Palaeoclimate -
Understanding the past to predict the future

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Points to discuss

- **Part I (Tuesday: 12.3.1 – 12.3.3)**
  - **Learn how we can reconstruct past climates**
    - **Palaeoclimate archives and – proxies**
  - **Climate change as a constant feature of Earth’s deep time history (the tectonic time-scale)**
  - **Cretaceous Greenhouse climate**
- **Part II (Wednesday) (12.3.4.-12.3.6)**
  - **“Icehouse” climates**
  - **The rhythm of past climatic changes (Milankovitch)**
  - **Post glacial climate variability and future climate change**

Resources

- Powerpoint presentations
- Pensum: Atmosphere, ocean, and climate dynamics: an introductory text J. Marshall and R.A. Plumb Chapter 12.3. Palaeoclimate and subchapters (1-6) pp. 269 - 288
- Additional reading:
  - W. F. Ruddiman Earth´s Climate

  Palgrave Macmillan ISBN 978-1-4292-5525-7
    - Chapters 3, 4-7…
- NOAA Paleoclimate Data
  - https://www.ncdc.noaa.gov/data-access/paleoclimatology-data
- Quote of the 1st lines ch.12.3: "Study of paleoclimate is an extremely exciting area of research, a fascinating detective story in which scientists study evidence of past climates recorded in ocean and lake sediments, glaciers and ice sheets, and continental deposits."

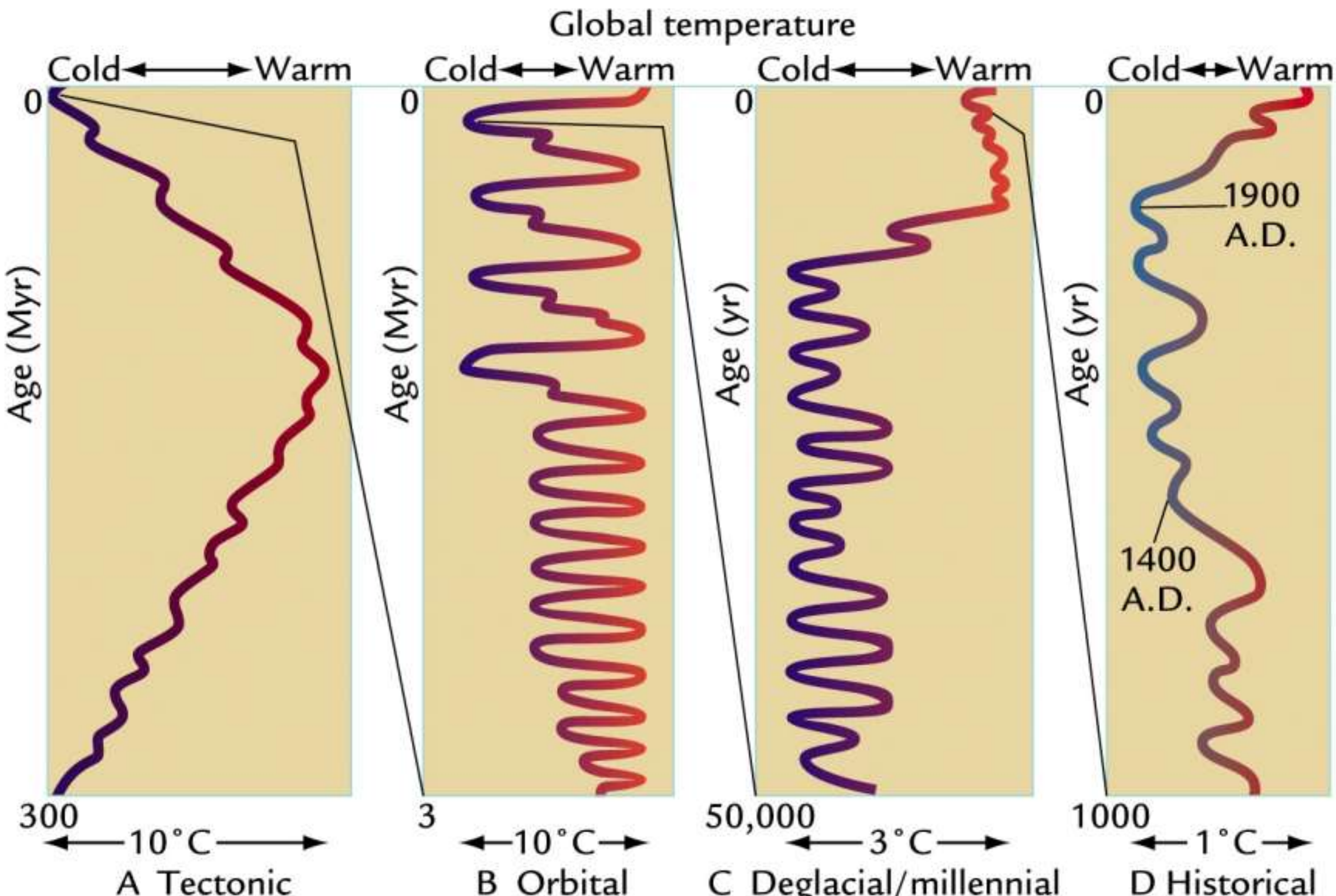
Climate Change

- What is climate?
  - Climate is the long term expression of weather.
- Climate changed since the beginning of the earth.
- Analysis of potential causes of past climate change offers predictions for the future.

Timescale	Days				Years		Thousands of years			Million of years	
	h/d	w	m	y	10y	102y	103y	104y	105y	106y	109y
weather	x	x									
Land surface	x	x	x								
Ocean mixed layer	x	x	x								
Sea ice		x	x	x							
Volcano		x	x	x							
Vegetation	x	x	x	x	x	x	x	x	x	x	
Thermocline				x	x	x					
Mountain glaciers					x	x					
Deep Ocean						x	x	x			
Ice sheets						x	x	x	x		
Orbital forcing								x	x		
Tectonics										x	x
Weathering									x	x	x
Solar “constant”				x	x	x	x	x	x	x	x

Processes

Figure 12.1

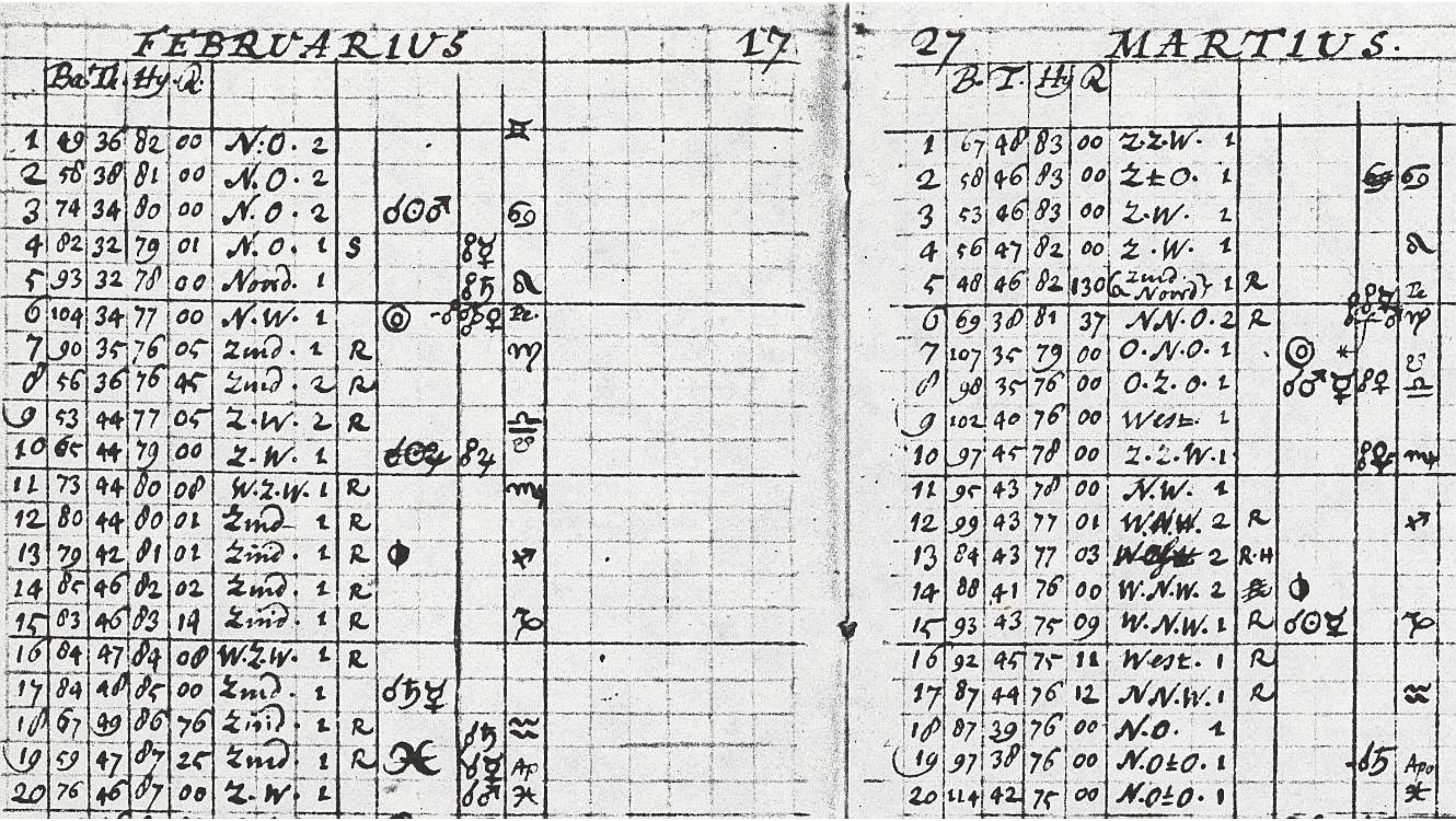


Global temperature
Cold Warm
Cold Warm
Cold Warm
Cold Warm
0
0
0
0
Age (Myr)
Age (Myr)
Age (yr)
Age (yr)
1900 A.D.
1400 A.D.
300
3
50,000
1000
10°C
10°C
3°C
1°C
A Tectonic
B Orbital
C Deglacial/millennial
D Historical

Archives and Proxies

- GOAL: Reading the history of past climate from the natural archive
- Measured weather records (time series)
  - **BUT instrumental record goes back only into 17th century (major parts on earth much less)**
- Historical Archives
- Geological (sedimentary archives)
- Climate proxies:
  - The term proxy (meaning "substitute" / "approximation") is used in palaeoclimatology because the extraction of climate signals from the indicators in the archive is NOT A DIRECT observation of the palaeoclimate.

Human archive



FEBRUARIUS 17

	Ba	Th	Hy	R					
1	49	36	82	00	N:O. 2				♊
2	58	38	81	00	N.O. 2				
3	74	34	80	00	N.O. 2		☌☉♂		♋
4	82	32	79	01	N.O. 1	S		☍☿	
5	93	32	78	00	Noord. 1			☍♄	♌
6	104	34	77	00	N.W. 1		◎ -☍	☍♀	Pe.
7	90	35	76	05	Zuid. 1	R			♍
8	56	36	76	45	Zuid. 2	R			
9	53	44	77	05	Z.W. 2	R			♎
10	65	44	79	00	Z.W. 1		☌☉♃	☍♃	☋
11	73	44	80	08	W.Z.W. 1	R			♏
12	80	44	80	01	Zuid 1	R			
13	79	42	81	02	Zuid. 1	R	◐		♐
14	85	46	82	02	Zuid. 1	R			
15	83	46	83	19	Zuid. 1	R			♑
16	84	47	84	08	W.Z.W. 1	R			
17	84	48	85	00	Zuid. 1		☌♄☿		
18	67	49	86	76	Zuid. 1	R		☍♄	♒
19	59	47	87	25	Zuid 1	R	[illegible]	☍☿	Ap
20	76	46	87	00	Z.W. 1			☍♂	♓

27 MARTIUS.

	B	T	Hy	R					
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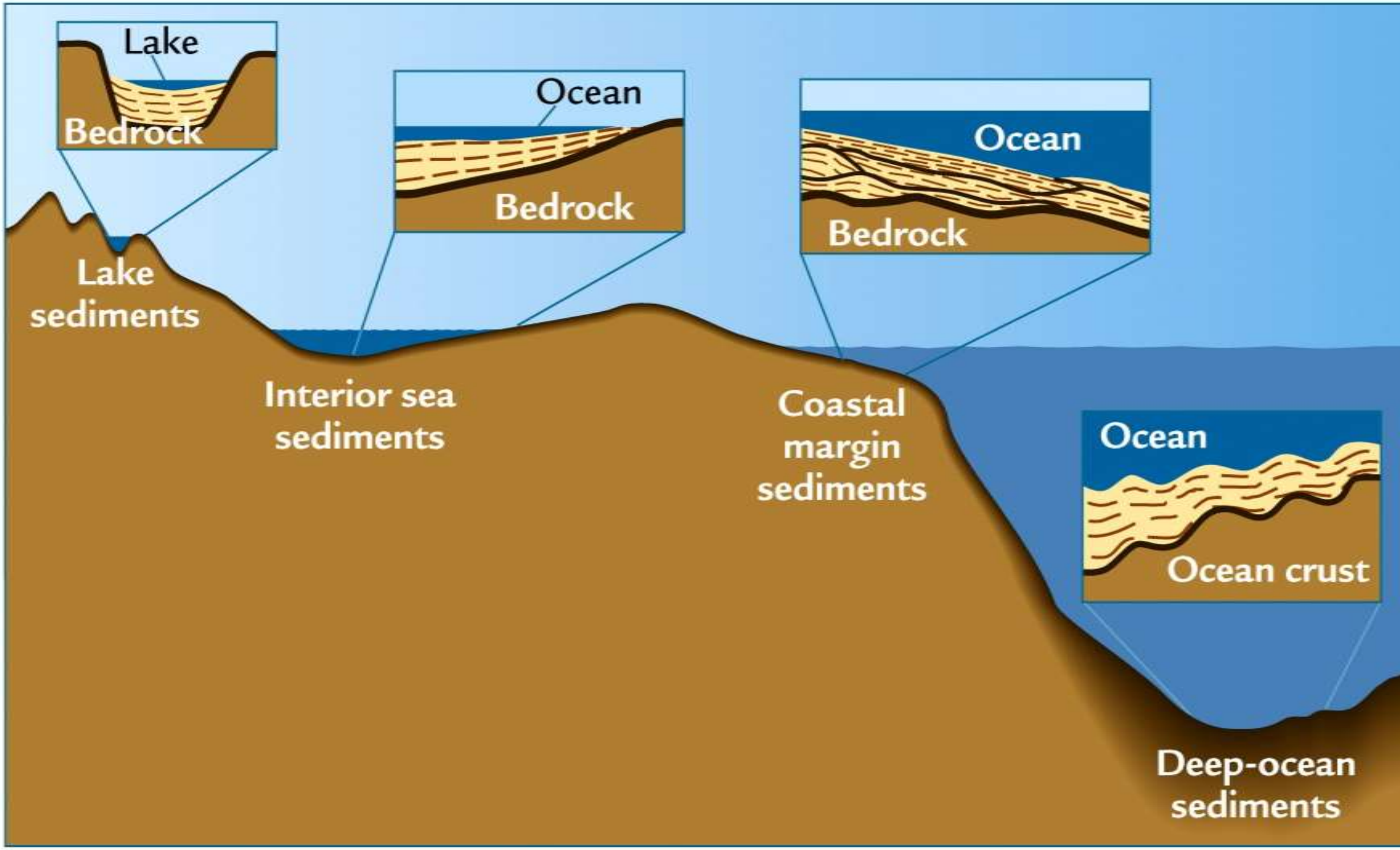
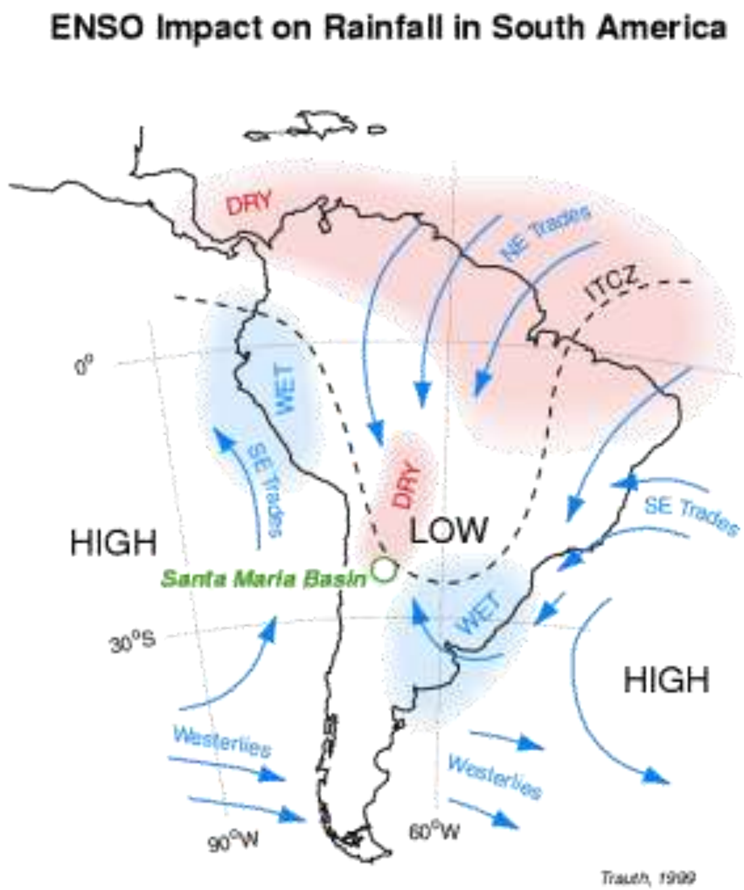
2	58	46	83	00	Z.t.O. 1			[illegible]	♋
3	53	46	83	00	Z.W. 1				
4	56	47	82	00	Z.W. 1				♌
5	48	46	82	130	Zuid Noord 1	R		☍♀	Pe
6	69	38	81	37	N.N.O. 2	R		☍♂	♍
7	107	35	79	00	O.N.O. 1		◎ *		☋
8	98	35	76	00	O.Z.O. 1		☌♂☿	☍♀	♎
9	102	40	76	00	West. 1				
10	97	45	78	00	Z.Z.W. 1			☍♀	♏
11	95	43	78	00	N.W. 1				
12	99	43	77	01	W.N.W. 2	R			♐
13	84	43	77	03	[illegible] 2	R.H			
14	88	41	76	00	W.N.W. 2	[illegible]	◐		
15	93	43	75	09	W.N.W. 1	R	☌☉☿		♑
16	92	45	75	11	West. 1	R			
17	87	44	76	12	N.N.W. 1	R			♒
18	87	39	76	00	N.O. 1				
19	97	38	76	00	N.O.t.O. 1			-☍♄	Apo
20	114	42	75	00	N.O.t.O. 1				♓

Observations Cruquius Delft in Rijnsburg february/march 1727
(source: Archief Hoogheemraadschap van Rijnland)

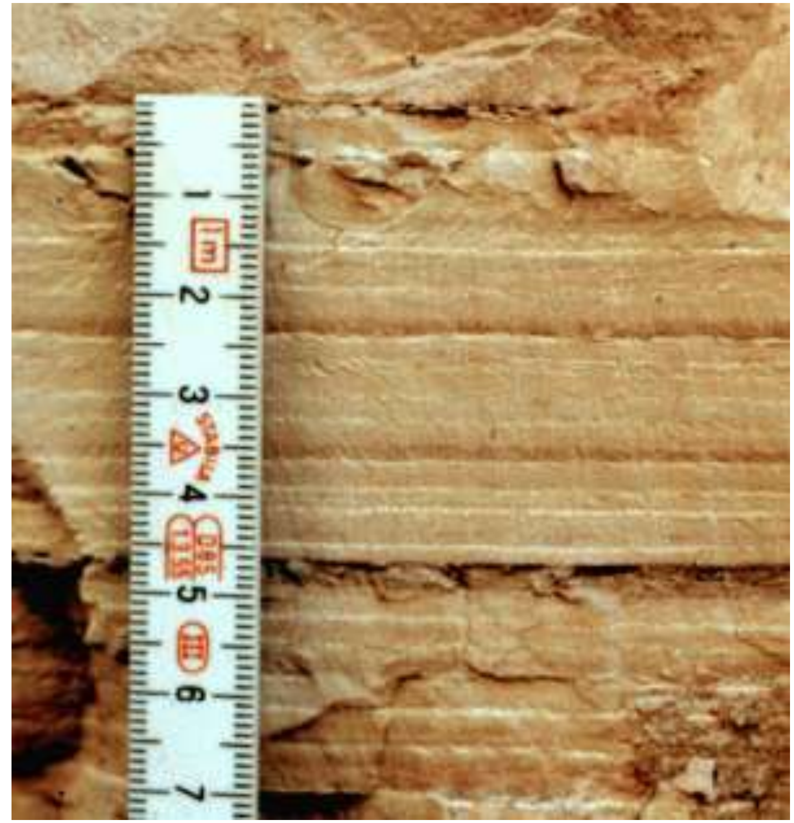
Types of proxies

- Sedimentary proxies
  - Type of sedimentary rock indicating for a certain climate (dunes, coals, grain size->varves)
- Biotic proxies
  - Organisms (animals / plants) preserved in the geological archive (terrestrial: plants, marine: corals)
- Geochemical proxies
  - Oxygen isotope composition of carbonate shells (palaeothermometer water)


Lake
Bedrock
Ocean
Bedrock
Ocean
Bedrock
Lake sediments
Interior sea sediments
Coastal margin sediments
Ocean
Ocean crust
Deep-ocean sediments

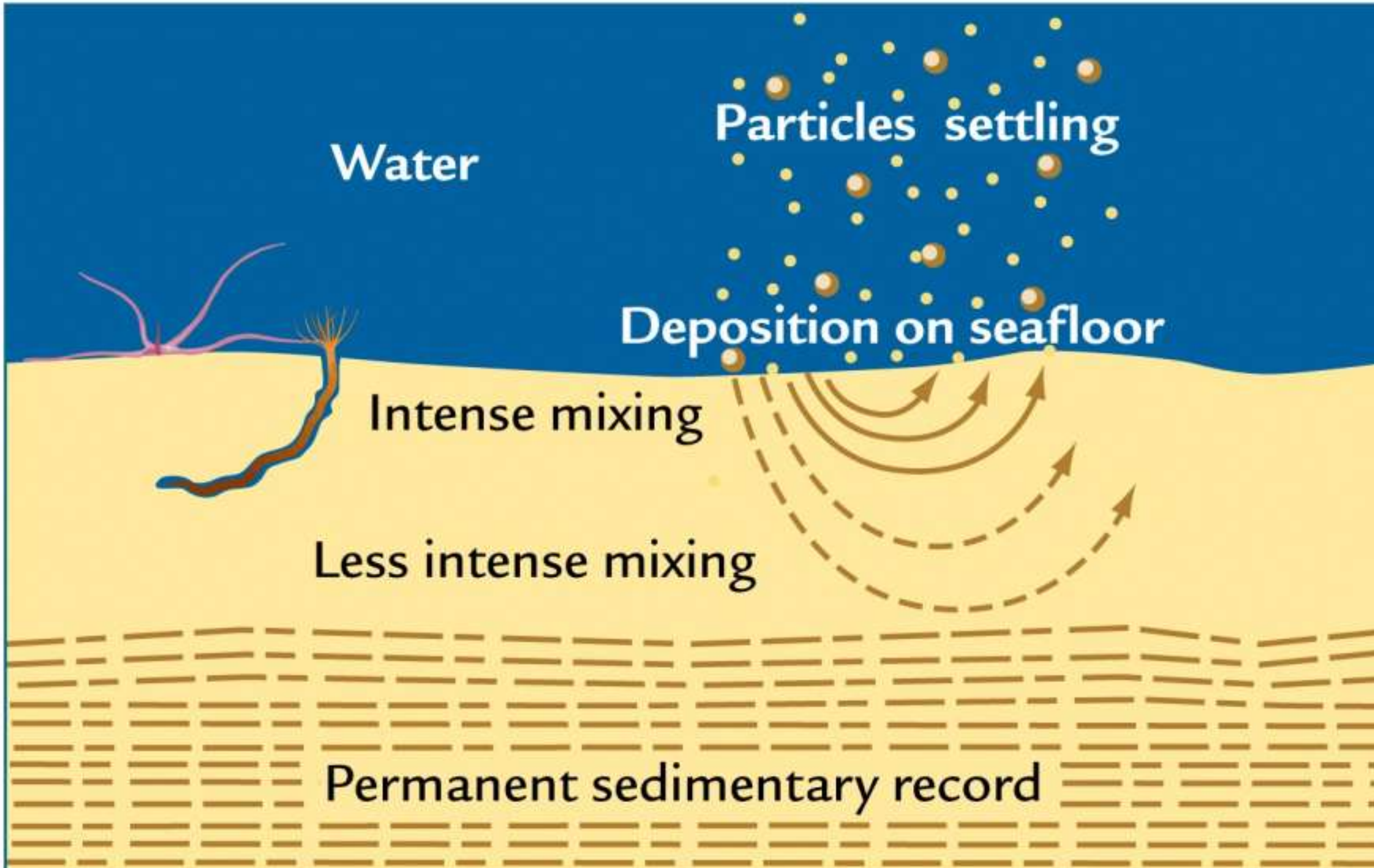


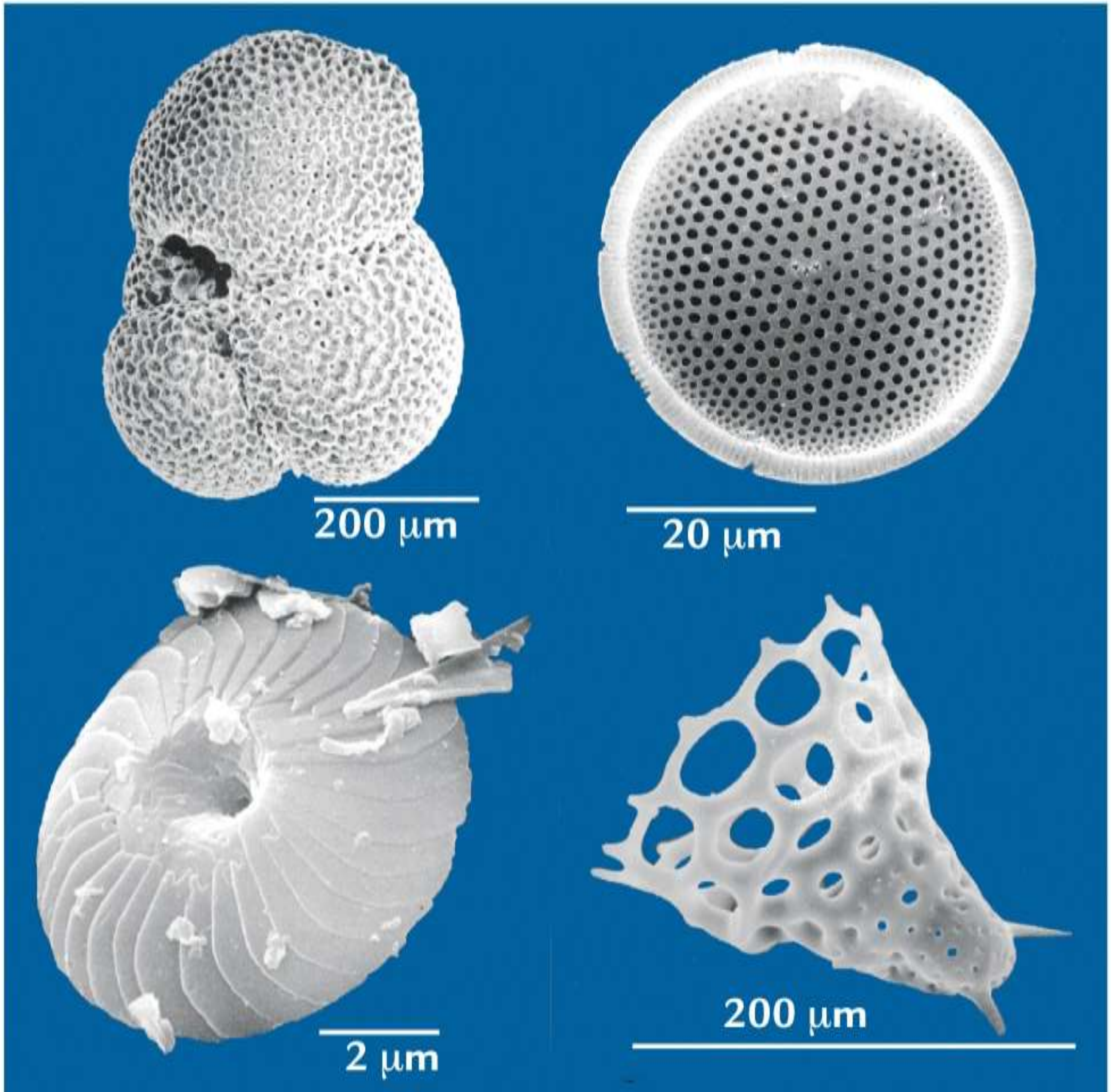
Natural archives: Lake sediments



- The Santa Maria Basin in NW Argentina between opposite El Niño influences.
- These influences have changed for the Santa Maria Basin during the Holocene. Varved lake sediments from the Santa Maria Basin offer an archive of variations in the rainfall 30000 years ago.

