QUATERNARY CLIMATE CHANGE, ICE AGES, AND LANDSCAPE LEGACY

1) PLEISTOCENE GLACIATIONS: EPISODIC GLACIAL HISTORY
   a) Pleistocene Glacial Record – geologist and geomorphologist have recognized evidence for ancient glaciation on landscape dating back to the 1700's
      i) Ancient lake beds
      ii) Erratics
      iii) Alpine and continental glacier landforms

   b) Periods of extensive glacial activity are evident from preserved rock/glacial record, field investigations have provided proof that many ice ages have existed in past.

   c) Evidence of more recent Pleistocene glaciations come from geomorphological evidence reflecting glacial-related landscape modifications.

      i) Geomorphological evidence is somewhat limited in longevity as glacial geomorphic phenomena are readily destroyed by subsequent weathering and fluvial surface erosion as well as subsequent glacial modifications.

         (1) Most recent ice advances are best preserved

   d) Geologic evidence of ancient glacial periods comes from the sedimentary rock record.

      i) Poorly sorted "Tillite" deposits (glacial diamicton)

      ii) "Dropstone" deposits

         (1) Ice Rafted Debris in Fine Mud/Shale

      iii) Paleofossil/Paleoclimatological Evidence

2) Pleistocene Ice ages- characterized by complex periods of glacial advance and retreat, separated by periods of warm climates

   a) Pleistocene Epoch- geologic time period between 10,000 years and 1.6 million years ago.

   b) Character of Pleistocene: refrigeration of high latitude and high altitude portions of earth, and subsequent development of extensive ice sheets and alpine glaciers.

   c) Glacial/interglacial relations: Classical Delineation of Glacial Deposits in Mid-Western U.S. = find evidence for four major glacial periods during the Pleistocene in North America (in order of occurrence)

      i) Nebraskan, Kansan, Illinoian, and Wisconsinan (most recent).

         (1) Each period was separated by a warm time known as an interglacial period; represented by paleosol development on till.

         (2) Wisconsin glaciation most recent: from 30,000 yr B.P. to 5,000-10,000? year B.P.

      ii) Modern Oxygen Isotope Record of Oceans
         (1) Paleothermometry studies suggest ~20 major cold/glacial cycles during the Pleistocene, with significant glacial advance on the landscape, and lowering of sea level.

   d) Extent of Pleistocene Glaciation

i) Total of 1/3 land area of earth with ice thickness ranging from 10's of feet to several thousands of feet.

ii) Pleistocene glaciation grew out from poles to lower latitudes

(1) “Laurentide Ice Sheet” = Covered most of Canada, extending down into the northern tier states of the U.S. (northern Washington, Idaho, Montana, North Dakota, Eastern South Dakota/Nebraska, Wisconsin, Minnisota, Illinois, Michigan, Ohio, Indiana, Iowa, northern Pennsylvania, New York and the New England/Maritime states).

(2) Europe, glaciers covered all of the scandinavian countries, northern Russia, Great Britain, Ireland, Denmark, Sweden, Poland.

iii) High Mountain areas also were significantly impacted by Pleistocene glaciation: Cascade Range, Sierra Nevada Mountains, the northern Rockies of Montana, Wyoming and Idaho, the intermountain west of Utah/Nevada, and the southern Rockies of Colorado and New Mexico. As well as the Alps, and Pyrenees of Europe.

e) Landscape modification: both in the glaciated regions as well as in "periglacial zones"

i) Periglacial zones- areas lying in the foreland of the glaciers, areas that were never covered by ice, but received extensive modification by erosional/depositional processes of meltwater. As well as sites of cold climate weathering/mass wasting processes (freeze/thaw, and permafrost conditions)

(a) Early Pleistocene 1.65-0.7 m.y. B.P.
(i) Nebraskan-Kansan glaciation

(b) Middle Pleistocene 0.7-0.13 m.y. B.P. (700,000 – 130,000 yrs)

(i) Illinoian glaciation

(c) Late Pleistocene (130,000 yr – 10,000 yrs)

(i) Wisconsinan – Laurentide ice sheet, most recent glaciation

(d) Holocene (<10,000 yrs)
(i) Warm Period = 8500 – 3500 yr BP
(ii) Glacial Advance ~3500 yr BP

(2) Isostatic Rebound Processes

(a) Crustal depression- under the weight of a great thickness of ice, the earth's crust in depressed downward into the asthenosphere. After the ice melts and the weight is removed, the crust is subsequently uplifted back to densiometric equilibrium.

(3) Eustatic Sea-Level Fluctuations

(a) Glacio-eustatic Sea Level Fluctuations- ice buildup on continents removes water from the hydrologic cycle, most of which comes from evaporation of sea water. Net result is lowering of sea level during glacial periods, and raising of sea level during interglacial periods. Drastically effects base level and fluvial response conditions.

(4) Pluvial Lake History

(a) Glacial/Pluvial Lake development- concomitant with increased moisture/evaporation during glacial periods, along with melt water, more water was available on continents, thus large glacial lakes often form.

