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12.740 Paleoceanography  
Spring 2008

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Paleoceanographic Tracers  
and  
Major Paleoceanographic and Paleoclimate Events  
of the Past 70 Million Years

12.740 Lecture 1 Spring 2008

# Why are ocean sediment cores, ice cores, and coral reefs so special?

Although evidence for past climate is found on land as well, the longest relatively complete record of climate change is contained in deep-sea sediment cores. Although ice cores are short in duration and limited in geographic coverage, they are unparalleled in detail and in their ability to reconstruct past atmospheric composition. With sub-annual resolution, surface reef-building corals contain detailed information about tropical paleoclimate on times scale of decades to millennia.

Paleoceanography is a young science. If you had been a respectable 'majoritarian' scientist of the year \_\_\_\_ you wouldn't have believed:

- 1850 Massive glaciers once covered the northern continents
- 1900 The earth is older than 20-40 m.y.
- 1950 There have been more than 4 major advances and retreats of massive continental glaciers in the last 2 m.y.
- 1965 Ice advances/retreats are paced by variations in the earth's orbit.

# The limits of “paleoceanography”

Most of the seafloor is <200 m.y. old; precious little is >100 m.y. This time scale sets the practical horizons of paleoceanography as most practitioners know it. Of course, oceans existed before then and some clues to them are preserved in rocks on the continent - but this is "geology" not paleoceanography; the tools and techniques available overlap but are used in very different manner.

"Typical" oceanic sedimentation rates: 0.1 - 3 cm/10<sup>3</sup> yrs, so 500,000 years is represented by 0.5 m to 15 m (covered by piston cores); 100 my requires 100m - 3000m (covered by DSDP, especially hydraulic piston coring). Bioturbation of upper 3-15 cm (in most but not all sites) reduces the time resolution obtainable from these sediments and induces artifacts into timing, precision, and magnitude.

# Paleoceanographic Indicators

Although paleoceanographers would like to be able to specify temperature, salinity, nutrient content,  $p\text{CO}_2$ , etc., we can often only know these indirectly through biological, chemical, and physical properties of sediments. How can we go about reconstructing these properties?

# Paleoceanographic Indicators

- **Paleotemperatures (e.g. oxygen isotopes) based on chemical/physical principles.** Problems: assumption of equilibrium etc. may not be valid in low temperature and/or biological systems; isotopic composition of seawater must be known or assumed.
- **Bio-ecological paleotemperatures (e.g. Imbrie-Kipp method) based on modern-day correlations between temperature and the distribution of organisms in the ocean and in sediments.** Problems: Correlation is observed, but causation is assumed but not proven (i.e. are population distributions really due to temperature tolerances of organisms?). How reliable is this assumption? Example: polar bears live quite well in the warm San Diego Zoo; the limit on their presence in temperate zones reflects not their temperature tolerances but rather their whiteness which aids their survival in the arctic. While it may be safe to assume that polar bears will not thrive naturally in warm climates, you have to be careful inferring temperature from their distribution. It is reasonable to expect that other factors are important to the distributions of organisms: light and nutrients (floral species); food availability and preferences (faunal species); ecological interactions (both).
- **Ocean paleochemistry:  $\delta^{13}\text{C}$ ; Cd/Ca, Ba/Ca, Zn/Ca** (tell us something about the distribution of nutrients and alkalinity in the ocean); carbonate dissolution indicators tell us about carbonate saturation in the deep ocean. Problem: reliability of tracers under certain conditions.
- **Terrigenous sediment sources: types of minerals; grain size;** windblown materials vs. physical transport (water and turbidity currents); erosion.
- **Geological Time Scale:** how do we determine time in geological systems? Most often, our direct information is spatial position: depth in ice or sediment core, etc.. Sometimes we have radioactive tracer information - e.g.  $^{14}\text{C}$ ,  $^{230}\text{Th}/\text{U}$  - but these may need calibration or have accuracy problems. Most often, we determine time indirectly, via cross correlation. As the primary information on true time expands, the ages of our samples is altered as if it were written on a rubber band.

