Παγετωνικοί κύκλοι και η αστρονομική θεωρία του Milanković

Πέτρος Ιωάννου
Τμήμα Φυσικής
Εθνικό και Καποδιστριακό Πανεπιστήμιο Αθηνών

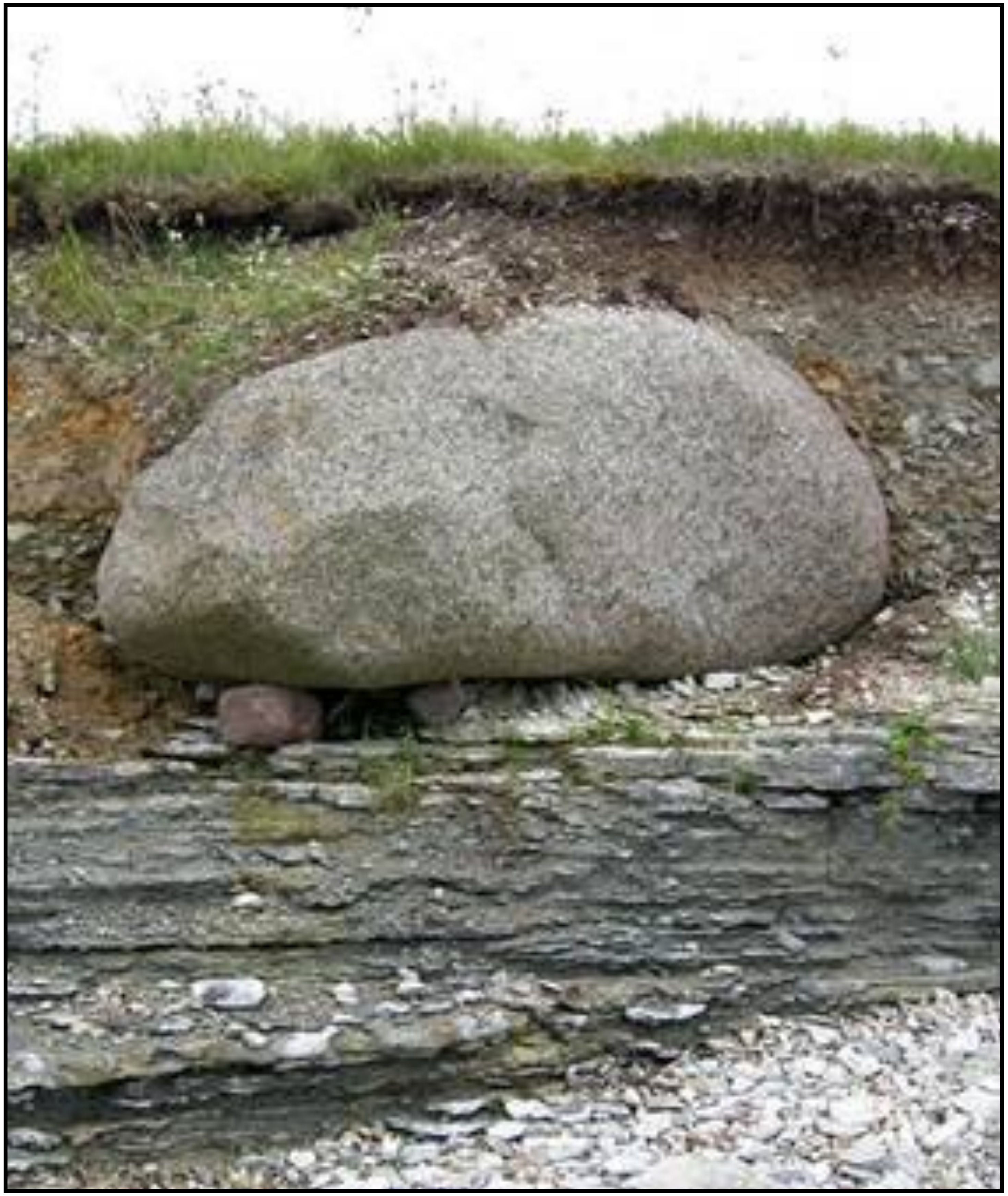
12 Μαΐου 2016

“Είναι ευρέως αποδεκτό ότι οι κλιματικές διακυμάνσεις στις χρονικές κλίμακες από1000 έως 100000 χρόνια προκαλούνται από την αστρονομική διέγερση του Milanković”

