



**Lectures 9 & 10**

**Climates of  
the Past**

# Laplace's Theory of the Solar System Formation (1796)

- ❑ A nebula, by virtue of radiating energy, would become cooler and gradually condense and collapse inwards under self-gravitational forces. To conserve angular momentum, rotate more rapidly and flatten along its rotational axis and take on a lenticular shape (**formation of the Sun ~ 4.6 billion years ago**).
- ❑ The orbiting material would separate from the central mass in a spasmodic way giving rise to a series of orbiting rings.
- ❑ Material in each ring would collect together to form agglomerations and one of them would attract and absorb all the others to form a single planet (**formation of the Earth ~ 4.5 billion years ago**).

# Characteristics of Planets

Planet	Mass <sup>1</sup>	Radius (km)	Mean Dist. (AU <sup>2</sup> )
Mercury	0.0552	2400	0.387
Venus	0.815	6250	0.723
<b>Earth</b>	<b>1.000</b>	<b>6378</b>	<b>1.000</b>
Mars	0.1075	3395	1.524
Jupiter	318.3	71100	5.203
Saturn	95.2	59650	9.539
Uranus	14.7	23550	19.19
Neptune	17.3	24200	30.07
Pluto	0.0025	0.723	39.46

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<sup>1</sup>Mass of the Earth ~  $6 \times 10^{24}$  kg, Sun ~  $2 \times 10^{30}$  kg

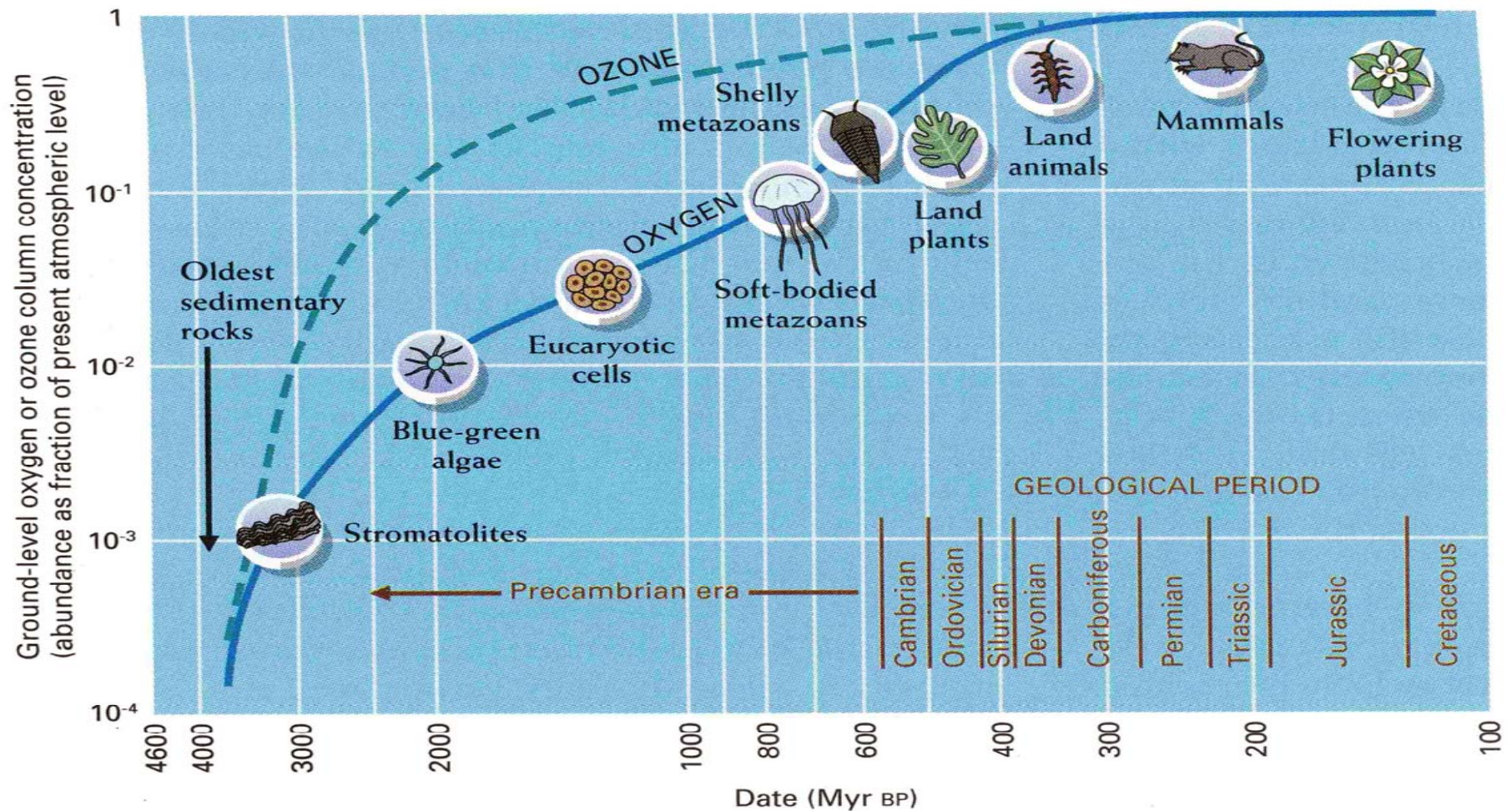
<sup>2</sup>1AU =  $1.5 \times 10^8$  km

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# Formation of the Earth and Its Present Atmosphere

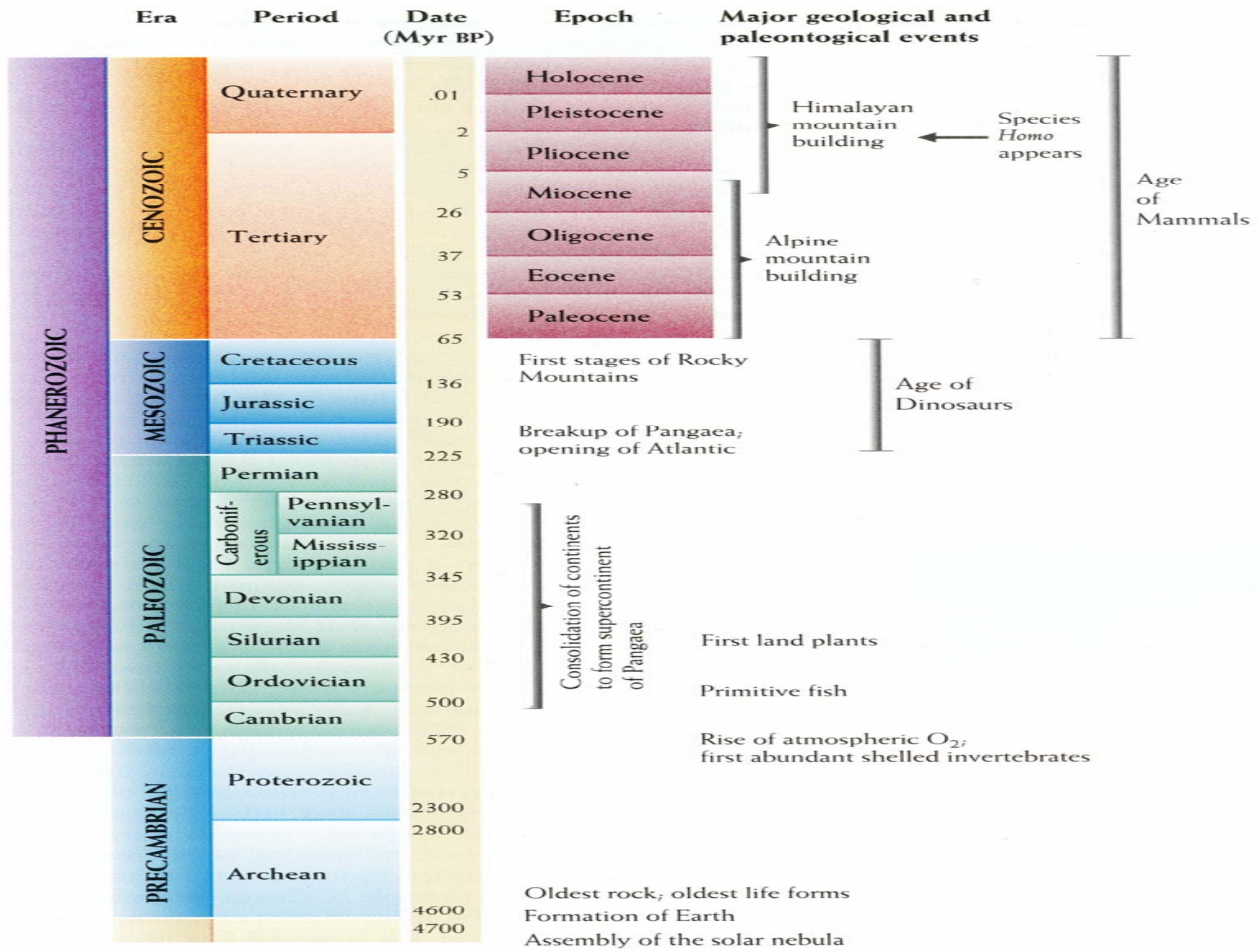
- ❑ The Earth's present atmosphere is believed to be a secondary atmosphere generated from volatile compounds within the solid planetesimals from which the Earth formed.
- ❑ The heavy bombardment of the Earth ended ~ 3.8 BY and life was probably extant by ~ 3.5 BY. The atmosphere might have contained  $\text{CH}_4$  and  $\text{NH}_3$ .
- ❑ Volcanic activities:  $\text{CO}_2$  and  $\text{N}_2$ ,  $\text{CO}$ , and  $\text{H}_2\text{O}$  (water).
- ❑ A large amount of  $\text{CO}_2$  and/or other greenhouse gases are likely to have evolved to compensate for the faint young Sun at ~ 3.5-3.8 BY.
- ❑ Major increase of  $\text{O}_2$  resulted from photosynthesis and organic carbon burial at ~ 1.9-2.2 BY.
- ❑ The formation of  $\text{O}_3$  screening out UV radiation.





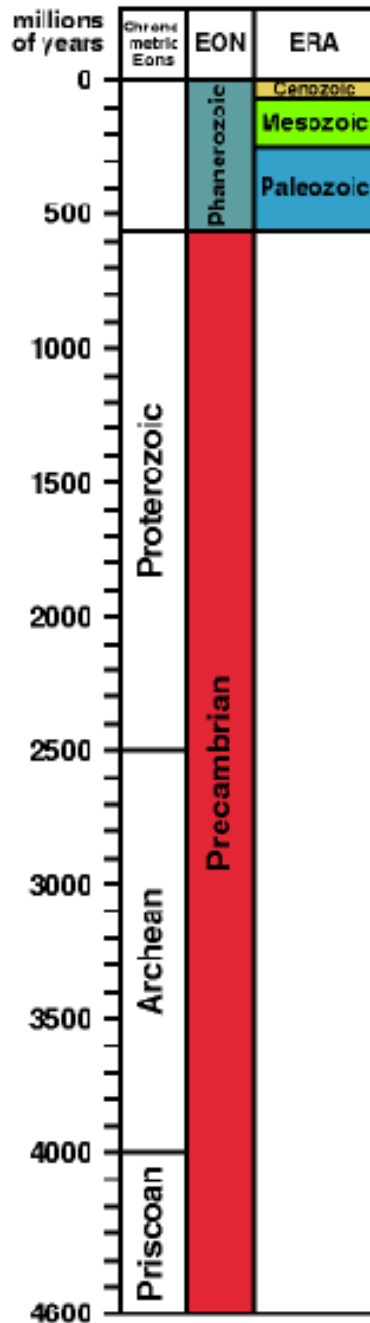
**A reconstruction of the evolutionary development of oxygen and ozone in Earth's atmosphere.** Land-based life could not have become established without sufficient ozone to provide protection against **ultraviolet radiation**. The oxygen curve is based on evidence from rocks and fossils; the ozone curve was developed from a photo-chemical computer model..



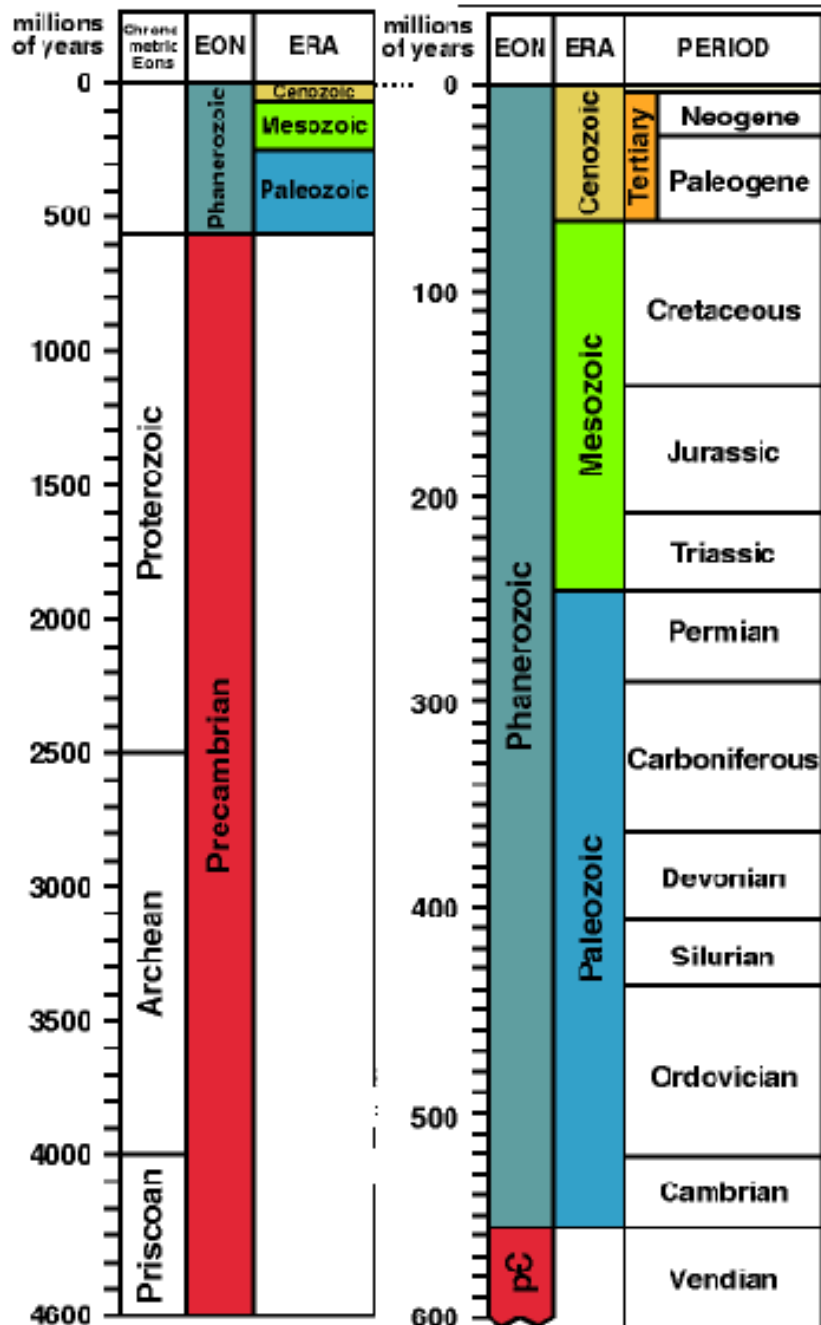


The geological time scale, expressed in millions of years before the present (Myr BP); the vertical scale is not linear. The boundaries between the eras and periods are defined by changes in fossil species types or abundances or by transitions from one major rock type to another.

