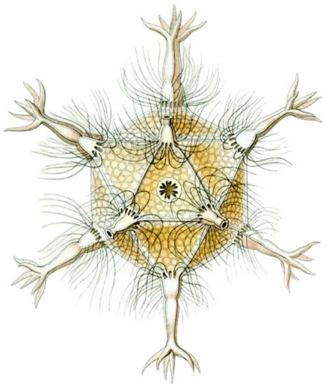
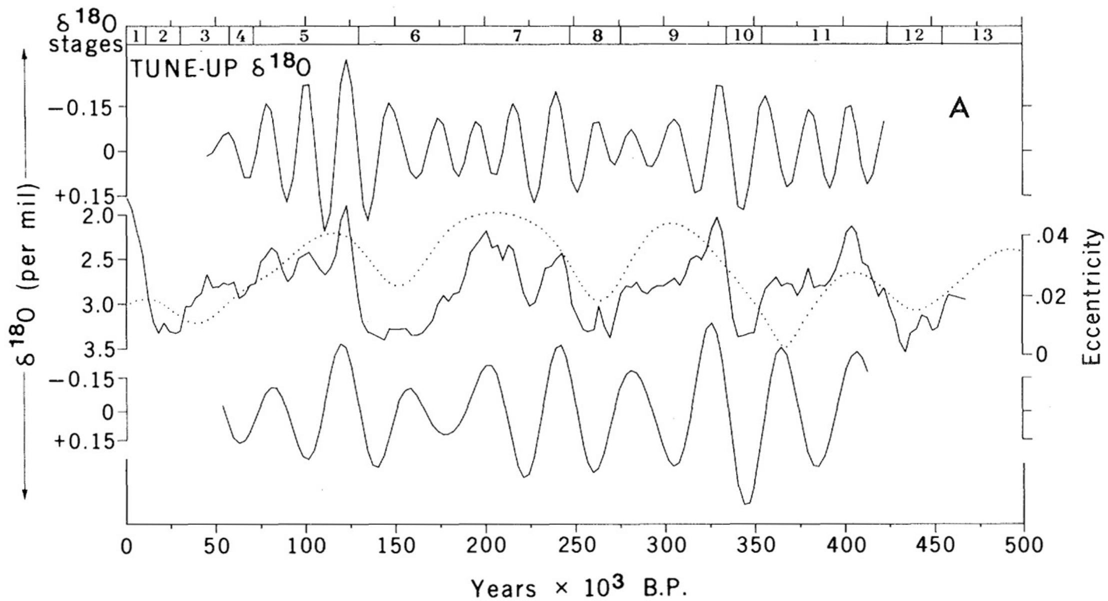


Variations in the Earth's Orbit: Pacemaker of the Ice Ages

For 500,000 years, major climatic changes have followed variations in obliquity and precession.

J. D. Hays, John Imbrie, N. J. Shackleton
Science, 1976



John Noble
Earth 206, UCSC

April 2009

J. D. Hays

Professor of Earth and environmental sciences at Columbia University.

Background

- BA from Harvard University
- MS from Ohio State University
- PhD from Columbia University

Current research

- History of climate change over the past three million years and the evolutionary history recorded by microfossils.

Papers

- Faunal Extinction and Reversals of the Earth's Magnetic Field, 1971, *Geological Society of America Bulletin*
- Lithospheric Plate Motion, Sea Level Changes and Climatic and Ecological Consequences, 1973, *Nature*

John Imbrie

Professor Emeritus at Brown, has been on the faculty of the Geological Sciences Department at Brown University since 1977, where he has held the Henry L. Doherty chair of Oceanography.

Background

- Undergrad: Coe College (Cedar Rapids, Iowa) and Princeton University.
- M.S. and Ph.D. from Yale University in 1950 & 1951, Geology and Geophysics

Awards

- William H. Twenhofel Medal by the Society for Sedimentary Geology, 1991
- Wilbur Cross medal
- Advancement of Basic and Applied Science

Prof. Sir. Nicholas J. Shackleton

Background

- Educated at Cranbrook School, Kent, Shackleton studied natural sciences at Clare College, University of Cambridge, graduating with the BA degree in 1961
- 1964, MA degree
- 1967 he was awarded at the same university a PhD degree, with his thesis entitled 'The Measurement of Paleotemperatures in the Quaternary Era'.

Awards

- Doctor of Science (ScD), University of Cambridge, 1984
- Fellow of the Royal Society (FRS), 1985
- Shepard Medal (SEPM) for excellence in marine geology 1985
- Carus Medal, Deutsche Akademie für Naturforscher 'Leopoldina' 1985
- Lyell Medal, Geological Society of London 1987
- Founding member, Academia Europaea 1988
- Fellow, American Geophysical Union 1990

Early climate research

Croll (1875) compared astronomical calculations of orbital history with the geologic record of climate, hypothesizing that evidence of multiple glaciations confirm the astronomical theory of the ice ages.

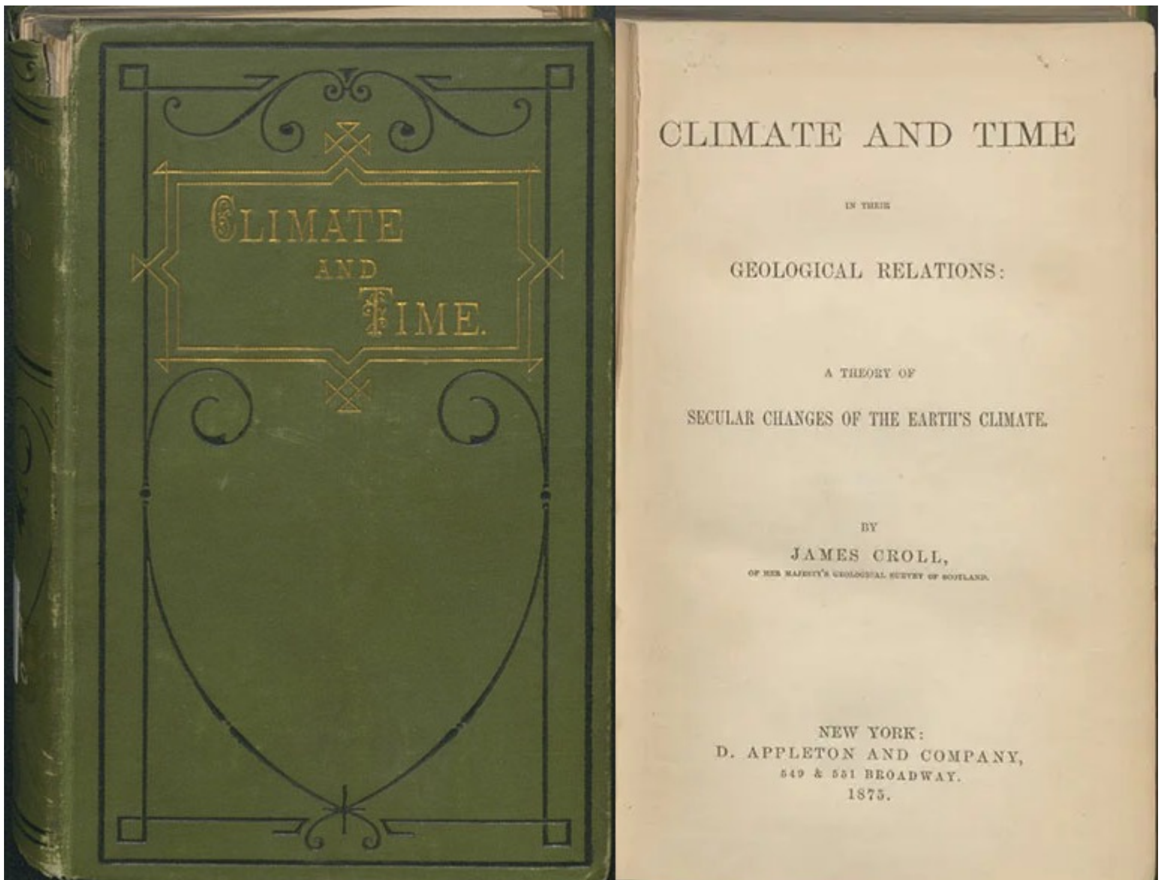


Diagram representing the variations in eccentricity for 4 million years

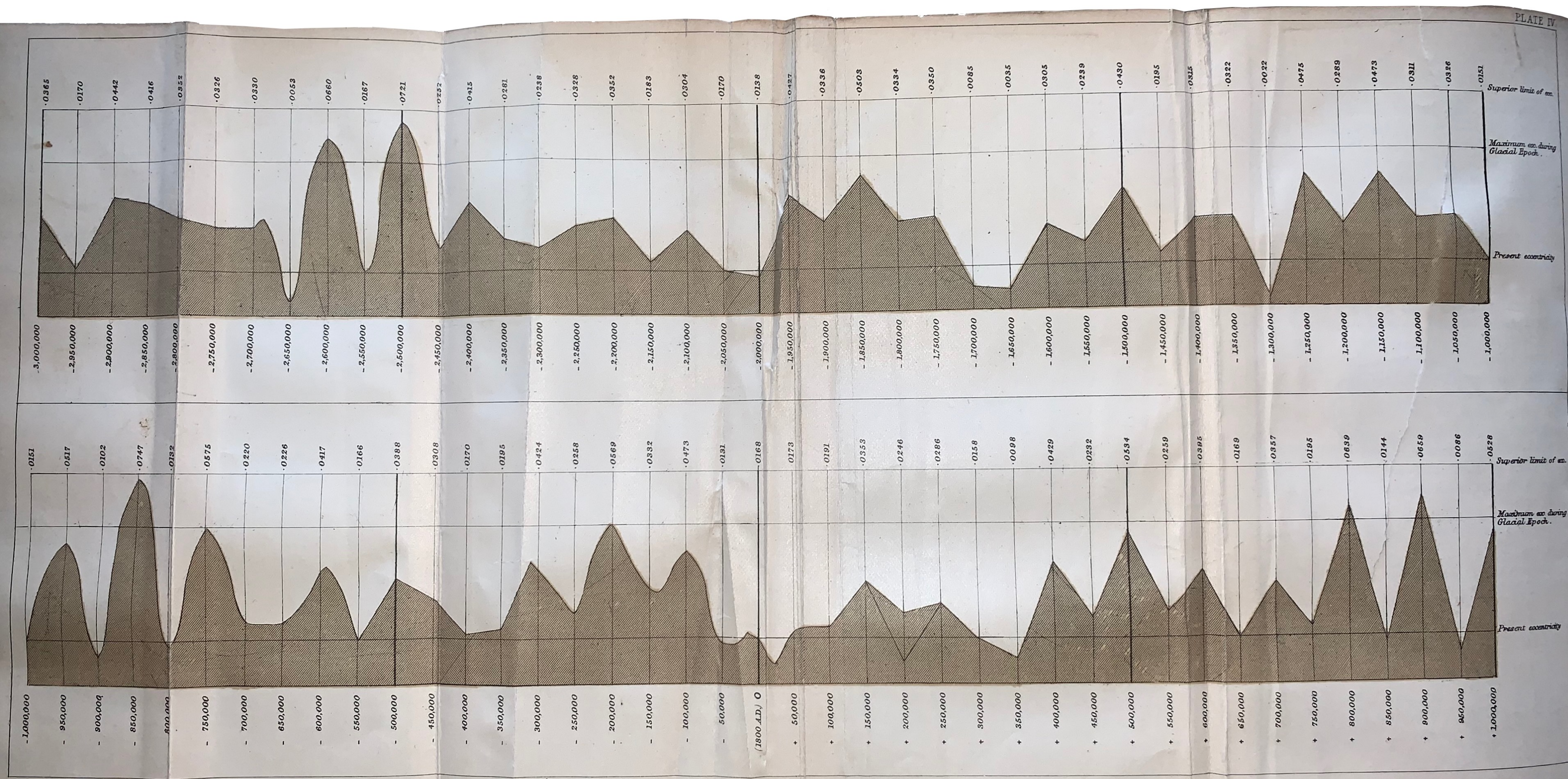


DIAGRAM REPRESENTING THE VARIATIONS IN THE ECCENTRICITY OF THE EARTH'S ORBIT FOR THREE MILLION OF YEARS BEFORE 1800 A.D. AND ONE MILLION OF YEARS AFTER IT.

The Ordinates are joined by straight lines where the values, at intervals of 10,000 years, between them have not been determined.

(Croll 1875)

Scientific questions and goals

Better understand the interplay of causes responsible for Pleistocene ice sheet fluctuations.

Goal: Create test to geologically determine frequencies

Methods and tests:

1. Geologic time series:
   1. Stratigraphic record of $\delta^{18}O$
   2. T_s, summer sea-surface temperature (SST)
   3. *Cycladophora davisiana* percentage

2. Frequency domain tests (spectral analysis)

3. Time domain tests for phase relationships

Possible explanations

Theories invoking variations of factors

1. External to climate system
   - Solar luminosity
   - Interstellar dust concentration
   - Earth's orbital geometry
   - Atmospheric volcanic dust content
   - Earth’s magnetic field

2. Internal to climate system (response times sufficiently long to yield 105-yr fluctuations)
   - Growth and decay of ice sheets
     - Arctic and Antarctic ice sheets
   - CO2 distribution between atmosphere and ocean
   - Deep circulation of the ocean

Orbital hypothesis

- Formulated to **predict frequencies** of major Pleistocene glacial fluctuations.

- Obliquity and precession are the underlying, controlling variables that influence climate through their impact on planetary insolation.