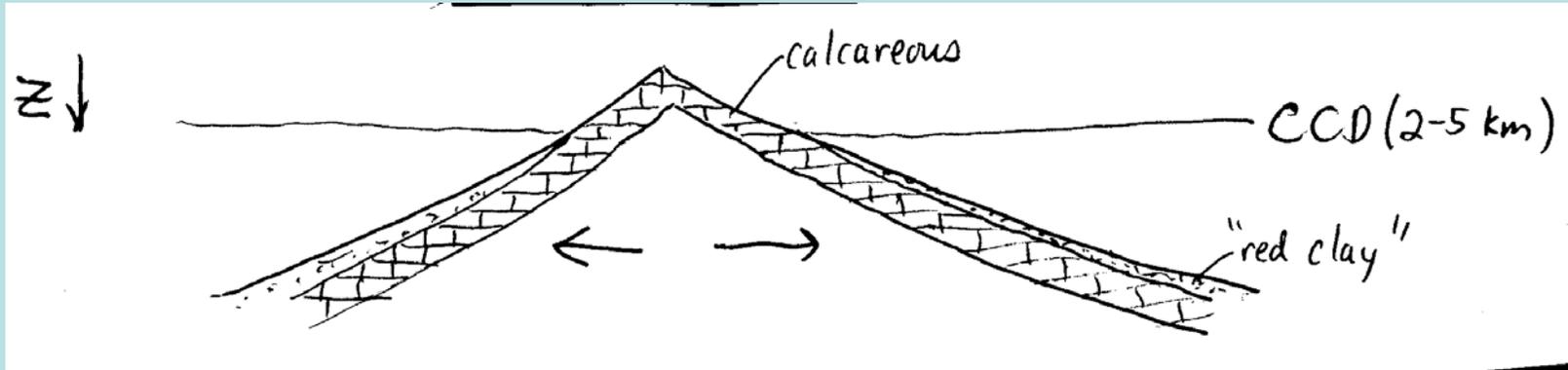
## SOME SIMPLE QUESTIONS :

1. WHAT WAS THE GLOBAL SEA LEVEL 18,000 YEARS AGO?
2. " " GLOBAL ICE VOLUME " " "
3. " " THE AVERAGE SALINITY OF THE OCEAN " " "
4. " " THE AVERAGE  $\delta^{18}O$  OF THE OCEAN " " "
5. " " THE AVERAGE  $\delta^{18}O$  OF ICE SHEETS " " "
6. " " THE AVERAGE DEEP OCEAN TEMPERATURE " " "
7. " " ATMOSPHERIC  $P_{CO_2}$  " " "
8. " " DEEP OCEAN CHEMICAL COMPOSITION " " "
9. " " OCEAN CIRCULATION PATTERNS " " "
10. " " CONTINENTAL BIOMASS " " "
11. " " TROPICAL HUMIDITY " " "
12. " " ATMOSPHERIC WIND SPEED " " "
13. " " OCEANIC PRODUCTIVITY " " "
14. HOW CAN THE DEEP-SEA SEDIMENT RECORD BE LINKED TO A CHRONOLOGY?
15. WHAT CONTROLS LONG-TERM CLIMATE CHANGE?

# Paleoceanographic Indicators

- **The "shifting paleotracer sand" problem:** Paleo indicators rarely prove to be as simple as they are initially assumed to be, and sometimes their interpretation changes radically. In part, this arises from the indirect nature of the estimated properties relative to measured properties; in part, it arises out of the limited knowledge available at the time that a tracer is introduced. A certain measure of historical perspective is needed to understand the limits and capabilities of paleo tracers.
- **"50 Year Event" (etc.) problem:** some events occur frequently (on geological time scales) but infrequently on human (or graduate student thesis or research grant) time scales. How do you calibrate something like this.

# Typical oceanic sedimentation pattern:



The study of paleoclimatology in deep sea cores requires stable indicators of past conditions and a reliable time scale. But the seafloor moves vertically and horizontally. Carbonate fossils, esp. foraminifera, provide the most information - but are not found in deeper waters. This is a special case of a more general problem: the "paleoceanographic uncertainty principle": some events leave no record.