# GEOLOGIC TIME



The earth is approximately 4.6 billion years old and has undergone large changes throughout its lifetime. The earliest forms of life might have appeared as early as about 3.5 billion years ago, with bacteria and algae-like creatures appearing about 2.5 billion years ago. Evidence has emerged recently that about **600-700 million years** ago, the Earth was probably completely ice-covered more than once (**snowball earth**). Then, about **540 million years** ago, the **Cambrian Explosion** occurred. This marks the first appearance of creatures with hard skeletons and is associated with a striking increase in biological diversity.



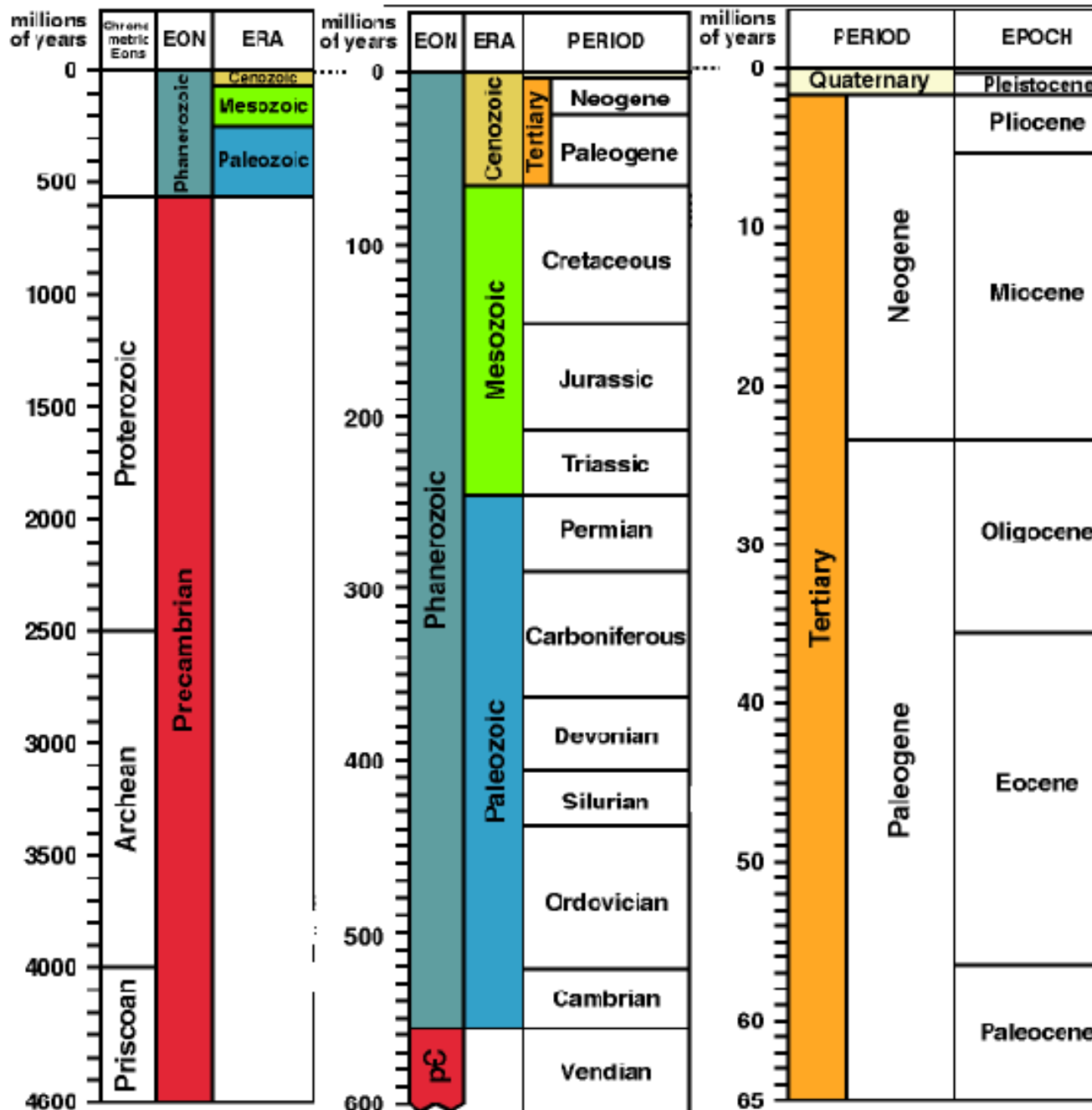
The period since the Cambrian explosion is known as the **Phanerozoic** and is divided into three eras: the **Paleozoic**, the **Mesozoic**, and the **Cenozoic**. These eras are further subdivided based on discontinuities in the fossil record (i.e. extinctions).



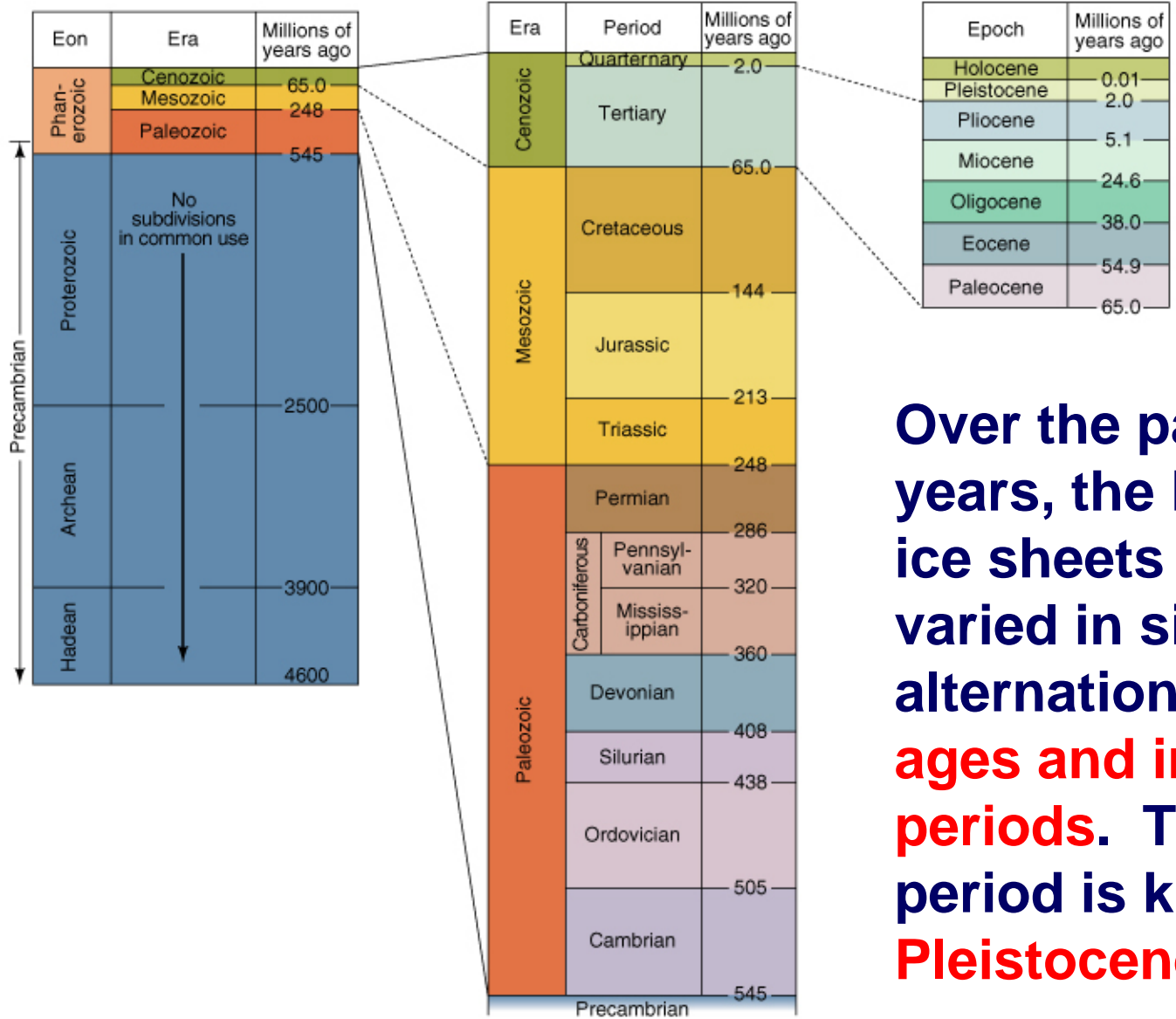
## **An Example of Abrupt Climate and Ecological Changes: Extinction of Dinosaurs ~ 65 My Ago**

The fossil record changes abruptly before and after this time indicating the disappearance of dinosaurs. In addition, the majority of other ocean and land animals went extinct. What happened? The evidence supports the idea that the Earth was struck by an asteroid. Asteroids are constantly colliding with planetary bodies, as evidenced by craters on their surfaces. Two possible consequences:

- 1. Creation of a global dust cloud sufficiently to block out solar radiation for several months (cooling), inhibit photosynthesis resulting in a rapid die-off of plants.**
- 2. Generation of shock heating leading to the production of  $\text{NO}_x$  ( $\text{NO}$  and  $\text{NO}_2$ ) that would rapidly react with  $\text{O}_3$  and remove it from the atmosphere, allowing initially more harmful UV radiation to penetrate through.**



Since the beginning of the **Cenozoic era**, the climate has cooled. The Antarctic ice sheet developed. Ice sheets grew and decayed intermittently in the northern hemisphere as well during the last two million years (a period known as the **Pleistocene**). The periods of northern hemisphere glaciation are known as the **ice ages**.



Over the past 2 million years, the Earth has had ice sheets which have varied in size, causing alternations between **ice ages and interglacial periods**. This entire time period is known as the **Pleistocene**.

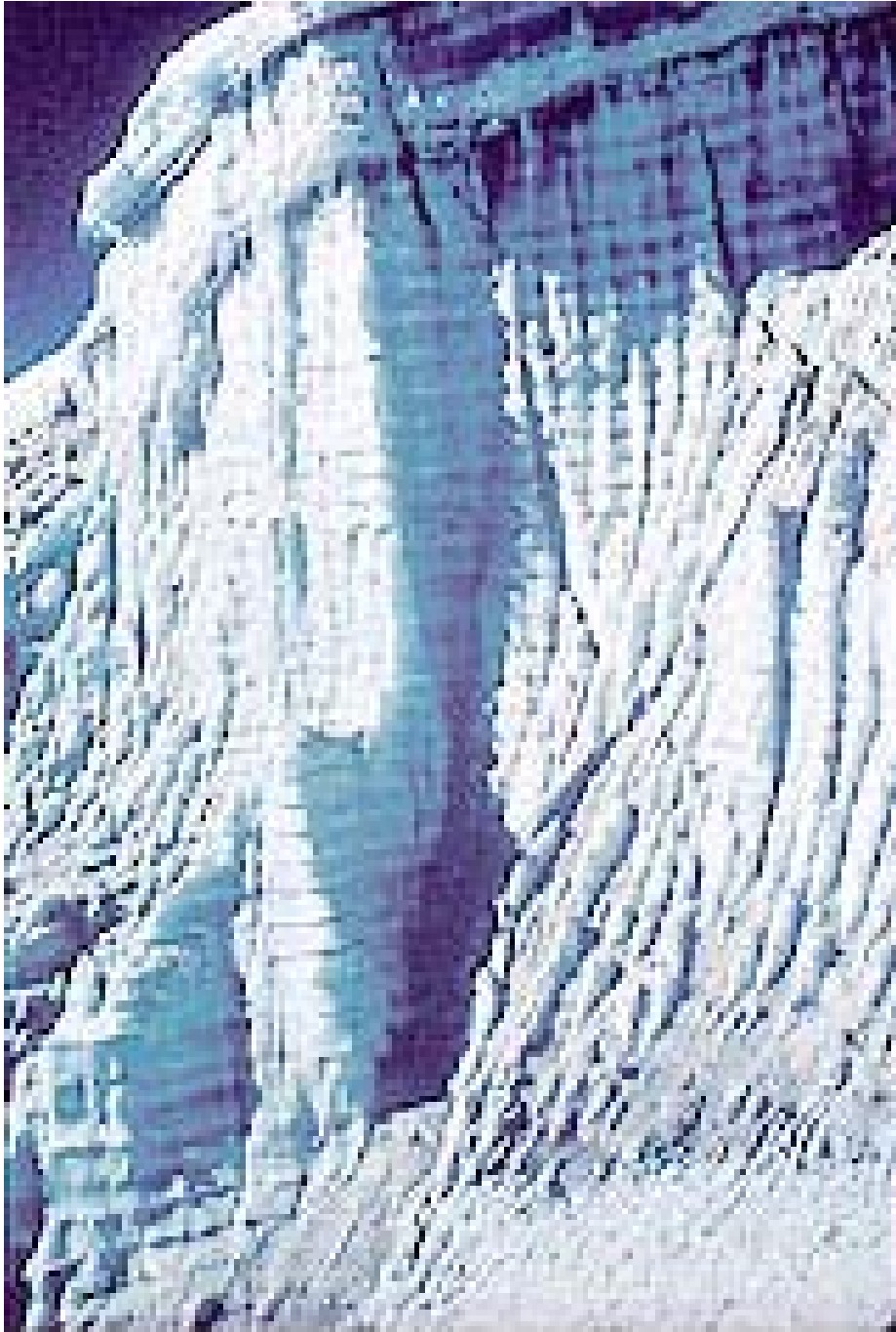
A photograph of a mountain valley. The foreground is a dark, rocky slope. In the middle ground, a valley floor is covered with a dense forest of evergreen trees. The background features several large, rugged mountain peaks, some of which are covered in snow. The sky is blue with scattered white clouds. The text "Paleoclimate and the Ice Ages" is overlaid in the center of the image.

