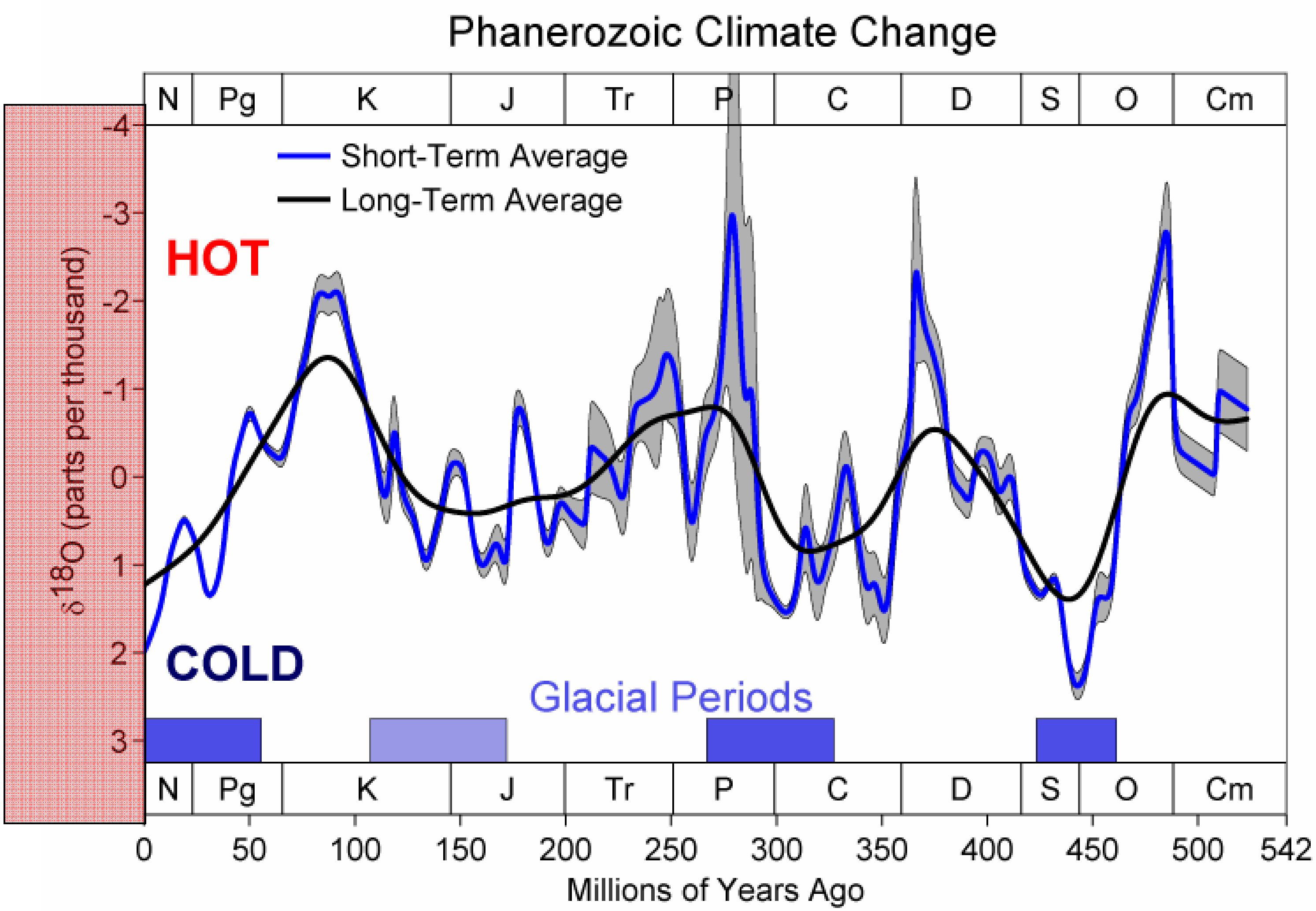
Climate and Environment

Oxygen Isotope Fractionation and Measuring Ancient Temperatures


Phanerozoic Climate Change
N
Pg
K
J
Tr
P
C
D
S
O
Cm
Short-Term Average
Long-Term Average
HOT
COLD
Glacial Periods
δ18O (parts per thousand)
-4
-3
-2
-1
0
1
2
3
0
50
100
150
200
250
300
350
400
450
500
542
Millions of Years Ago

Oxygen Isotope Ratio Cycles

Oxygen isotope ratio cycles are cyclical variations in the ratio of the mass of oxygen with an atomic weight of 18 to the mass of oxygen with an atomic weight of 16 present in some substance, such as polar ice or calcite in ocean core samples.

The ratio is linked to water temperature of ancient oceans, which in turn reflects ancient climates. Cycles in the ratio mirror climate changes in geologic history.

Oxygen Isotope Fractionation

Oxygen (chemical symbol O) has three naturally occurring isotopes: ^{16}O, ^{17}O, and ^{18}O, where the 16, 17 and 18 refer to the atomic weights.

- The most abundant is ^{16}O, with a small percentage of ^{18}O and an even smaller percentage of ^{17}O.
- Oxygen isotope analysis considers only the ratio of ^{18}O to ^{16}O present in a sample.

- ^{18}O is heavier than ^{16}O and it takes more energy to vaporize water with $H_2{}^{18}O$ than to vaporize $H_2{}^{16}O$.
- Therefore the first water vapor formed during evaporation of liquid water is enriched in $H_2{}^{16}O$.
- And the water left behind is enriched with $H_2{}^{18}O$.

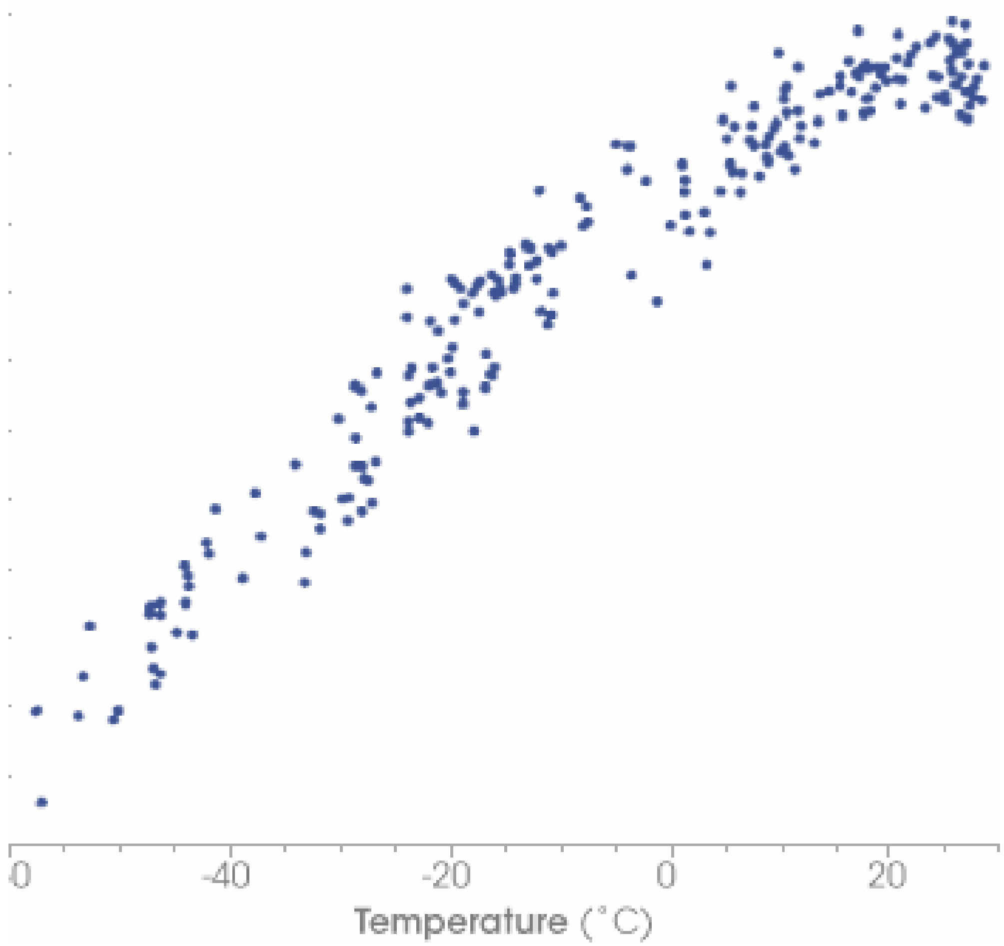
Oxygen Isotope Fractionation

Conversely, when water vapor condenses into liquid, $H_2{}^{18}O$ preferentially enters the liquid, while $H_2{}^{16}O$ is concentrated in the remaining vapor.

BUT, the ratio of ^{16}O to ^{18}O is dependent on the ambient temperature.

- A relatively warm temperature produces snow or rain of a relatively higher concentration of the heavier isotope.
- And a relatively cooler temperature produces snow or rain of a relatively lower concentration of the heavier isotope.

Oxygen Isotope Fractionation



The concentration of ^{18}O in precipitation decreases with temperature. This graph shows the difference in ^{18}O concentration in annual precipitation compared to the average annual temperature at each site. The coldest sites, in locations such as Antartica and Greenland, have about 5 percent less ^{18}O than ocean water. (Graph adapted from Jouzel et. al., 1994)

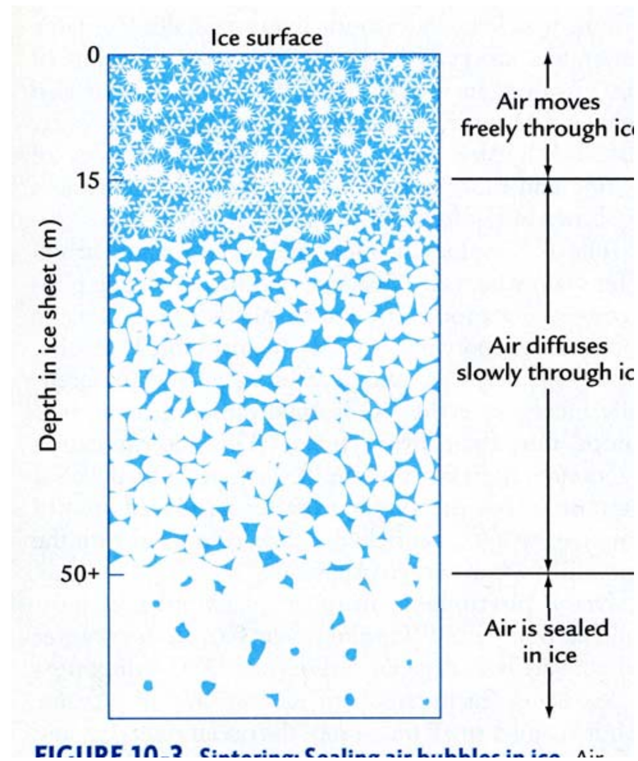
http://earthobservatory.nasa.gov/Study/Paleoclimatology_OxygenBalance/oxygen_balance.html

Oxygen Isotope Fractionation

Therefore, variations in the ratio of ^{16}O to ^{18}O can be used to measure the temperature of the environment at the time the deposits were formed.

Deposits with oxygen isotopes show up in a variety of abundant and widely distributed substances.

- Rain, and snow, and glacial ice.

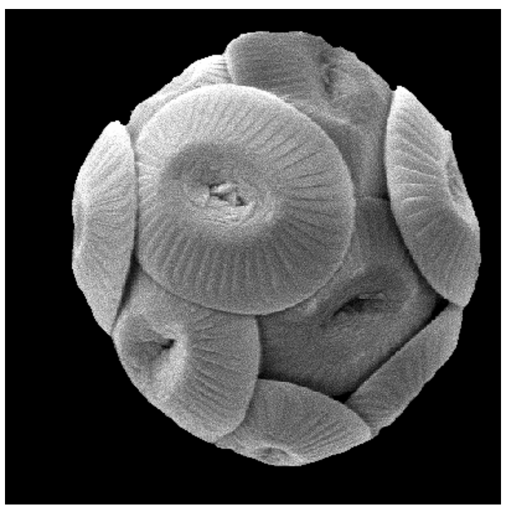


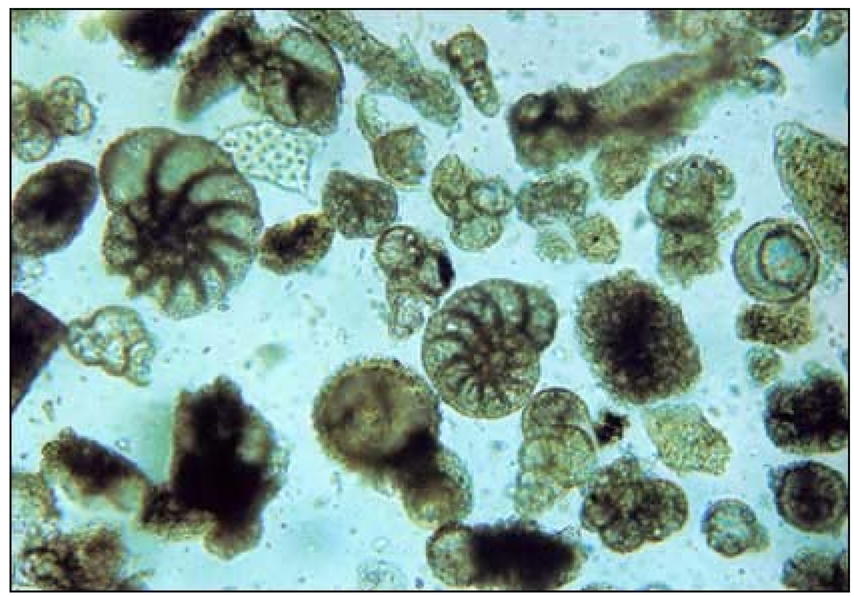
Oxygen Isotope Fractionation

Therefore, variations in the ratio of ^{16}O to ^{18}O can be used to measure the temperature of the environment at the time the deposits were formed.

Deposits with oxygen isotopes show up in a variety of abundant and widely distributed substances.

- Rain, and snow, and glacial ice.
- Carbonate sea shells.

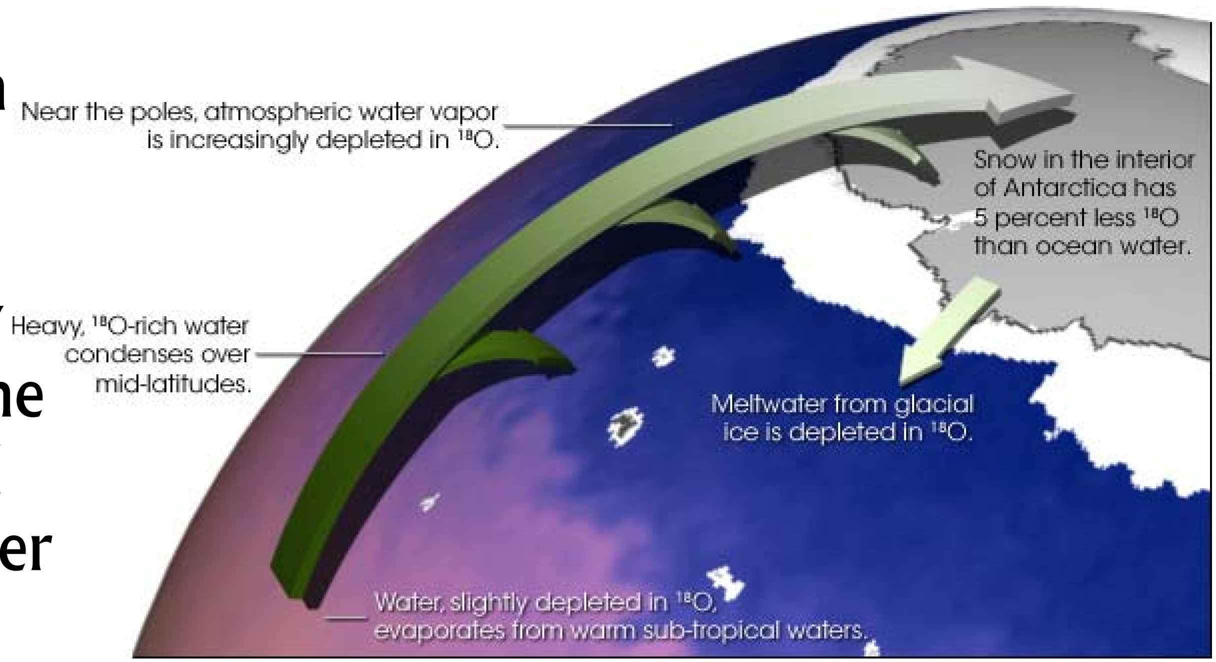




During Ice Ages . . .

. . . cooler temperatures extend toward the equator, so the water vapor containing heavy oxygen rains out of the atmosphere at even lower latitudes than it does under milder conditions. The water vapor containing light oxygen moves toward the poles, eventually condenses, and falls onto the ice sheets where it stays.

The water remaining in the ocean develops increasingly higher concentration of heavy oxygen compared to the universal standard, and the ice develops a higher concentration of light oxygen.