# A Brief Review of Climate Events during the Past 70 Million Years

- The "Little Ice Age" (mid-late second millennium)
- "Medieval Warm Period" (centered on end of first millennium)
- 'Hypsithermal' or "Climatic Optimum" ~8000 yrs b.p.
  - e.g.:
    - sand dunes in Minnesota ( $^{14}\text{C}$  dates);
    - oases and lakes in the Sahara; pollen in lakes and peat bogs

# Massive continental glaciation

~20,000 yr b.p.

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Evidence:

a) Glacial features on continents: moraines; scratches; drumlins; eskers; glacial rebound (link to earth's viscosity, viscous earth geodynamics). But note: continental glaciation is self-erasing; very large glaciations tend to destroy evidence of previous smaller glaciation.

b)  $^{14}\text{C}$  dating.

c) Oceanic faunal changes: T-correlated foraminifera and radiolaria: cooling of high-latitude North Atlantic;  $5^\circ$  latitude equatorward shift of Antarctic Circumpolar Front

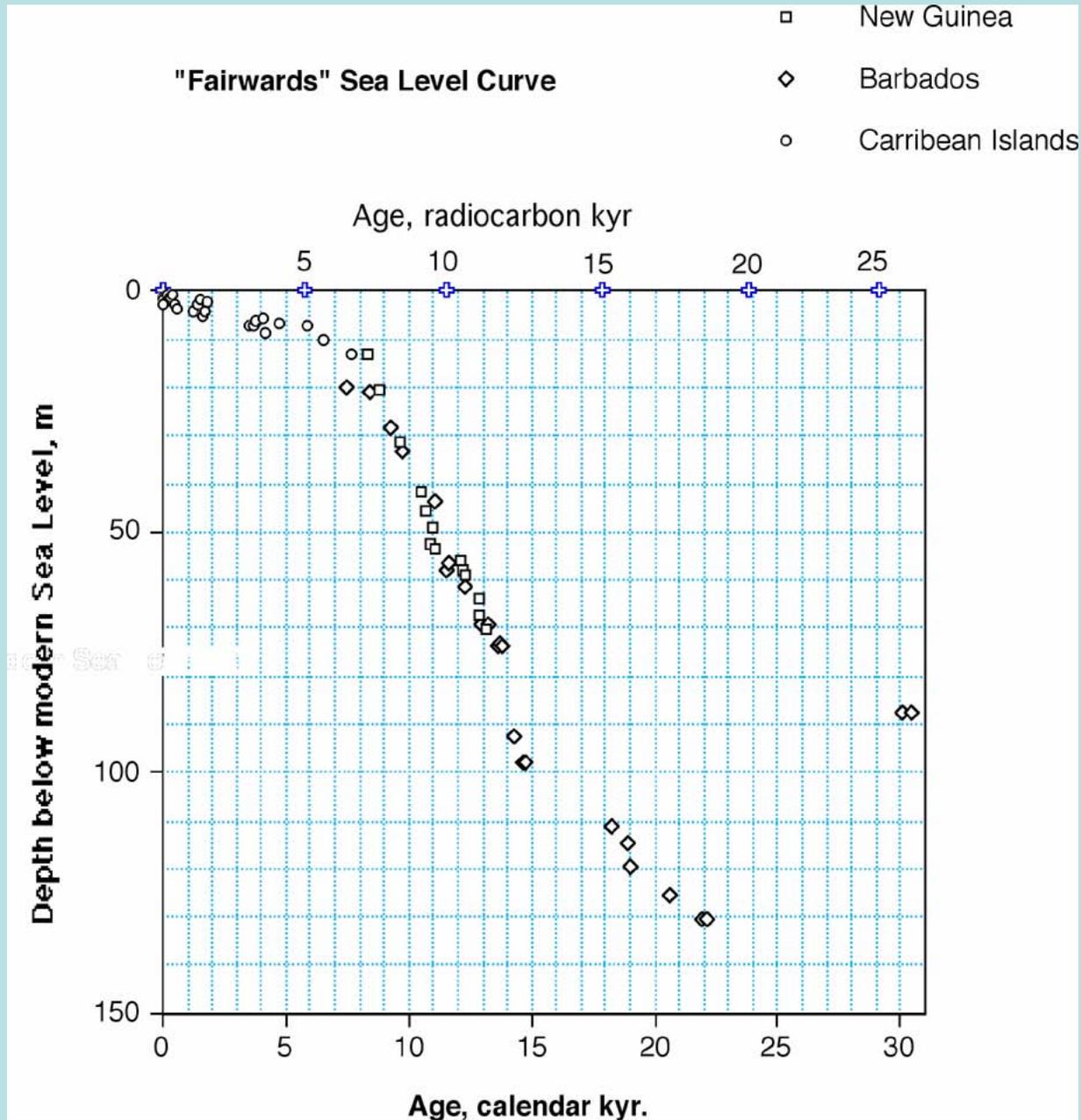
d) Sea level evidence: ancient shore lines on stable and emergent islands