(b) Western Interior U.S. = wetter during glacial climates, lake development in arid regions

(i) Post-pluvial dessication = diminished lakes and playas

(c) The Great Lakes are a remnant of glacio-pluvial processes.

(5) Missoula Floods / Channel Scablands: Catastrophic outburst flooding in Pacific Northwest

(6) Oxygen Isotope Record – “Isotope Stages” as measured by oxygen isotope record in seafloor sediments = “proxy” for climate change and time.

(a) Seafloor sediments / fossil oxygen isotope content

(7) Sea Floor Record / Ice Core Record

(8) Sea level record based on coral reef terrace elevations

I. Oxygen Isotope Paleothermometry

A. Approach: use of modern mollusks living in a wide range of water temperatures

1. organism shells are composed of CaCO3 which is biogenically precipitated in the ocean water environment

a. mollusks

b. foraminifera

c. coral

2. measured ^{18}O ratios in shells

3. determined temperature relationships

II. Origin of Oxygen Isotope Variations

A. O^{18}/O^{16} ratios are variable in space and time

1. temperature significantly effects the evaporation of water molecules that are constructed of O^{18} and O^{16}

2. Temperature and evaporation siginificantly impact the marine ^{18}O calcite record in shells through time

B. Water Cycle and Oxygen Isotopes

1. General Circulation

a. evaporation of H_2O at equator and transport toward poles

2. Ease of evaporation of isotopically "light" and "heavy" water molecules

a. H_2O^{18} = resistant to evaporation (less reactive)

b. H_2O^{16} = easily evaporated (more reactive)

NET RESULT = "isotopic fractionation" in ocean water

3. Isotopic Fractionation

a. Seawater Evaporation

(1) $>H_2O^{16}$ in water vapor

(2) $<H_2O^{16}$ in remaining seawater

(a) relative enrichment of H_2O^{18} in seawater

b. Atmospheric Condensation

(1) condensation of rain from clouds:

(a) concentrates H_2O^{16} in snow

c. Thus temperature controls ^{18}O values in seawater, and result calcium carbonate shells

4. Latitudinal Changes in ^{18}O in modern ocean water
   a. Low Latitudes = warm temp = > evaporation
      (1) tropical seawater enriched in ^{18}O
         (a) ~ -2 parts per thousand
   b. High Latitudes = cold temp = < evaporation
      (1) polar seawater depleted in ^{18}O
         (a) ~ -20 parts per thousand

5. O isotope changes according to salinity

   a. Increased evaporation not only enriches O18, but also increases salinity in remaining water
   b. direct correlation between increase in salinity and increase in O18
   c. Empirical relationships based on modern variations

6. Glacial / Interglacial Influences on Oxygen Isotopes
   a. Glacial Climate
      (1) build-up of ice sheets, removal of water from ocean
      (2) ^{16}O is easily evaporated and stored in ice sheets
         (a) ice sheets show low amounts of ^{18}O
         (b) Ice sheets are enriched in ^{16}O, hence causing the $^{18}O/^{16}O$ ratio to decrease (in the ice sheet)
      (3) relative concentration of ^{18}O increases in ocean
      (4) The ocean change in ^{18}O is opposite of that in the related ice sheet

   b. Interglacial Climate
      (1) melting of ice sheets, release of water from storage to ocean
      (2) ^{16}O is released back to ocean
      (3) results in relative decrease in ^{18}O ratio

   c. Example Last Glacial Episode (late Wisconsinan)
      (1) maximum ice build-up at ~20,000 years ago
      (2) sea level ~120 m lower than present (< in 3% of ocean volume)
         (a) ^{18}O content of sea water 20,000 yr ago compared to SMOW ~1.2 parts per thousand
            i) i.e. the ^{18}O content was higher in the oceans 20,000 years ago, due to increased evaporation / removal of ^{16}O.

III. Oxygen Isotope Stratigraphy - Looking Back in Time

A. Seafloor sediment analysis of oxygen isotopes
   1. deep sea drilling and core samples
   2. layer-cake stratigraphy of sediment
   3. planktonic foraminifera fossils
      a. calcium carbonate microfossils

B. Oxygen isotope patterns in sediment layers
   1. cyclic patterns of low and high ^{18}O calcite
   2. interpretation
      a. low spikes = interglacial (warm climate)
         (1) < ice volume globally (dilution of O18)
      b. high spikes = glacial (cold climate)
         (1) > ice volume globally (enrichment of O18)

   3. Oxygen isotope stages - letters and numbers applied to patterns
      a. stage 1 = present interglacial

b. stage 2 = last glacial maximum (~20,000 yrs BP)

IV. Solar Activity and Causes of Global Climate Change in Last 2 m.y.

A. Characteristics of Glacial / Interglacial Climate on Earth

1. Common glacial / interglacial climates in last 2 m.y., but NOT commonly observed in the record prior to 2 m.y. ago
2. Global Temperatures fluctuate between 2^{o}C to 6^{o}C during glacial and interglacial climates
3. Snowlines in alpine regions fluctuate by about 1000 m during glacial / interglacial climate cycles
4. Glacial and interglacial climates are synchronous in both northern and southern hemispheres
5. Desert areas experience increased rainfall ("pluvial" conditions) during glacial climate cycles