**Paleoclimate and  
the Ice Ages**



**Ruth Valley Glacier Alaska--**The glacier occupying Yosemite Valley probably looked similar.





**Glaciers also exist at high altitudes in the tropics. The annual accumulation of snow, which provides climate information at yearly resolution, is clearly visible in this photograph of a tropical glacier.**

Photo: L.G. Thompson

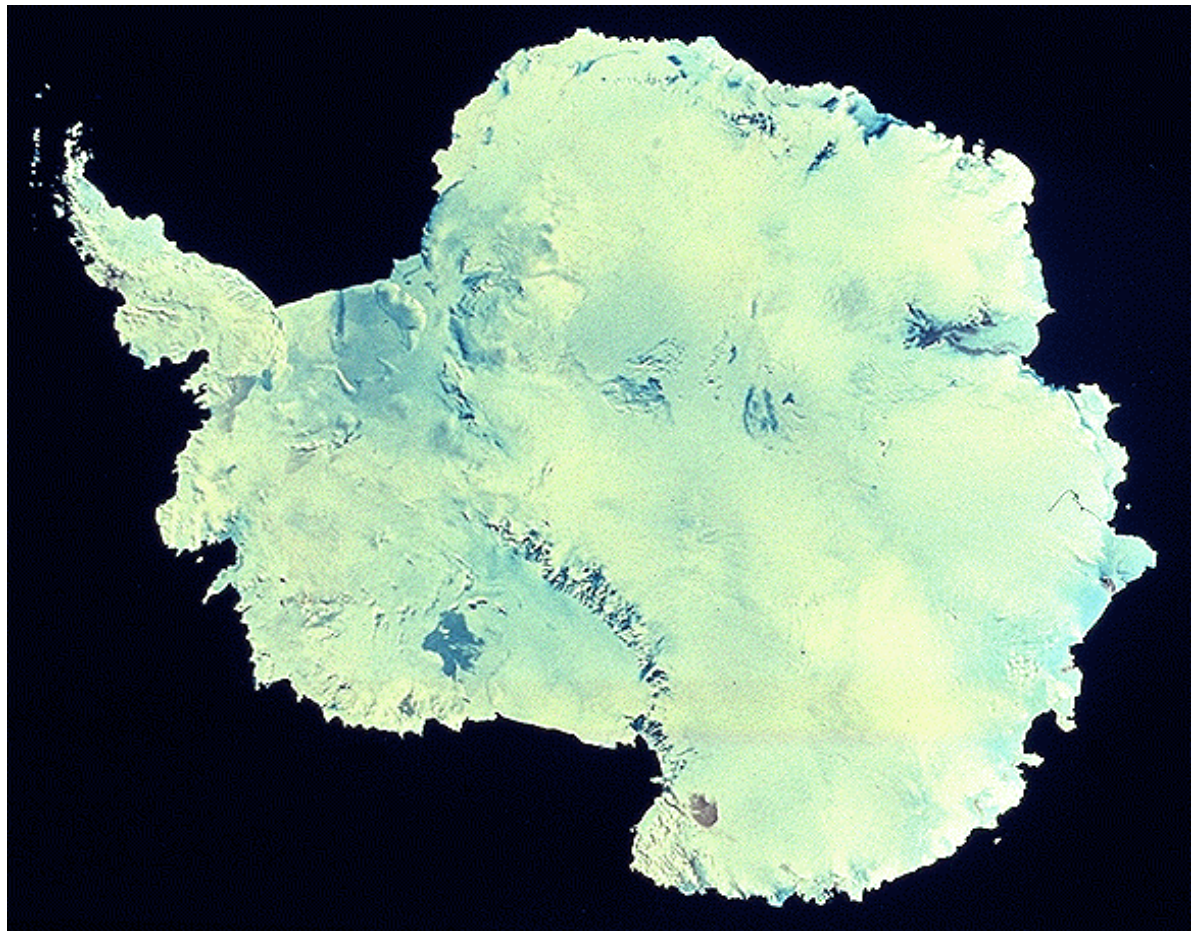
## Where are the ice sheets in the present-day climate?

In the northern hemisphere, Greenland is covered by an enormous ice sheet which is a few kilometers thick and more than five times larger than the state of California in area. If this ice sheet were to melt, global sea level would rise by about 7 meters. This is all that remains of the huge ice sheets that covered North America and Eurasia during **the last glacial maximum, about 20,000 years ago.**



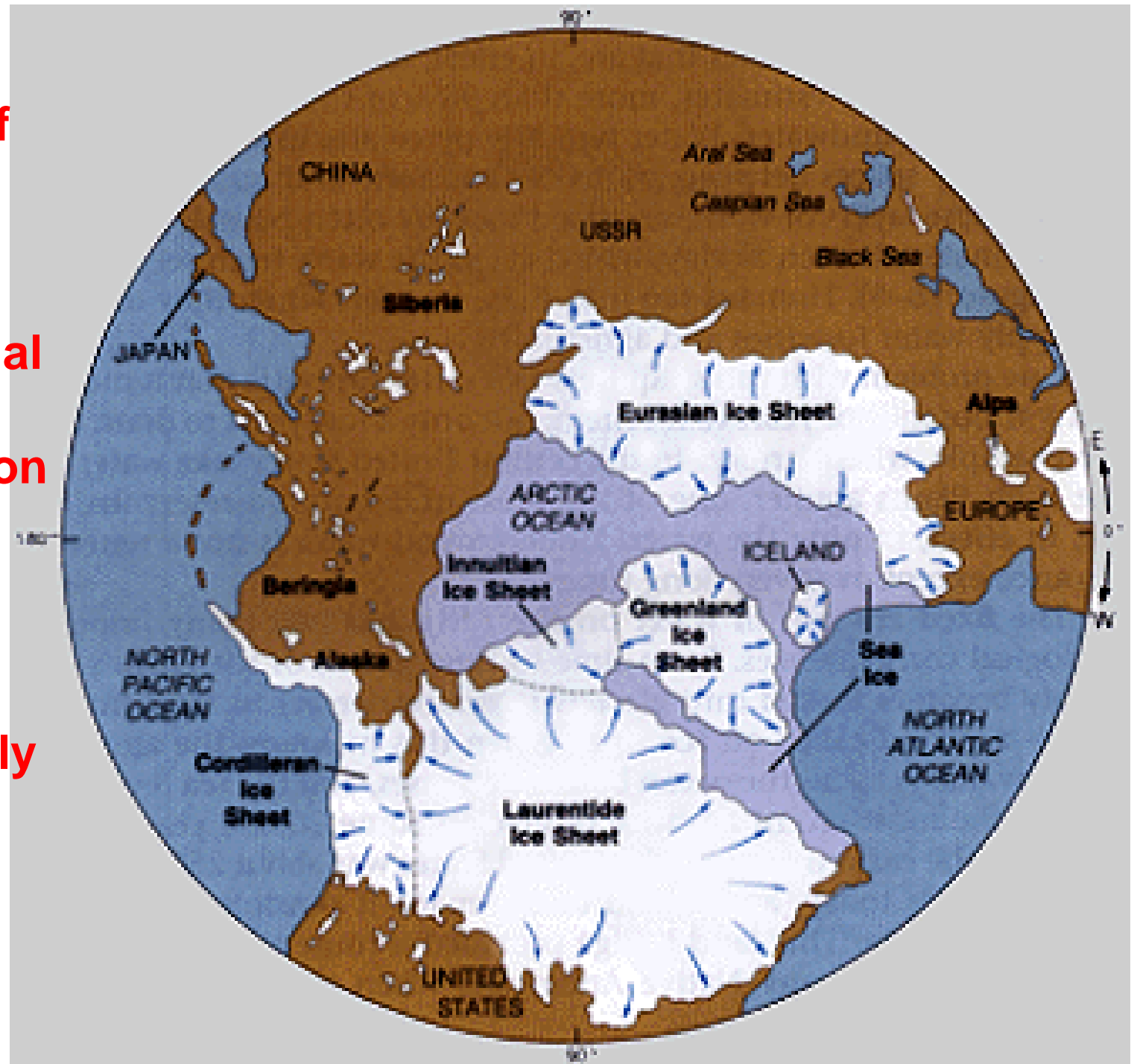
**In the southern hemisphere, the Antarctic continent is covered with an even larger ice sheet. The Antarctic continent is about 25% larger than the United States. If this ice sheet were to melt entirely, global sea level would rise by about 70 meters. About 80% of the planet's**

**freshwater is locked up in this ice sheet. The Greenland ice sheet contains about 9% of the planet's freshwater, with the remainder being contained mostly in lakes and mountain glaciers.**



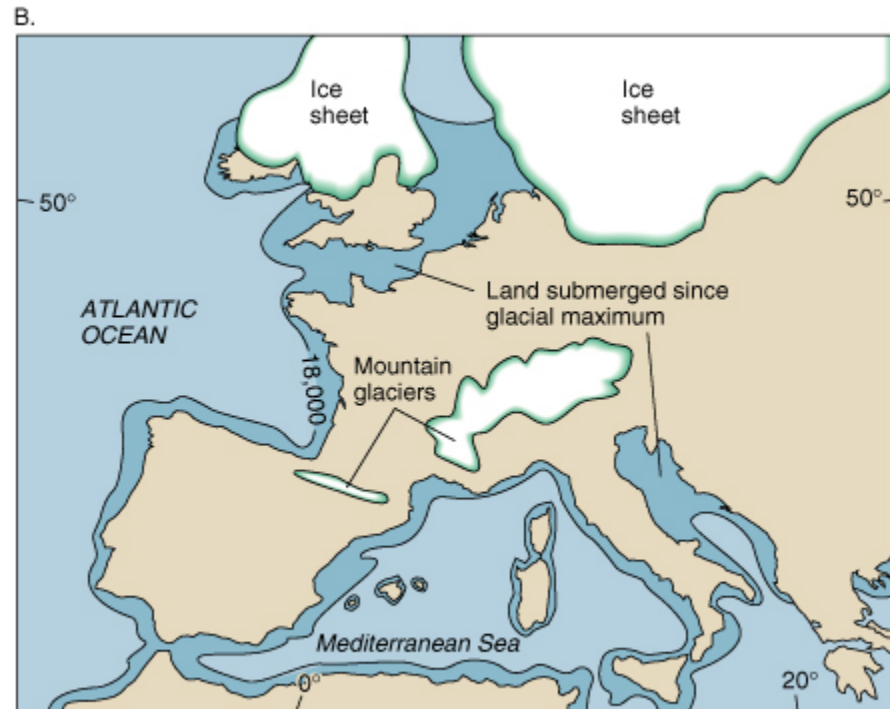
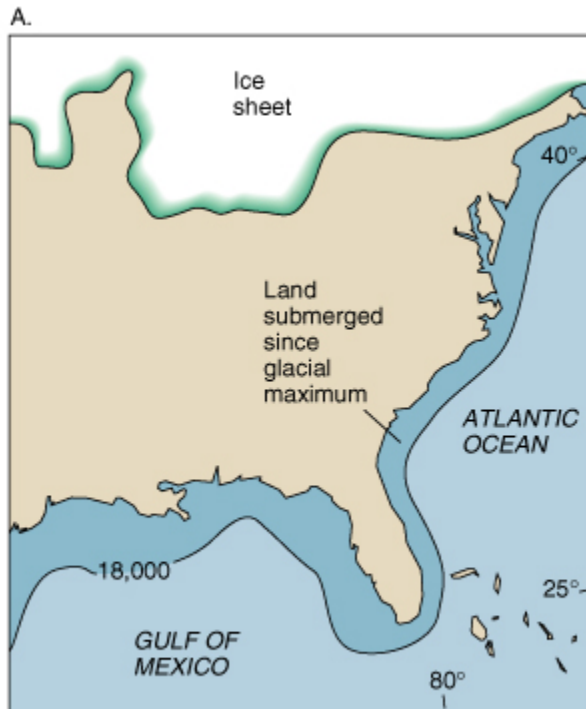


The extent of the northern hemisphere ice sheets at the last glacial maximum. The expansion of these ice sheets resulted in a sea level approximately 130 meters lower than today's.





