Paleoclimatology

- **Background and History**
  - Louis Agassiz (1840): recognition of Ice Ages
  - Harold Urey (1947): *The Thermodynamic Properties of Isotopic Substances*
    - calculated temperature dependence of oxygen isotope fractionation between calcium carbonate and water
    - Proposed use of oxygen isotopes to quantify paleotemperatures.
  - Samuel Epstein (Urey's postdoctoral associate) grows mollusks in water of various temperatures. Finds following empirical relationship:
    - $\Delta = \delta^{18}O_{cal} - \delta^{18}O_{water} = 15.36 - 2.673\,(16.52 + T)^{0.5}$

The Record of Climate Change in Deep Sea Sediments

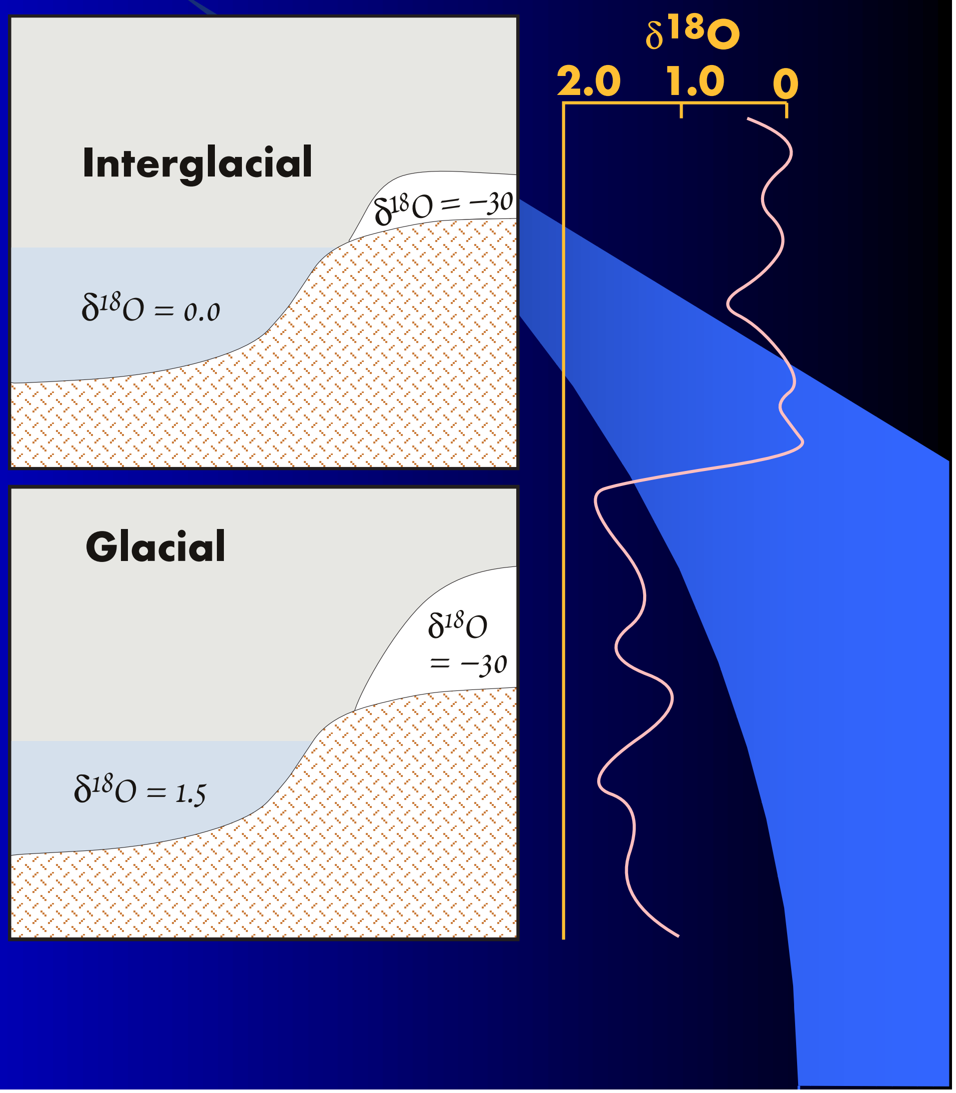
- **Ironically, while glaciers are a continental phenomenon, our best record of them is from the oceans.**
  - Each period of continental glaciation destroys record of previous one.
  - Deep sea sediments not disturbed by glaciation.
- **The question of chronology resolved through isotopic studies of deep sea biogenic sediments.**
  - **Principle:** fractionation of oxygen isotopes between carbonate and water is temperature dependent.
  - **Complication**: Isotopic composition of a shell also depends on the isotopic composition of water in which the organism grew.