  – Obliquity: ~ 41,000-yr period
  – Precession of the equinoxes: ~ 21,000–yr period

- Broecker, Imbrie, and others have provided strong suggestive evidence that orbital changes induced climatic change

Uncertainties

1. Which aspects of the radiation budget are critical to climatic change? *e.g.* different predictions from same astronomical data depending on latitude & season used:

    - 65^{o} N summer insolation curve for world climate prediction; should be critical to the growth and decay of ice sheets (Milankovitch 1930; Köppen and Wegener 1924)

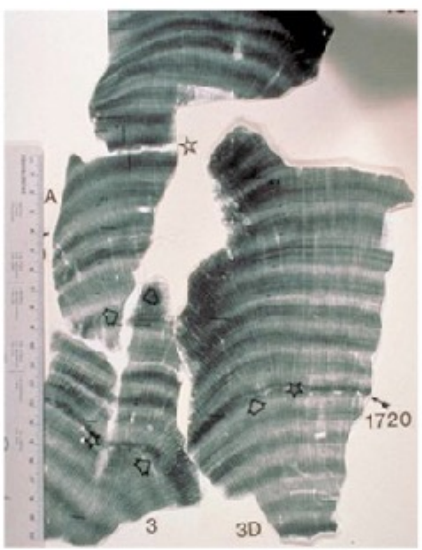
    - Critical time may be September and October in both hemispheres (Kukla 1975)

⇒ Resulting in range for last interglacial from 80,000 – 180,000 yr ago

Uncertainties

2. Geological chronology

- 150,000-yr testing interval limit due to dating method inaccuracies (until ~mid 1970s)
- Data: Barbados, New Guinea, and Hawaiian coral terraces record episodes of high sea level (∴ low ice volume) consistent with Milanković–theory



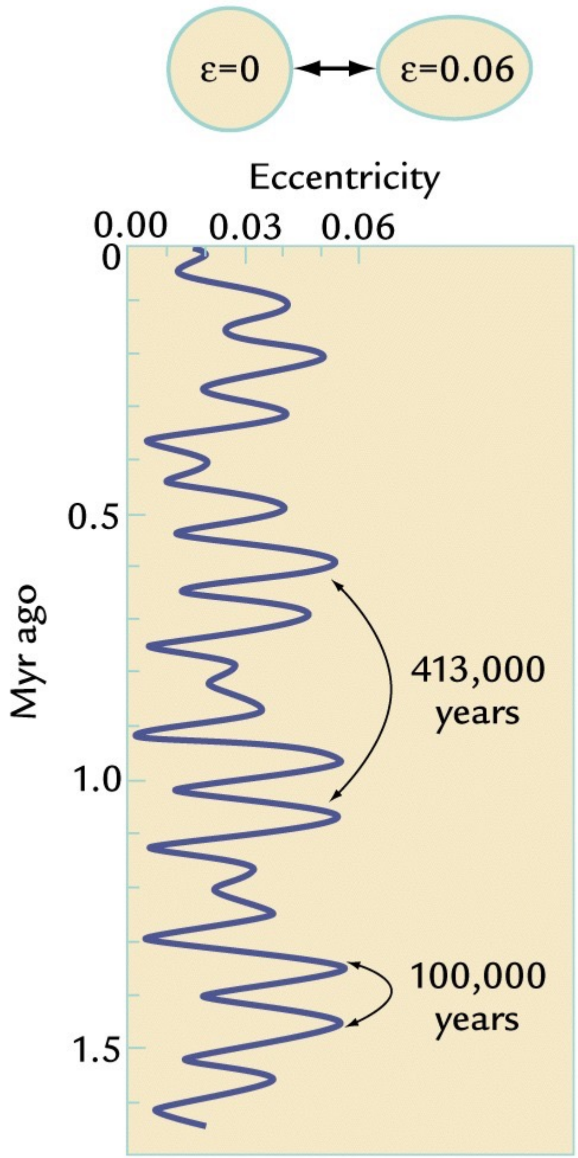
X-ray image of a coral sample showing seasonal growth bands. By counting the growth bands, scientists who study past climate (paleoclimatologists) can date the sample.

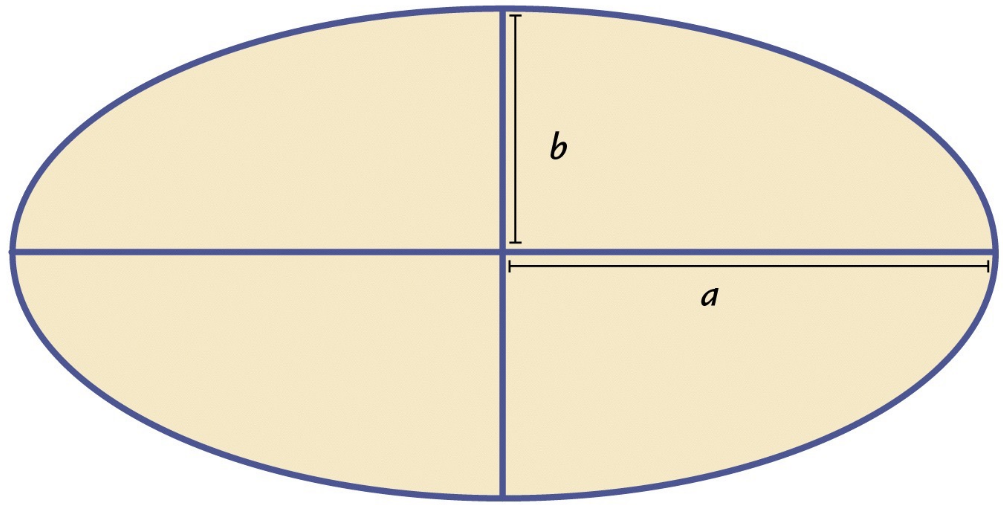
Jerry Wellington, University of Houston

Lines representing annual growth bands are drawn after the core has been x-rayed. These bands show the age and the growth rate of the coral. Scientists can use these growth rates to figure out the general conditions that existed each year.

Rob Dunbar, Rice University

Eccentricity



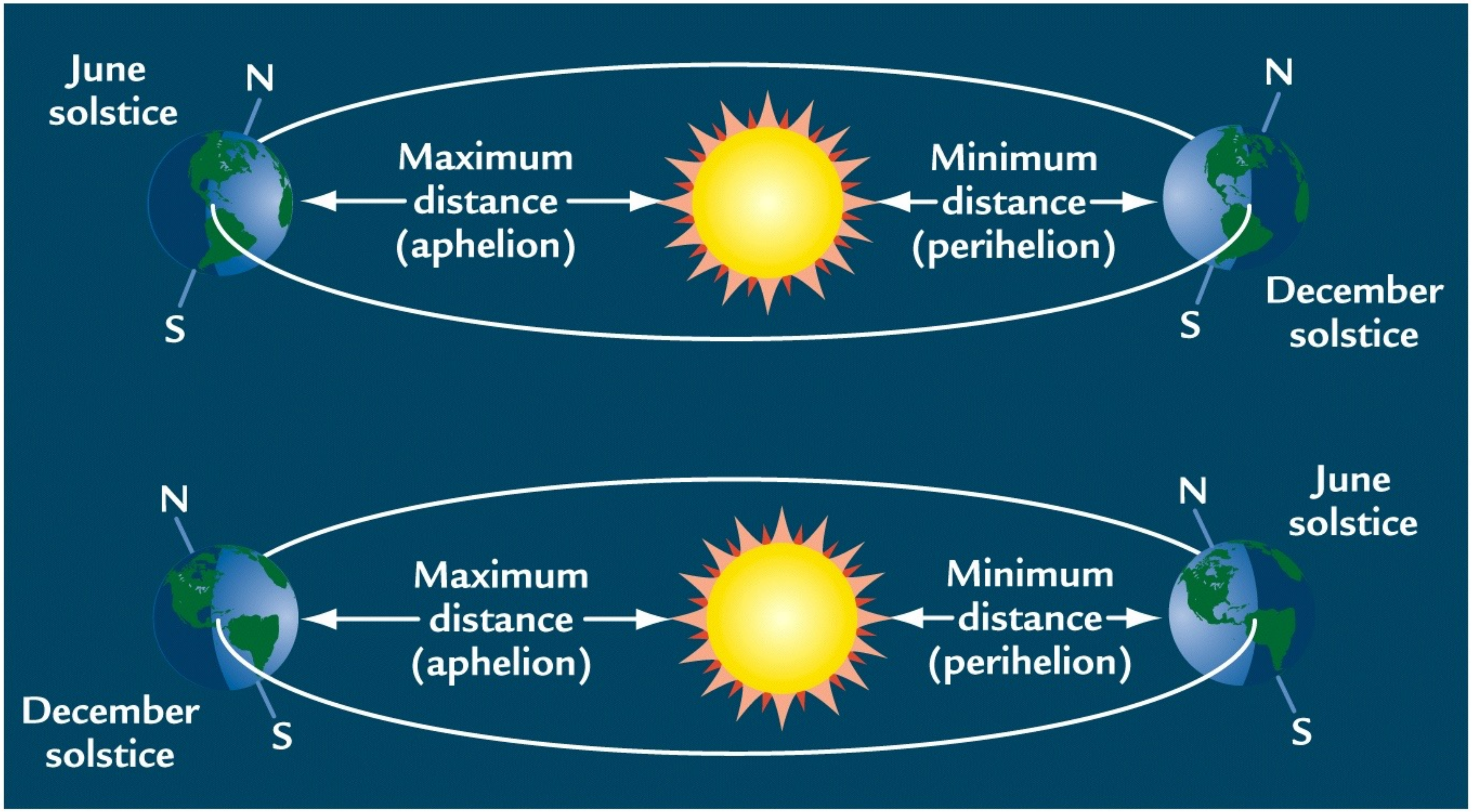


$$\text{Eccentricity } \varepsilon = \frac{(a^2 - b^2)^{1/2}}{a}$$

(Ruddiman 2001)

Eccentricity

At perihelion, Earth receives ~3.5% more radiation than at aphelion



(Ruddiman 2001)

Obliquity

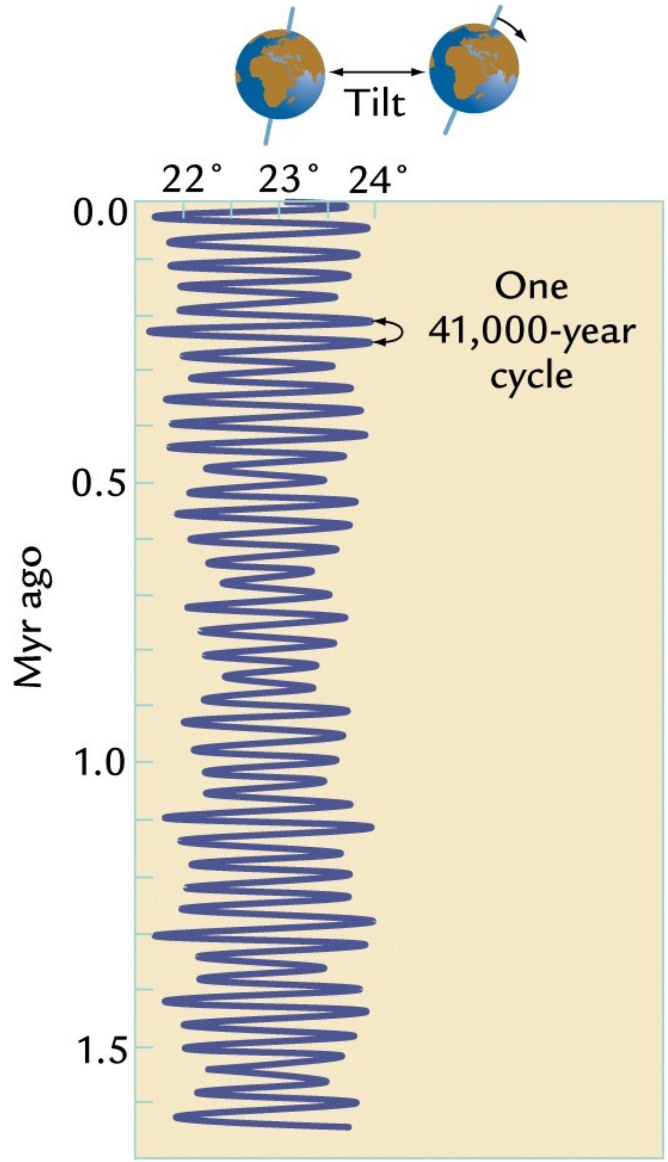
- Obliquity is the angle between the equatorial and ecliptic planes

