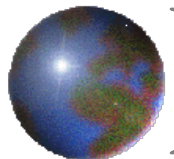


Paleoclimatology

Anna Klene

Department of Geography

University of Montana



3 Objectives

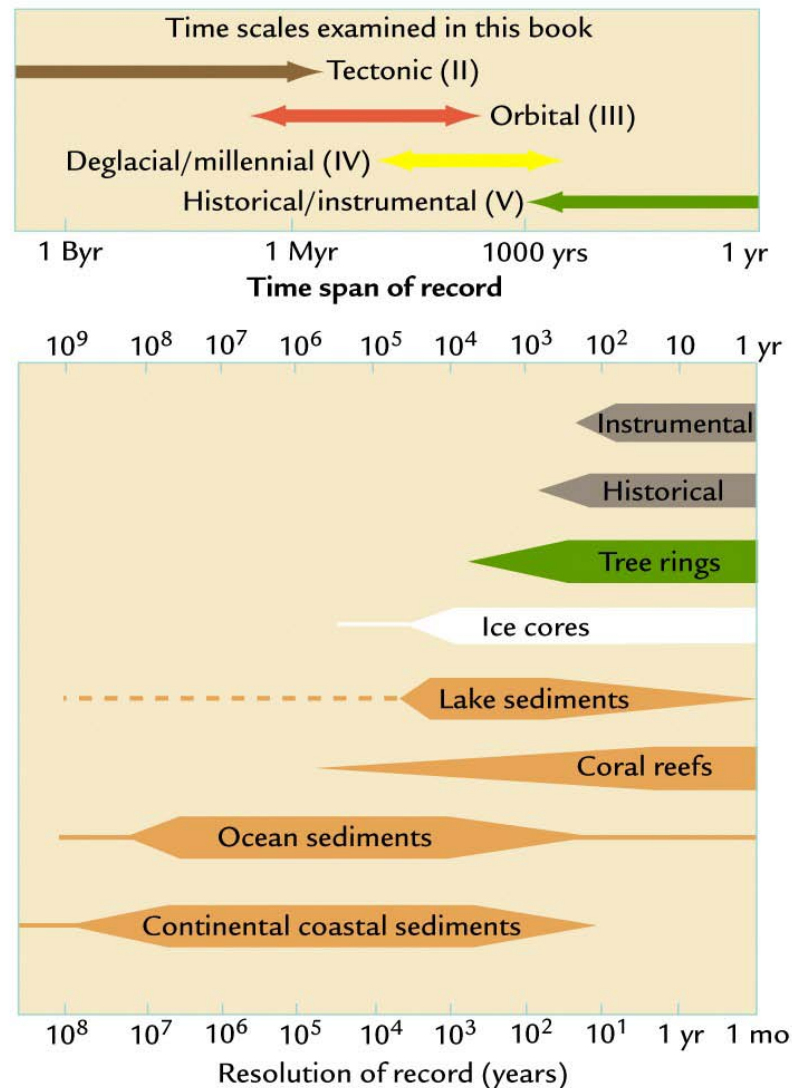
- Discuss climate archives
 - ▣ Piecing the puzzle together

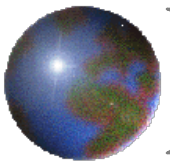
- Discuss key climate events using these different archives
 - ▣ Current understanding of atm evolution

- Review key time periods of interest to current warming



Time scales for Proxy Data





Archives of Climate Change:

Geological

Biological: Fossils & Pollen

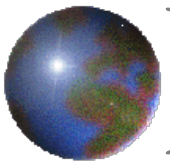
Cryological: Ice Cores

Historical

Biological: Tree-Rings

Instrumental Records

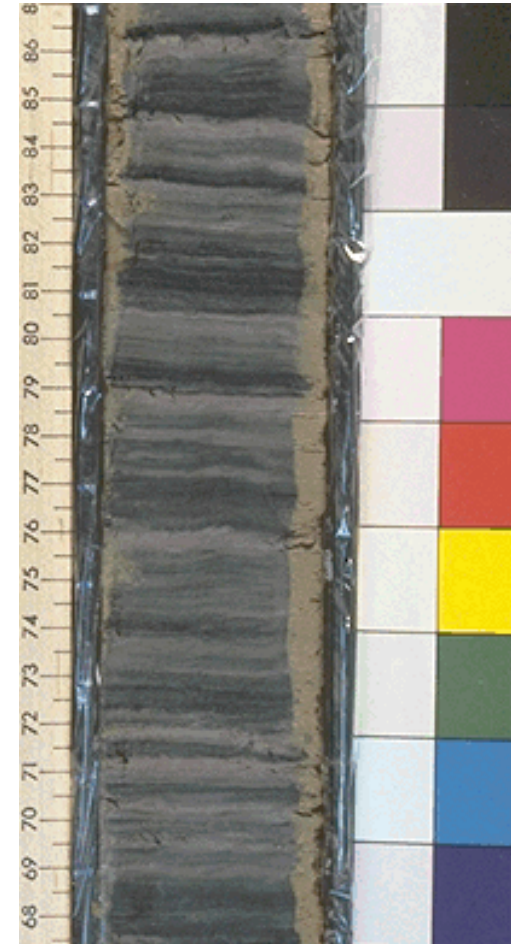
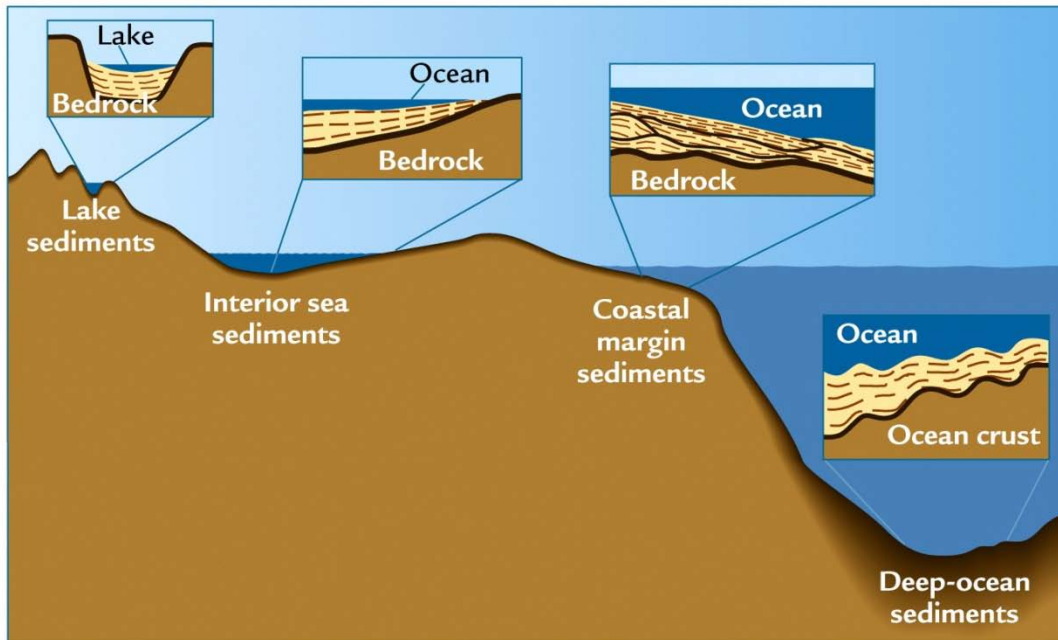
- Proxy: Using one thing in place of another...
- Always better if 2 different, independent proxies agree 😊

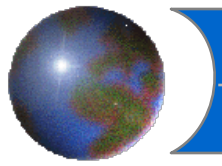


Archives of Climate Change:

Geological

- Sediment structures & material (loess)
- Glacial moraines
- Lake sediments
- Coastal & Deep Ocean sediments





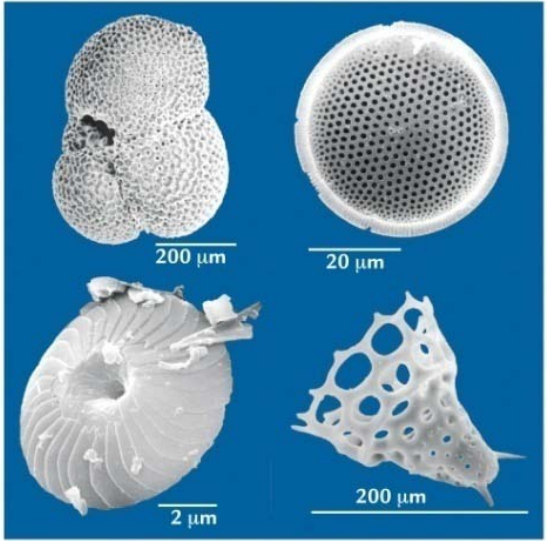
Archives:

Biological

Fossils or dead material

Trees

Critters (macro: mammals, beetles, etc.
& micro: corals, plankton, forminifera, etc.)

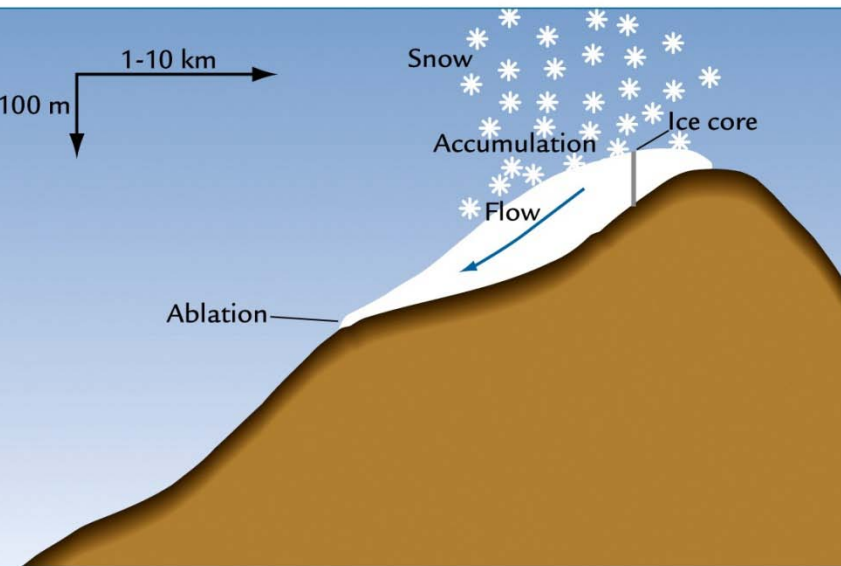




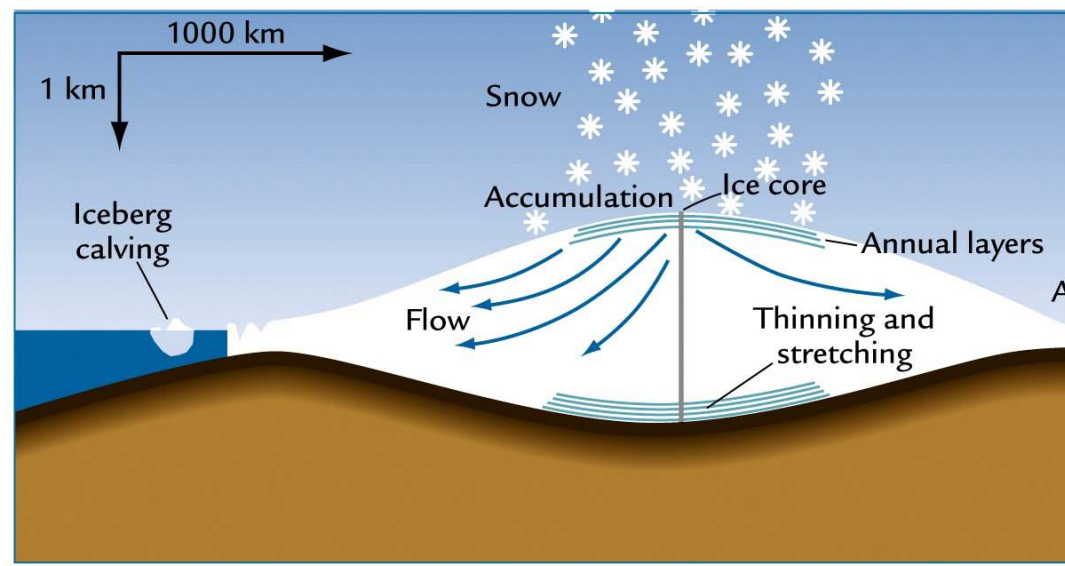
Archives of Climate Change:

Cryological

Glaciers & Ice Caps



A Mountain glaciers



B

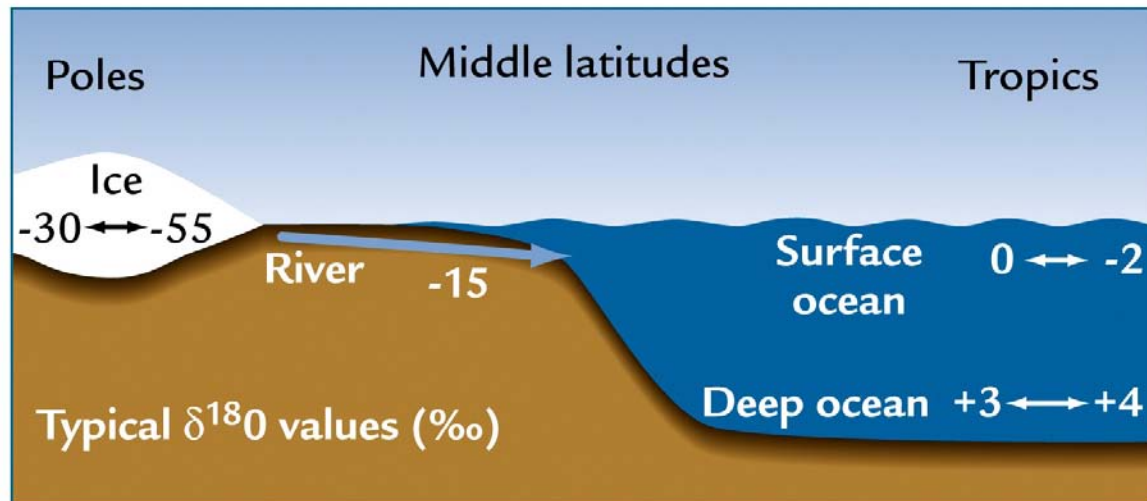
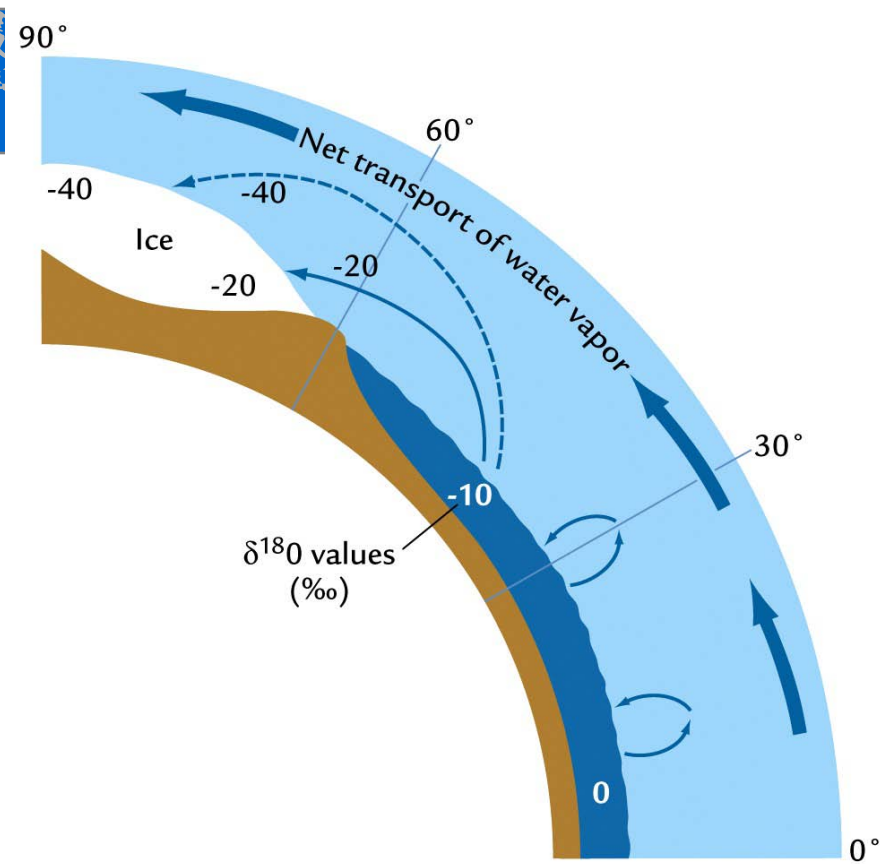
Continental ice sheets

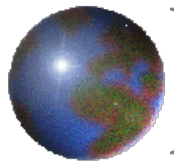


Ice & Sediment Cores

Oxygen-isotope analysis:

- ❑ $\delta^{18}\text{O}$
- ❑ Measure ratio of ^{16}O to ^{18}O
- ❑ Water from ocean enriched in 18 as 16 evaporates better...
- ❑ When glaciers advance, more 16 frozen, so even more 18 in water...

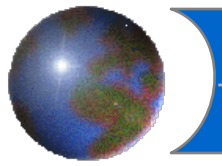




Ice Cores & Sediment Cores

- deuterium/hydrogen ratio:
 - ❑ $\delta D\text{‰}$
 - ❑ Measure ratio of ^2H to ^1H ...
 - ❑ Deuterium is heavier than normal Hydrogen, so it takes more energy to evaporate any water molecule made with “heavy hydrogen”.
 - ❑ The result is that the colder it gets, the less Deuterium ends up in precipitation.
 - ❑ The smaller the D/H ratio, the colder the climate.



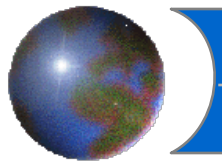


Ice Cores

● Ice cores:

- ❑ volcanic ash
- ❑ particulates (dust),
- ❑ pollen,
- ❑ chemical composition of the air trapped inside,
- ❑ etc..