Deformation of the land surface, such as **glacial moraines**, are evidence of ice sheet extent

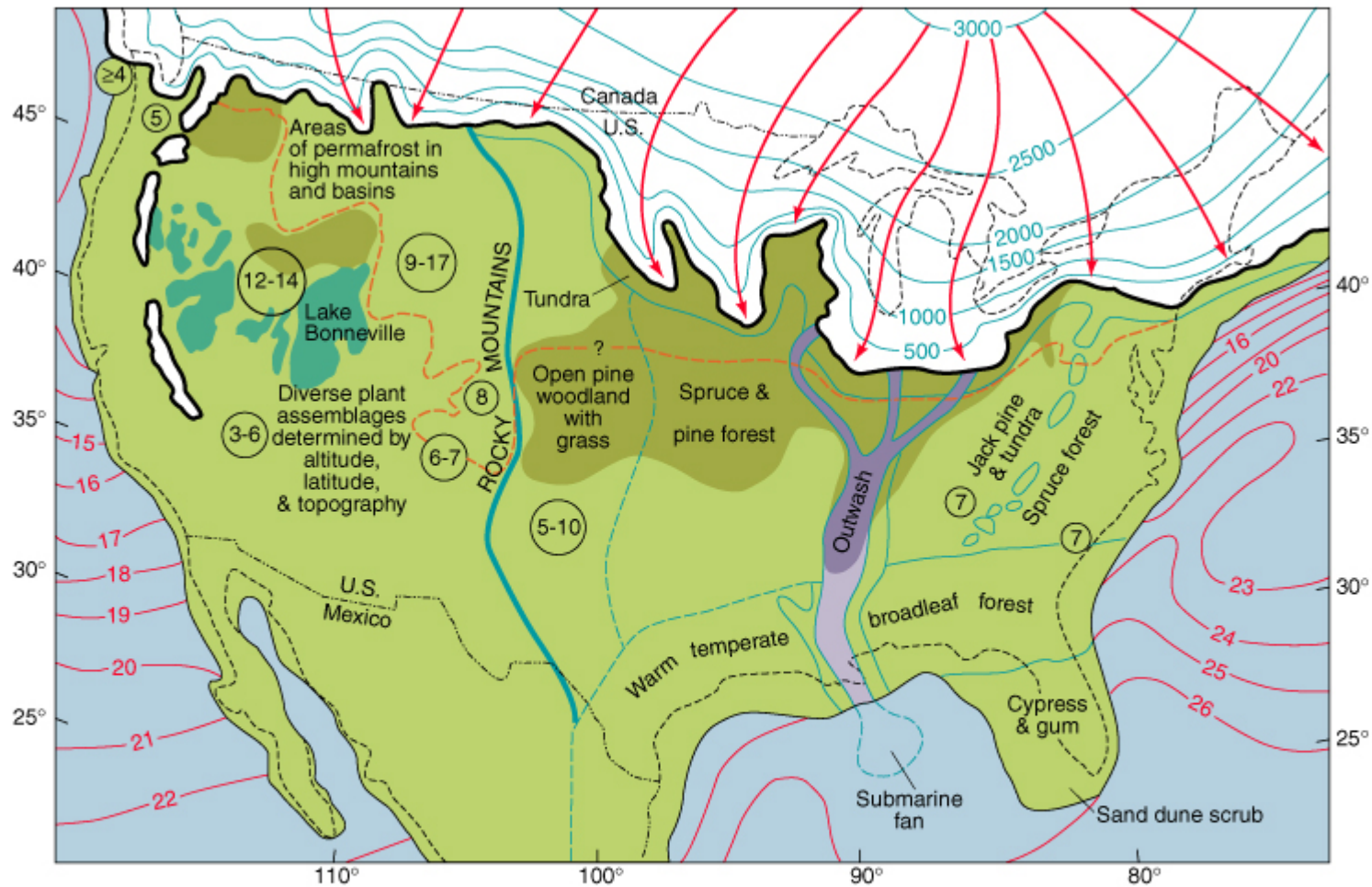


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**Because of the lowered sea level, the coastlines during the last ice age differed significantly from today's. North America was connected to Eurasia by a land bridge where the Bering strait is today, and the Mediterranean basin was cut off from the Atlantic.**

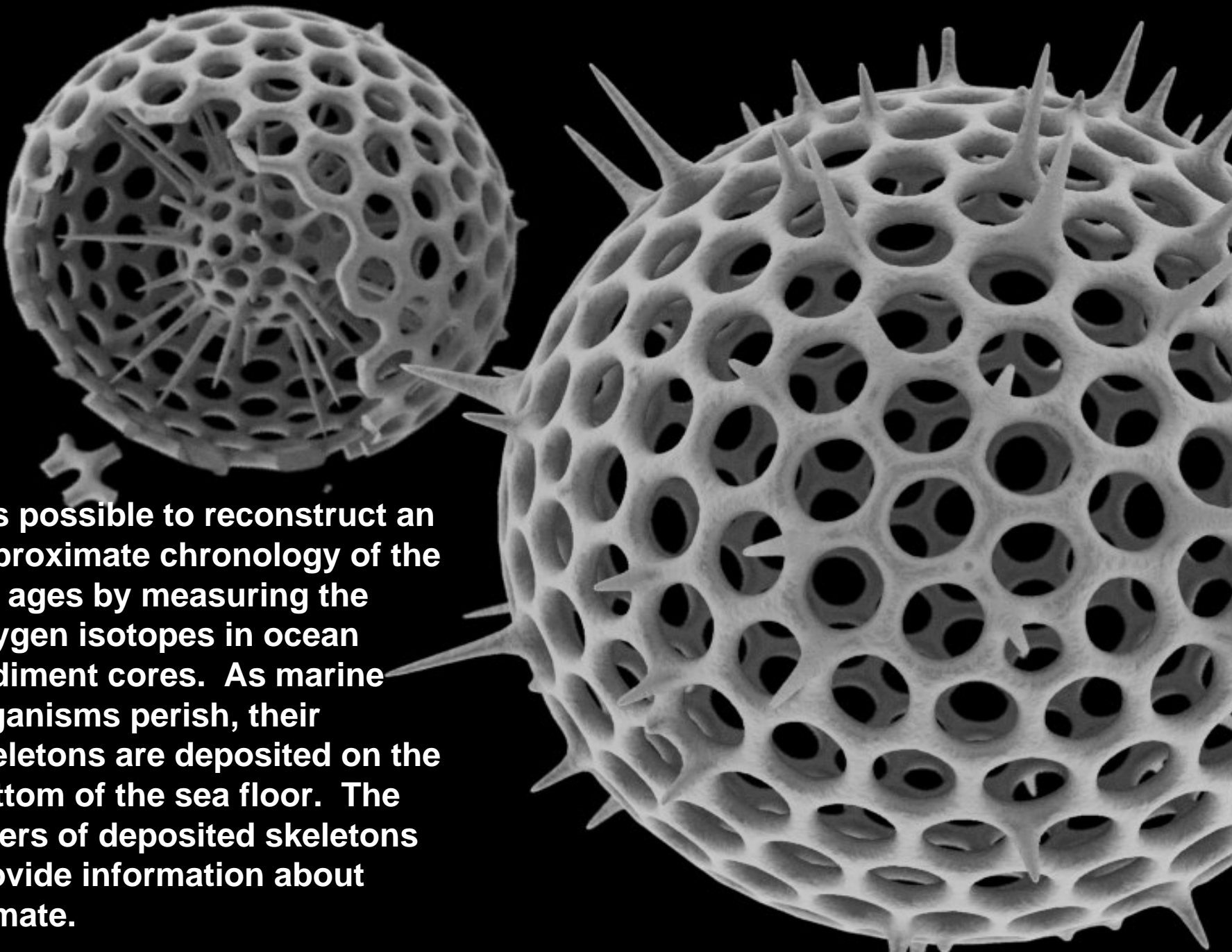


# The climate in North America was significantly different...



- Present coastline
- Glacier limit
- 17- August sea-surface temperatures (°C)
- 1500- Glacier surface contours (m)
- - - - - Approximate southern limit of permafrost
- █ Principal areas of dune sand and loess





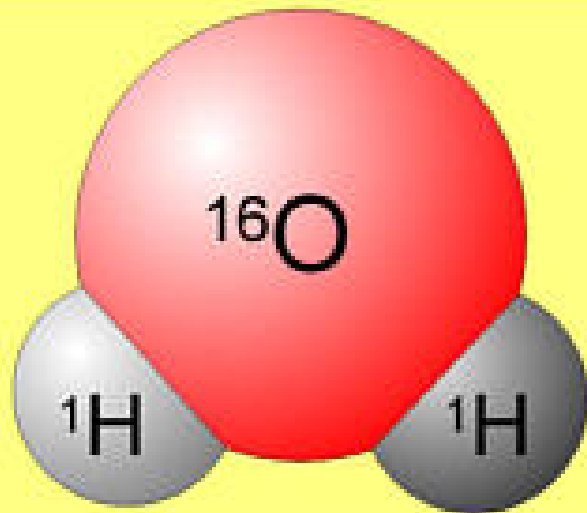
**It is possible to reconstruct an approximate chronology of the ice ages by measuring the oxygen isotopes in ocean sediment cores. As marine organisms perish, their skeletons are deposited on the bottom of the sea floor. The layers of deposited skeletons provide information about climate.**

## OXYGEN ISOTOPES

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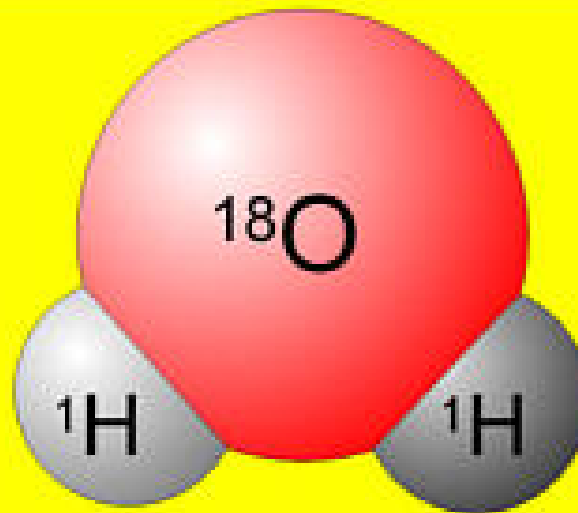
The chemical elements are often found in more than one form. The number of **protons** in the atomic nucleus is constant for any given element, but the number of **neutrons** in the nucleus can vary. The chemical behavior of isotopes of the same element is very similar, the main difference being their weight. Oxygen primarily comes in two isotopes: Oxygen 16 ( $^{16}\text{O}$ ) and Oxygen 18 ( $^{18}\text{O}$ ). Oxygen 18 has two extra neutrons, making it about 10% heavier than Oxygen 16.

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$1+1+16 = \underline{18}$   
Molecular weight  
of  $^{16}\text{O}$  water

Makes up 99.8% of  
water, evaporates  
more easily,  
precipitates less easily.



$1+1+18 = \underline{20}$   
Molecular weight  
of  $^{18}\text{O}$  water

0.2% of water, 11%  
heavier, evaporates  
less easily, precipitates  
more easily.

Superscripts  
show atomic  
masses of  
hydrogen and  
oxygen

## **ICE VOLUME EFFECT ON OXYGEN ISOTOPES**

The ratio of the heavier to the lighter oxygen isotope varies in the ambient seawater because of the variations in total ice volume. The water molecules containing the heavier isotope are less likely to evaporate and be incorporated into the ice sheet. So as total ice volume increases, the ocean becomes increasingly enriched in the heavier isotope of oxygen.

## **TEMPERATURE EFFECT ON OXYGEN ISOTOPES**

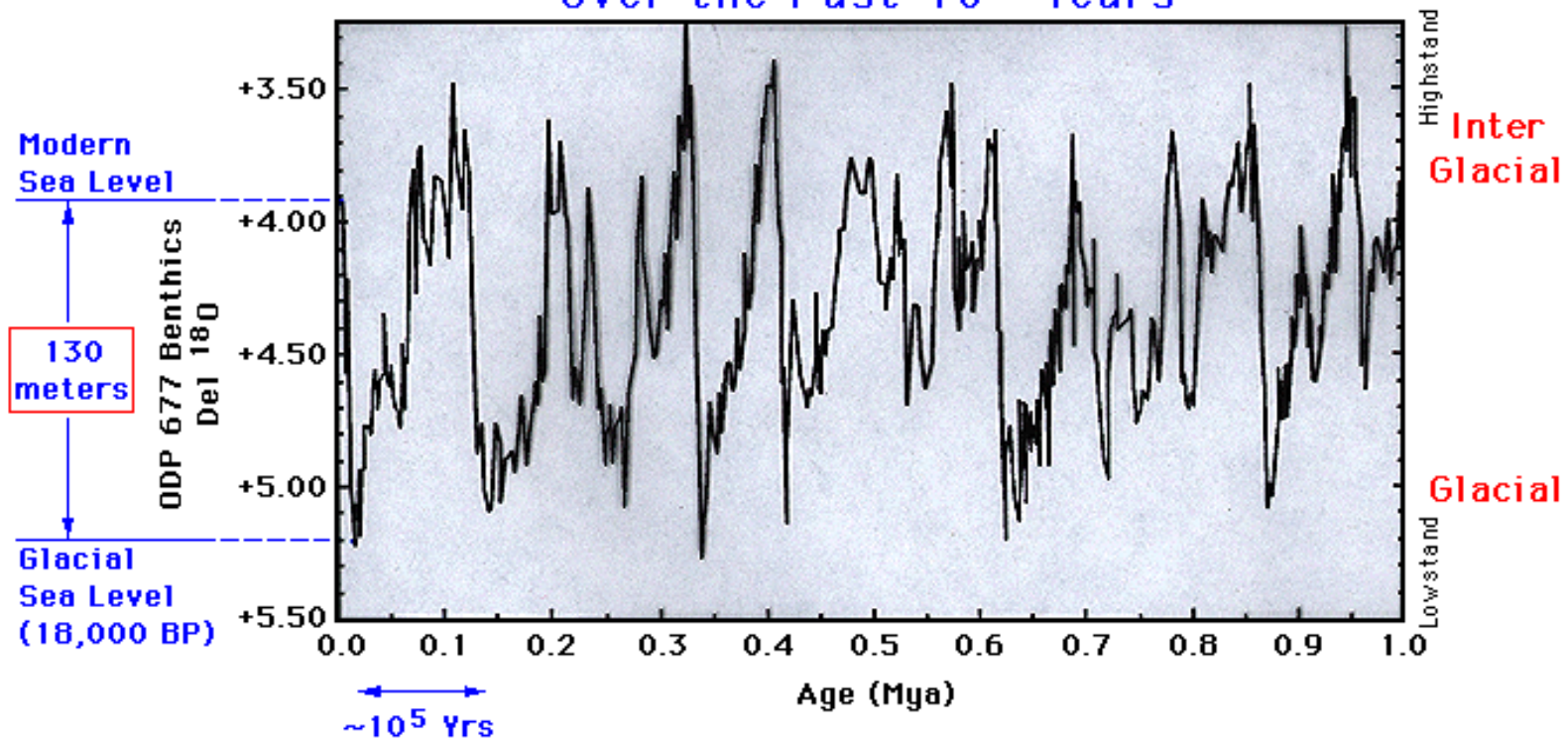
When temperatures are colder, the organisms incorporate more of the heavier isotope of oxygen into their skeletons. Measuring the ratio of the heavier to the lighter oxygen isotope in the skeletons therefore indicates how warm the water was when the organism was alive.