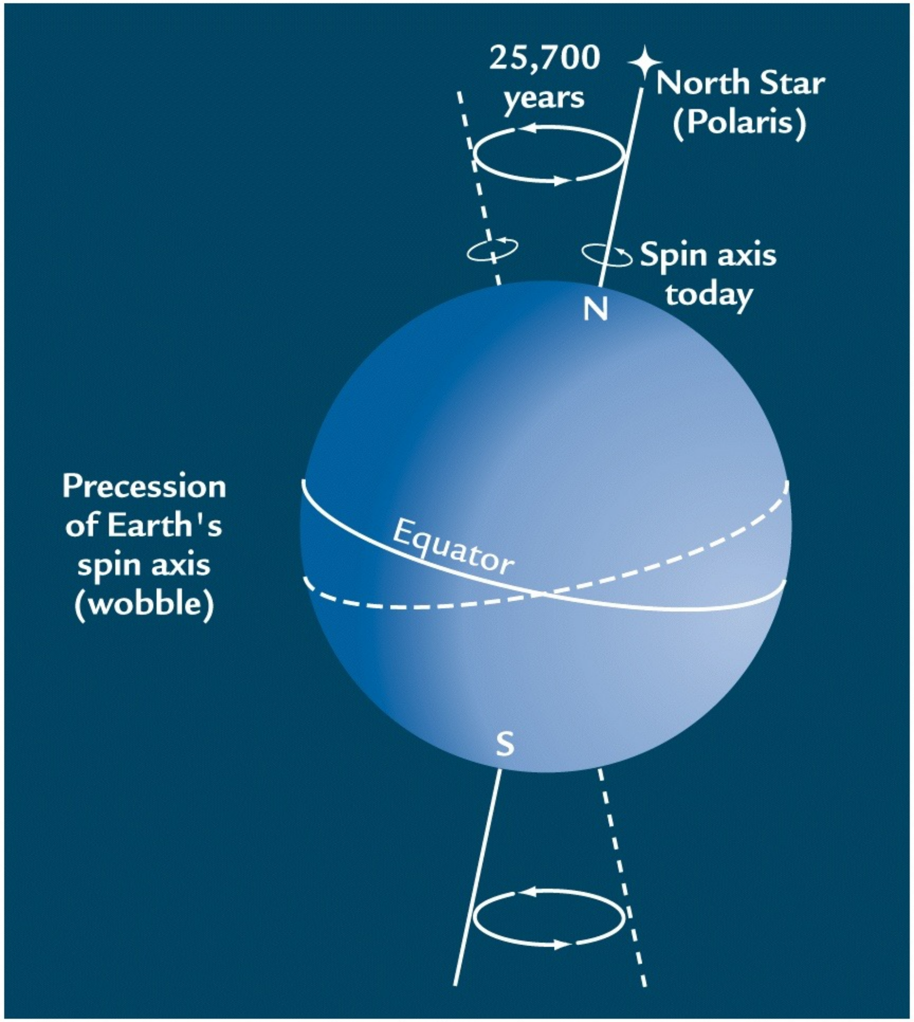
  – Current value: 23.4°
    - range: 22.1° to 24.5°

  – ~ 41,000-yr mean period.

  – As obliquity increases:
    - Summer radiation increases (at high-latitudes)
    - Winter radiation totals decline

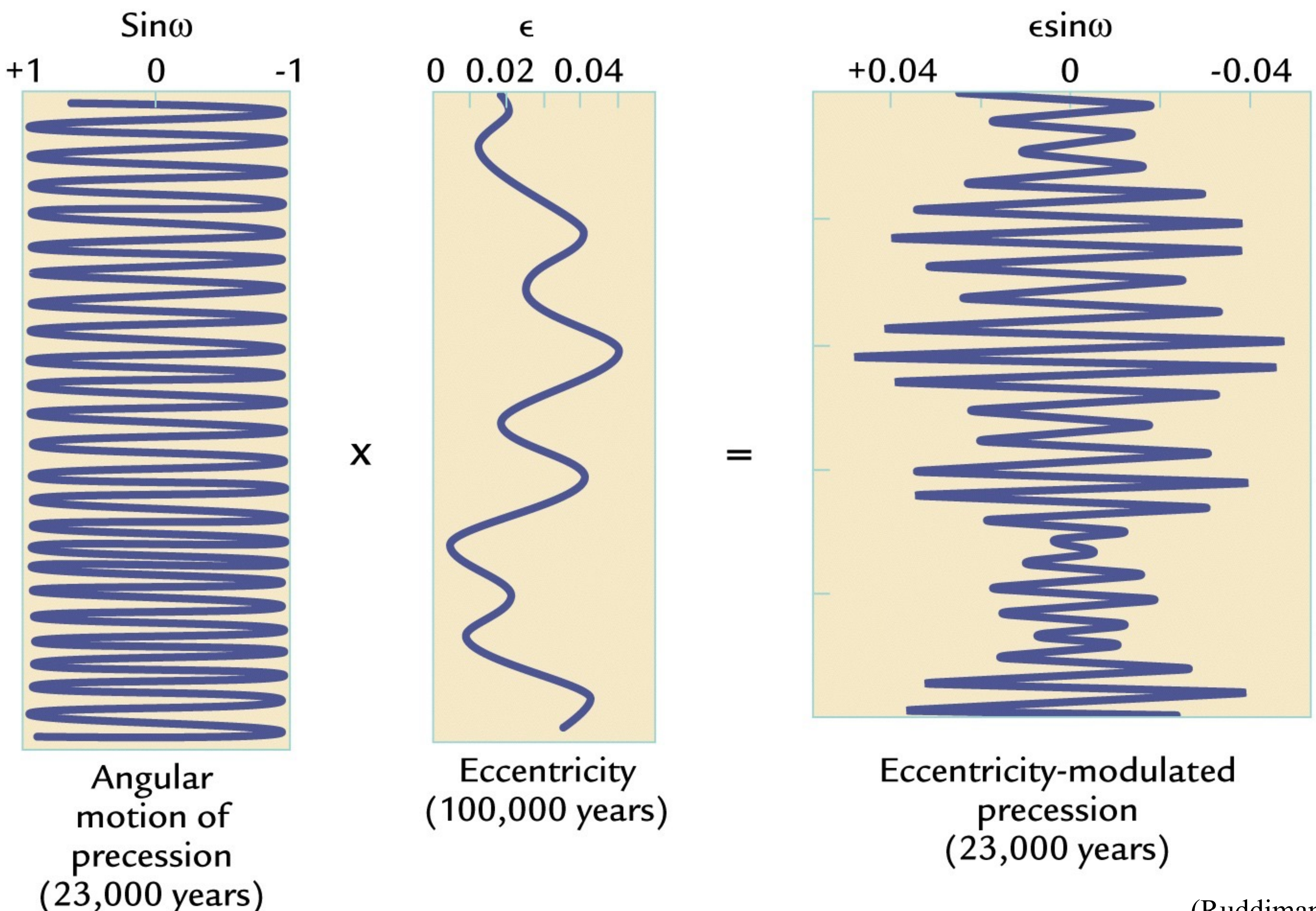
Tilt and precession



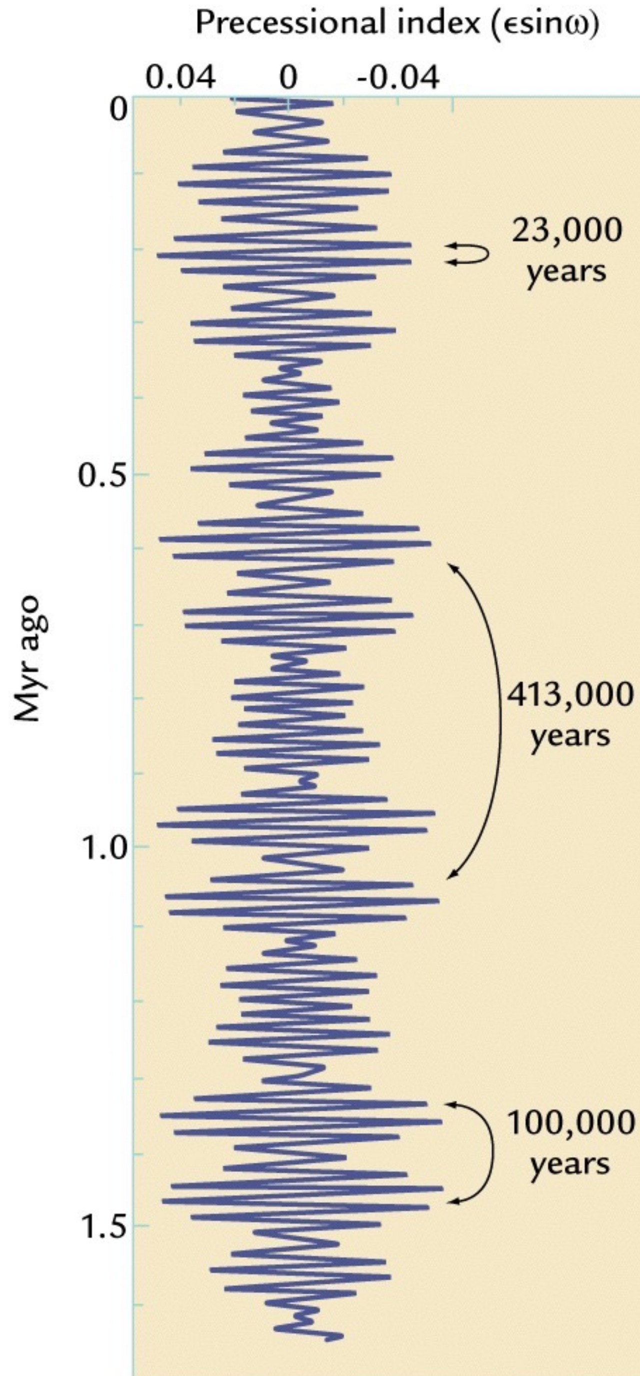


(Ruddiman 2001)

Eccentricity-modulated precession

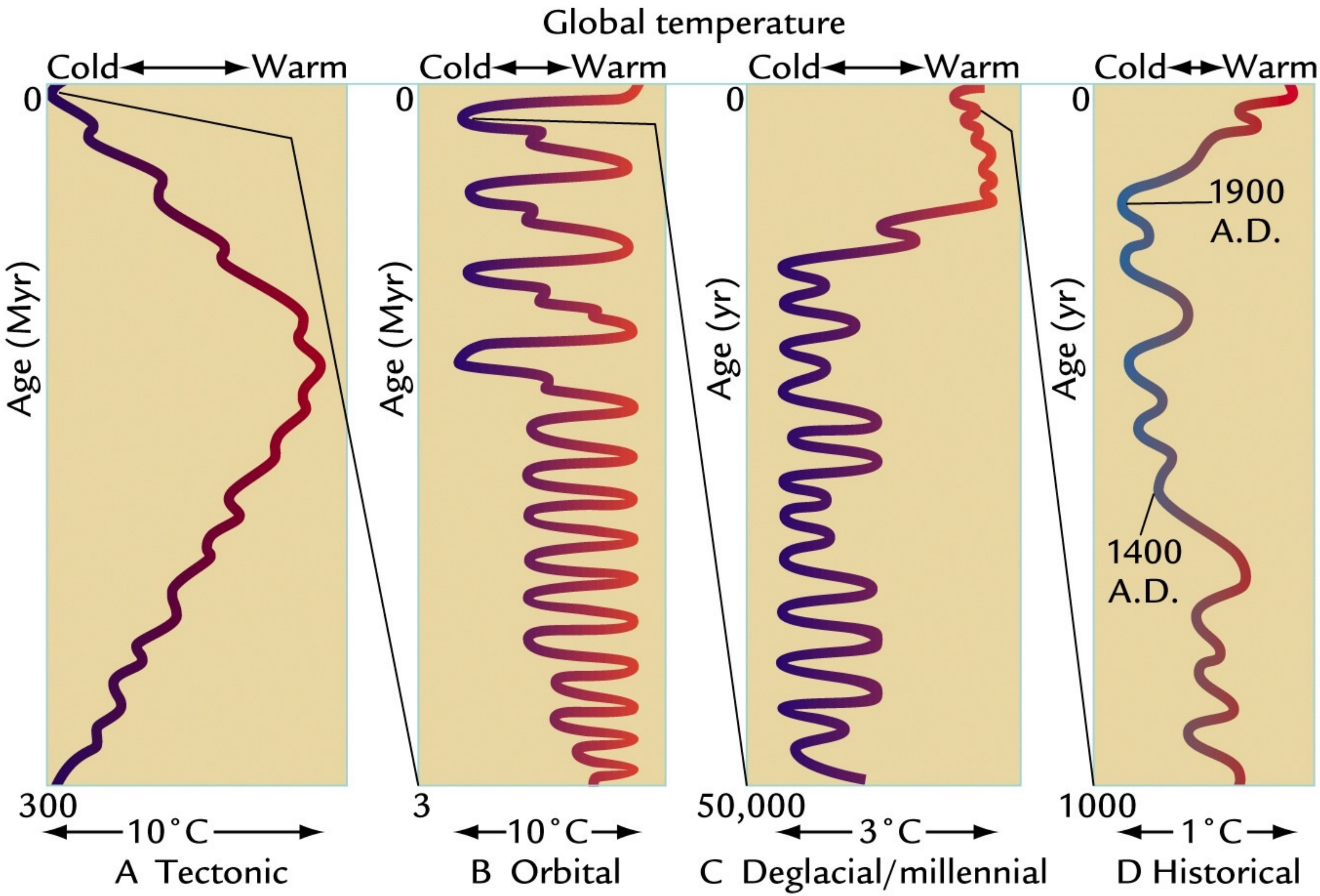


(Ruddiman 2001)



(Ruddiman 2001)

Global temperature



(Ruddiman 2001)

Strategy

Most of these hypotheses single out mechanisms of climatic change which are presumed to respond to particular elements in the insolation regime

Hays *et al.* generalization and assumption:

- Treat secular orbital changes as a forcing function of a system whose output is the geological record of *climate-without identifying or evaluating the mechanisms through which climate is modified by changes in the global pattern of incoming radiation*.

- Assumption: climate system responds linearly to orbital forcing.

Methods: core selection

Hays *et al.* selected two CLIMAP cores (RC11-120 and E49-18) for testing the orbital hypothesis.

- 450,000-yr continuous climatic record
- Accumulation rates (> 3 cm 1,000 yr^{-1}) resolve climatic fluctuations with periods below 20,000 yr.
- Location provides an opportunity to monitor simultaneously both Northern Hemisphere (NH) ice volume and Southern Hemisphere (SH) temperature.