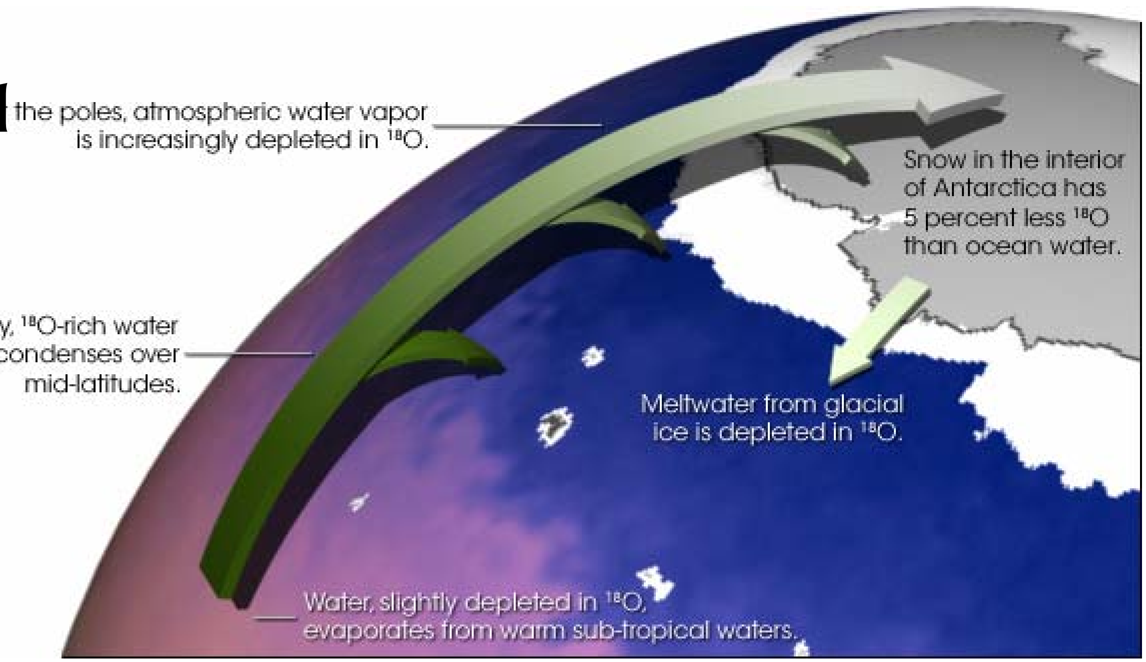


http://earthobservatory.nasa.gov/Study/Paleoclimatology_OxygenBalance/oxygen_balance.html

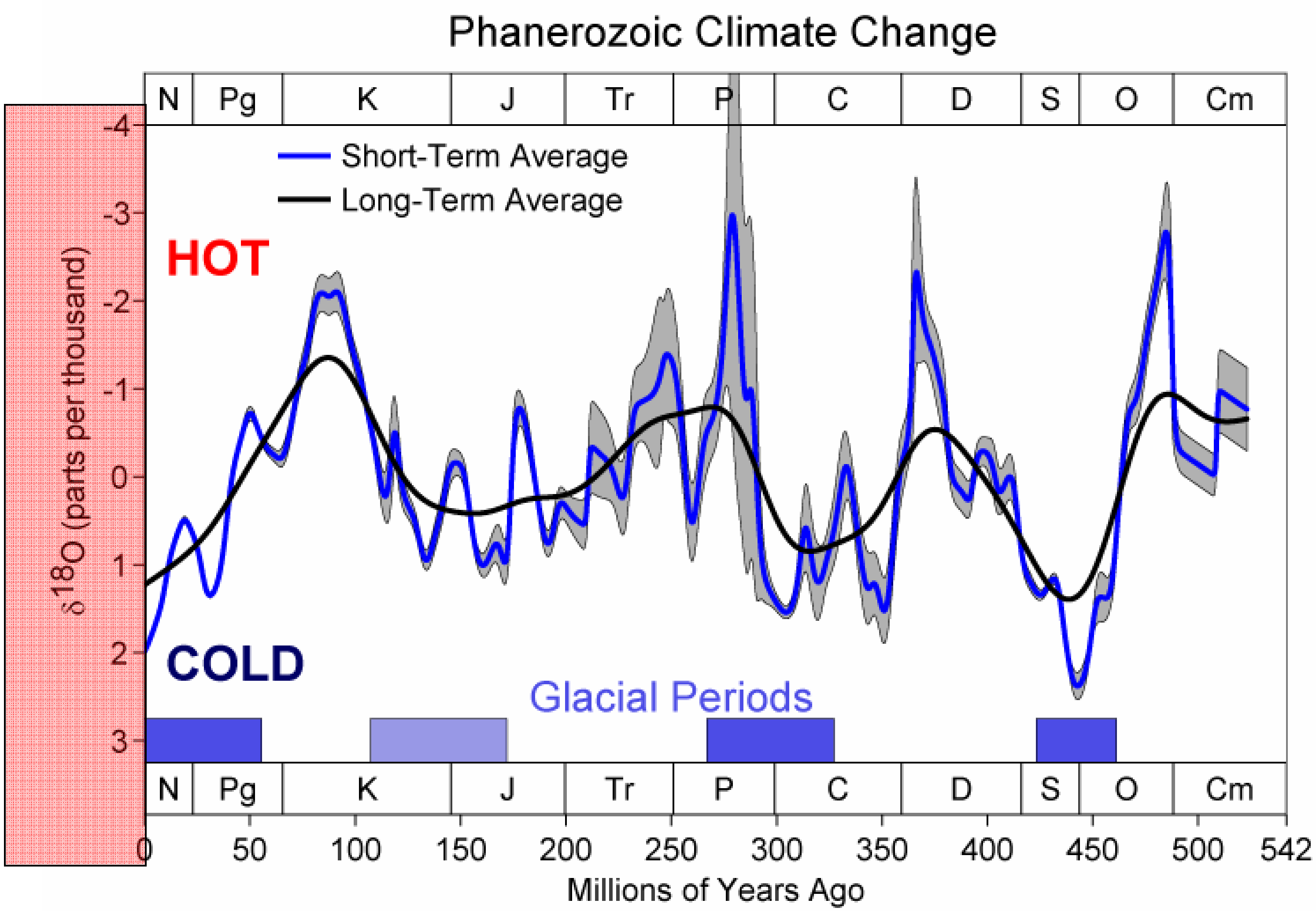
Between Ice Ages . . .

. . . as temperatures rise, ice sheets melt, and freshwater runs into the ocean. Melting returns light oxygen to the water, and reduces the salinity of the oceans worldwide.

Higher-than-standard global concentrations of light oxygen in ocean water indicate that global temperatures have warmed, resulting in less global ice cover and less saline waters.



http://earthobservatory.nasa.gov/Study/Paleoclimatology_OxygenBalance/oxygen_balance.html


Phanerozoic Climate Change
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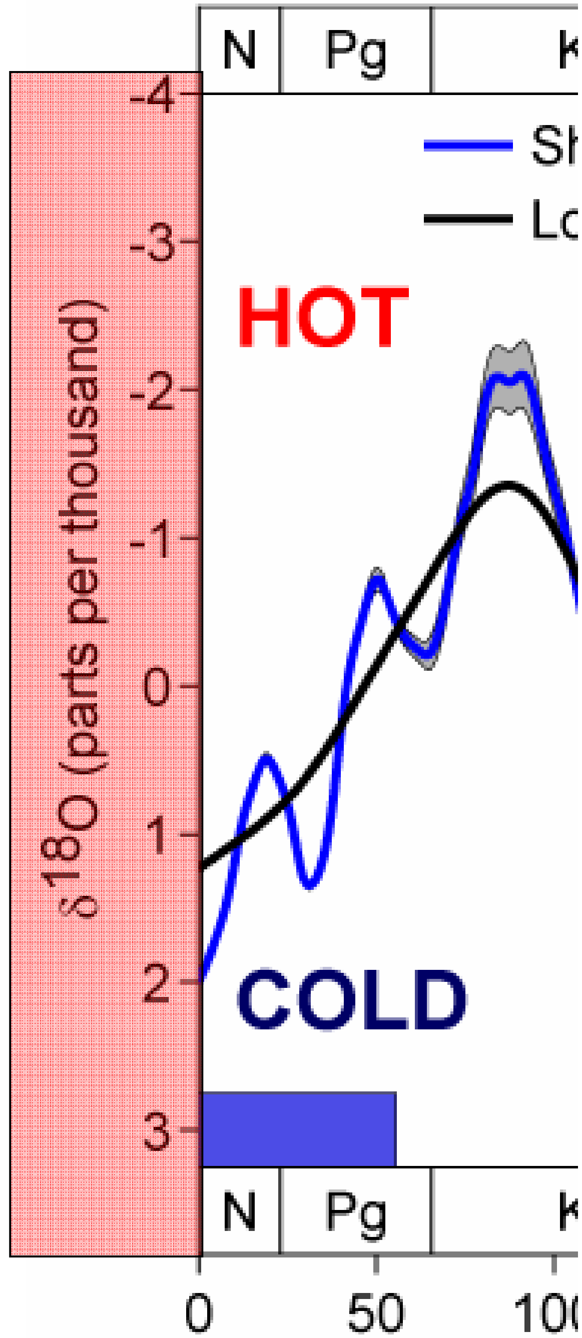
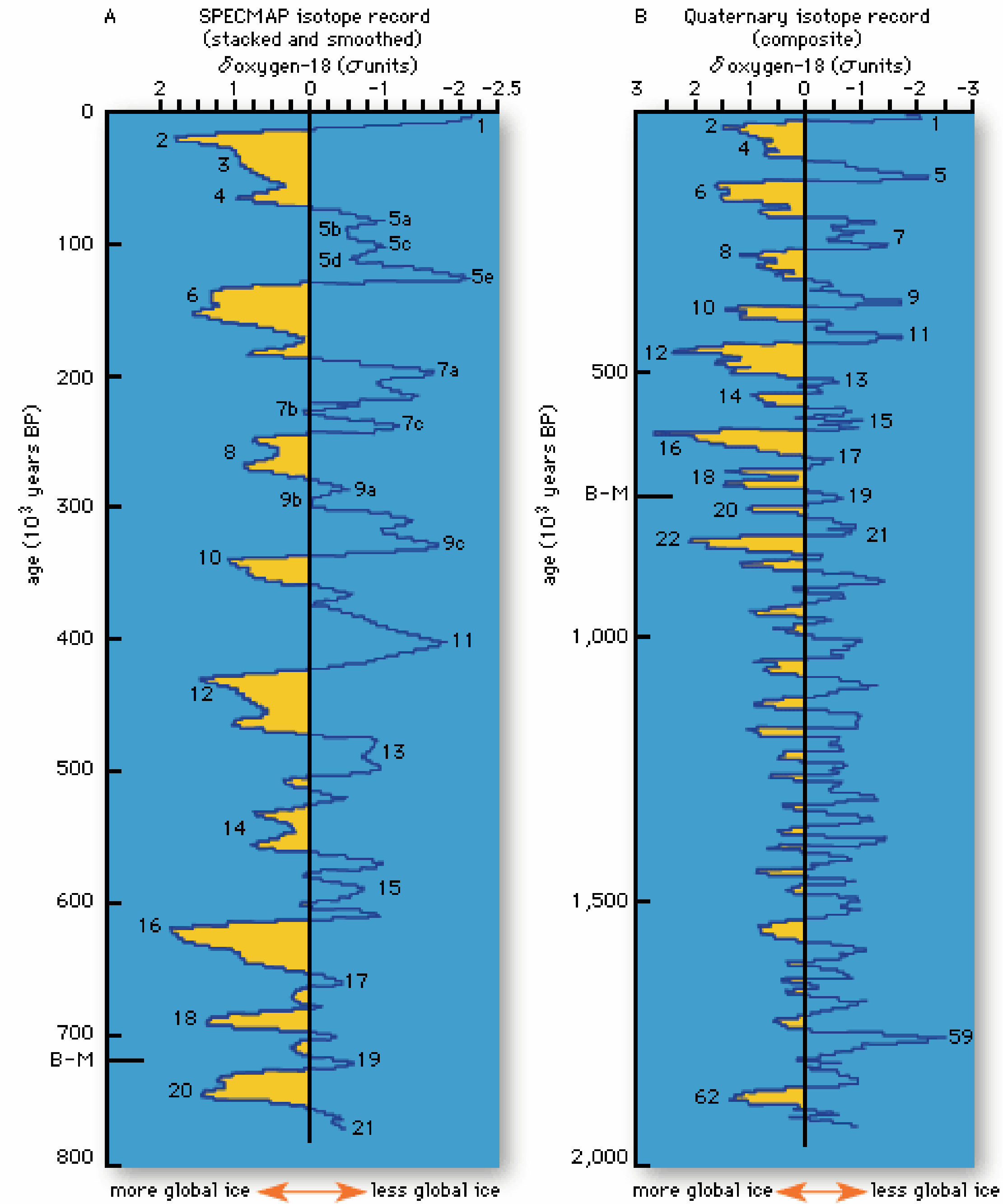
Millions of Years Ago

Negative numbers of ^{18}O mean the temperature is warm

Negative means warm
Positive means cold

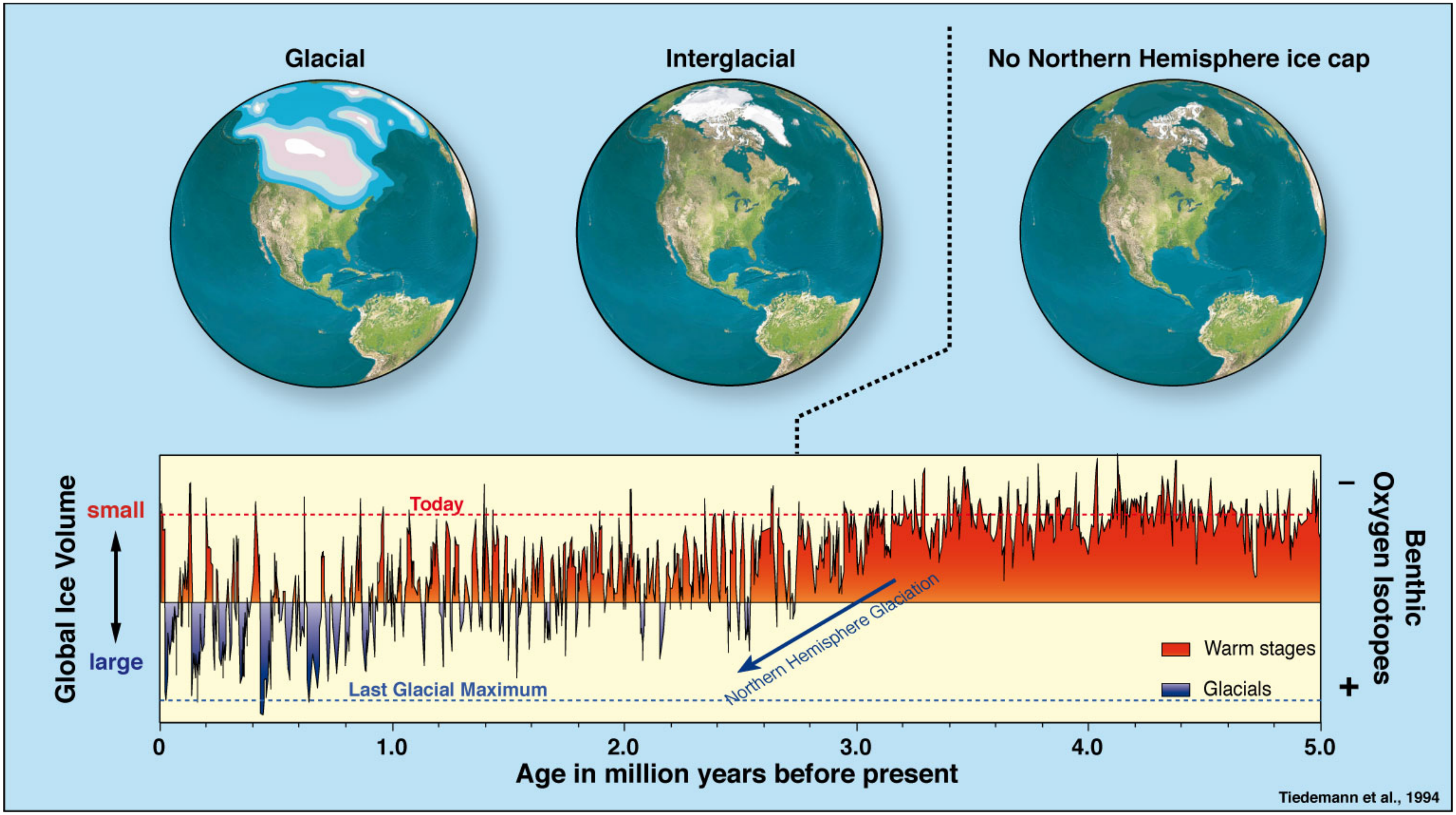
Positive numbers of ^{18}O mean the temperature is cold.





(A) The SPECMAP (Spectral Mapping Project) record based on five low- and middle-latitude deep-sea cores and (B) a composite record of four cores from the equatorial Pacific, the Caribbean, and the North Atlantic. Isotopic stages and substages are indicated; B-M shows the level of Brunhes-Matuyama reversal.

ıica.com/ebc/art/print?id=1720



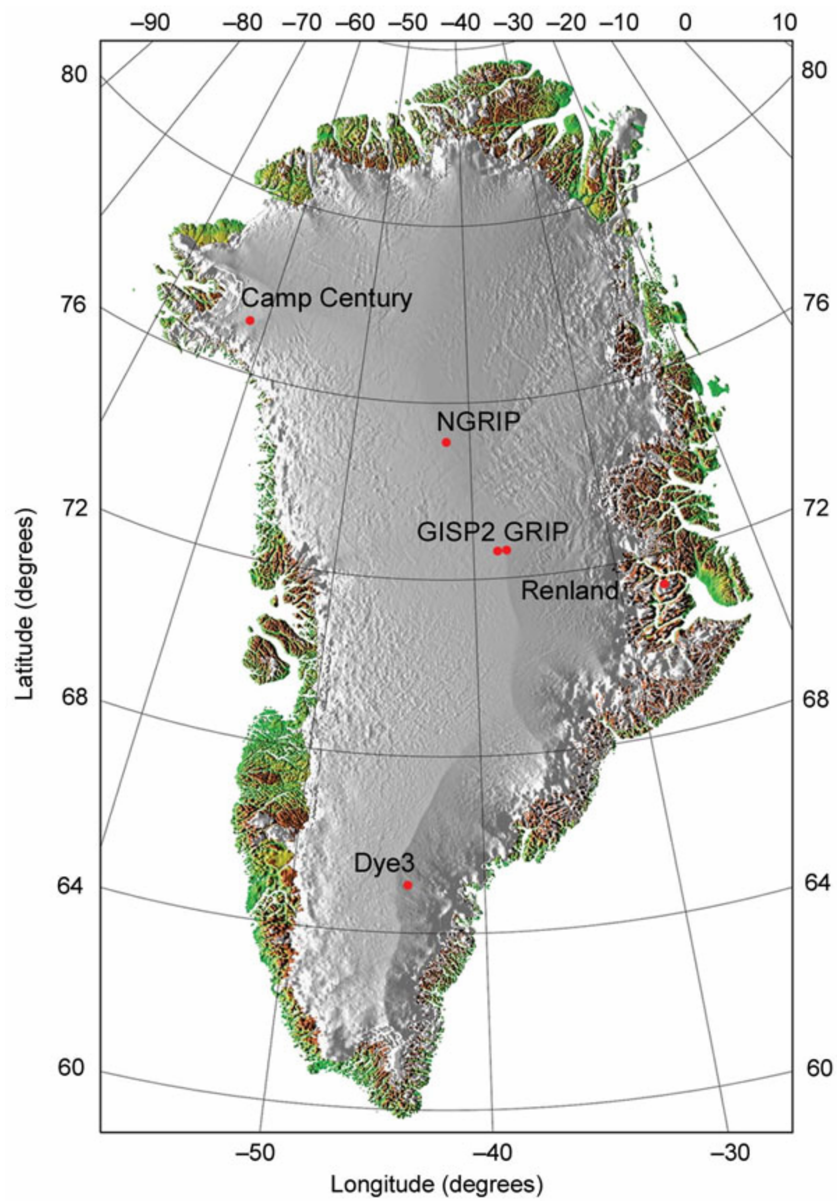
The benthic oxygen isotope curve reflects the global climate evolution of the last 5 million years, as it is a measure of changes in global ice volume and deep-water temperature. The Pliocene warm period from ~5 to ~3 million years ago is believed to hold clues for assessing future climate change. This time interval, with atmospheric CO2-concentrations close to modern ones, was significantly warmer than today. High-latitude sea surface temperatures were up to 7°C higher, the modern Northern Hemisphere ice cap over Greenland was absent, and the sea level was about 30 m higher than today. Hence, it represents a possible future climate scenario predicted by numerical models. The long-term increase in oxygen isotope values from ~3–2.5 million years ago marks the development of a permanent Northern Hemisphere ice cap with varying size. The last 3 million years are characterized by alternating glacial and interglacial climate stages, while glacial ice sheets reached their largest size during the last 700.000 years.

http://www.awi.de/de/forschung/fachbereiche/geowissenschaften/marine_geology_and_paleontology/

Glacial Ice Drilling Projects

Camp Century and other Greenland Research Stations

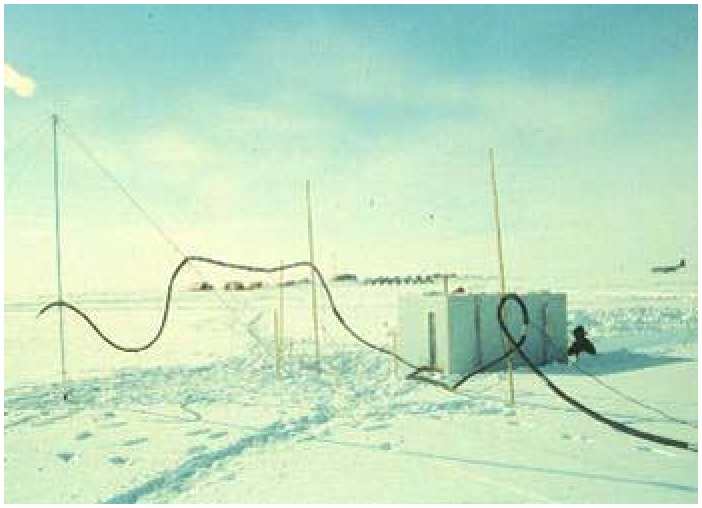
From 1989 to 1994, the U.S. and European scientific communities supported a bold undertaking to acquire an extensive paleoclimate record for the Northern Hemisphere.