e)  $\delta^{18}\text{O}$ : in water vapor, a function of mean annual temperature - so ice deposited during glacials (still resident in Greenland and Antarctica) is isotopically depleted; annual cycles for exact and approximate dating; G/I variation.

f) Because of d), when there is a lot of ice, the oceans became isotopically heavier - this change is recorded in the  $\text{CaCO}_3$  shells of forams:  $\delta^{18}\text{O}_{\text{foram}} = \delta^{18}\text{O}_{\text{water}} + f(T) + \text{species-dependent constant}$

g) Pollen - in peat bogs, lakes, and continental margin sediments

# Sea-level estimates from drilling submerged coral terraces



# Climate variations during the past 150,000 years:

a) Time scale:  $^{230}\text{Th}$  ingrowth in corals, and interpolation between core top and Brunhes-Matuyama magnetic reversal [780,000 years,  $^{40}\text{K}(^{39}\text{Ar})/^{40}\text{Ar}$ ]

b) Neither present nor glacial maximum are typical of last 135,000 years; climate has varied between these extremes:

0 - 11 ka 'Interglacial'

11 - 73 ka 'Glacial' (with 28-62 somewhat warmer)

73 - 127 ka 'Interglacial' (with three peaks, and only

~118-125k truly comparable to present)

127- 187 'Glacial'