## **OXYGEN ISOTOPE SIGNATURE IN SEDIMENT CORES**

When ocean temperatures are cold and ice volume is large, the skeletons should be enriched in the heavier isotope. Presumably temperature and ice volume are tightly correlated, so an examination of the oxygen isotope record in ocean sediment cores gives us a clear picture of when the ice ages occurred.



## Record of Volume of Continental Glaciers Over the Past $10^6$ Years



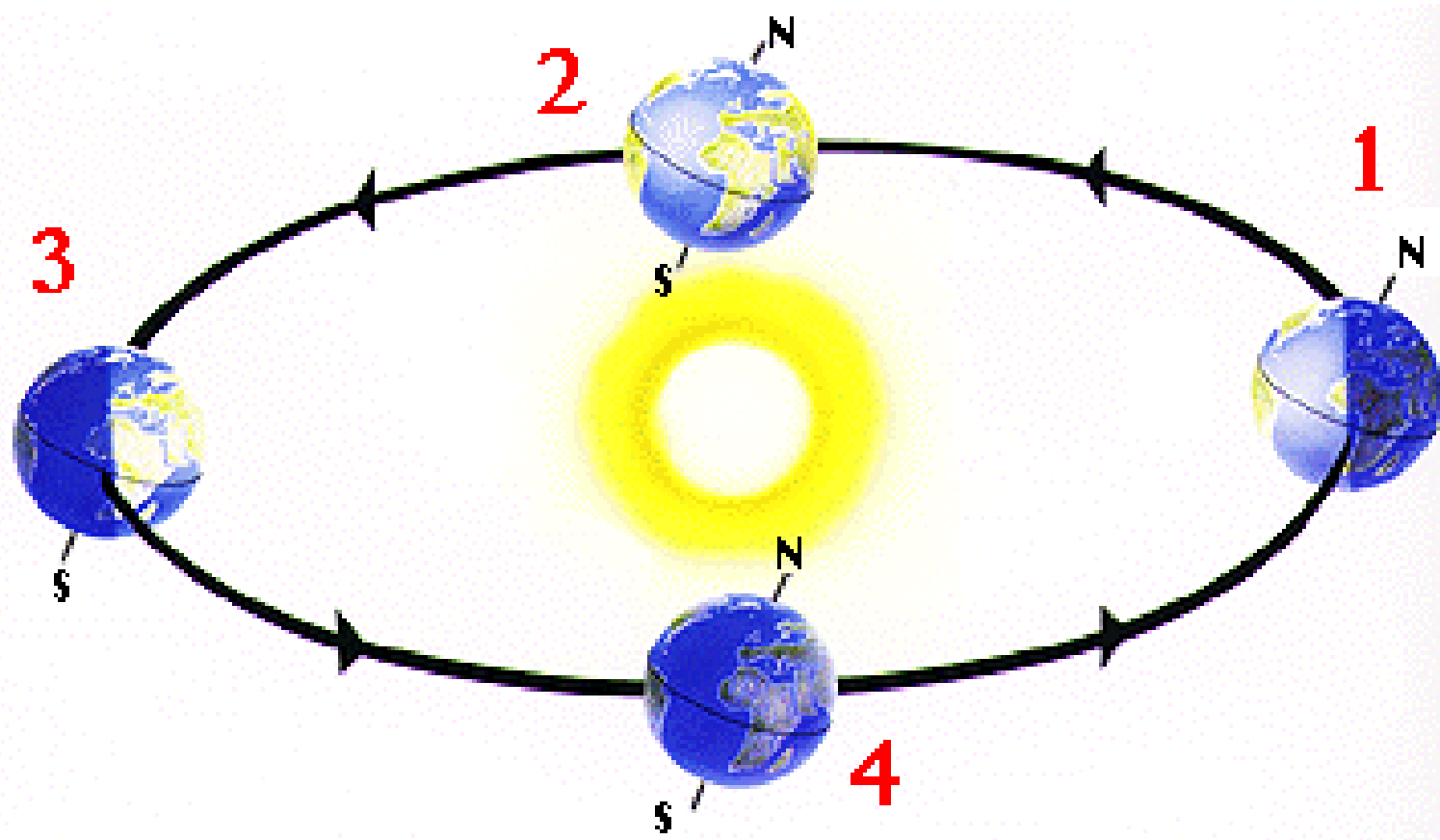
Oxygen isotope record from deep Pacific Ocean sediments

**The oxygen isotope record from the Pacific Ocean off the coast of South America. It reveals that the ice ages occurred approximately once every 100,000 years.**

# **Theory of Climate Change During the Pleistocene (Ice Sheet Fluctuation)**

- ❑ Variations in the output of the Sun: Solar energy (solar constant)**
- ❑ The Earth's orbital changes (incoming solar radiation distribution): The Milankovitch theory of climate change**
- ❑ Volcanic dust content of the atmosphere**
- ❑ Distribution of carbon dioxide between the atmosphere and the oceans**

# The Orbital (Milankowitch) Theory of Climate Change (Ice Ages)



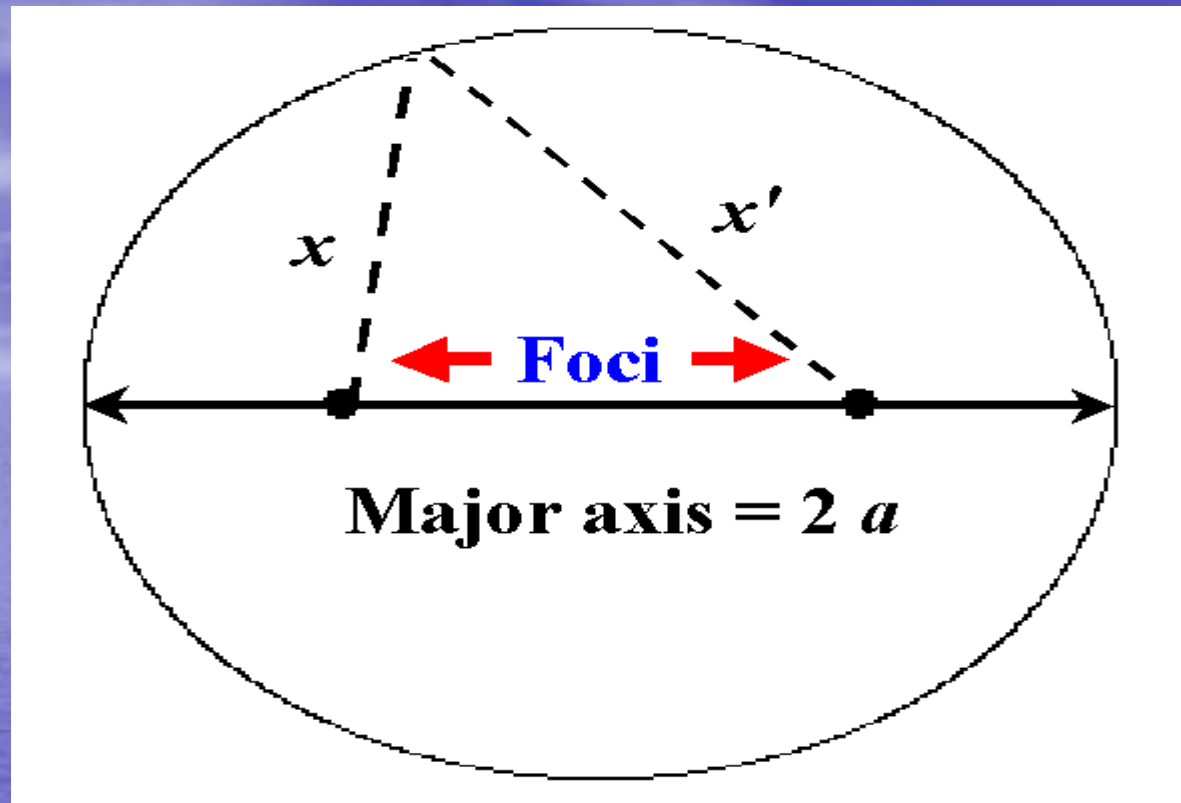
**The laws that govern the Earth's orbit about the Sun (Kepler, 1599): Distance between the Earth and the Sun**

**Kepler's first law: The law of orbits; orbital ellipse**

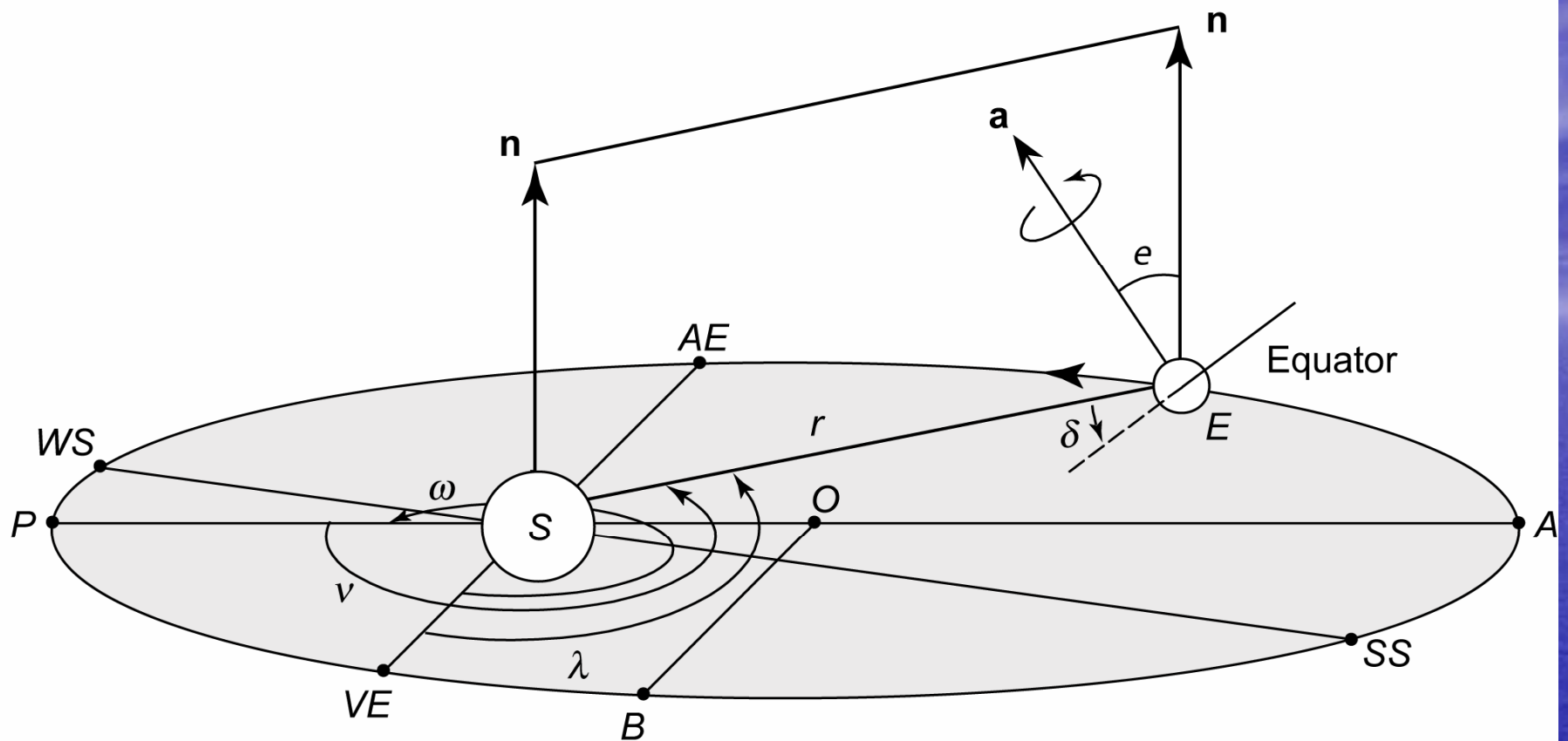
**Kepler's second law: The law of areas; conservation of angular momentum**

**Kepler's third law: The law of periods; balance between gravitational and centrifugal forces**

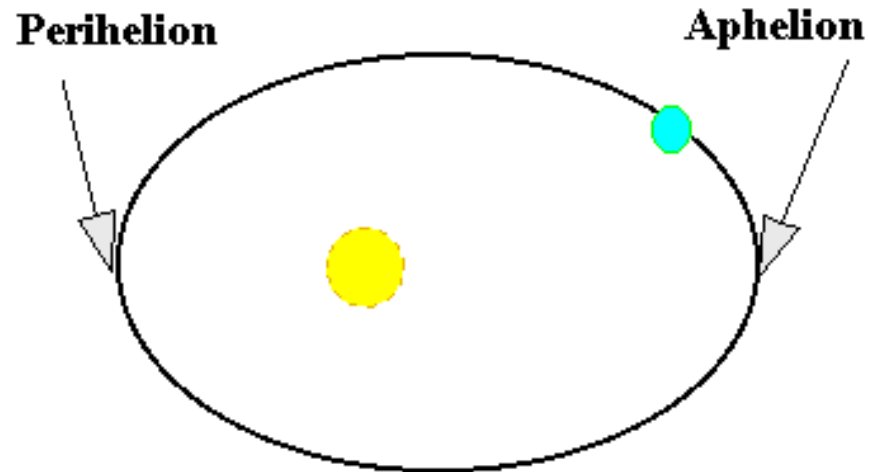




The orbits of the planets are **ellipses** (from Kepler's 1<sup>st</sup> law). Take any two points (called foci) in space, one can define an ellipse as the collection of points whose combined distance to the two points is a constant. In the case of the planets' orbit, the Sun is located at one of the two foci of the elliptical orbit.