Emiliani and The Quaternary $\delta^{18}O$ Record

- **First work on deep-sea sediment cores done by Emiliani (student of Urey) in 1955. Analyzed $\delta^{18}O$ in benthic and planktonic foraminifera from piston cores from world ocean.**
- **Emiliani's Conclusions:**
  - Last glacial cycled ended about 16,000 years ago.
  - Temperature increased steadily between then and about 6000 years ago.
  - Recognized 14 other global glacial–interglacial cycles over the last 600,000 years.
  - Bottom water in the Atlantic was 2° C cooler; bottom water in the Pacific was only 0.8° C cooler during glacial periods.
  - Fundamental driving force for Quaternary climate cycles was variations in the Earth's orbit and rotation (Milankovitch Hypothesis).

Revisions since Emiliani

- **Refining the time scale**
  - paleomagnetic stratigraphy as well as new geochronological tools (^{10}Be, Th isotopes, etc.)
- **Revision of the temperature scale.**
  - Average $\delta^{18}O_{SMOW}$ of glacial ice is –30 to -35‰, not –15‰ that Emiliani assumed.
  - Shackleton and Opdyke (1973):
  - Same isotopic variations occurred in both planktonic (surface-dwelling) and benthic (bottom dwelling) foraminifera.
  - Storage of isotopically light water in glacial ice was main effect causing oxygen isotopic variations; temperature effect secondary.



How much will glaciation affect d180 of the ocean?

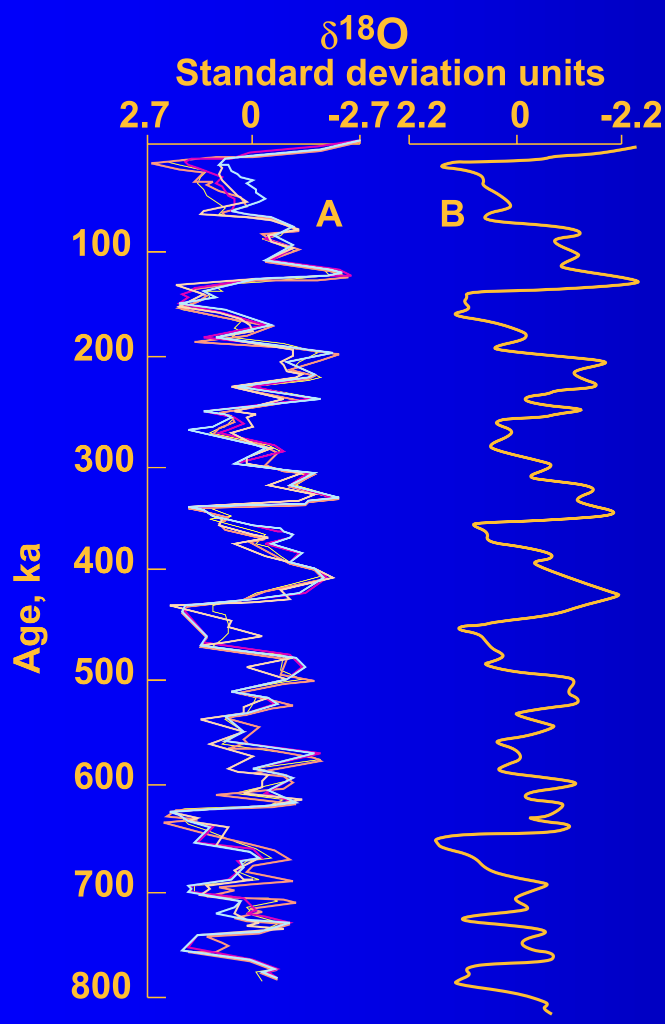
- **Assume glacial ice has a mean $\delta^{18}O$ of –30‰ relative to SMOW,**
  - the present volume of continental ice is 27.5×10^6 km^3
  - the volume of the oceans is 1350×10^6 km^3 (ice is 2.037% of the oceans)
  - total hydrosphere then has $\delta^{18}O$ of –0.6‰ (neglecting freshwater).