B. Short Term Climate Changes as Related to Solar Energy

1. Sun Spot Activity
   a. Sun Spots - dark spots on the surface of the sun
      (1) up to 1000's of miles in diameter
      (2) short-lived
         (a) hours to days up to months
      (3) lower temperature spots
         (a) ~1500 K less than surrounding part of photosphere
      (4) Sun Spot Cycles
         (a) the number and frequency of sun spots changes over time
            i) 11 year cycle: > in sun spot activity
               a) switching between high frequency and low

   b. Low Sun Spot Activity
      (1) polar winds / high pressure increase
      (2) shift of mid-latitude storm tracks toward equator
      (3) increased evaporation / storms
      (4) colder and wetter climates, in general

   c. High Sun Spot Activity
      (1) polar winds / high pressure decreases
      (2) mid-latitude storm tracks shift poleward
      (3) decreased evaporation / storms
      (4) warmer and drier climates

C. Long Term Climate Changes: Milankovitch Theory - Orbital Forcing of Climate Change

1. glacial climate variation the result of changes in levels of solar energy influx due to variations in Earth's orbital parameters

   a. redistribution of solar energy on Earth

2. Frequency of climate change recorded in oxygen isotope record, climate cycles (glacial-interglacial frequency) on order of:
   a. 100,000 yr (The dominant frequency predicting glacial / interglacial)
   b. 40,000-43,000 yr
   c. 19,500 - 24,000 yr

3. Astronomical Changes in Earth Orbit Parameters

a. **Obliquity:** Axial wobble

(1) Axis wobbles, circumscribing a circle on the celestial sphere

(a) present: north pole points to polaris

(b) 2000 BC north pole poined between big dipper and little dipper

(c) 4000 BC, north pole pointed to handle of big dipper

(2) Tilt of earth's axis changes over time

(a) range from 21.8^o to 24.4^o

(3) Periodicity of axial tilt: ~41,000 yr cycle

(4) Effects on Climate

(a) > tilt angle, > seasonal difference in climate: hotter summers and colder winters

b. **Precession of Equinoxes**

(1) precession: axial wobble and rotation of elliptical orbit cause equinoxes and solstices to shift slowly along orbital path

(a) summer solstice occurs at position closest to sun vs. farthest from sun

i) present, summer solstic occurs when earth is farthest from sun

ii) position relative to distance from sun shift through time

(b) Frequency of precession

i) 21,000 yrs

(c) Climate Effect

i) tilt-distance seasonality relationships

ii) when tilt towards sun is maximized at closest position in orbital path, results in increased intensity of seasons

a) hotter summers and colder winters

c. **Eccentricity** of Earth's Orbital Path through Time

(1) circular vs. elliptical orbital path - varies through time

(a) the more circular, the less variation in seasonal heating / cooling

(b) the more elliptical, the more variation in seasonal heating / cooling

i) > distance at closest and farthest points relative to the sun

(2) Present Configuration

(a) Northern Hemisphere Summer Solstice = at pt. farthest from sun

(b) Southern Hemisphere Winter Solstice = at pt. closest to sun

(3) variations in Eccentricity will effect intensities of seasons

(4) Frequency : eccentricity ~ 100,000 yr cycle

D. Summary of Climate Models

1. The correlation between the oxygen isotope / climate change record and the predicted Earth orbital parameters suggest that changes in the orbit of the Earth about the Sun may cause climate change from glacial to interglacial.

2. It appears that eccentricity of Earth orbit accounts for most of major glacial - interglacial climate change ~ 100,00 yr cycle

3. Maximized Glacial Conditions (Cold Climate)

a. maximum eccentricity (elliptical) orbit

b. maximum tilt angle of earth axis

c. correlation of solstices with farthest points away from sun during elliptical orbit

d. Requirement: maximized cold climate conditions at poles, maximized evaporation / atmospheric moisture at equatorial zone

4. Seasonality effects on glaciation

a. < summer solar influx, > glacier size = accumulation

b. >summer solar infllux, < glacier size = melting

c. positive feedback

(1) > ice area, > albedo, < incoming solar radiation, < temperatures, > ice accumulation

vice versa for melting of

At present, high-latitude precipitation returns to the oceans through summer melting. During glacial intervals, however, large ice sheets store the lighter isotope (^{16}O). The difference in $\delta^{18}O_{water}$ values between the ice sheet and mean ocean was large ($\delta^{18}O_{ice}$ = -35 to -40 per mil versus $\delta^{18}O_{water}$ mean ocean = ~0 per mil). As a result, variations in ice sheet sizes are reflected in the variable oceanic $\delta^{18}O_{water}$ values. The most recent glacial to interglacial transition provides the best illustration of how ice sheets affect the ocean $\delta^{18}O_{water}$ value (Fig. 2). During the last glacial maximum, the amount of water stored in ice sheets caused the global sea level to be 120 m lower than present (Fairbanks, 1989). This change in sea level represents a decrease of ~3 percent in the ocean vol-