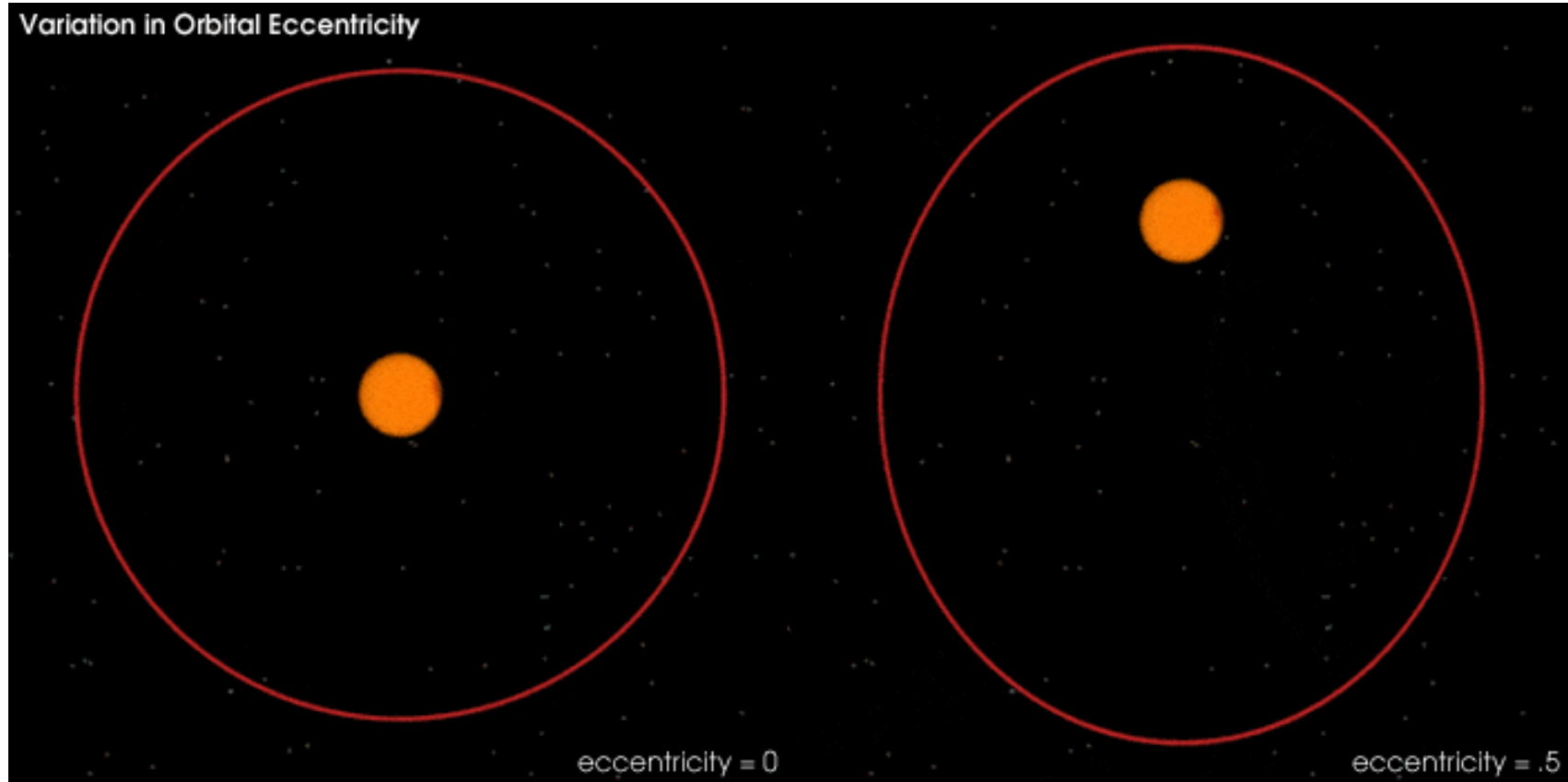


The Earth-Sun geometry.  $P$  denotes the perihelion,  $A$  the aphelion,  $AE$  the autumnal equinox,  $VE$  the vernal equinox,  $WS$  the winter solstice,  $SS$  the summer solstice;  $n$  is normal to the ecliptic plane;  $a$  is parallel to the Earth's axis;  $\delta$  is the declination of the sun,  $e$  the oblique angle of the earth's axis,  $\omega$  the longitude of the perihelion relative to the vernal equinox,  $v$  the true anomaly of the earth at a given time,  $\lambda$  the true longitude of the earth,  $O$  the center of the ellipse,  $OA$  (or  $OP = a$ ) the semi-major axis,  $OB (= b)$  the semi-minor axis,  $S$  the position of the sun,  $E$  the position of the earth, and  $ES (= r)$  the distance between the Earth and the Sun.



The point in the orbit when the a planet is closest to the Sun is called **perihelion**. The point when the planet is furthest from the sun is called the **aphelion**.

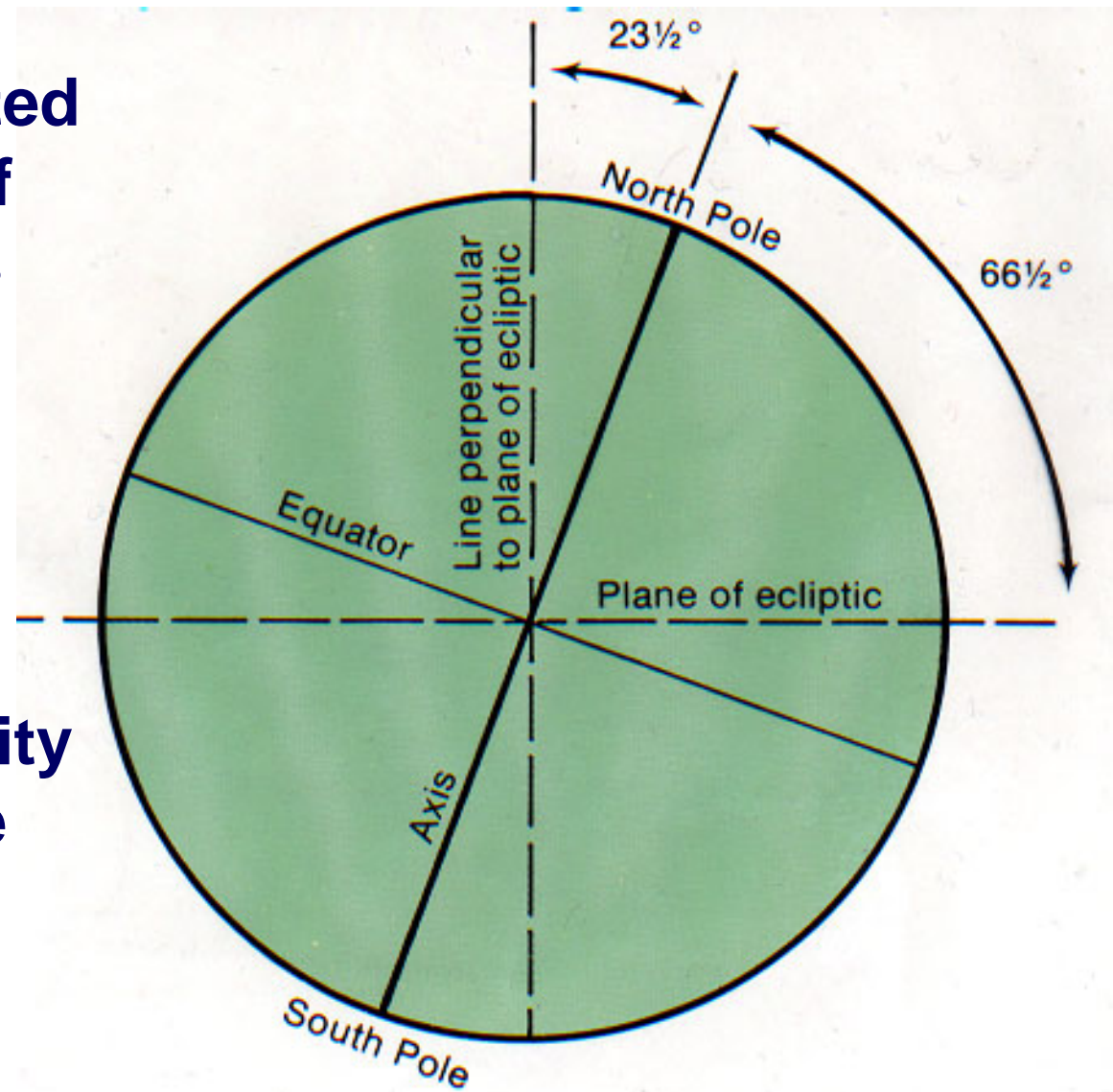
In the case of Earth's orbit, perihelion occurs in early January, while aphelion occurs in early July. The planet gets more sunshine at perihelion, and less at aphelion, because of the **inverse square law**.



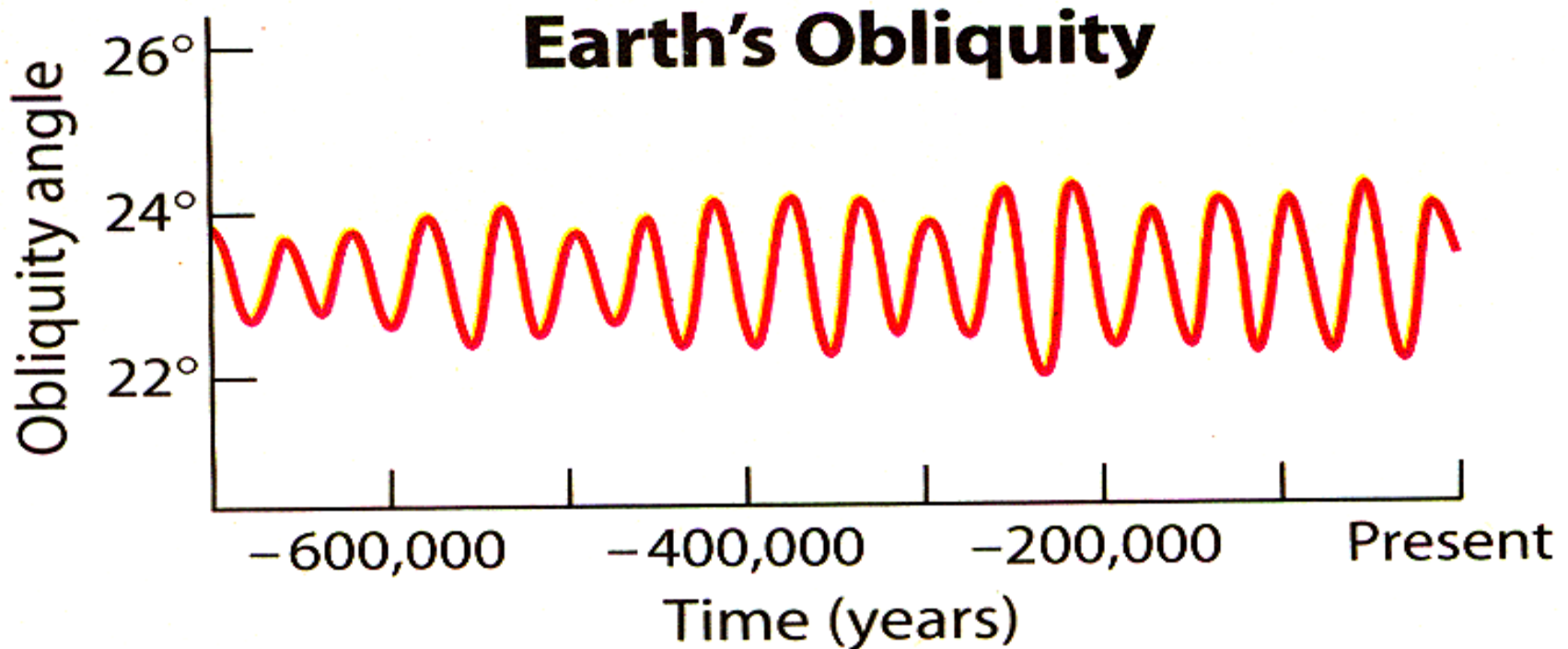
The **eccentricity** ( $e = (a^2 - b^2)^{1/2} / a$ ,  $e = 0$  for sphere) of the Earth's orbit varies between **0 and 0.06** with a period of about **100,000 years** and 400,000 years. This variation is due to the gravitational pull of other planets.