Greenland Ice Core Project

Greenland Ice Sheet Project Two (GISP2)

/v431/n7005/fig_tab/nature02805_F1.html



http://zero.eng.ucmerced.edu/rcbales/Summit/whitepaper.html

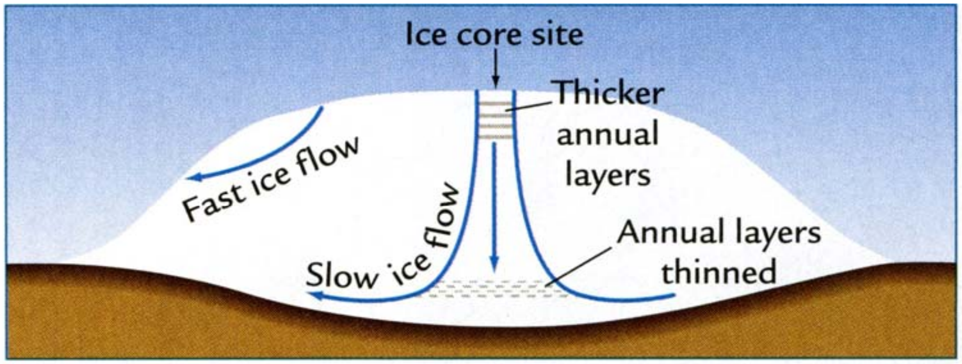
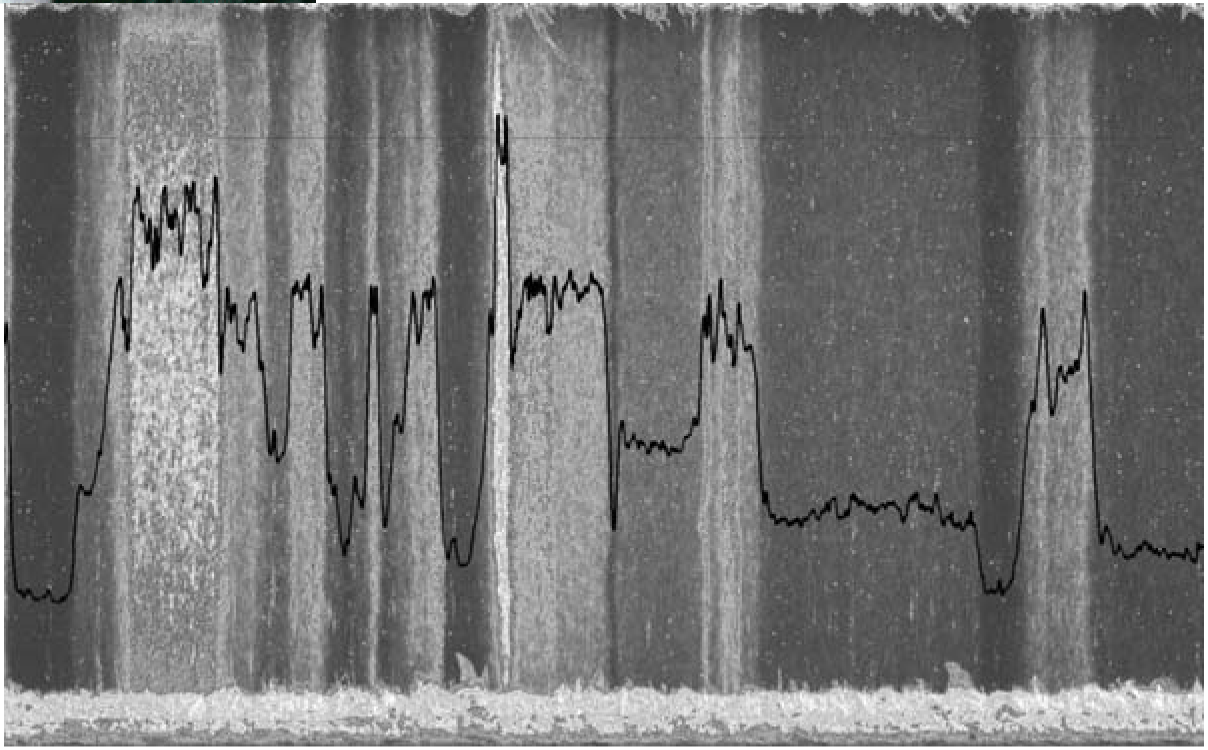


FIGURE 10-1 **Ice coring** The best place on an ice sheet to take ice cores is at the top of the ice dome because ice flows slowly down into the ice sheet and old ice is preserved at the bottom.

http://www.aip.org/history/climate/xCampCent.htm

http://www.emporia.edu/earthsci/student/tinsley1/drilling.jpg



Here is a photo of ice in a core collected by from the North Greenland Ice Core Project showing annual layers of the ice from about 1800 m depth, which means the ice is about 20 000 years old. The curve shows the variations in light intensity measured by a line scanner showing the light intensity scattered from the ice.

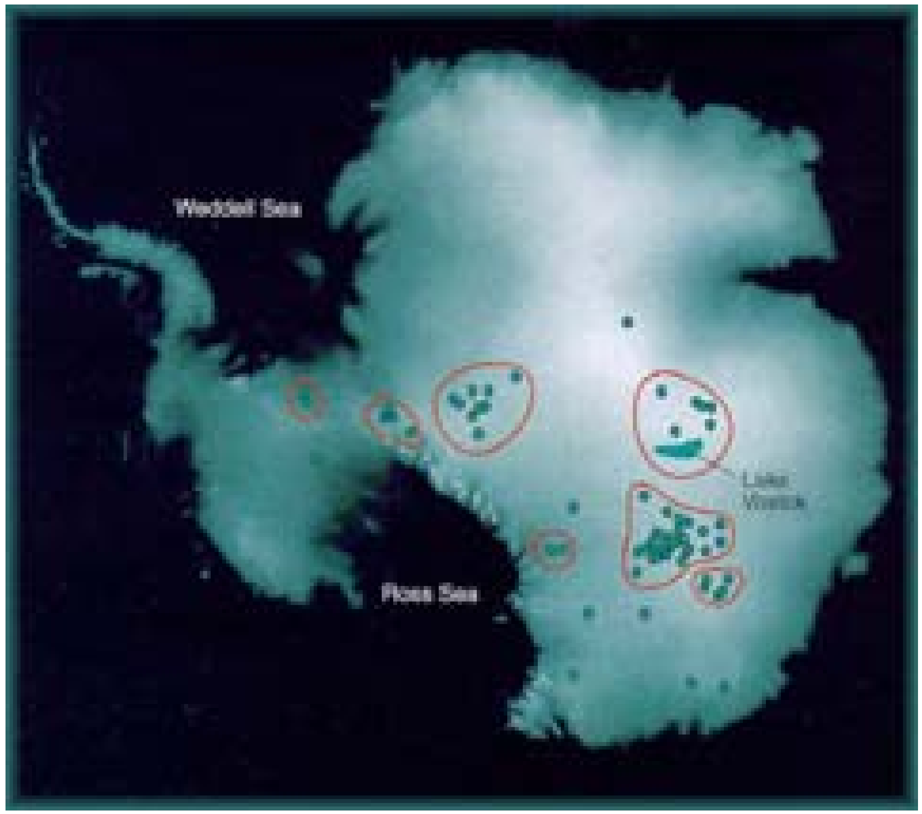
http://oceanworld.tamu.edu/resources/oceanography-book/Images/kennedy(2006)-fig.gif

http://www.ssec.wisc.edu/icds/gallery/albums/DISC/NICL_core_tray_set_up_001.jpg

Vostoc and Other Antartic Research Stations

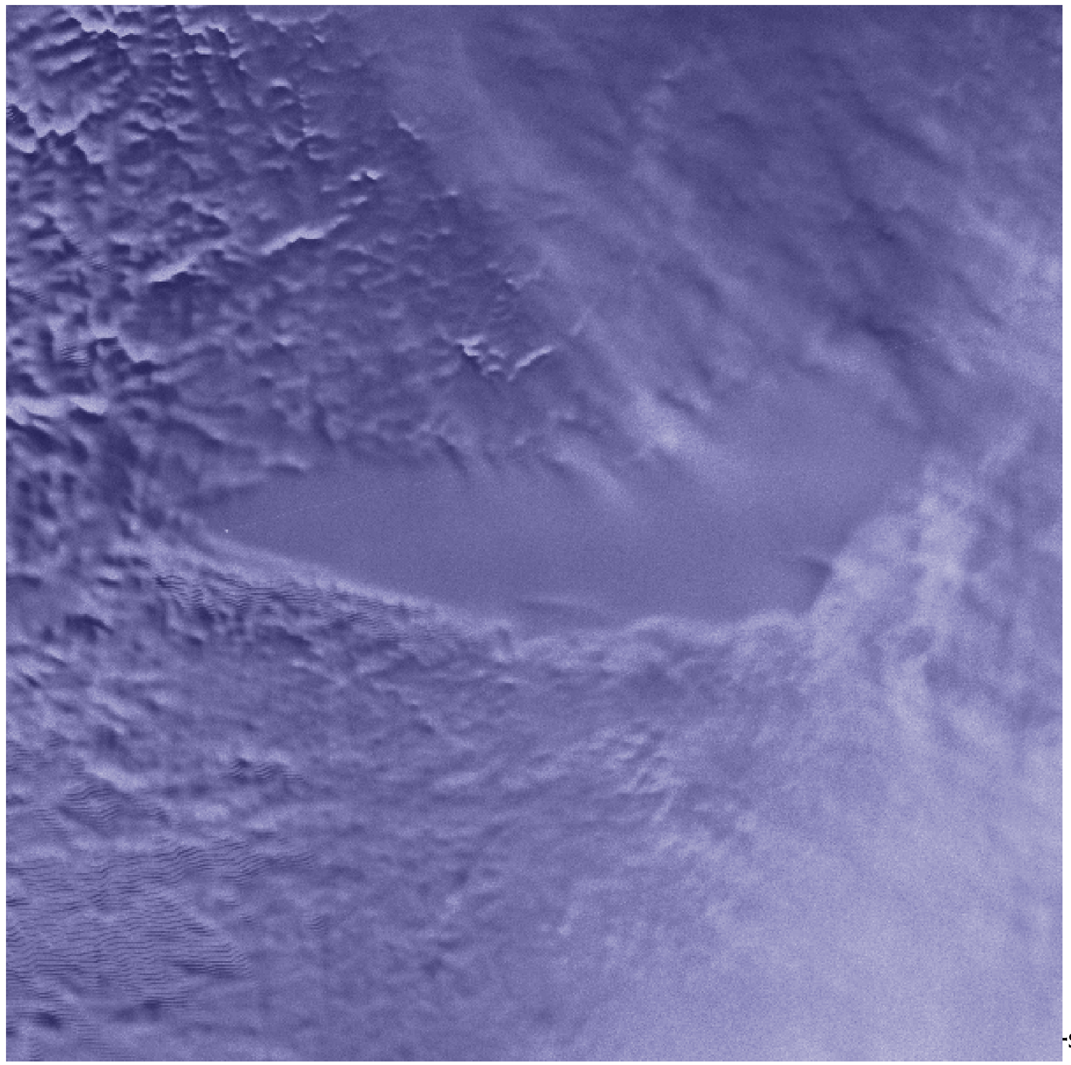
http://salegos-scar.montana.edu/docs/Images.htm

Vostoc and Other Antartic Research Stations



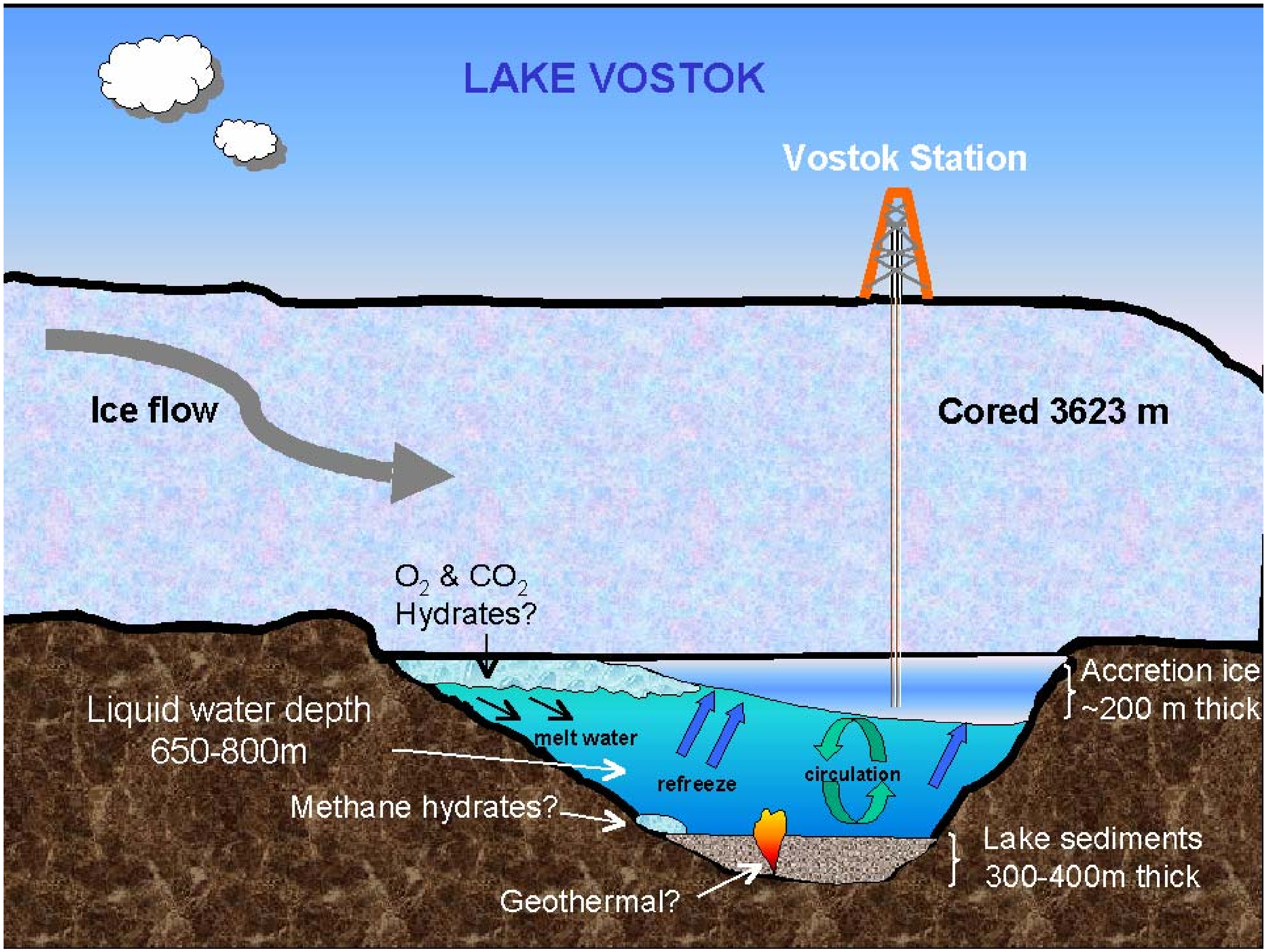
http://salegos-scar.montana.edu/docs/Images.htm

Lake Vostoc Antartic Research Station



-scar.montana.edu/docs/Images.htm

Vostoc and Other Antartic Research Stations



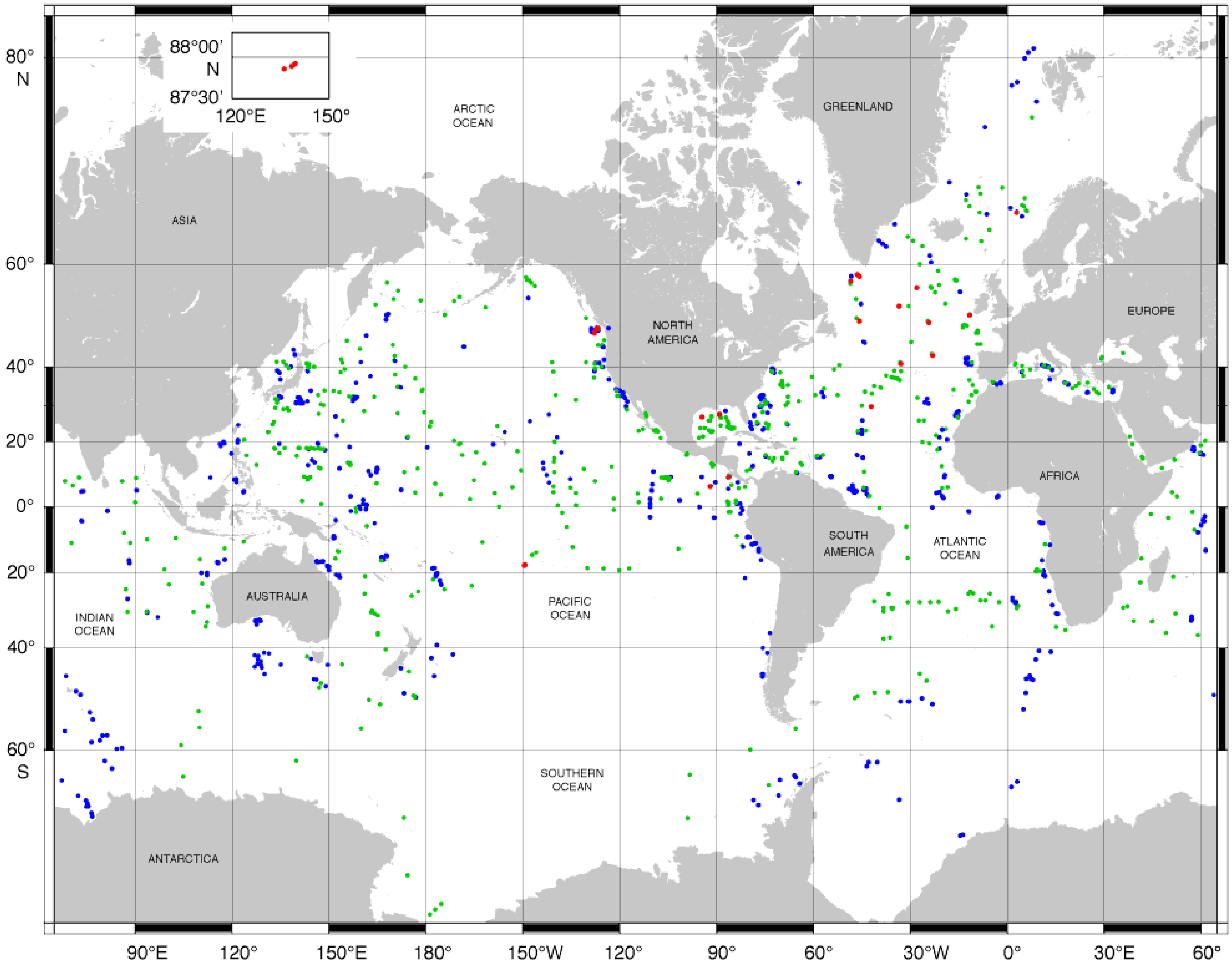
http://current.com/items/88797217_arctic_meltdown_newsweek_interview_with_robert_corell