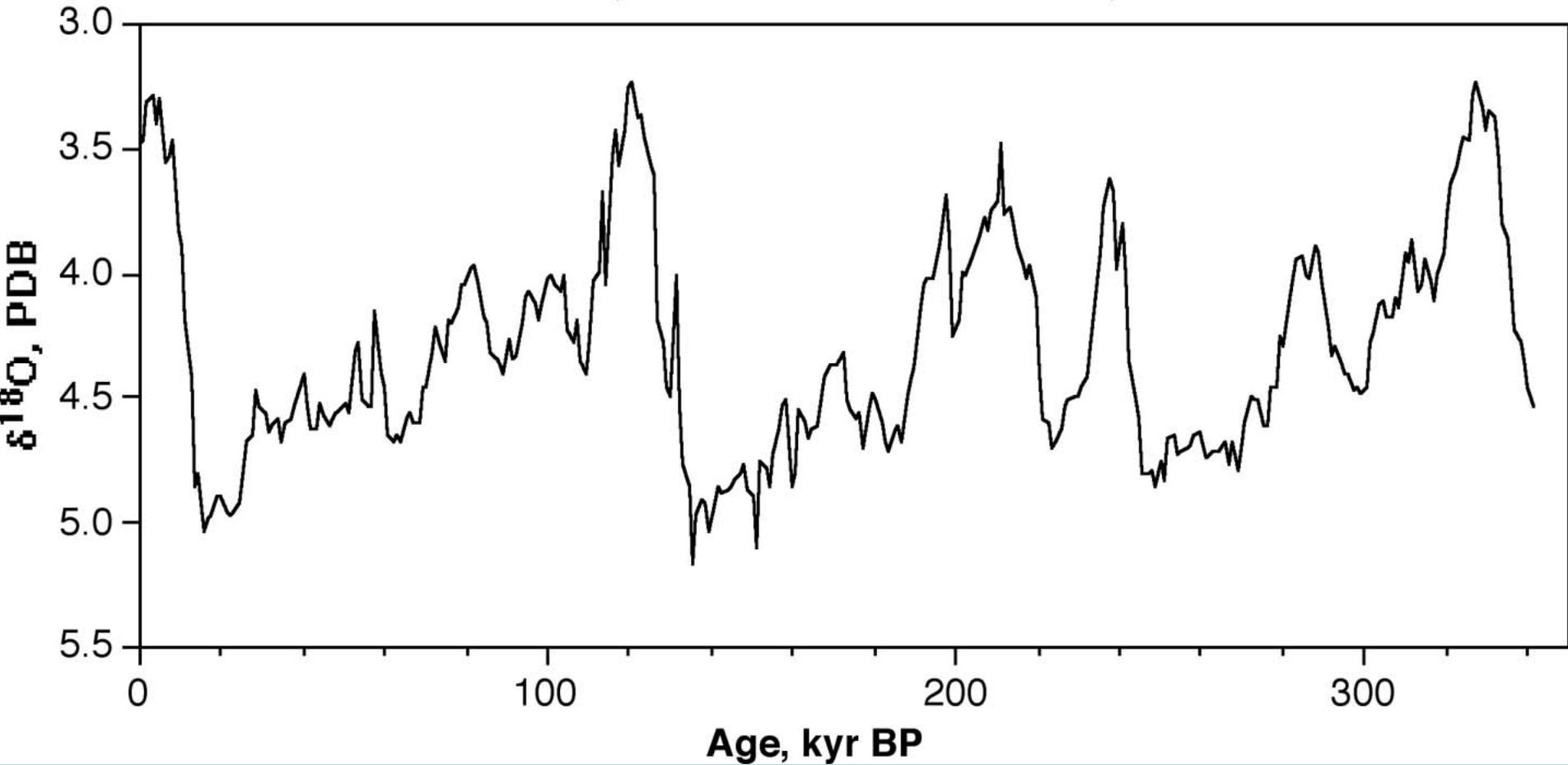
Emiliani's  $\delta^{18}\text{O}$  Stage notation