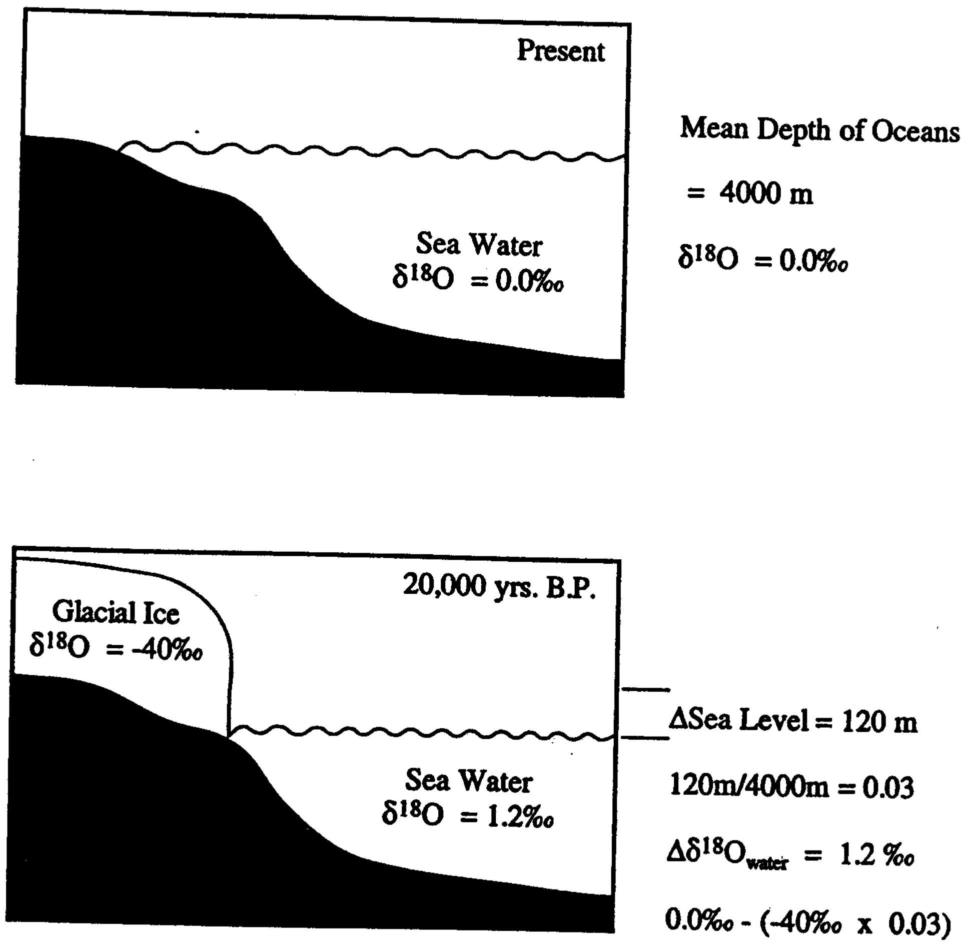

Figure 2. The effect of large ice sheets on the $\delta^{18}O$ composition of the ocean can be significant. The removal of 3 percent of the ocean's water during the last glacial maximum lowered sea level by 120 m. The $\delta^{18}O$ difference between the ocean and the ice is 40 per mil, causing a whole ocean $\delta^{18}O$ change of 1.2 per mil.

