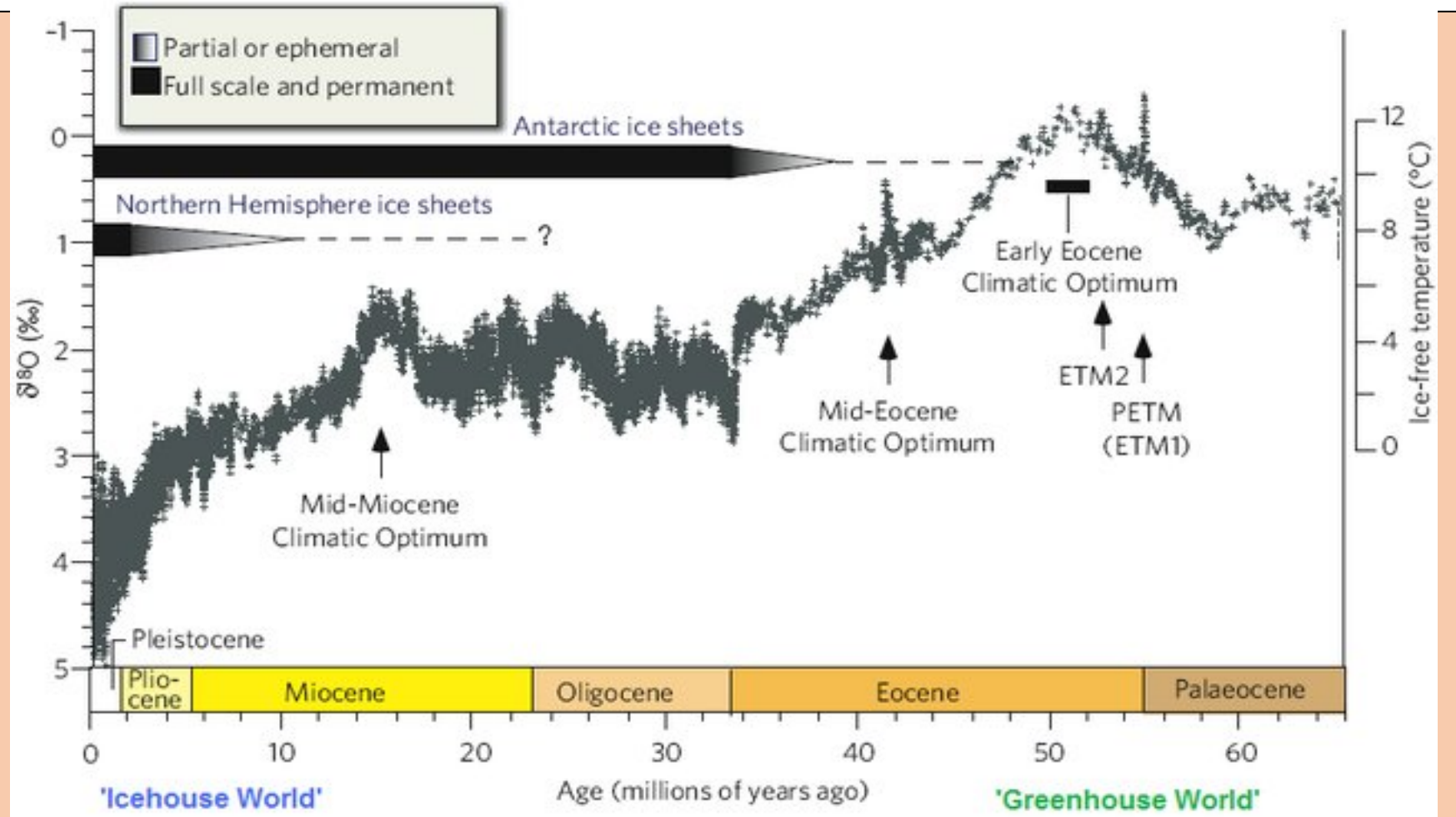


**Pleistocene: 11,700-2.6 million years ago**

Characterized by 'sawtooth' pattern of temperatures, slow build up to glaciers and rapid retreat