Seeming correlation with insolation record

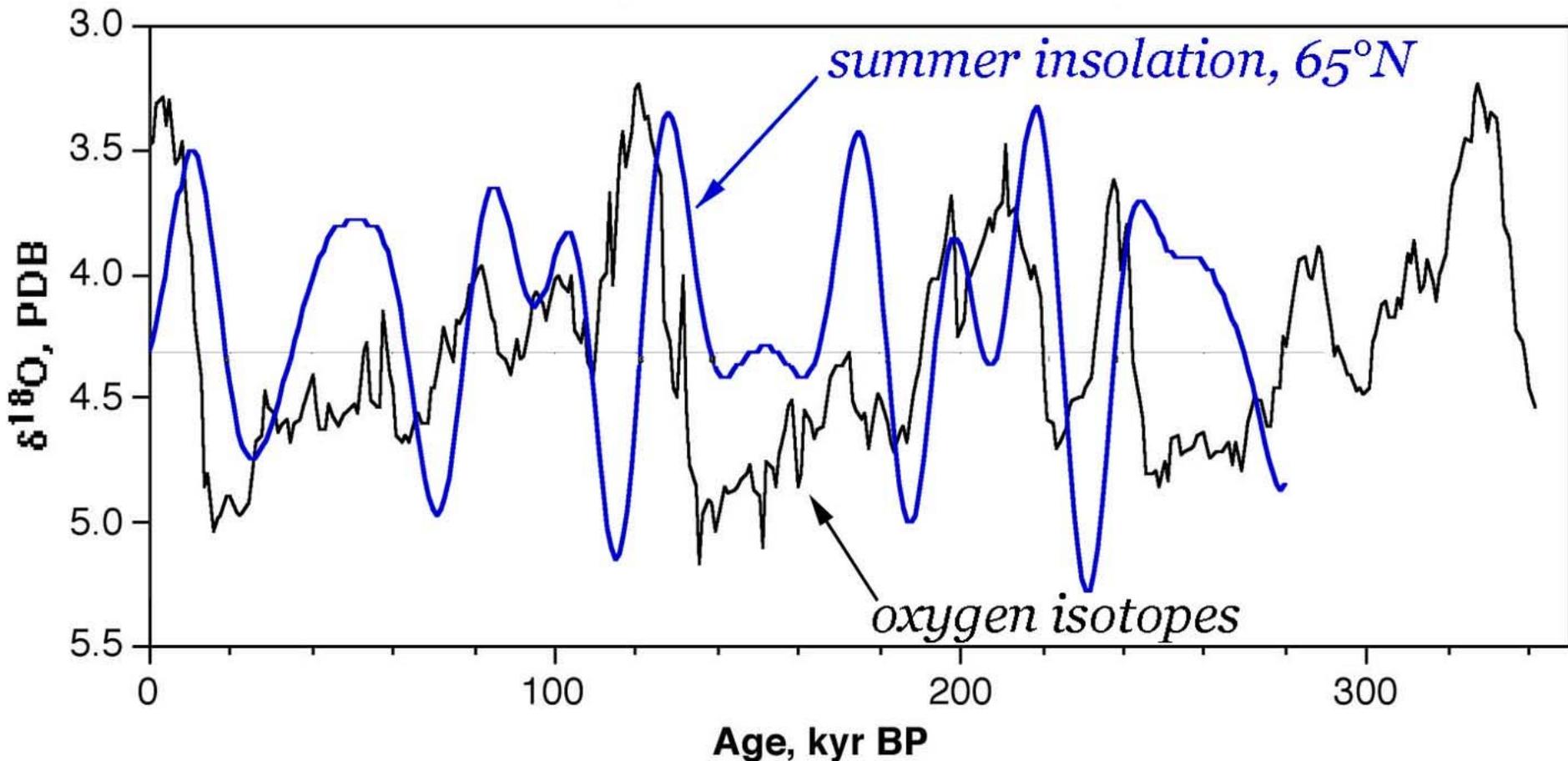
c) Abrupt climate change during the past 110,000 years: Stadial/Interstadial transitions.

# Deep sea $\delta^{18}\text{O}$ for the past 350,000 years

V19-30 (Shackleton and Pisias, 1984)



Milankovitch hypothesis:  
Deep-sea oxygen isotopes  
compared to summer insolation at 65°N