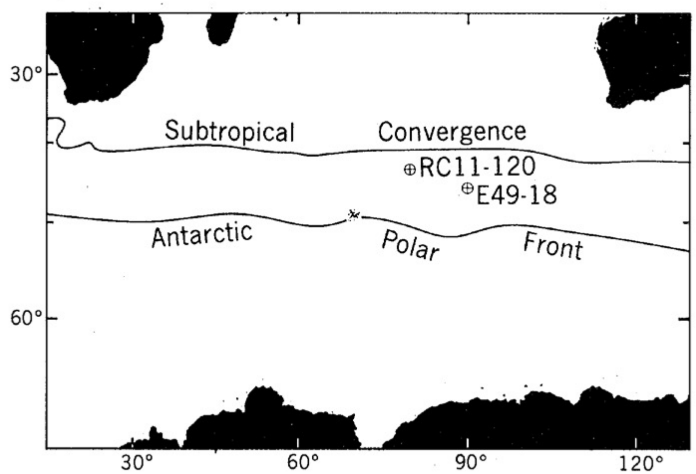


Fig. 1. Locations of cores in the southern Indian Ocean.

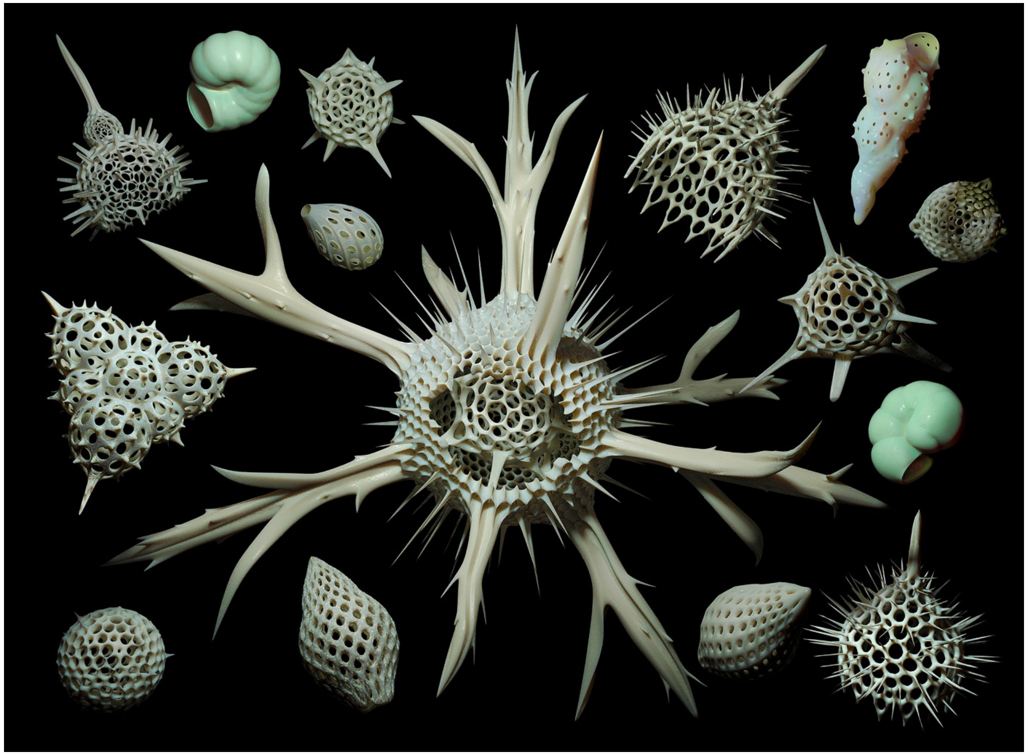
Table 1. Core locations and depths.

Core	Length (cm)	Water depth (m)	Latitude	Longitude
RC11-120	954	3135	43°31′S	79°52′E
E49-18	1459	3256	46°03′S	90°09′E

(Hays *et al.* 1976)

Geologic data

1. δ^{18}O, planktonic foraminifera
2. T_s, summer sea-surface temperature (SST) derived from statistical analysis of radiolarian assemblages
3. Percentage of *Cycladophora davisiana*, the relative abundance of a radiolarian species not used in the estimation of $T_s \delta^{18}$O



$\delta^{18}O$

- ^{16}O accounts for ~ 99.8% of natural oxygen
- $^{18}O/^{16}O \sim 1/400 = 0.0025$

- Average $\delta^{18}O$ value of ocean water = 0.0‰
- 1 $^{o}/_{oo} \downarrow \delta^{18}O$ in foraminifera shells $\Rightarrow$ 4.2ºC $\uparrow$
- Ice sheet growth causes $\delta^{18}O \uparrow$

- $\Delta\, \delta^{18}O_c = \Delta\, \delta^{18}O_w$ x $0.23\, \Delta T$

- $\delta^{18}O$ variations are recorded in $CaCO_3$ benthic foraminifera shells that take oxygen from bicarbonate ions

Stratigraphic sequence

- Deep-sea sediments provide a basic 1,000,000-yr stratigraphy
- 1000-yr resolution limited by mixing and bioturbation

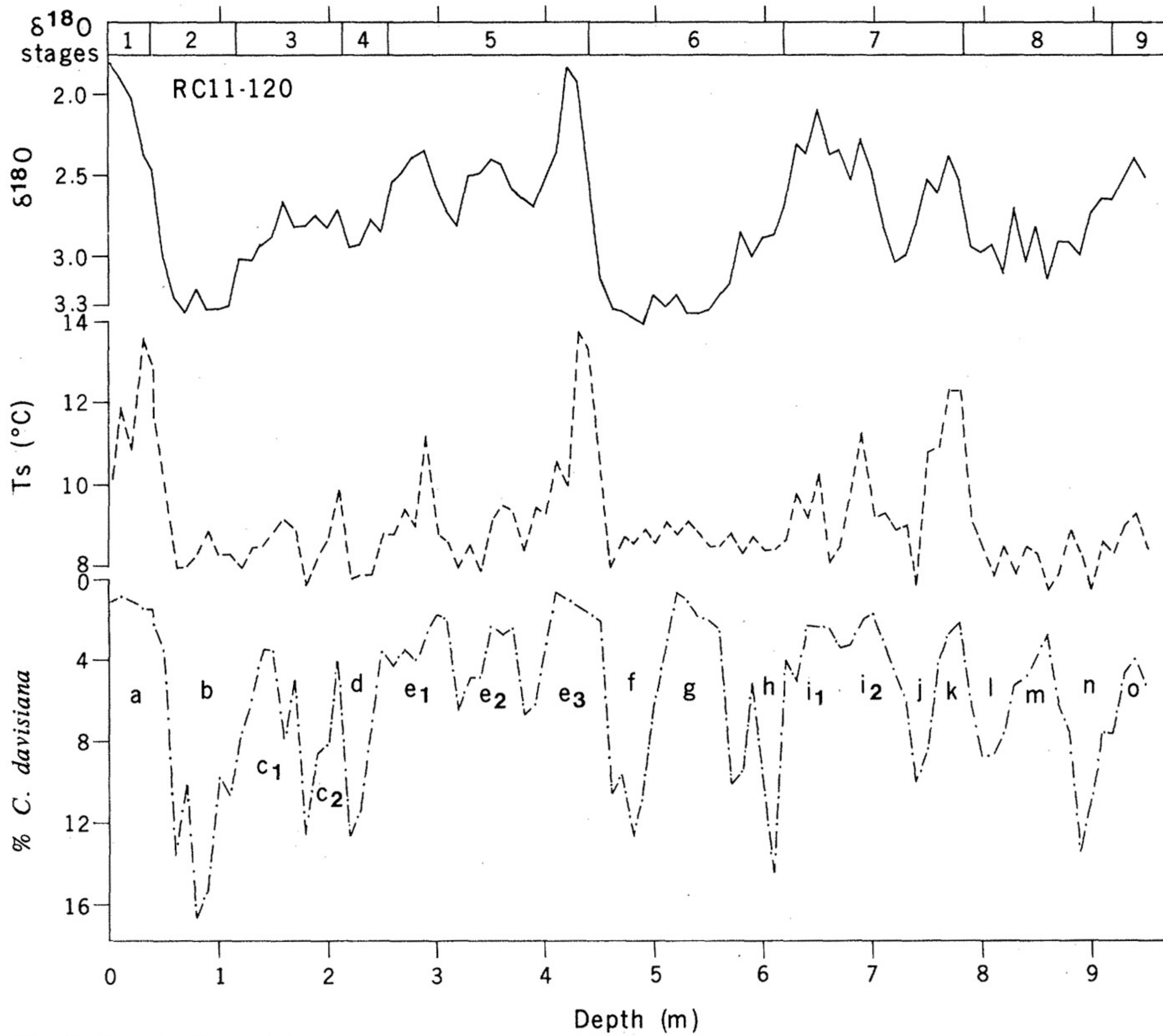


Fig. 2. Depth plots of three parameters measured in core RC11-120: $\delta^{18}O$ (solid line), *Ts* (dashed line), and percentage of *C. davisiana* (dash-dot line). Letter designations of peaks on the latter curve are informal designations of various parts of the record.

(Hays *et al.* 1976)

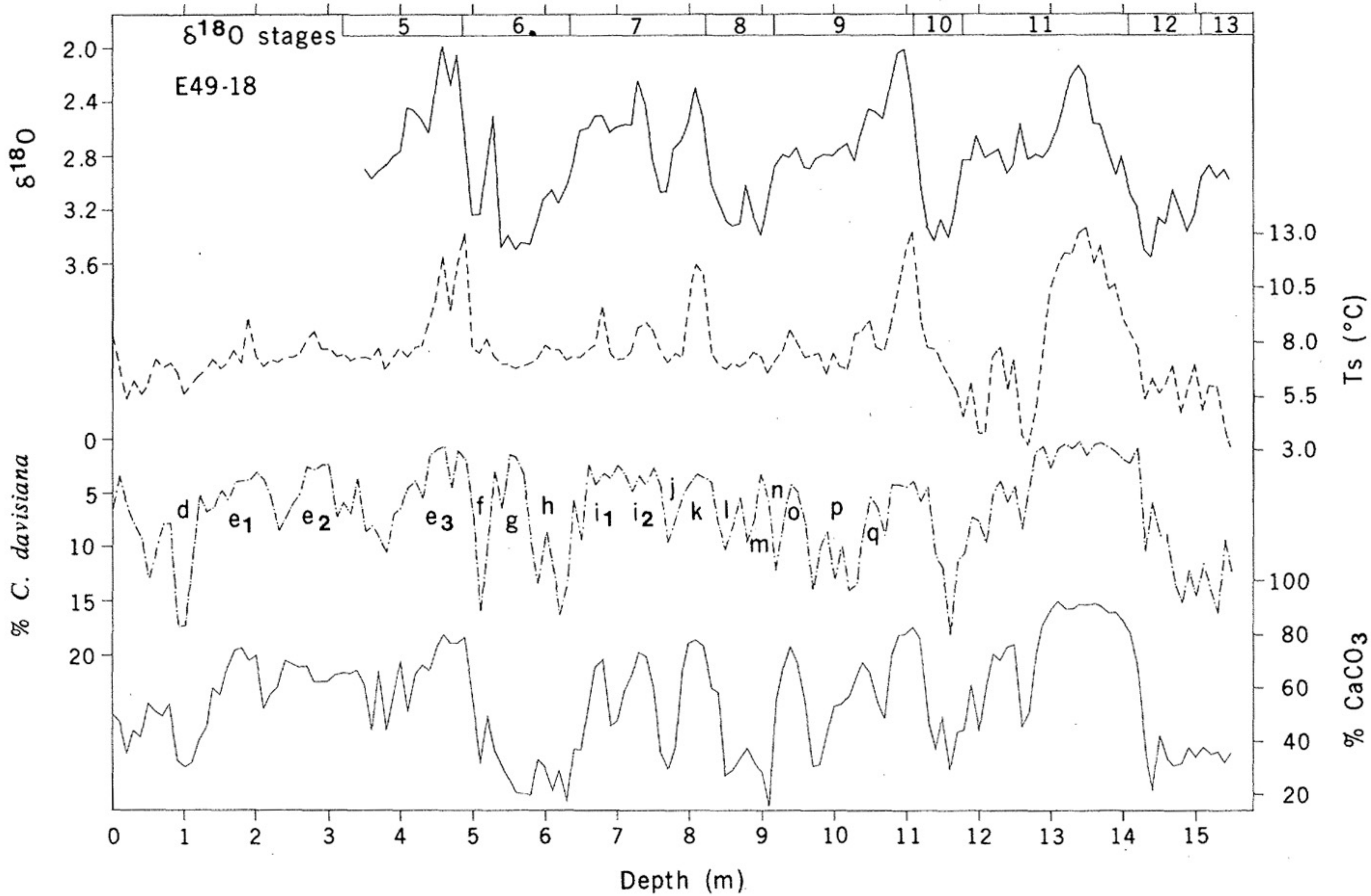


Fig. 3. Depth plots of four parameters measured in core E49-18: $\delta^{18}O$ (solid line at the top), *Ts* (dashed line), percentage of *C. davisiana* (dash-dot line), and percentage of $CaCO_3$ (solid line at the bottom). The technique used for $CaCO_3$ measurement is that of Hülsemann (*81*). A comparison of the lettered intervals of the *C. davisiana* curve for this core with those for core RC11-120 (Fig. 2) shows that the time represented by the top 1.5 m of RC11-120 is not present in E49-18.