Ocean Drilling Projects

Ocean Drilling Project (ODP)
The Glomar Challenger

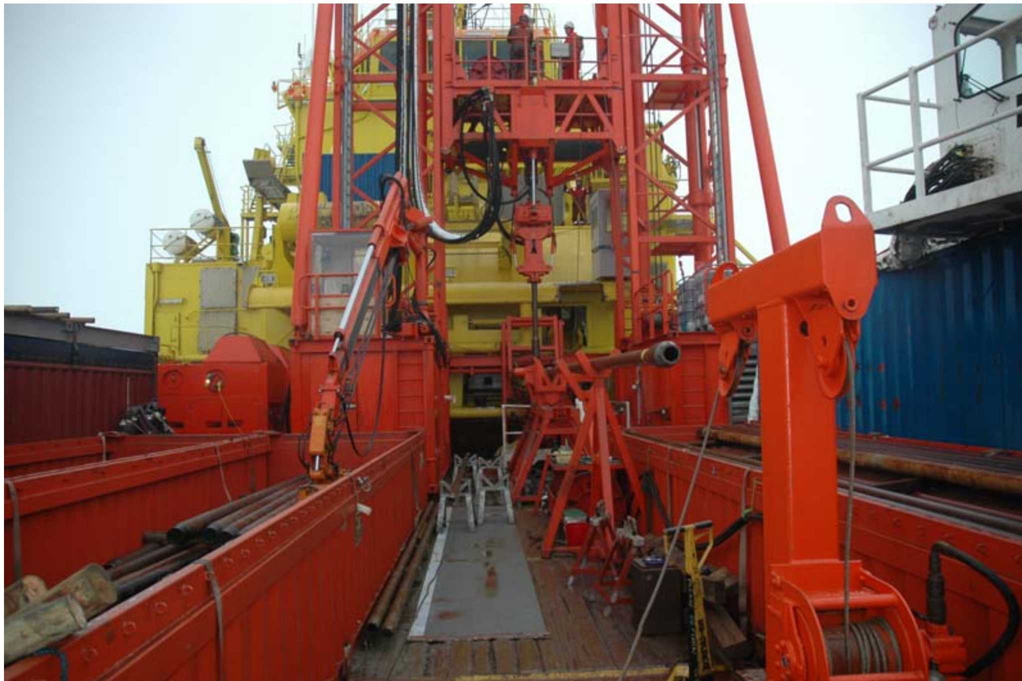
http://oceanz.tamu.edu/~wormuth/hist.html

Drill Site Locations



DSDP Legs 1–96 (●), ODP Legs 100–210 (●), IODP Expeditions 301–312 (●)

http://iodp.tamu.edu/scienceops/maps.html




KAMINSKI

From Coring Site to Core Repository

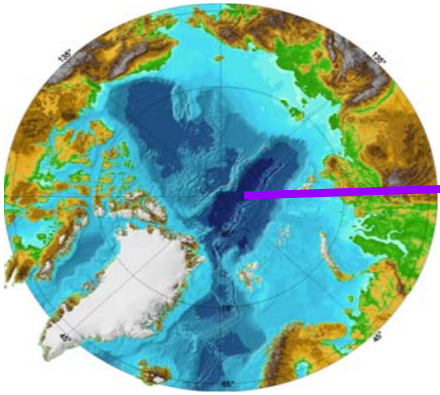
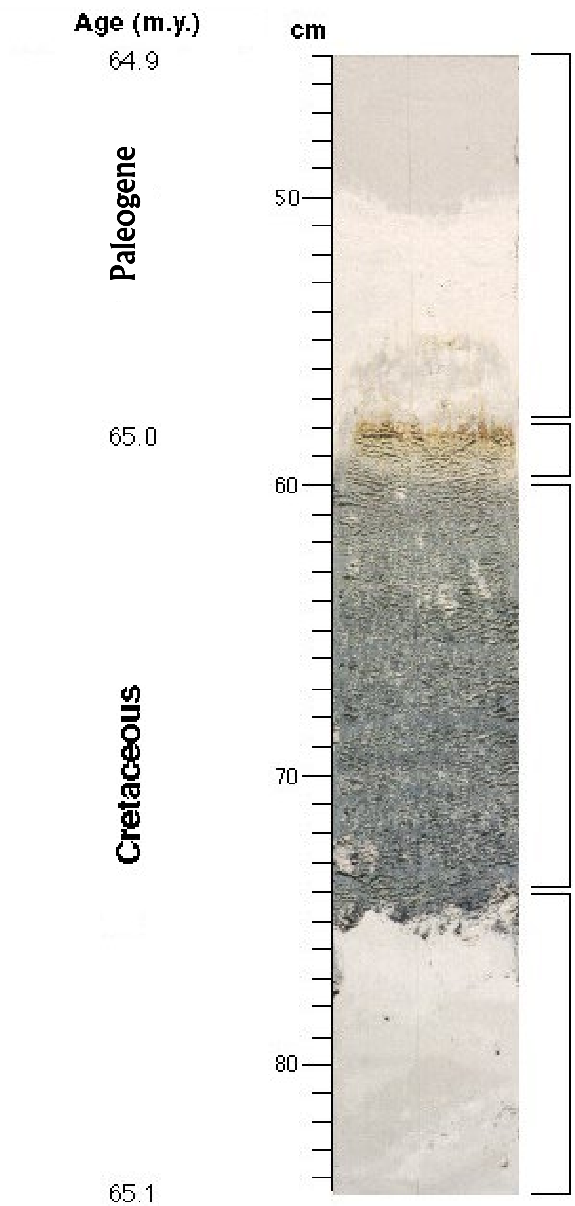


Photo from *New York Times* article Nov 30 2004

Ocean Drilling Project (ODP)

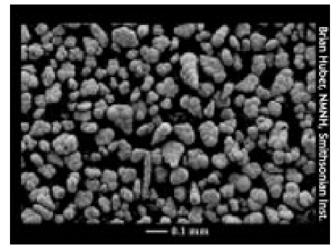
http://oceanz.tamu.edu/~wormuth/hist.html

Recovered Cores =
Cylinders of sediment and rock =
Time capsules of Earth history



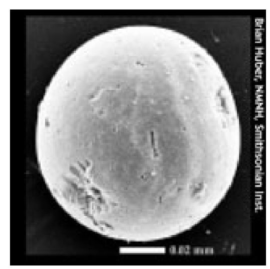
Events

Post-extinction Layer:
Sediments containing microfossils from after the dinosaurs



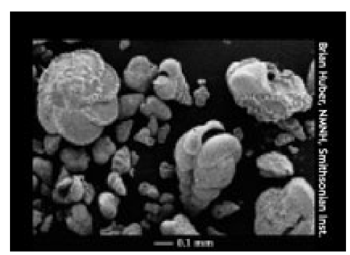
Fireball Layer:
Dust and ash fallout from the asteroid impact

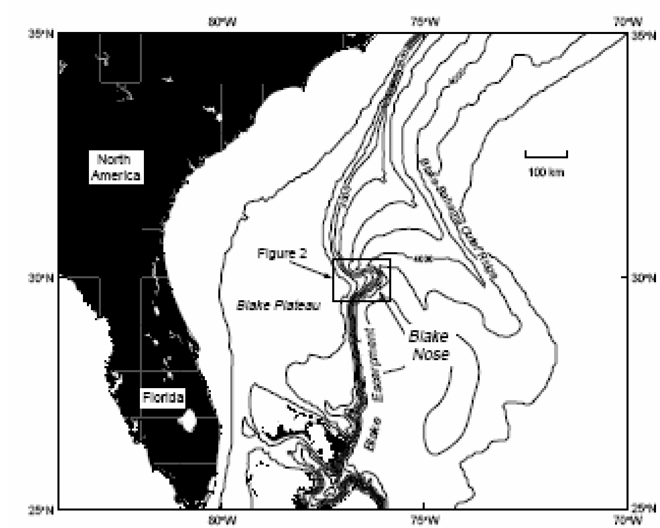
Ejecta Layer:
Material blasted from the crater and deposited here within days to months

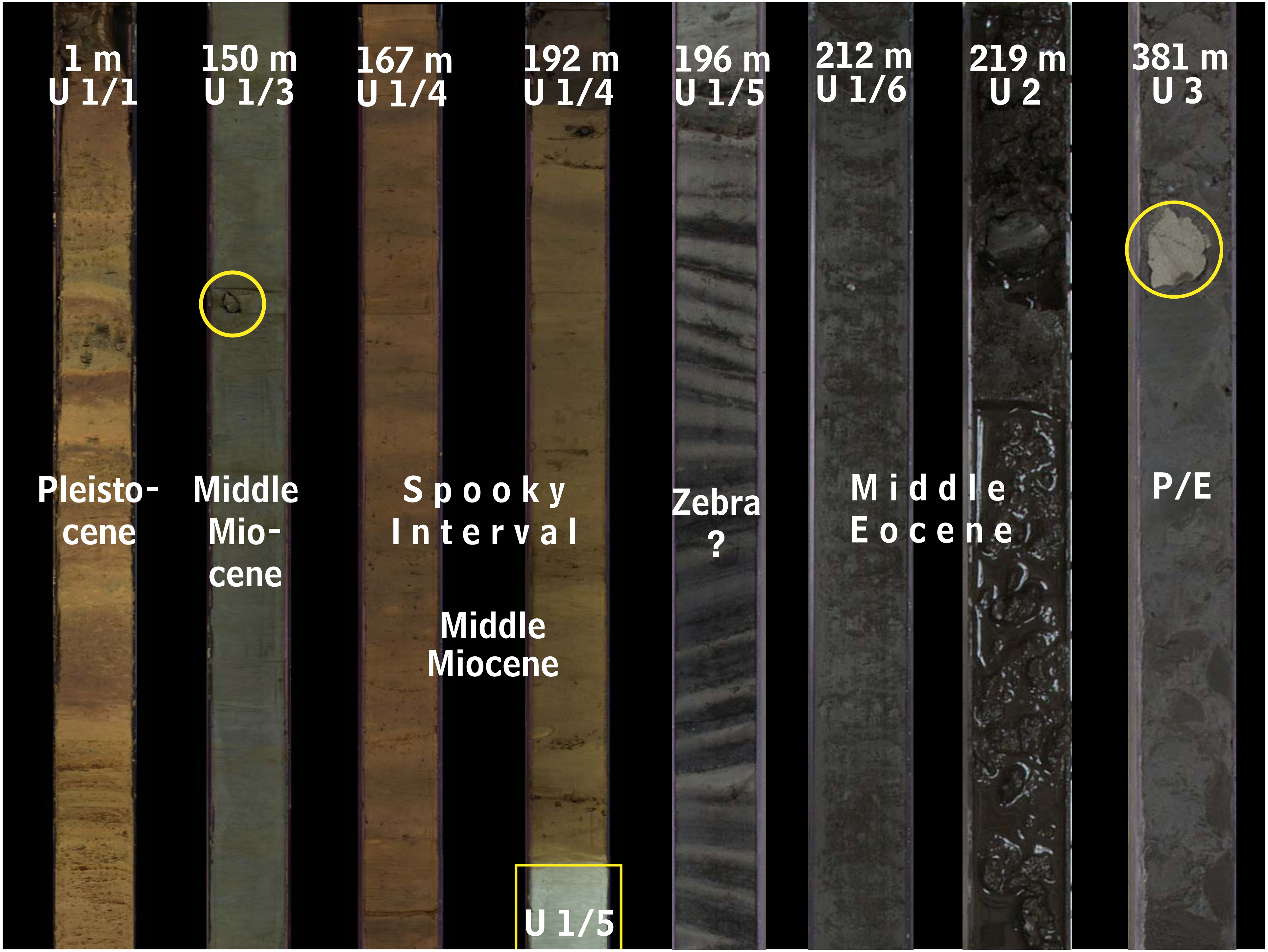


Moment of impact: "K-T boundary"

Pre-extinction Layer:
Sediments containing microfossils from the time of the dinosaurs






1 m
U 1/1
150 m
U 1/3
167 m
U 1/4
192 m
U 1/4
196 m
U 1/5
212 m
U 1/6
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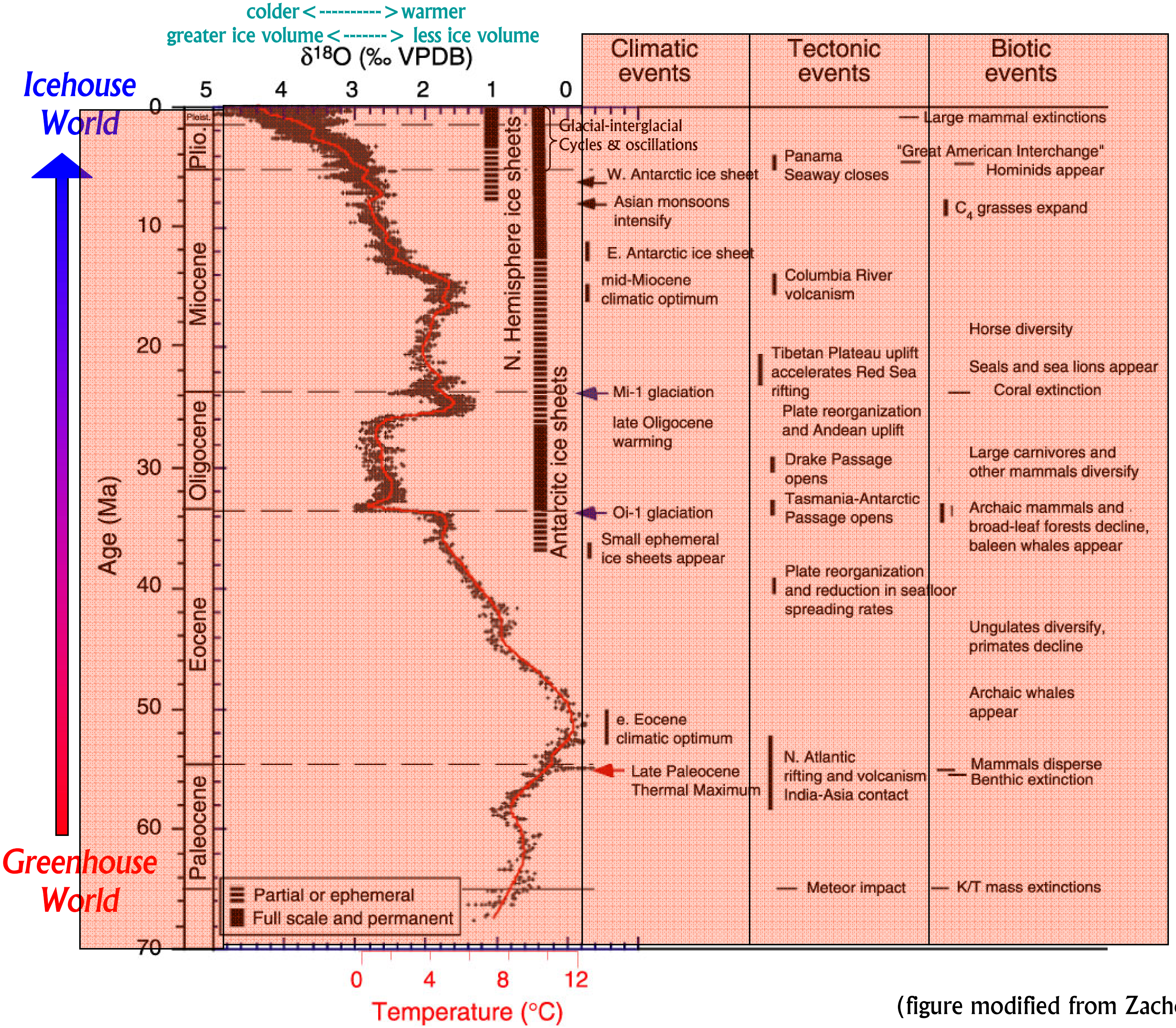
Spooky
Interval
Middle
Miocene
Zebra
?
Middle
Eocene
P/E
U 1/5

Cenozoic Evolution - Global Earth History



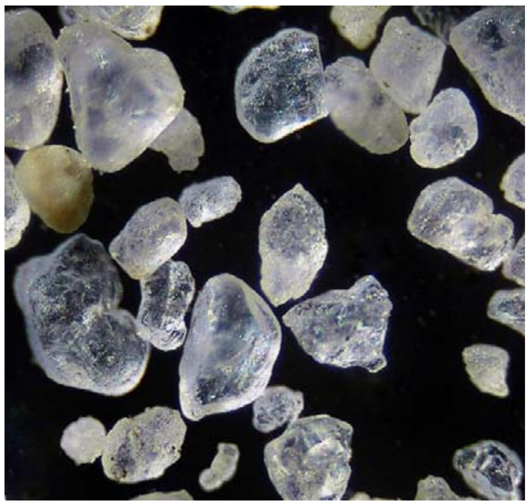
(figure modified from Zachos et al., 2001)

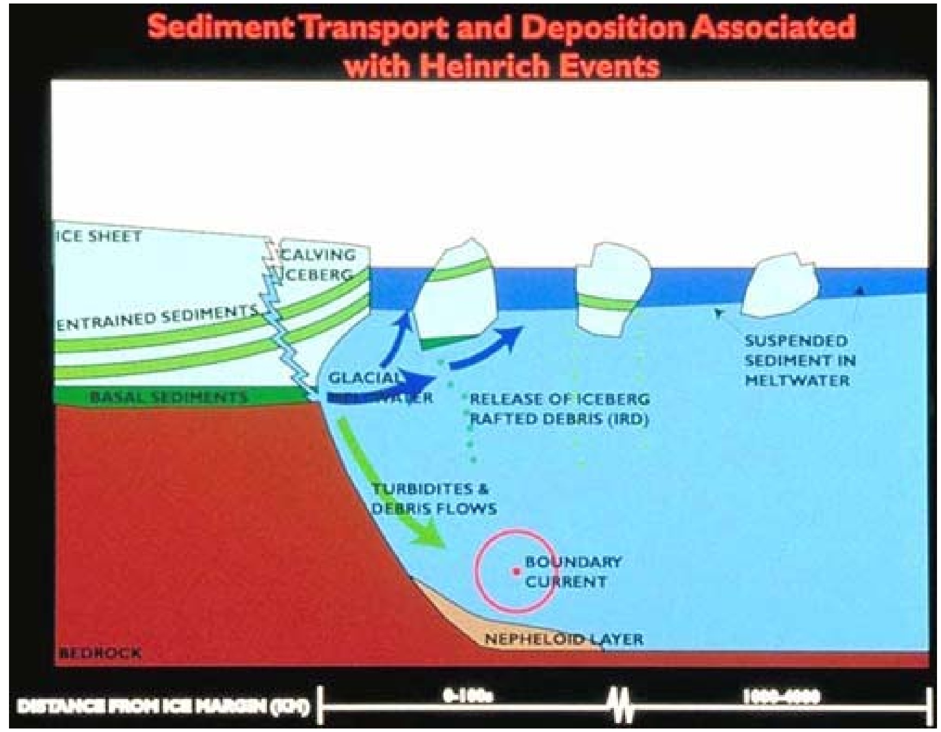
Looking for Patterns in the Signs

Greenland Ice Sheet and North Atlantic

First Discoveries of Glacial Cycles
Heinrich Events

The appearance of coarser ice rafted debris layers periodically in the cores.