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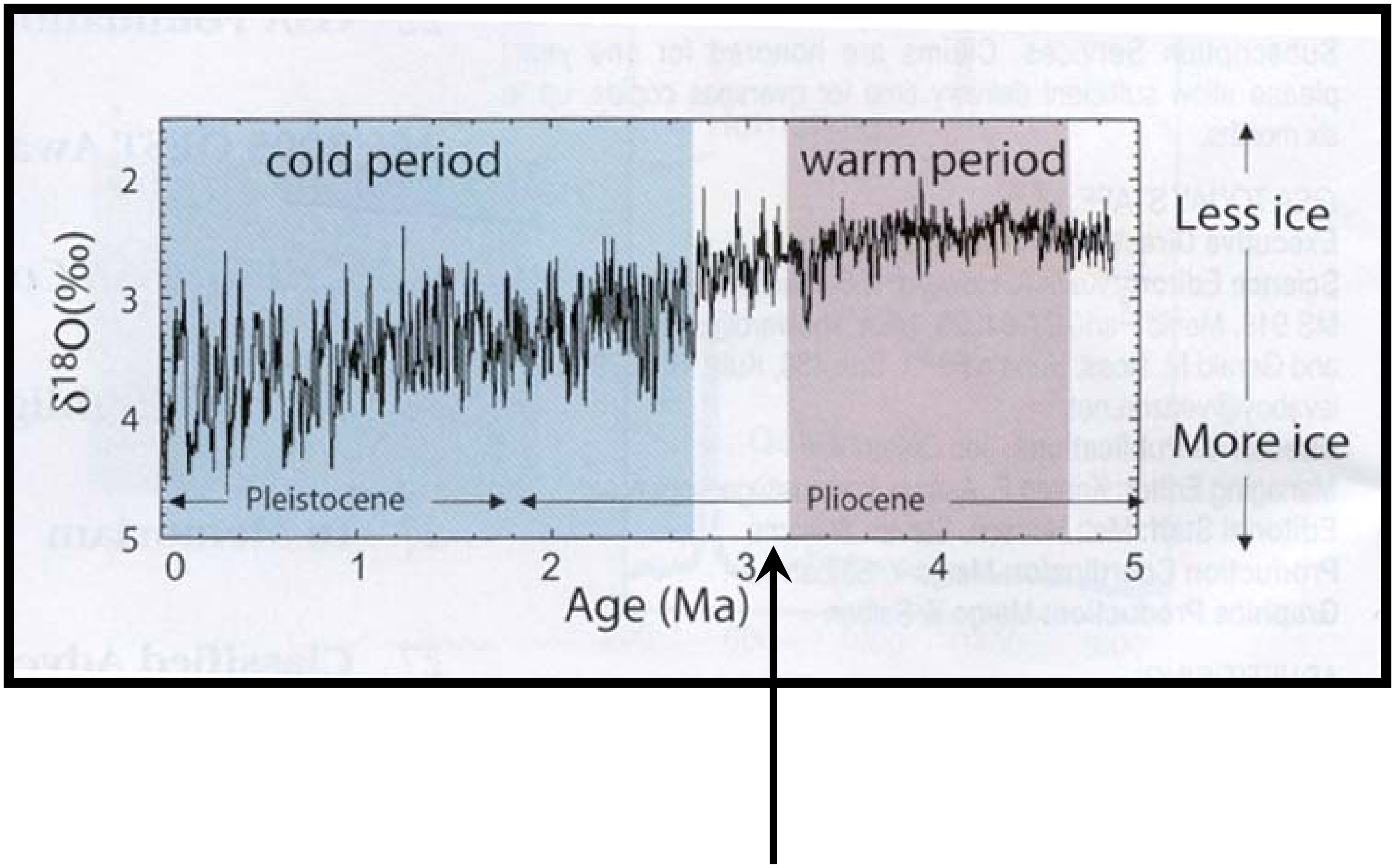
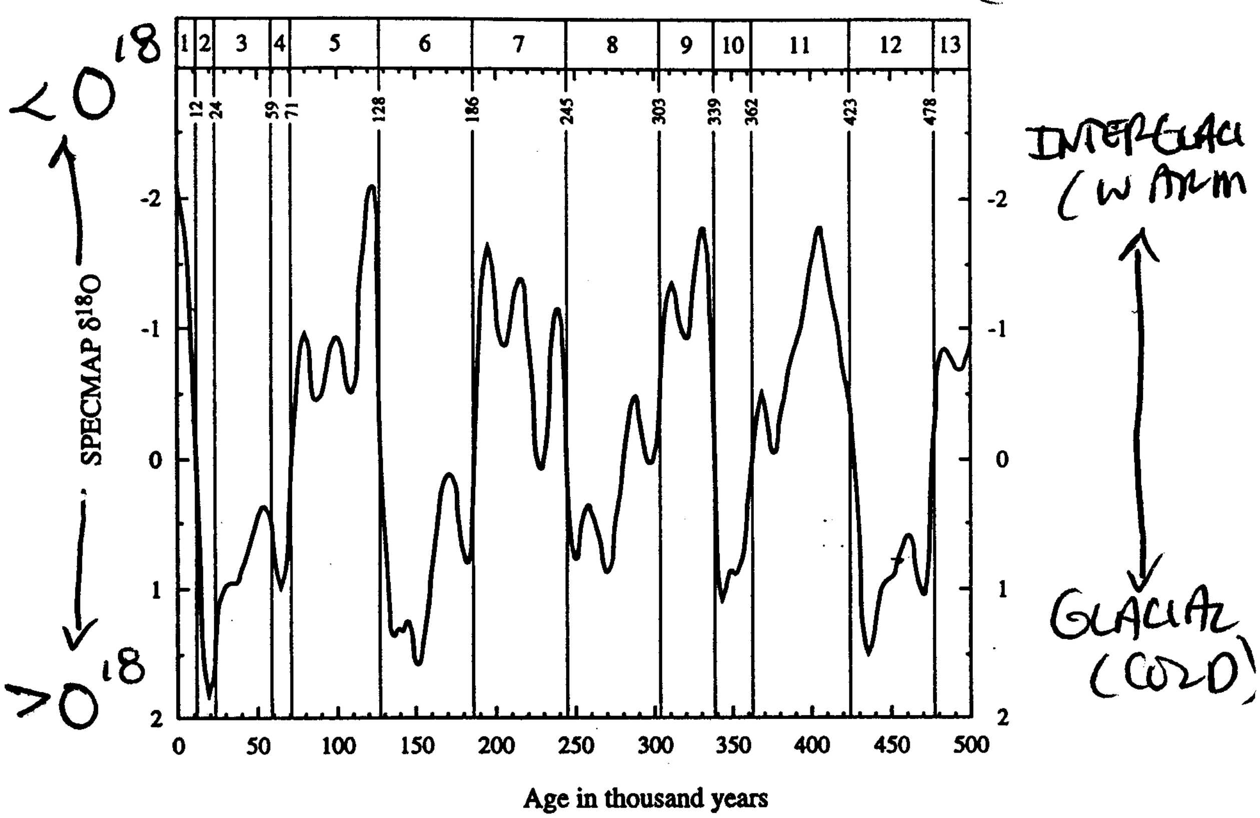
Oxygen Isotope-Climate Record (0 – 5 m.y. BP)