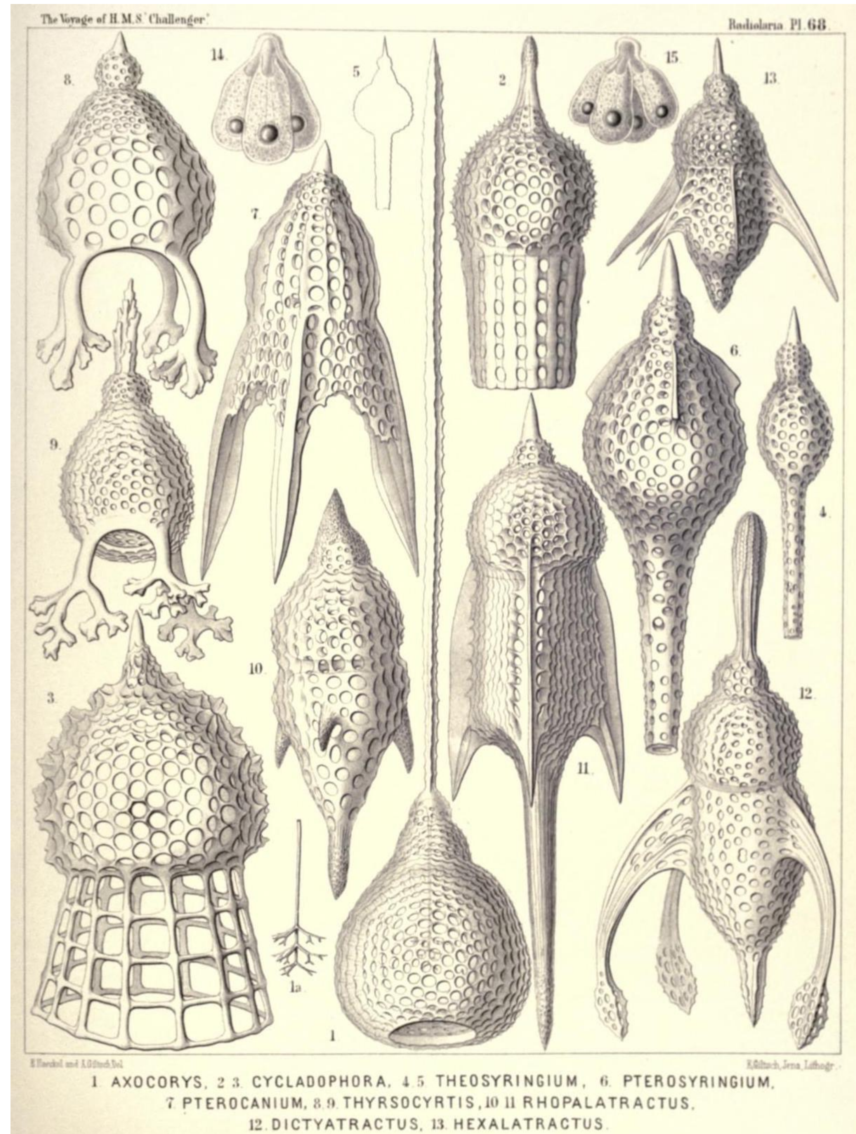
(Hays *et al.* 1976)

Cycladophora davisiana correlations

Maxima are ~ correlated in time with:

- T_s minima
- $\delta^{18}O$ maxima

Not correlated in amplitude



(Haeckel 1887)

Chronological assumptions of age models

Table 2. Chronologic assumptions of age models. Interpolation within and extrapolation beyond control points shown is linear. For the combined PATCH ELBOW and PATCH TUNE-UP records, data from 0 to 785 cm in RC11-120 were combined with data below 825 cm in E49-18.

Age model	Core	Depth (cm)	Age (× 10^3 years)	Sedimentation rate (cm/10^3 years)
SIMPLEX	RC11-120	0	0	3.46
		440	127*	
	E49-18	490	127*	2.92
		1405	440†	
ELBOW	RC11-120	0	0	
		39	9.4‡	4.14
		440	127*	3.40
		785	251†	2.78
	E49-18	490	127*	
		825	251†	2.70
		1405	440†	3.06
TUNE-UP	RC11-120	0	0	
		39	9.4‡	4.14
		440	127*	3.40
		785	247	2.87
	E49-18	490	127*	
		825	247	2.79
		1405	425	3.26

*Age of isotopic stage 6–5 boundary (*17*). †Age of isotopic stage 8–7 boundary (251,000 years) and boundary 12–11 (440,000 years) (*31*). ‡Carbon-14 determination (*35*).

(Hays *et al.* 1976)

Frequency-domain tests

Table 3. Frequency-domain test of orbital theory based on SIMPLEX chronology for two deep-sea cores. Values are mean periods (in thousand years per cycle) of peaks in unprewhitened geologic and orbital spectra.

Geologic data						Orbital data	
Core	Time interval ($\times 10^3$ B.P.)	Frequency band	*Ts*	$\delta^{18}O$	*C. davisiana* (%)	Spectral estimate	Element
		a	87	91	106		
RC11-120	0–273*	*b*	38	38	37	40.8	Obliquity (ϵ)
		c	21	23		22.6	Precession (P)
		b/c	1.8	1.7		1.8	ϵ/P
		a	94	109	119		
E49-18	127–489†	*b*	43	47		41.1	Obliquity (ϵ)
		c	24	24		21.9	Precession (P)
		b/c	1.8	1.9		1.9	ϵ/P

*Geologic and orbital spectra for this interval were calculated with $n = 91$ and $m = 40$ (*57*). †Geologic and orbital spectra for this interval were calculated with $n = 121$ and $m = 50$ (*57*).

(Hays *et al.* 1976)

Frequency-domain tests

- Milankovitch theory postulates two systems operating in series:
  1. Radiation system transforms orbital signals (obliquity and precession) into a set of insolation signals (dependent on latitude and season).
  2. Insolation signals are transformed by a second, explicitly formulated climate-response system into (predicted) climate curves.

- Hays *et al.* postulate a single, radiation-climate system that transforms orbital inputs into climatic outputs.

  Assumptions:

  – Time–invariant, linear system that can be described by a linear differential equation with constant coefficients.

Precessional index, $\Delta e \sin \Pi$

- Climatic effect of precession is a function of
  - Π, the longitude of perihelion based on the moving equinox
  - *e,* changes in Π reflect the interaction of precession with the changing orientation of the orbital ellipse.

- Intensity of solar radiation (latitude & season dependent) varies as $e\sin\Pi$

- Precessional index $\Delta e \sin \Pi$ $\approx$ to deviation from 1950 value of June Earth-sun distance

- Index range: +0.03 to -0.07

- Mean period ~ 21,000 yr

Frequency-domain tests

Table 4. Frequency-domain test of orbital theory using ELBOW chronology for PATCH core. Values are mean periods (in thousand years per cycle) of peaks and subpeaks in geologic and orbital spectra [$n = 163$ and $m = 50$ (57)]. Orbital data calculations cover the past 468,000 years.

Frequency band	Geologic data						Orbital data		
	Unprewhitened spectra			Prewhitened spectra					
	Ts	$\delta^{18}O$	*C. davisiana* (%)	*Ts*	$\delta^{18}O$	*C. davisiana* (%)	Spectral estimate	Time domain estimate	Element
a	94	106	122				105	97	Eccentricity (e)
b	40	43	43	42	43*	42*	41.1	40.6	Obliquity (ϵ)
c_1	23	24	24	24*	24	24	23.1		Precession (P_1)
c_m				22*	22	22	21.8	21.6	Precession (P_m)
c_2		19.5		19.5	19.5	19.5	18.8		Precession (P_2)
b/c_1	1.7	1.8	1.8	1.8	1.8	1.7	1.78		ϵ/P_1

*Peaks in prewhitened spectra are significant at $P = .05$.

(Hays *et al.* 1976)

Frequency analysis of astronomical data

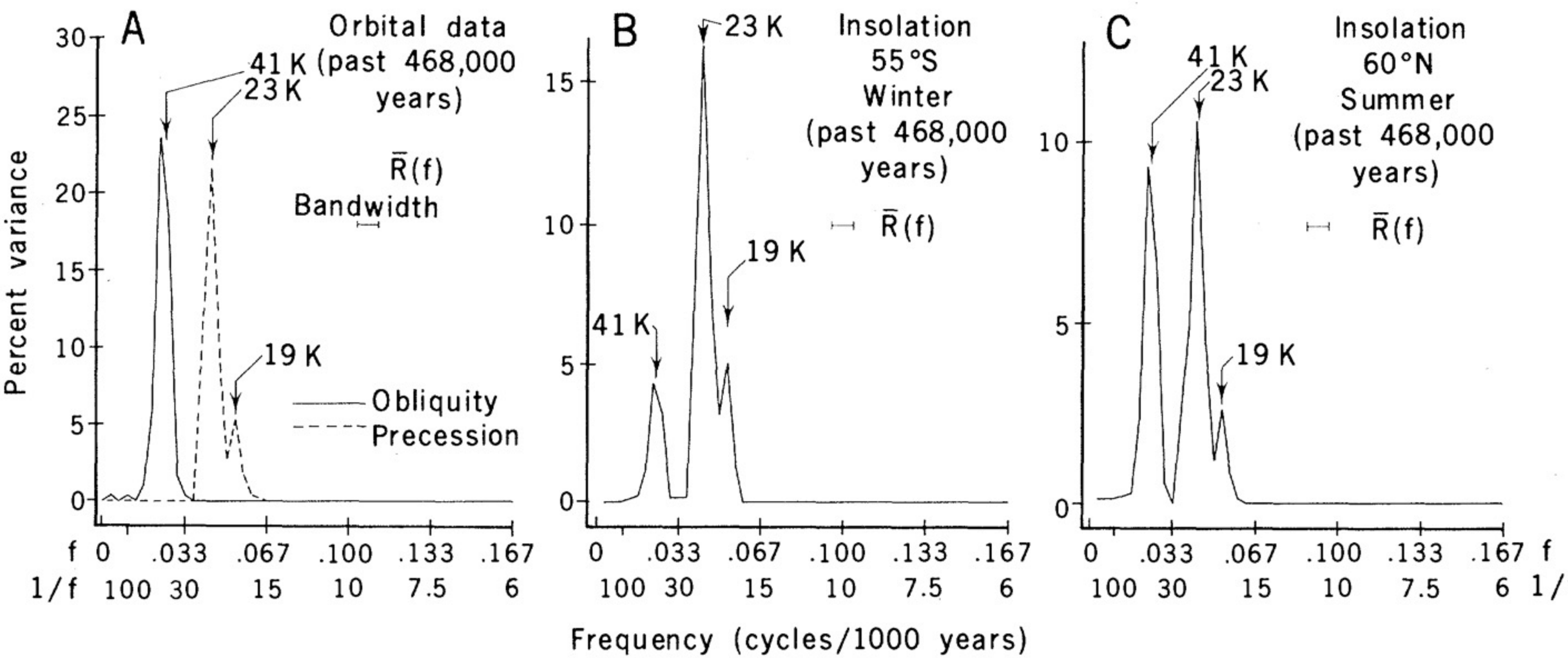
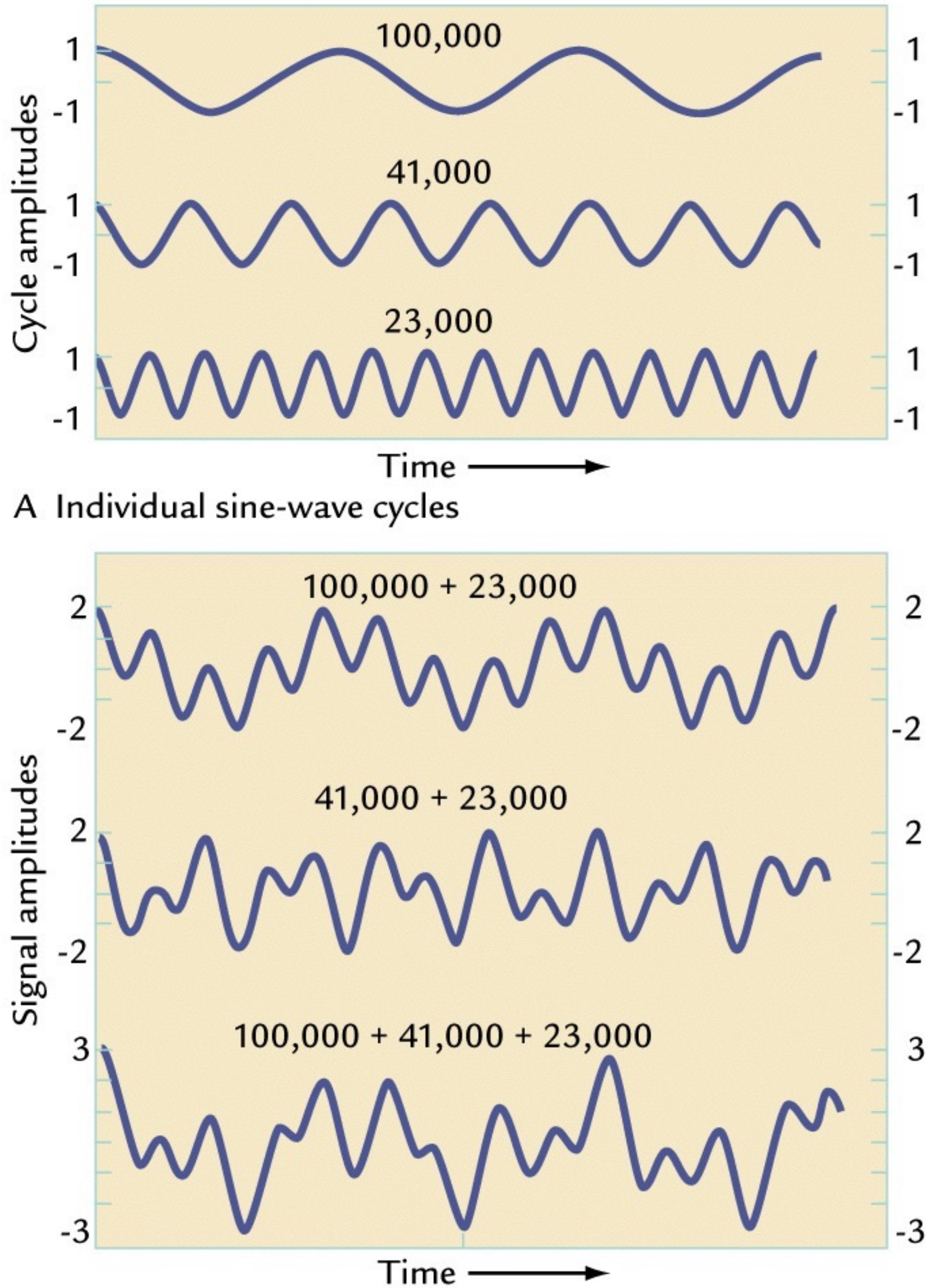