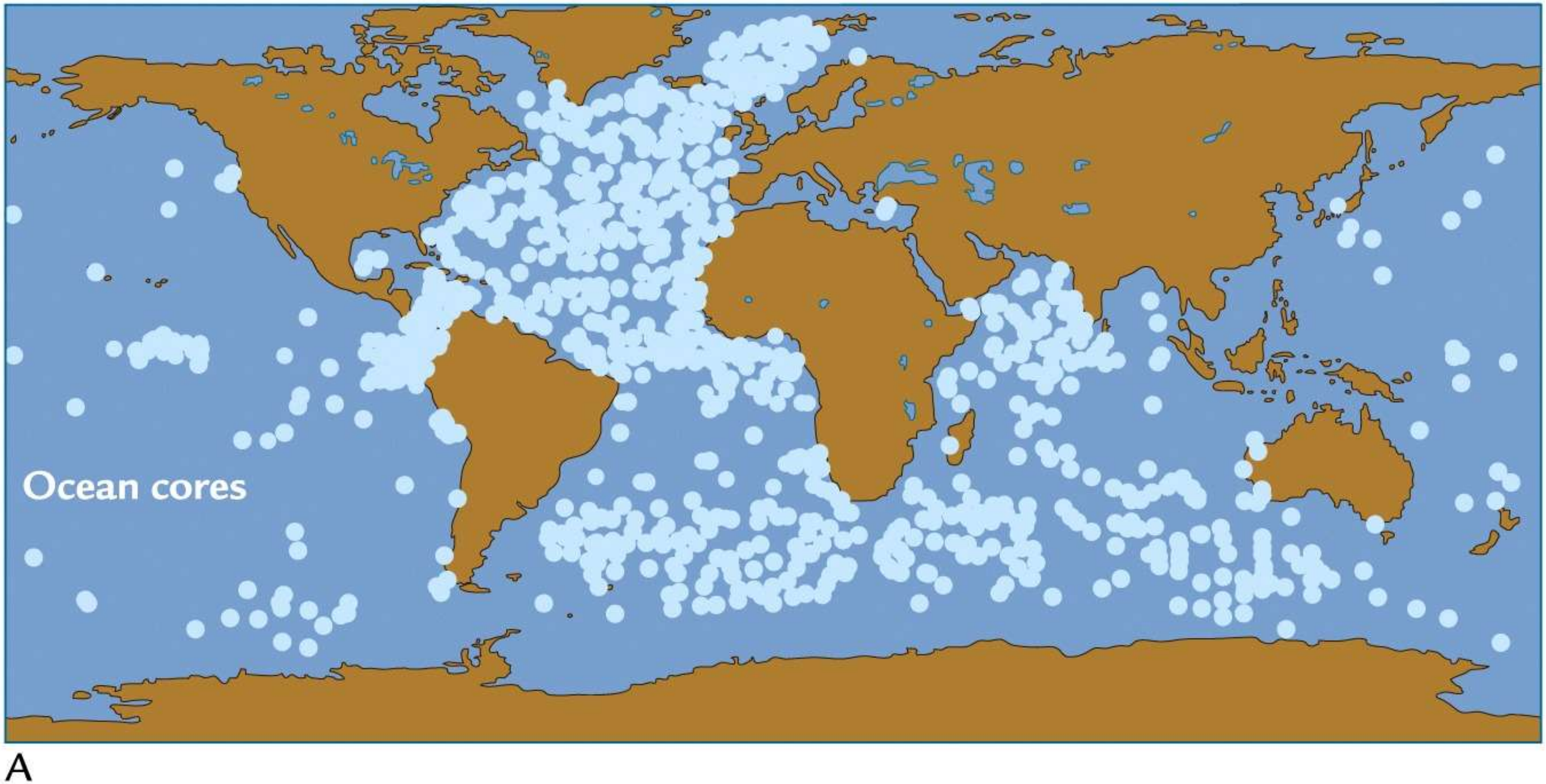



Particles settling
Water
Deposition on seafloor
Intense mixing
Less intense mixing
Permanent sedimentary record

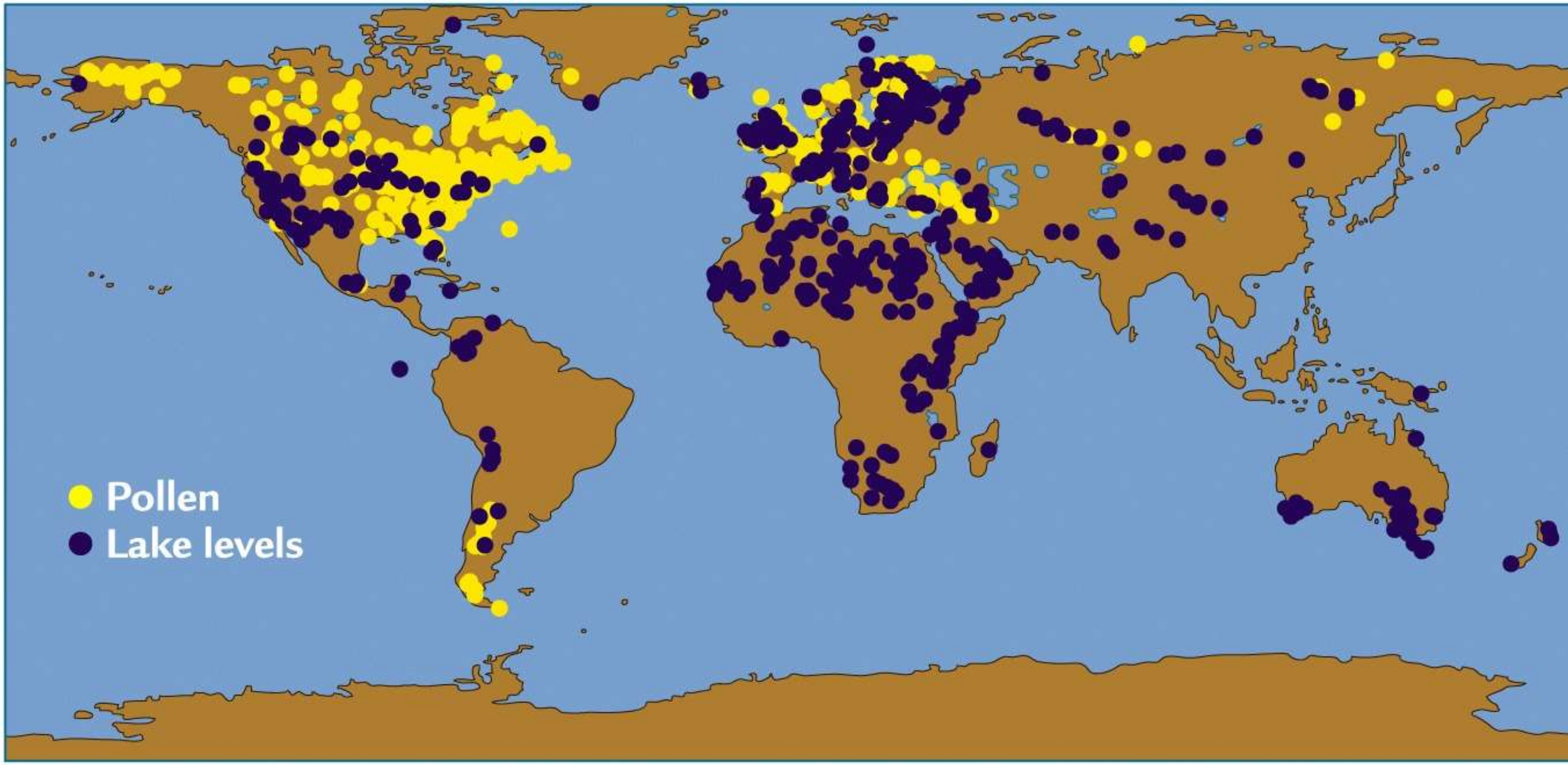


200 μm
20 μm
2 μm
200 μm

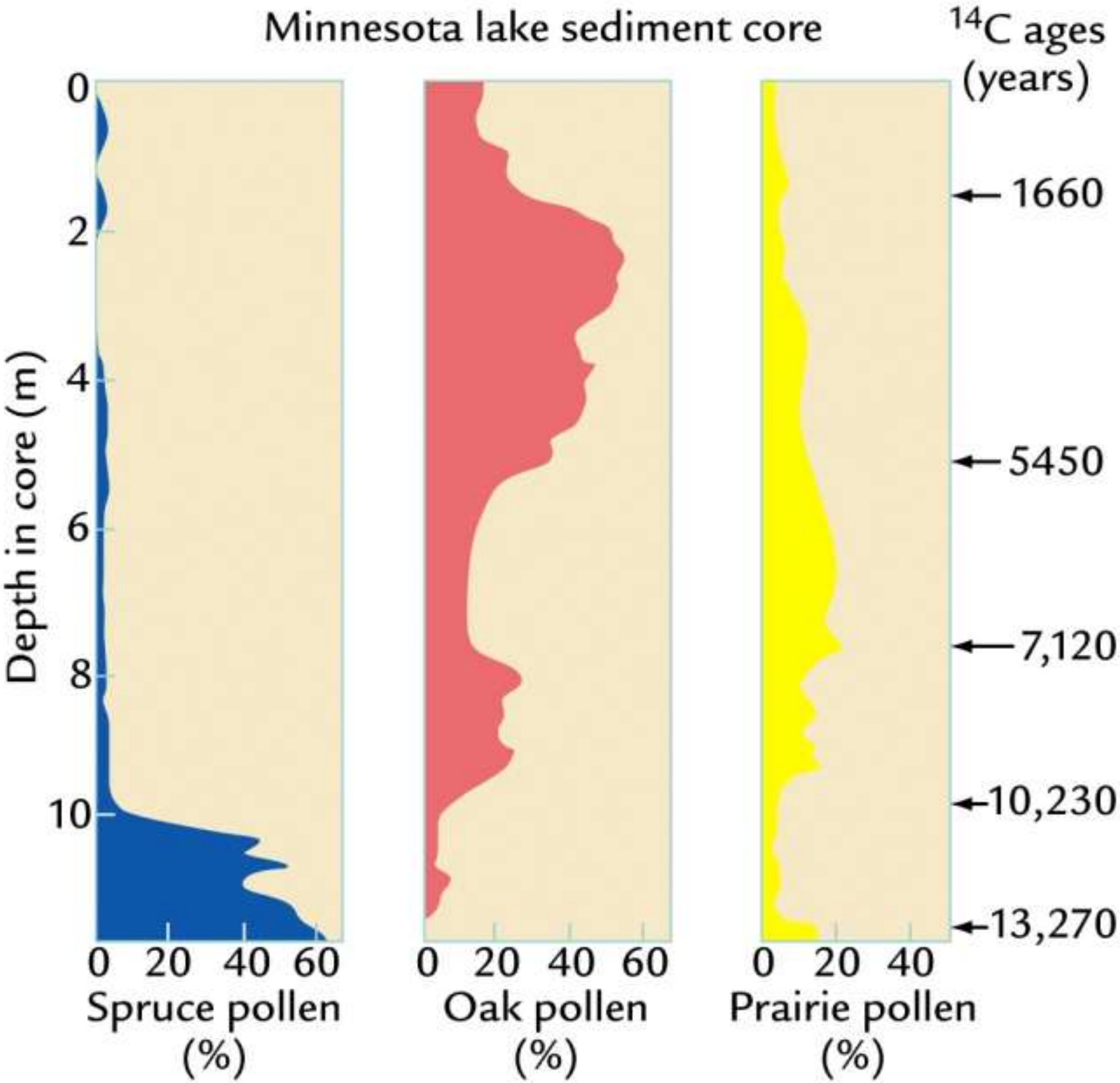
Distribution of natural climate archives

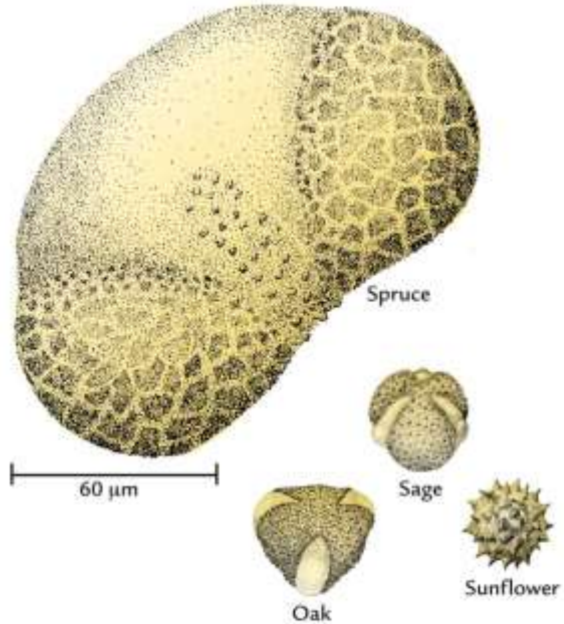


Distribution of natural climate archives

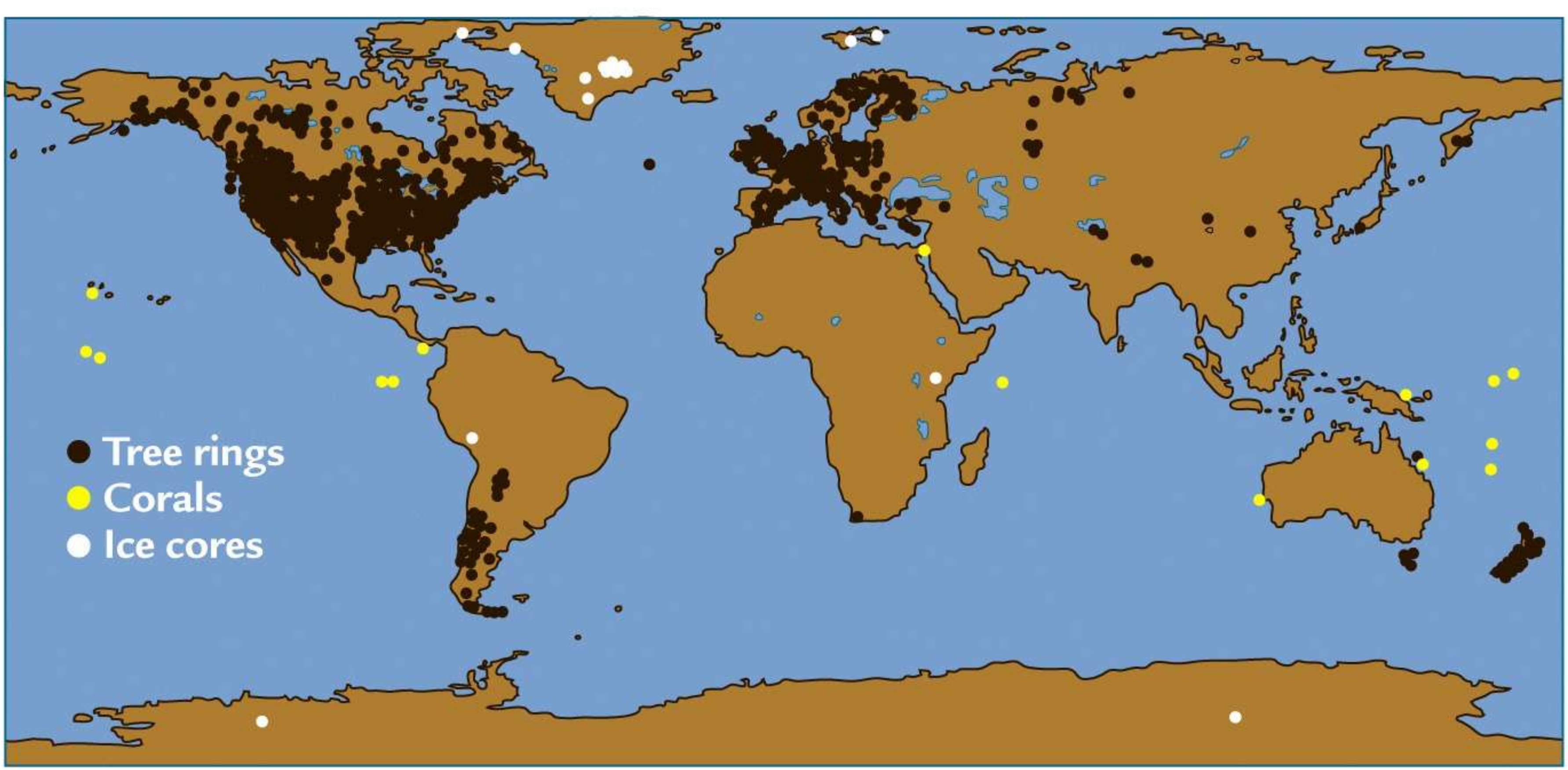


Pollen distribution diagram from lake sediments

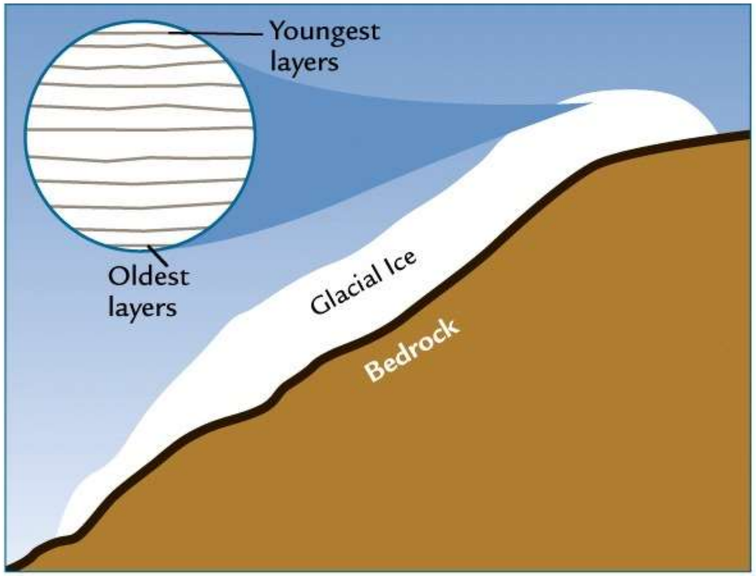




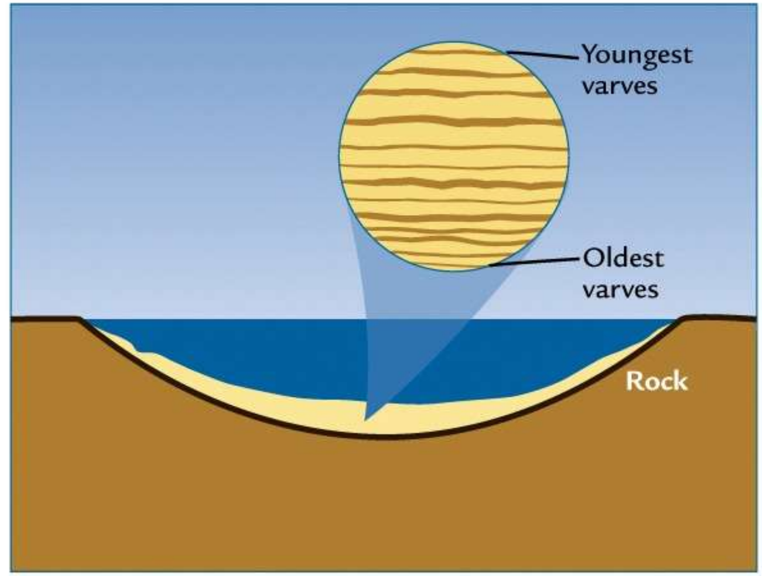
Distribution of natural climate archives



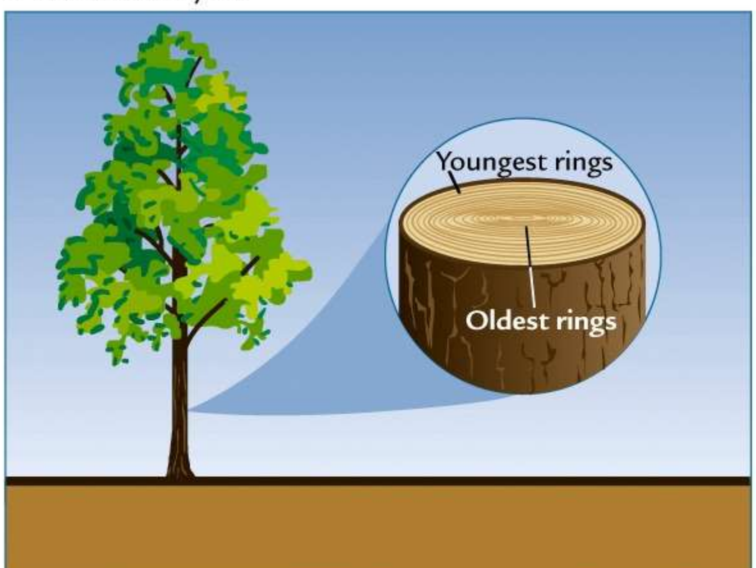
Annual …



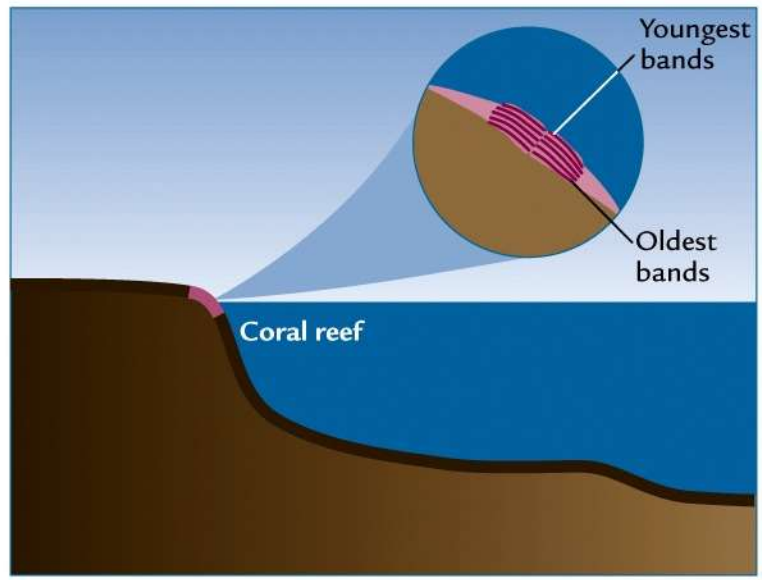
A Annual ice layers



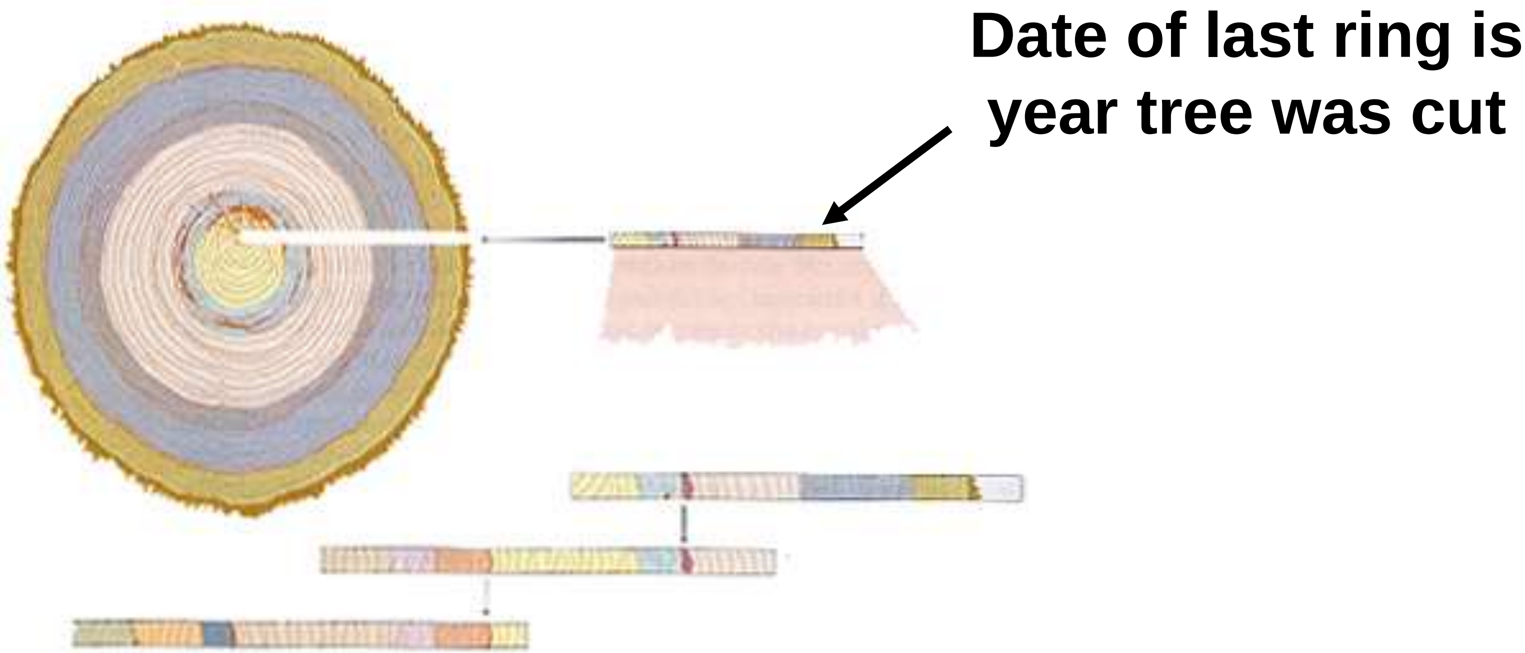
B Annual sediment varves



C Annual tree rings



D Annual coral bands



- <u>dendrochronology</u> -- the study of the annual variability of tree ring widths
- climate information: temperature, runoff, precipitation, soil moisture
- present-8000 years of climate change

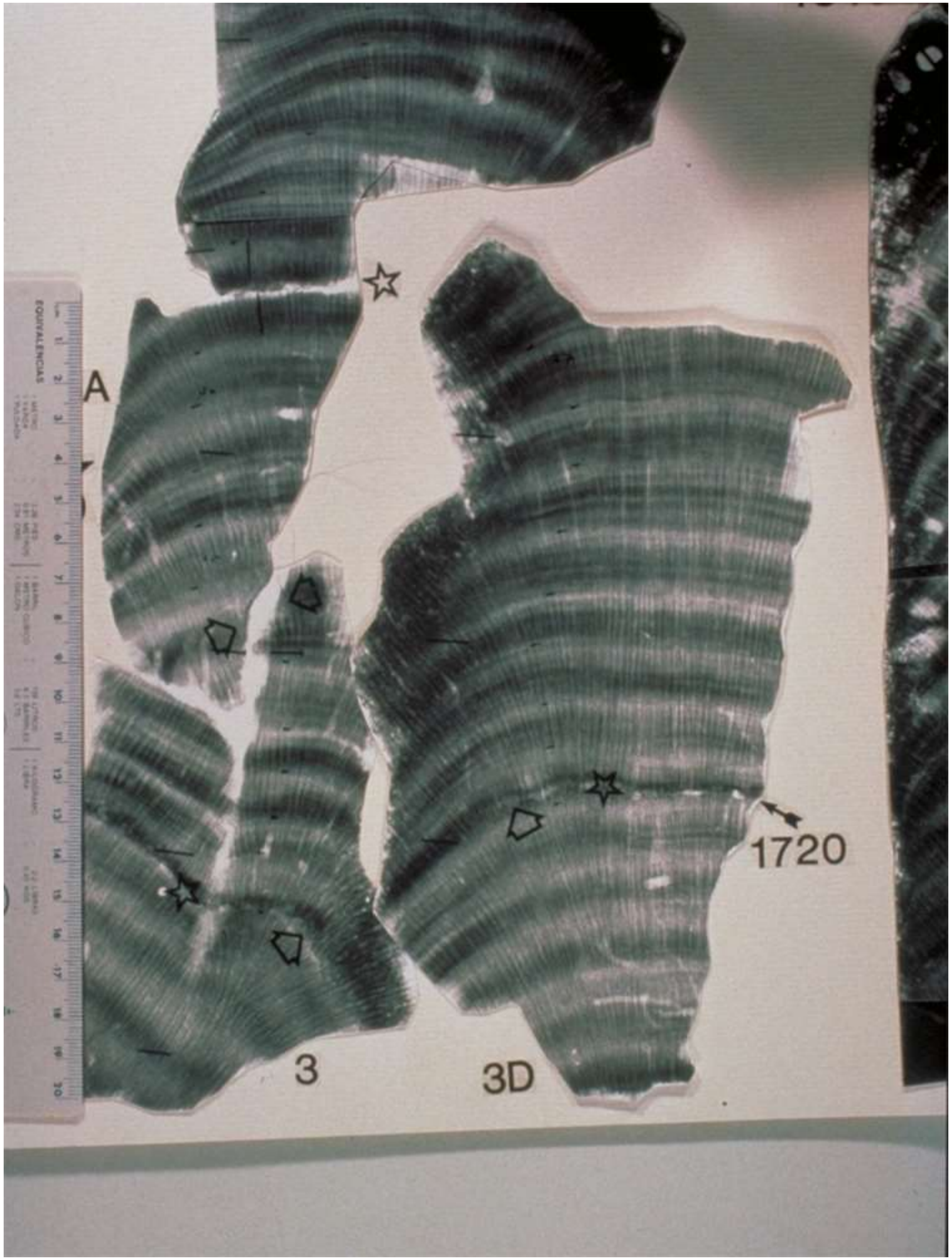
- see *Our Changing Planet*, Table 11-1

ENSO

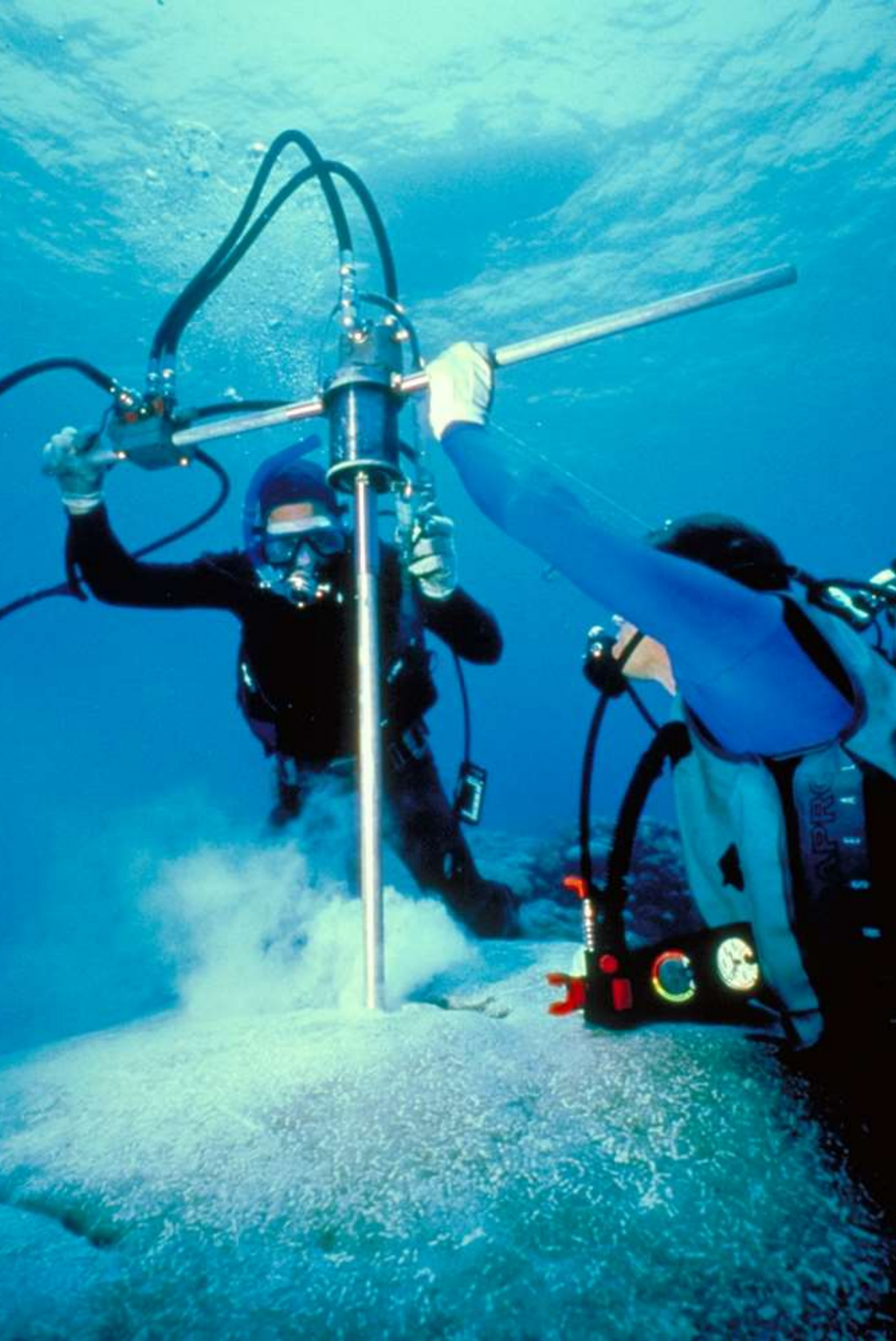
palaeo-records

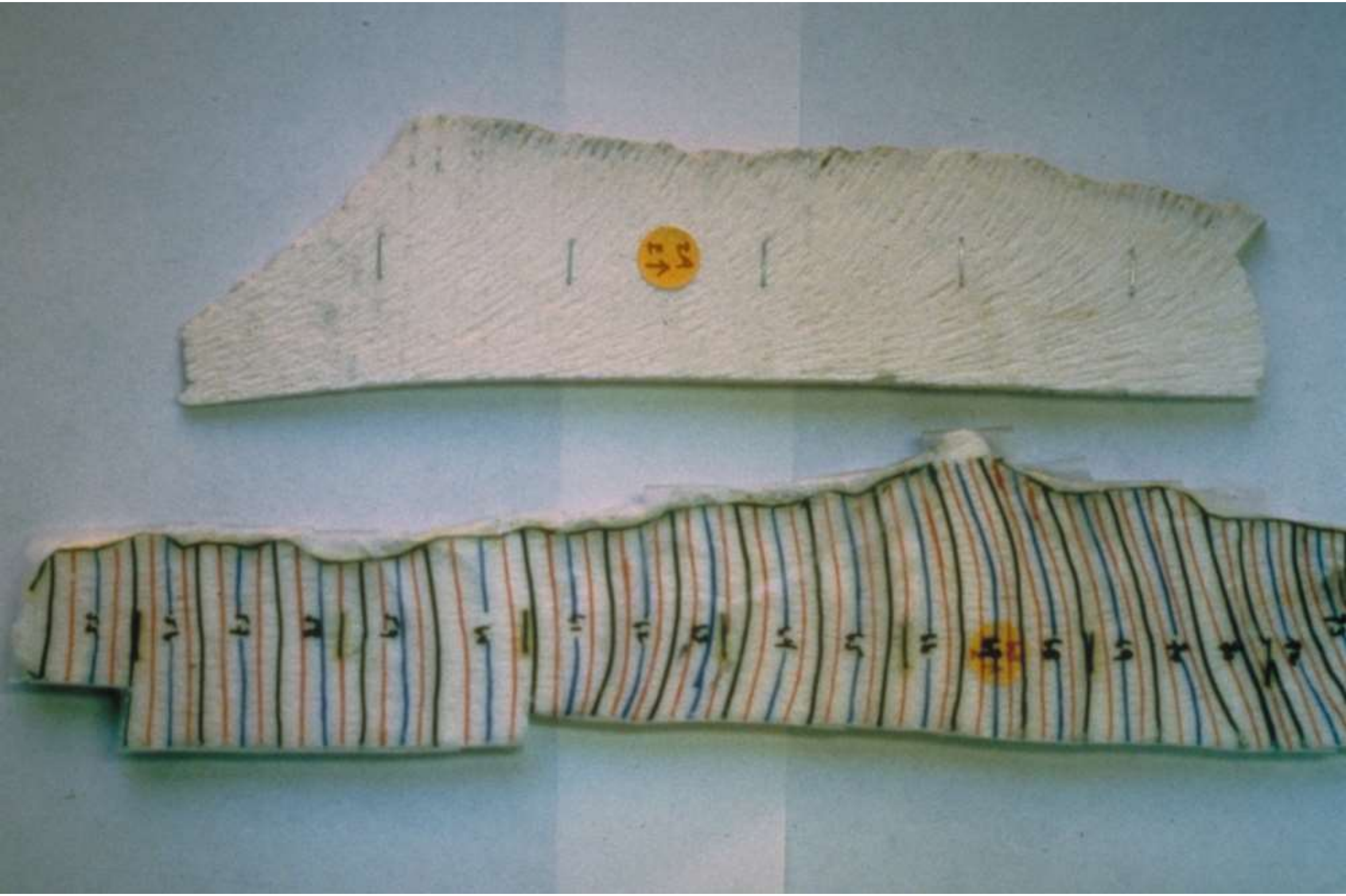
Annual growth “rings” in a *Pavona clavus* coral