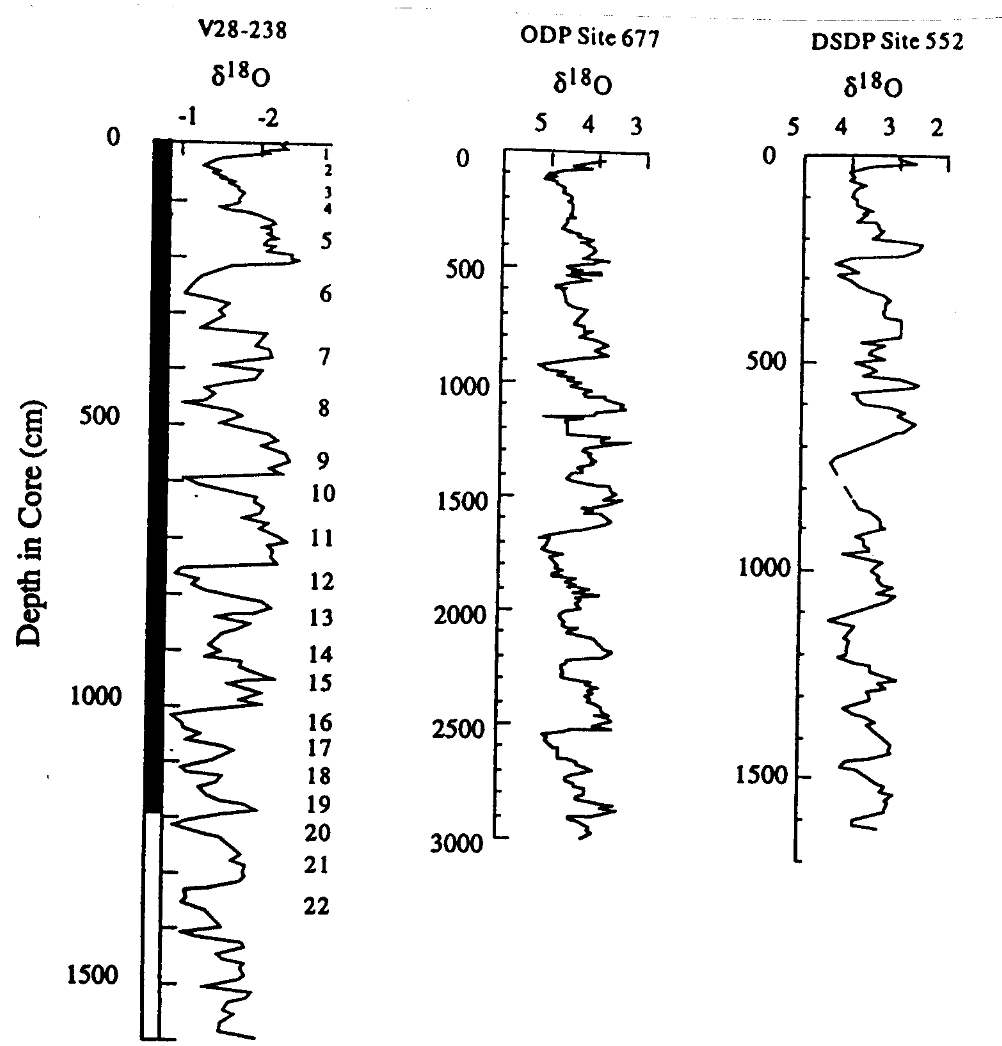
Benthic forams; ODP 1990 and 2001

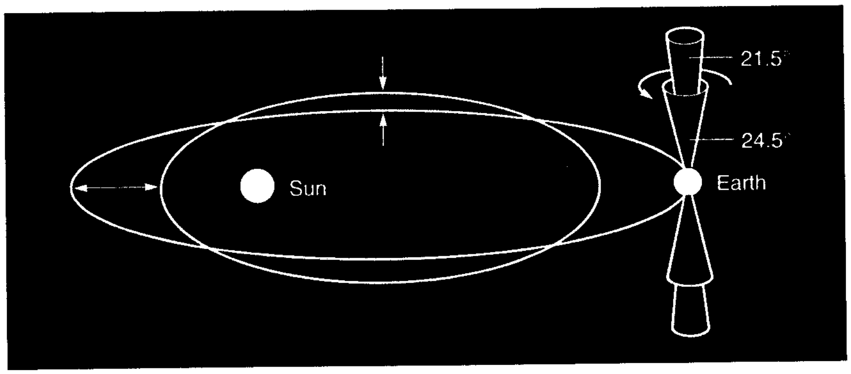


Onset of Northern Hemisphere Glaciation ~ 3 Ma

GLOBAL CLIMATE RECORD (O18/O16)