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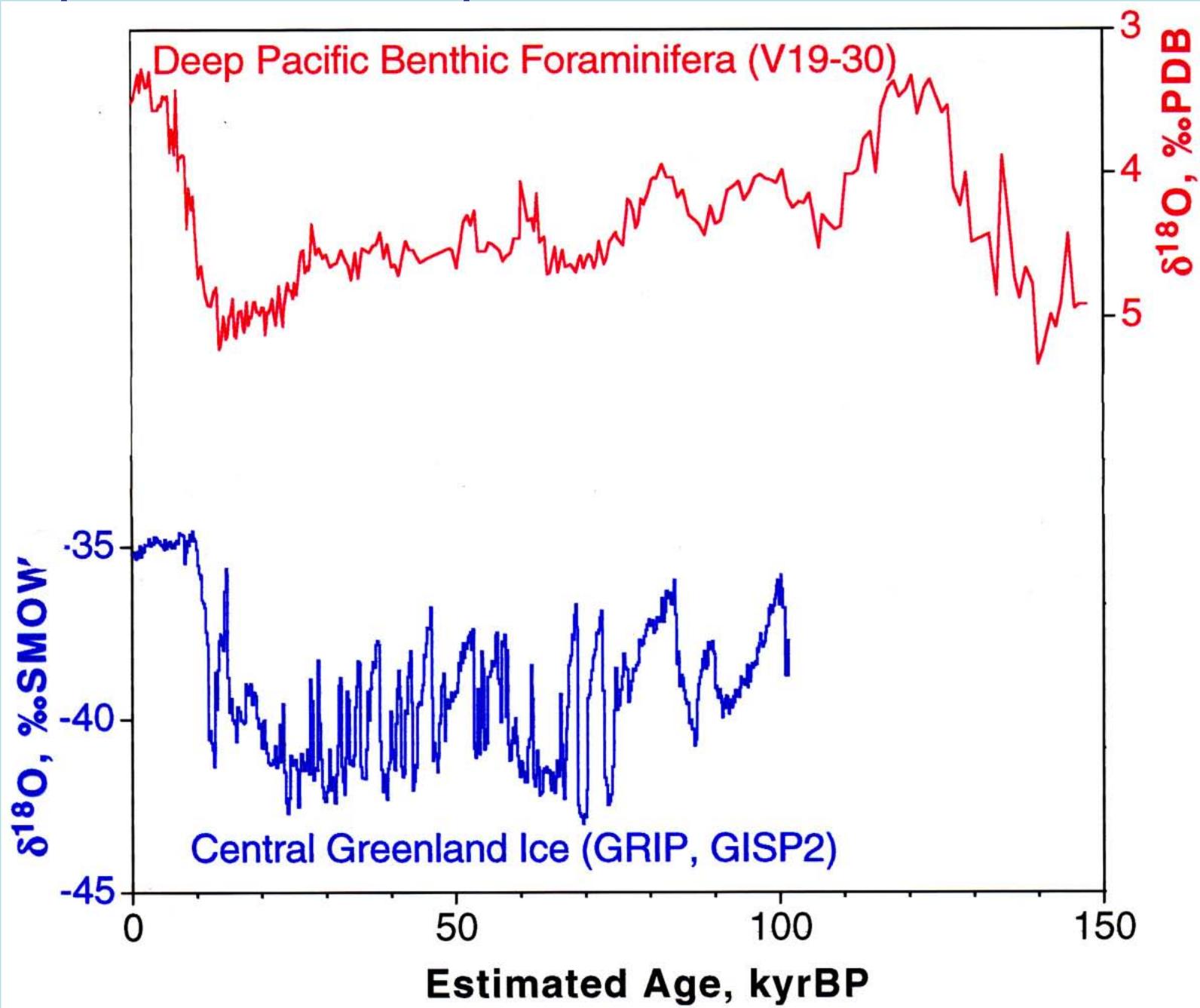
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# Deep Sea $\delta^{18}\text{O}$ compared to Greenland Ice Core $\delta^{18}\text{O}$