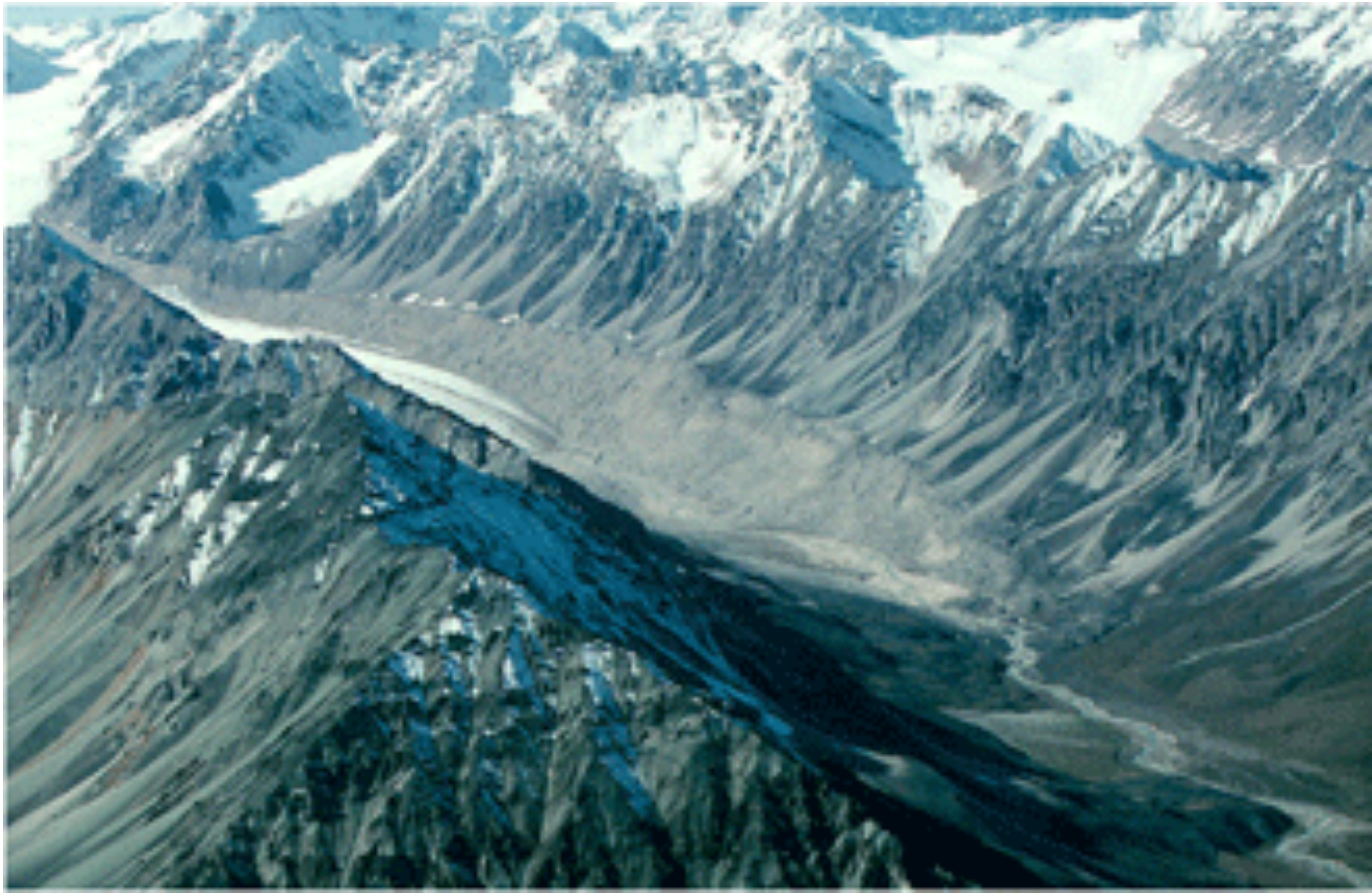
McDermott et al Science (2001)