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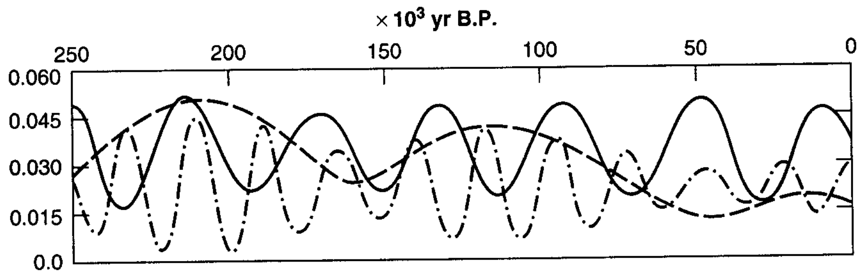

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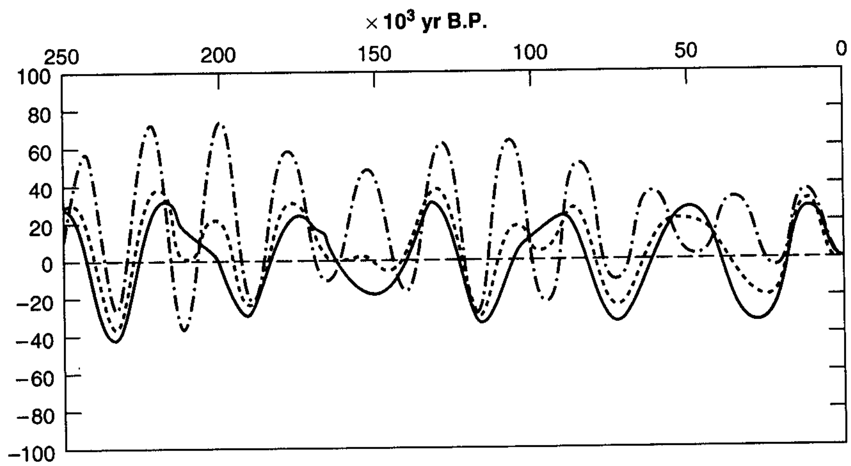

C.

FIGURE 14–23
(A) Cyclic changes in earth-sun relationships; (B) variation of eccentricity (----), precession (-··-··-), and obliquity (— —) over the last 250,000 years; (C) Northern Hemisphere summer solar radiation at 80°N (— —), 65°N (·····), and 10°N (_._.) latitude (expressed as departures from A.D. 1950 values). The radiation signal at high latitudes is dominated by the ~41,000-year obliquity, whereas the ~23,000-year precessional cycle is dominant at lower latitudes. (B and C, from Bradley, 1985; after Berger, 1978)