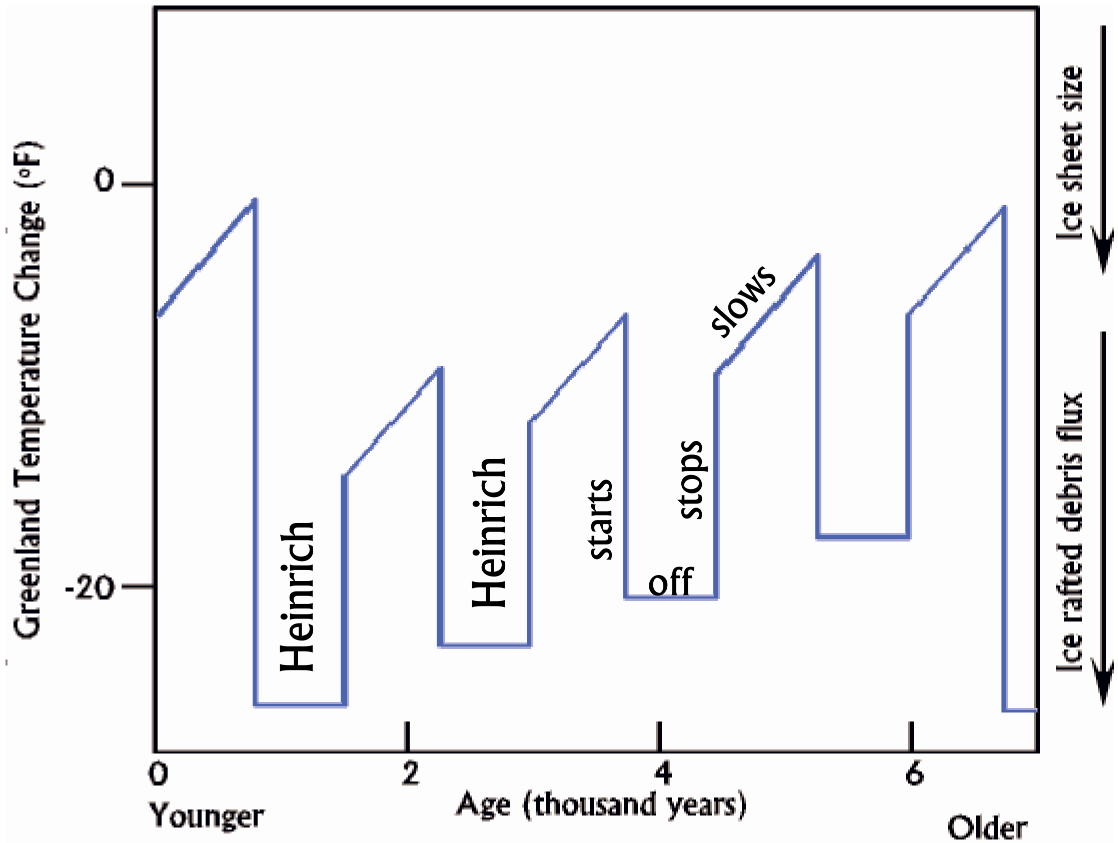
Heinrich's original observations were of six layers in ocean sediment cores with extremely high proportions of rocks of continental origin, "lithic fragments"(Heinrich 1988). The larger size fractions cannot be transported by ocean currents, and are interpreted as ice rafted.

Represents a surge of melting of the ice occurring because the thick ice pressure melts at the bottom.

http://www.uwsp.edu/geo/faculty/lemke/geol370/lecture_notes/15_ice_age_chronology.html

Patterns in the North Atlantic Ocean Cores

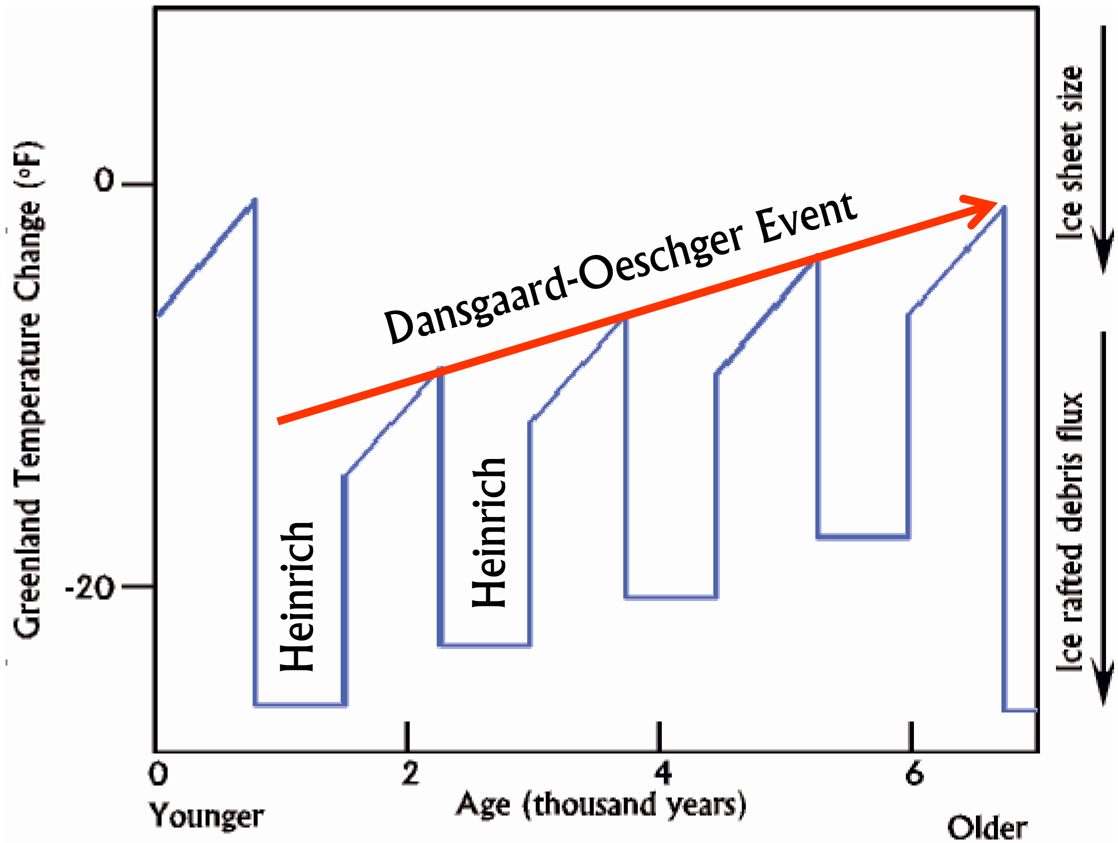
Heinrich Events



Heinrich events last about 750 years, occur during some, but not all, of the periodic cold spells during an ice age, and take only a couple of years to start.

Patterns in Greenland Ice Cores

Dansgaard-Oeschger Oscillations

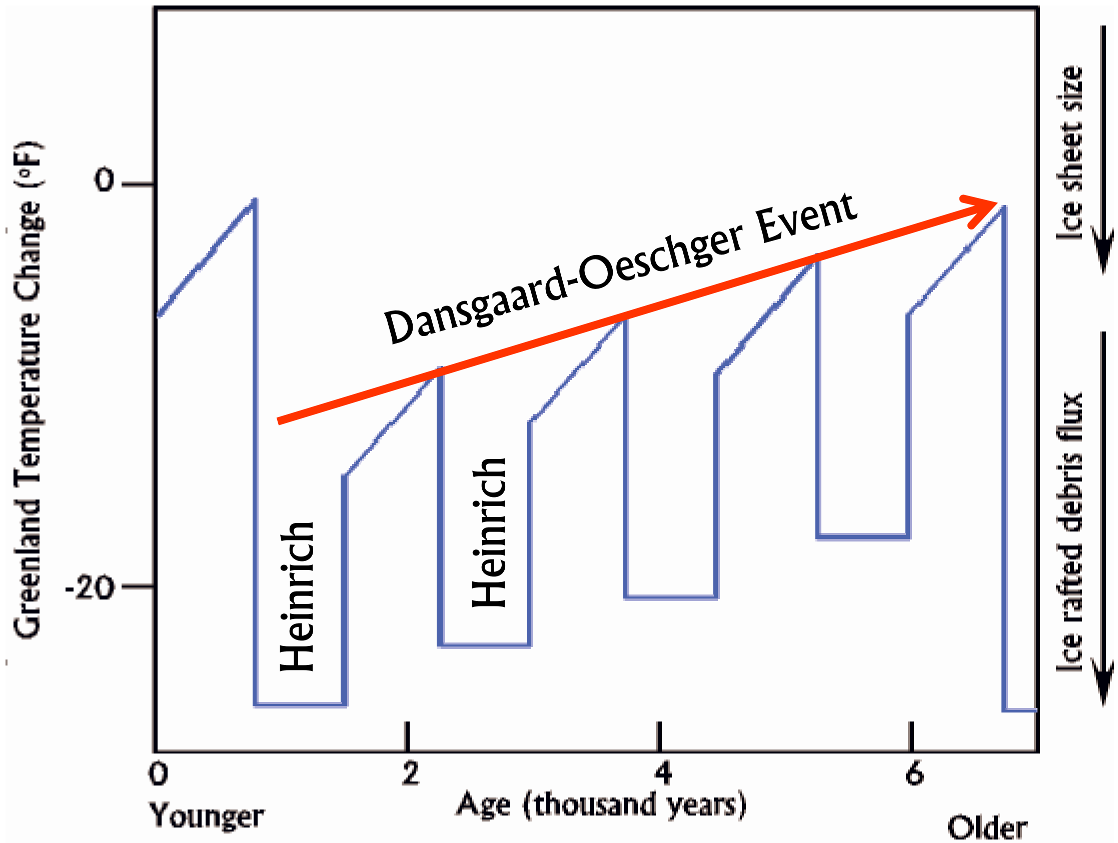


Appear as rapid warming episodes, typically in a matter of decades, each followed by gradual cooling over a longer period.

The D-O events contain within them Heinrich cycles.

Patterns in Greenland Ice Cores

Dansgaard-Oeschger Oscillations

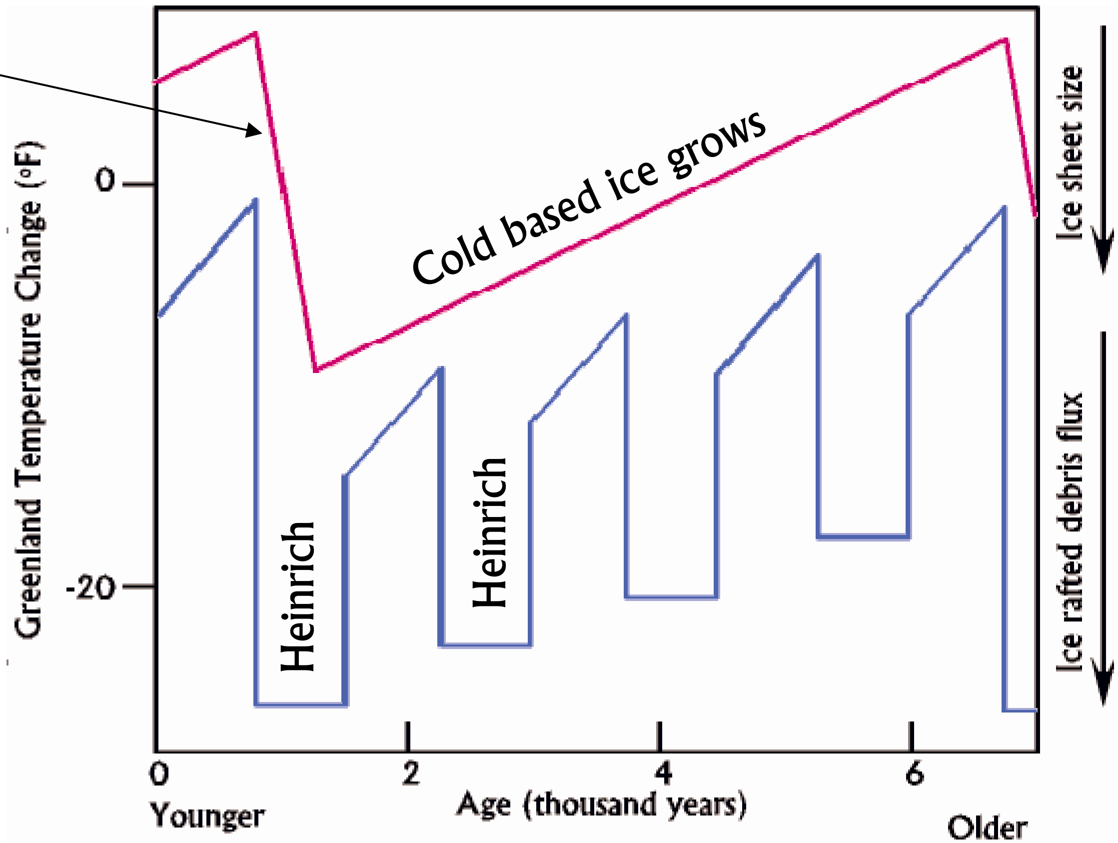


Dansgaard-Oeschger events are rapid climate fluctuations occurring every ≈1470 (± 532) years. Twenty-three such events have been identified between 110,000 and 23,000 years BP

Patterns in Greenland Ice Cores

Bond Cycles

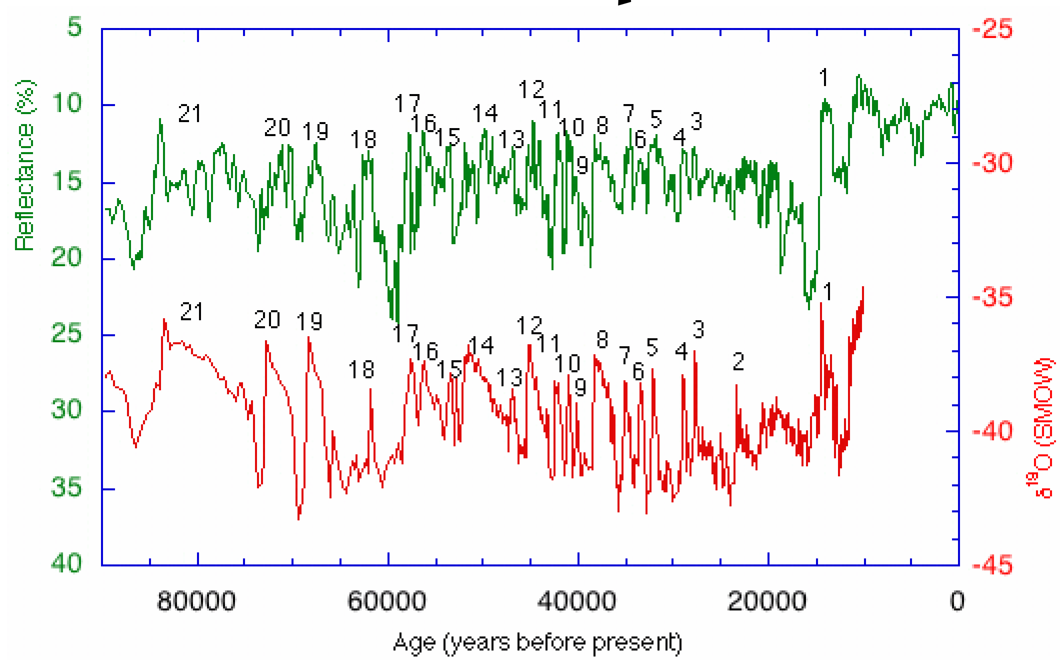
Rapid surge of ice, with melting, leading to rapid cooling of ocean waters



Bond events are rapid coolings of North Atlantic sea water, followed by slow rises in temperature occurring every ≈ 1470 years throughout the Holocene. Eight such events have been identified.

Patterns in the Ocean Cores

Bond Cycles



Abrupt climate events are found in Greenland ice cores, and some other locations such as the Cariaco Basin in the Caribbean Sea. Warm (interstadial) events are numbered in the ice core (red). The data are significant because they reveal ocean-wide climate changes occurring within a century or less, altering the temperatures in the far North Atlantic, and the sea surface conditions close to the equator. In both regions, conditions appear to flip back and forth between two different states.