-seasonal differences

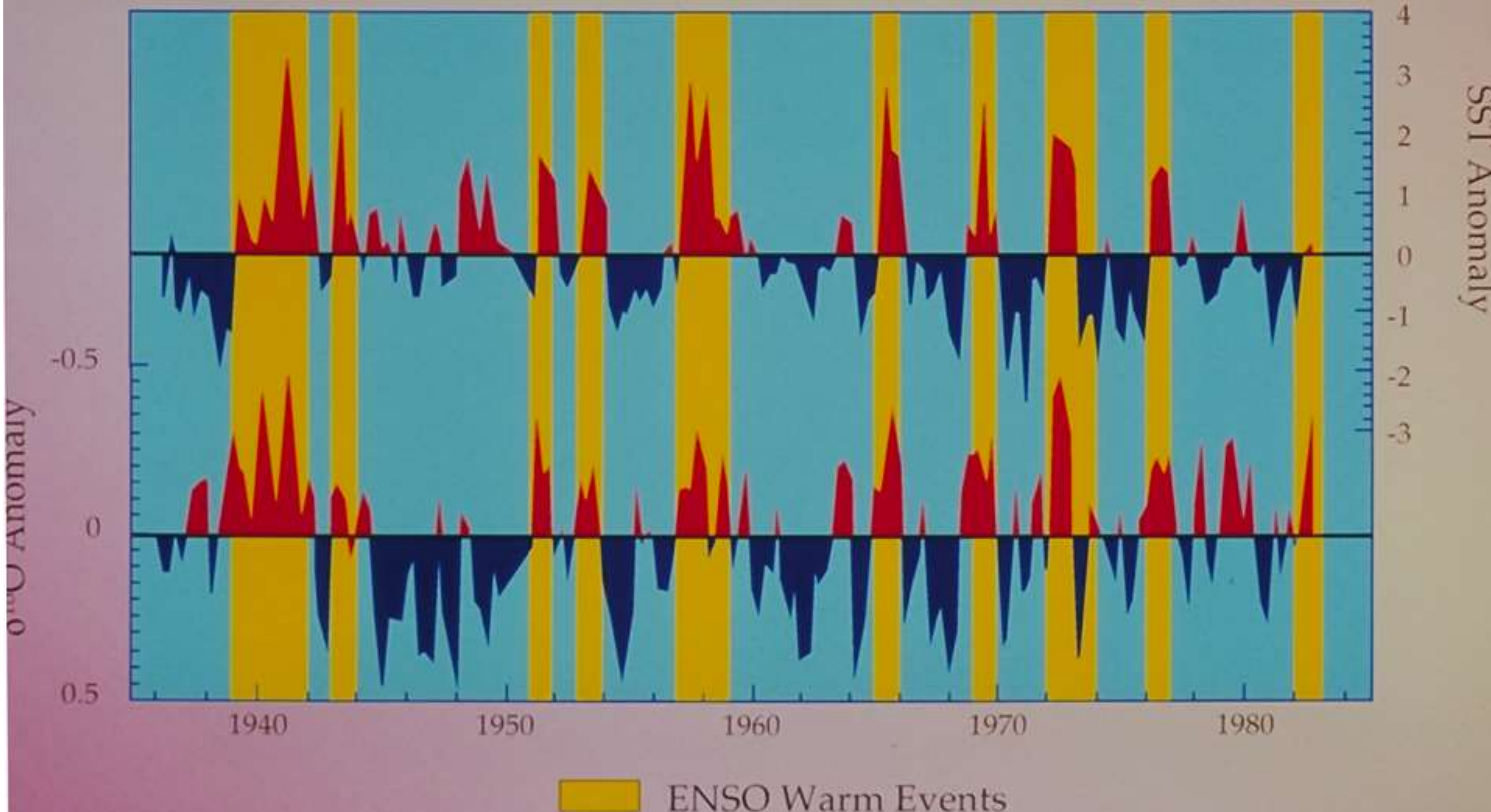



WAHOO



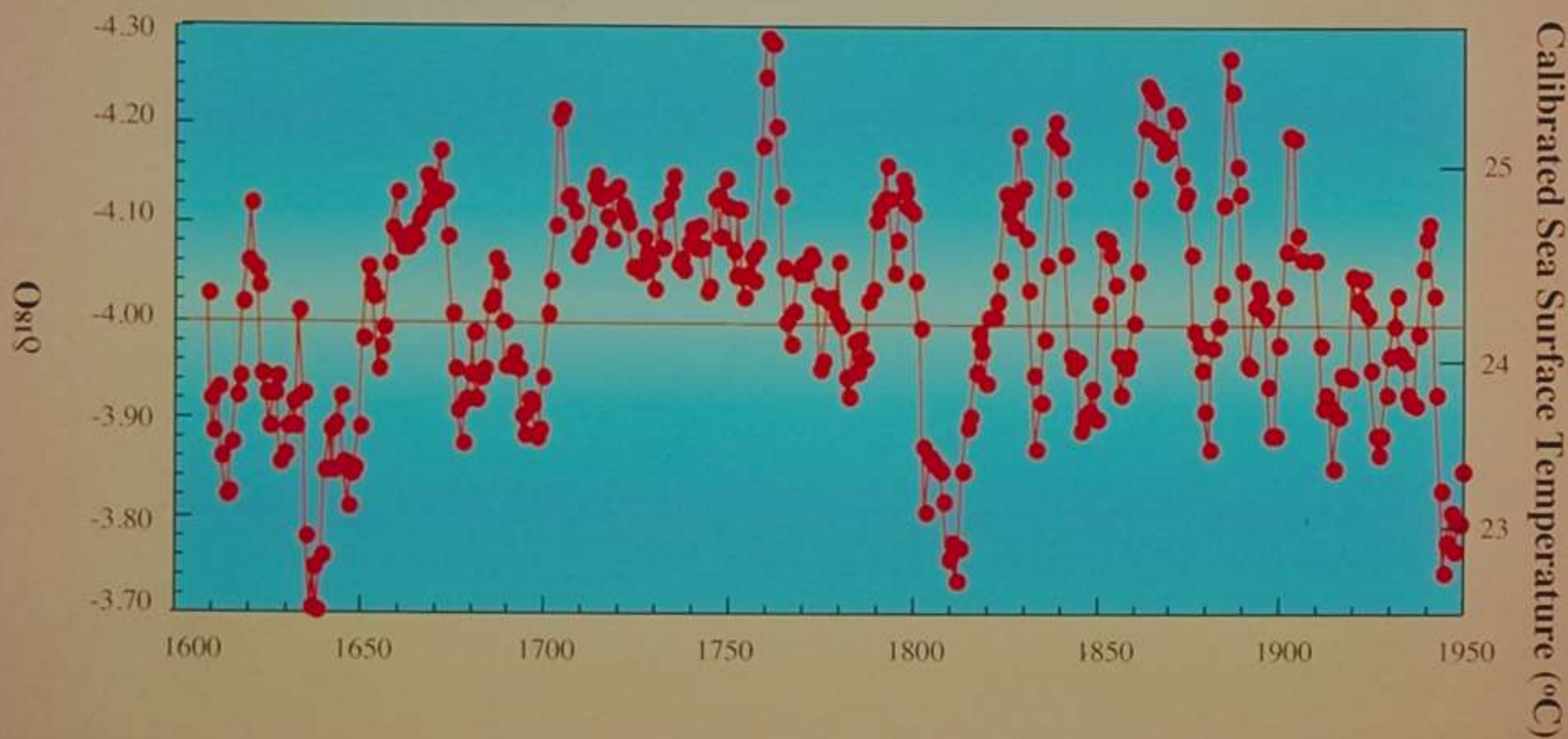



Coral δ18O at Punta Pitt, Galápagos Provides a Record of Sea Surface Temperatures in an El Niño Sensitive Area

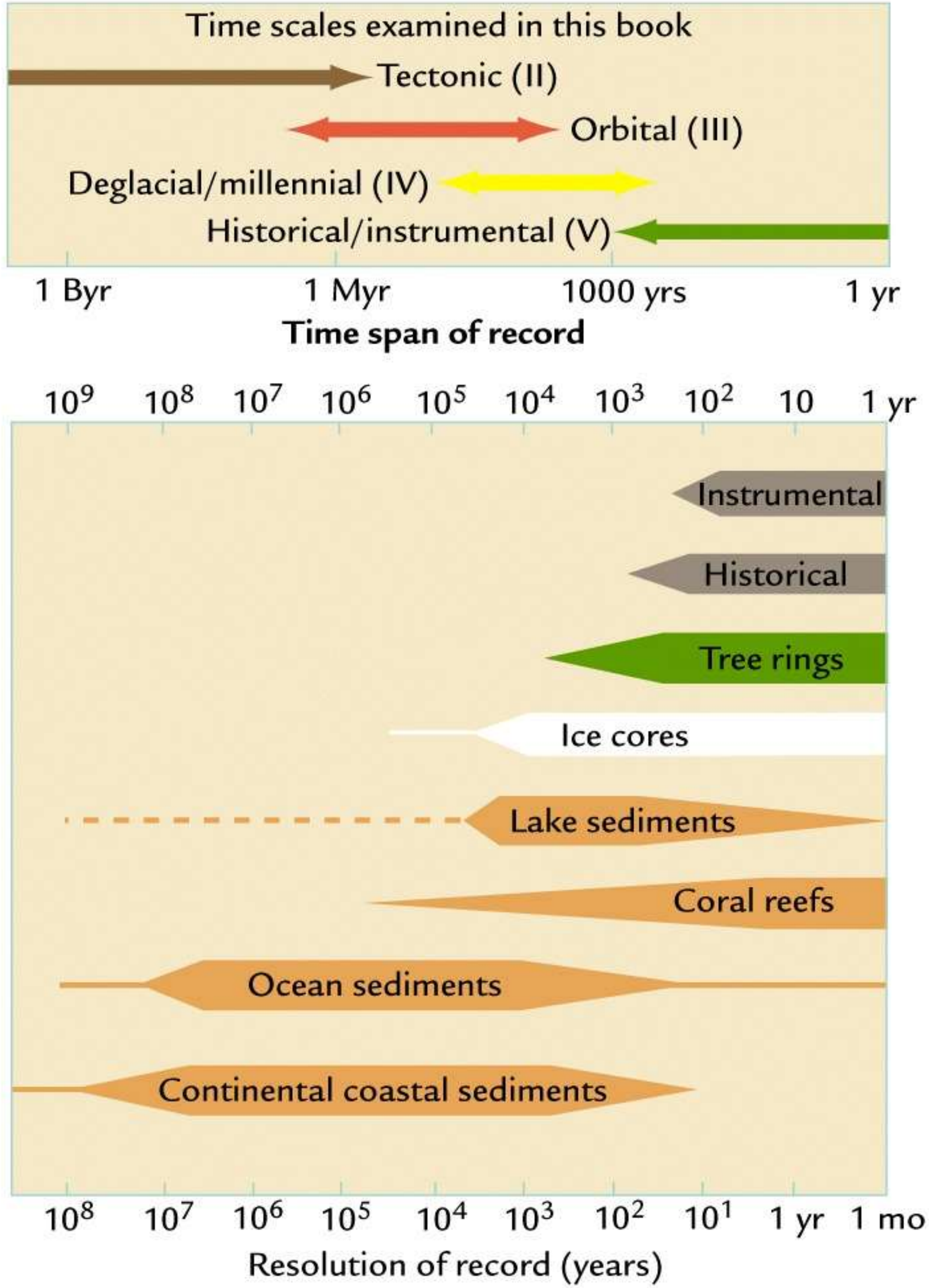


Data from Shen *et al.* (1992)

A 350-year $\delta^{18}O$ Record from a Specimen of *Pavona clavus* Provides a History of Paleotemperature in the Eastern Pacific (Urvina Bay, Galápagos)



Data from Dunbar *et al.* (1994). Graph presented as a 5-year moving average to filter out high frequency variability.



Time scales examined in this book
Tectonic (II)
Orbital (III)
Deglacial/millennial (IV)
Historical/instrumental (V)
1 Byr
1 Myr
1000 yrs
1 yr
Time span of record
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1 yr
Instrumental
Historical
Tree rings
Ice cores
Lake sediments
Coral reefs
Ocean sediments
Continental coastal sediments
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1 yr
1 mo
Resolution of record (years)

Earth has been habitable for about 3.55 Billion Years

- Sediments amount to an ancient and long record of liquid water
- Life present at 3.55 billion years or earlier
- Earth was never frozen (or boiled)
- Two main climate states:
  - **icehouse** – ice sheets present
  - **greenhouse (hothouse)** - no ice sheets present

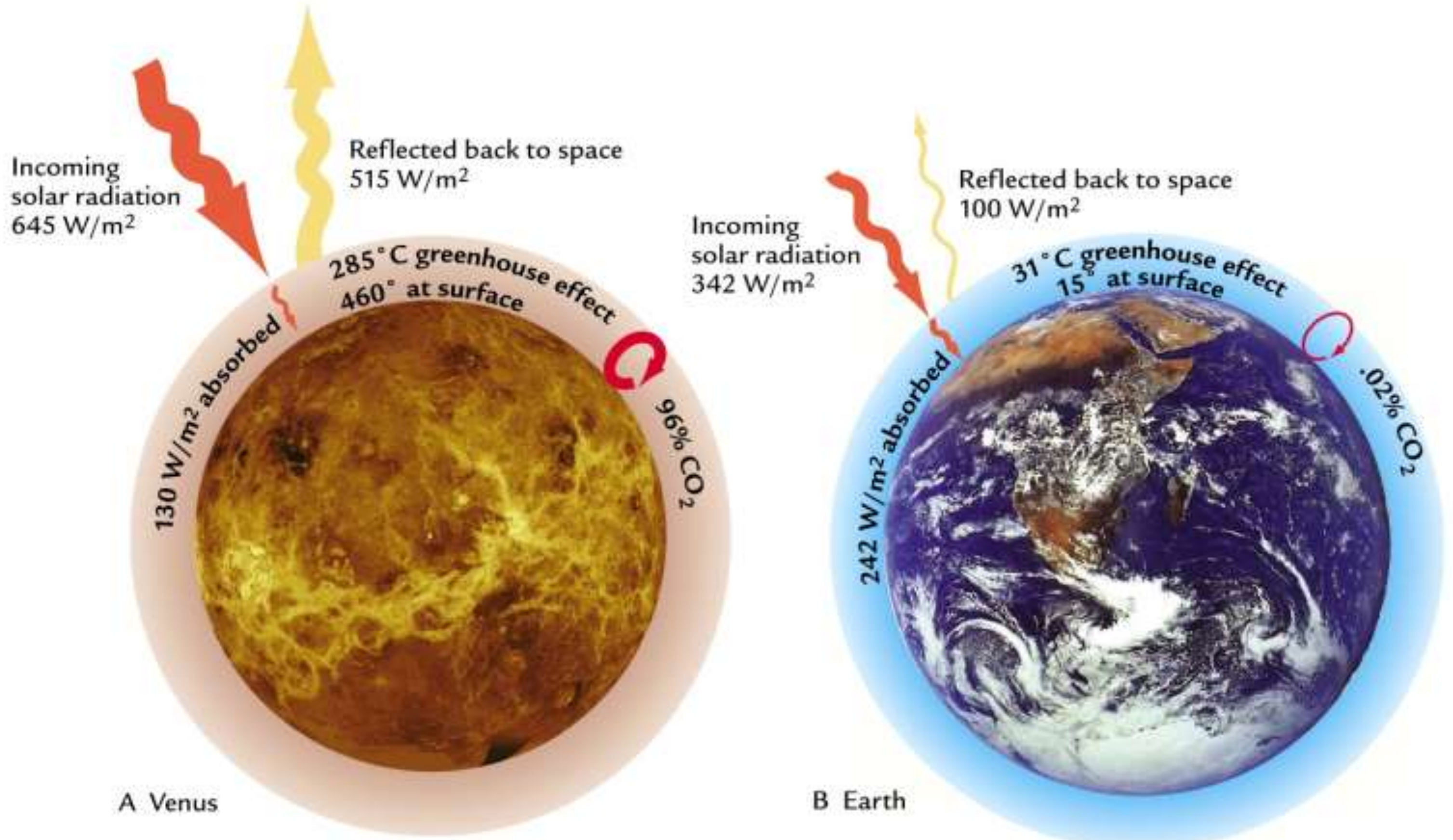
Why Has Earth Been Habitable?

Venus compared to Earth:

Twice the solar flux

Same carbon, but **<u>all</u>** in atmosphere as CO_2

Higher albedo



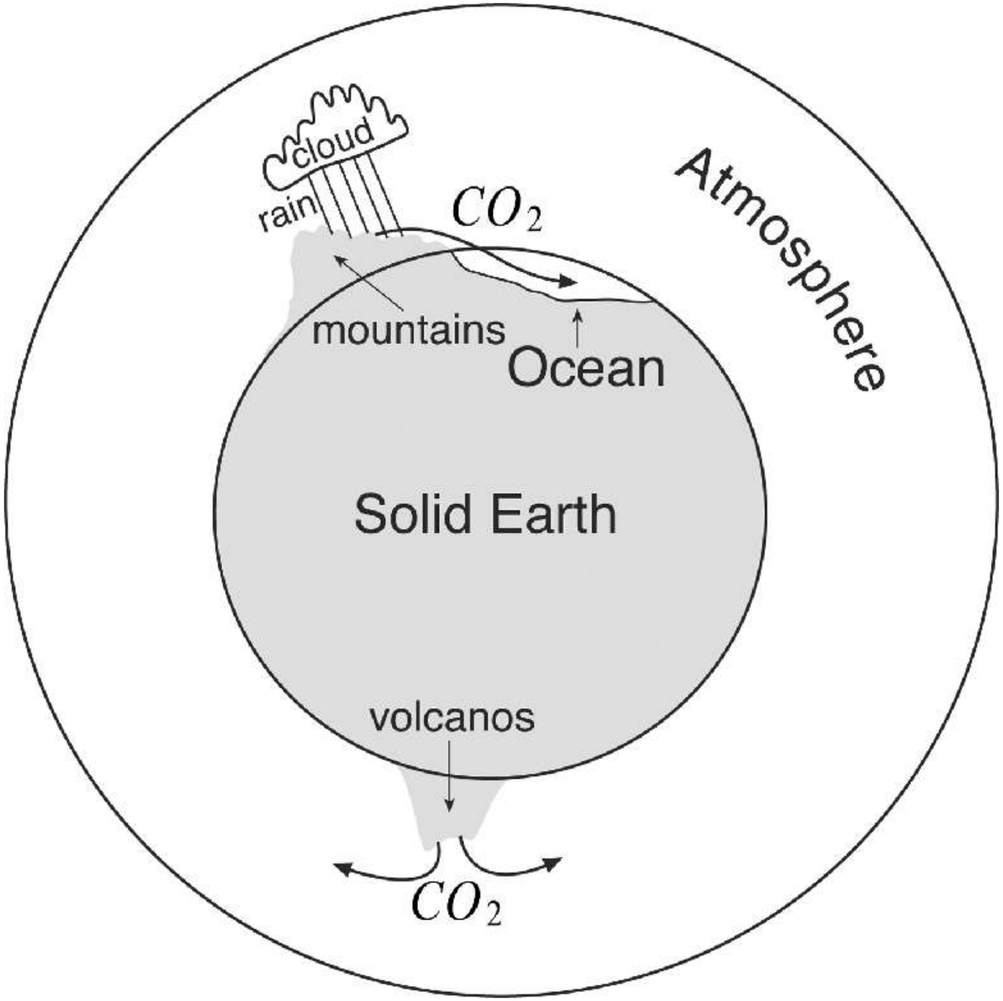
- Venus stinking hot, Earth "just right"
- Factors? Distance from Sun? radiation balance?

Tectonic-Scale Climate Change /Faint Young Sun Paradox

- **Due to lower solar luminosity, there must have been more greenhouse gas in Earth's early atmosphere**
  - **competition between volcanism (source) and weathering (sink) of CO_2**
  - **3.0 billion years ago (50-100x PAL) surface temperatures near 60^{o}C?**

Climate over Earth´s history (12.3.1)

Phanerozoic 543M y⟶0	Cenozoic 65M y⟶0	Quaternary 1.8M y⟶0	Holocene 10K y⟶0
			Pleistocene 1.8M y⟶10Ky
		Tertiary 65⟶1.8M y	Pliocene 5.3⟶1.8M y
			Miocene 24⟶5.3M y
			Oligocene 33⟶24M y
			Eocene 55⟶33M y
			Paleocene 65⟶55M y
	Mesozoic 248⟶65M y	Cretaceous 144⟶65M y	
		Jurassic 206⟶144M y	
		Triassic 248⟶206M y	
	Paleozoic 543⟶248M y	Permian 290⟶248M y	
		Carboniferous 354⟶290M y	
		Devonian 417⟶354M y	
		Silurian 443⟶417M y	
		Ordovician 490⟶443M y	
		Cambrian 543⟶490M y	
Precambrian 4500⟶543M y	Proterozoic 2500⟶543M y		
	Archaen 3800⟶2500M y		
	Hadean 4500⟶3800M y		