Fig. 4. High-resolution spectra of orbital and insolation variations over the past 468,000 years. Variance (as percentage of total variance per unit frequency band) is plotted as a function of frequency (cycles per thousand years). Arrows indicate weighted mean cycle lengths of spectral peaks (in thousands of years). (A) Spectra for obliquity and precession ($\Delta e \sin\Pi$). (B) Spectrum for winter insolation at 55°S. (C) Spectrum for summer insolation at 60°N. [All data are from Vernekar (*39*)]

(Hays *et al.* 1976)

Frequency analysis of astronomical data

- The three dominant cycles in these spectra (41,000, 23,000, and 19,000 years) correspond to those observed in the obliquity and precession spectra.
- Insolation spectra are characterized by frequencies reflecting obliquity and precession, but not eccentricity.
- The relative importance of the insolation components due to obliquity and precession varies with latitude and season.



B Combination of cycles

(Ruddiman 2001)

Frequency analysis of astronomical data

Same techniques as applied to astronomical data

Table 3. Frequency-domain test of orbital theory based on SIMPLEX chronology for two deep-sea cores. Values are mean periods (in thousand years per cycle) of peaks in unprewhitened geologic and orbital spectra.

Geologic data						Orbital data	
Core	Time interval ($\times 10^3$ B.P.)	Frequency band	*Ts*	$\delta^{18}O$	*C. davisiana* (%)	Spectral estimate	Element
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E49-18	127–489†	*b*	43	47		41.1	Obliquity (ϵ)
		c	24	24		21.9	Precession (*P*)
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*Geologic and orbital spectra for this interval were calculated with $n = 91$ and $m = 40$ (57). †Geologic and orbital spectra for this interval were calculated with $n = 121$ and $m = 50$ (57).

(Hays *et al.* 1976)

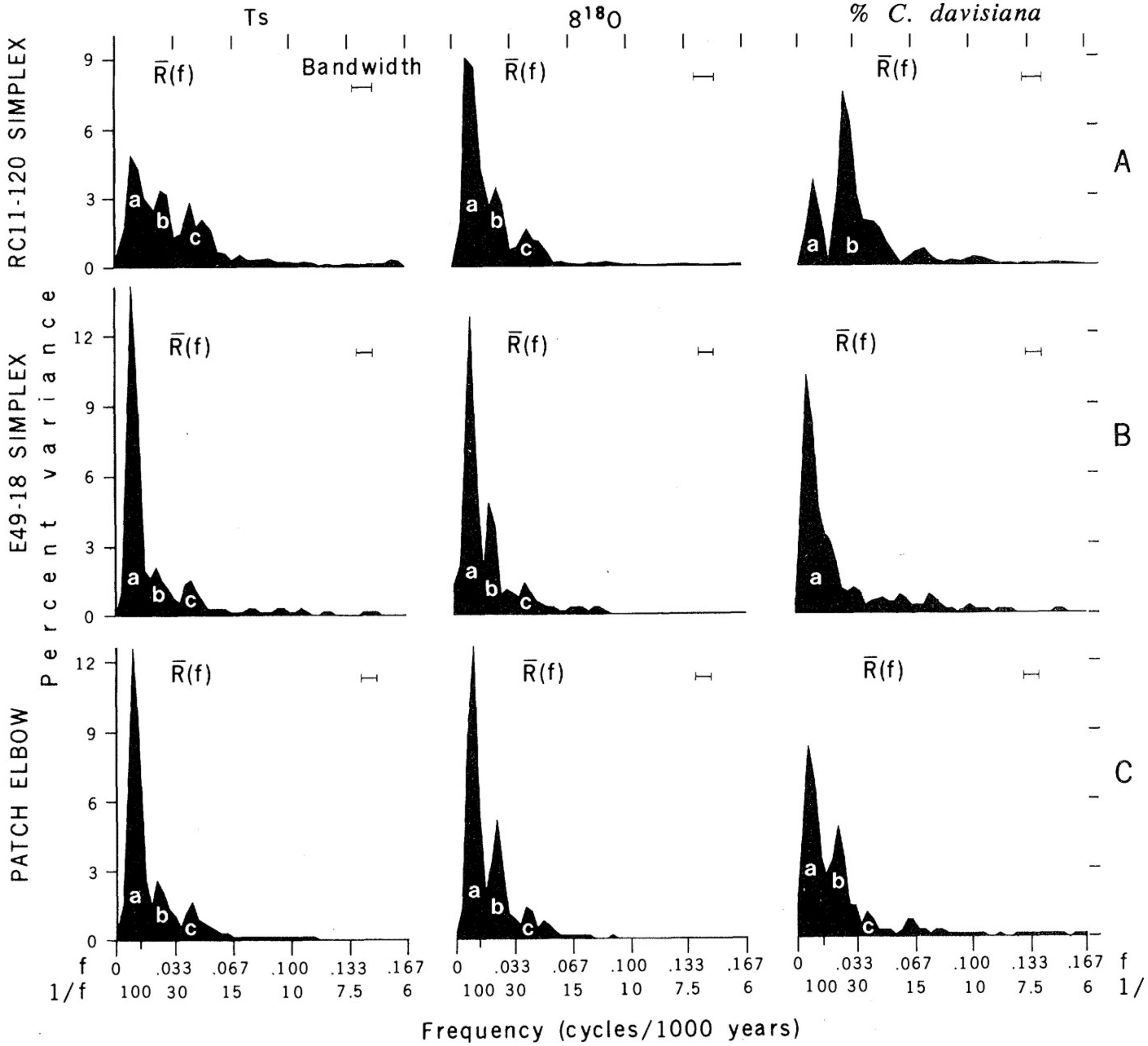


Fig. 5. High-resolution spectra of climatic variations in *Ts*, $\delta^{18}O$, and percentage of *C. davisiana*. Variance (as percentage of total variance per unit frequency band) is plotted as a function of frequency (cycles per thousand years). Prominent spectral peaks are labeled *a*, *b*, and *c*. Arrows indicate weighted mean cycle lengths (in thousands of years). The age models used in the calculations are given in Table 2. (A) Spectra for core RC11-120 are calculated for the SIMPLEX age model. (B) Spectra for core E49-18 are calculated for the SIMPLEX age model. (C) Spectra of the combined (PATCH) record are calculated for the ELBOW age model.

(Hays *et al.* 1976)

Spectra of climatic variations

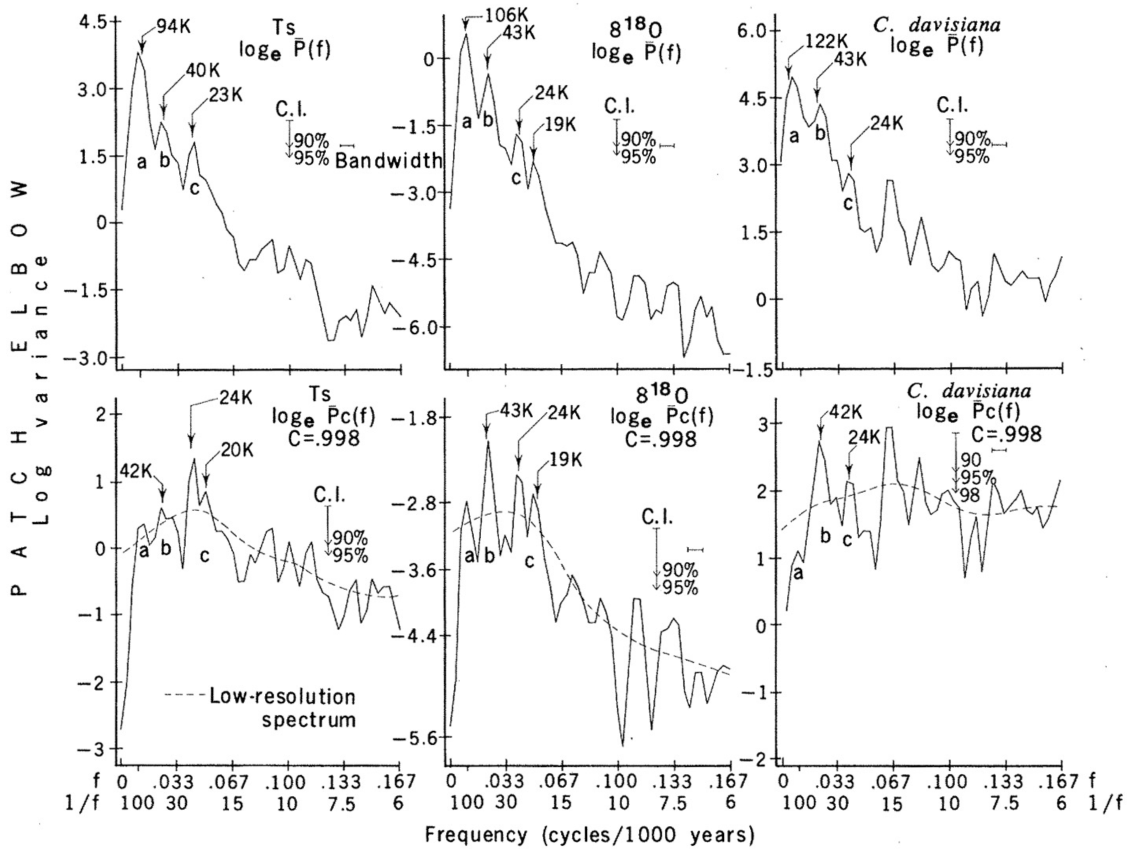


Fig. 6. Spectra of climatic variations (in *Ts*, δ^{18}O, and percentage of *C. davisiana*) in the combined (PATCH) record from two subantarctic deep-sea cores. Calculations are based on the ELBOW age model (Table 2). Arrows without crossbars indicate weighted mean cycle lengths of spectral peaks (in thousands of years). Arrows with crossbars show one-sided confidence intervals (*C.I.*) attached to estimates in the high-resolution spectrum. Prominent spectral peaks are labeled *a*, *b*, and *c*. (Top row) High-resolution spectra from Fig. 5C expressed as the natural log of the variance as a function of frequency (cycles per thousand years). (Bottom row) High-resolution spectra (solid line) and low-resolution spectra (dashed line) after prewhitening with a first-difference filter.

(Hays *et al.* 1976)

Variations in eccentricity: 500,000 years

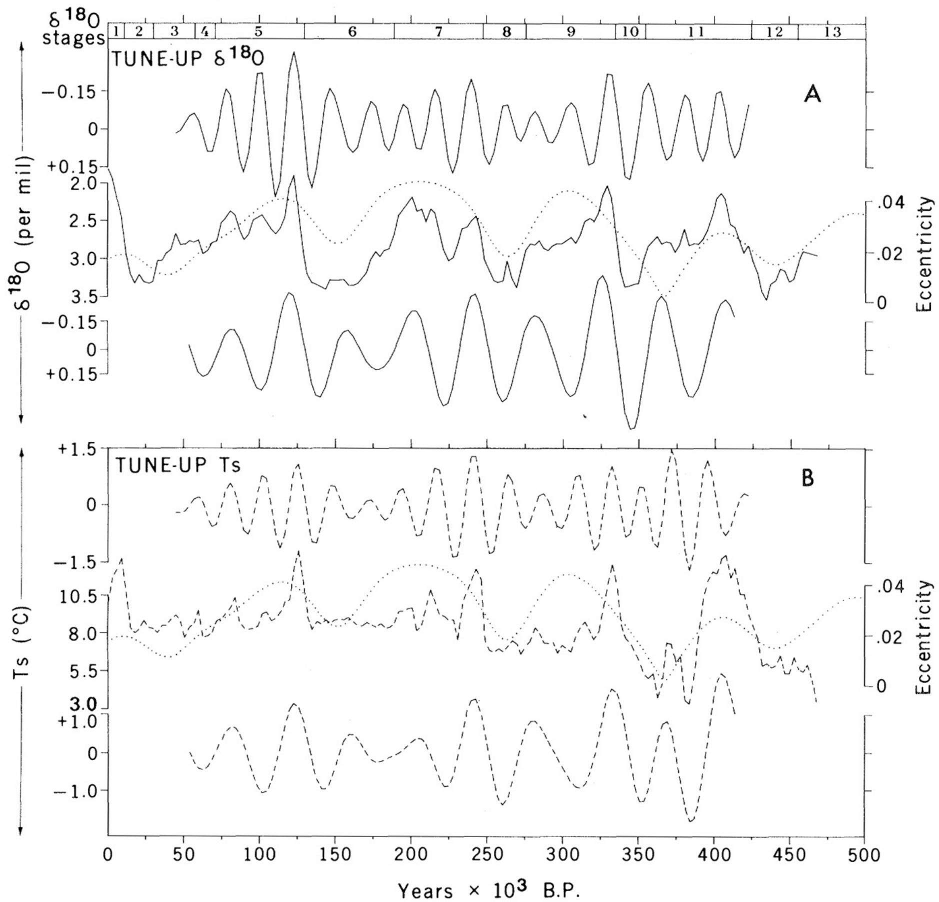


Fig. 9. Variations in eccentricity and climate over the past 500,000 years. Climatic curves are obtained from the combined (PATCH) record of two subantarctic deep-sea cores and plotted on the TUNE-UP time scale (Table 2). (A) Solid line in center shows variations in $\delta^{18}O$. Dotted line is a plot of orbital eccentricity (*39*). Upper curve is the 23,000-year frequency component extracted from $\delta^{18}O$ by a band-pass digital filter (Fig. 6). Lower curve is the 40,000-year frequency component extracted from $\delta^{18}O$ by a band-pass digital filter (Fig. 6). (B) Dashed line in center shows variations in estimated sea-surface temperature (*Ts*). Dotted line is a plot of orbital eccentricity data from Vernekar (*39*). Upper curve is the 23,000-year frequency component extracted from *Ts* by a band-pass digital filter (Fig. 6). Lower curve is the 40,000-year frequency component extracted from *Ts* by a band-pass digital filter (Fig. 6).