- **At the height of the Wisconsin Glaciation, the volume of glacial ice increased by 42×10^6 km^3, corresponding to a lowering of sea level by 125 m.**
- **If the $\delta^{18}O$ of ice was the same (–30‰), the $\delta^{18}O$ of the ocean would have increased by 1.59‰.**

How does this affect calculated temperature?

- Emiliani would have calculated that an increase in $\delta^{18}O$ of 2‰ corresponds to $\Delta T = 6°$ C (assuming 0.5‰ change in $\delta^{18}O$ of water).
- If the change in $\delta^{18}O$ is actually 1.5‰, the calculated ΔT is only about 2° C.
- Volume of glacial ice and its isotopic composition is important and must be resolved before paleotemperatures can be calculated.
- Comparison of sealevel curves derived from dating of terraces and coral reefs indicate that each 0.011‰ variation in $\delta^{18}O$ represents a 1 m change in sealevel.

SPECMAP δ18O



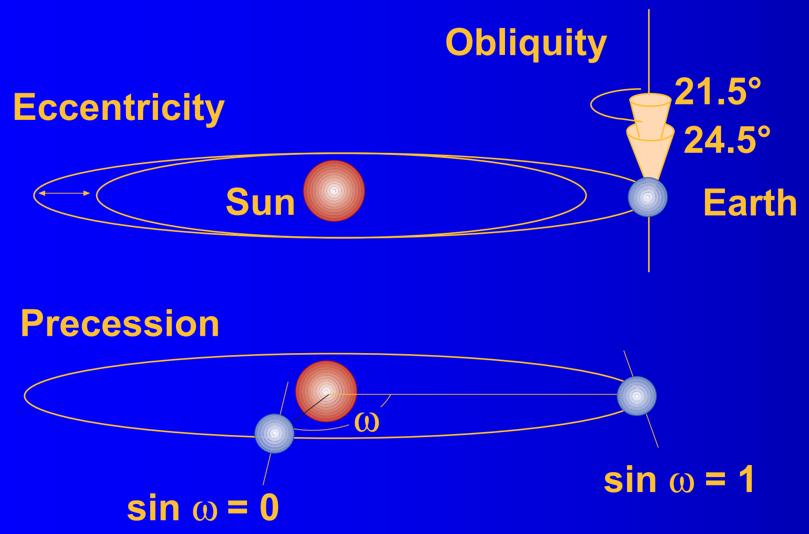
- **Correlating from core to core can sometimes be difficult but is the first step in understanding the global climate change signal.**
  - A. "Stacking of five cores" selected by Imbrie et al. (1984).
    - Because the absolute value of $\delta^{18}O$ varies in from core to core, the variation is shown in standard deviation units.
  - B. Smoothed average of the five cores in A.
- **Global curve shows a periodicity of approximately 100,000 yrs.**

The Cause of Quaternary Glaciations

- **The same 100,000 yrs periodicity was apparent in Emiliani's initial work and led him to conclude that the glacial-interglacial cycles were due to variations in the Earth's orbital parameters.**
  - These are often referred to as the Milankovitch cycles, after M. Milankovitch, a Serbian astronomer who argued they caused the ice ages in the early part of the twentieth century†.

†While Milankovitch was a strong and early proponent of the idea that variations in the Earths orbit caused ice ages, J. Croll of Britain first suggested it in 1864, and published several subsequent papers on the subject.

Milankovitch Parameters



- **Eccentricity, *e***: degree the Earth's orbit departs from circular.
- **Obliquity, ε**: tilt of the Earth's rotation axis with respect to the plane of the ecliptic; varies between 21.5° and 24.5°.
- **Precession, ω** : variation in the direction of tilt at the Earth's closest approach to the Sun (perihelion). ω is the angle between the Earth's position on June 21 and perihelion.

How does this affect climate?

- Changes in these parameters have negligible effect on the total radiation the Earth receives, but they do affect the pattern of incoming radiation (insolation).
- Tilt of the rotational axis determines the latitudinal gradient of insolation and therefore seasonality. It is this gradient that drives atmospheric and oceanic circulation.
- Precession relative to the eccentricity of the Earth's orbit also affects seasonality. For example, the Earth presently is closest to the Sun in January. As a result, northern hemisphere winters (and southern hemisphere summers) are somewhat milder than they would be otherwise. For a given latitude and season, precession will result in a ±5% difference in insolation

Periodicity

- Variation in tilt approximates a simple sinusoidal function with a period of 41,000 yrs.
- Variations in eccentricity can generally be adequately described with characteristic period of 100,000 years. In detail, however, variation in eccentricity is complex, and is more accurately described with characteristic periods of 123,000 yrs, 85,000 yrs, and 58,000 yrs.
- Variation in precession has characteristic periods of 23,000 and 18,000 yrs.