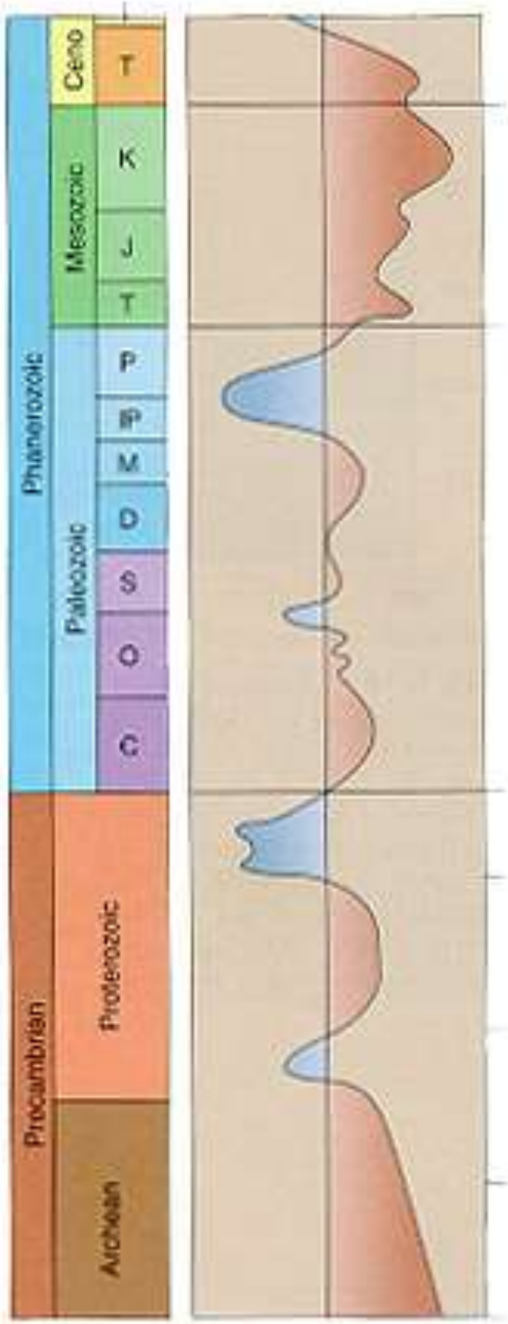


Climate change on a million-year time scale

A. Alternating greenhouse and icehouse states

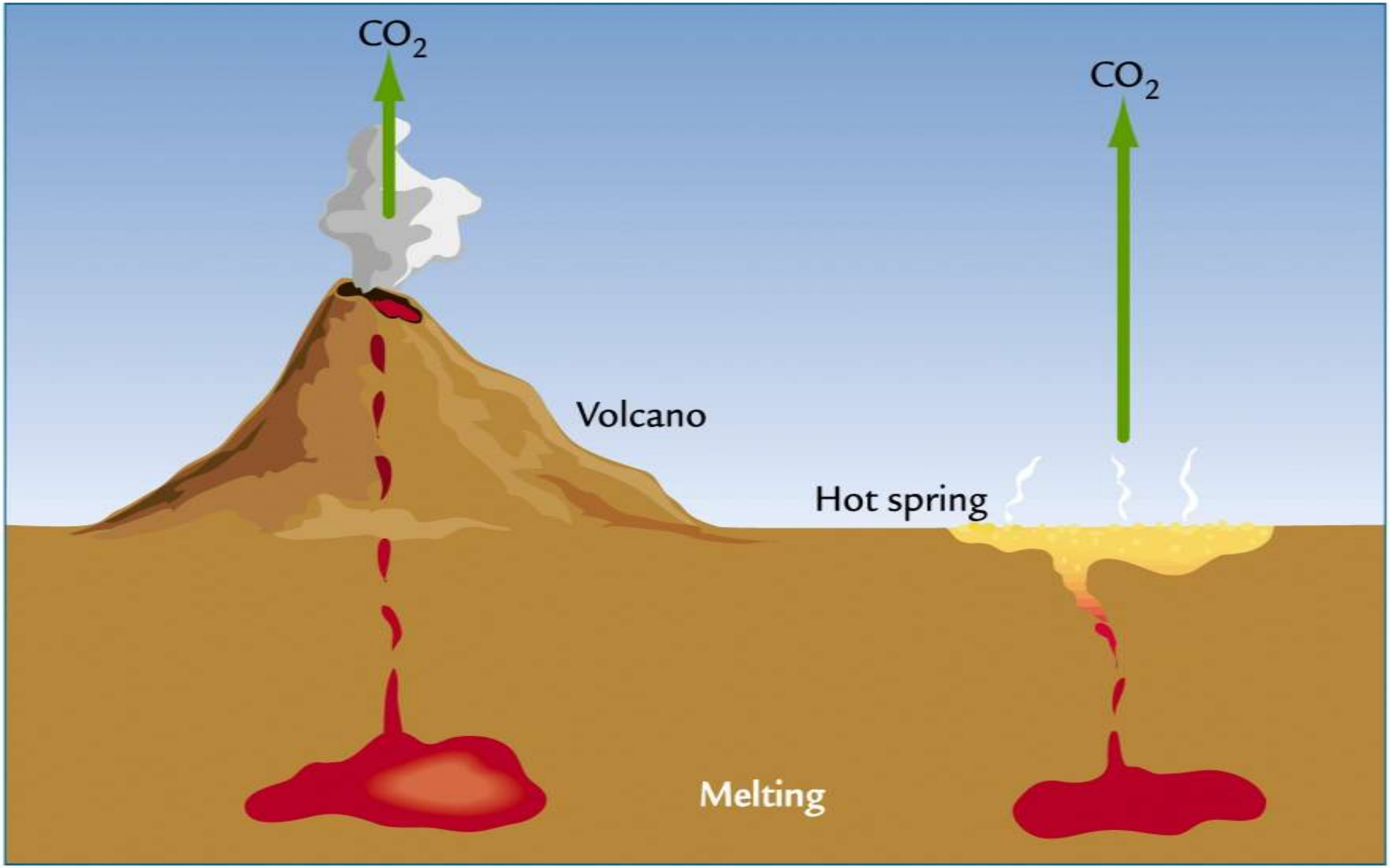
B. The Cretaceous greenhouse

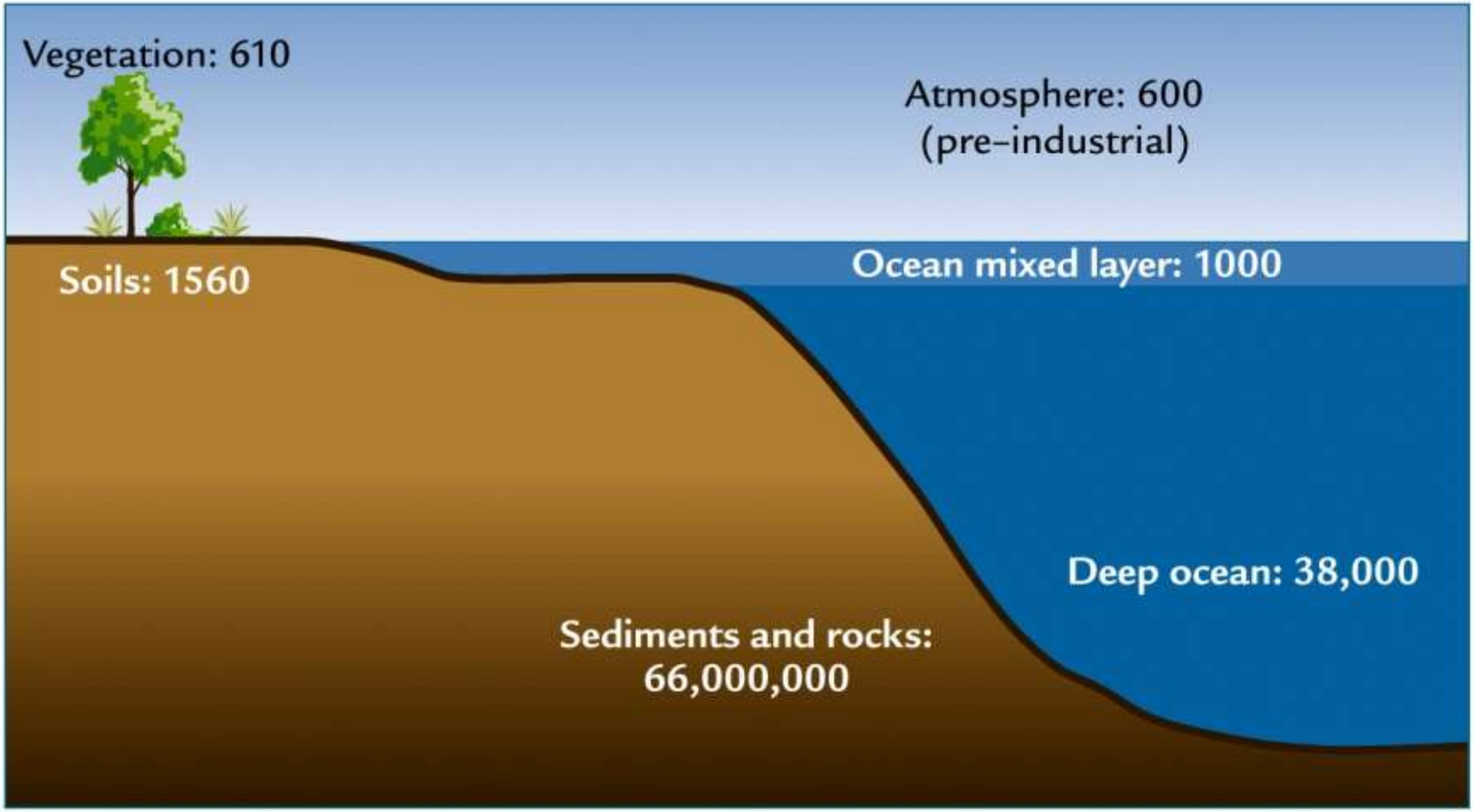
C. post-Cretaceous cooling



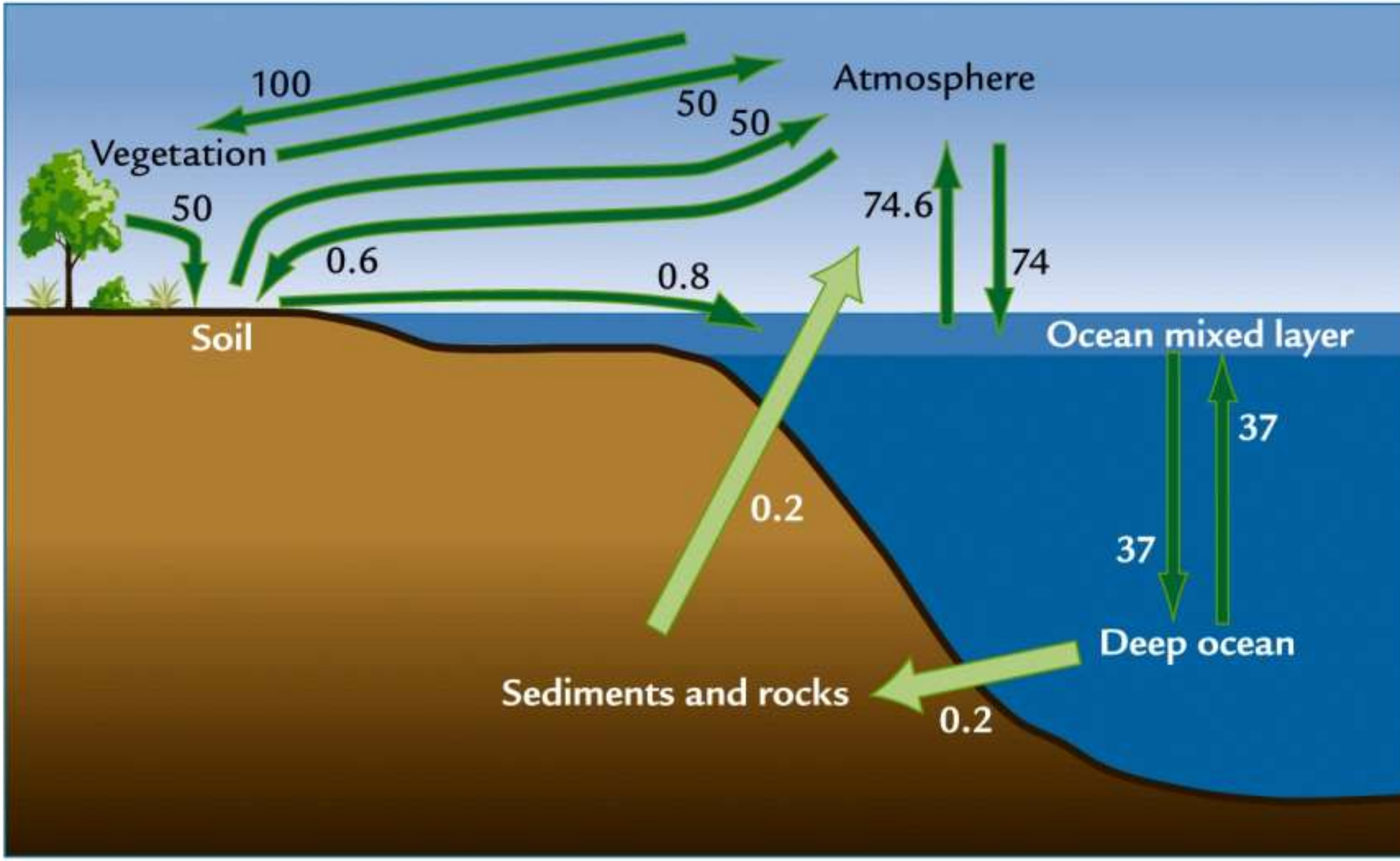
Major ice ages occurred in the

Pleistocene, Permian and Carboniferous, Ordovician, late and early Proterozoic

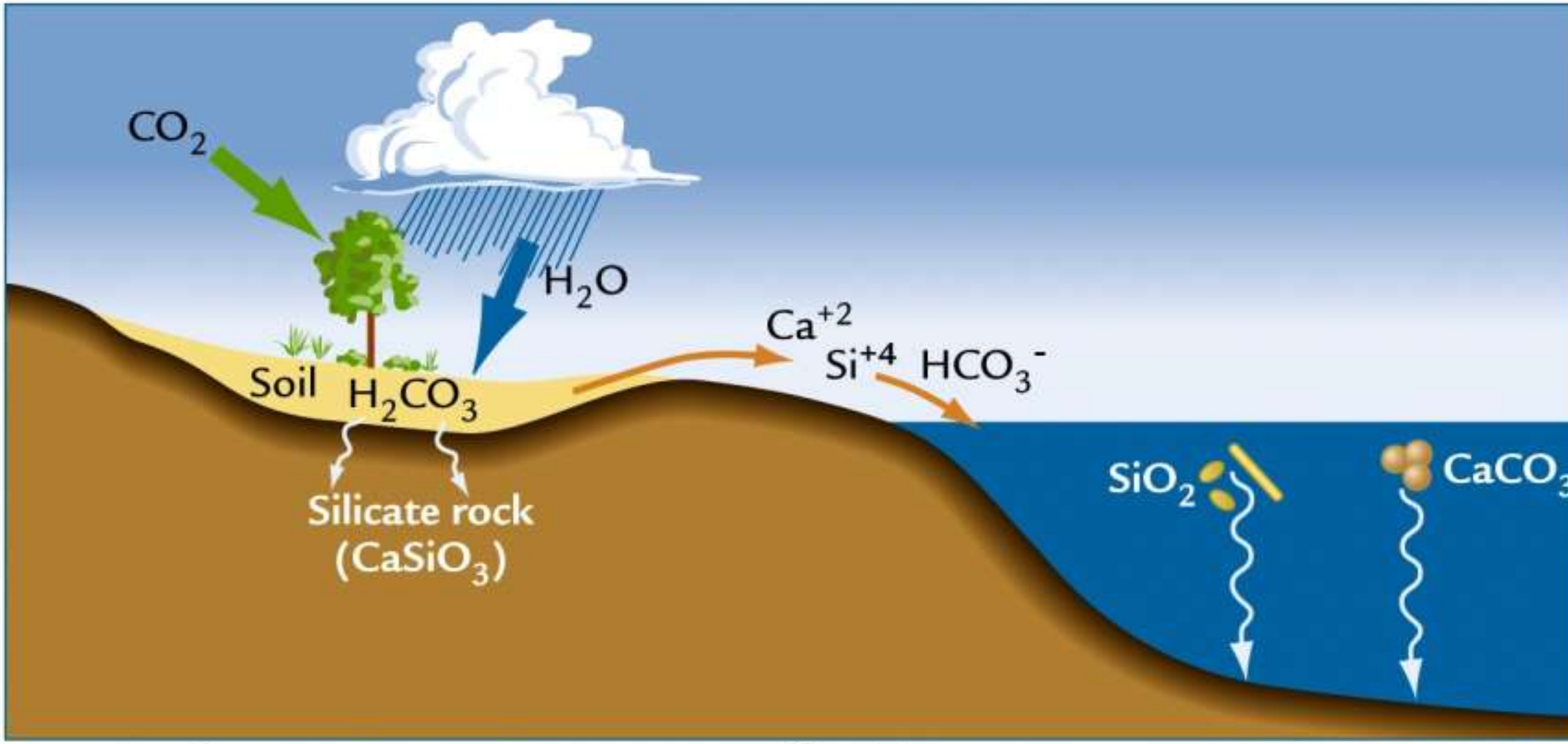

CO_2
CO_2
Volcano
Hot spring
Melting



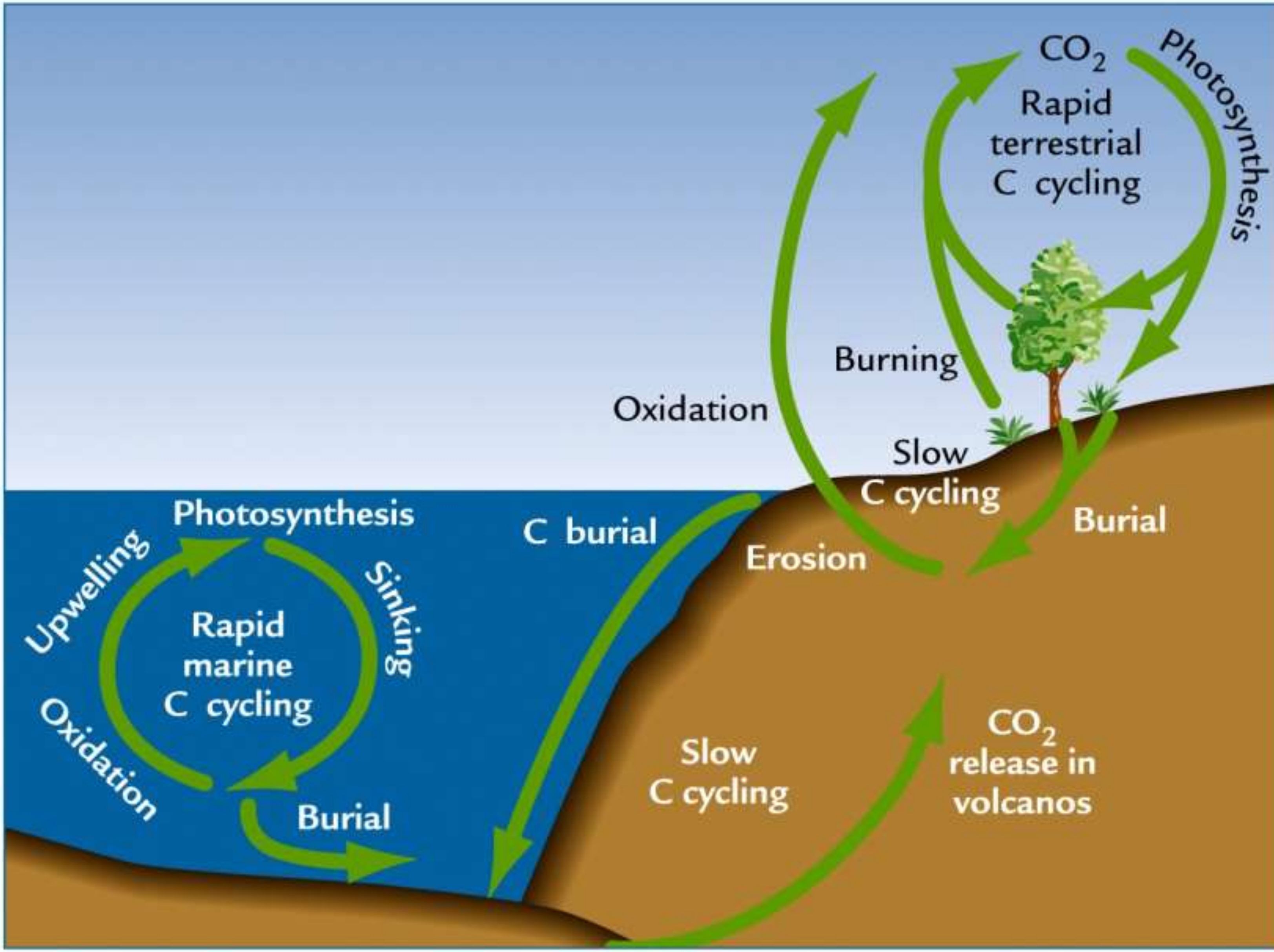
A Major carbon reservoirs (gigatons; 1 gigaton = 10^{15} grams)



B Carbon exchange rates (gigatons/year)



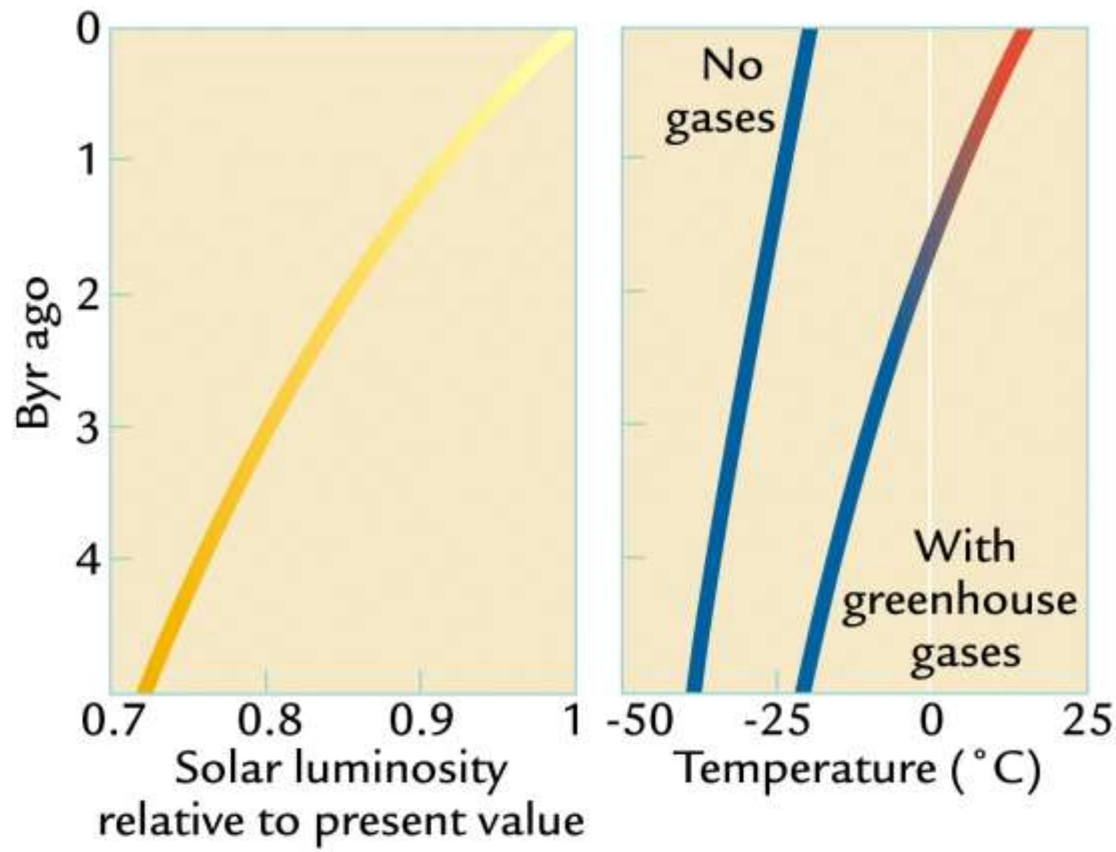
$CaSiO_3$ + H_2CO_3	Ca^{+2} Si^{+4} HCO_3^-	SiO_2 + $CaCO_3$
Silicate bedrock; Carbonic acid in soils	Ions dissolved in river water	Shells of ocean plankton
Weathering on land	Transport in rivers	Deposition in ocean



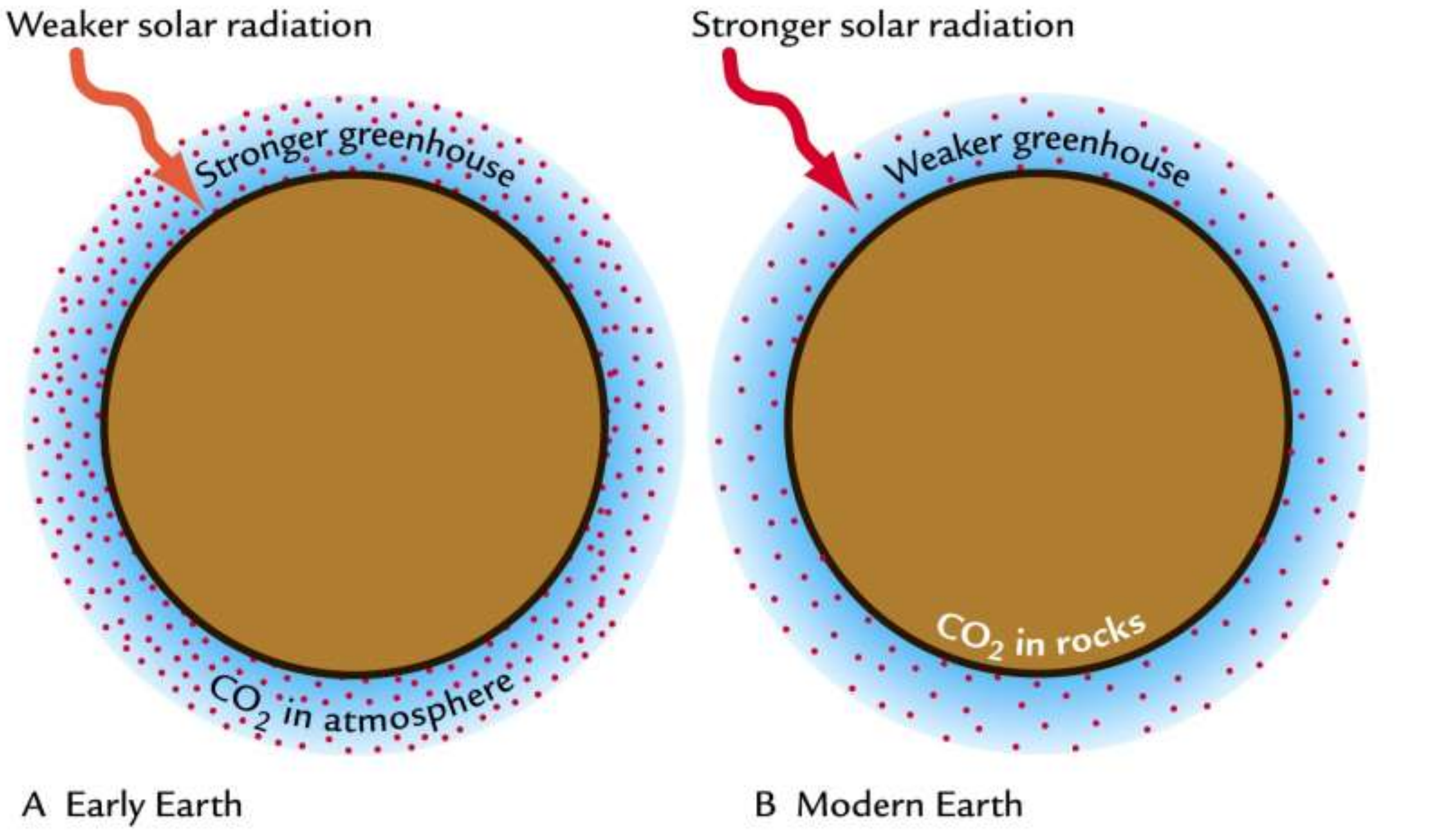
CO_2
Rapid terrestrial C cycling
Photosynthesis
Burning
Oxidation
Slow C cycling
Burial
Erosion
C burial
Photosynthesis
Upwelling
Sinking
Rapid marine C cycling
Oxidation
Burial
Slow C cycling
CO_2 release in volcanos

“Faint Young Sun” Paradox

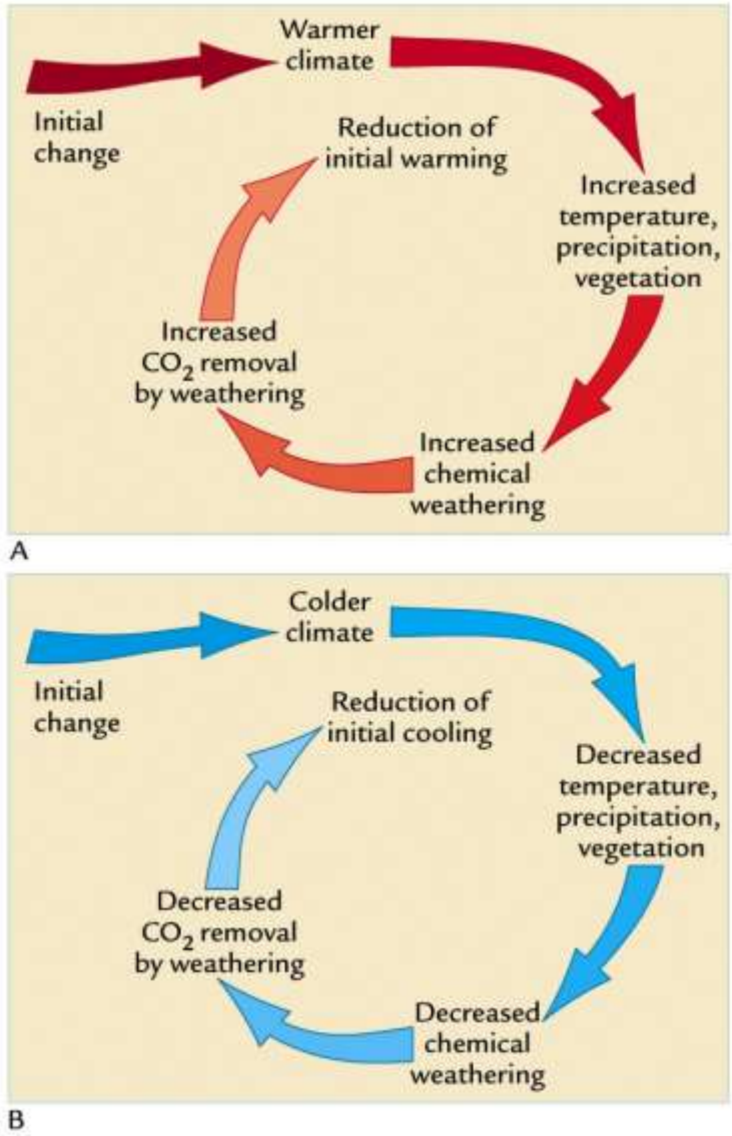
- Sun’s output must have increased by ~50%
- Somehow the increase in solar output has just been compensated
- Implies a natural thermostat exists
- Greenhouse gases must be involved



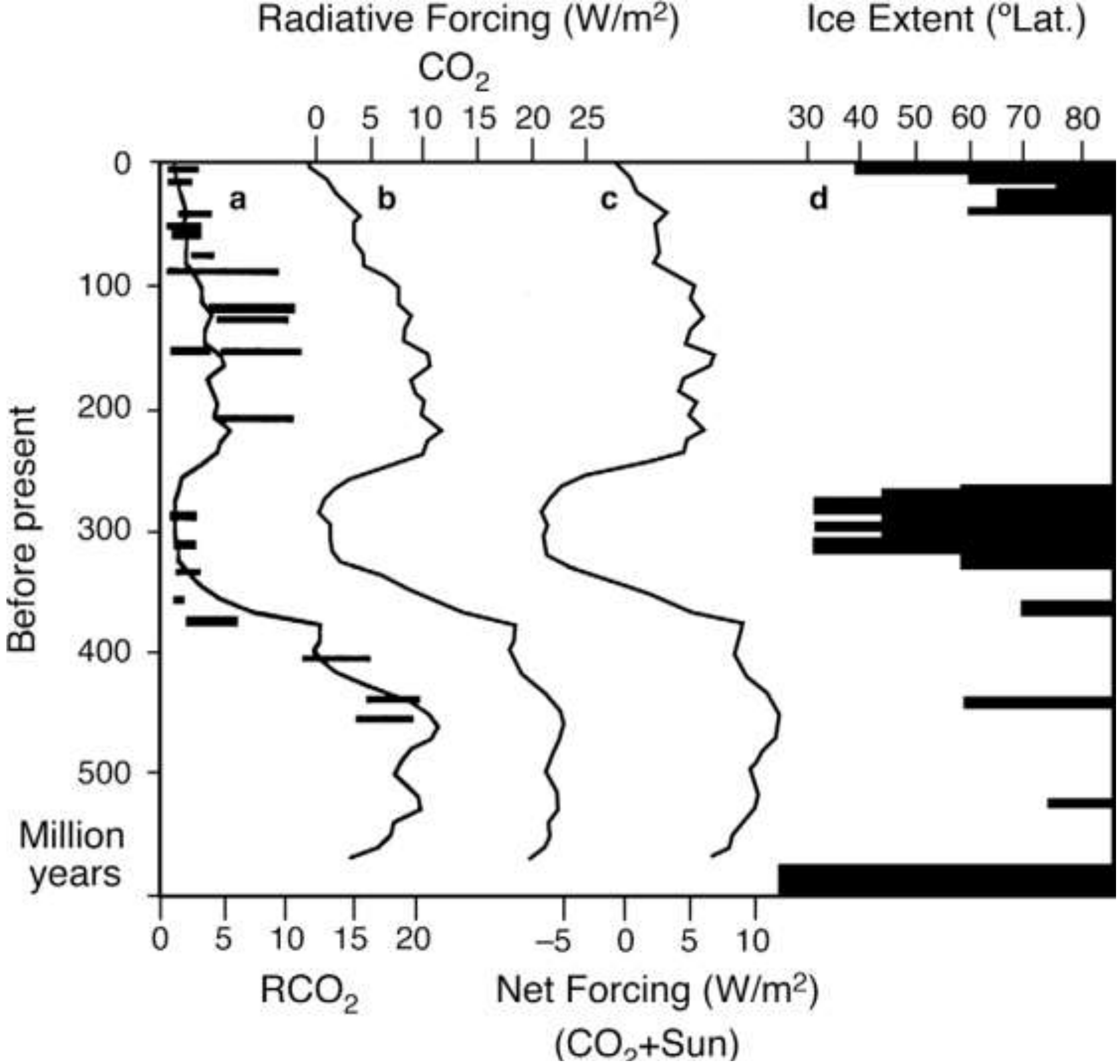
Even with a modern atmosphere,Earth frozen for much of its history

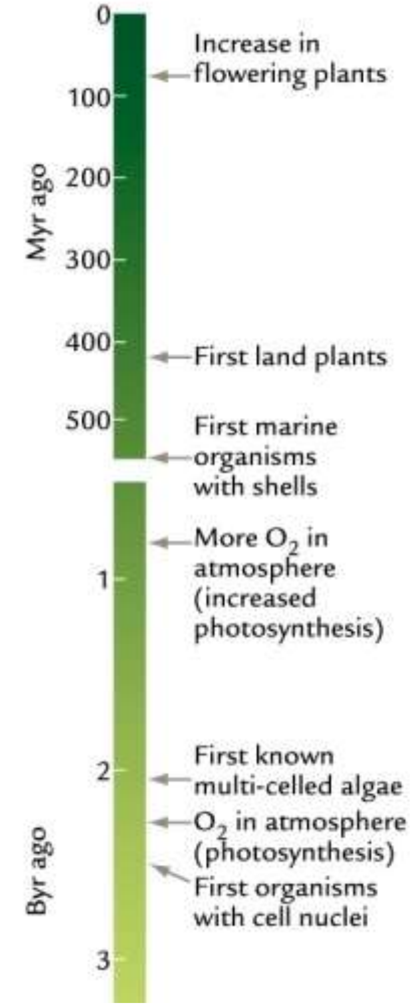


Plausible explanation of the faint young Sun paradox: (A) the weakness of the early Sun was compensated by a stronger greenhouse effect due to higher CO_2 in atmosphere (or CH_4). (B) when Sun strengthend increased chemical weathering transfers atm. C into rocks.

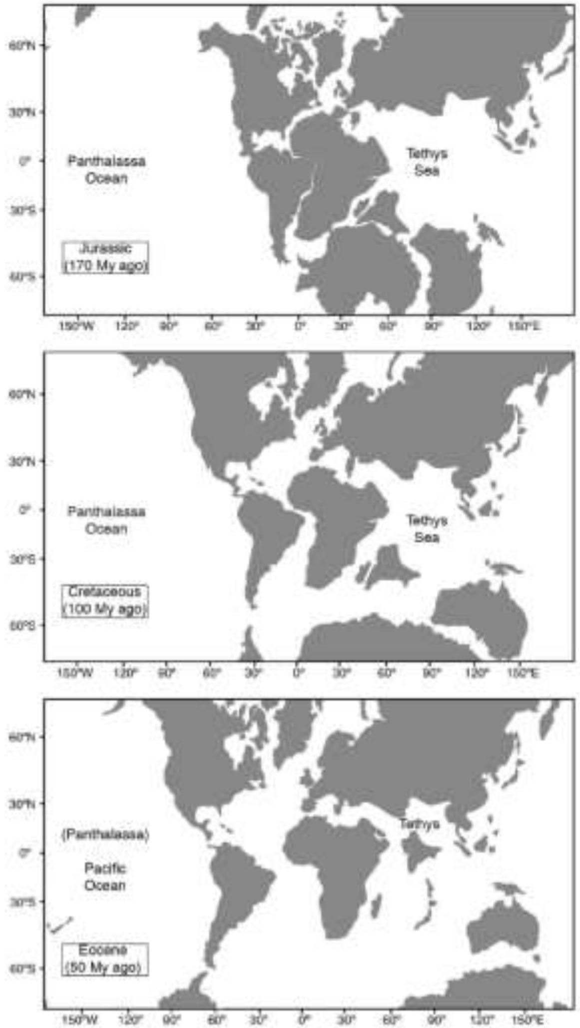


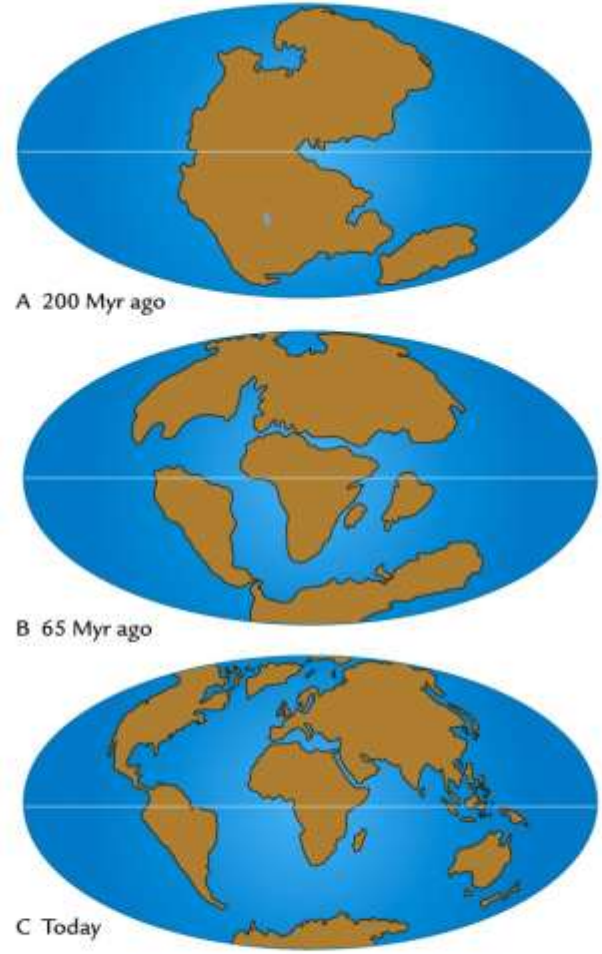
Negative feedback loop: Chemical weathering acts as a negative climate feedback by reducing the intensity of imposed climate warming (A) and climate cooling.