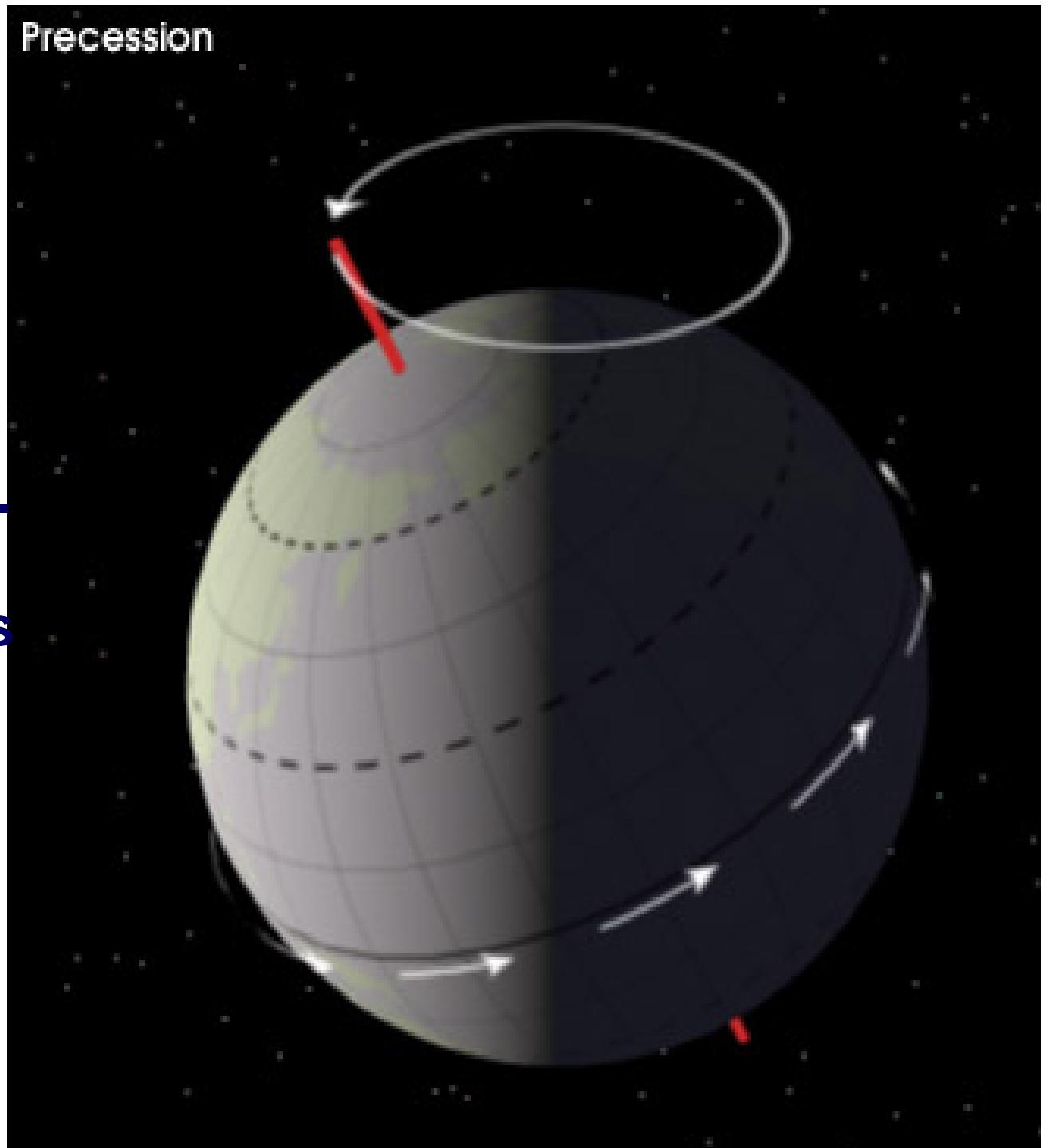
The axis about which the earth rotates is tilted relative to the plane of the earth's orbit. This tilt, called **obliquity**, is **the reason why our planet has seasons**. Currently the earth's **obliquity is 23.5 degrees**. If the obliquity were 0 (i.e. no tilt), the northern hemisphere would get about the same amount of sunshine all year round.

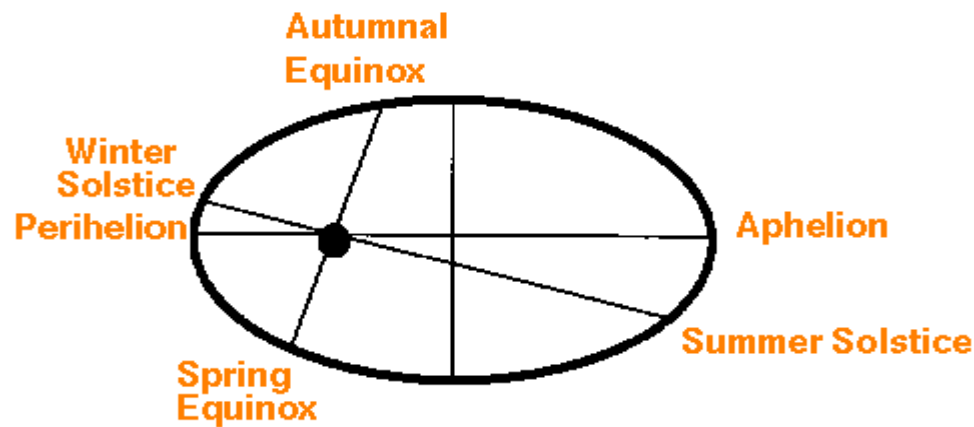


The tilt of a spinning object can vary; Earth is no exception. The obliquity of the Earth varies between about **22 and 24 degrees** with a period of about **41,000 years**.

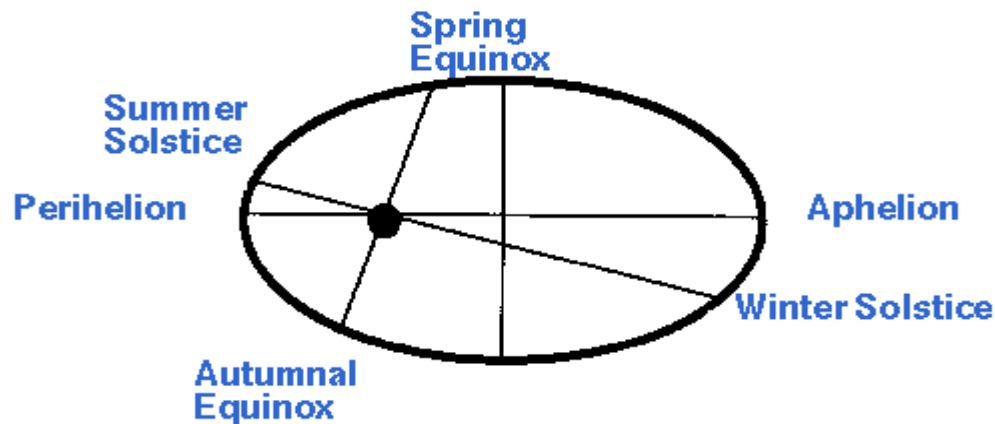


The direction of the Earth's spin axis also **precesses**. This means that the earth's spin axis traces out a circle. Like obliquity, precession occurs on very long time scales. It takes **about 20,000 years** for the spin axis to trace out a circle once.





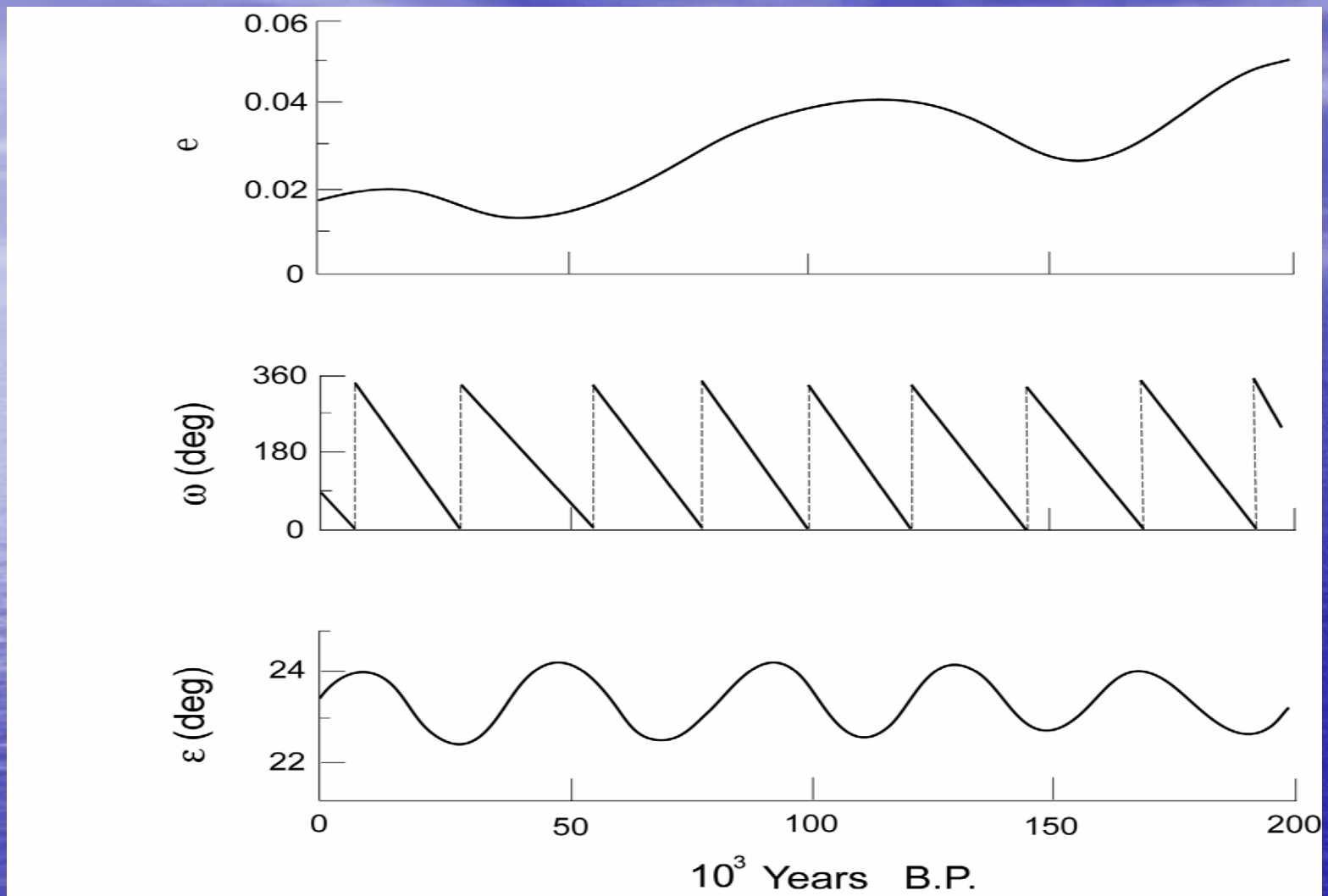
The situation now. Perihelion occurs in early January and coincides with northern hemisphere winter.



The situation about 10,000 years ago in the opposite phase of the Earth's precessional cycle. Perihelion occurs in early July and coincides with northern hemisphere summer.

Advancement of perihelion by about 25 minutes per year:  $365 \text{ days} \times 24 \text{ hrs} \times 60 \text{ min} / 25 \text{ min} \sim 21,000 \text{ yrs}$ , precession index.





The eccentricity  $e$ , the obliquity of the ecliptic  $\epsilon$ , and the longitude of the perihelion  $\omega$  of the earth as functions of year before the present.

## Summary: how orbital variations affect sunshine

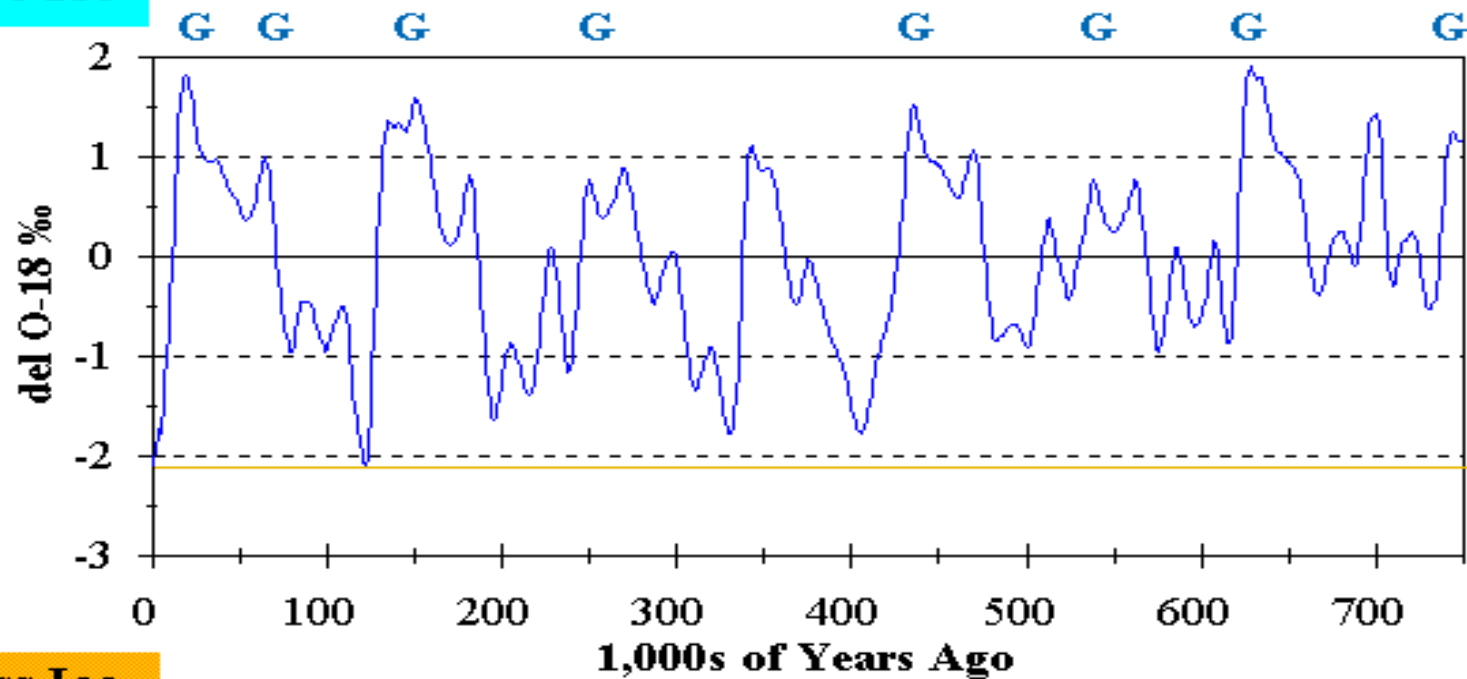
**Obliquity** When obliquity is high, seasonality is enhanced. In mid and high latitudes, more sunshine comes in summer, and less comes in winter. Averaged over the whole year, the high latitudes receive more sunshine, and the low latitudes receive less.