# Review– The Last 50 million Years

EONOTHEM / EON	ERATHEM / ERA	SYSTEM, SUBSYSTEM / PERIOD, SUBPERIOD	SERIES / EPOCH	Age estimates of boundaries in mega-annum (Ma) unless otherwise noted	
Phanerozoic	Cenozoic (Cz)	Quaternary (Q)	Holocene	11,700 ± 99 yr*	
			Pleistocene		
		Tertiary (T)	Neogene (N)	Pliocene	2.588*
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			Paleogene (Pt)	Oligocene	23.03 ± 0.05
				Eocene	33.9 ± 0.1
				Paleocene	55.8 ± 0.2
				Upper / Late	65.5 ± 0.3



**2.5-50 million years ago: Climate is overall much warmer than the Pleistocene and the Holocene**

# Review– Deep Time

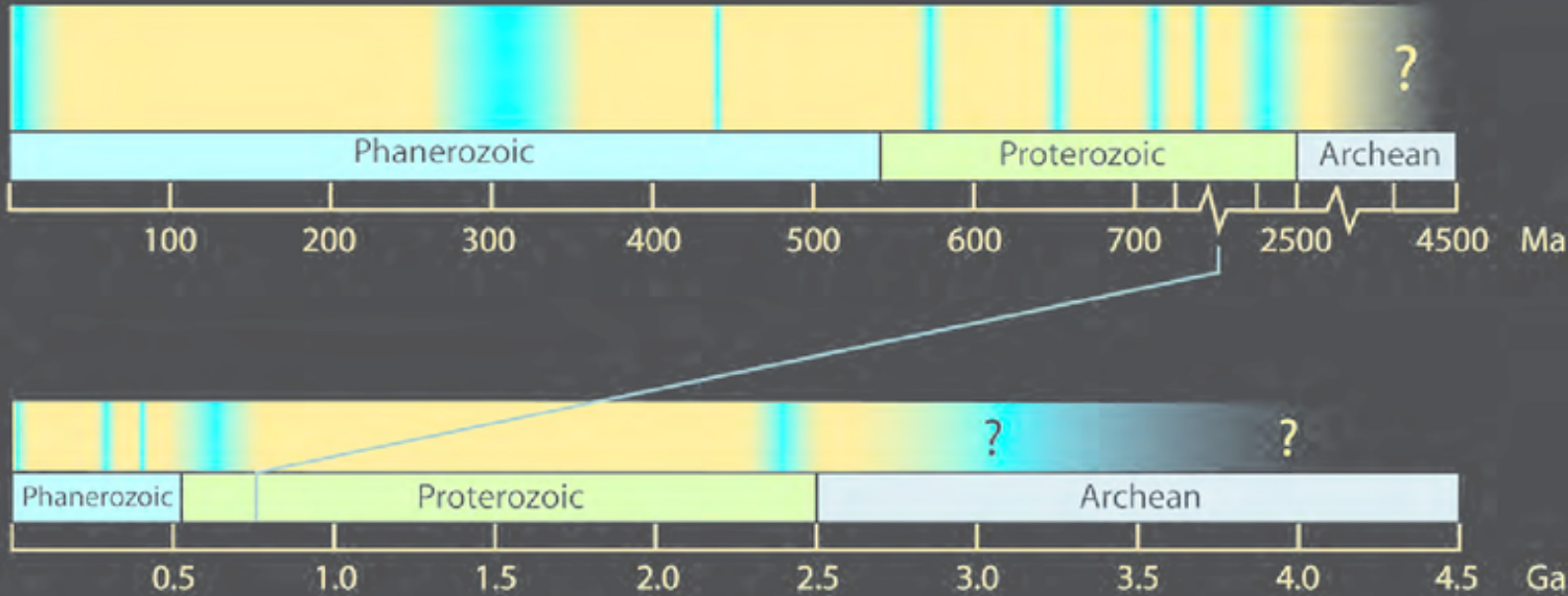


Figure from Parrish and Soreghan, 2013

Over long timescales, Earth has fluctuated between Greenhouse and Icehouse conditions

Changes driven by plate tectonics

# Review Session Time

- Exam is the same format as last time– 1 essay, short answer questions.
- Not cumulative, just paleoclimate.
- Has to be taken during class time.
- Still open book and open note.
- On your honor not to give or receive help from anyone.
  
- This is your time, ask us questions!