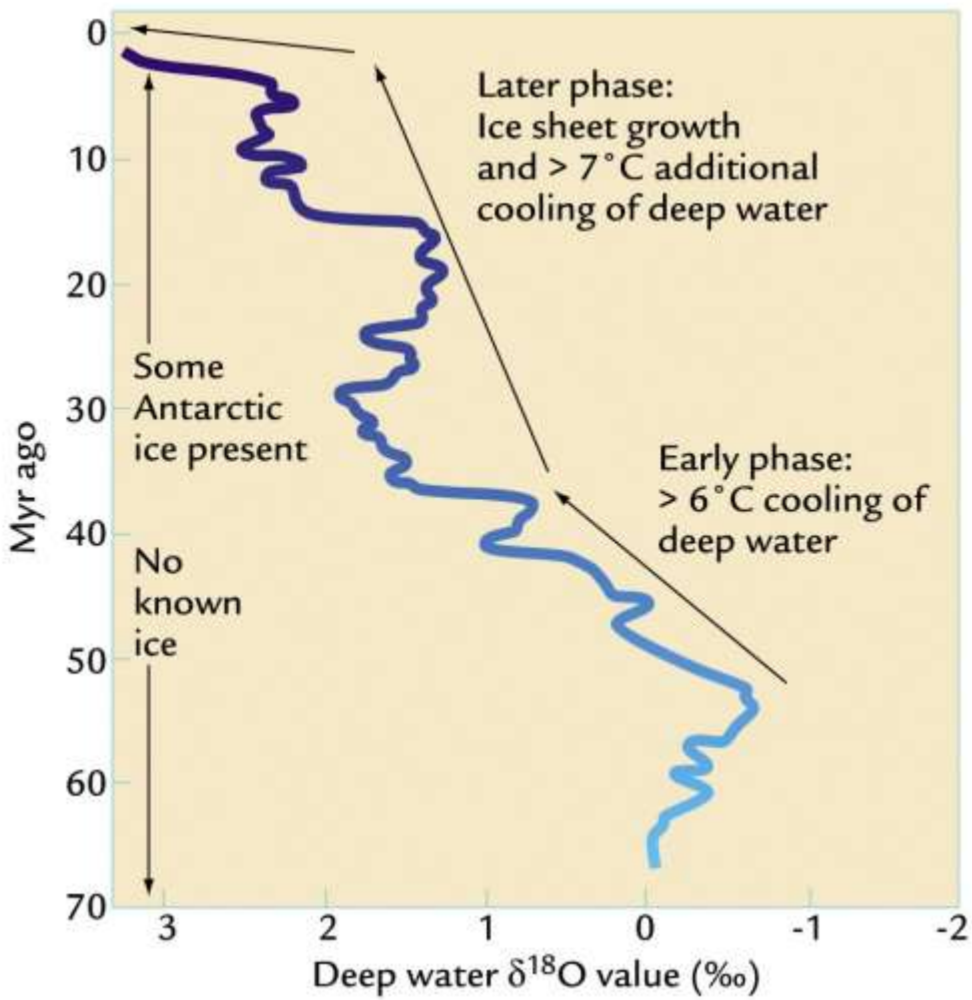
(a) Comparison of CO2 concentrations from a geochemical model (continuous line) with a compilation (Berner, 1997) of proxy CO2 observations (horizontal bars). RCO2 is the ratio of past atmospheric CO2 concentrations to present day levels.
(b) CO2 radiative forcing effects. (c) Combined CO2 and solar radiance forcing effects.
(d) Glaciological evidence for continental-scale glaciation deduced from a compilation of many sources.



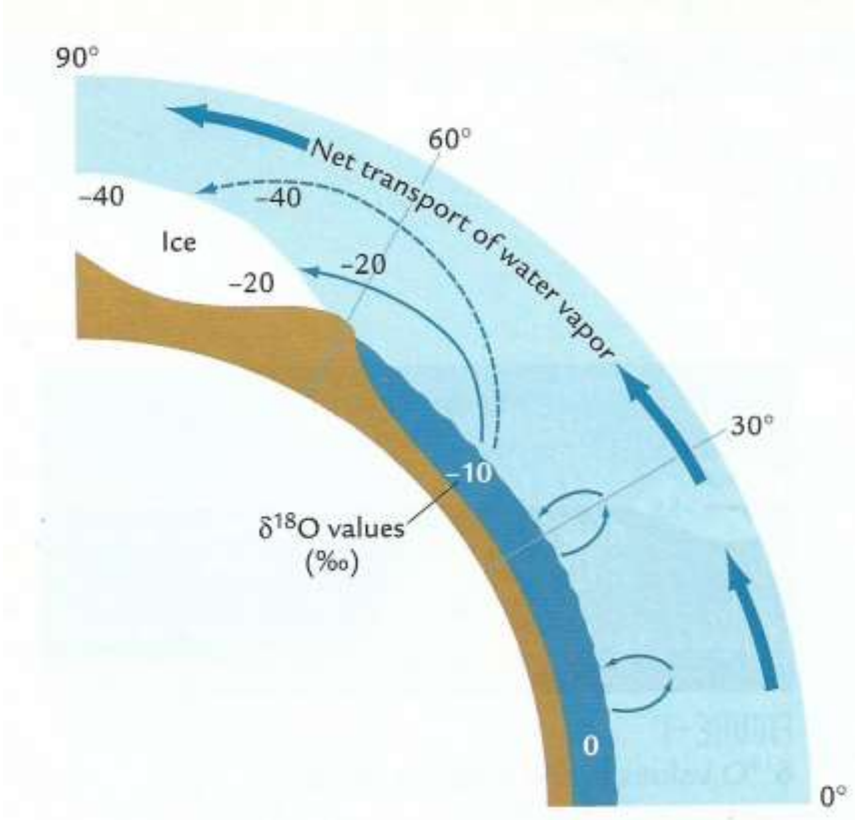


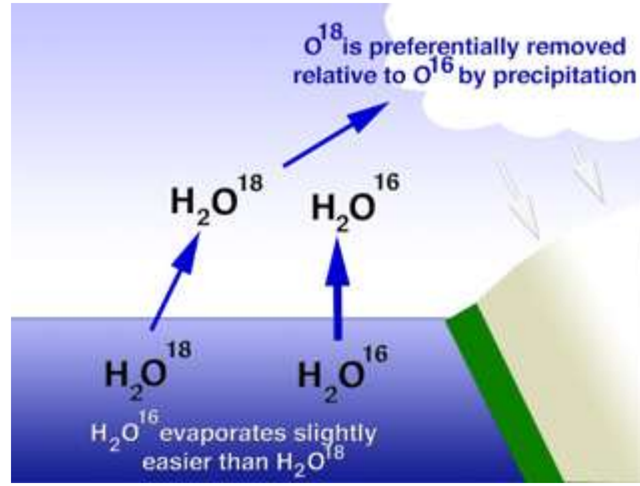
Paleogeographic reconstructions for (top) the Jurassic (170 My ago), (middle) the Cretaceous (100 My ago), and (bottom) the Eocene (50 My ago). Panthalassa was the huge ocean that in the paleo world dominated one hemisphere. Pangea was the supercontinent in the other hemisphere. The Tethys Sea was the body of water enclosed on three sides by the generally “C-shaped” Pangea.

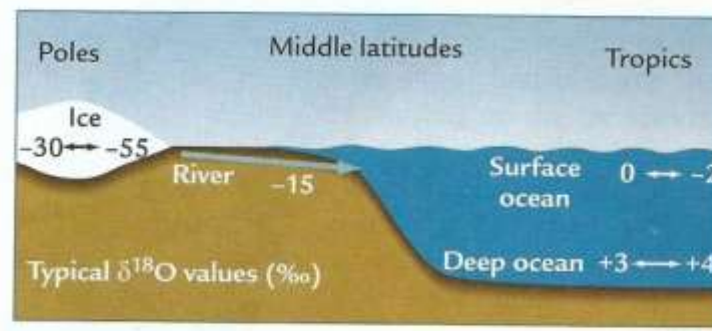
Long term trend in temperatures over the past 70 Mio. Years (12.3.2.)



Isotopes of Oxygen



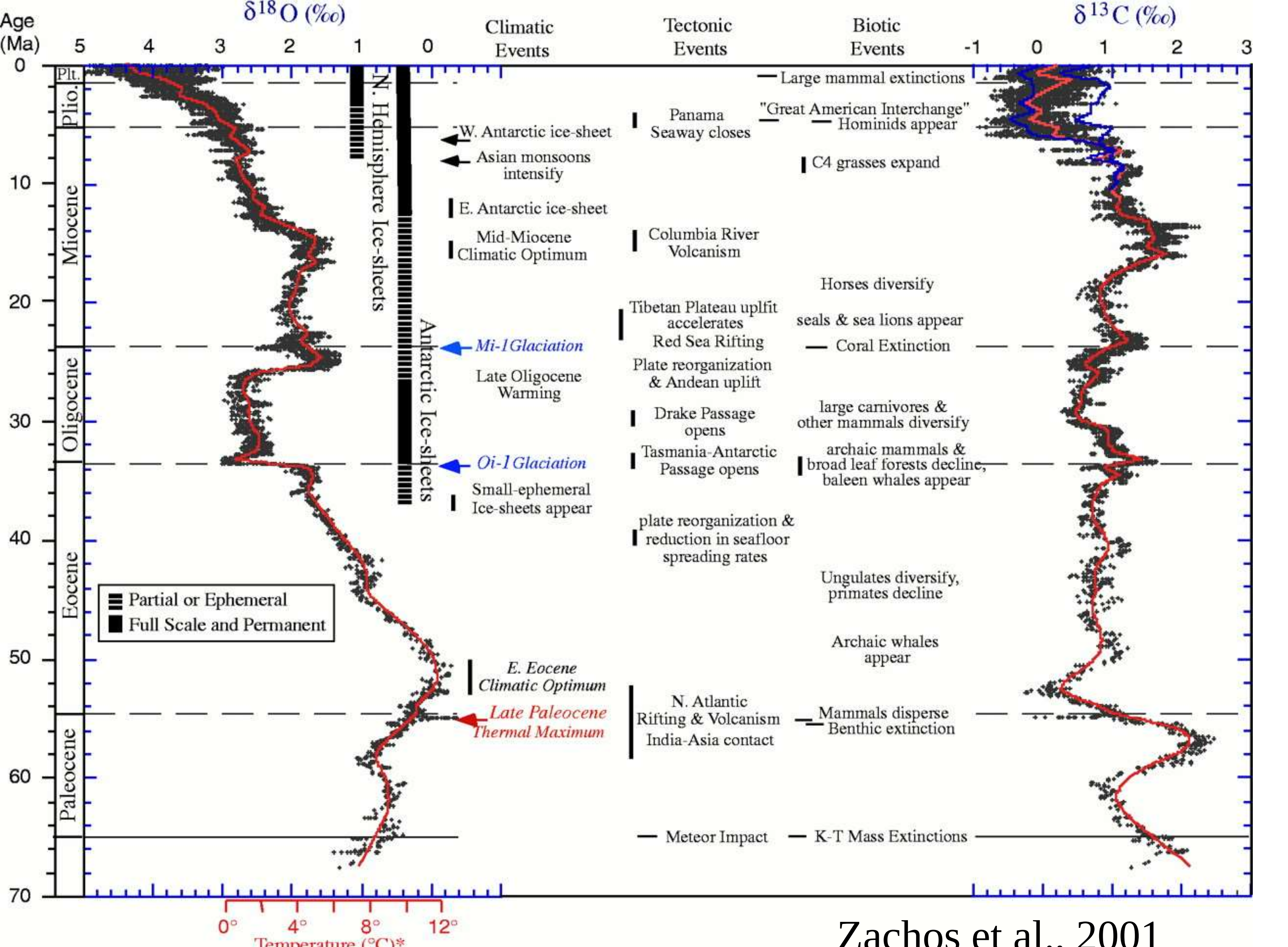




$$\underset{(\text{in } ‰)}{\delta^{18}O} = \frac{(^{18}O/^{16}O)_{\text{sample}} - (^{18}O/^{16}O)_{\text{standard}}}{(^{18}O/^{16}O)_{\text{standard}}} \times 1{,}000$$

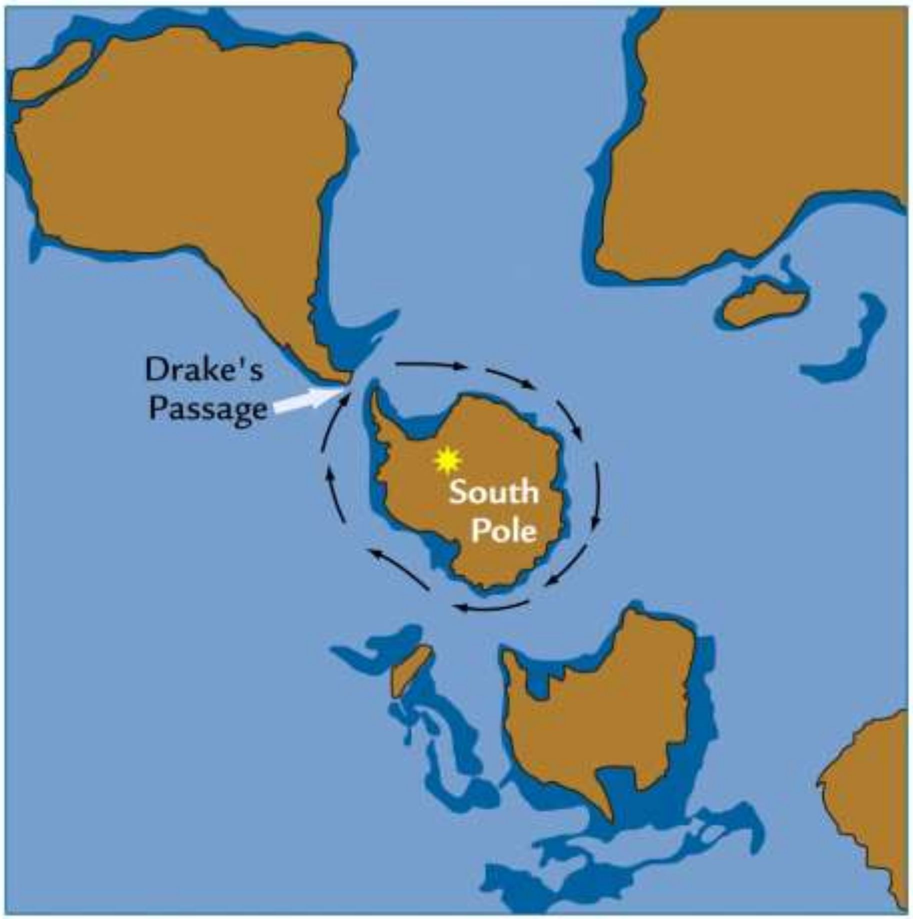
^{16}O is 99% of the total amount of O

More negative values mean enrichment in the lighter ^{16}O

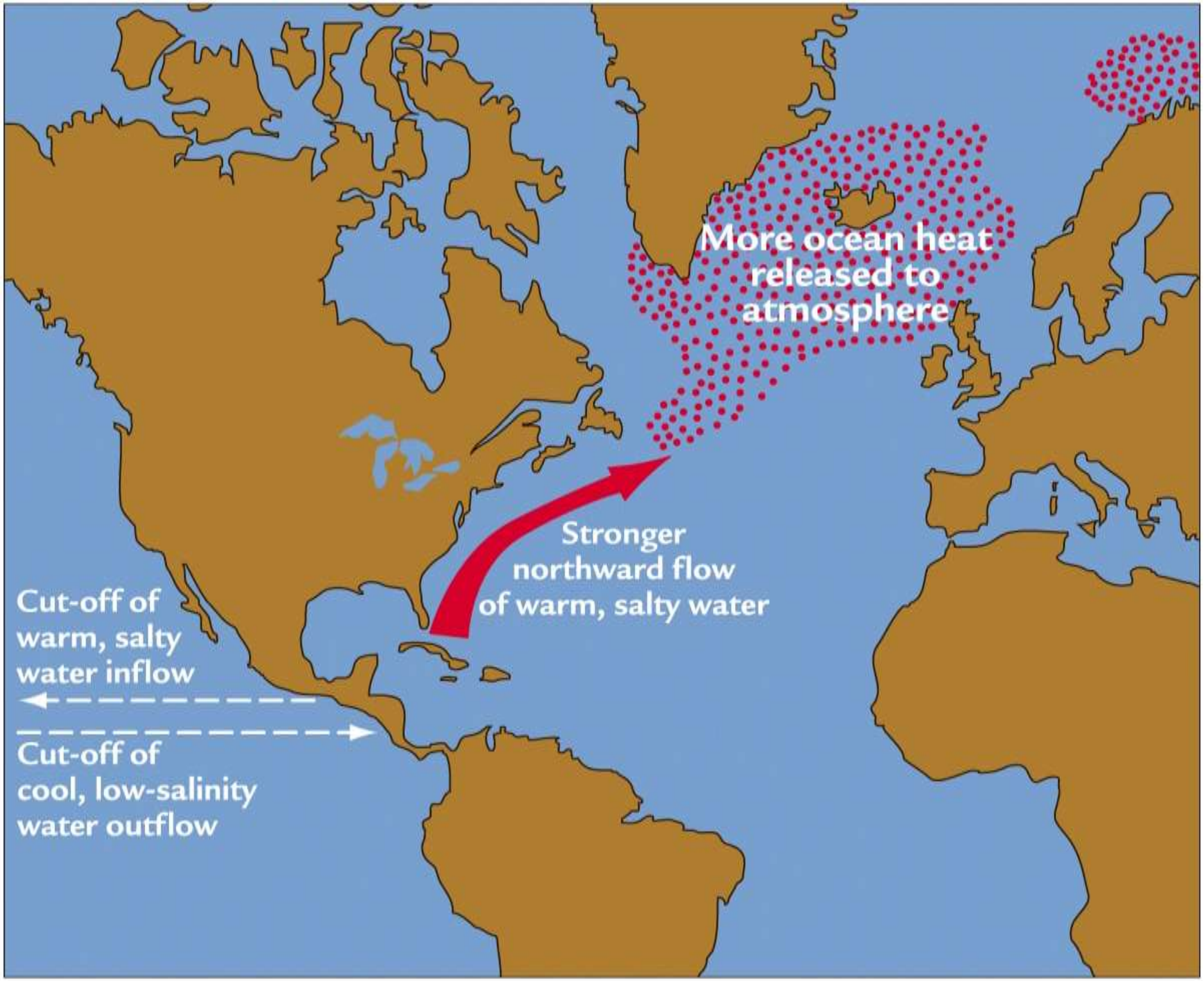


Zachos et al., 2001

Influences of oceanic gateways on long term climate change



Opening of an ocean gap between S-America and Antarctica around 25 Mio years allow strong Antarctic circumpolar current to flow uninterrupted around the Antarctic continent. The passage between Australia and Antarctica had opened around 10 Mio years earlier.


More ocean heat released to atmosphere
Stronger northward flow of warm, salty water
Cut-off of warm, salty water inflow
Cut-off of cool, low-salinity water outflow

High latitudes vegetation

Early Tertiary

Present day

Cenozoic orogeny and cooling

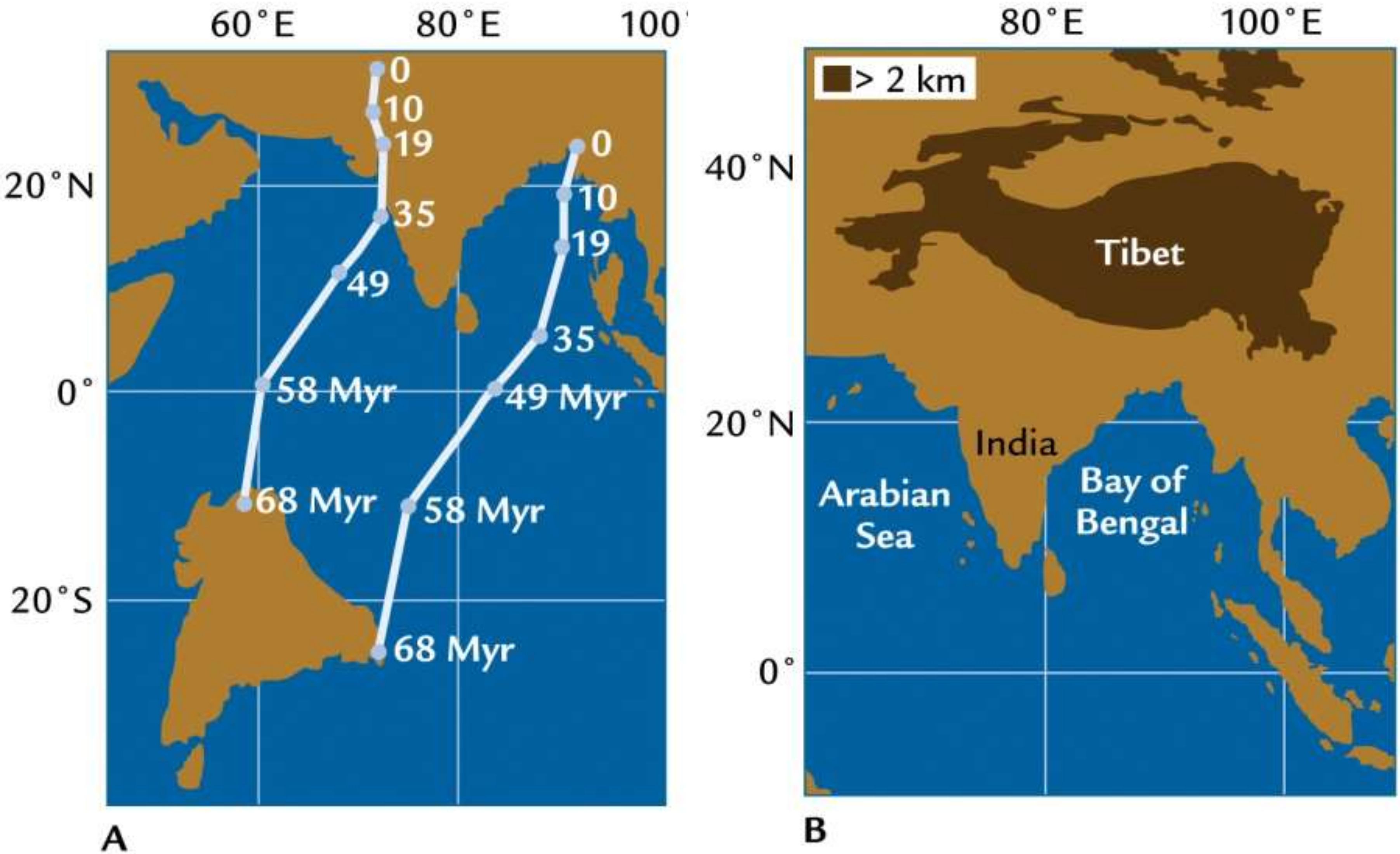
Increased weathering of the continents due to uplift of the Himalaya Mountains and Tibetan Plateau

Tectonic Uplift Hypothesis

after Raymo & Ruddiman (1985)

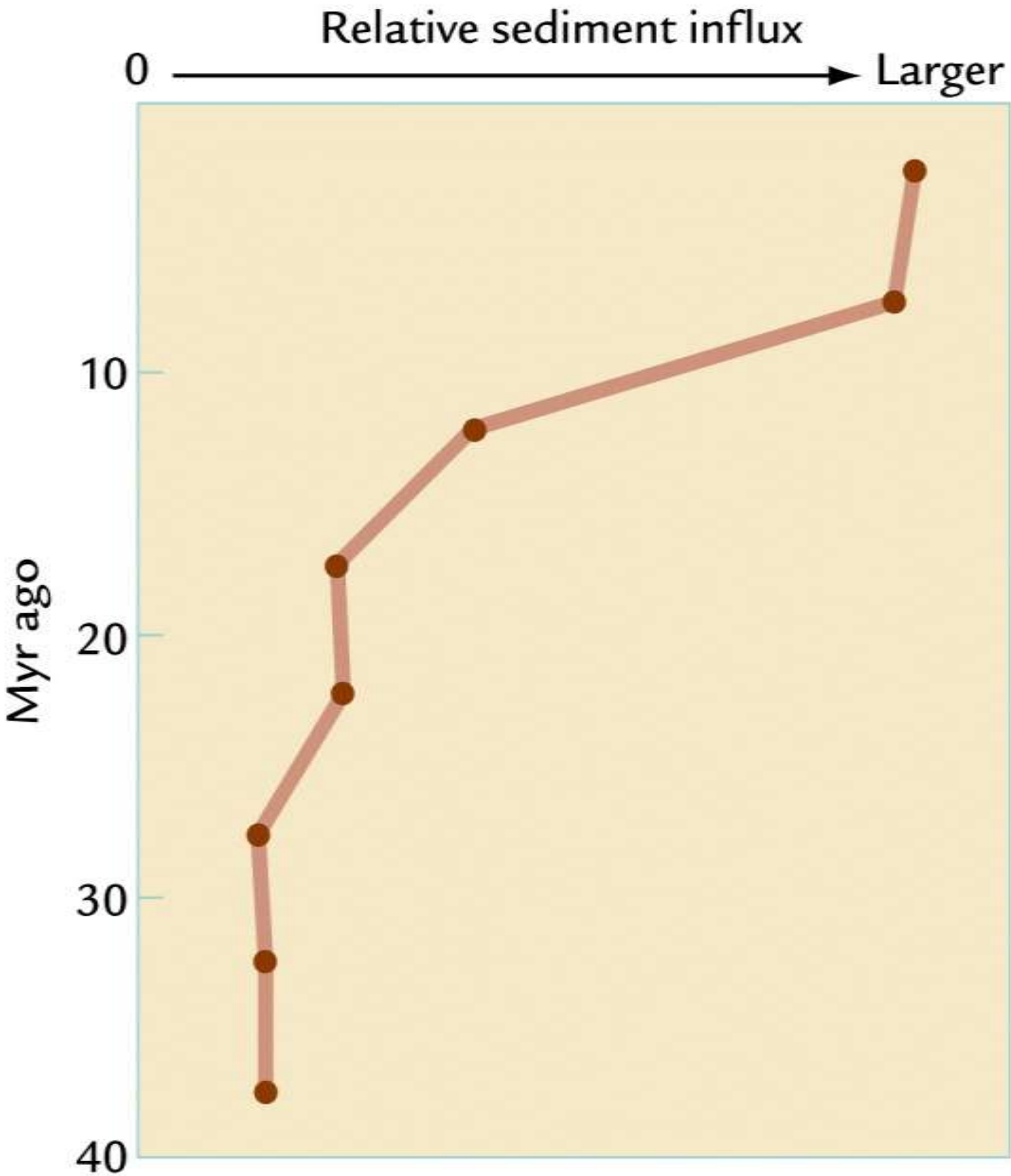
- Tectonic uplift of the Himalayas
- Enhanced silicate weathering
- Reduction of atmospheric CO_2
- Inverse greenhouse effect triggers cooling and extension of East Antarctic Ice Sheet

India - Asia collision and Tibet

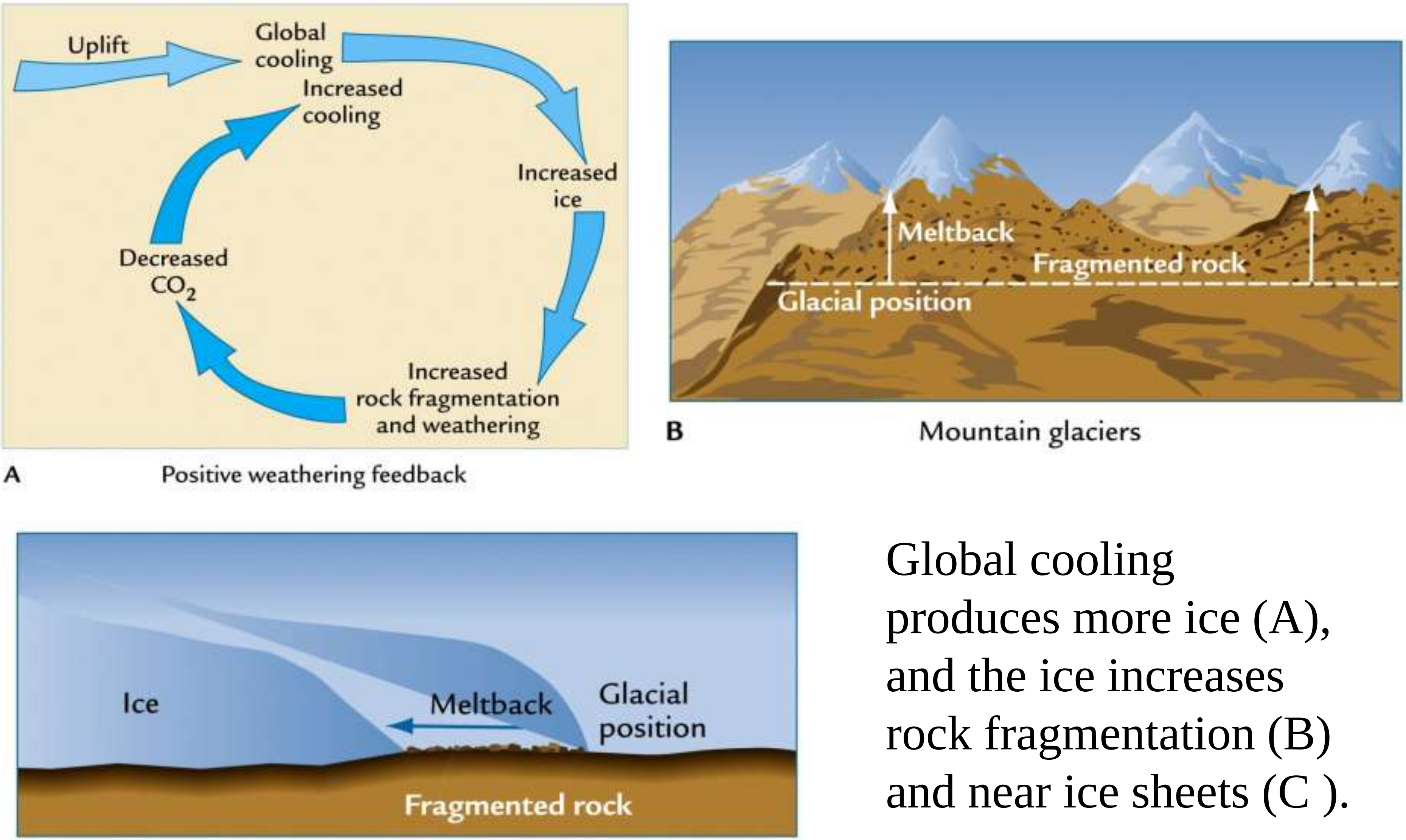


Collision of India and Asia produced the Tibetan plateau

Himalayan sediments in the Indian Ocean



The rate of influx of sediments from the Himalayas and Tibet to the deep Indian ocean has increased 10fold since 40 Mio years ago