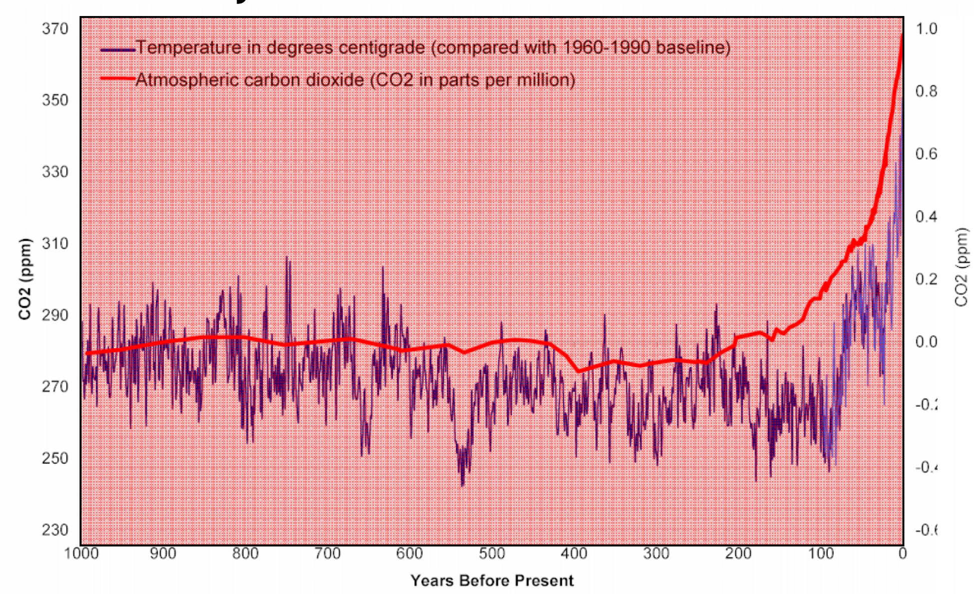
http://www.ncdc.noaa.gov/paleo/abrupt/data_glacial2.html

Patterns within patterns within patterns

Fractal Temperature Patterns in Time

What you can see depends on the scale of observation

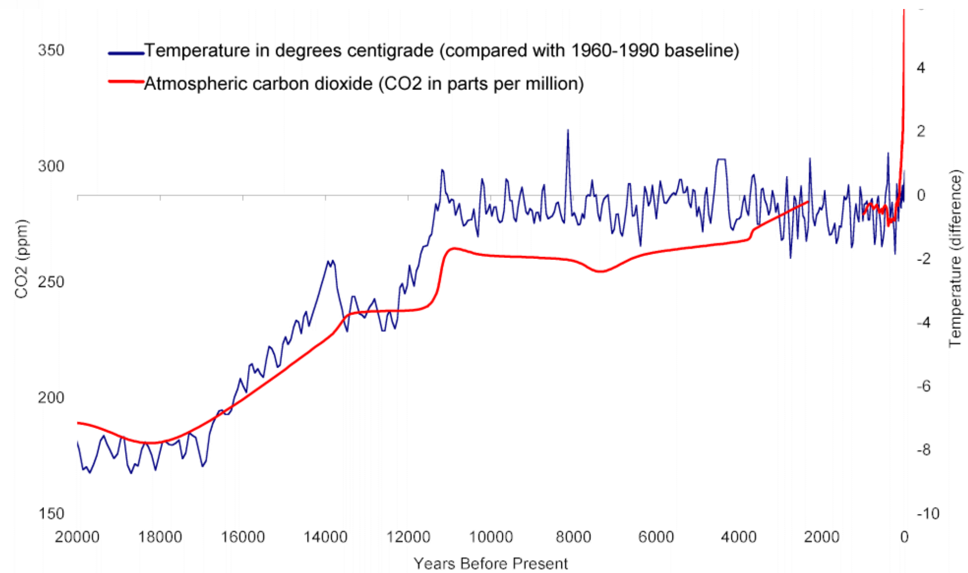
1,000 Year Record



Heinrich Events

Last about this long

20,000 Year Record



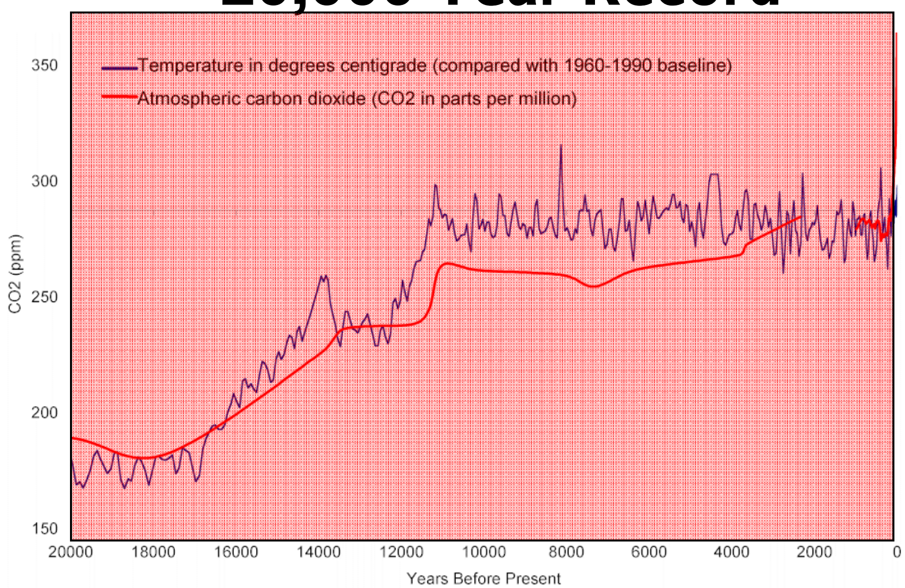
Bond Cycles

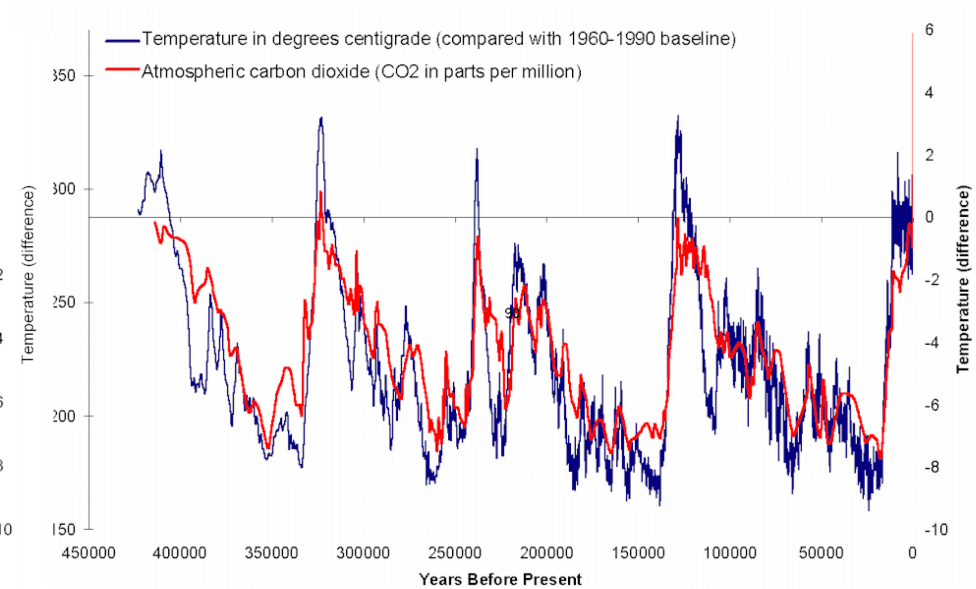
Last about this long

Fractal Temperature Patterns in Time

450,000 Year Record

20,000 Year Record

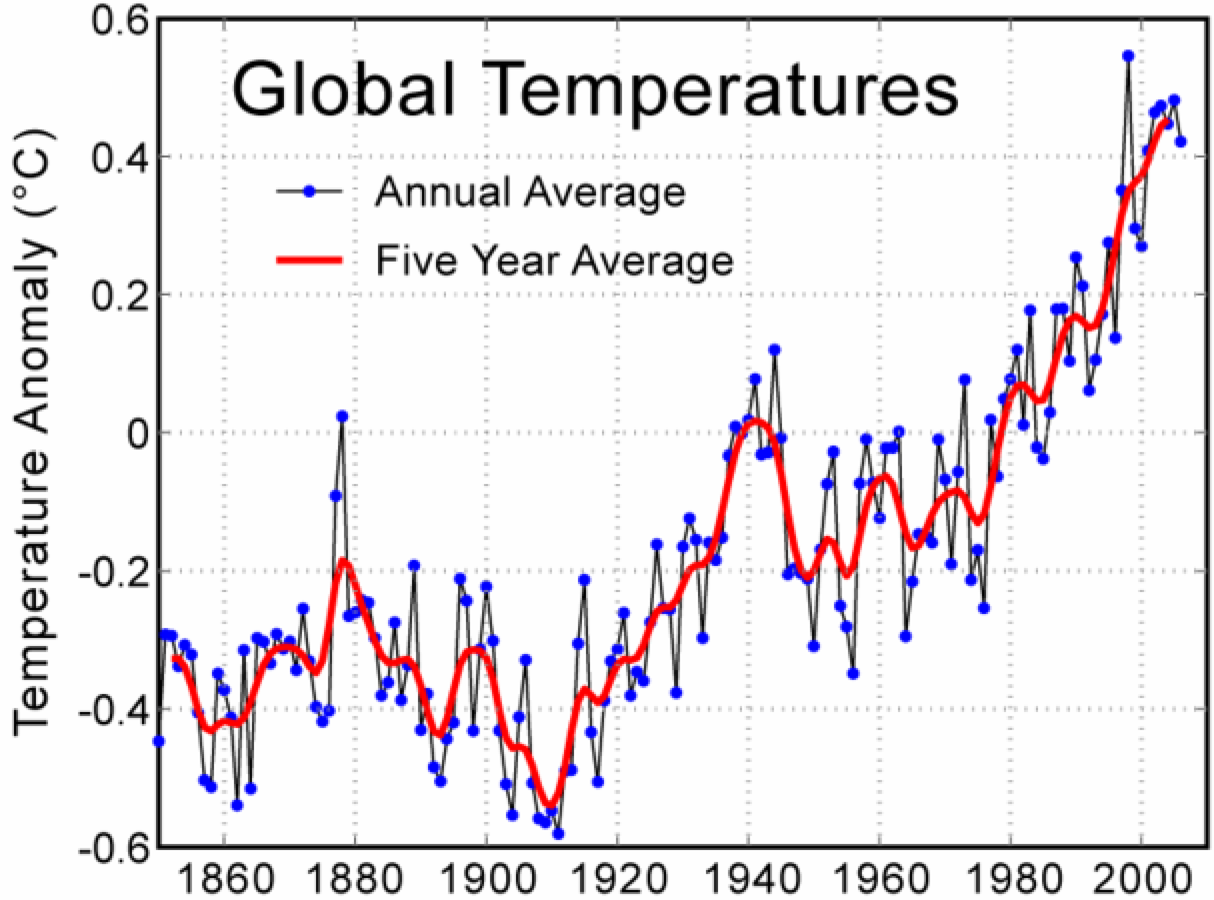




Bond Cycles
Last about this long

100,000 year glacial cycles
last about this long

And, of course, there are cycles going on at smaller times scales too.



Patterns within patterns within patterns

FRACTAL

But, just observing these patterns does not explain them

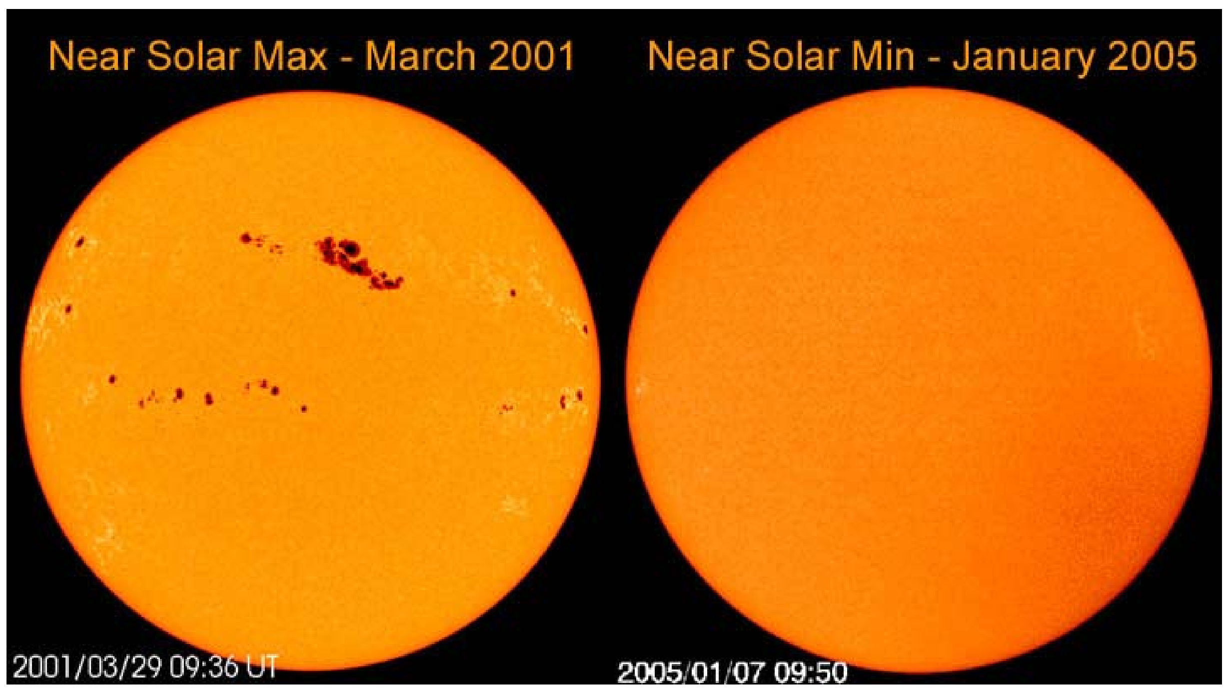
Possible Explanations

Explanations for climate changes, and for glaciations, are legion.

Part of the difficulty is that explanations for events of one scale may not work at all for events at a larger scale.

1. Sunspot Cycles

These two images of the Sun show how the number of sunspots varies over the course of a sunspot cycle. The image on the left, with many sunspots, was taken near solar max in March 2001. The righthand image, in which no spots are evident, was taken near solar min in January 2005.

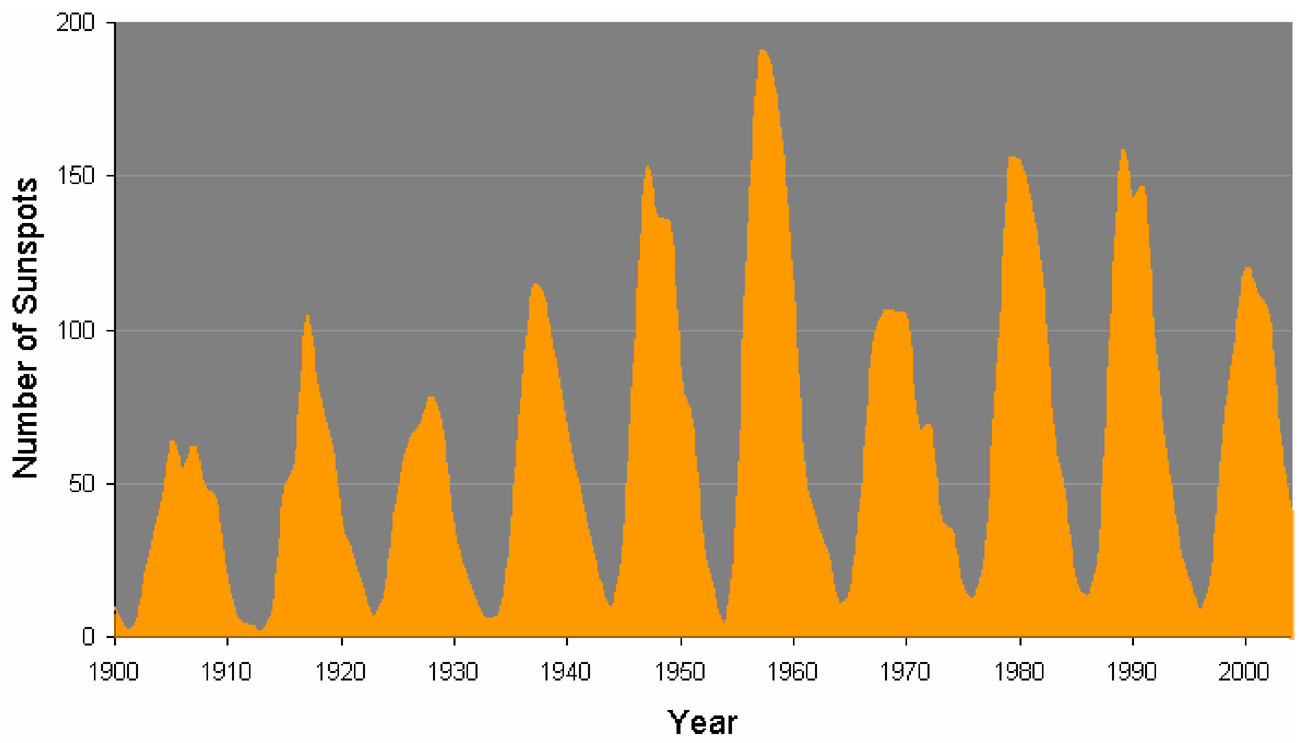


Explanations for climate changes, and for glaciations, are legion.

Part of the difficulty is that explanations for events of one scale may not work at all for events at a larger scale.

1. Sunspot Cycles

Sunspot populations quickly rise and more slowly fall on an irregular cycle about every 11 years. Significant variations of the 11 year period are known over longer spans of time.



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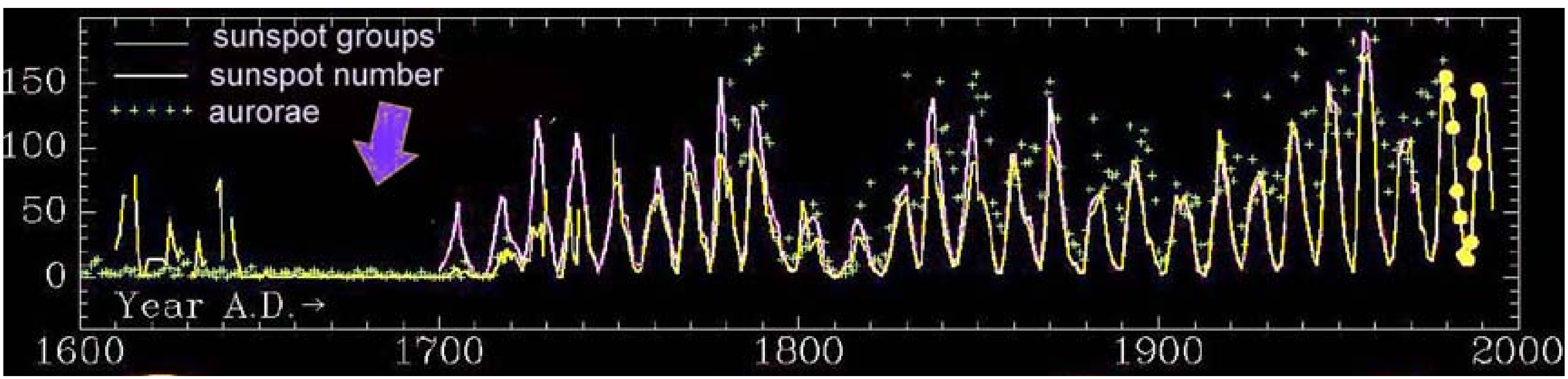



USGS

Explanations for climate changes, and for

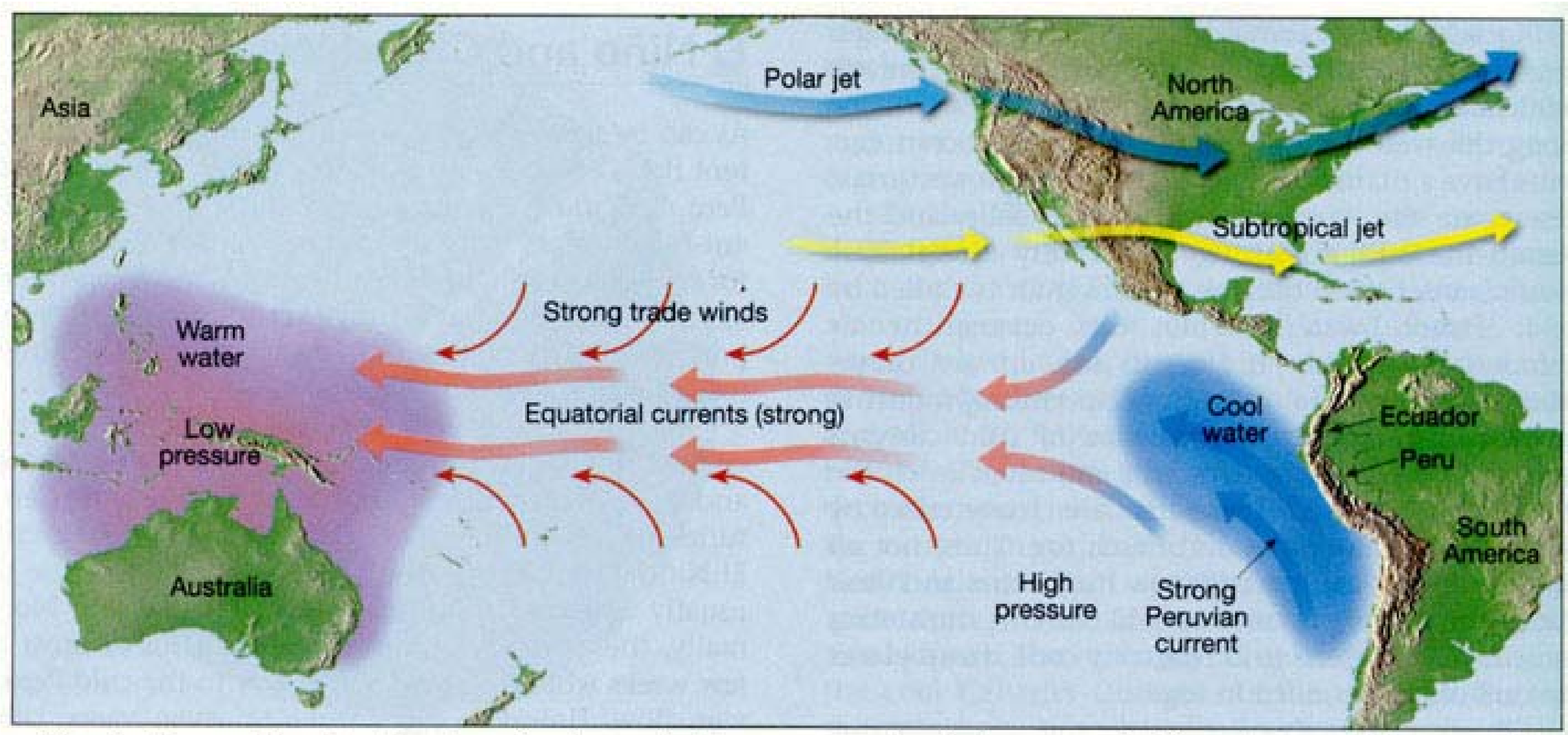
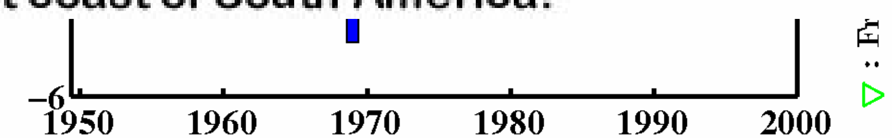


Fig.6 Normally, the trade winds and strong equatorial currents flow toward the west. At the same time, an intense Peruvian current causes upwelling of cold water along the west coast of South America.