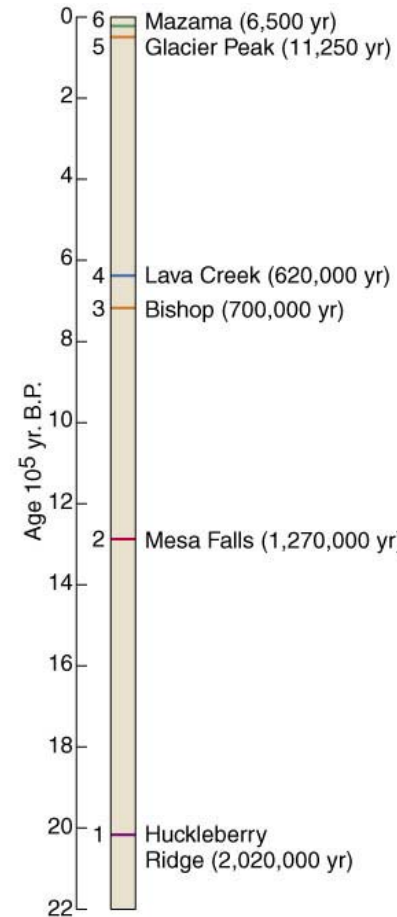


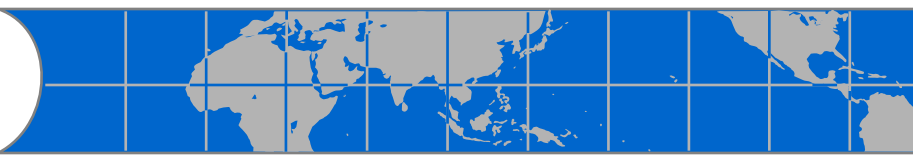
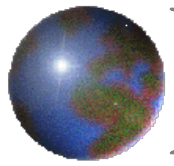
Archives

- Volcanic Ash
- Source by chemical signature
- Provides a calibration layer across variety of deposits



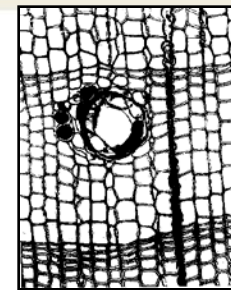
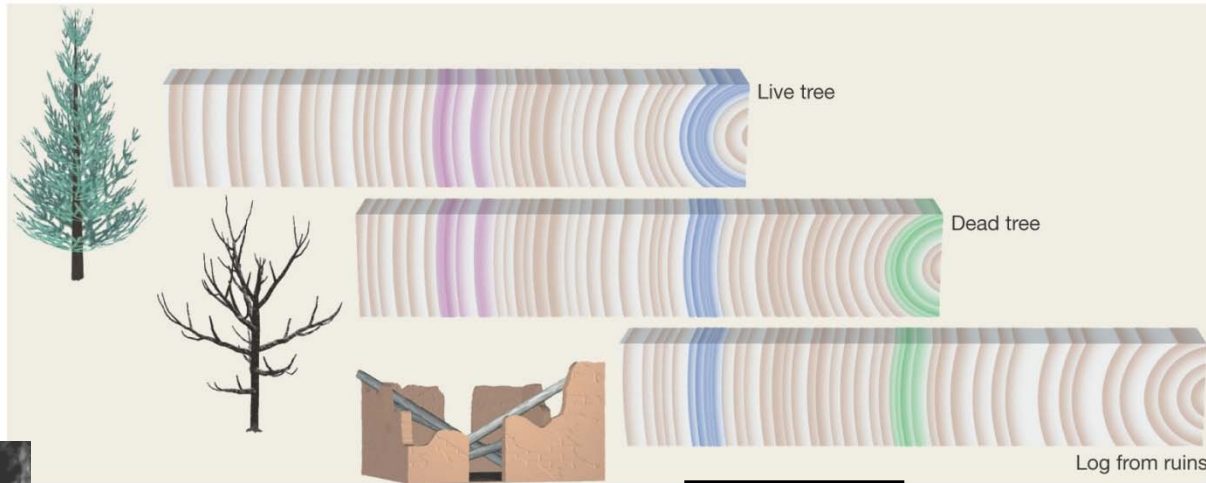
● Source volcanoes or calderas





Tree-rings:

- Annual layers of growth
 - ❖ Depends on temp, precip, evapotrans.
 - ❖ Varies from species to species





Archives of Climate Change:

Historical Records

Letters, Diaries, Other Records

- ***Hunters in the Snow*, 1565**
Pieter Bruegel the Elder
(Netherlandish, ca. 1525/30—1569)
Oil on panel; 46 1/8 x 63 7/8 in. (117 x
162 cm)

Image courtesy of the Kunsthistorisches
Museum, Vienna

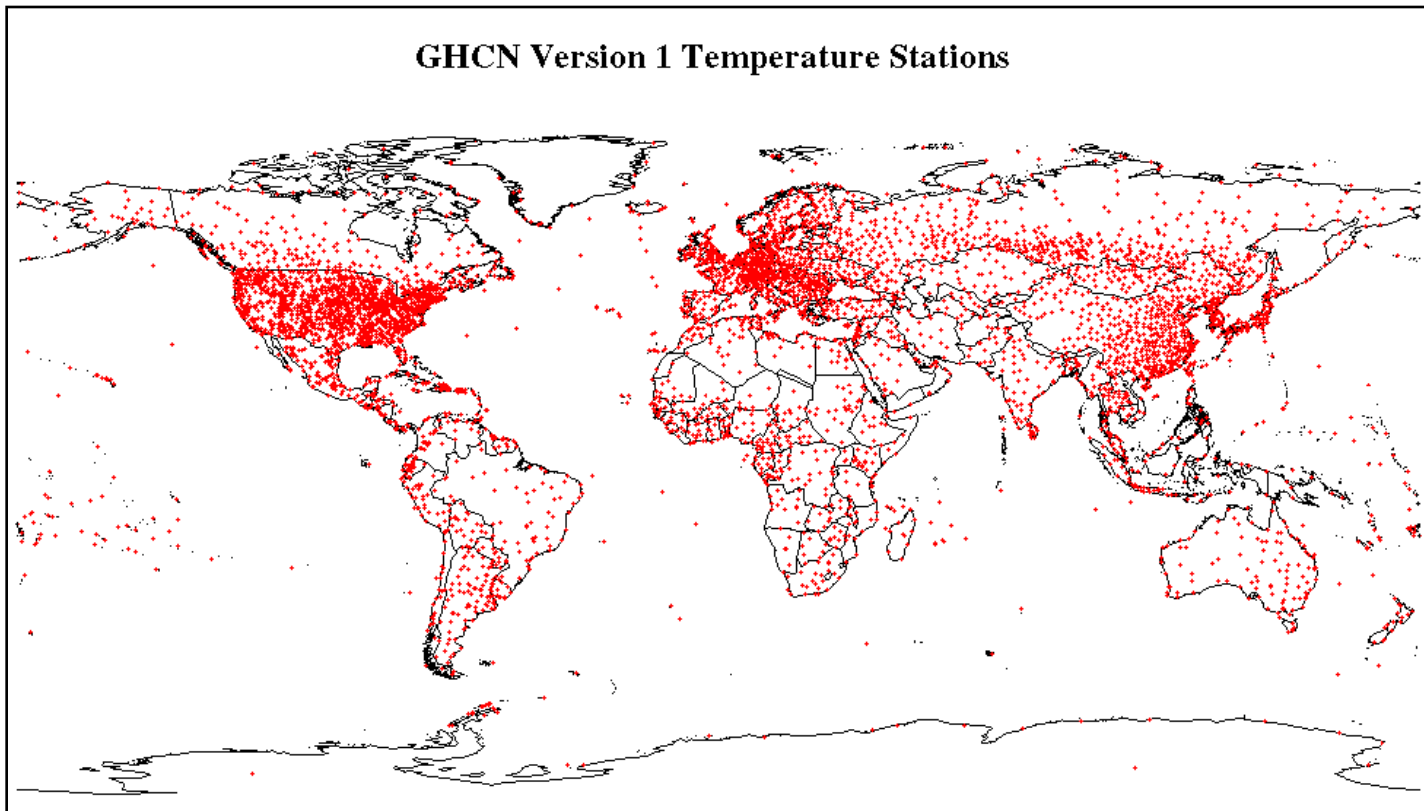


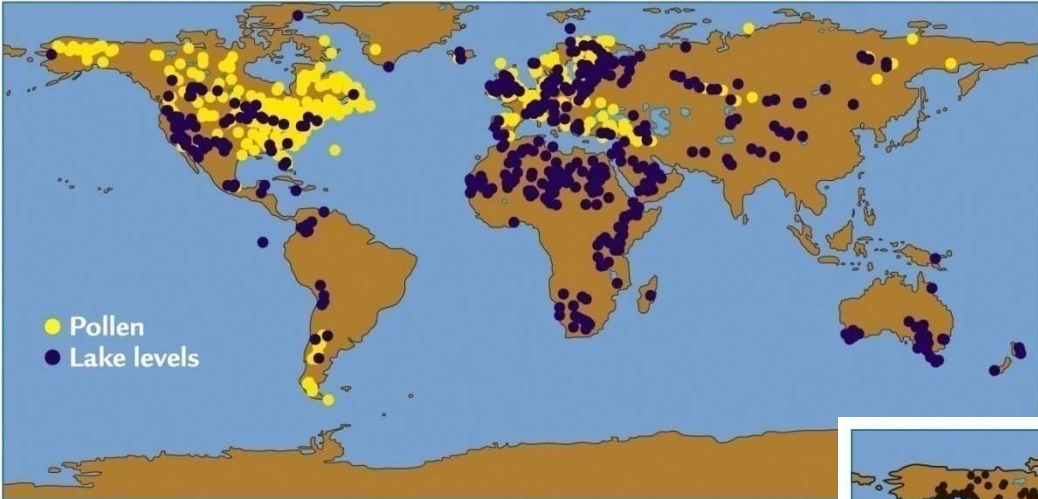


Archives of Climate Change:

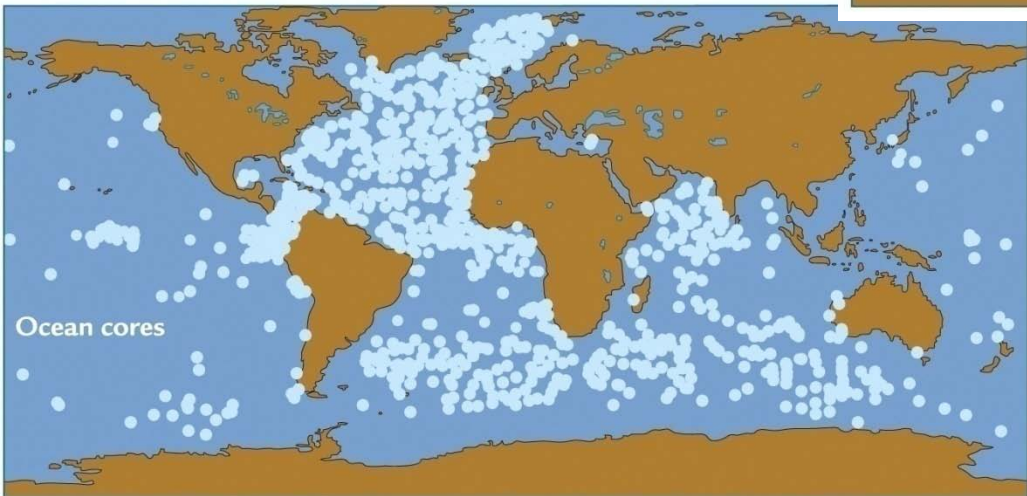
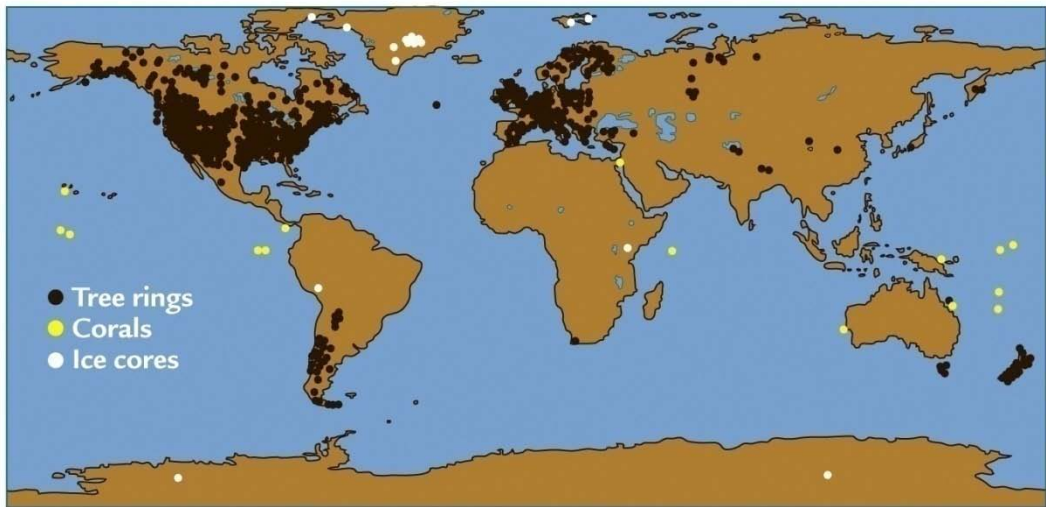
Instrumental Records

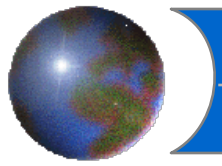
Only within last ~200 years





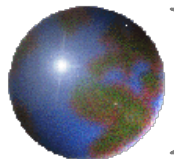
● Location, location, location!





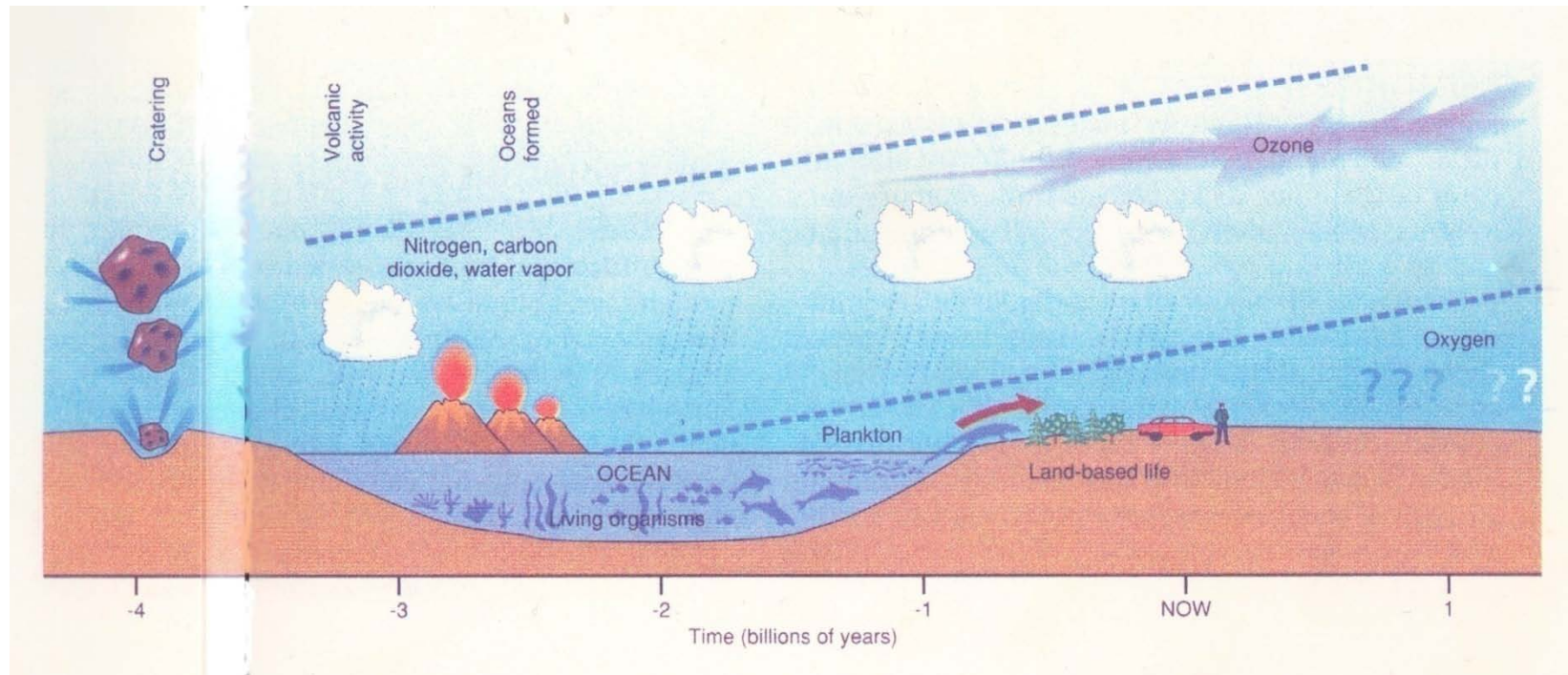
Earth's Evolution

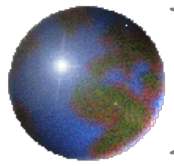
- ~4+ BYA: All blown away
 - ~4: Magnetic field forms & atm held in place – no O₂
 - ~3.8: Out-gassing continues but liquid earth possible as planet cools below 100 C
 - ~3.5 BYA: First life forms release O₂
 - ~500 MYA: O₂ levels high enough for ozone layer & plants & animals can now colonize land
- **All from geological evidence!!**



Earth's Primordial Atmosphere

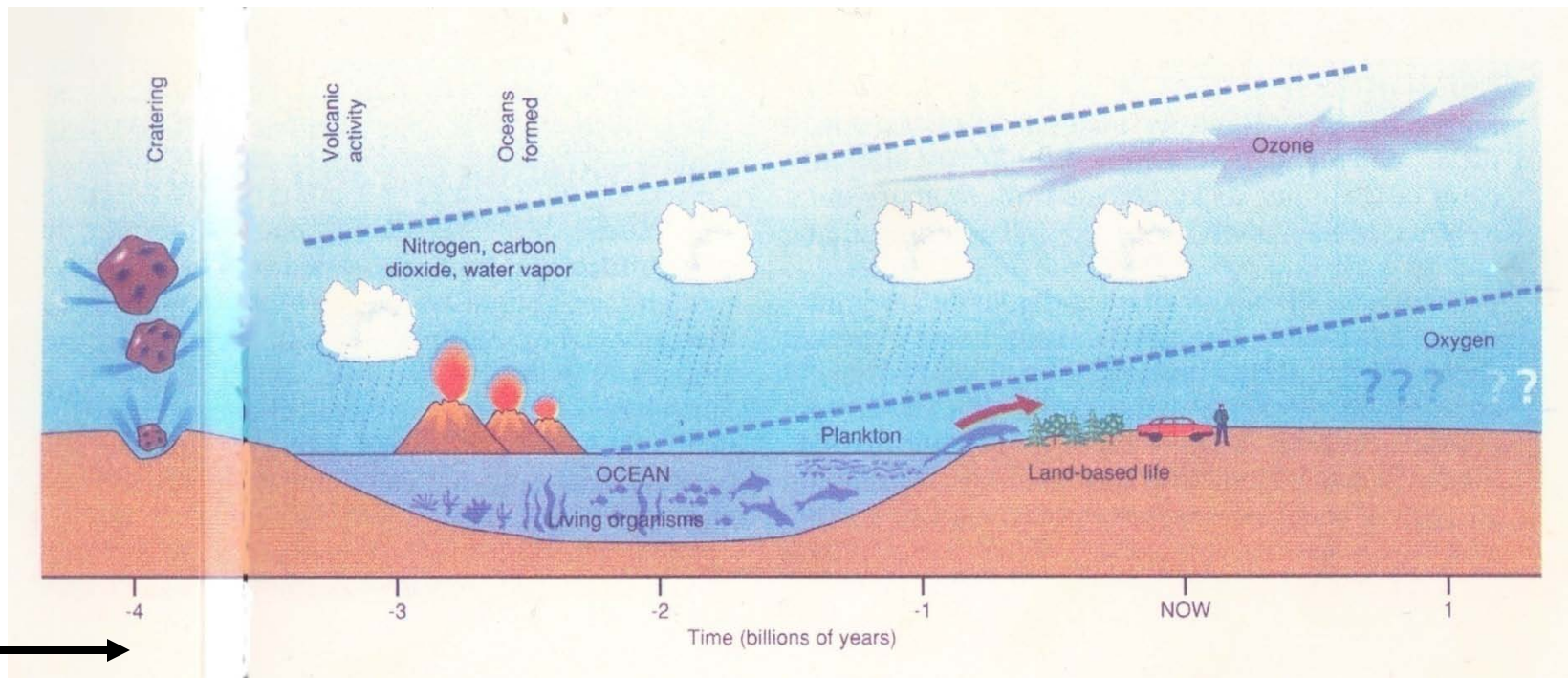
- 4+ billion years ago (Y.A.)
- Consisted of gases most abundant in solar system, hydrogen and helium (lightest elements)
- Mainly blown away

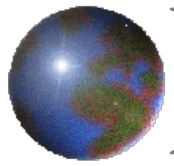




Earth's Primordial Atmosphere

- 4+ Billion Y.A.
- Begins build up once magnetic field developed
- Consists of CO_2 , NO^* , H_2O



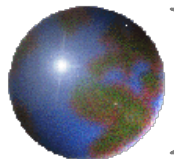


Stromatolites

Photosynthesis

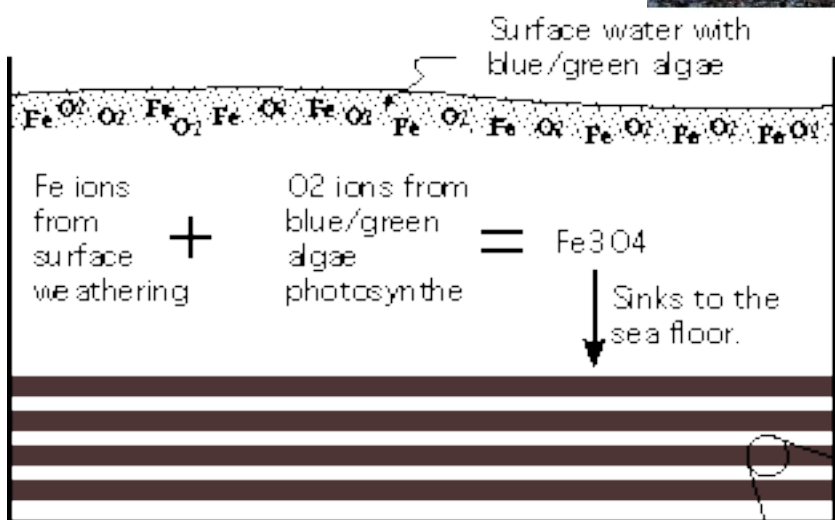
- $\text{CO}_2 + \text{H}_2\text{O} + \text{light} \rightarrow \text{CH}_2\text{O} + \text{O}_2$
- Cyanobacteria (Eubacteria) aka blue-green algae, appear ~ 3.5 bya
 - ◆ Release O_2 as byproduct
- Accumulation of O_2 in the atmosphere didn't start until oceanic Fe_2^+ was oxidized (~2 bya).