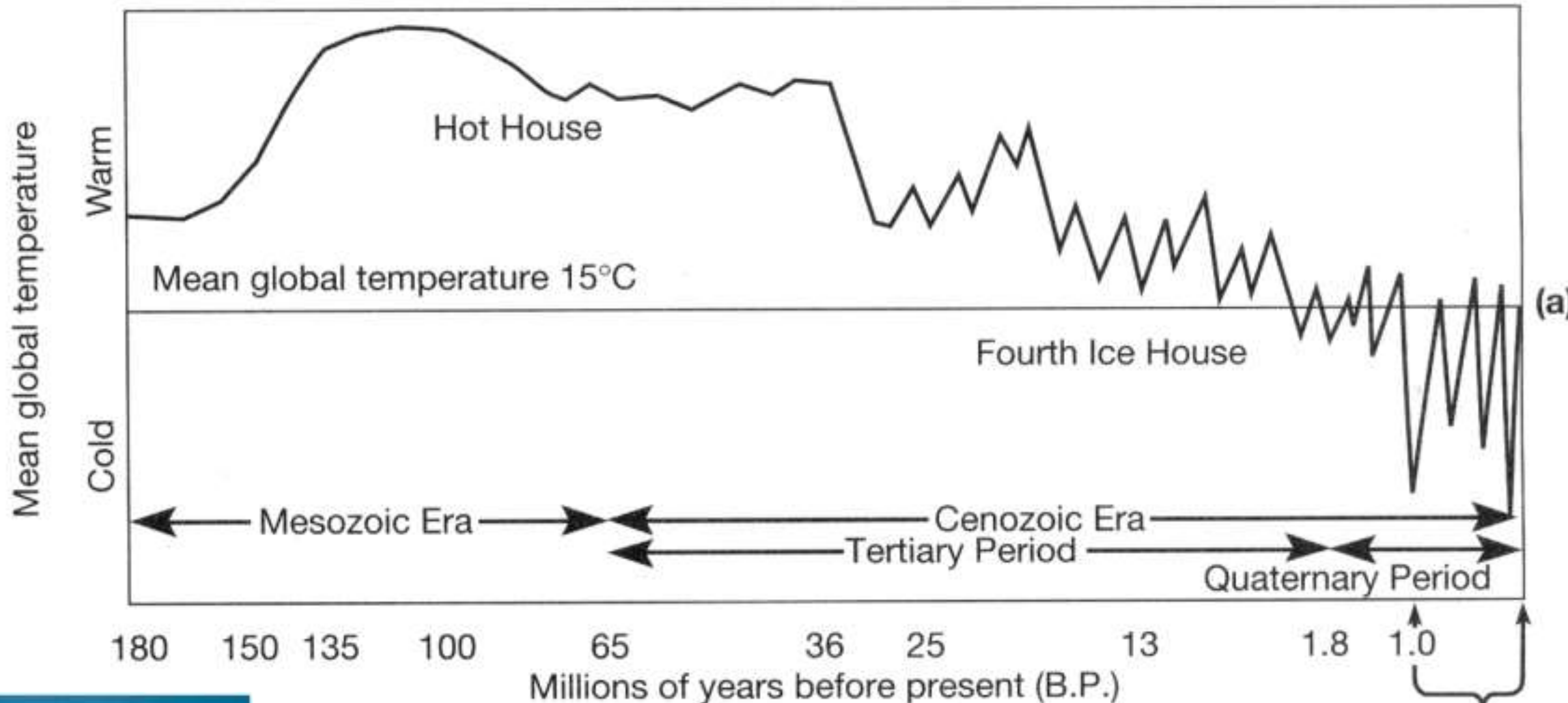
A Positive weathering feedback

B Mountain glaciers

C Continental ice sheets

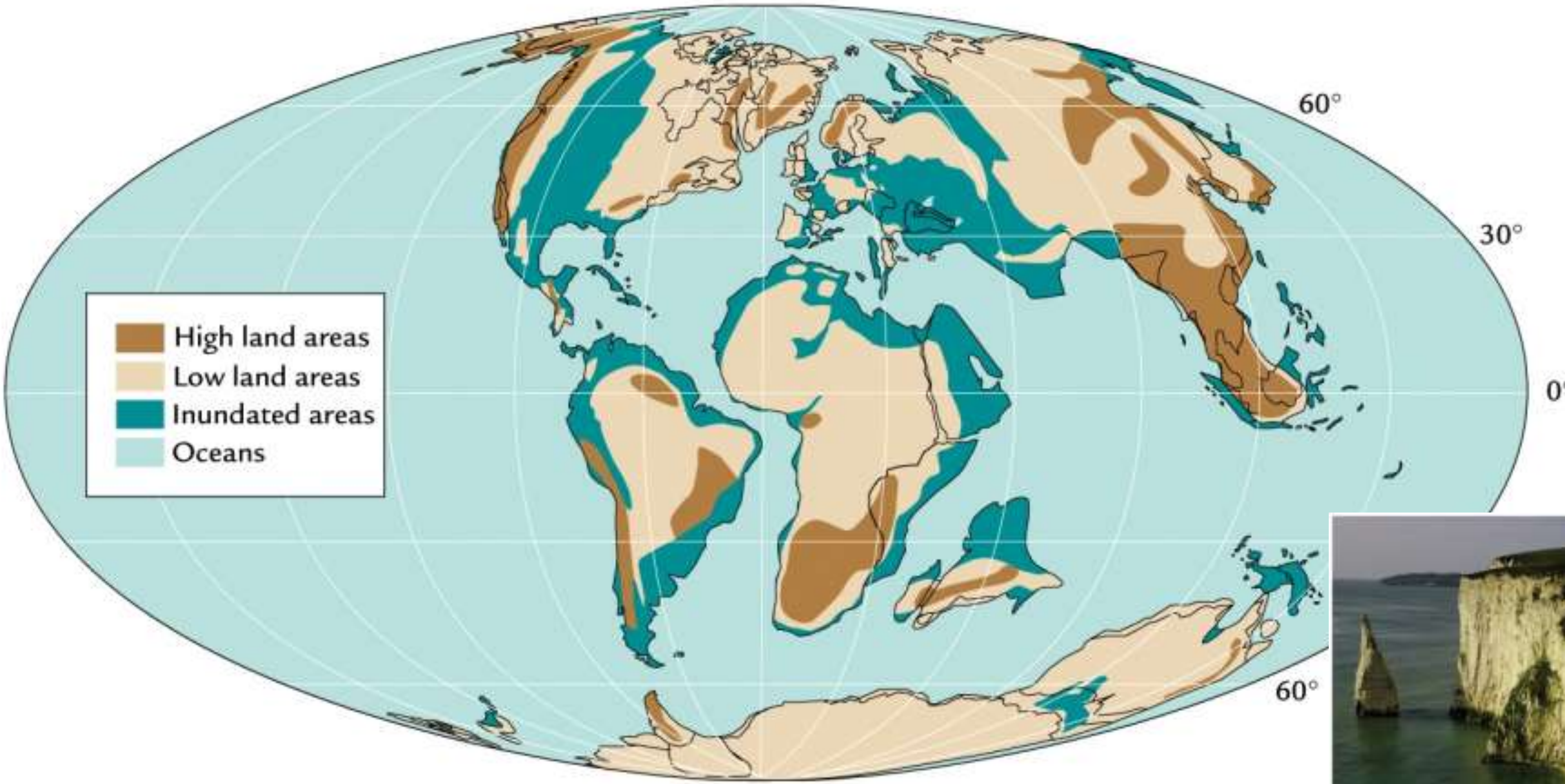
Global cooling produces more ice (A), and the ice increases rock fragmentation (B) and near ice sheets (C).

Greenhouse climates (ch. 12.3.3)



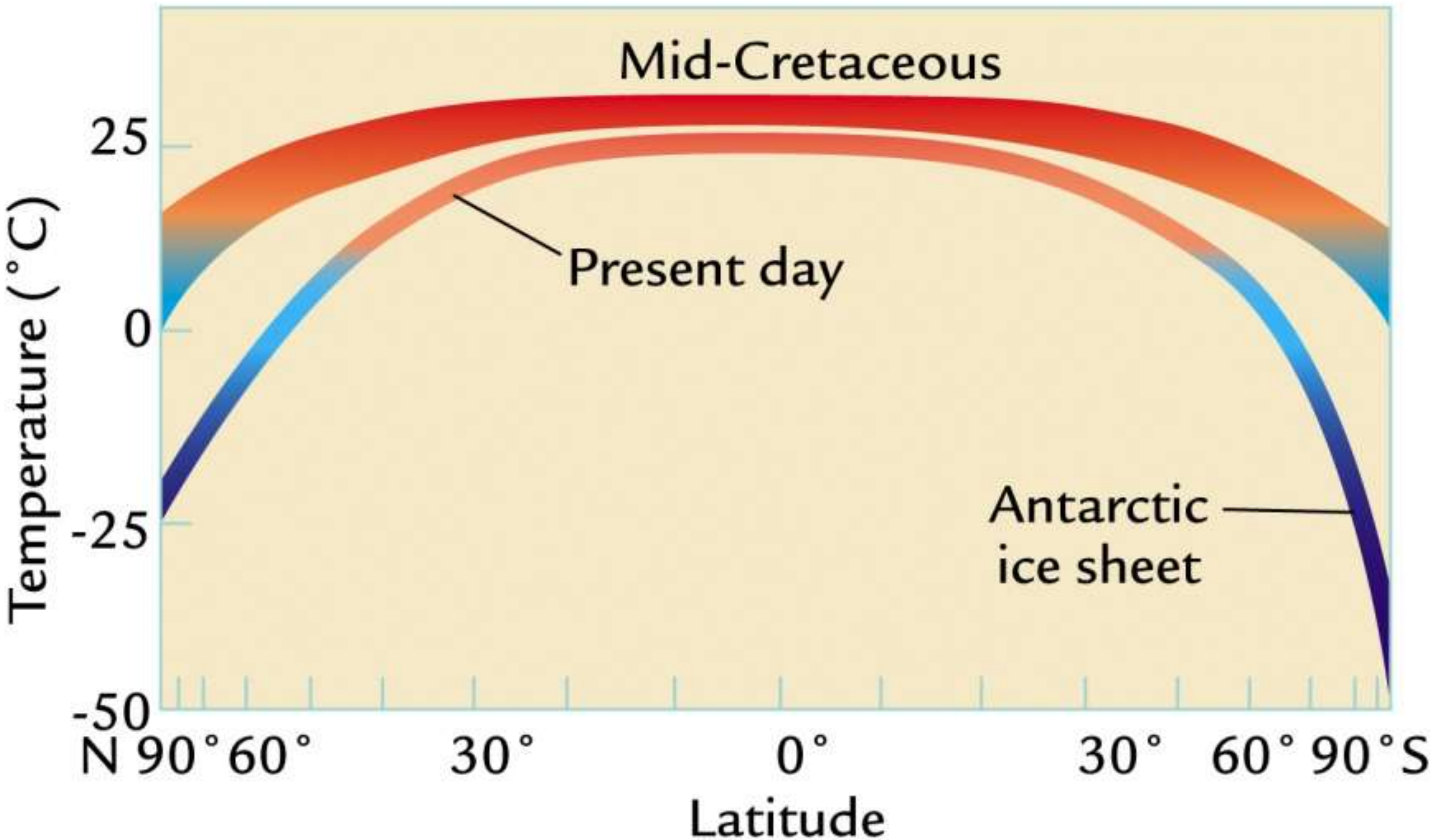
- fossil evidence for reptiles, tropical plants in the Arctic
- atmospheric CO_2 some 3-5x PAL
- abundant volcanism

The world in the Cretaceous period (100 Mio years ago)

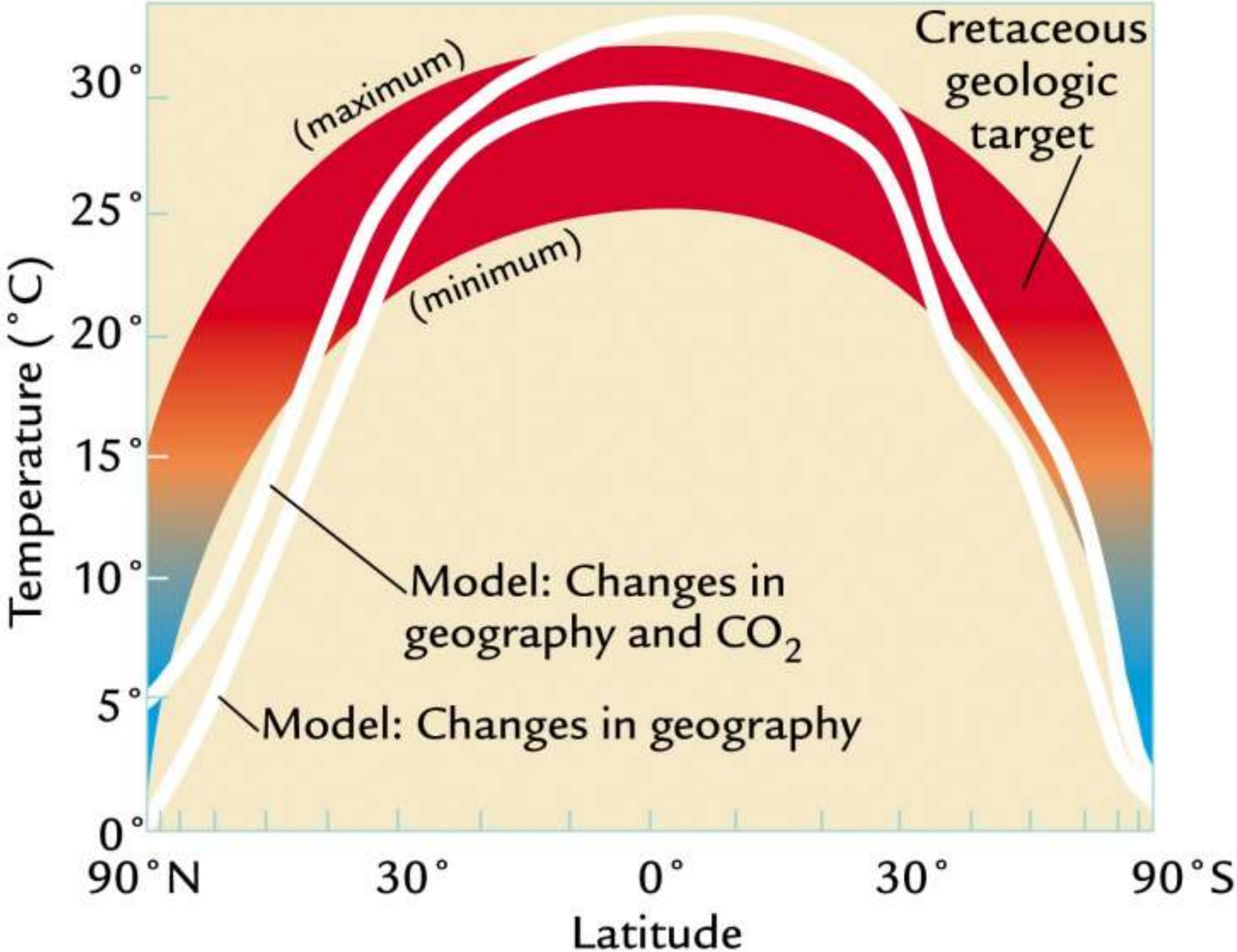


Pangean supercontinent broke apart in smaller continente which were flooded by shallow seas

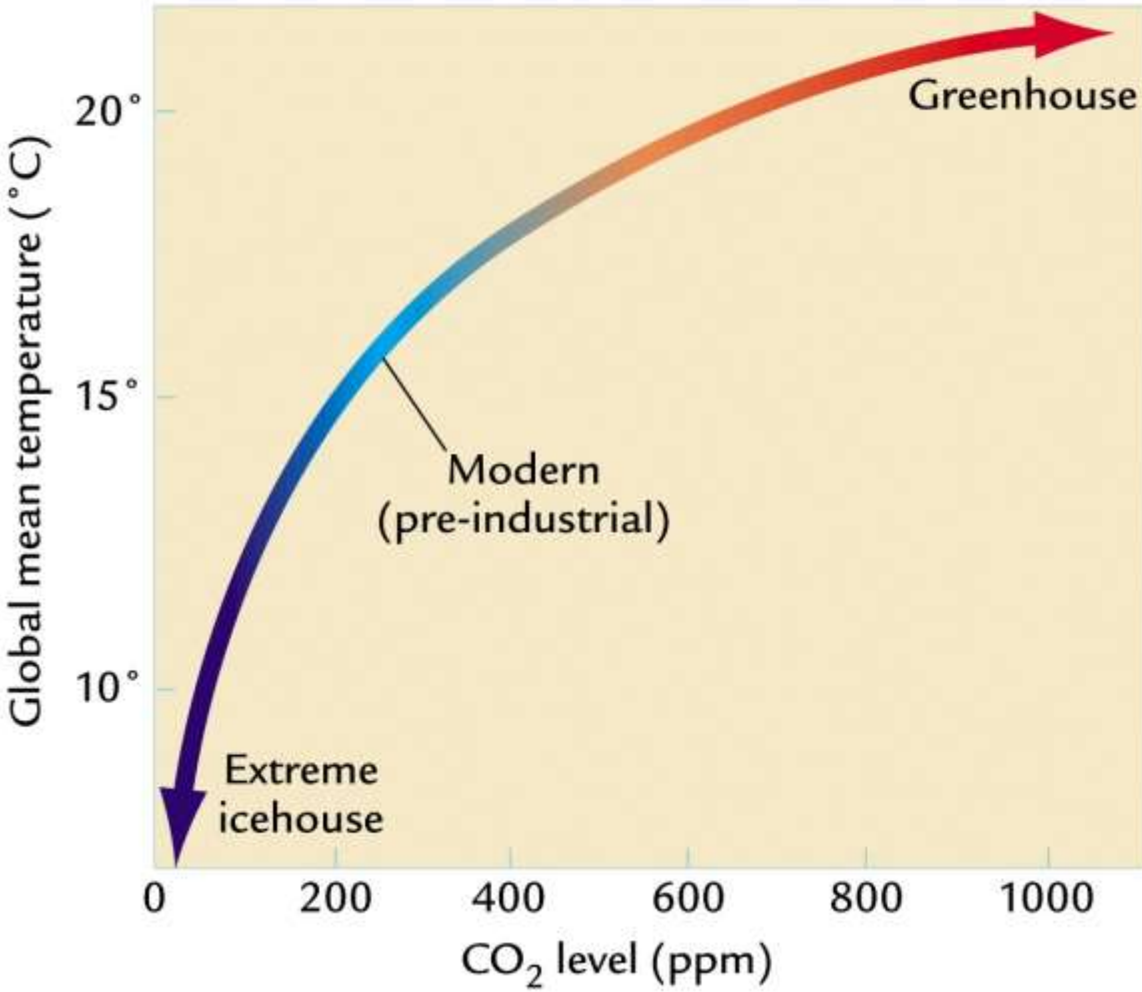
Cretaceous Greenhouse climate



Palaeoclimate scientist gathered geological data (fauna, flora, and geochemical) to compile an estimate of temperature. Temperature was warmer than present day at all latitudes, in particular in the high latitudes.



Climate models are matched against the palaeotemperature data inferred from geological data, One model with changes in geography and another model with changes in geography plus palaeoatmos. CO2 reproduce some aspect of the palaeoclimate data but noe of them can reproduce the warmth at high latitudes.



Greenhouse world (>800): Large changes in CO2 have little effect on temperature (CO2 saturation effect)

Icehouse world (<400): Small changes in CO2 have a great effect on temperature because of the positive feedback of lower temperature on snow and seas ice extension and related changes in albedo.

Climate models (GCM) run sensivity test of the effects of elevated CO2 on global temperature show greater warmth for higher CO2 levels, but the rise is not a linear relationship.

Unresolved problems of the Cretaceous greenhouse climate

- Possible causes:
  - High pCO2 (3-5x present day CO2 level)
  - Enhanced oceanic heat transport poleward
  - Oceanic deep water was warmer and saltier causing convection in the low latitudes (tropics)
- Presence of reptiles and tropical plants indicates warm frost free winters
- climate models simulate freezing conditions in the continental interior

Cold Climates (12.3.4.)

Quaternary ice age

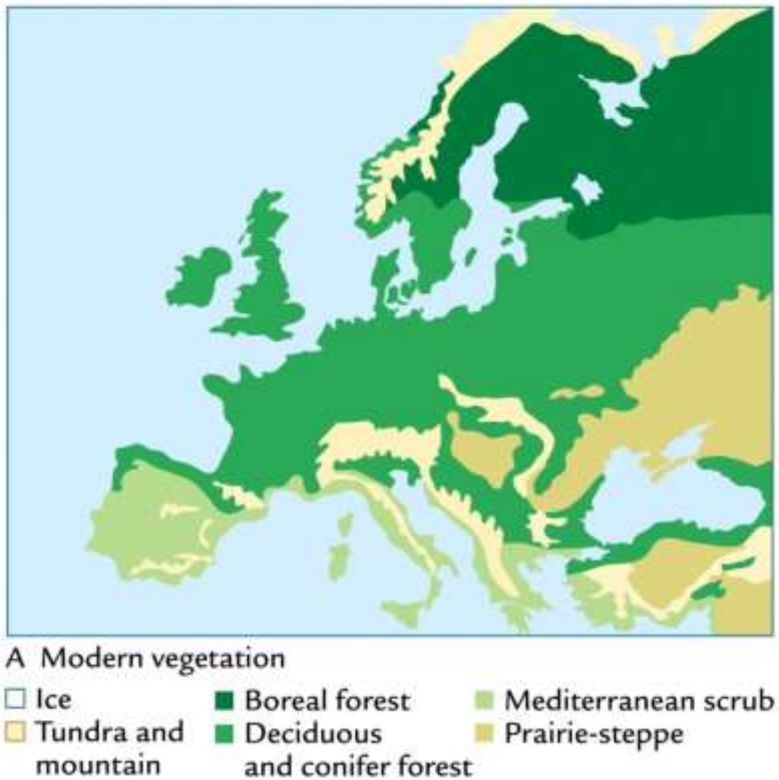
- Quaternary is characterized by ice ages which show a prominent cycle between cold "glacial stages" and warm "interglacial stages".
- The Quaternary starts with the establishment of the N-Atlantic ice shield at ~2.1 Mio years ago.
- The glacial-interglacial changes appear to occur periodically.
- What causes this periodicity?

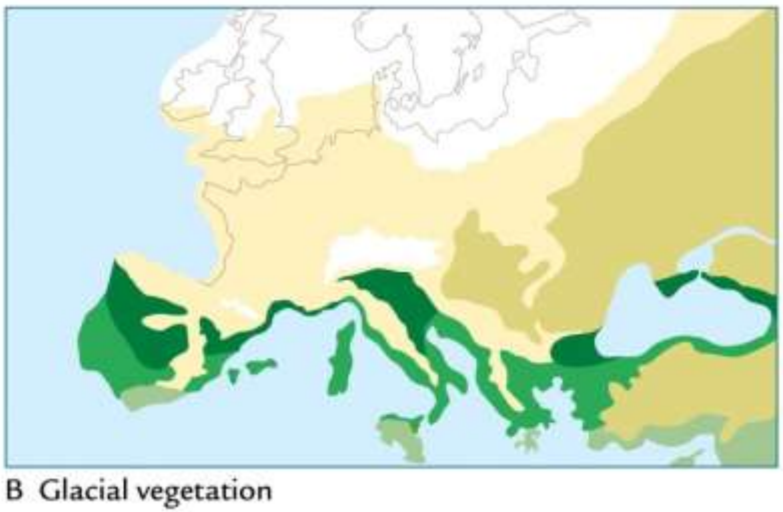
Several lines of evidence for ice ages

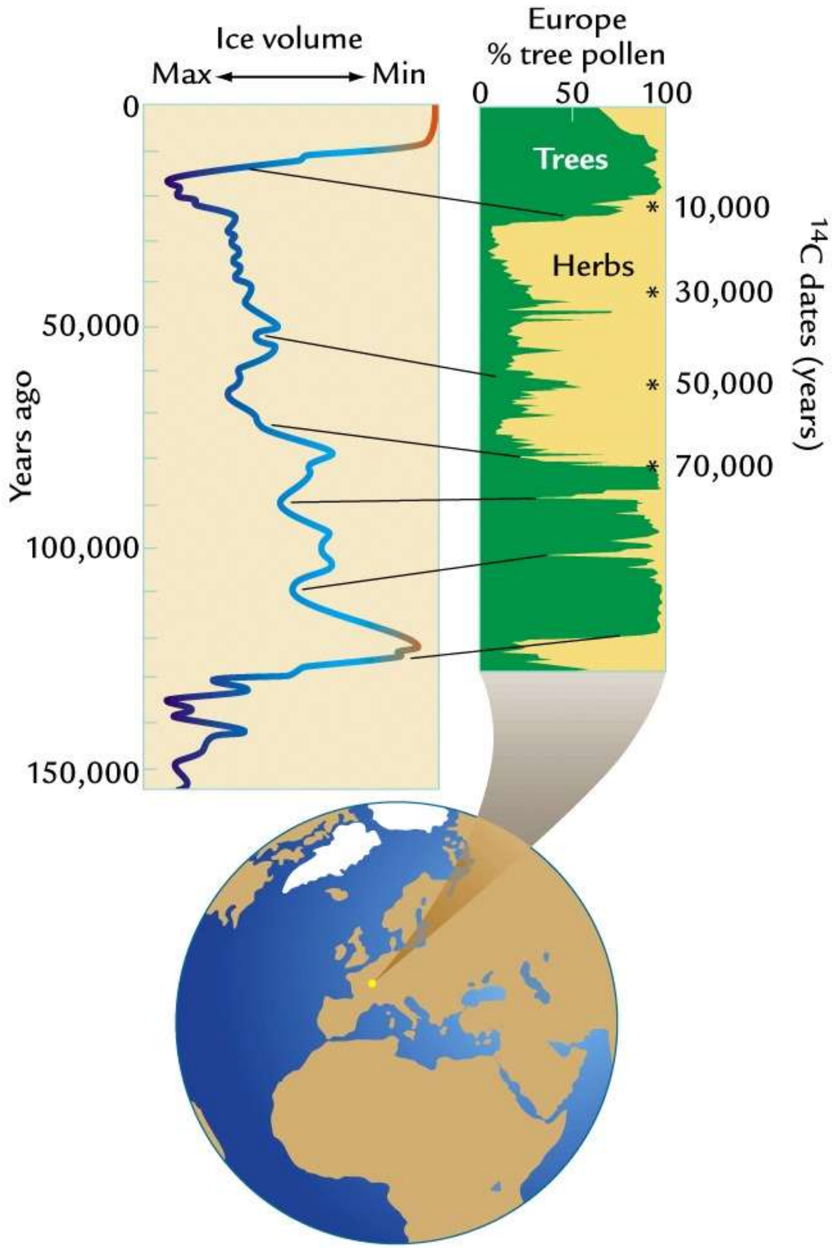
- Landscape formed by glaciers
  - U form valleys
- Occurrence of ice transported rocks (Erratics)
- Surface structures on bedrocks parallel striations
- Vegetation changes



Natural vegetation in Europe:

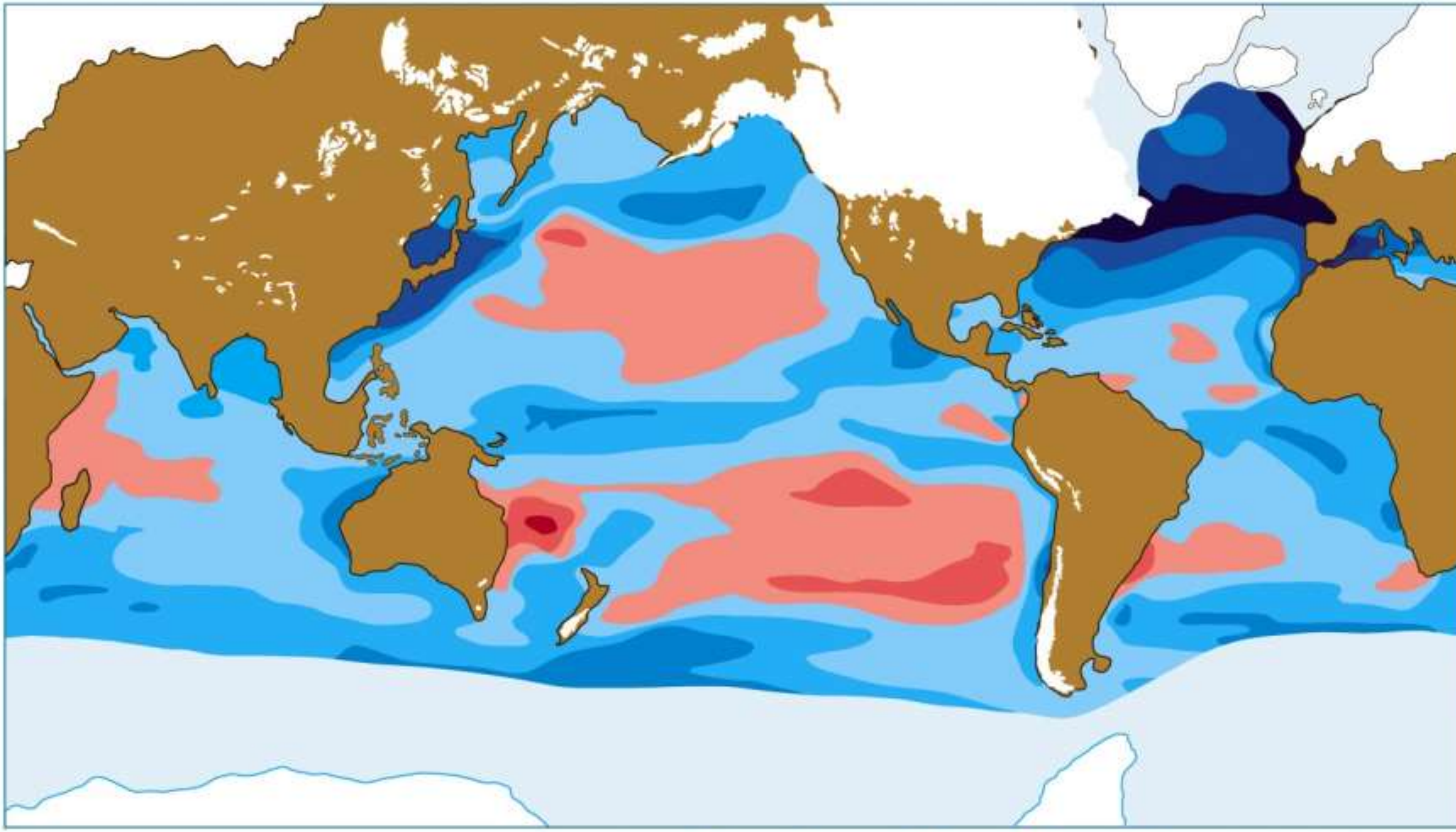




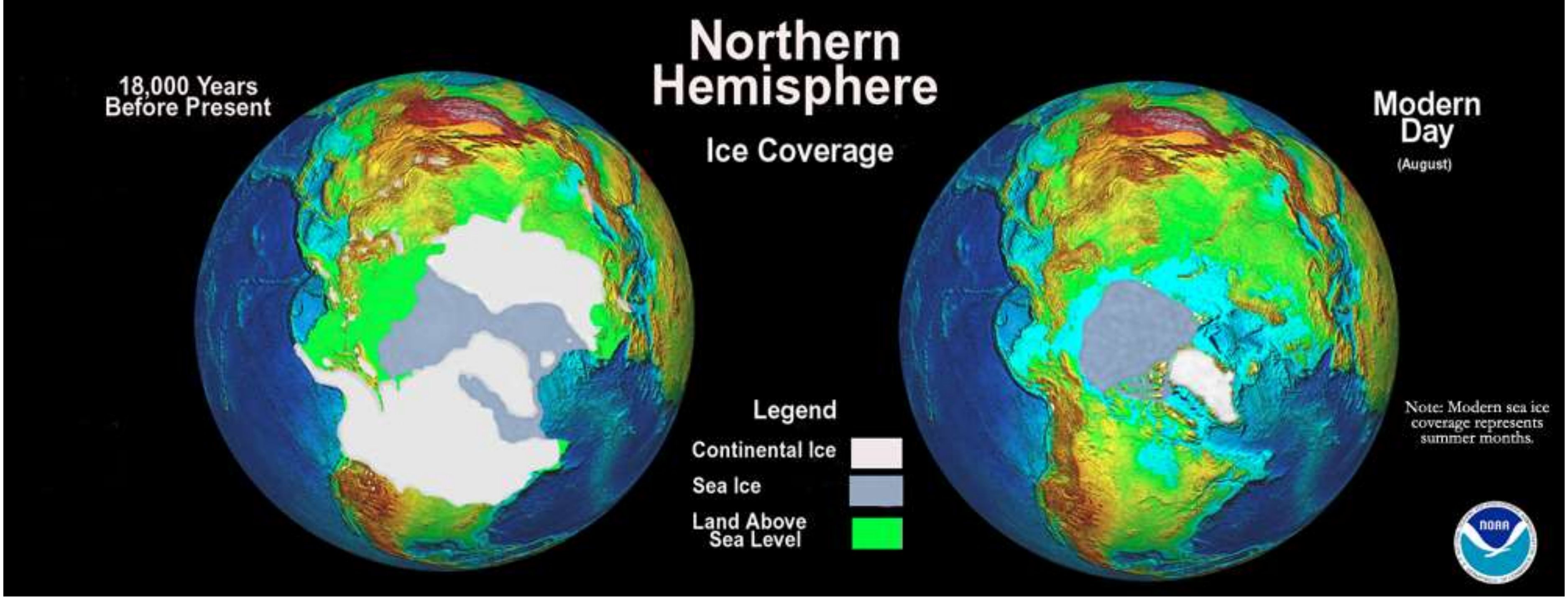


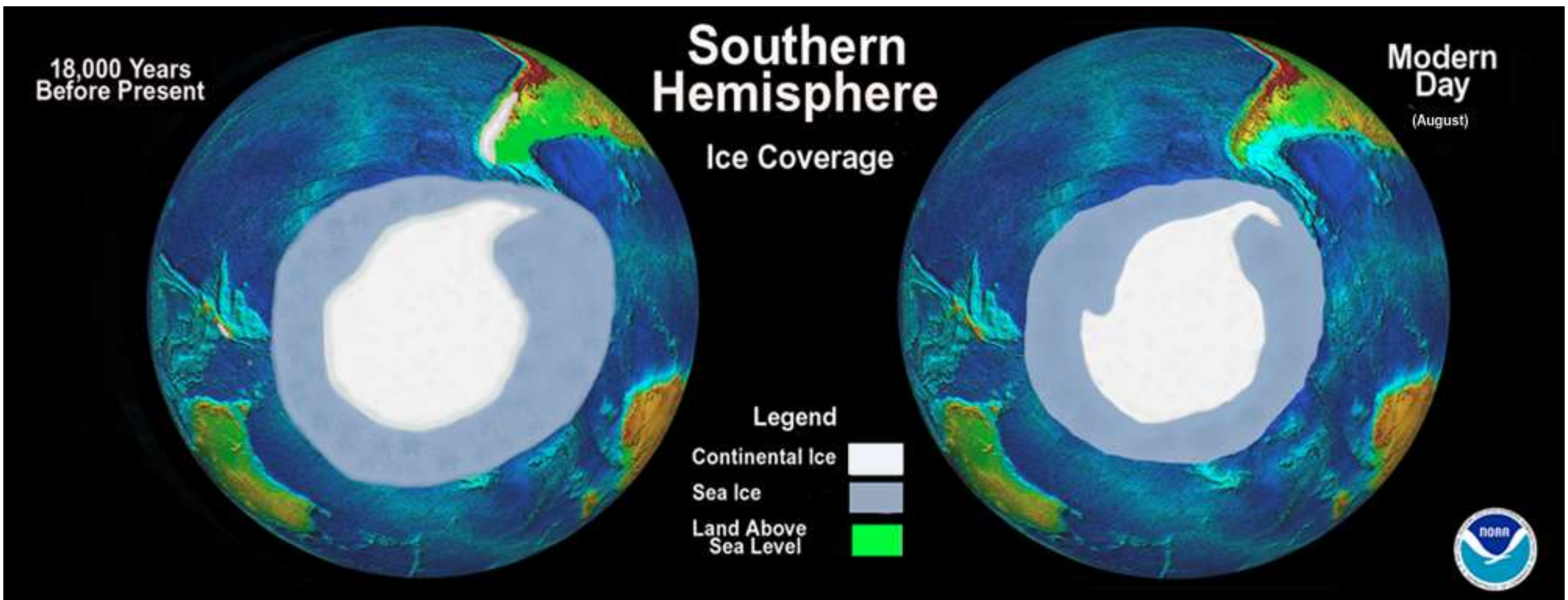
Pollen diagram indicating vegetation changes during Glacial – Interglacial climate cycle

CLIMAP reconstruction of glacial maximum ocean temperatures

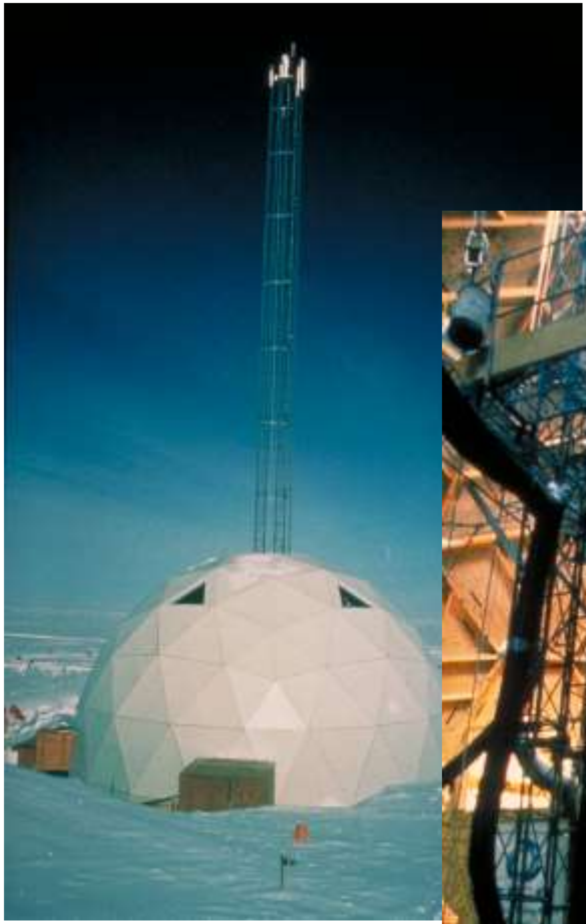


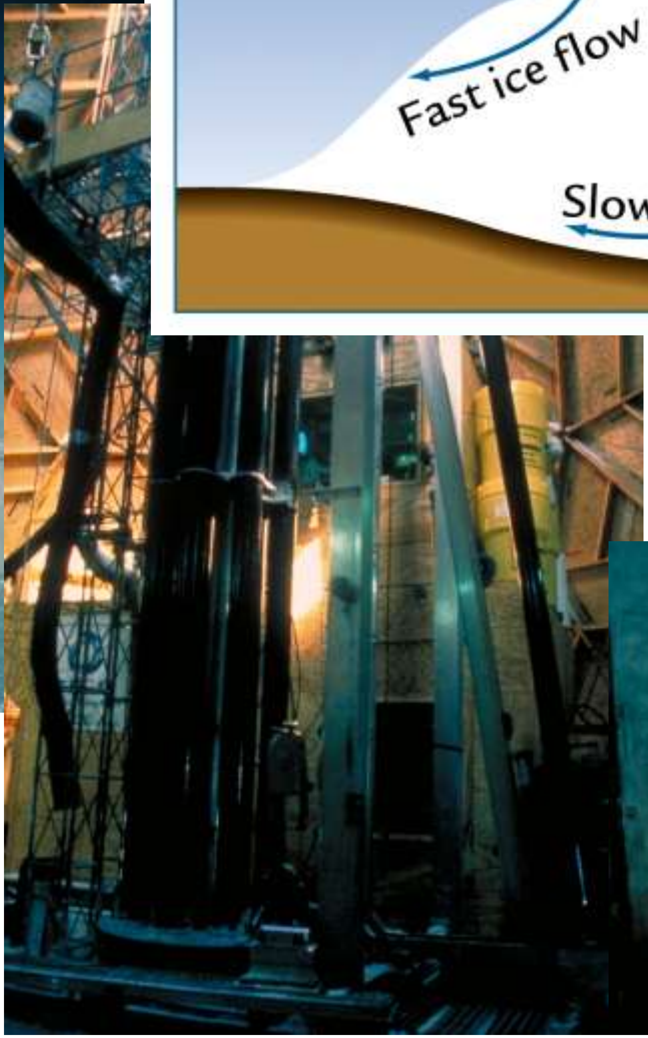
Map showing the changes in sea surface temperature between LGM and today

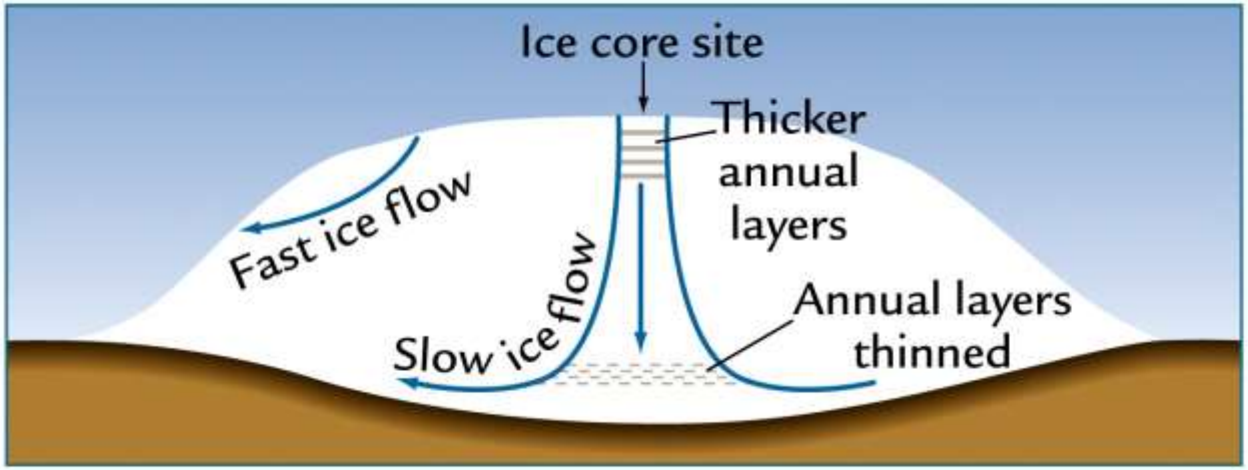

Northern Hemisphere
Ice Coverage
18,000 Years Before Present
Modern Day
(August)
Note: Modern sea ice coverage represents summer months.
Legend
Continental Ice
Sea Ice
Land Above Sea Level
NOAA

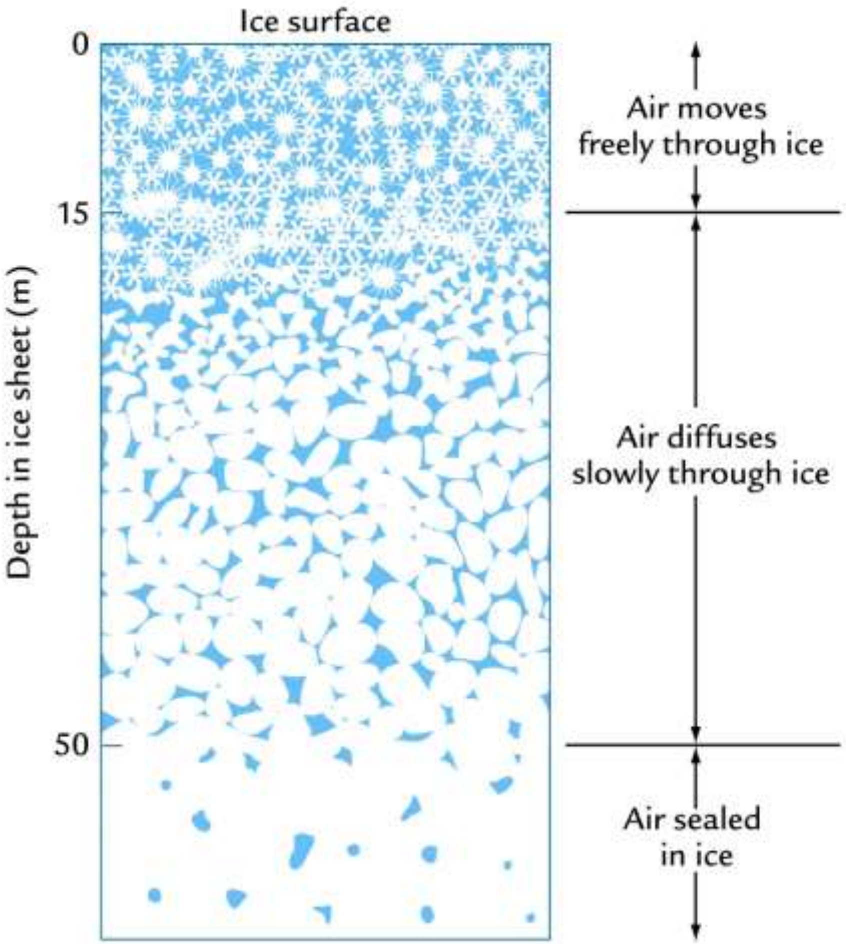

Southern Hemisphere
Ice Coverage
18,000 Years Before Present
Modern Day
(August)
Legend
Continental Ice
Sea Ice
Land Above Sea Level
NOAA

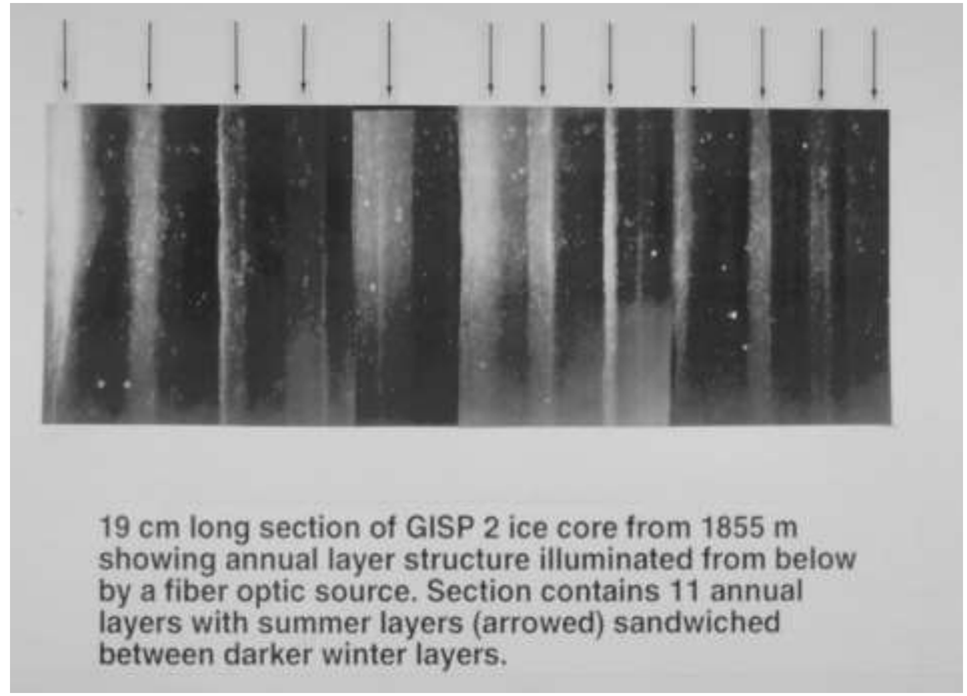
Greenland ice sheet as palaeoclimate archives



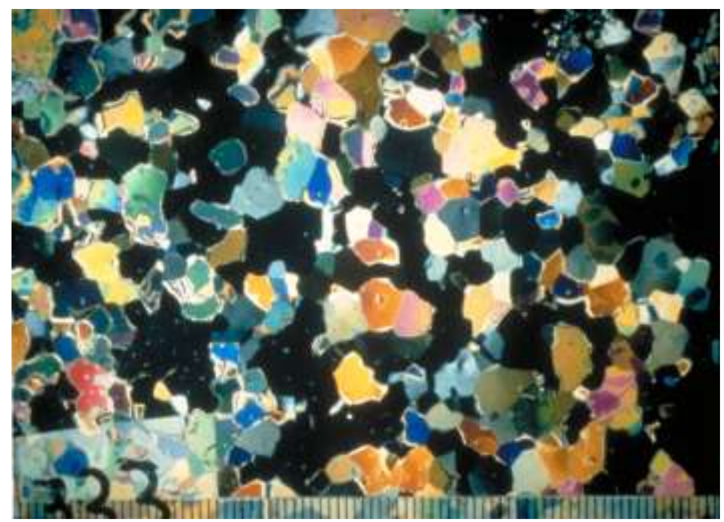


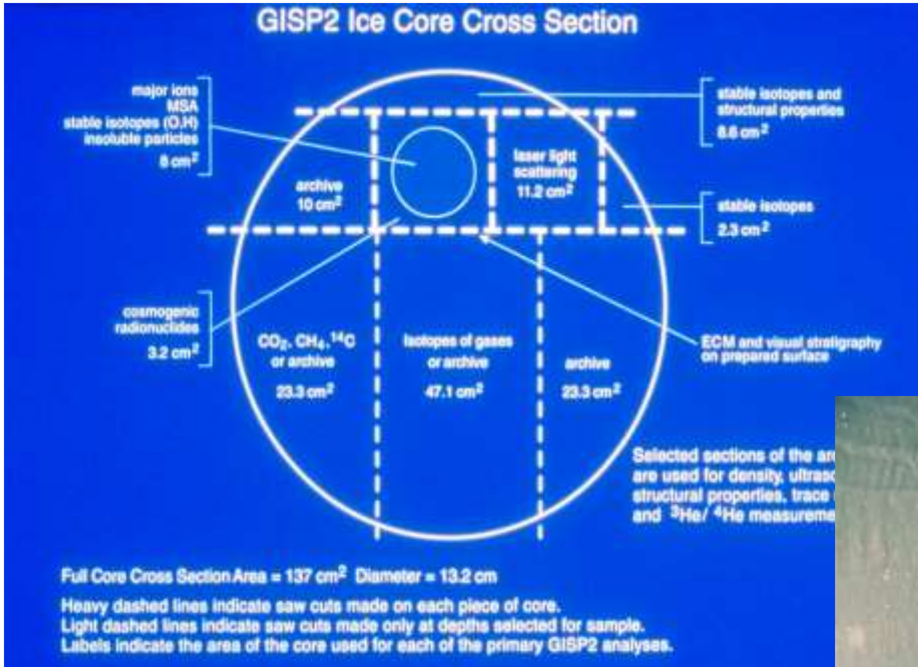


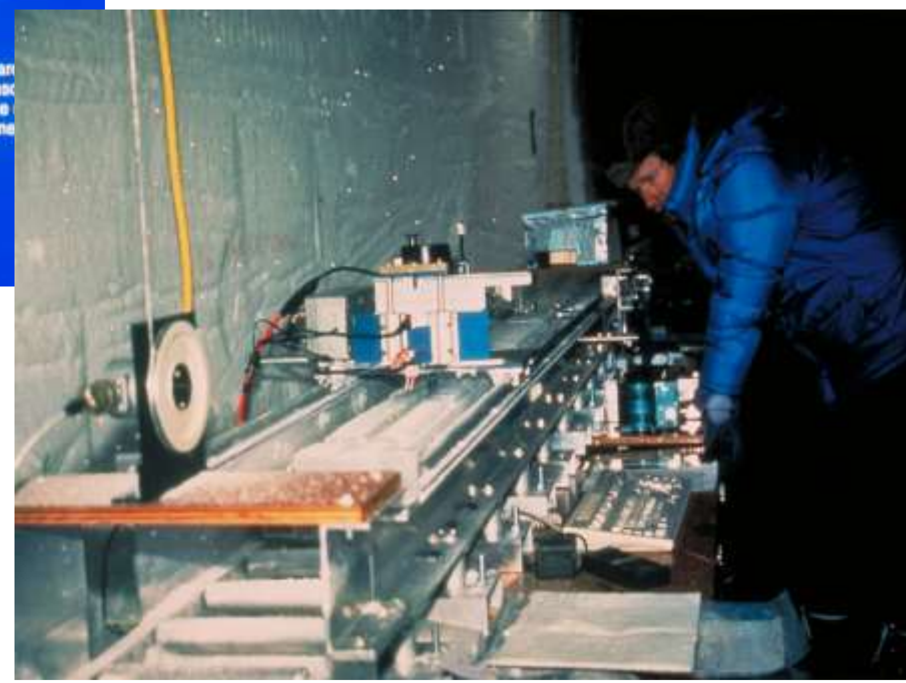


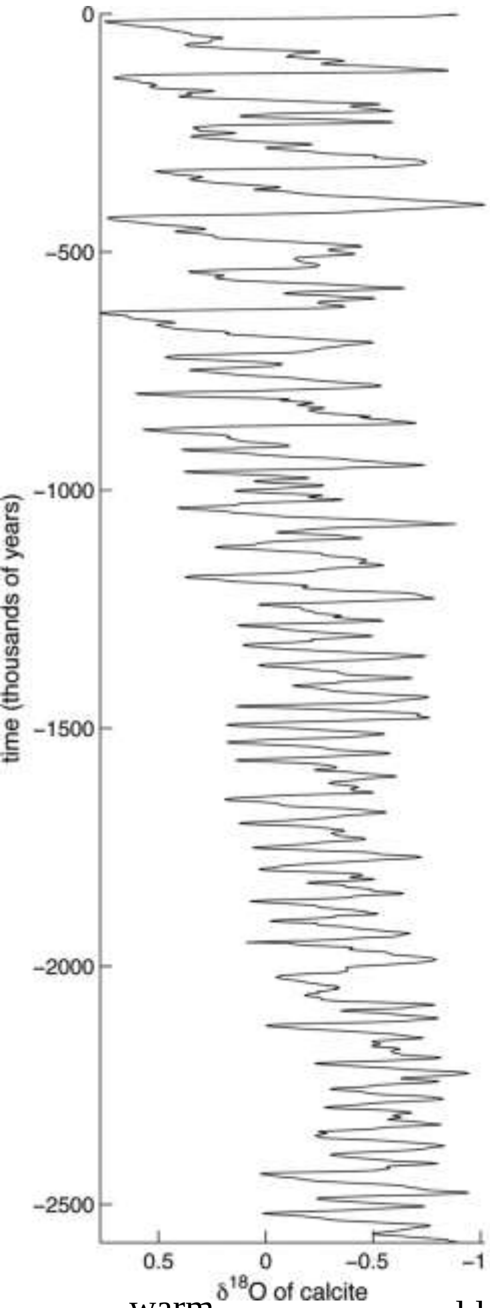


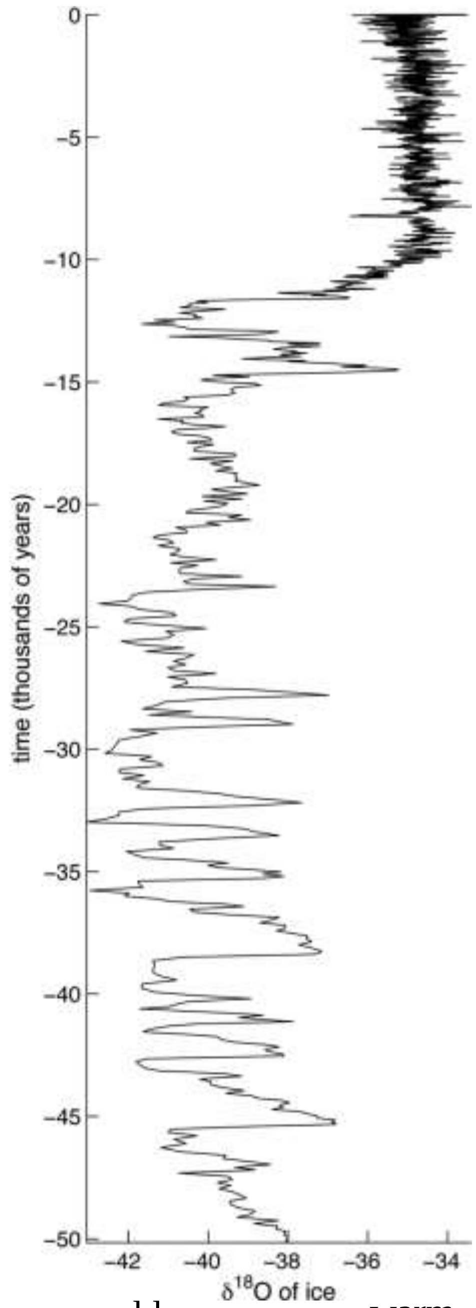
19 cm long section of GISP 2 ice core from 1855 m showing annual layer structure illuminated from below by a fiber optic source. Section contains 11 annual layers with summer layers (arrowed) sandwiched between darker winter layers.



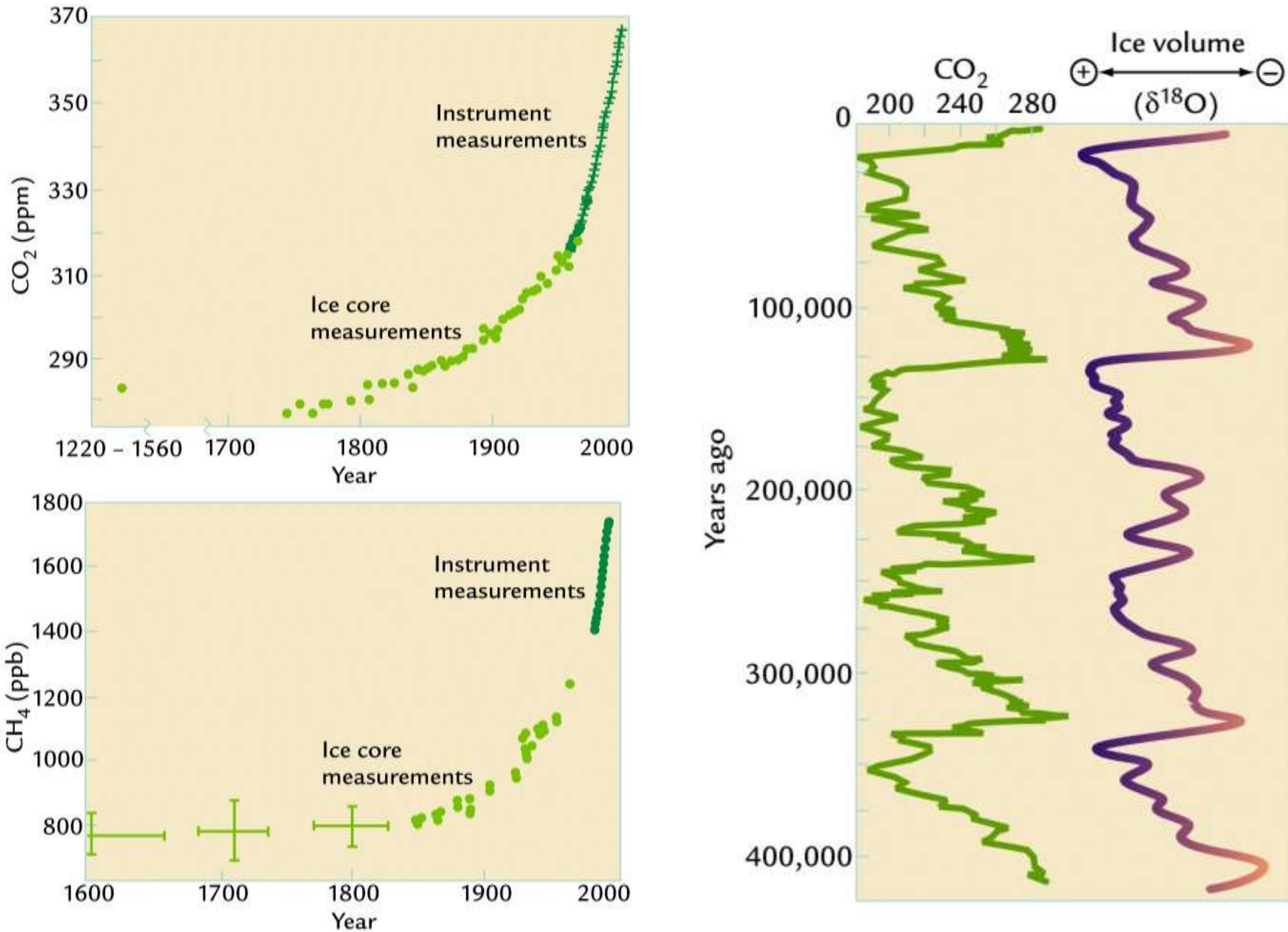

GISP2 Ice Core Cross Section
major ions
MSA
stable isotopes (O,H)
insoluble particles
8 cm²
archive
10 cm²
laser light
scattering
11.2 cm²
stable isotopes and
structural properties
8.6 cm²
stable isotopes
2.3 cm²
cosmogenic
radionuclides
3.2 cm²
CO₂, CH₄, ¹⁴C
or archive
23.3 cm²
isotopes of gases
or archive
47.1 cm²
archive
23.3 cm²
ECM and visual stratigraphy
on prepared surface
Full Core Cross Section Area = 137 cm² Diameter = 13.2 cm
Heavy dashed lines indicate saw cuts made on each piece of core.
Light dashed lines indicate saw cuts made only at depths selected for sample.
Labels indicate the area of the core used for each of the primary GISP2 analyses.