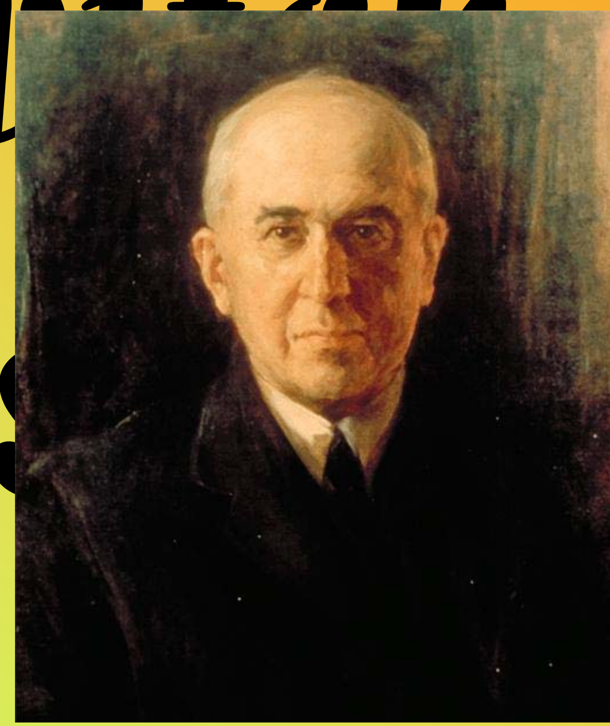


But, just observing these patterns does not explain them

Milankovitch Cycles

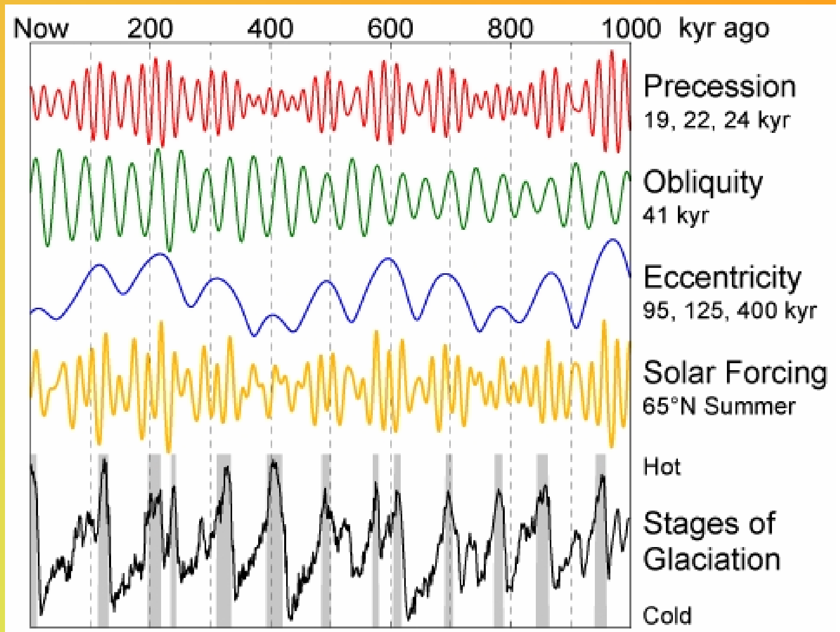
Milankovitch Cycles

Changes in the Earth's climate that results from changes in the Earth's orbital movements named after Serbian civil engineer and mathematician Milutin Milanković.



Milankovitch proposed that the changes in the intensity of solar radiation received from the Earth were effected by three fundamental factors.

The first is called eccentricity, a period of about 100,000 years in which the nearly circular orbit of the Earth changes into a more elliptical orbit.

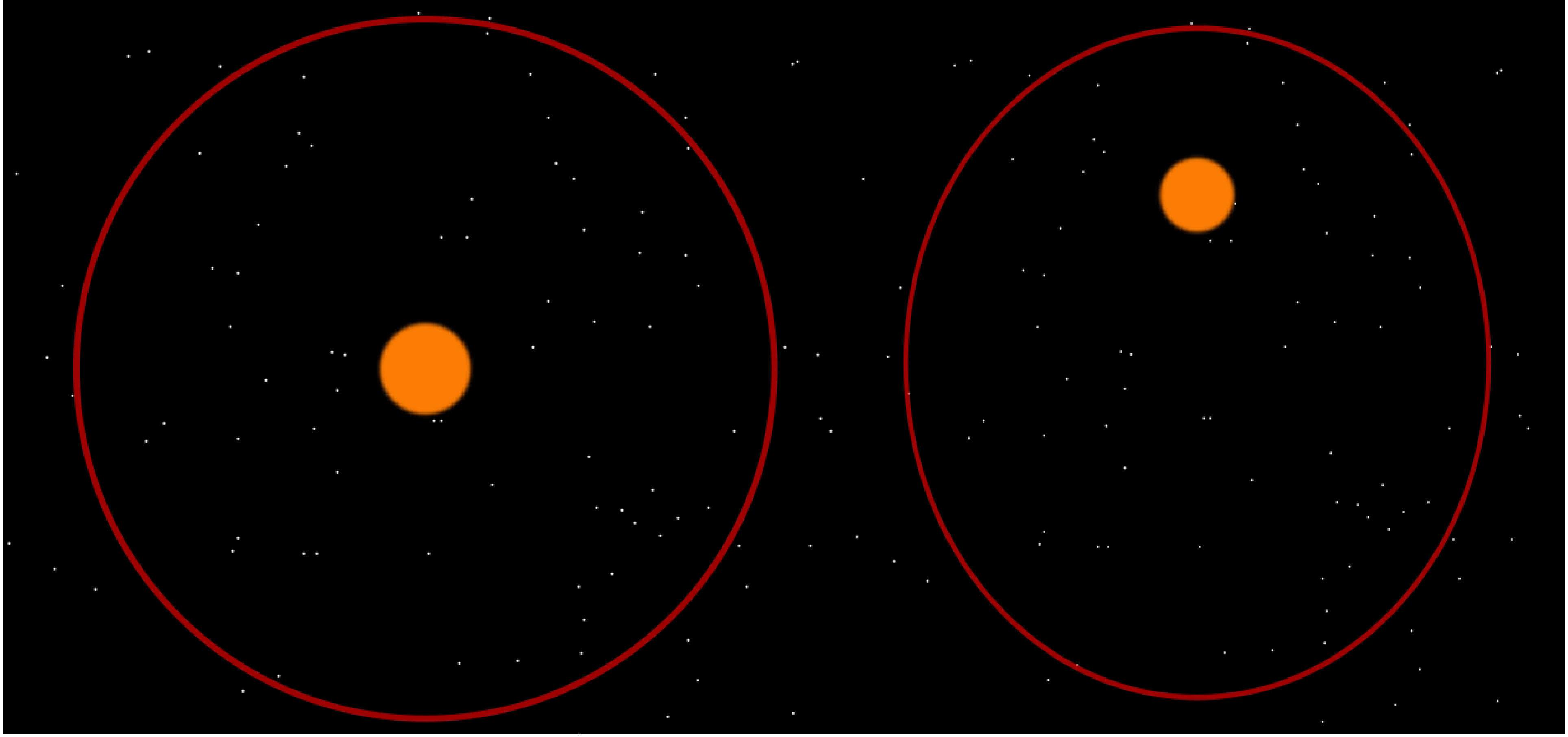


The second is called obliquity, a period of about 41,000 years where the Earth's axis tilt varies between 21.5 and 24.5 degrees.

The third is called precession, a period of approximately 23,000 years where the Earth's axis wobbles like a spinning top.

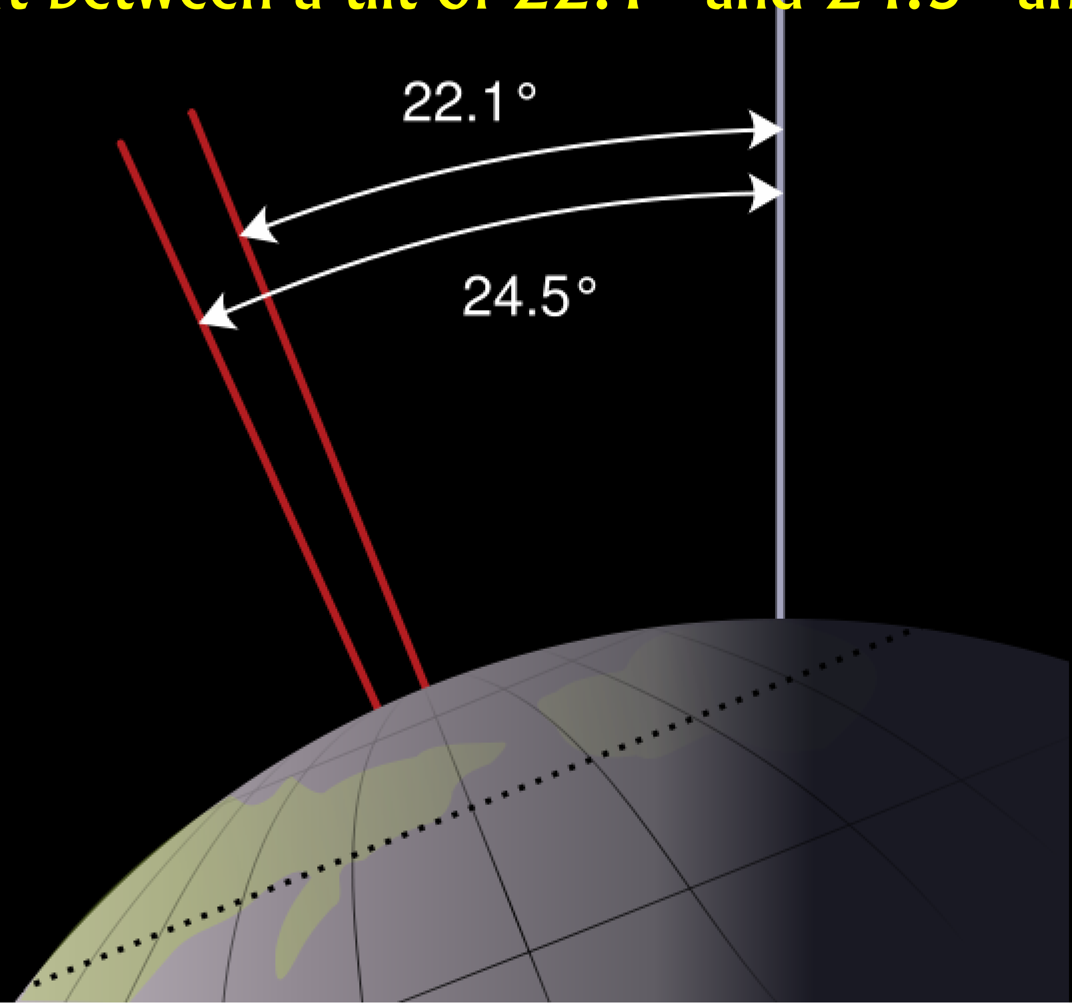
Milankovitch Cycles - Eccentricity

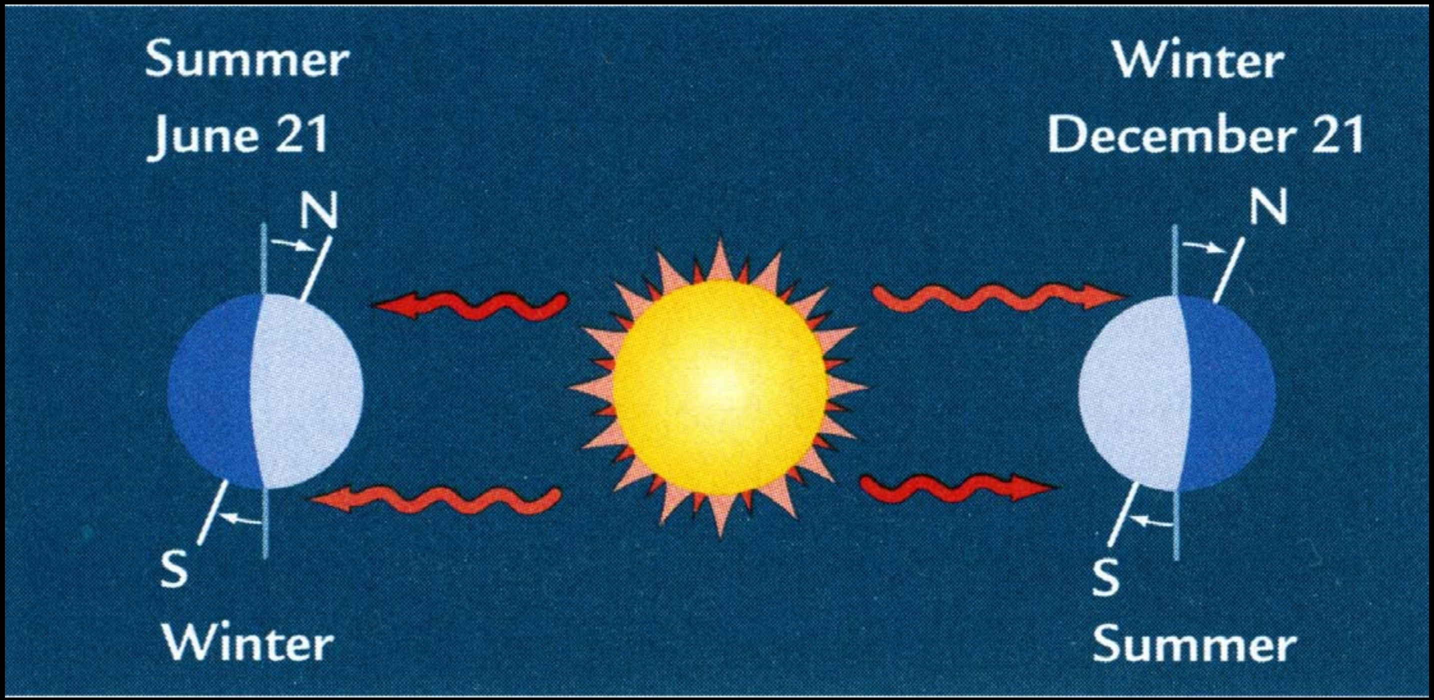
The shape of the Earth's orbit varies from being nearly circular to being mildly elliptical. The major component of these variations occurs on a period of 413,000 years but a number of other terms vary between 95,000 and 136,000 years, and loosely combine into a 100,000-year cycle



Milankovitch Cycles - Obliquity

The angle of the Earth's axial tilt (obliquity) varies with respect to the plane of the Earth's orbit. These slow 2.4° obliquity variations are roughly periodic, taking approximately 41,000 years to shift between a tilt of 22.1° and 24.5° and back again.

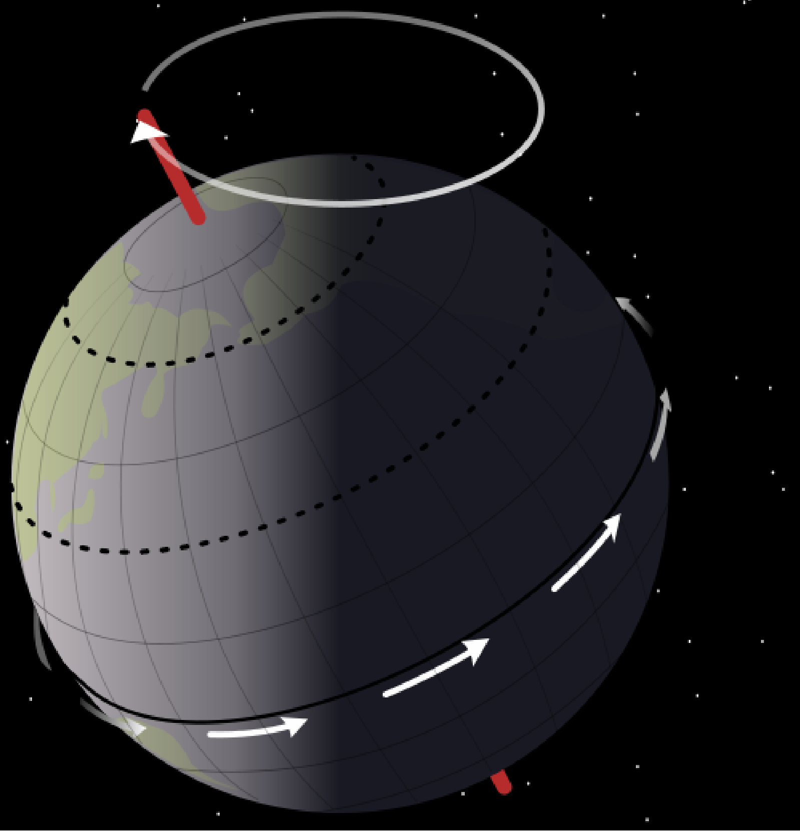


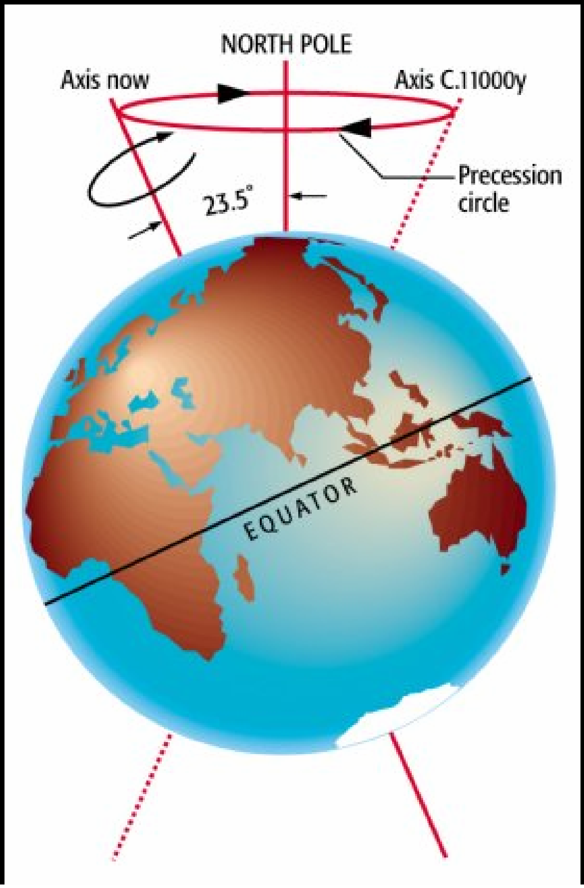


Effect of increased tilt on polar regions. Increased tilt brings more solar radiation to the two summer season poles and less radiation to the two winter season poles.