Banded Iron Formations

- Water with O₂ (from blue-green algae) & Fe from surface weathering.
- Get deposits (iron-rich layer) This cleans algae's environment.
- Too much algae, produce too much O₂, not enough Fe to remove it...
- O₂ toxic to algae, population collapse... (get white layer)



After combining the Fe and O₂ ions into Magnetite (Fe₃O₄), the mineral grains sink to the sea floor, where they accumulate into iron-rich and iron-poor layers.



The red bands are hematite, and are interbedded with chert.

In an ideal setting, you would expect the magnetite-rich layers to exhibit a reversed graded bedding. Looking from the bottom up, this would involve a slow transition into the magnetite-rich layers, representing slowly increasing O₂ levels in the upper sea water in response to the increasing population of blue/green algae. The upper contact of each magnetite-rich layer would be relatively abrupt, reflecting the sudden extinction of the population due to O₂ poisoning, and the resulting loss of available O₂ in the water to combine with the iron ions.



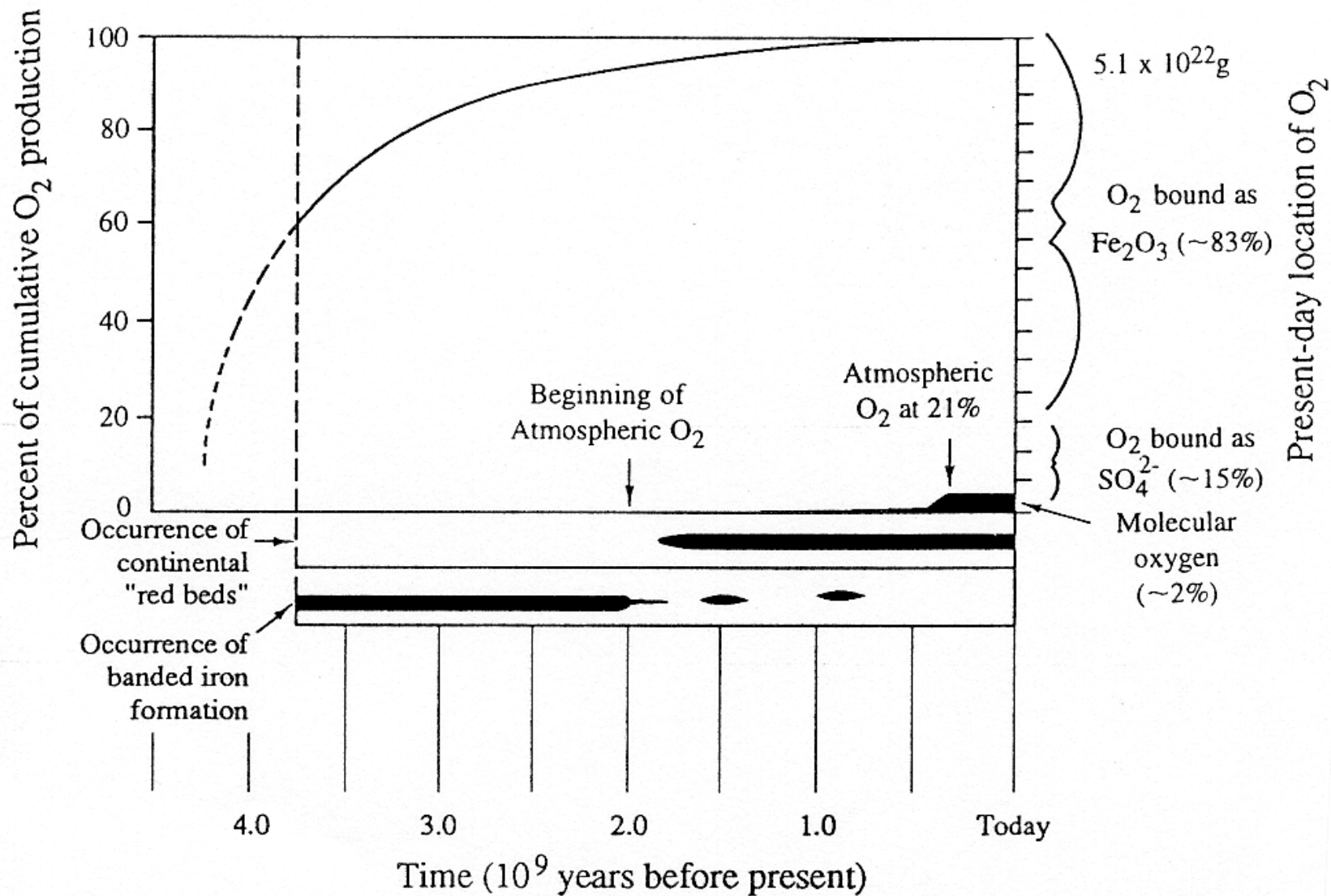


Figure 2.7 Cumulative history of O₂ released by photosynthesis through geologic time. Of more than 5.1×10^{22} g of O₂ released, about 98% is contained in seawater and sedimentary rocks, beginning with the occurrence of Banded Iron Formations at least 3.5 billion years ago (bya). Although O₂ was released to the atmosphere beginning about 2.0 bya, it was consumed in terrestrial weathering processes to form Red Beds, so that the accumulation of O₂ to present levels in the atmosphere was delayed to 400 mya. Modified from Schidlowski (1980).



Core from the Permian red beds that underlie the High Plains aquifer in southwestern Kansas and the Oklahoma panhandle

Red Beds

- ~1.8 BYA once all iron in ocean reacted with O_2 , it could build up in the atmosphere, leading to the oxidation of iron on exposed surface.
- This Fe_2O_3 is seen in geological formations called Continental Red Beds
- Only after the surface iron reacted could O_2 then build up in the atmosphere



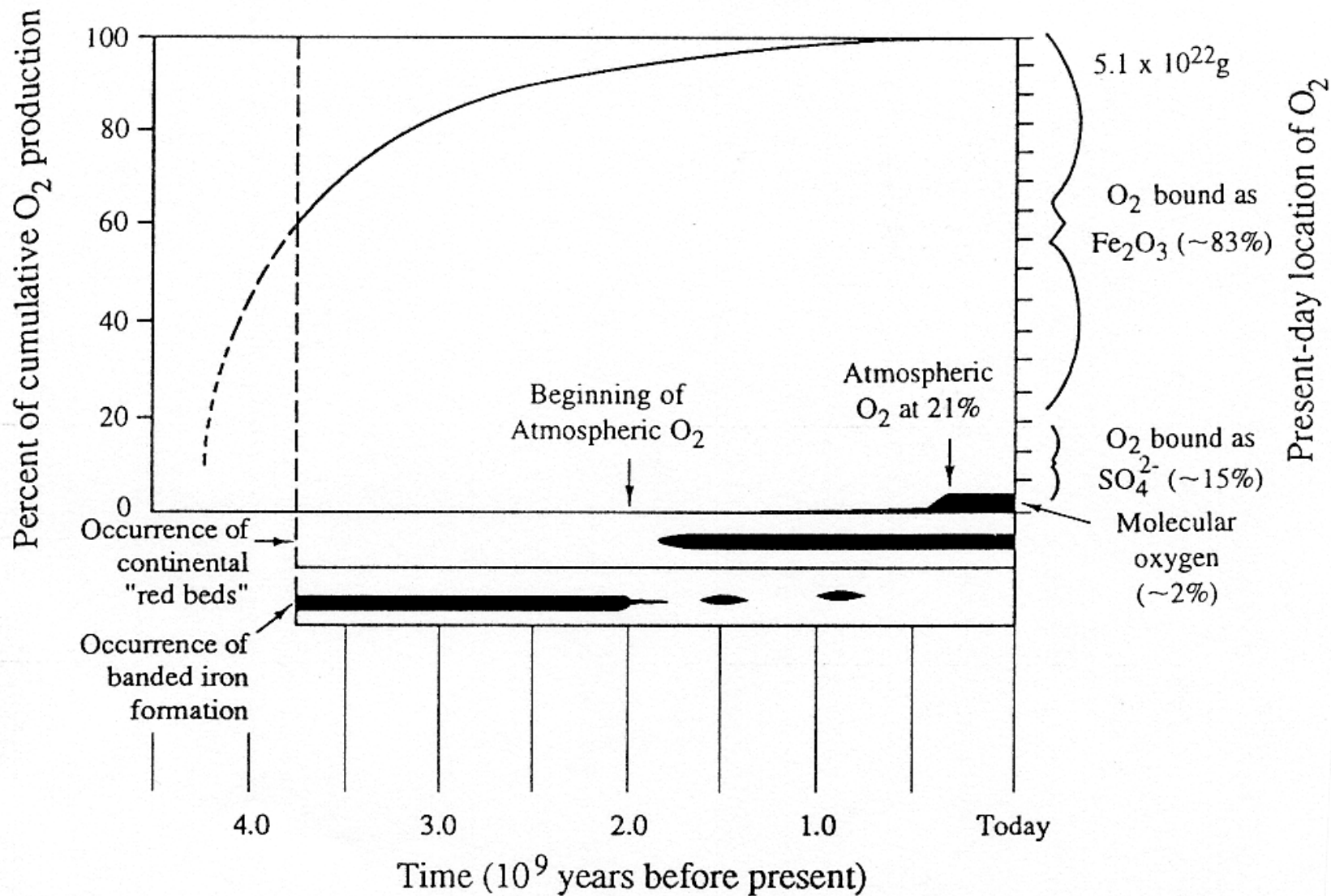
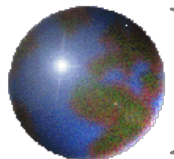
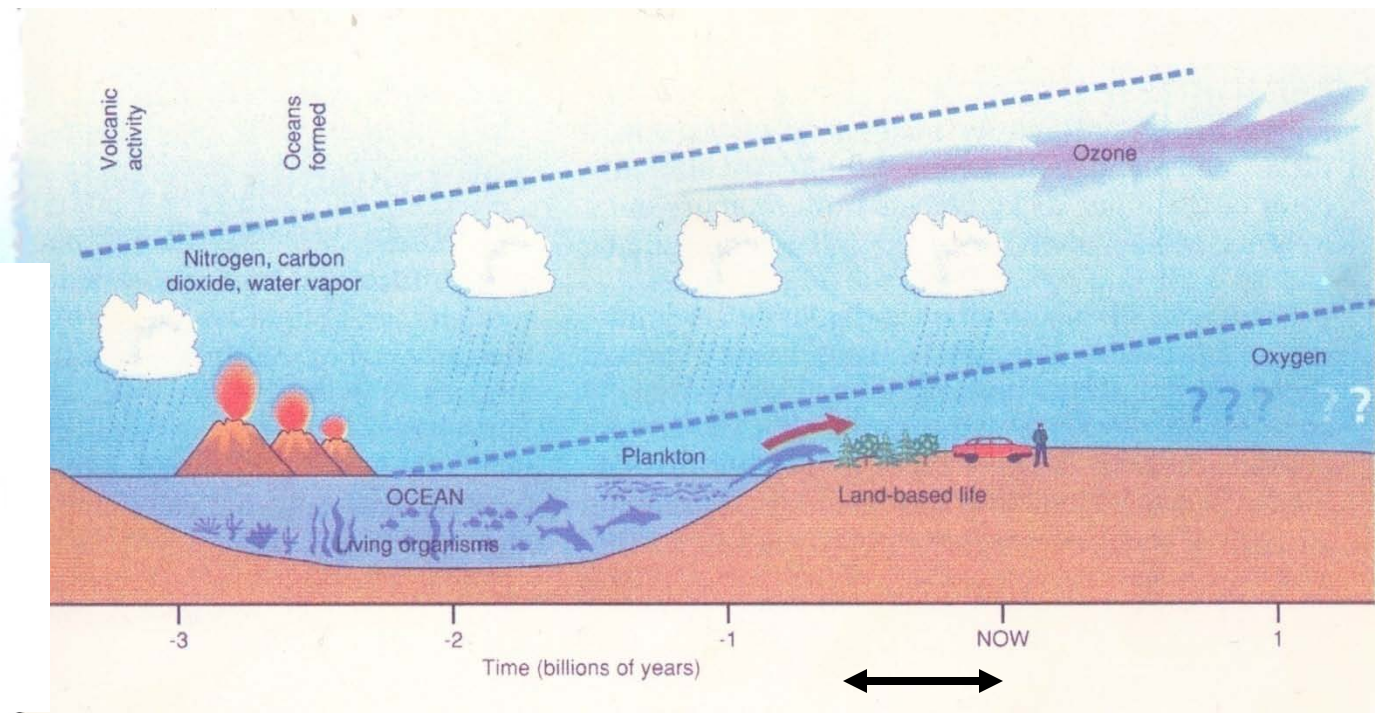
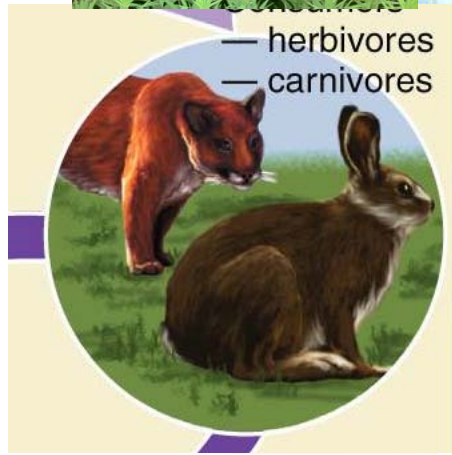


Figure 2.7 Cumulative history of O₂ released by photosynthesis through geologic time. Of more than 5.1×10^{22} g of O₂ released, about 98% is contained in seawater and sedimentary rocks, beginning with the occurrence of Banded Iron Formations at least 3.5 billion years ago (bya). Although O₂ was released to the atmosphere beginning about 2.0 bya, it was consumed in terrestrial weathering processes to form Red Beds, so that the accumulation of O₂ to present levels in the atmosphere was delayed to 400 mya. Modified from Schidlowski (1980).



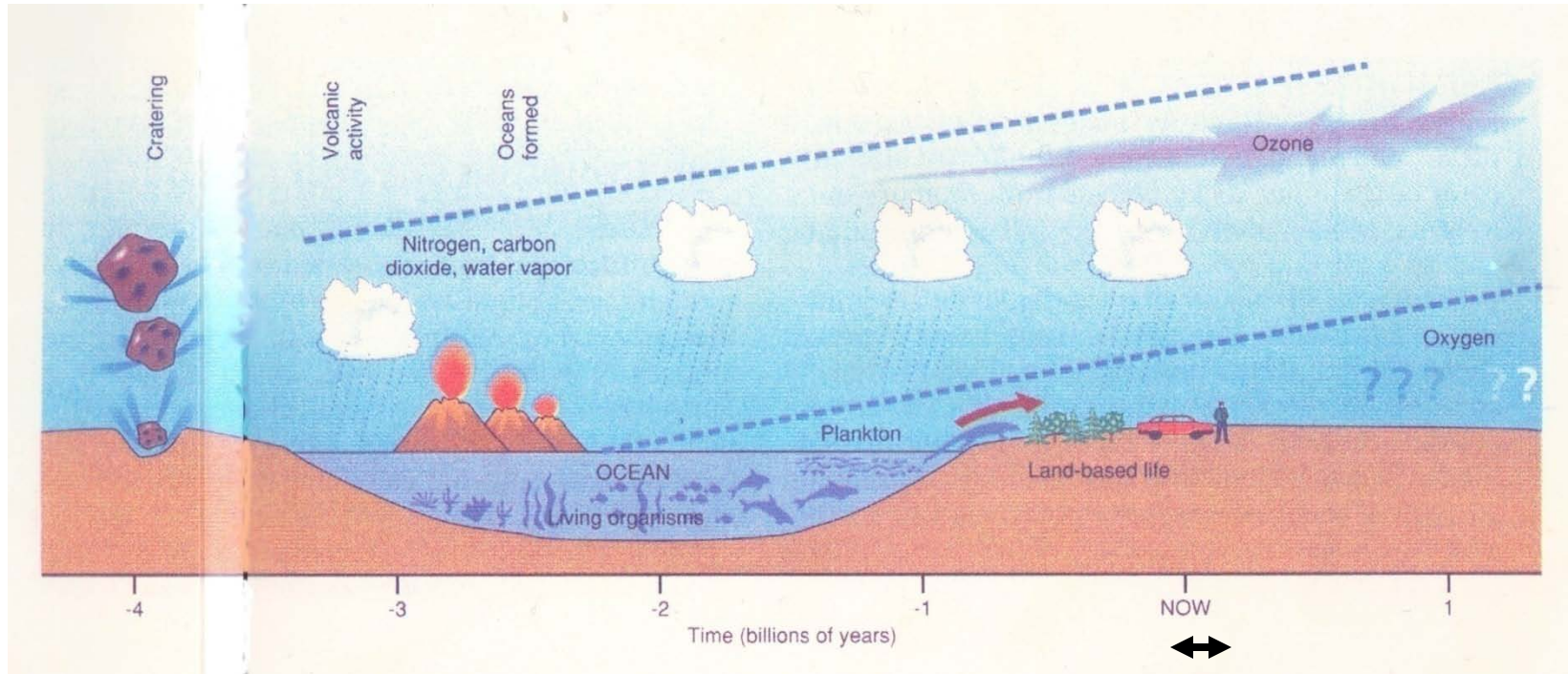
Earth's Modern Atmosphere

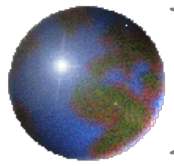
- 500 MYA enough O₂ that O₃ layer began
- That protects green plants to colonize land



Atmospheric Composition

- The release of O_2 by photosynthesis is probably the most significant effect of life on the geochemistry of the Earth.....until man!