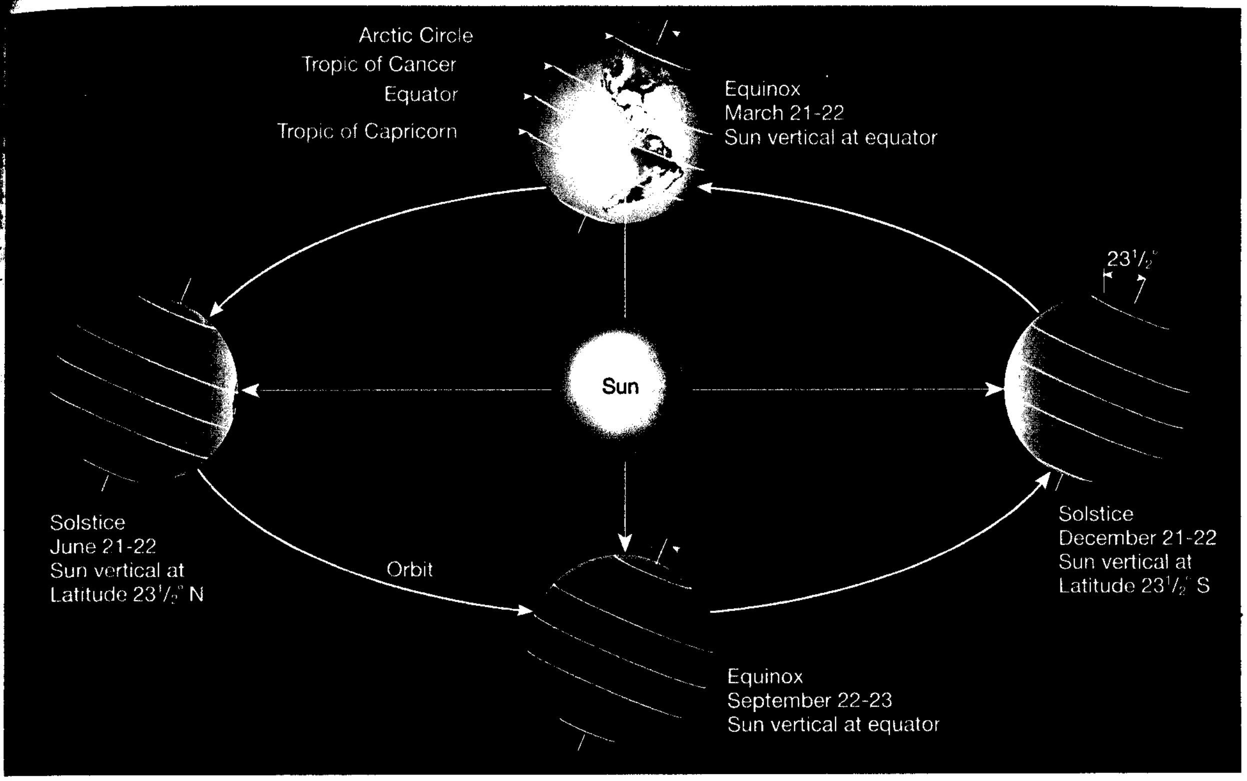

Figure 14.10 Earth–Sun relationships.

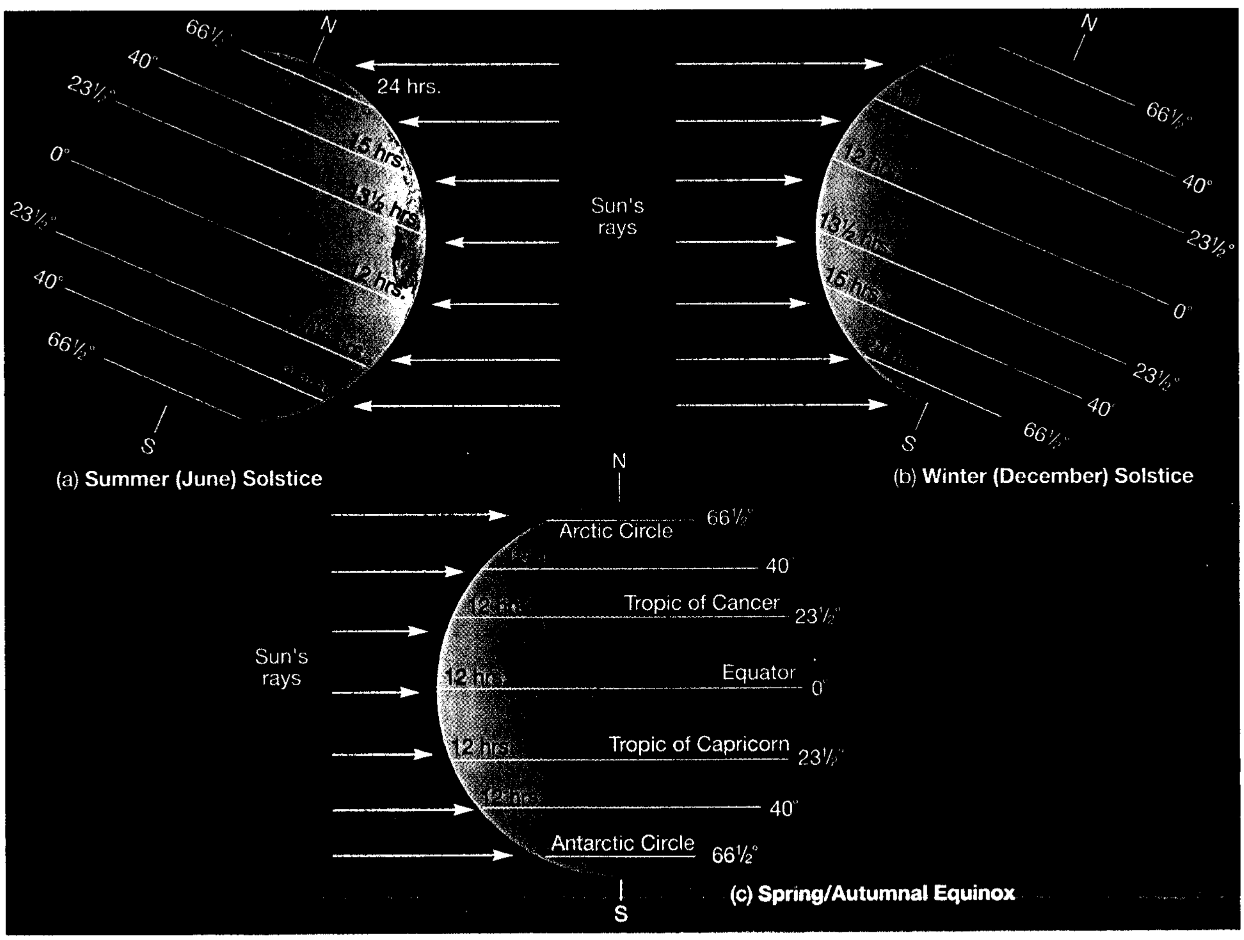

Figure 14.11 Characteristics of the solstices and equinoxes.