Quantifying the Milankovitch Hypothesis: Hayes and others (1976)

- First quantitative approach to the problem was that of Hayes et al. (1976). They applied Fourier analysis to the $\delta^{18}O$ curve, a mathematical tool that transforms a complex variation to the sum of a series of simple sin functions.
- Then used spectral analysis to show that much of the spectral power of the $\delta^{18}O$ curve occurred at frequencies similar to those of the Milankovitch parameters.

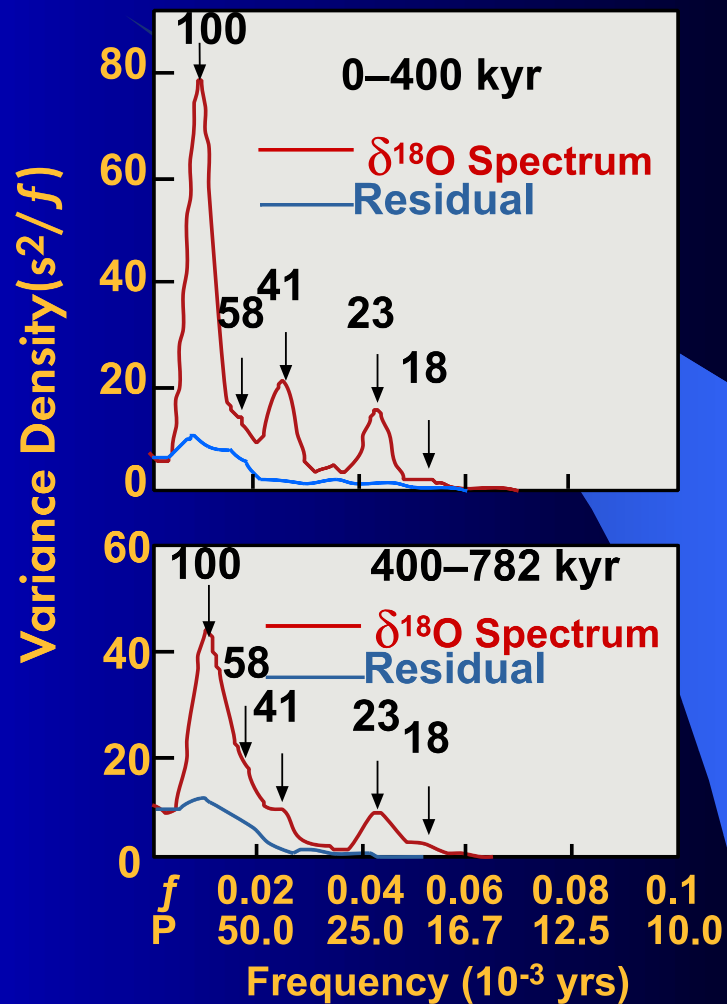
Quantifying the Milankovitch Hypothesis: Imbrie (1985)

- Imbrie noted Milankovitch parameters might vary with time, as might the climate system's response to them. Thus, Imbrie treated the first and second 400,000 years of SPECMAP curve separately.
- Also noted that the climate might not respond immediately and might have different sensitivities to different parameters.
- Mathematically stated, if there are two forcing factors (x), each might have its own gain (g) and phase lag (ϕ), so the response (y) would be