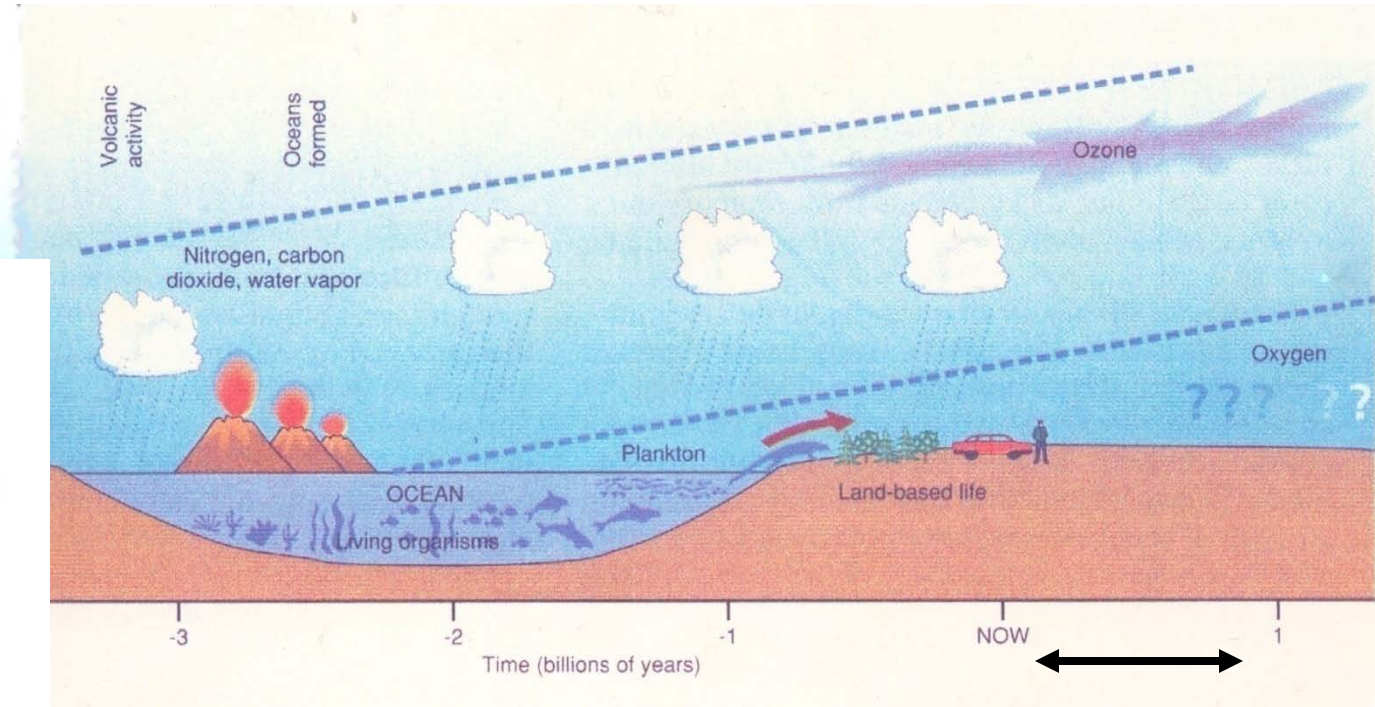


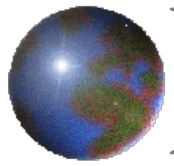
Earth's Modern Atmosphere

- Just 2% of all O₂ released over 3.8 BY is in atm.
- Now, a balance between O₂ producers and users??

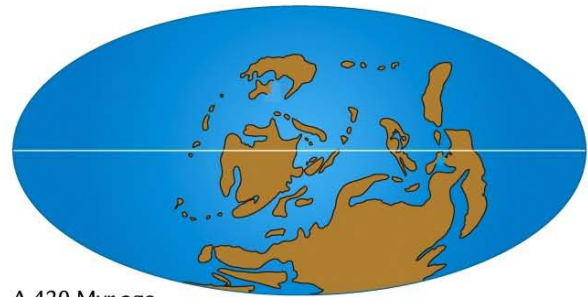


— herbivores
— carnivores

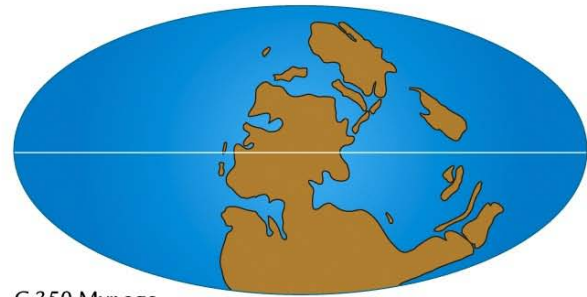




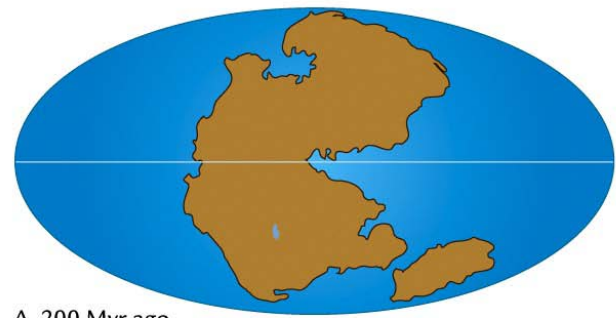
The last 500 MYA or so...



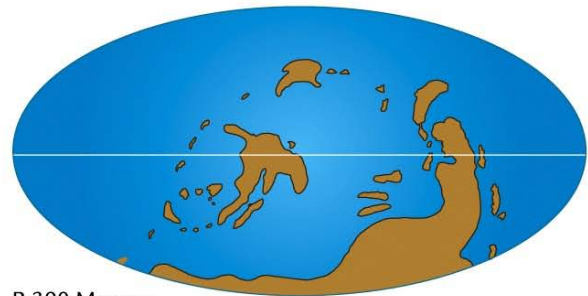
A 420 Myr ago



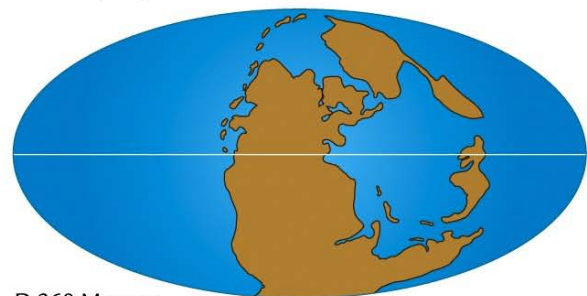
C 350 Myr ago



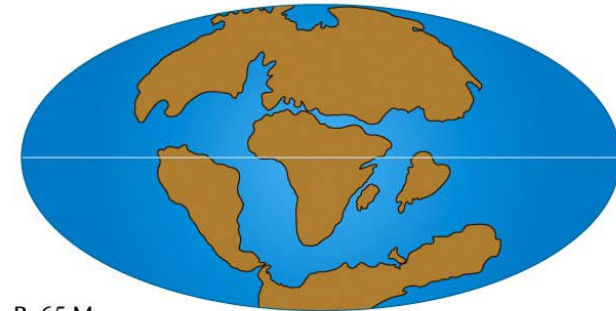
A 200 Myr ago



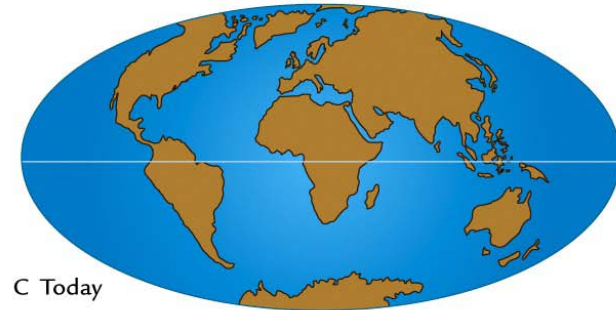
B 390 Myr ago



D 260 Myr ago

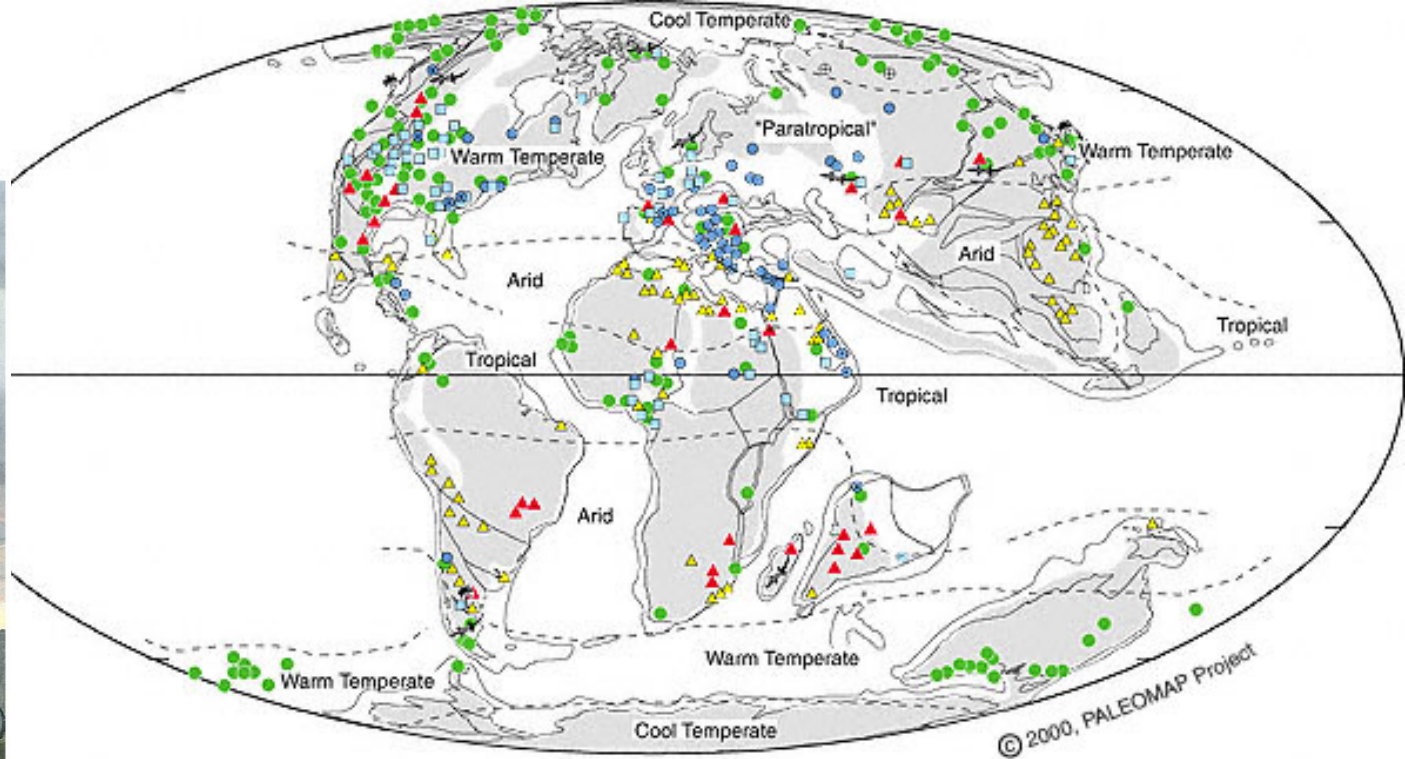
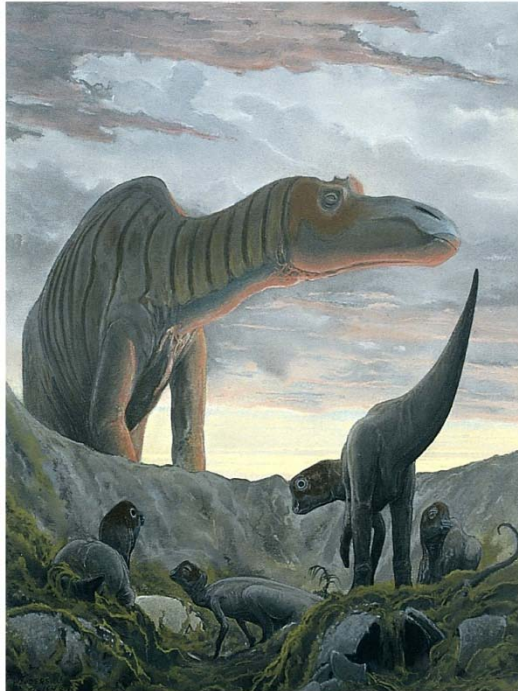


B 65 Myr ago



C Today

Fossils



Upper Cretaceous

LEGEND

	WARM	COOL
WET	<i>Tropical</i> ● Coal ● Bauxite ● Laterite	<i>Cool Temperate</i> ● Coal & Tillites
	<i>Warm Temperate</i> ■ Kaolinite (& coal & evaporite) 🌴 Crocodiles 🐊 🌴 Palms & Mangroves 🌴	
	DRY	<i>Arid</i> ▲ Evaporite ▲ Calcrete

"Paratropical" = High Latitude Bauxites

- Cretaceous (100 million ya):
+15 C warmer than now
– Sea level 200 m higher

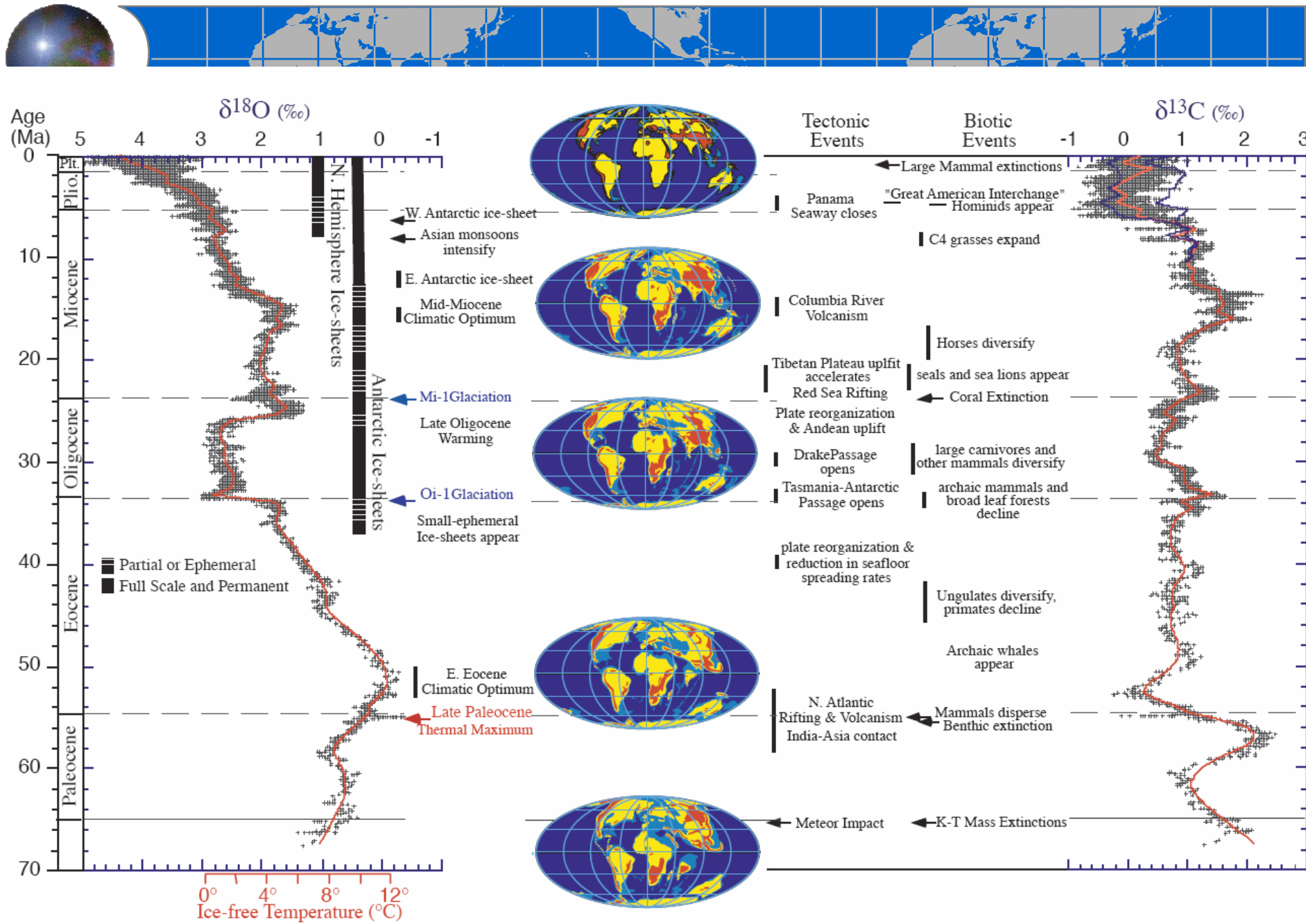
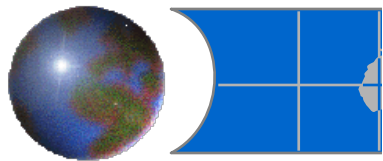
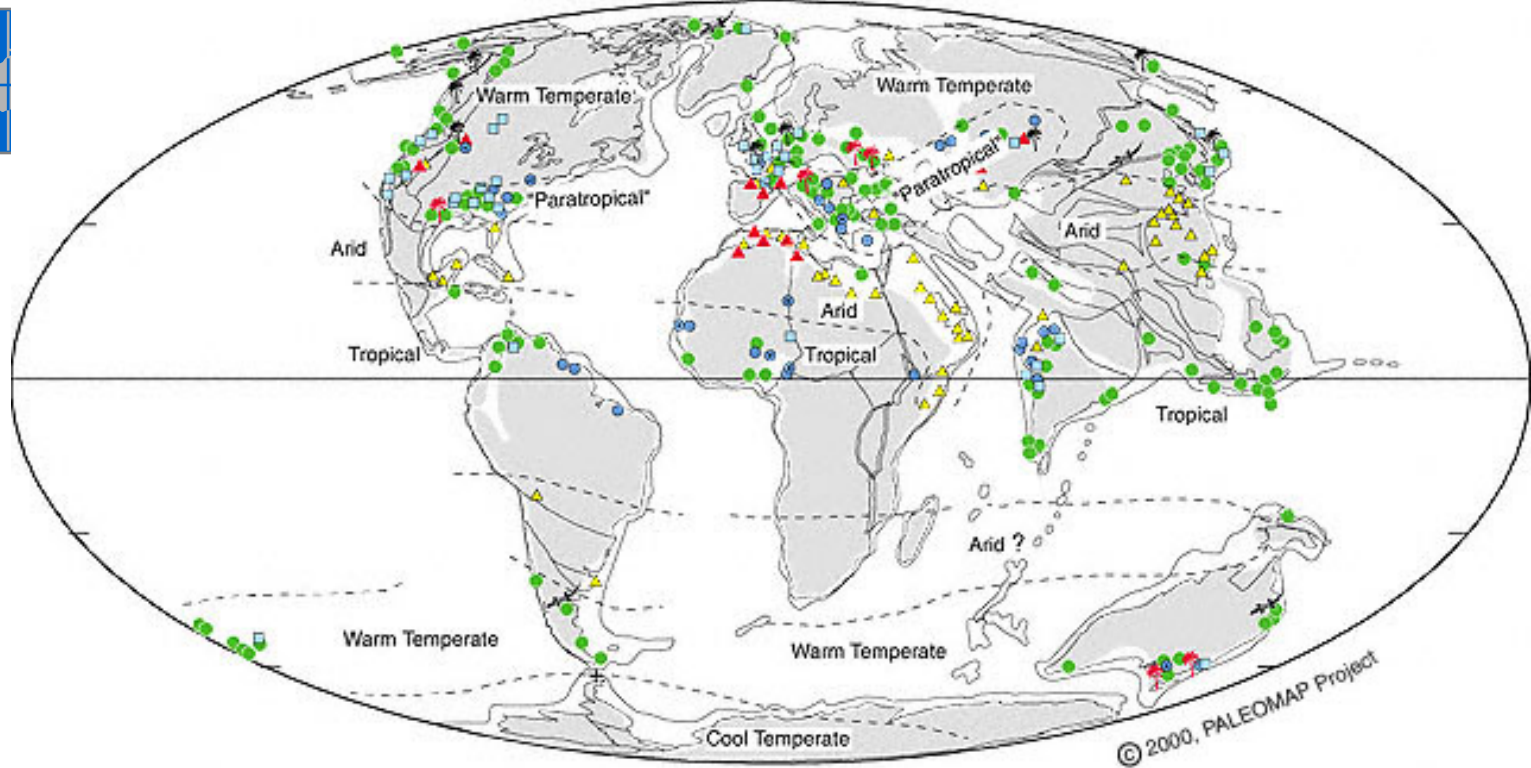