(Hays *et al.* 1976)

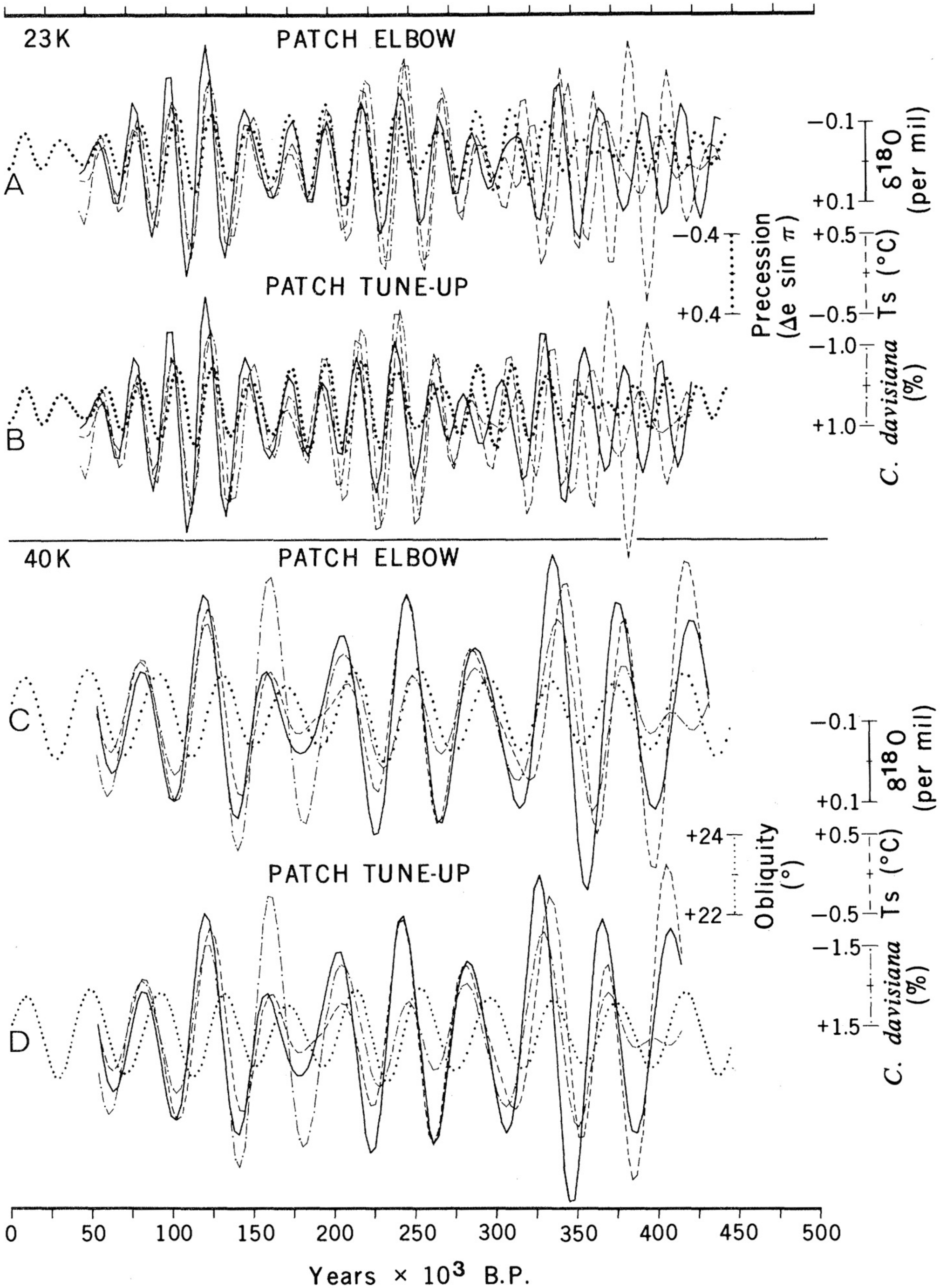
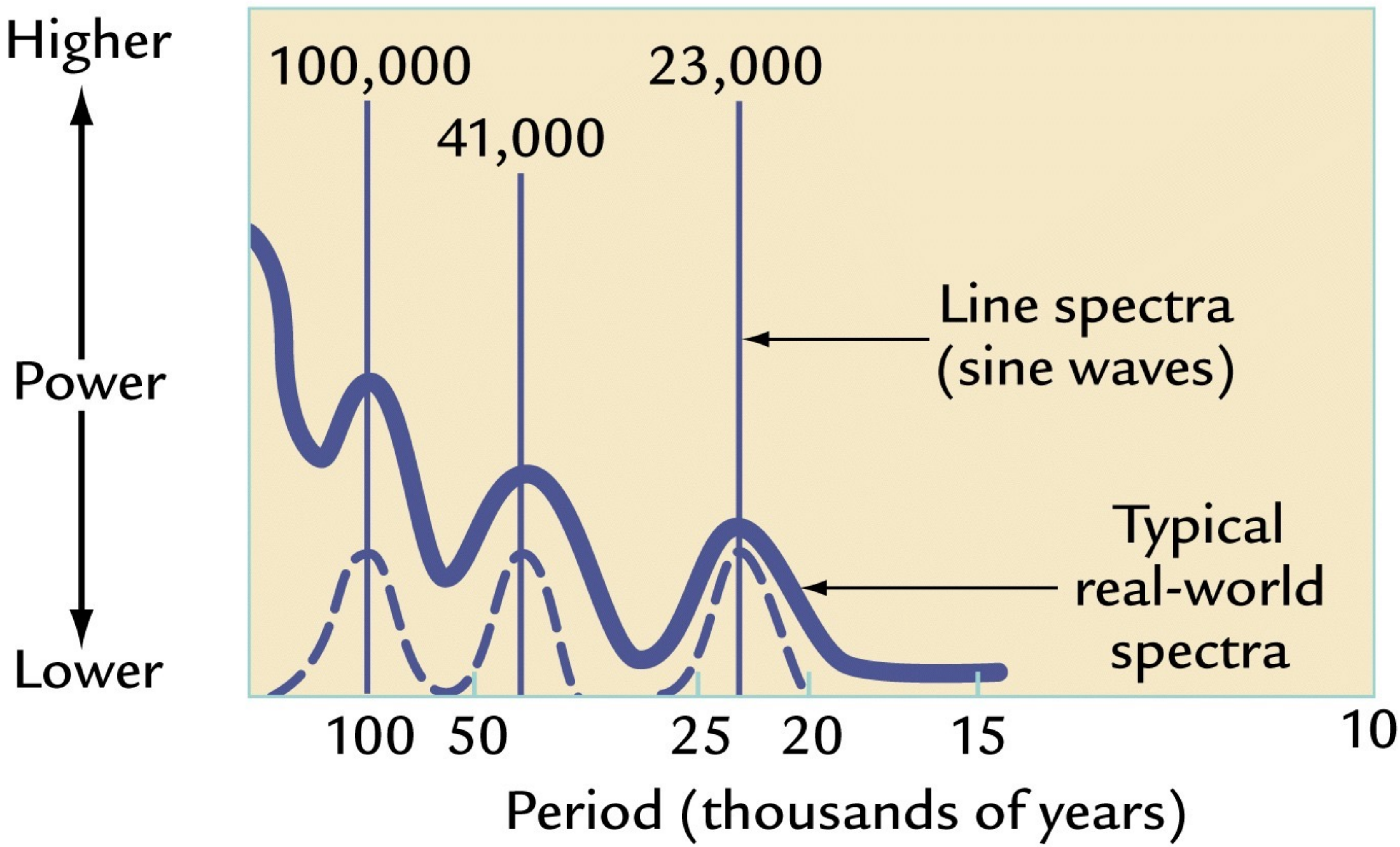


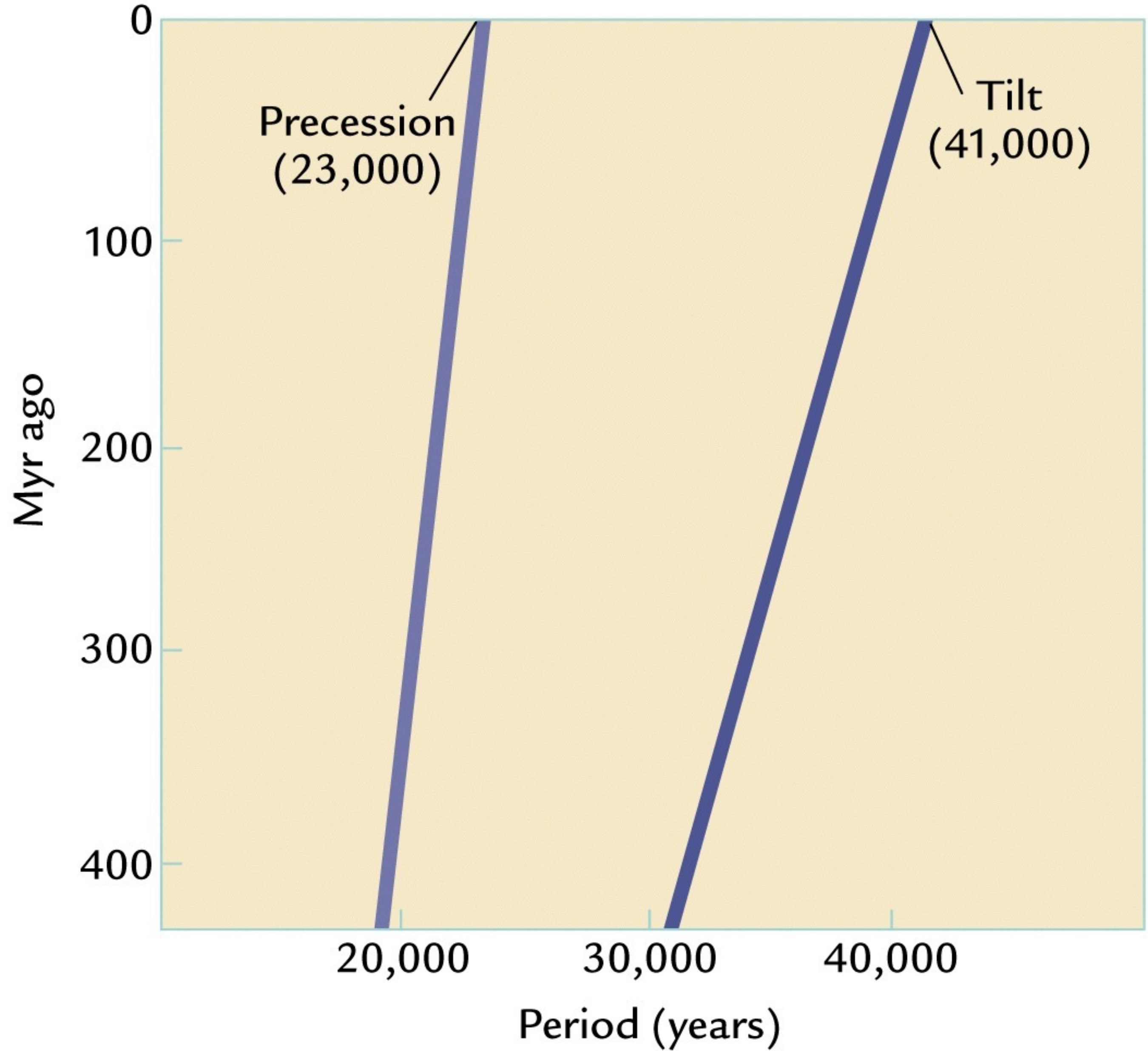
Fig. 8. Variations in obliquity, precession, and the corresponding frequency components of cli- mate over the past 500,000 years. Orbital data are from Vernekar (39). Climatic curves are variations in $\delta^{18}O$, T_s, and percentage of *C. davisiana* plotted against alternate geological time scales (ELBOW and TUNE-UP) as defined in Table 2. The variations shown are frequency components extracted from the raw-data curves by means of digital band-pass filters (Fig. 7). The two sets of curves in (A) and (B) include the precession curve and the 23,000-year frequency components of climate based on the ELBOW (A) and TUNE-UP (B) time scales. The two sets of curves in (C) and (D) include the obliquity curve and the 40,000-year frequency components of climate based on the ELBOW (C) and TUNE-UP (D) time scales.