$$y = g_1(x_1 - \phi_1) + g_2(x_2 - \phi_2)$$

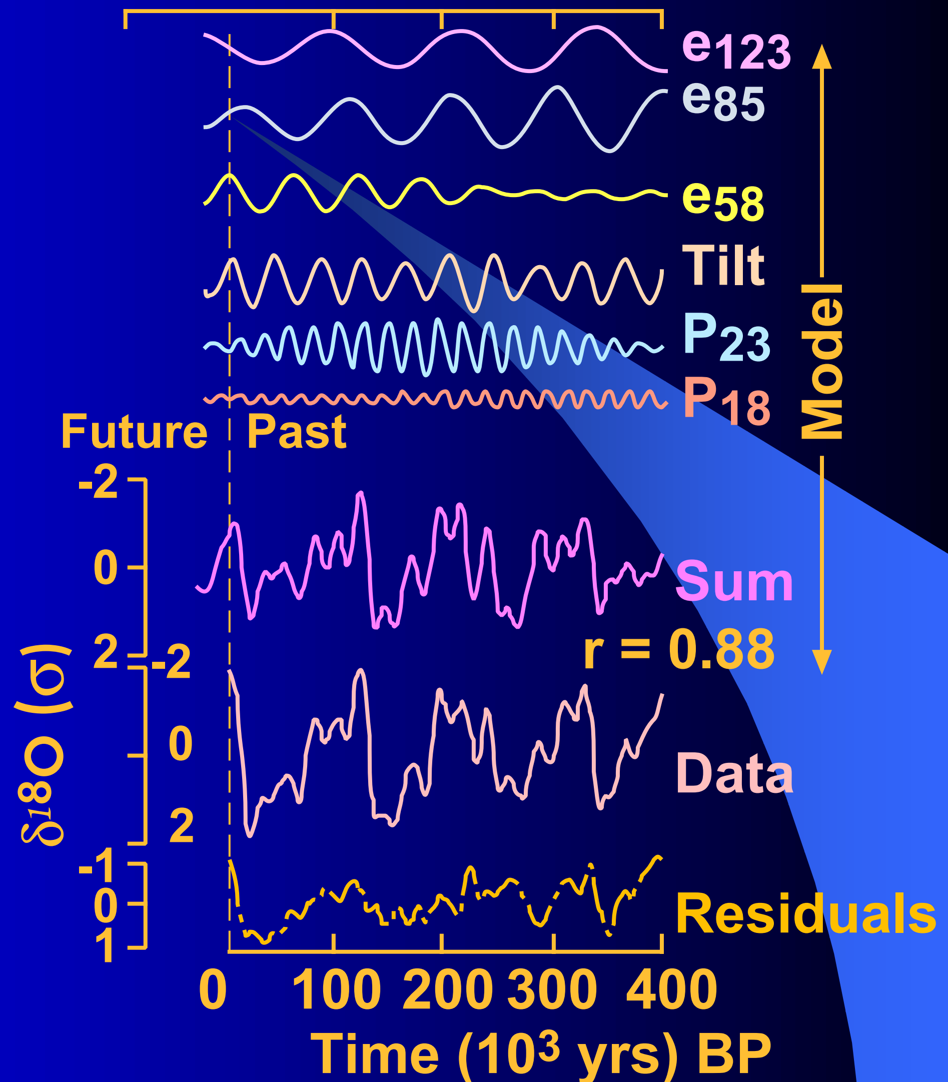
Imbire's Gain and Phase Model

- Imbrie constructed a model for response of global climate (as measured by the $\delta^{18}O$ curve) in which each of the 6 Milankovitch forcing functions was associated with a different gain and phase.
- Values of gain and phase for each parameter were found statistically by minimizing the residuals of the power spectrum.



Imbrie's Model

- Model compared with the $\delta^{18}O$ for the past 400,000 years and the next 25,000 years
- The model has a correlation coefficient, r, of 0.88 with the data, meaning that 77% (r^2) of the variation in $\delta^{18}O$, (and presumably in ice volume) can be explained by Milankovitch hypothesis.
- The correlation for the period 400,000–782,000 yrs is a little weaker, 0.80.



Why does Imbrie's model work?

- Variations in the Earth's orbital parameters do not affect average annual insolation the Earth receives, but only the pattern in space and time.
- The key factor seems to be the summer insolation at high northern latitudes. This is, the area where large continental ice sheets develop. Glaciers apparently develop when summers are not warm enough to melt the winter's accumulation of snow.
- The southern hemisphere, except for Antarctica, which is fully glaciated even in interglacial periods, is largely ocean, and therefore not subject to glaciation.

The Need for "Feedback" Mechanisms

- **Variation in insolation not enough to drive climate variations.**
- **Feedback mechanisms must amplify the Milankovitch forcing function.**
  - Albedo
    - Identified by Agassiz.
    - Snow and ice reflect much of the incoming sunlight back into space. Thus as glaciers advance, they will cause further cooling.
    - Additional accumulation of ice in Antarctica does not increase albedo, because the continent is fully ice covered even in glacial times.
    - Hence the dominant role of northern hemisphere insolation in driving climate cycles.
  - Other feedback mechanisms?
  - carbon dioxide
  - ocean circulation