Figure 1. Global deep-sea oxygen and carbon isotope records based on data compiled from more than 40 DSDP and ODP Sites (Zachos et al., 2001). The



Fossils



Lower Eocene

LEGEND

	WARM	COOL	
WET	<i>Tropical</i> ● Coal ● Bauxite ● Laterite	<i>Cool Temperate</i> ● Coal & Tillites	
	<i>Warm Temperate</i> ■ Kaolinite (& coal & evaporite) 🌴 Crocodiles 🐊 🌴 Palms & Mangroves 🌴		
	DRY	<i>Arid</i> ▲ Evaporite ▲ Calcrete	<i>Cold</i> + Tillite ⊕ Dropstone ● Glendonite

"Paratropical" = High Latitude Bauxites

- Early Eocene (55 million ya):
+7 C warmer than now
- Spike may have been a methane release

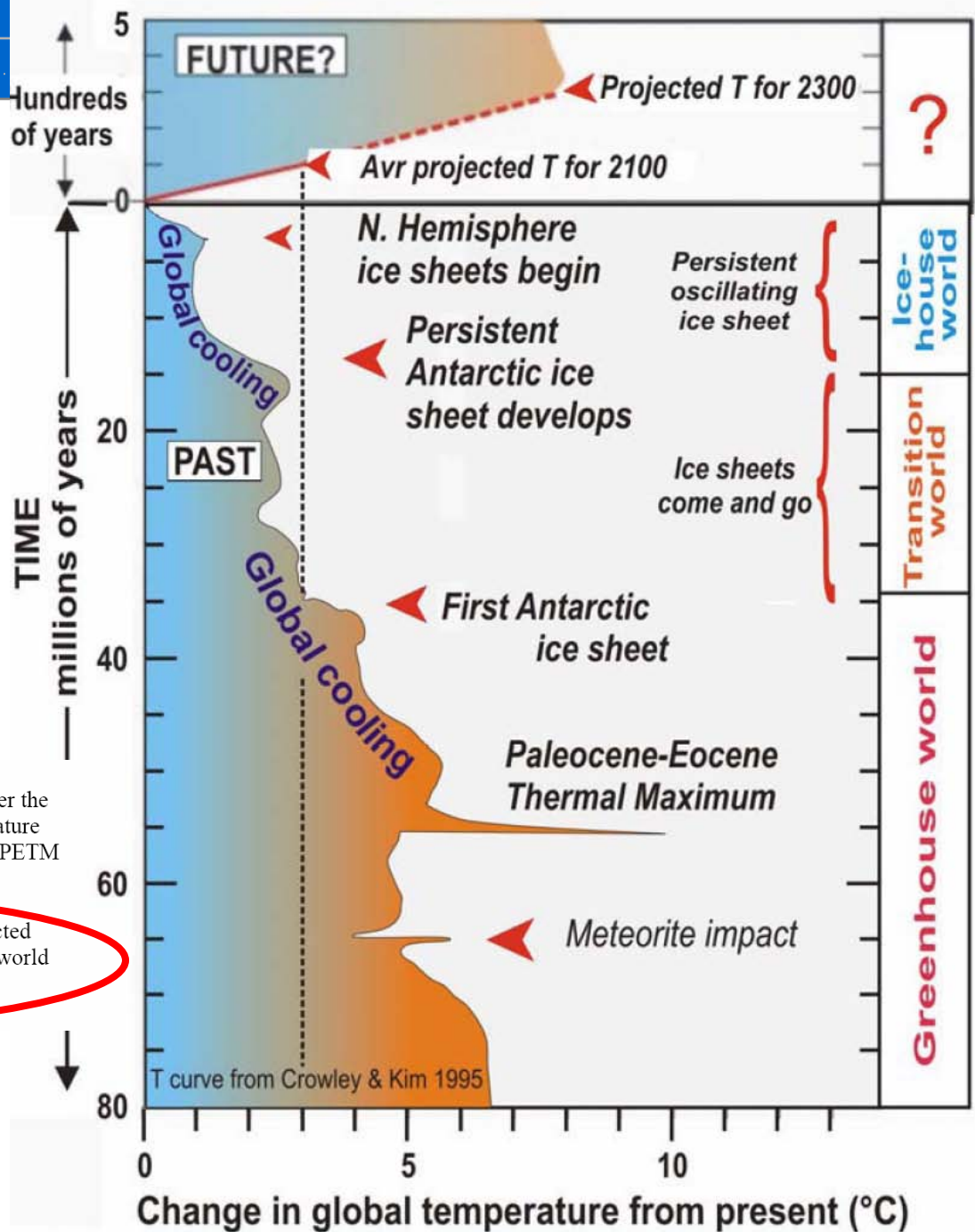
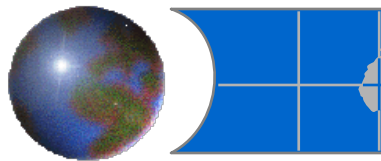
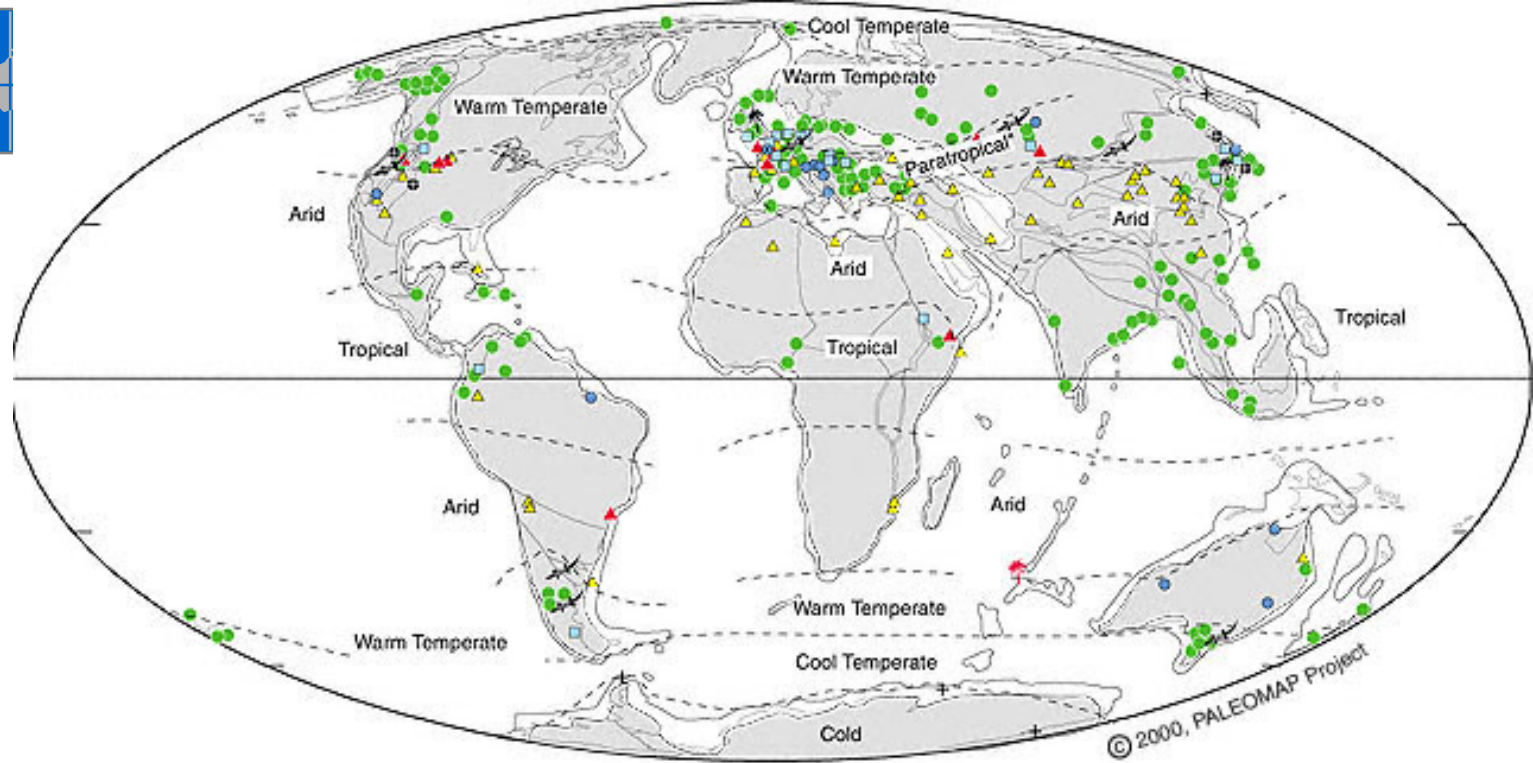


Figure 3. A graph showing the change in average global temperature over the last 80 million years (modified from Barrett, 2003, based on the temperature curve of Crowley and Kim, 1995, with the addition of the effects of the PETM methane discharge described by Zachos et al., 2005).

The "Future" part of the graph shows the rise in temperature to be expected from energy projections, with the earth warming into the "greenhouse" world of more than 34 million years ago soon after the turn of this century.



Fossils



Oligocene

LEGEND

	WARM	COOL
WET	<i>Tropical</i> ● Coal ● Bauxite ● Laterite	<i>Cool Temperate</i> ● Coal & Tillites
	<i>Warm Temperate</i> □ Kaolinite (& coal & evaporite) 🌴 Crocodiles 🐊 🌴 Palms & Mangroves 🌴	
	<i>Arid</i> ▲ Evaporite ▲ Calcrete	<i>Cold</i> + Tillite ⊕ Dropstone ⊙ Glendonite
DRY		

"Paratropical" = High Latitude Bauxites

- Messinian Crisis (5-6 Mya):
may be coldest, sea level well
over 100 m lower than today

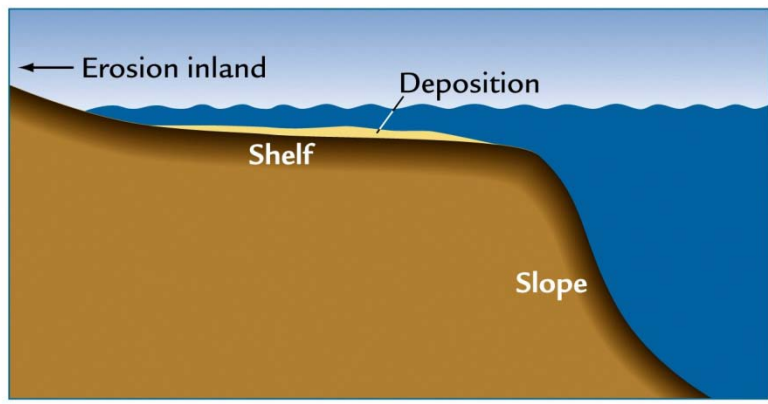


Sea-level changes

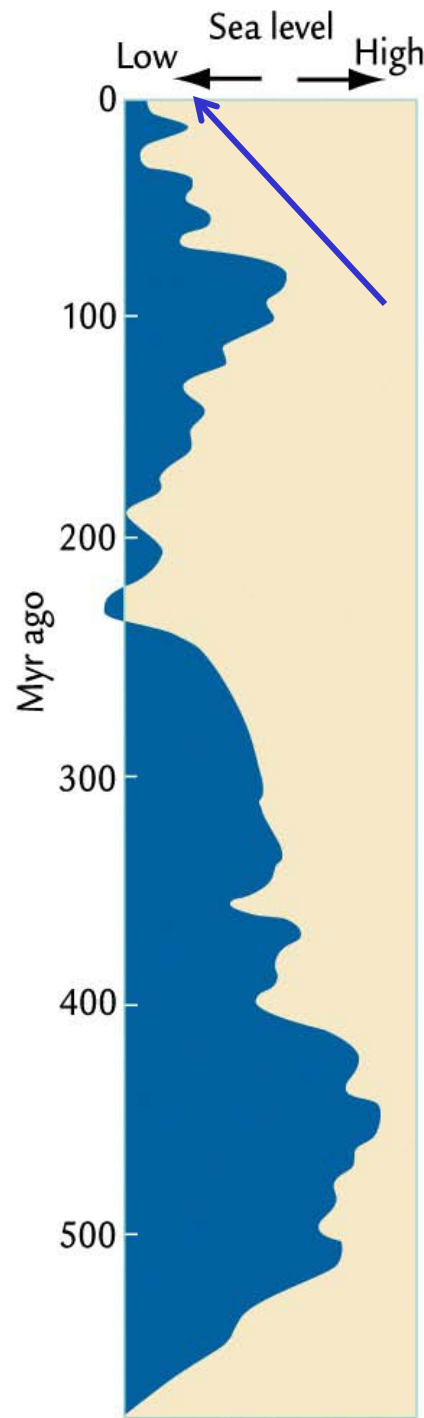
● Can think of sea level as reflecting relative warmth of whole planet

● Basin factors

- ❑ Shape
- ❑ Slower sea-floor spreading
- ❑ Continental collisions
- ❑ Volcanic plateaus

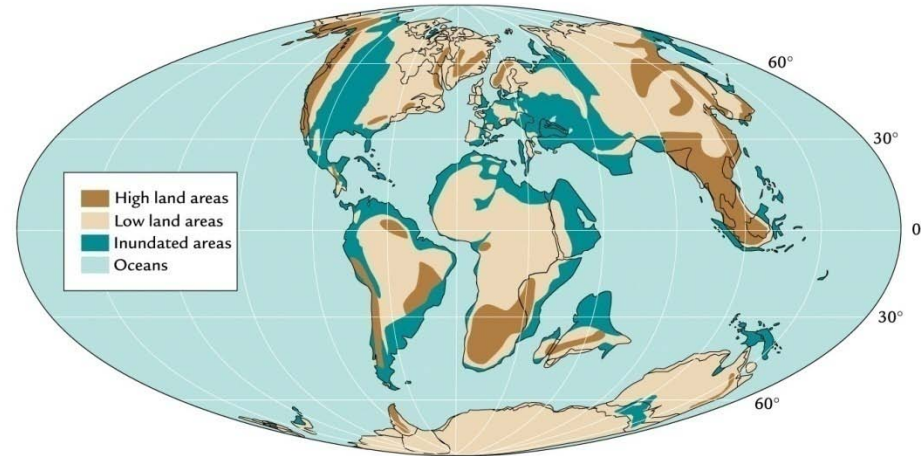


B High sea level





Sea-level changes



Climate factors

- ❑ Ice sheets
- ❑ Thermal expansion
(0.015% for each 1 C)

TABLE 6-1 Factors Contributing to Sea Level Fall in the Last 80 Million Years

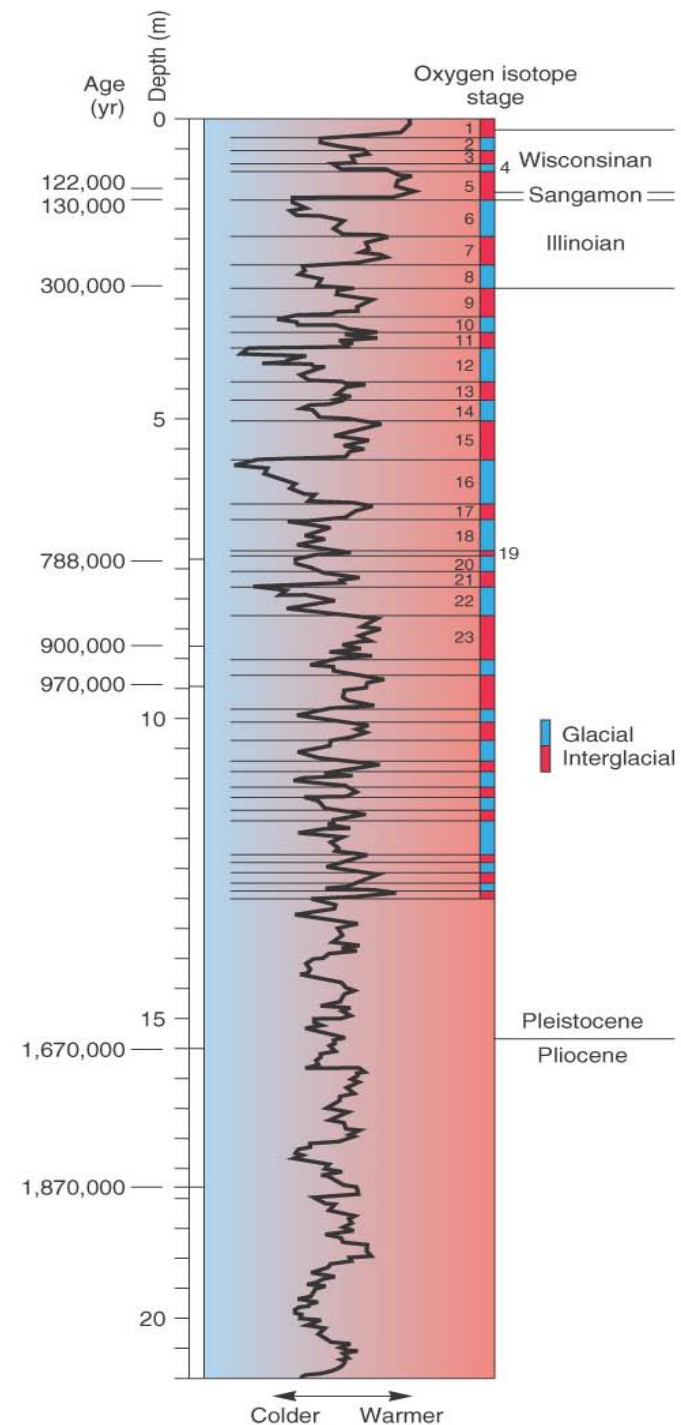
Cause of sea level change	Estimated change (meters)
Decrease in ocean ridge volume	-200 to -300
Collision of India and Asia	-40
Decrease in volcanic plateau volume	-10 to -40
Water stored in ice sheets	-50
Thermal contraction of seawater	-7
All factors	-300 to -440



Past 2.75 Million Years

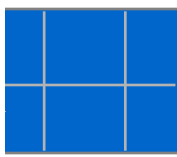
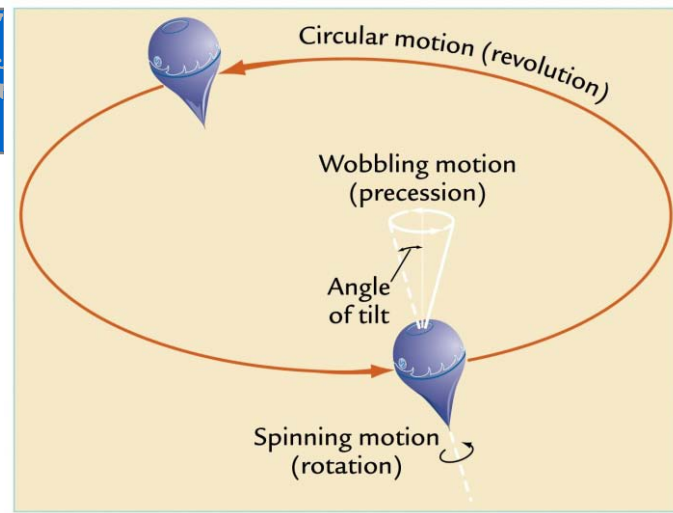
● From deep-sea drilling:

- ❑ At least 50 glacial-interglacial cycles superimposed on the long term cooling trend...
- ❑ 90% of last 0.9 MY there were ice sheets on Earth



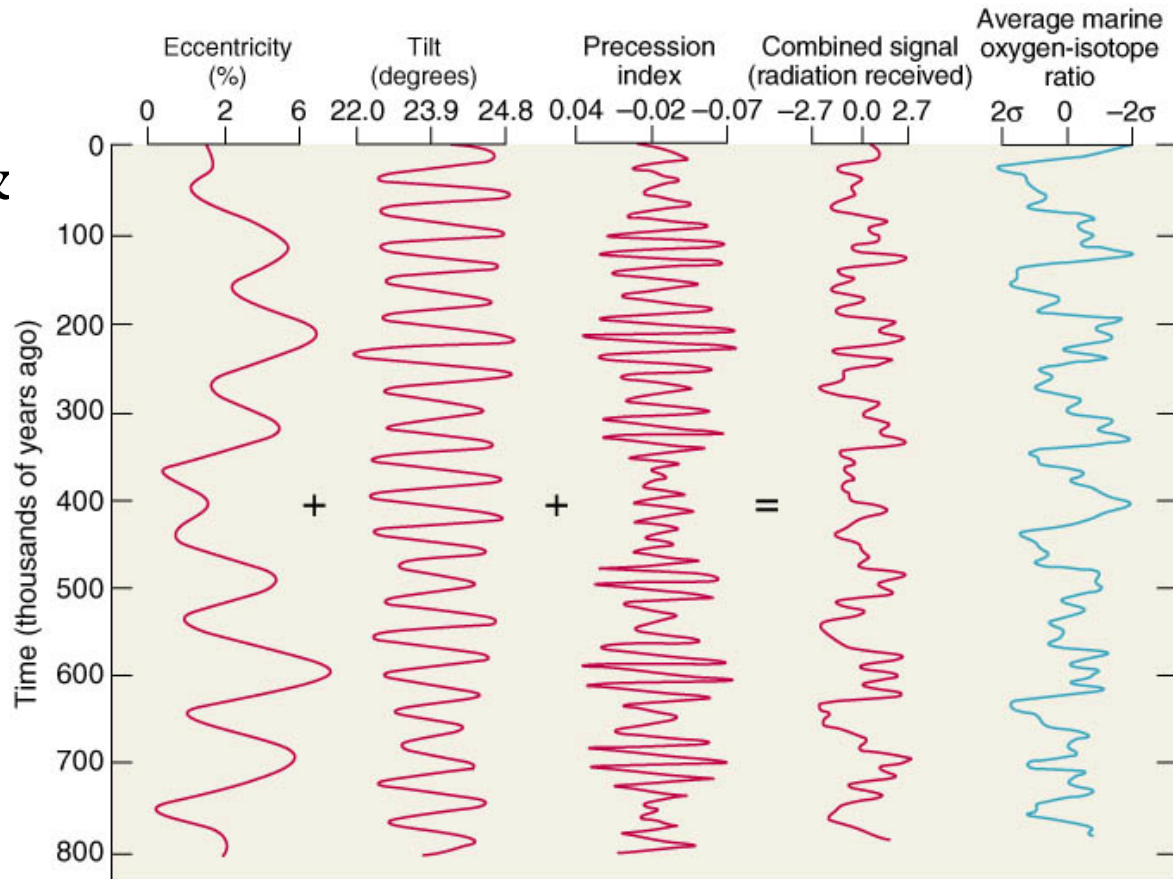


Astronomy



1911: Milutin Milankovitch proposes:

- ❑ All 3 cycles (23, 41, & 100 KYA) together control ice ages
- ❑ Summer insolation is driver

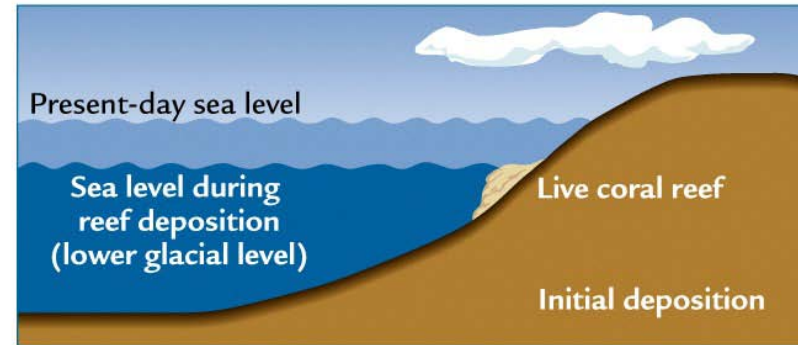




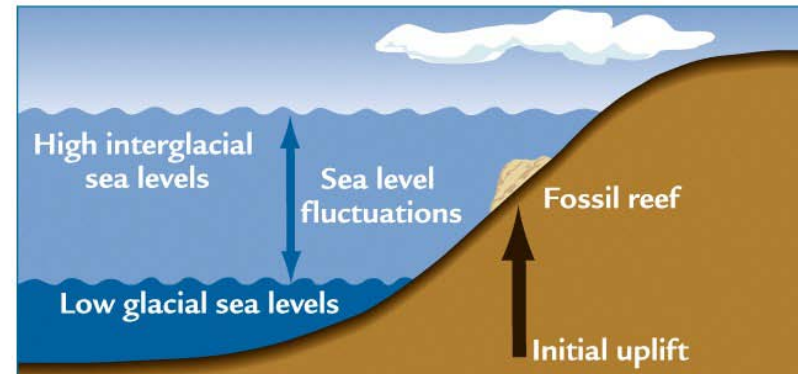
Milankovitch Cycles

1976: Jim Hays, John Imbrie, and Nick Shackleton publish first confirmation of Milankovitch theory

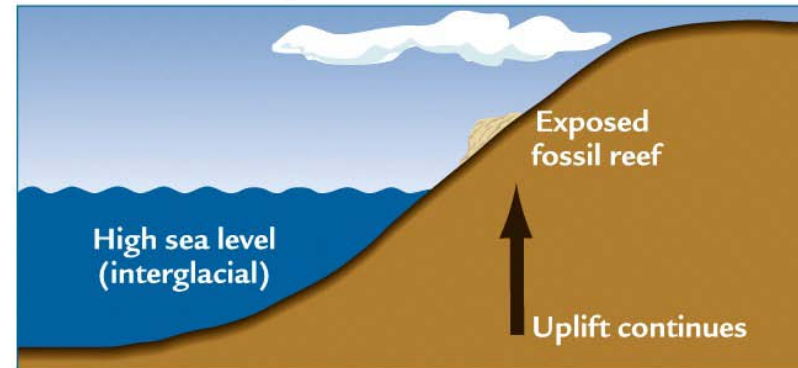
- Used corals to give dates with uranium decay isotope analysis



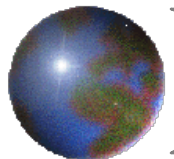
A Deposition of coral reef



B Subsequent changes

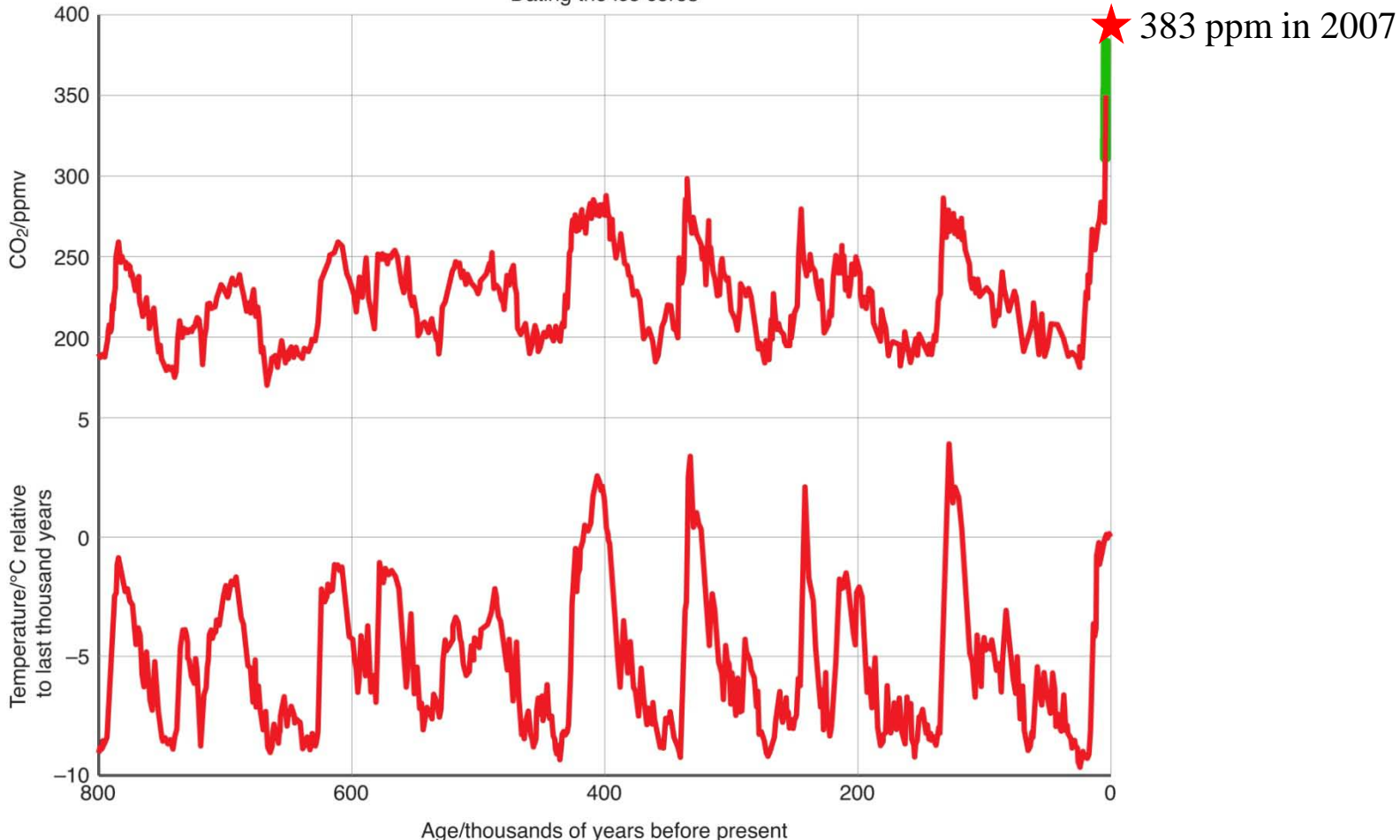


C Present day



CO₂ over past 800,000 years

Dating the ice cores



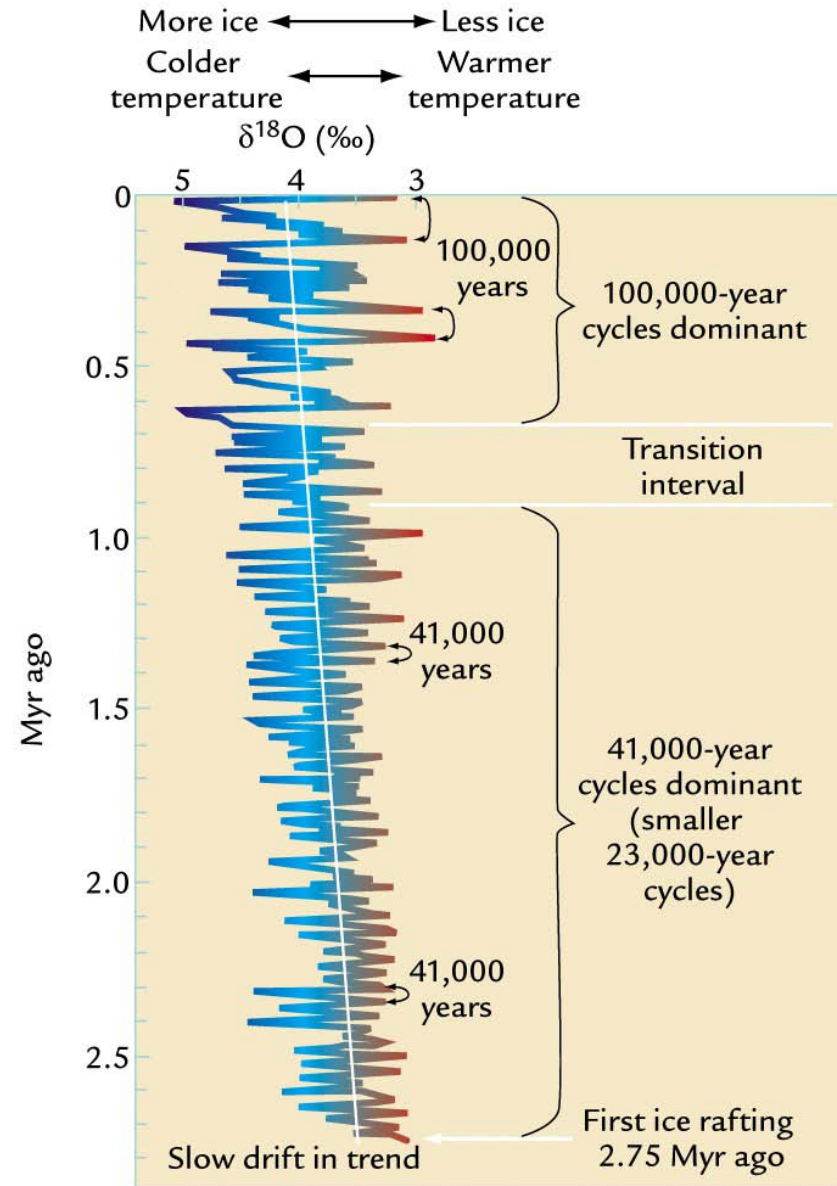
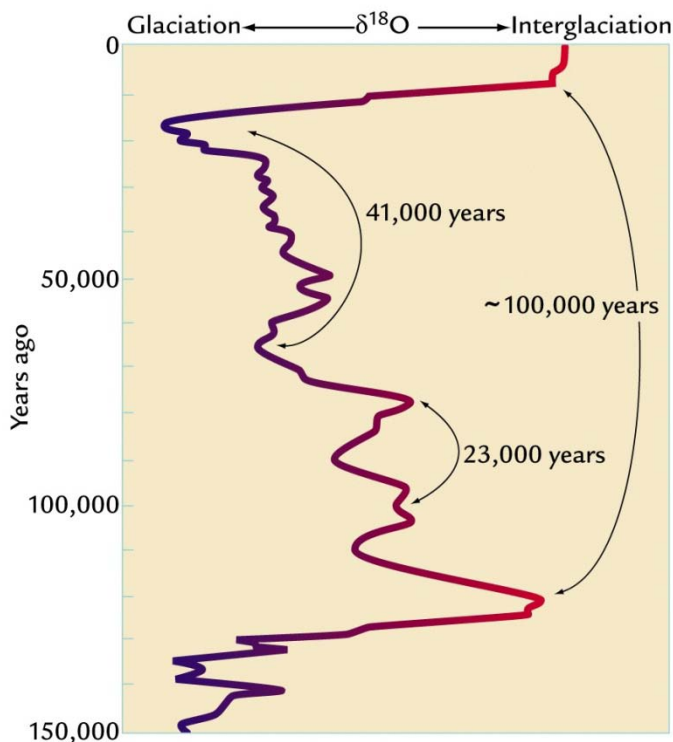
The top plot shows levels of carbon dioxide in the atmosphere. The data shown in green is actual concentrations measured at Mauna Loa in Hawaii. The red line on the CO₂ plot is from Law Dome and the remaining data from two other ice core sites in Antarctica; Vostok and Dome C.

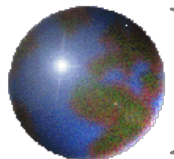
Plots courtesy of EPICA. Data from Luethi et al 2008 (CO₂) and Jouzel et al 2007 (temperatures). Thanks to Eric Wolff of BAS for supplying the information



Milankovitch Cycles

- Get reconstructed temps.
 - Switch from 41 & 23 dominant to 100 dominant about 800 KYA

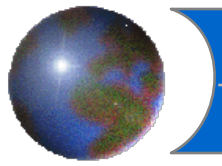




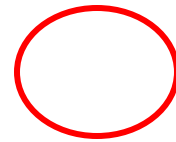
Chronology of Pleistocene Glaciations

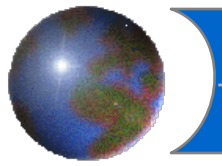
North America	Alpine Region	Years before Present
		— 10,000
WISCONSINIAN	Würm	— 75,000
Sangamon	Riss-Würm	— 125,000
ILLINOIAN	Riss	— 265,000
Yarmouth	Mindel-Riss	— 300,000
KANSAN	Mindel	— 435,000
Aftonian	Günz-Mindel	— 500,000
NEBRASKAN	Günz	— 1800,000
Pre-Nebraskan	Pre-Günz	

In North America, the glacial stages are Nebraskan, Kansan, Illinoian, and Wisconsinian. These terms correspond approximately to the Günz, Mindel, Riss, and Würm in Europe.



The Last 50,000 Years

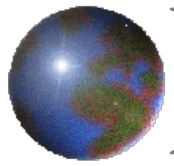




Last Glacial Maximum

- World sea level fell at least 100 m, thereby causing large expanses of the shallow continental shelves to emerge as dry land
- Disruption of major stream systems.
- The Missouri and Ohio rivers to move into new courses beyond the ice margin.