Milankovitch Cycles - Precession

Precession is the change in the direction of the Earth's axis of rotation relative to the fixed stars, with a period of roughly 26,000 years. This gyroscopic motion is due to the tidal forces exerted by the sun and the moon on the solid Earth, associated with the fact that the Earth is not a perfect sphere but has an equatorial bulge





Milankovitch Cycles - Precession

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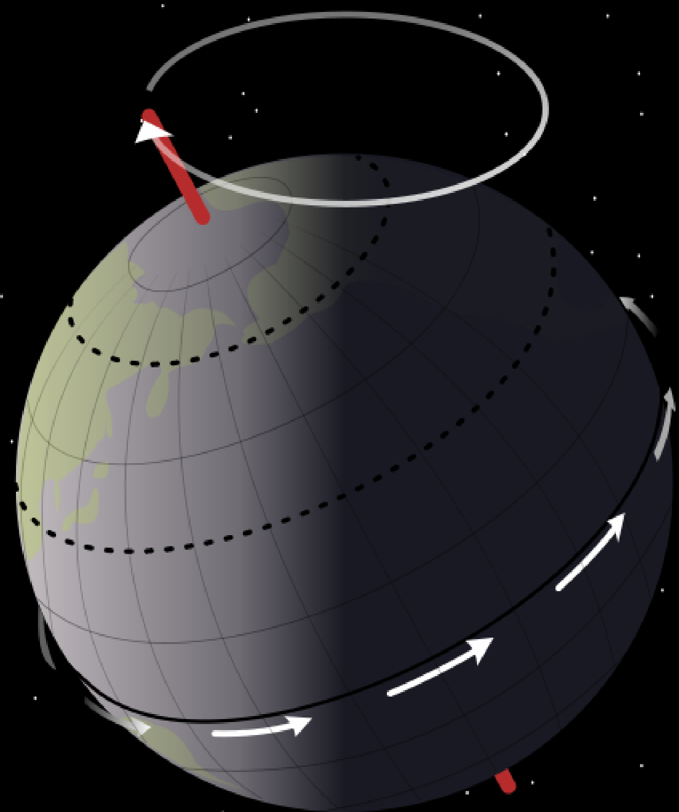
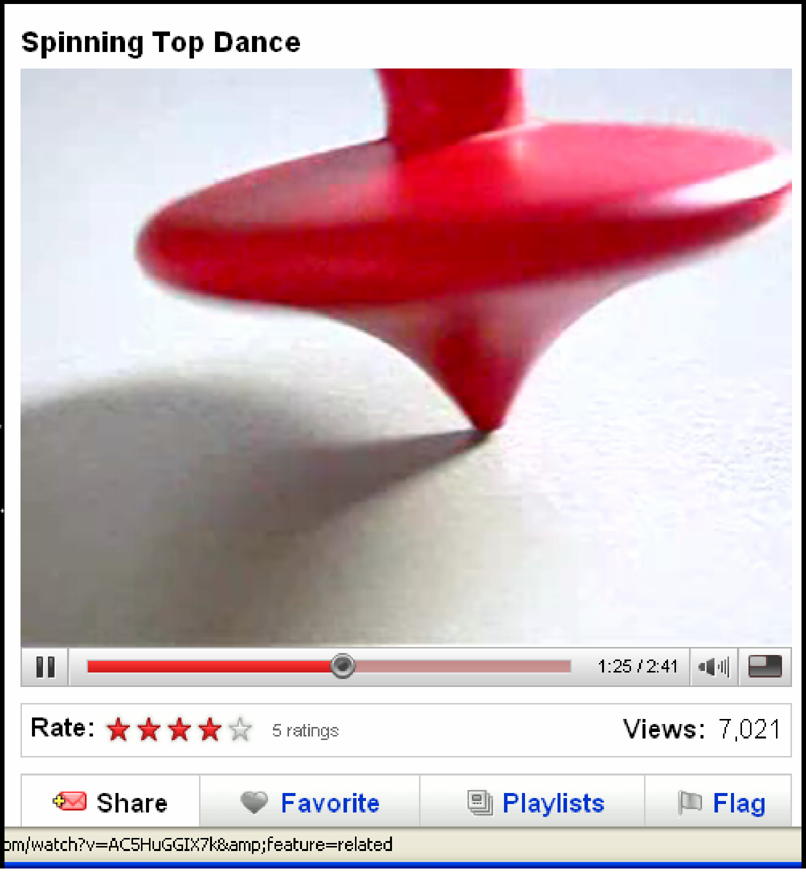
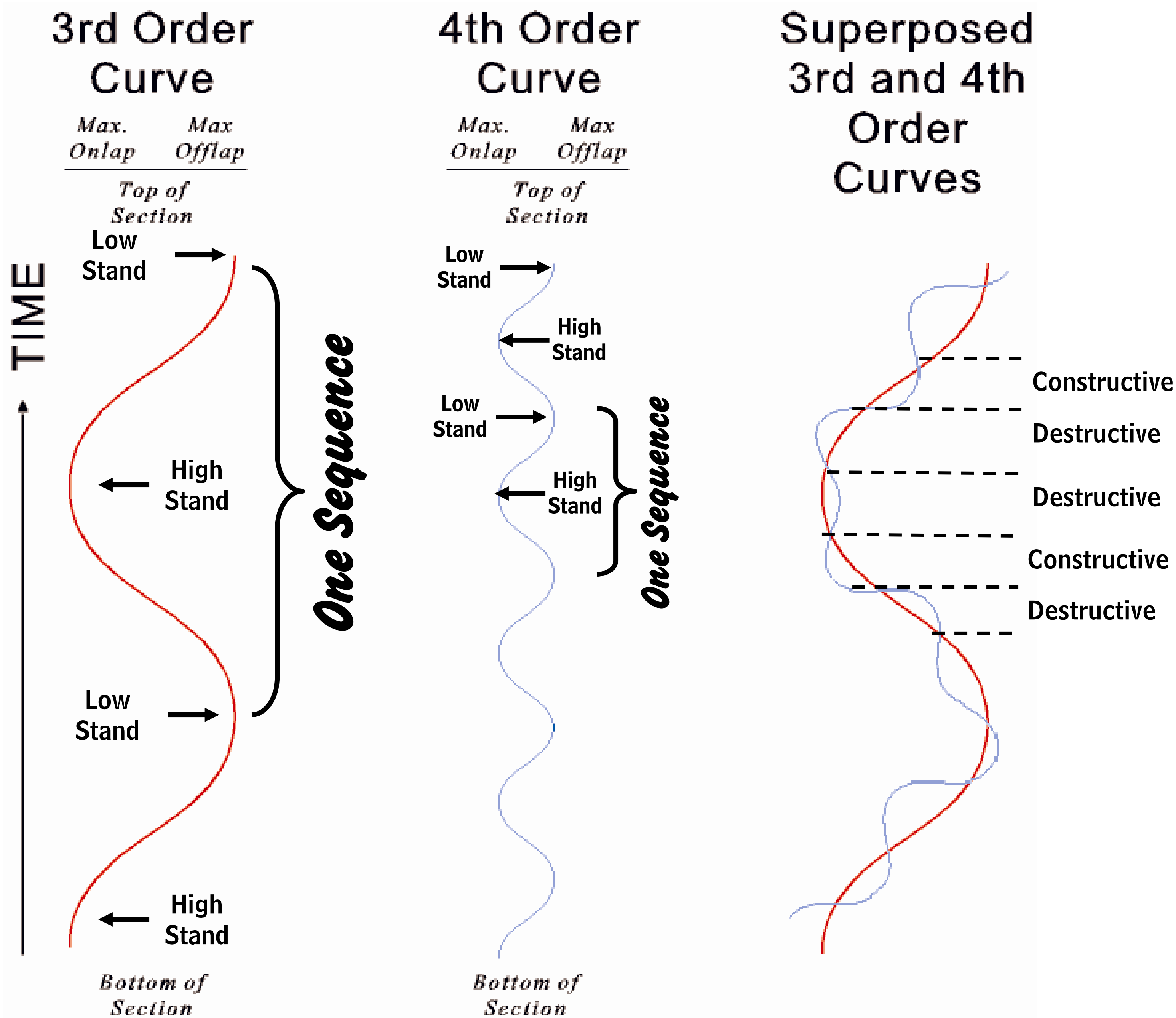





3rd Order Curve
Max. Onlap
Max Offlap
Top of Section
Low Stand
High Stand
Low Stand
High Stand
TIME
One Sequence
Bottom of Section
4th Order Curve
Max. Onlap
Max Offlap
Top of Section
Low Stand
High Stand
Low Stand
High Stand
One Sequence
Bottom of Section
Superposed 3rd and 4th Order Curves
Constructive
Destructive
Destructive
Constructive
Destructive

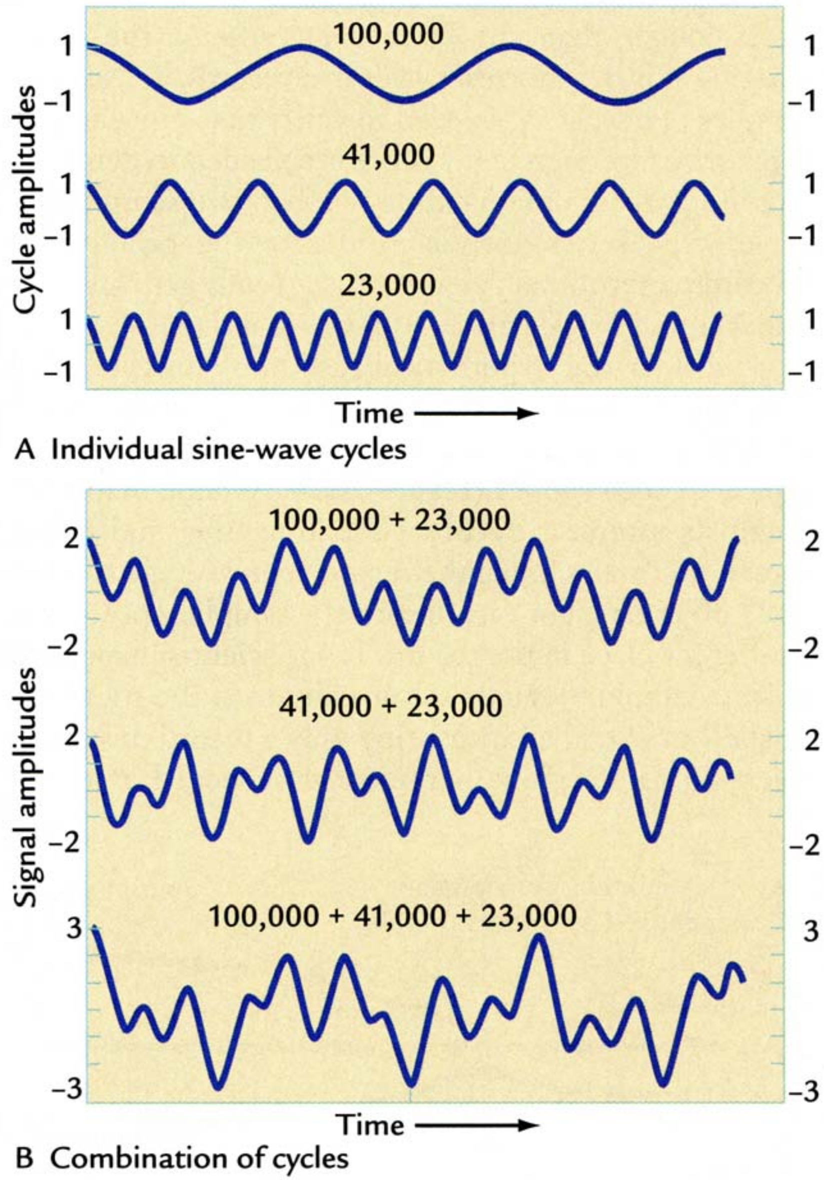


FIGURE 7-20 Complications from overlapping cycles If perfect sine wave cycles with periods of 100,000, 41,000, and 23,000 years are added together so that they are superimposed on top of one another, the original cycles are almost impossible to detect by eye in the combined signal.

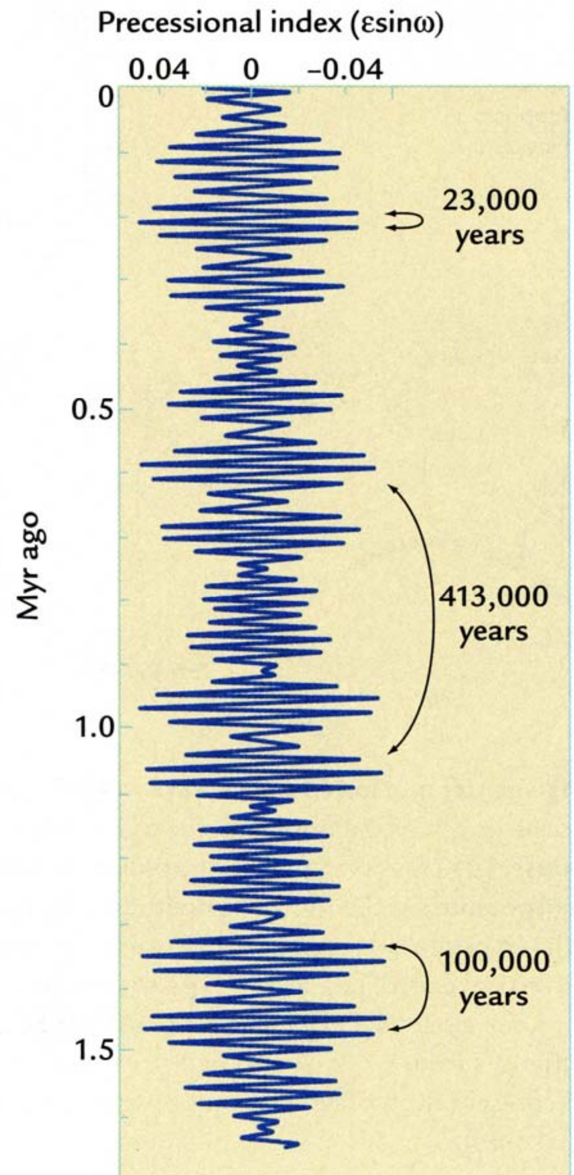
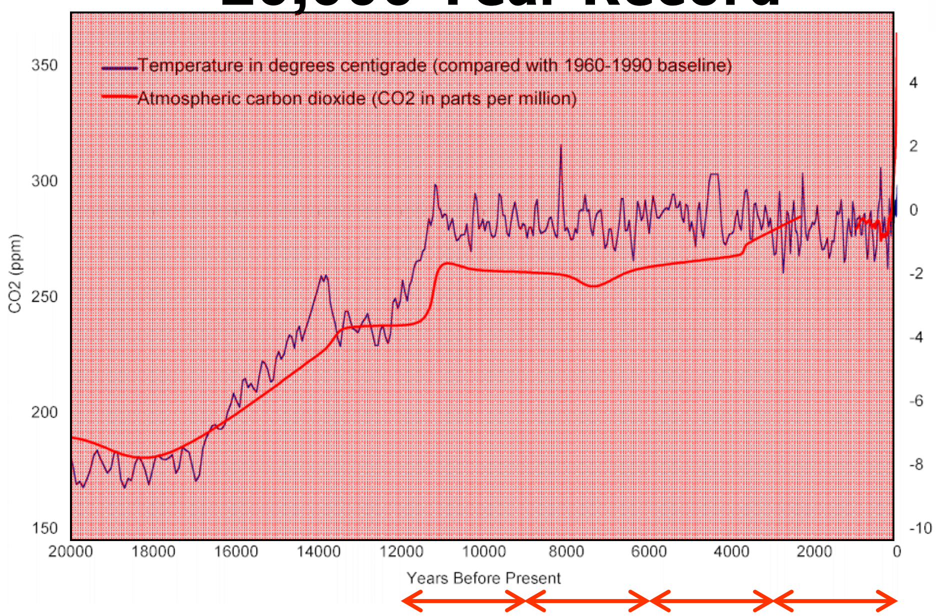


FIGURE 7-15 Long-term changes in precession The precessional index (εsinω) changes mainly at a cycle of 23,000 years. The amplitude of this cycle is modulated at the eccentricity periods of 100,000 and 413,000 years.

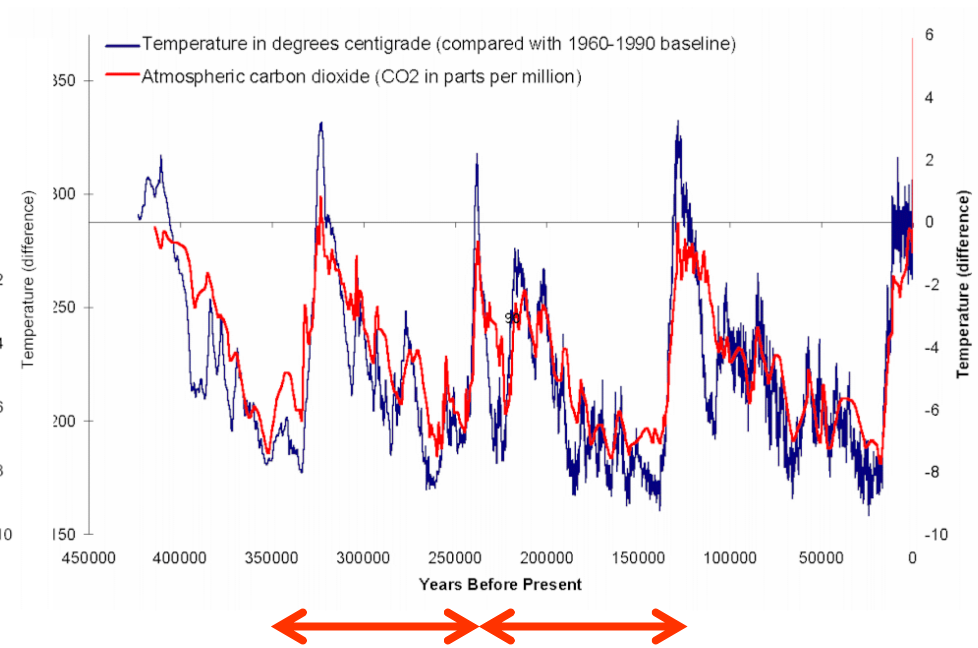
Fractal Temperature Patterns in Time

20,000 Year Record



Bond Cycles
Last about this long

450,000 Year Record



100,000 year events
last about this long