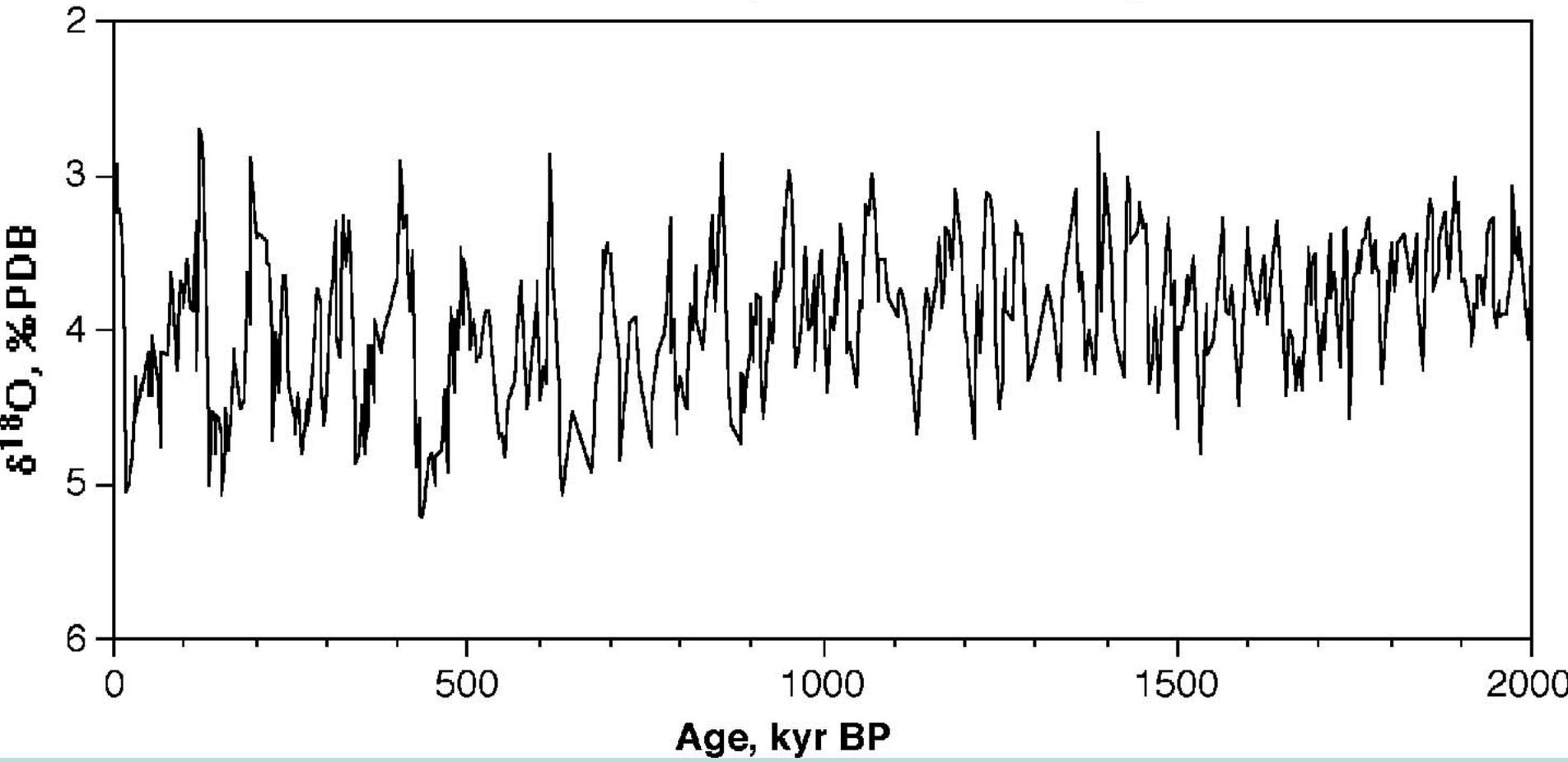


# The past 2 million years

Several more “100 kyr” “cycles”,

then: lower amplitude, "40K world"

ODP Site 659 (Tiedeman et al., 1994)



# Cenozoic Cooling 80->0 Ma

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Cretaceous/Cenozoic Meteor Impact!

# Absolute chronology and its importance for paleoclimatology

- Carbon-14 dating: 0-25 kyr BP (where reliable “initial C14” calibrations exist)
- Layer counting in sediments and ice cores: 0-40 kyr BP varves, density bands, annual dust cycles (but do you miss some bands or see two where only one should be?)
- $^{234}\text{U} \rightarrow ^{230}\text{Th}$  ingrowth in corals and speleothems: 0-250,000 kyr BP
- $^{40}\text{K} \rightarrow ^{40}\text{Ar}$  (best method uses  $^{39}\text{Ar}$  to measure  $^{40}\text{K}$ ) dating of basalts at magnetic reversals, applicable 0-200 million years B.P.
- Pb/U geochronology (past 200 ma and older yet...)

# How do we estimate a time scale for a marine sediment core or ice core?

- We measure depth and assume it is an increasing function of the age of the deposit (stratigraphy).
- For sediments <25 kyr BP containing appropriate carbonate or organic) fossils, we can measure the  $^{14}\text{C}$  content and determine the age from the atmospheric radiocarbon calibration.
- We can determine the  $\delta^{18}\text{O}$  of carbonate fossils and correlate the features to sea level events of known age (from  $^{230}\text{Th}$ - $^{234}\text{U}$  dating).
- For sediments with appropriate magnetic minerals, we can measure the magnetic alignment and determine the position of known ( $^{40}\text{Ar}/^{39}\text{Ar}$  dated) magnetic reversals.
- In-between these known dates, we must interpolate using some plausible (but un-provable) scheme.