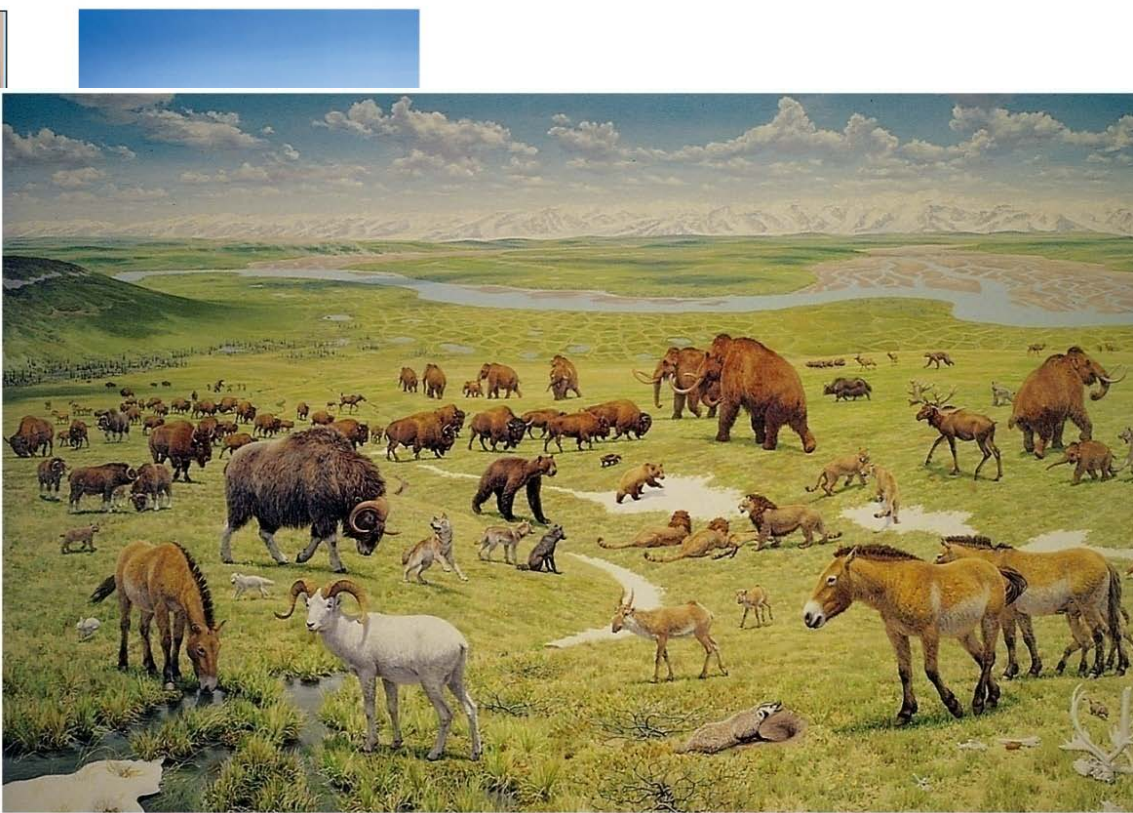




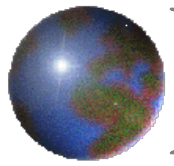
Last Glacial Maximum



(a)



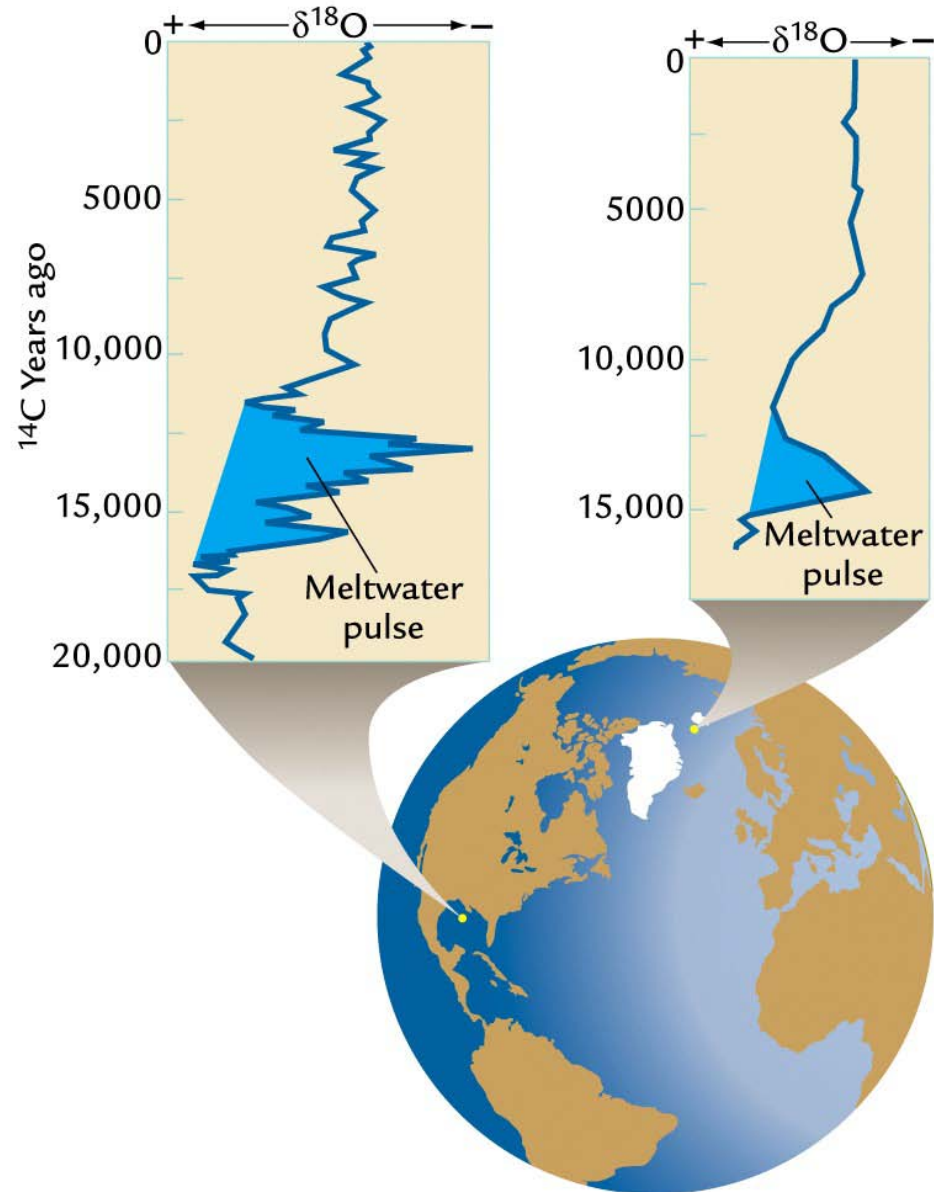
(d) Severe Dry Lake

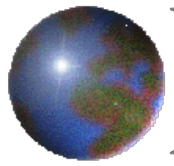


Deglaciation

Meltwater pulses...

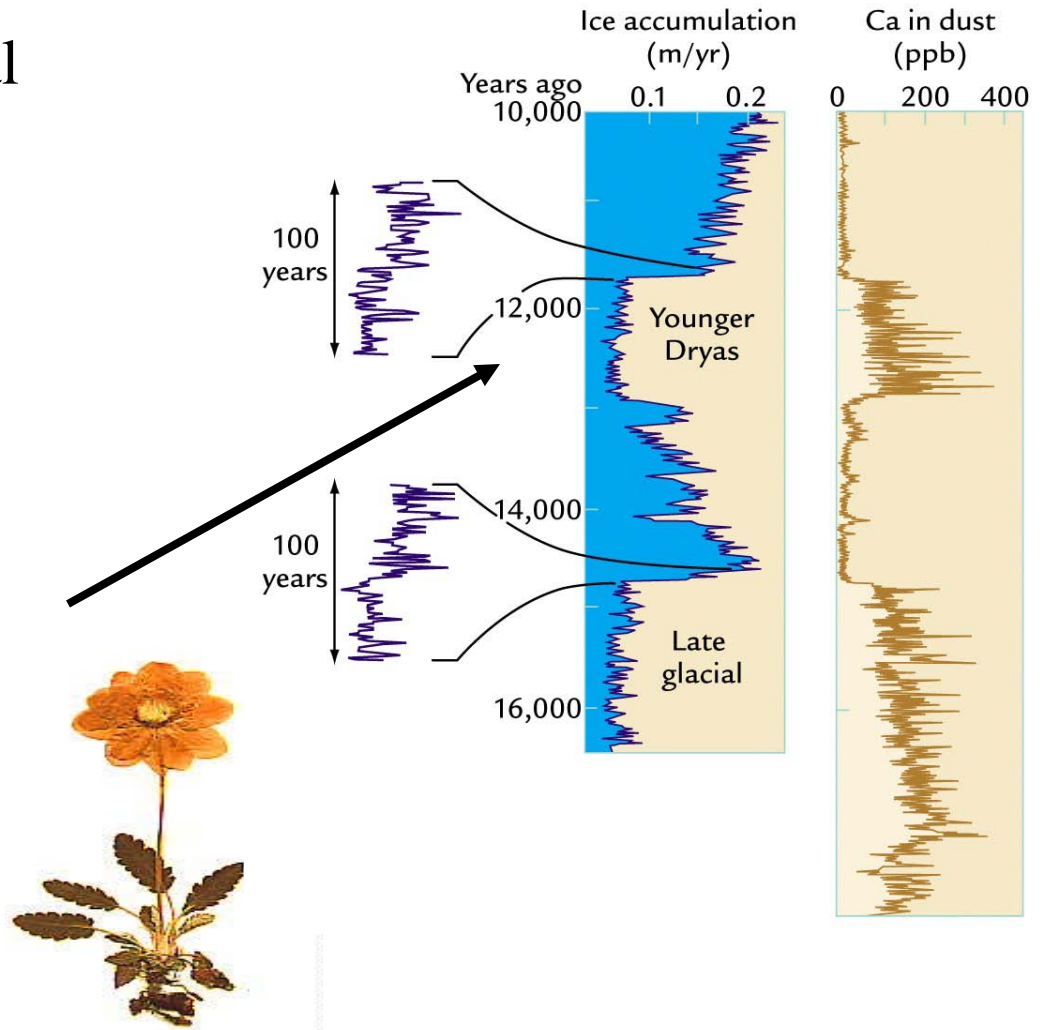
- Several different ones interrupt steady retreat of ice sheets





Younger Dryas

- ~3,000 year return to glacial conditions in midst of deglaciation
- “Younger Dryas”
 - ❑ 15-12,000 years ago
 - ❑ Pollen of dryas returns to Europe
 - ❑ Scary part: transitions very sudden, within a decade!!!

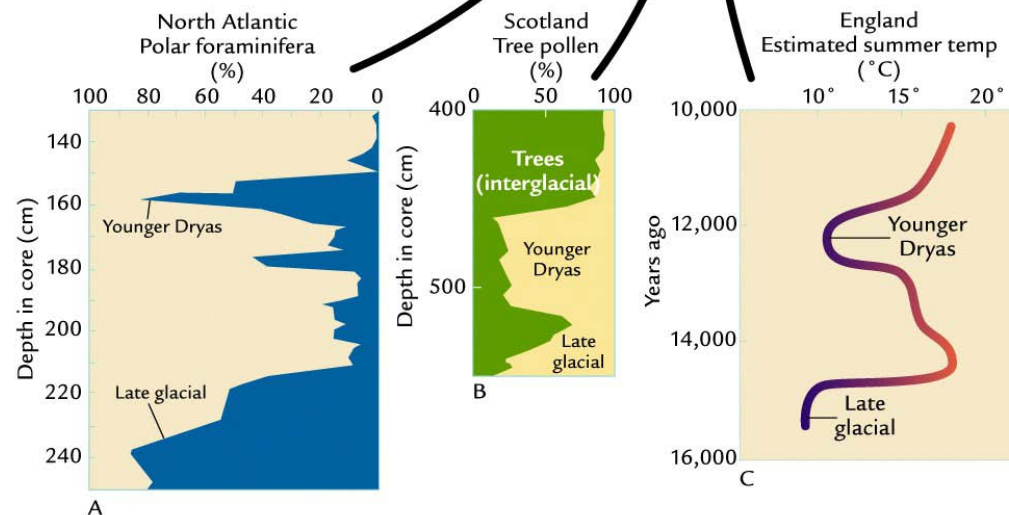
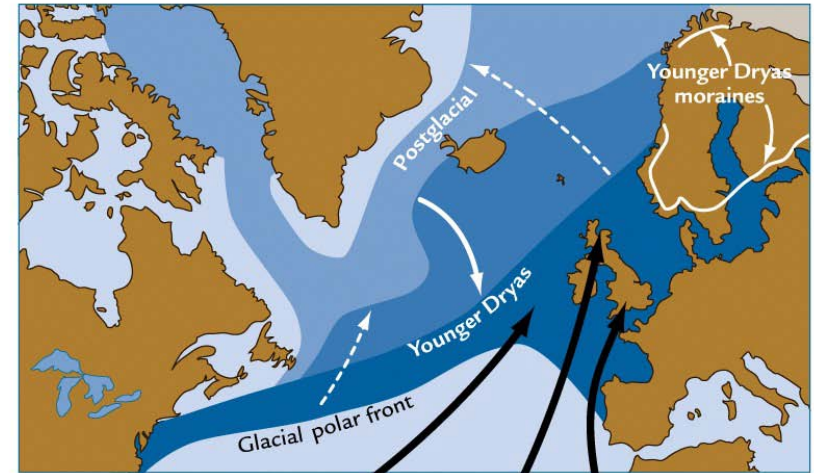


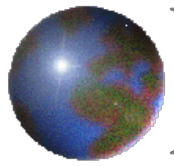


Younger Dryas

Think caused by movement in polar front.

- ❖ Front: area between two air masses
- ❖ Was S of England during glacial, shifts N during interglacial.
- ❖ During YD, it reverted...

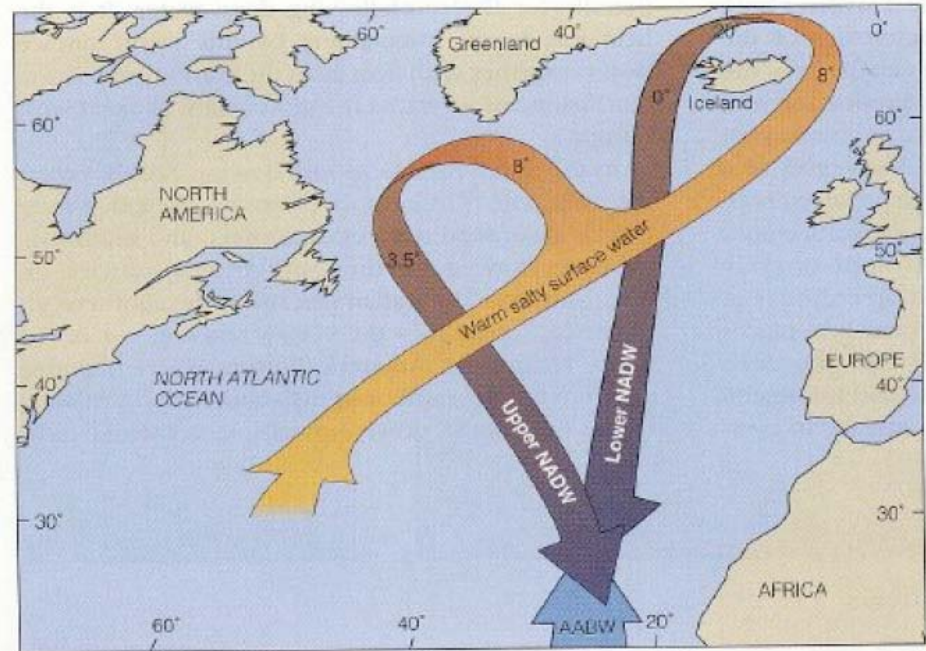




Thermohaline Circulation

Wally's hypothesis:

- ❖ Cut off NADW = return to glacial conditions
- ❖ Must suddenly change input into North Atlantic...
- ❖ What could happen???



1977

Quelccaya Ice Cap, Peru

2002



Photos: Lonnie G. Thompson: C

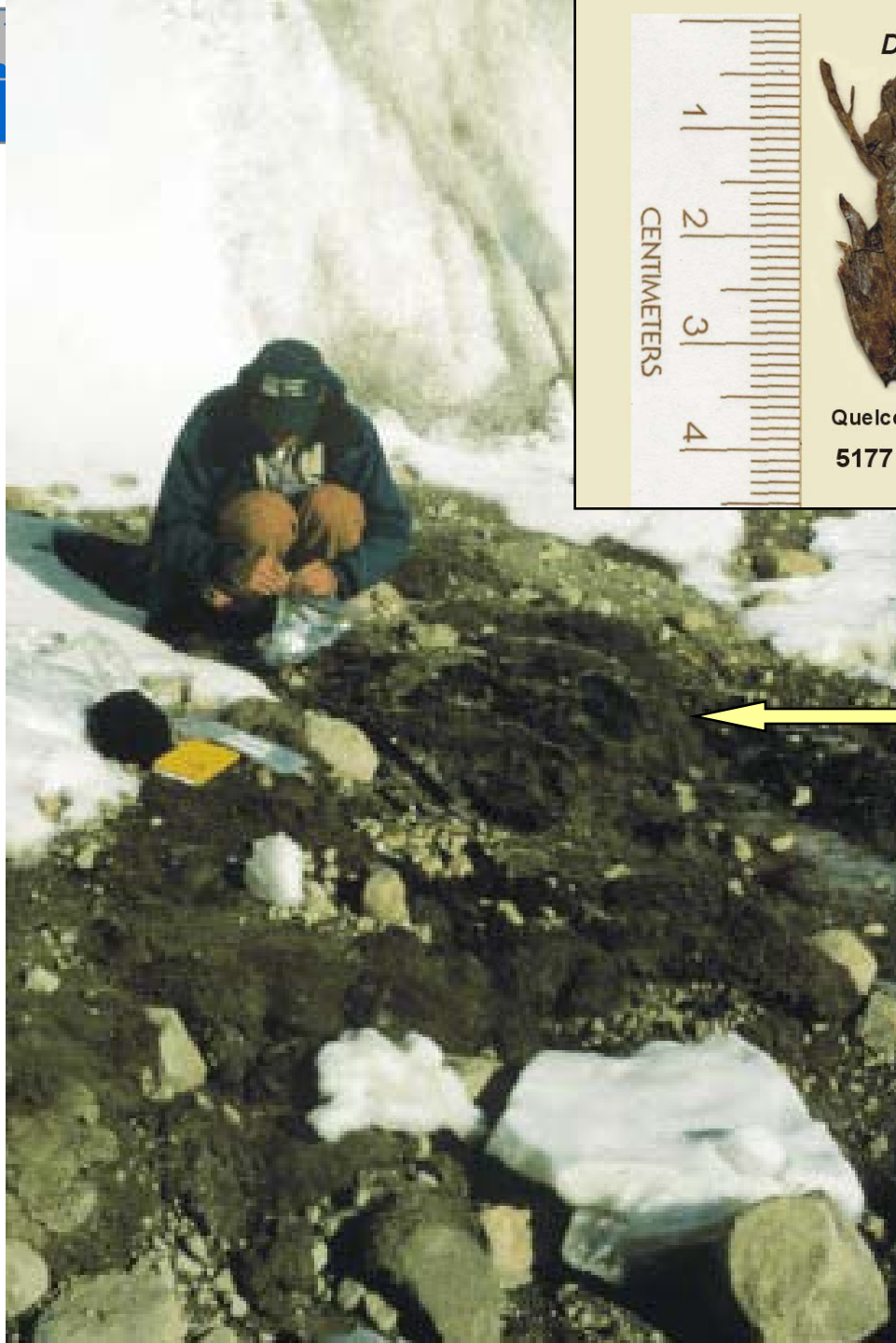


Quelccaya

Ice Cap, 2002

**200 – 400 m
above its
modern range**

**Photos: Lonnie G. Thompson
Ohio State University**



Distichia muscoides



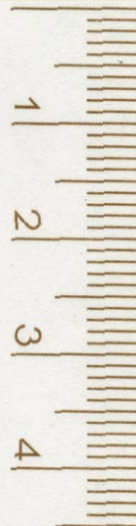
Quelccaya Plant

5177 ± 45 yr. B.P.



Modern

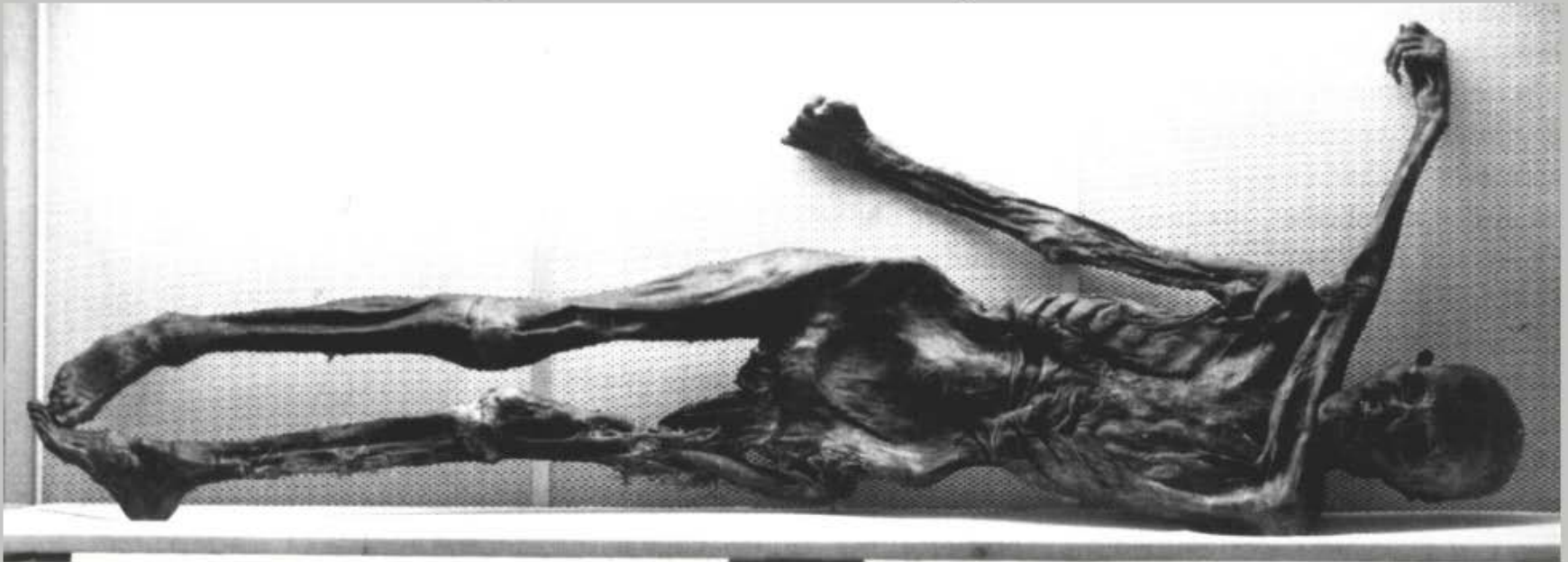
CENTIMETERS



**Cushion
Plant**

"The Tyrolean Iceman" - "Ötzi" "Man from the Hauslabjoch"

Age 5175 ± 125 years



Source: <http://info.uibk.ac.at/c/c5/c552/Forschung/Iceman/iceman-en.html#Finding>



“Drought Events”

- Now looking for more evidence of that shift in climate 5000 years ago...
- Kind of show both linear & cyclic trend depending on which examined...
- Very messy picture, especially on regional scale.