(Hays *et al.* 1976)

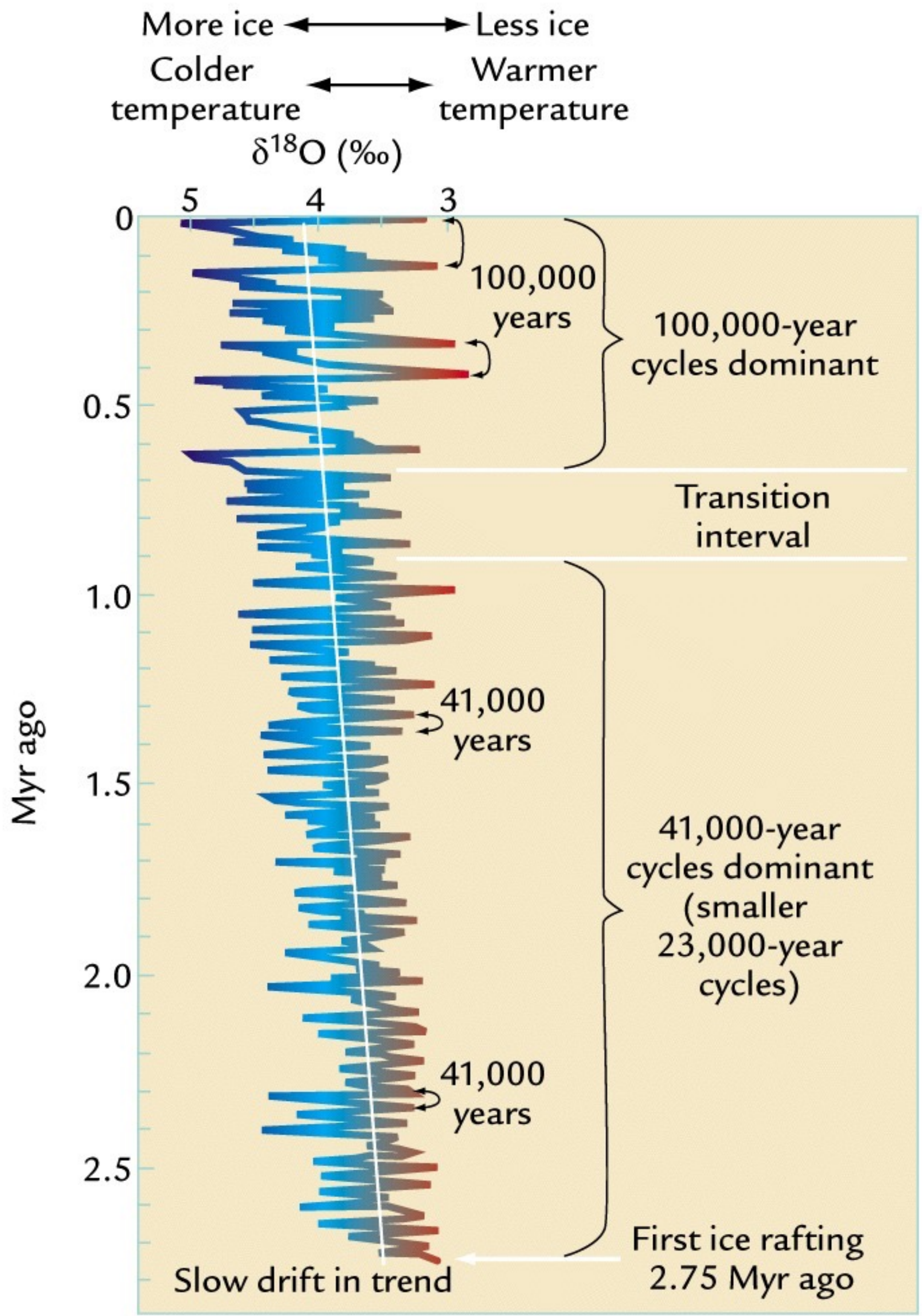
Power spectra



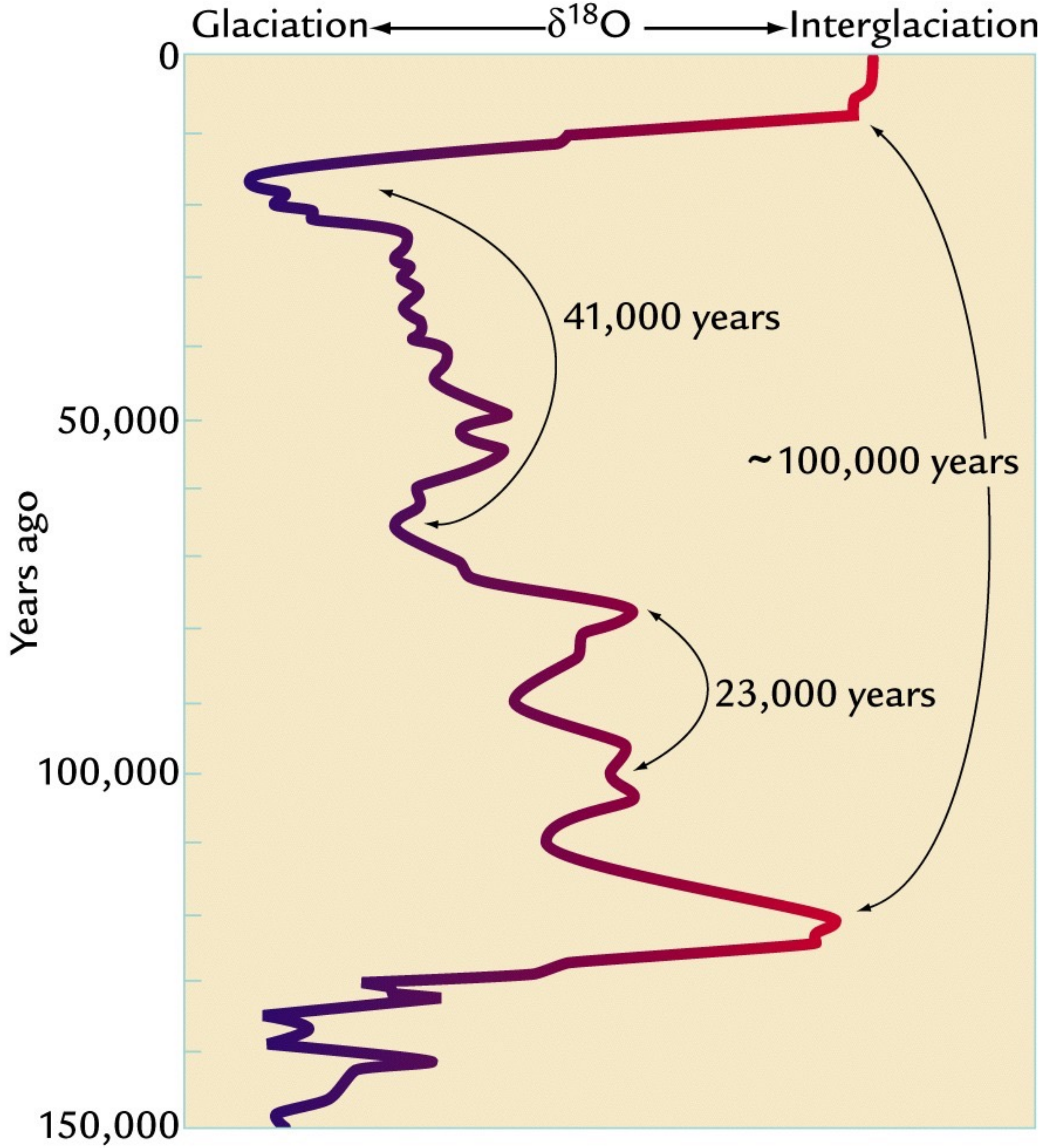
(Ruddiman 2001)



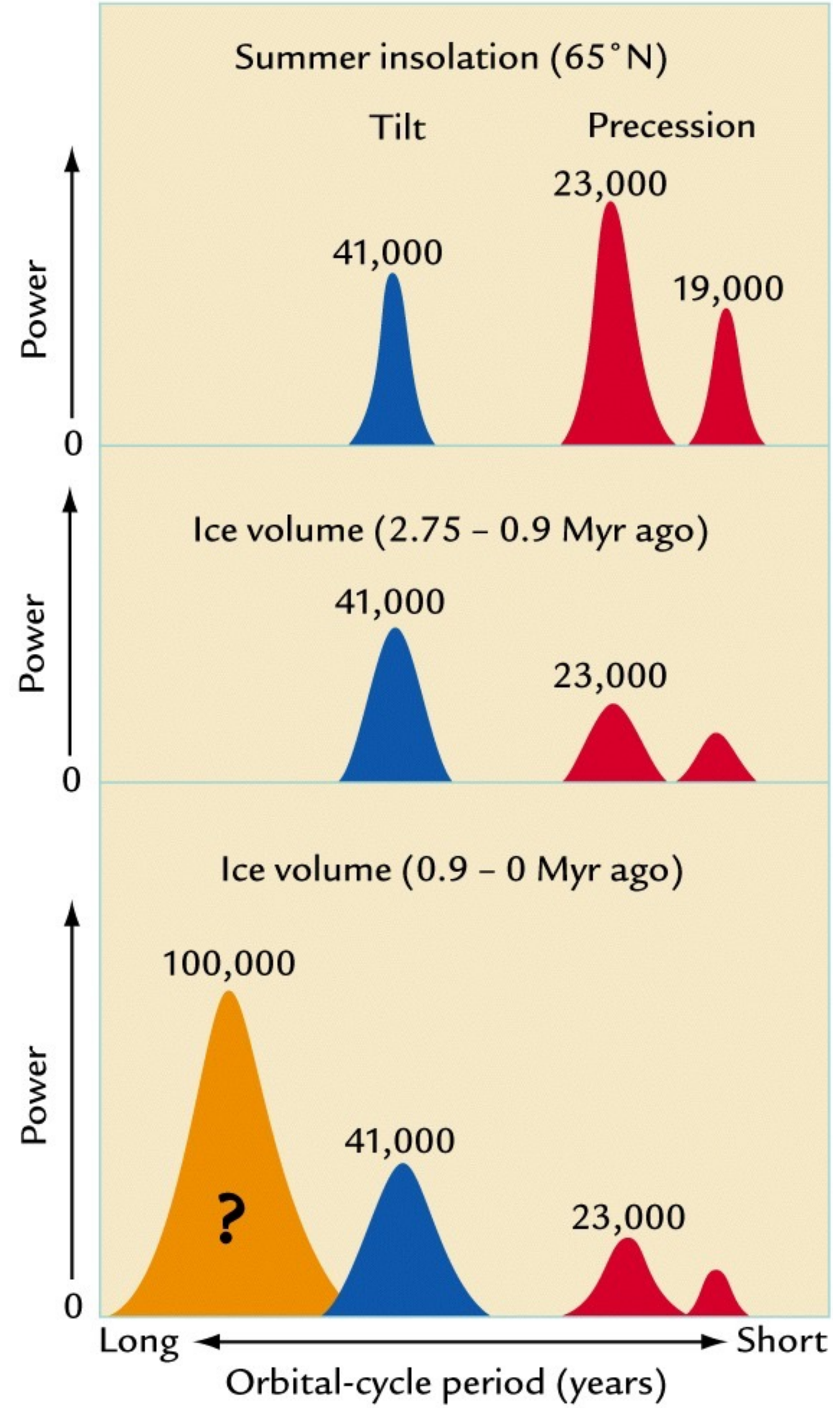
(Ruddiman 2001)



(Ruddiman 2001)



(Ruddiman 2001)



(Ruddiman 2001)

Summary

1. Three indices of global climate (T_s, $\delta^{18}O$, *C. davisiana* %) have been monitored in the record of the past 450,000 years in SH ocean-floor sediments.

2. Over the frequency range of 10^{-4} to 10^{-5} cycle/year, climatic variance of these records is concentrated in three discrete spectral peaks at periods of 23,000, 42,000, and ~ 100,000 years, corresponding to the dominant periods of the earth's solar orbit, and containing respectively ~ 10, 25, and 50% of the climatic variance.

3. The 42,000-yr climatic component has the same period as variations in the obliquity of the earth's axis and retains a constant phase relationship with it.

4. The 23,000-year portion of the variance displays the same periods (about 23,000 and 19,000 years) as the quasi-periodic precession index.

Summary

5. The dominant 100,000-yr climatic component has an average period close to, and is in phase with, orbital eccentricity. Unlike the correlations between climate and the higher-frequency orbital variations (which can be explained on the assumption that the climate system responds linearly to orbital forcing), an explanation of the correlation between climate and eccentricity probably requires an assumption of non-linearity.

6. It is concluded that changes in the earth's orbital geometry are the fundamental cause of the succession of Quaternary ice ages.

7. A model of future climate based on the observed orbital-climate relationships, but ignoring anthropogenic effects, predicts that the long-term trend over the next several thousand years is toward extensive Northern Hemisphere glaciation.

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