**Precession** When perihelion occurs at summer solstice, the contrast between summer and winter is enhanced. When perihelion occurs at winter solstice, seasonality is weakened. Precession has little effect on annual mean sunshine.

**Eccentricity** Changes in the eccentricity of the earth's orbit have very little effect on the annual mean sunshine anywhere. However, they do have a large impact on the amplitude of the precessional cycle. If the earth's orbit is very eccentric, the timing of perihelion in the calendar year becomes more critical.

## Ice Volume Planktonic Foram O-18 as Proxy

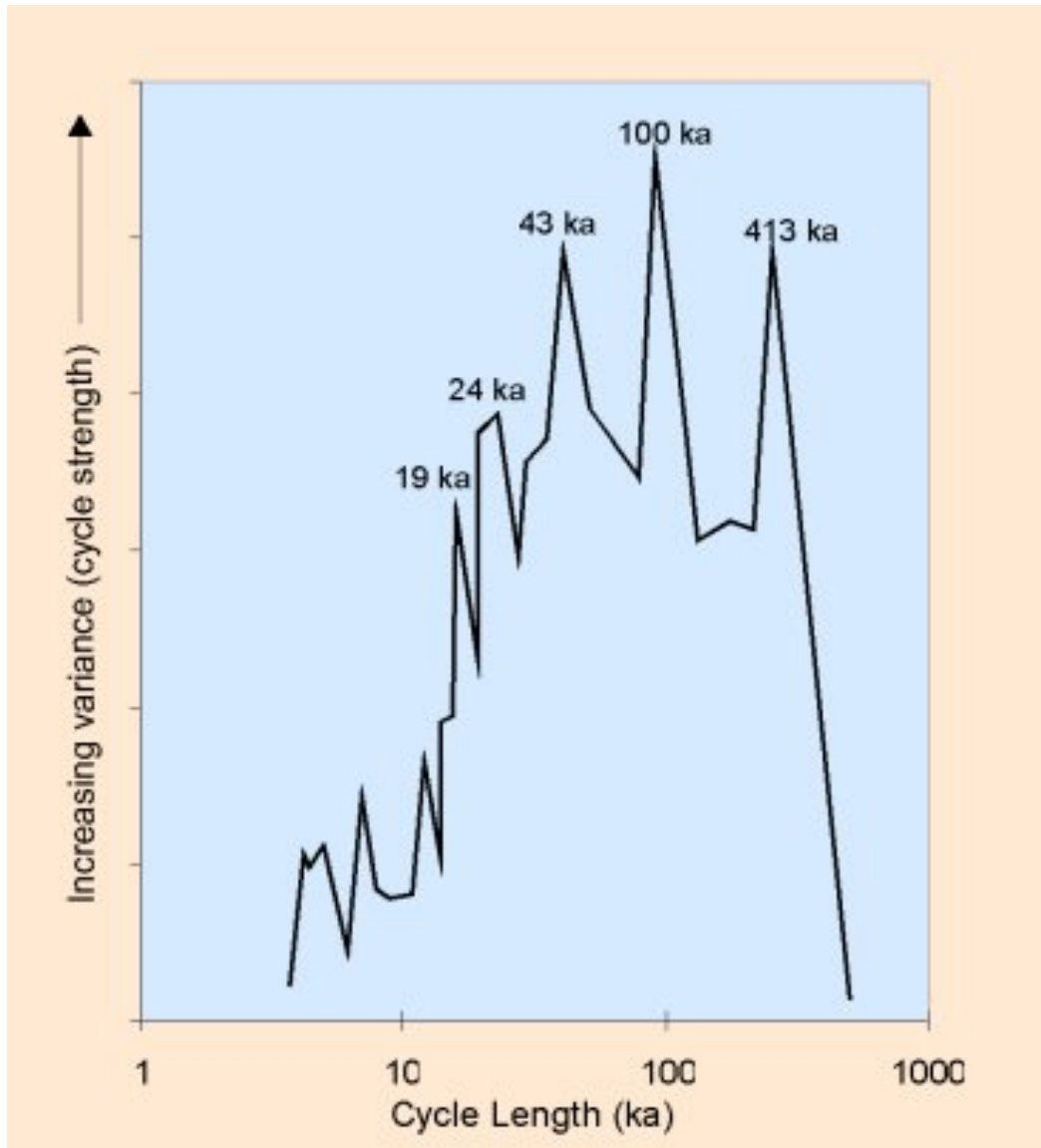
More Ice



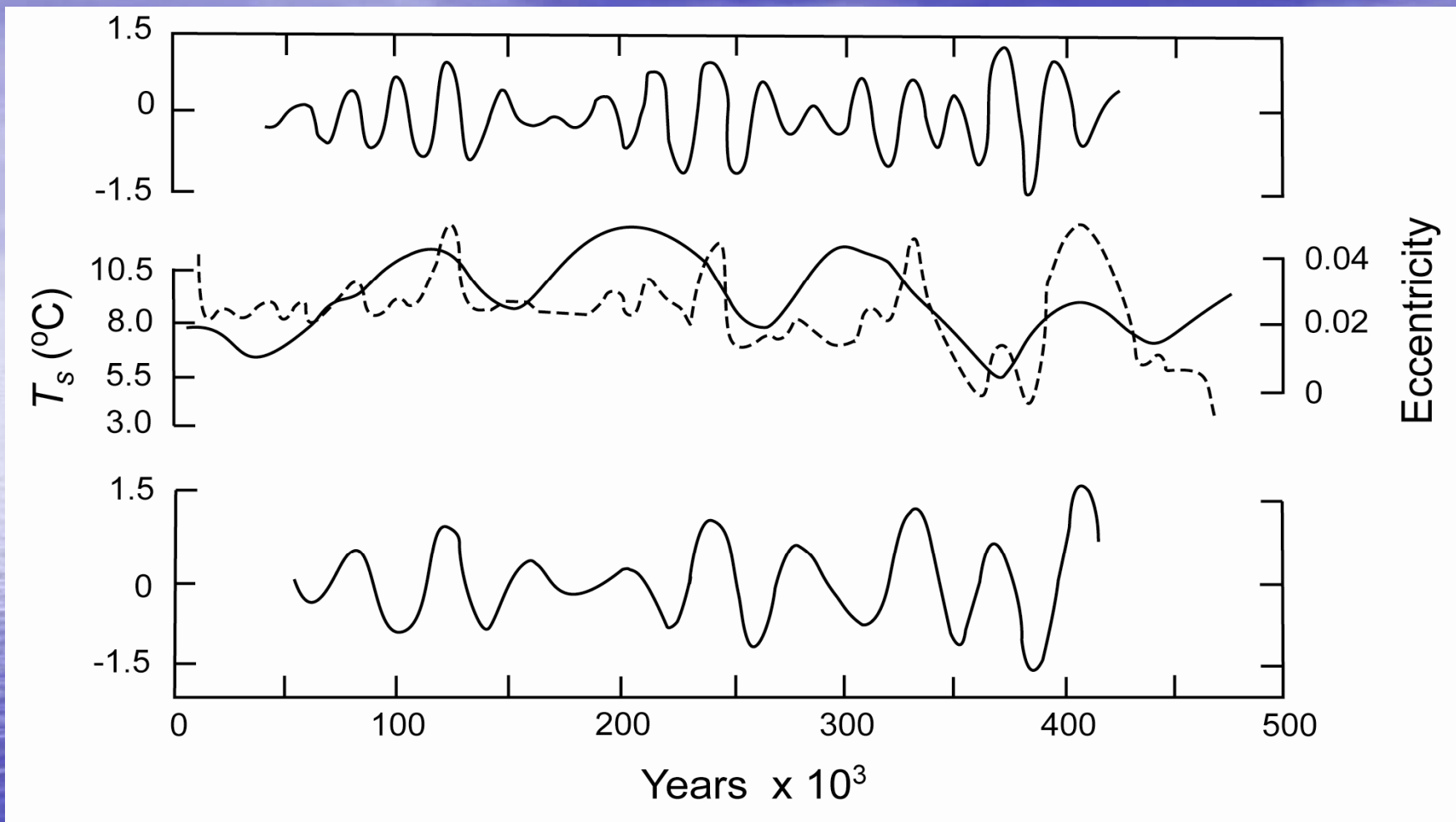
Less Ice

The periodicities associated with variations in the Earth's orbit are dominant in chronologies of ice volume!

## Spectrum of ice volume history

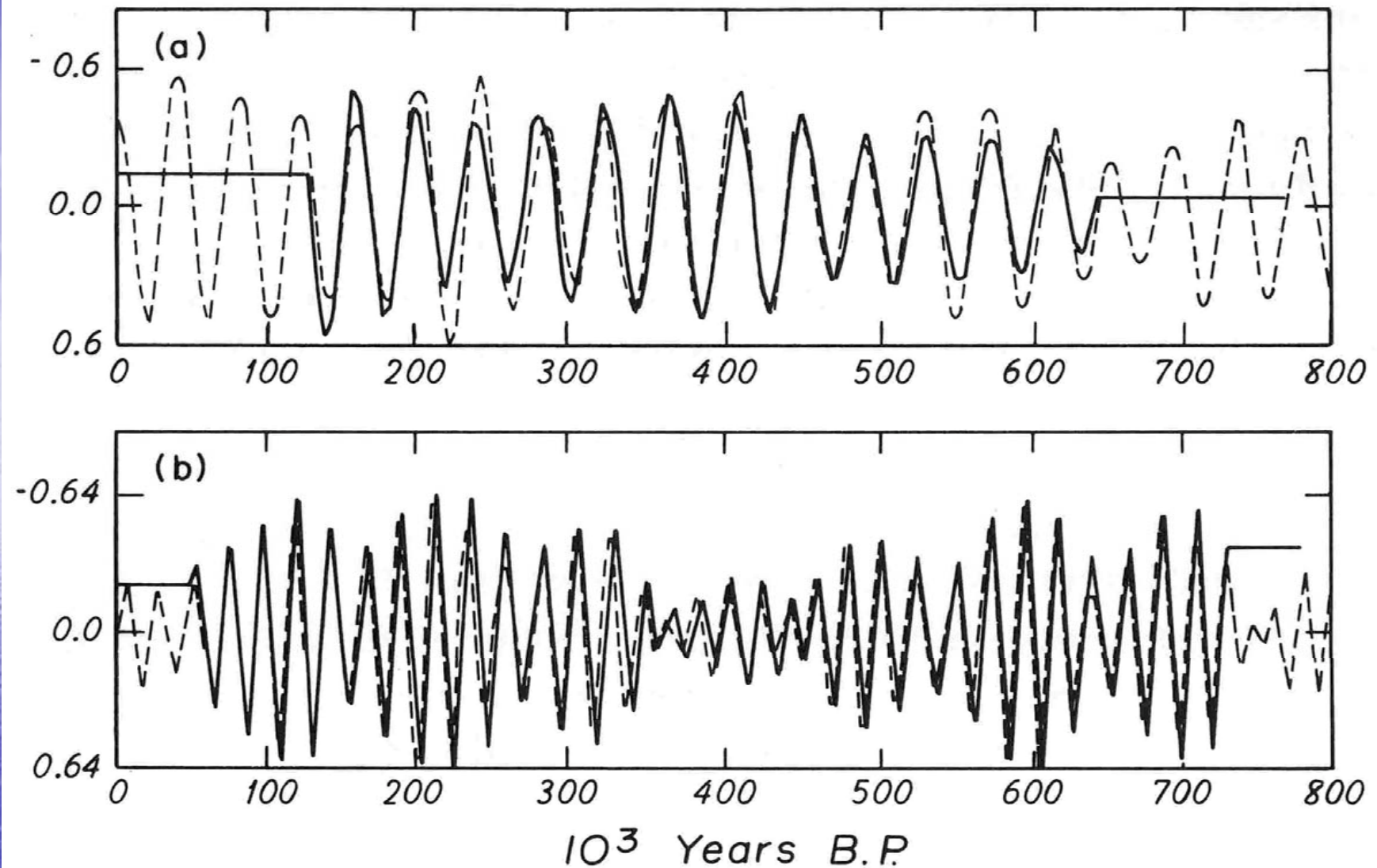


Note the clear peaks in the spectrum at the time scales associated with orbital variability. In fact over 95% of the variability occurs at these time scales. The idea that orbital variations might be responsible for climate variability is called the **Milankovitch theory of climate.**



Variation in eccentricity and surface temperature over the past 500,000 years. Dashed line in the center shows variations in the estimated sea-surface temperature  $T_s$ . Solid line denotes the orbital eccentricity. Upper and lower curves are the 23,000- and 40,000-year frequency components extracted from  $T_s$  based on a statistical filter method (data taken from Hays et al., 1976).





Variations in obliquity, precession, and the corresponding frequency components of  $\delta^{18}\text{O}$  over the past 780,000 years. Solid lines are filtered versions of the  $\delta^{18}\text{O}$  record. Dashed lines are phase-shifted versions of (a) obliquity and (b) precession curves. All curves have been transformed to have zero means with arbitrary scales (after Imbrie et al., 1984).

# Summary

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- ❑ On the basis of the statistical spectral analysis of oxygen isotope data (proxy for ice volume) and the solar insolation available to the Earth, the orbital theory appears to be able to explain the ice sheet fluctuations in the past 700 thousand years.
- ❑ However, questions still remain as to the roles of the Sun's output, particularly the sunspot variability, and the  $\text{CO}_2$  content in the atmosphere.