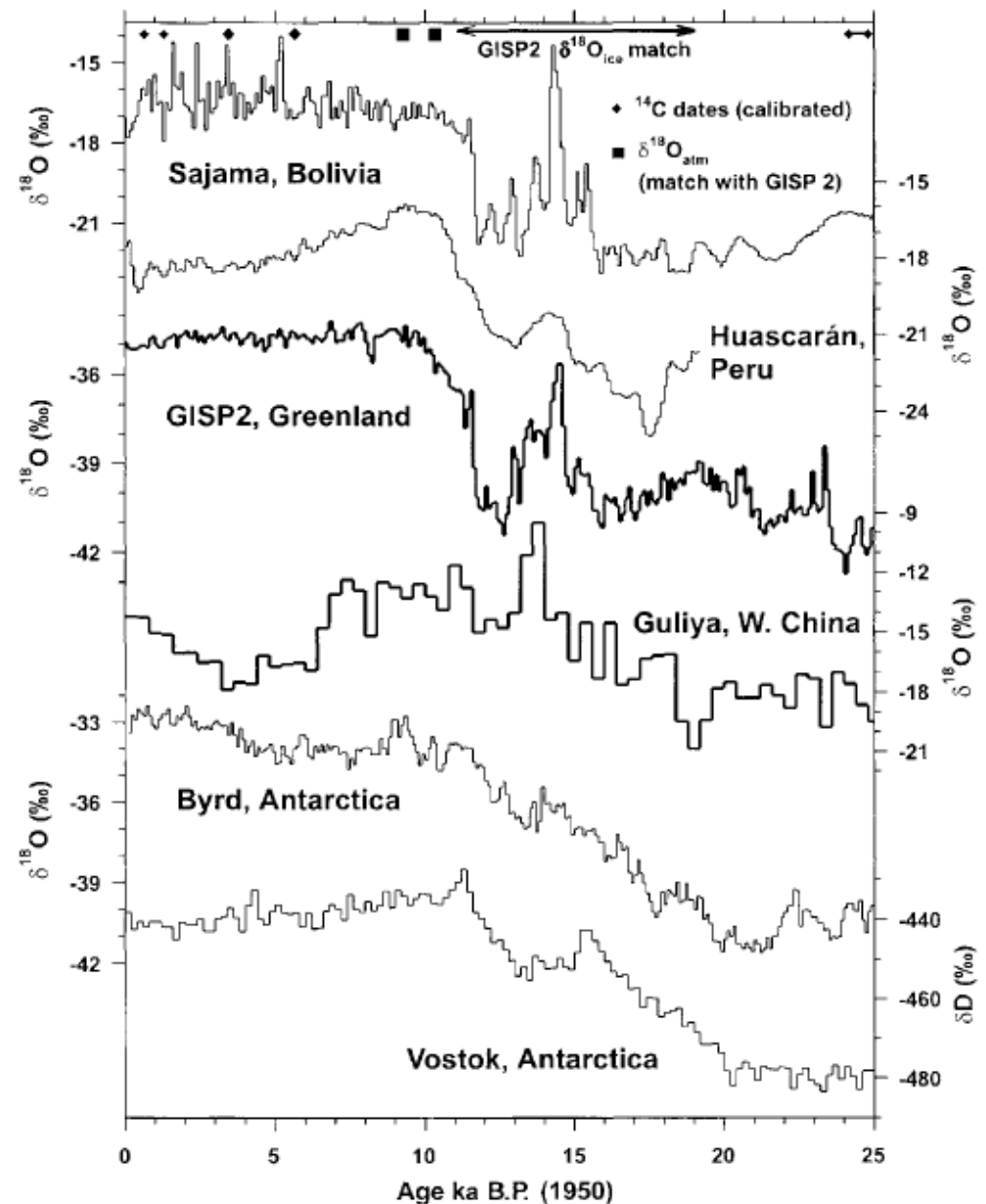
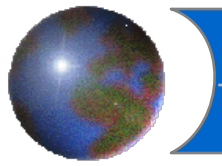
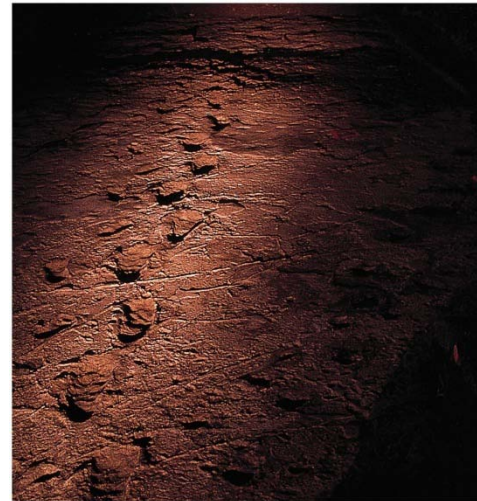


Figure 4. The $\delta^{18}\text{O}_{\text{ice}}$ histories for the last 25,000 years for six cores from the tropics to the poles show similar isotopic depletion (~ 5 to 7‰) in the Late Glacial Stage ice relative to Holocene ice.



Anthropocene

- Term used for climate where humans are the dominate controlling mechanism...

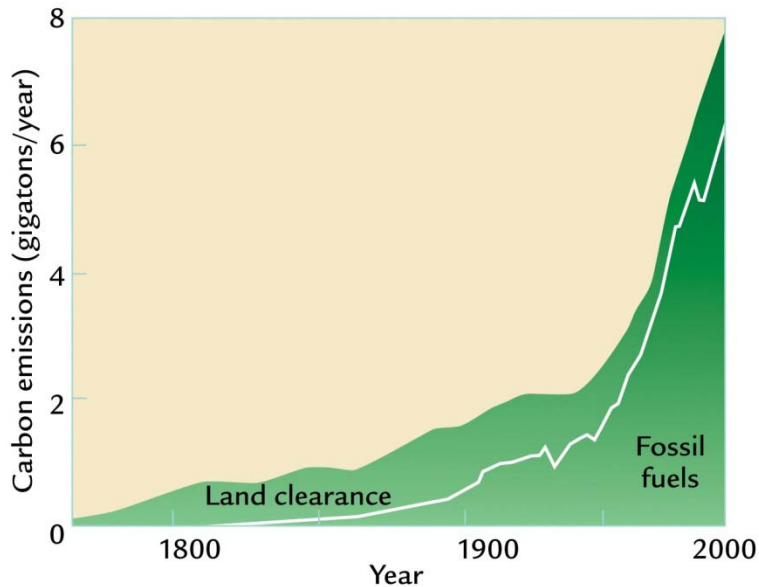




Clearing of Land

● Deforestation:

- ❖ Since 8000 years ago in Europe...
- ❖ Sagan proposed in 1970s
- ❖ Ruddiman proposes change in CO₂ since then

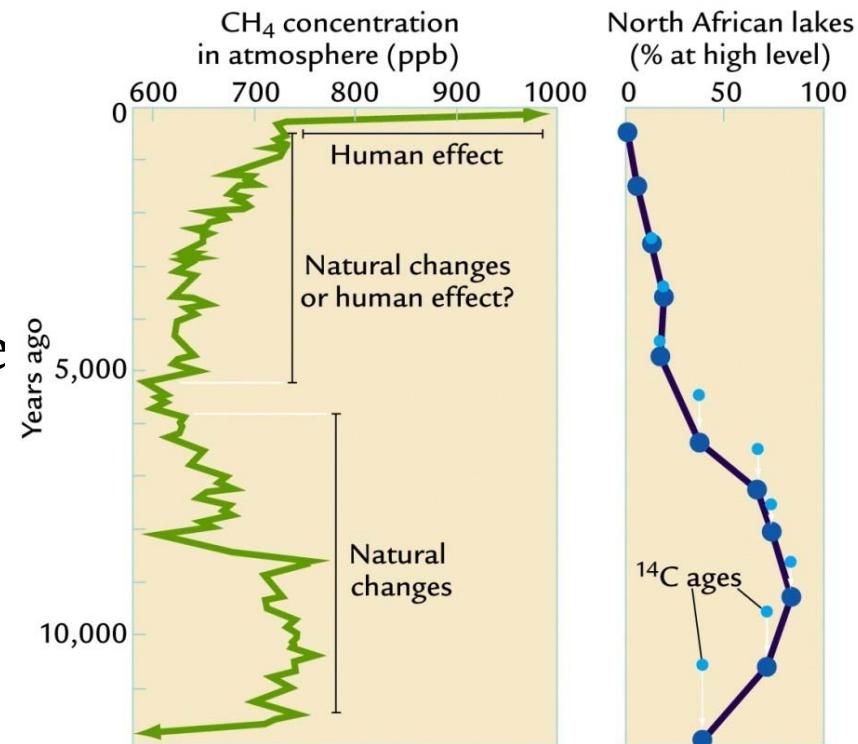
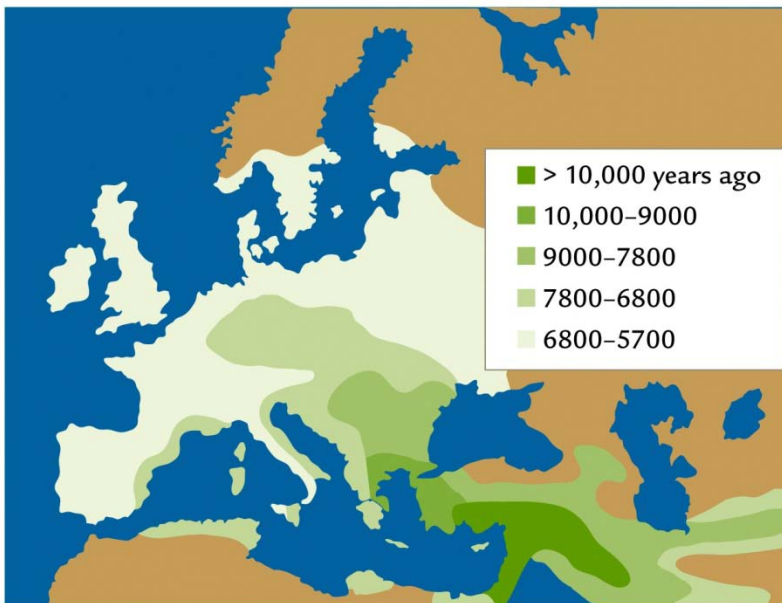




Effects of Agriculture

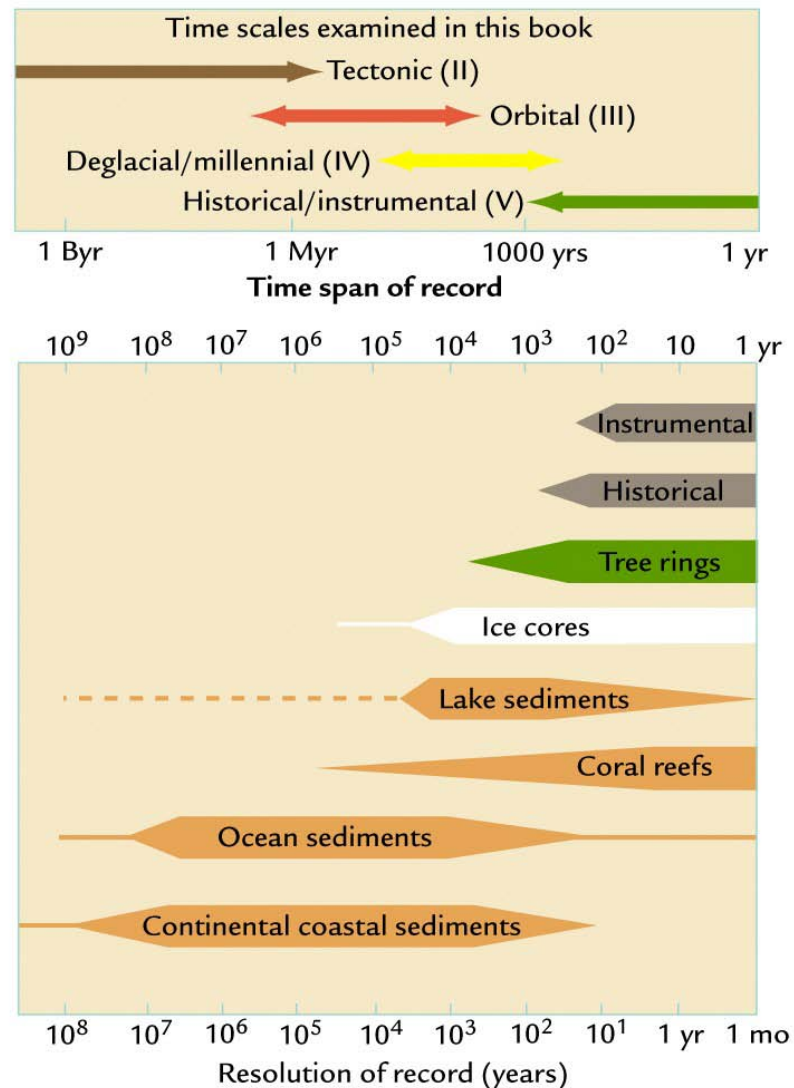
Agriculture:

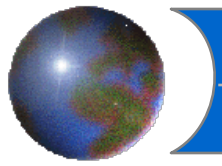
- ❑ First arose in fertile crescent & Yellow River Valley in China...
- ❑ Unexplained rise in methane
- ❑ Ruddiman credits irrigation of rice





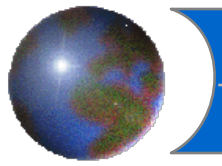
Time scales for Proxy Data





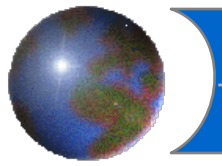
Take Home

- Proxy data is very important to our understanding of climate.
- We are improving our ability to read these signals and what they tell us about the Earth's past.
- They are revealing a complicated but fascinating story about our Earth's climatic evolution.
- We still have a great deal to learn.



Climate of the Last 2000 Years...

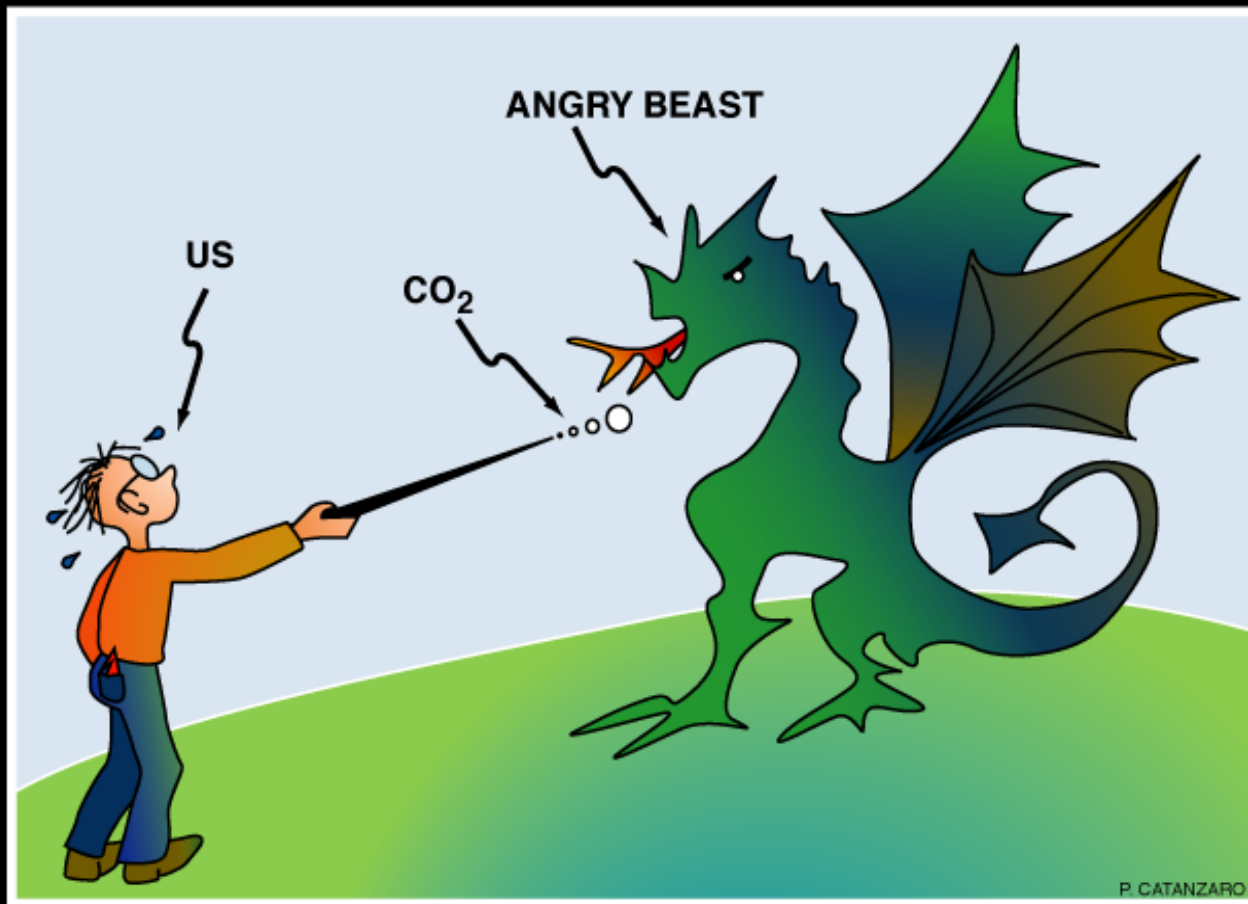
● Coming Thursday...



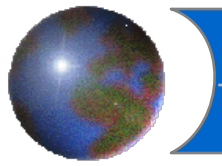
Resources

- W. Ruddiman. *Earth's Climate: Past and Future*. 2008. W.H. Freeman.
- E.C. Pielou. *After the Ice Age: The Return of Life to Glaciated North America*. 1992. University of Chicago Press.
- Broecker & Kunzig. *Fixing Climate*. 2008. Hill & Wang.

FOSSIL FUEL CO₂ AND THE ANGRY CLIMATE BEAST



W.S. BROECKER



Additional Courses

- GEOS 108N – Climate Change: Past&Future
- GPHY 303N – Weather & Climate
- GEOS 382 – Global Change
- FOR 407 – Biogeochemistry
- GPHY 550 – Seminar in Paleoclimate & Global Change