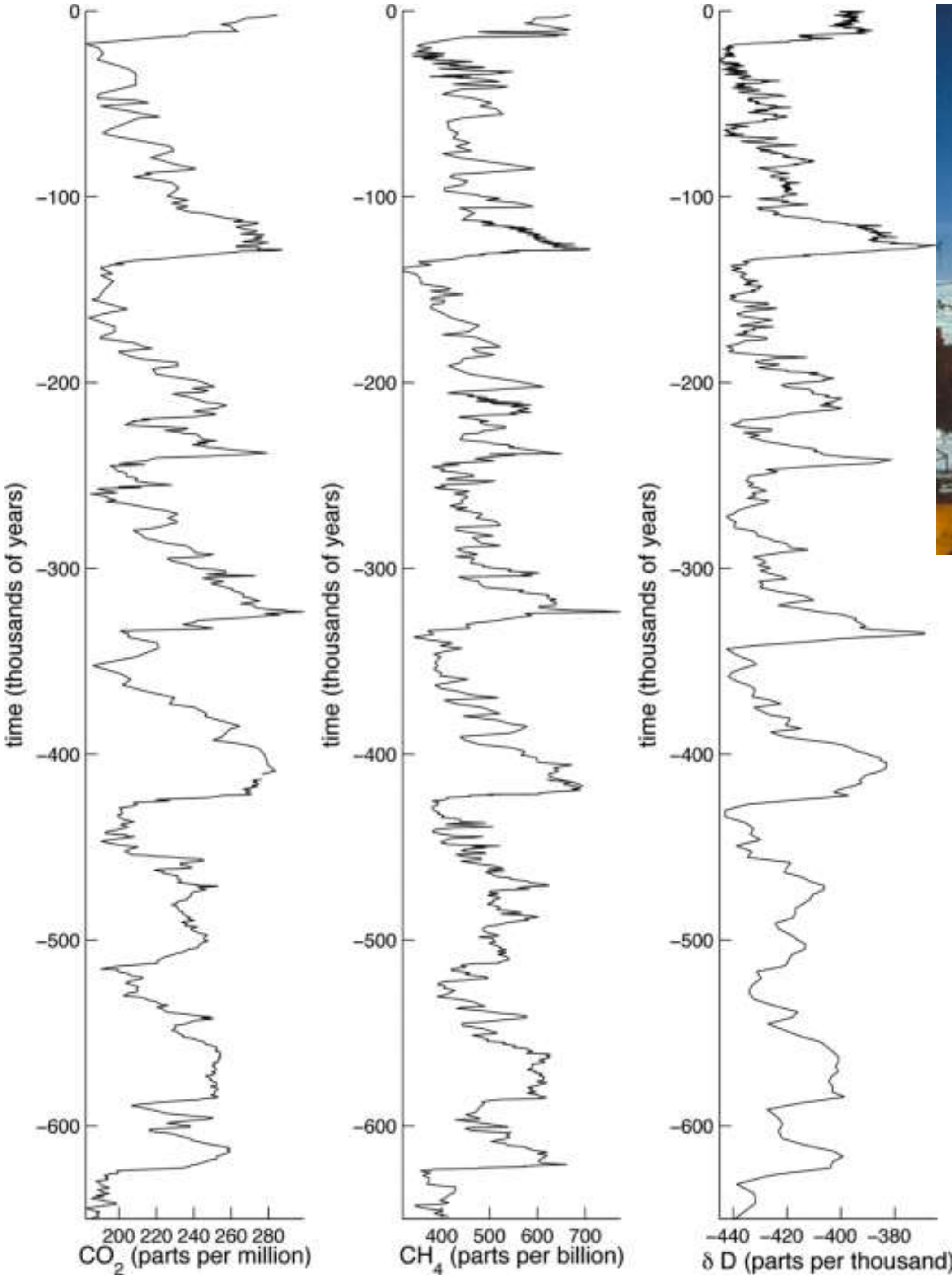




Left: δ18 O over the last 2.5 million years recorded in the calcite shells of bottom dwelling foraminifera. Shown is the average of tens of δ18 O records sampled from various marine sediment cores (Huybers, 2006). Values are reported as the anomaly from the average δ18 O over the past million years. **More negative** values (rightward) **indicate warmer temperatures** and **less ice volume**. Right: δ18 O of ice over the last 50 k y years measured in the **GISP2** ice-core (Grootes and Stuiver, 1997). In contrast to the δ18 O of marine shells, **less negative values in the δ18 O of ice indicate warmer** atmospheric temperatures, in this case in the vicinity of Greenland.



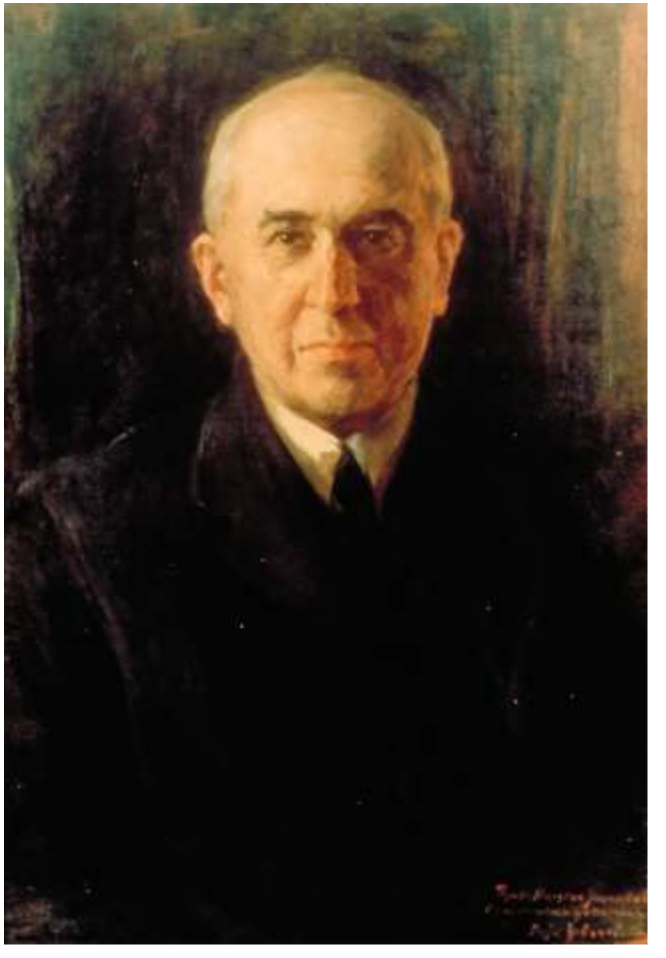
370
350
330
310
290
CO_2 (ppm)
Instrument measurements
Ice core measurements
1220 – 1560
1700
1800
1900
2000
Year
1800
1600
1400
1200
1000
800
CH_4 (ppb)
Instrument measurements
Ice core measurements
1600
1700
1800
1900
2000
Year
Ice volume
CO_2
200
240
280
($\delta^{18}O$)
0
100,000
200,000
300,000
400,000
Years ago

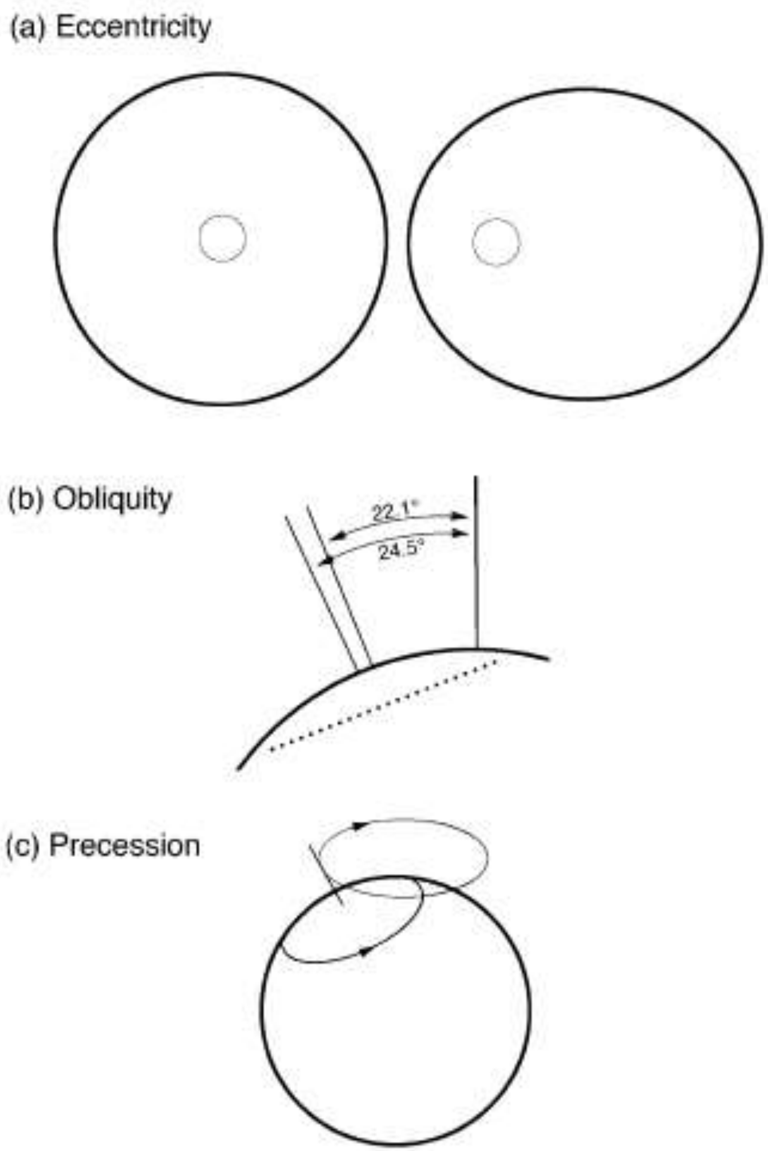


Ice-core records of atmospheric carbon dioxide (left) and methane (middle) concentrations obtained from bubbles trapped in Antarctic ice. Values to 400 k y ago are from Vostok), whereas earlier values are from EPICA Dome C. (right) δ D concentrations from EPICA Dome C measured in the ice, as opposed to the bubbles, are indicative of local air temperature variations, similar to δ18 O of ice measurements.

Milankovitch theory (1941)

- Glaciations are a function of variations in the Earth's orbital parameters and the resulting changes in the distribution of the solar radiation.
- The availability of continuous palaeoclimatic records from the ocean floor makes testing of this hypothesis possible.

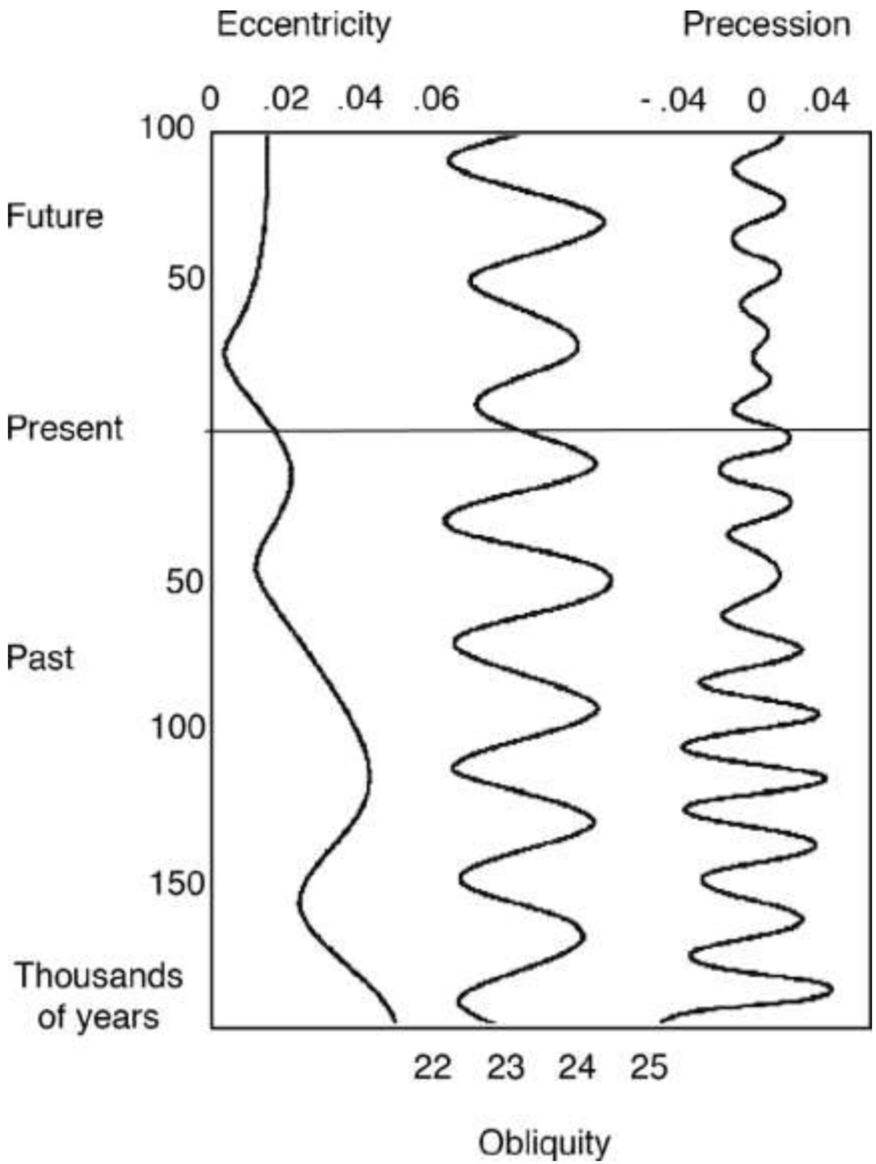




(a) The eccentricity of the Earth’s orbit varies on a 100k y & 400k y timescale from (almost) zero, a circle, to 0.07, a very slight ellipse. The ellipse shown on the right has an eccentricity of 0.5, vastly greater than that of Earth’s path around the Sun.

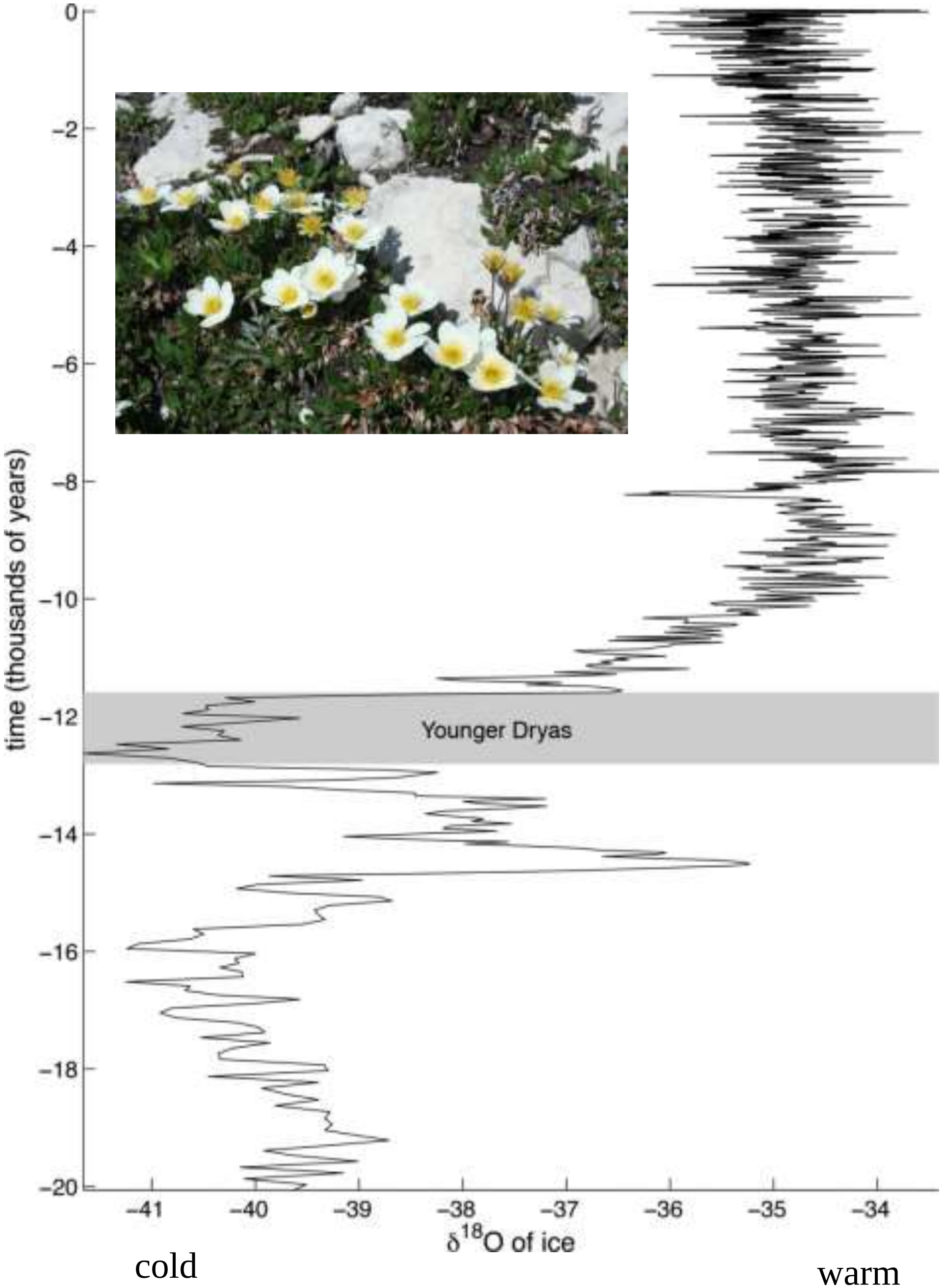
(b) The change in the tilt of the Earth’s spin axis—the obliquity—varies between $22.1^{\circ}$and 24.5° on a timescale of 41k ys. The tilt of the Earth is currently 23.5°.

(c) The direction of the Earth’s spin vector precesses with a period of 23k y.

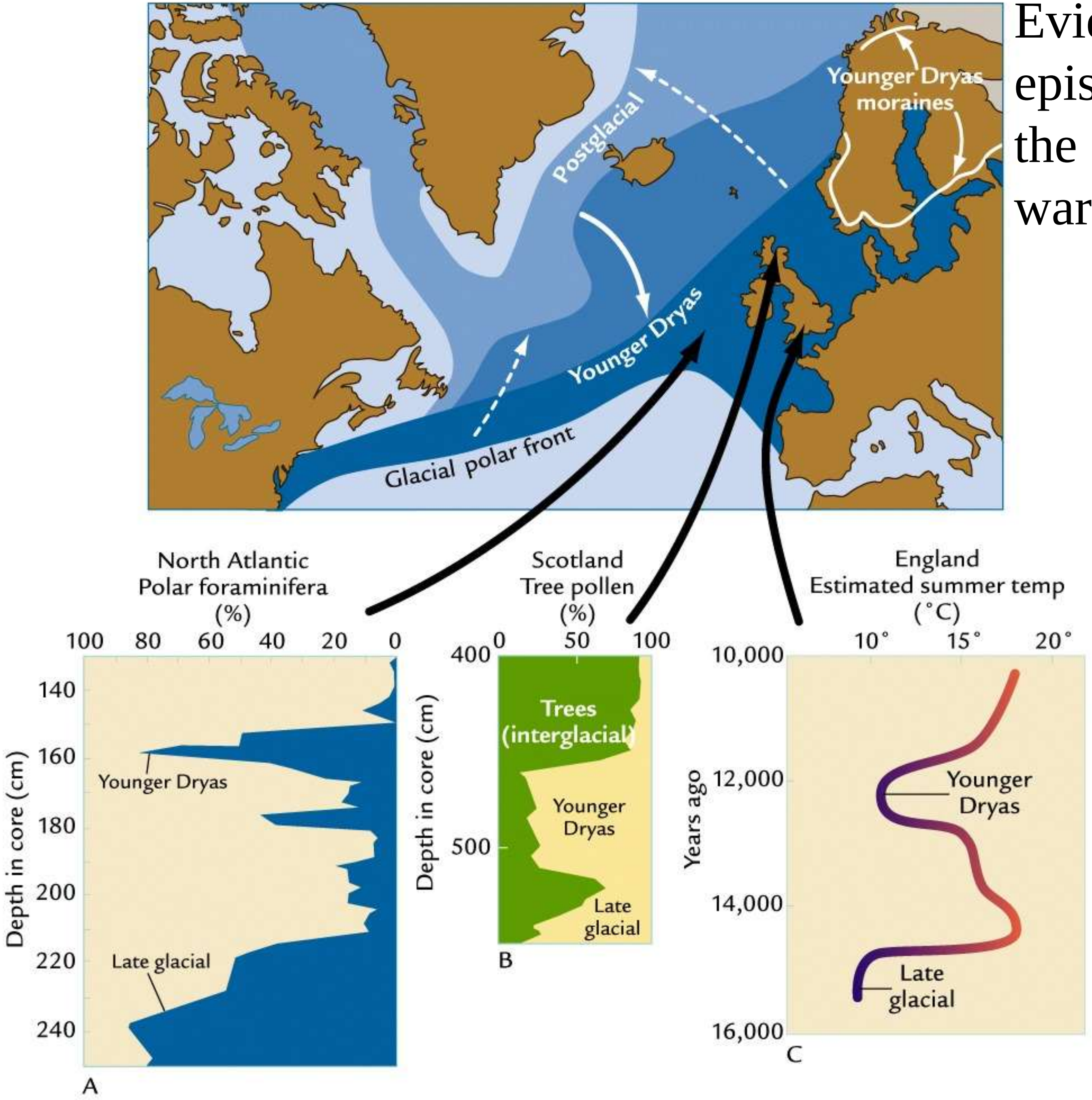


Variations in eccentricity, precession, and obliquity over 300k y, starting 200k y in the past, through the present day and 100k y in to the future. From Berger and Loutre, (1992).

Abrupt Climate Change



The transition from the Last Glacial Maximum to the relatively ice-free conditions of the Holocene took roughly ten thousand years. In certain regions this transition was punctuated by rapid climate variations having timescales of decades to millennia. Shown is the GISP2 ice-core (Grootes and Stuiver, 1997) with shading indicating the return to glacial-like conditions known as the **Younger Dryas**. The Younger Dryas is a prominent feature of many North Atlantic and European climate records and its presence can be detected in climate records across much of the Northern Hemisphere.



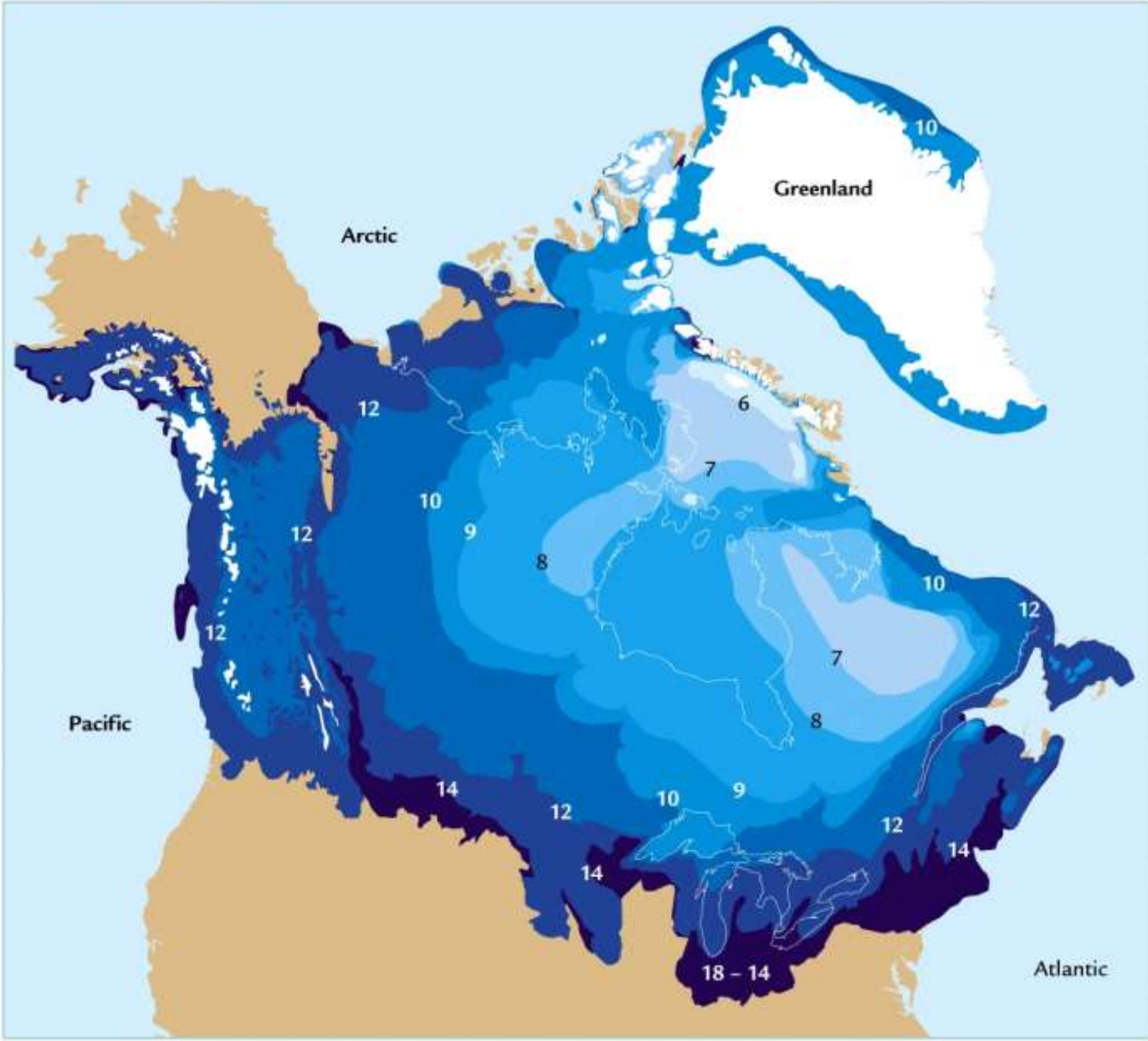
Evidence of a cold episode that interrupted the general deglaciation warming:

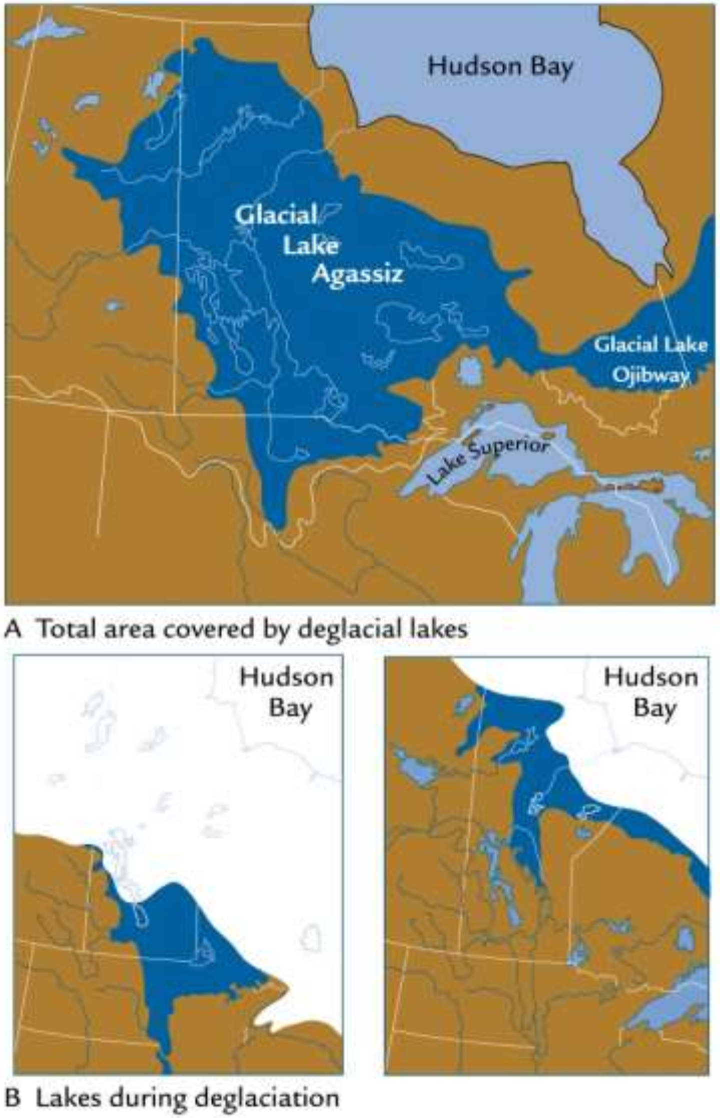
(A) Southward return of cold polar water in the N-Atlantic

(B) Reversal toward Arctic vegetation in Europe (Dryas)

(c) cooler continental temperatures indicated by fossil insects

Retreat of the N-American ice sheet during deglaciation

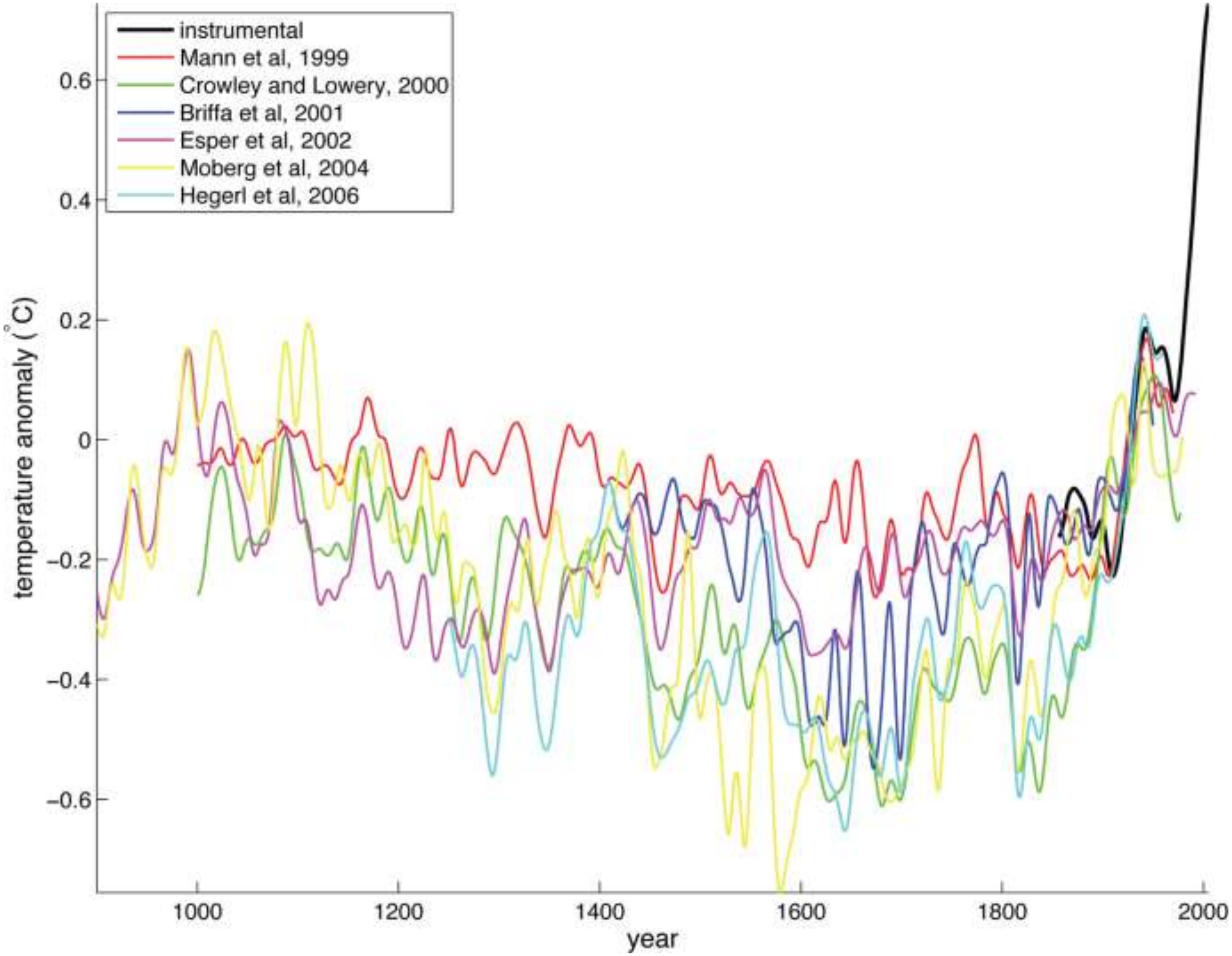




Formation of proglacial lakes in morphological depressions

Routes of meltwater flow:

During the deglaciation the main water flow changed from southward to the Golf of Mexico to the north into the Arctic Ocean late in the deglaciation



The spread between the reconstructions indicates a lower-bound on the uncertainty in these estimates. All records have been smoothed using a 20-year running average and adjusted to have zero-mean between 1900 and 1960.

Estimates of Northern Hemisphere surface air temperature during the last 1100 years. Temperatures obtained from instruments (Jones and Moberg, 2003) are shown in black. Colored curves indicate different proxy reconstructions of temperature. Proxies, such as tree rings, ice cores, and corals, are necessary for estimating temperature before widespread instrumental coverage, before about 1850.