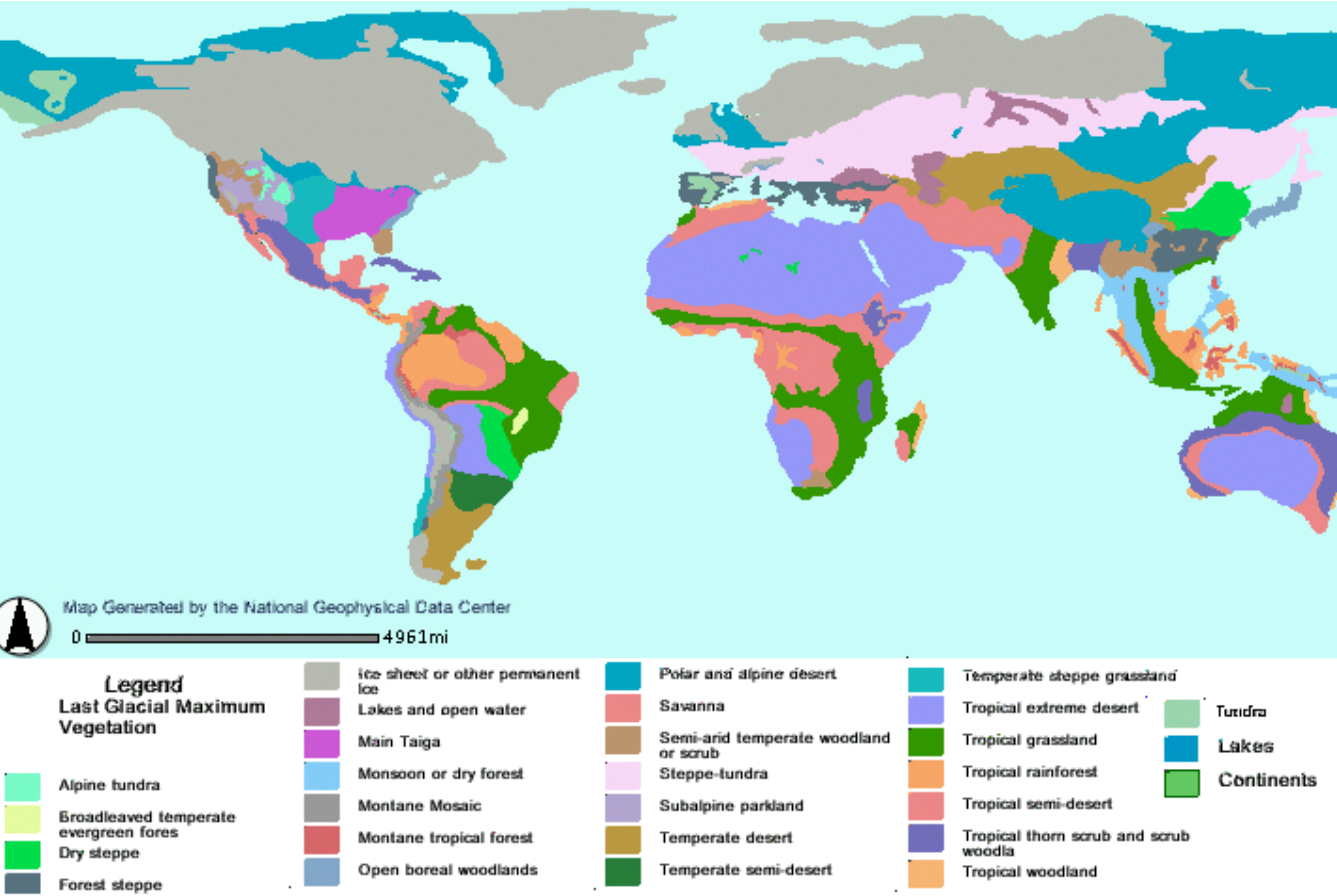
N°1. PIERRE DES MARMETTES.

The massive Pierre des Marmettes erratic, Monthey, Switzerland.
Note size in relation to people.
(Charpentier, 1841)



Moraines (λιθώματα)




Map Generated by the National Geophysical Data Center
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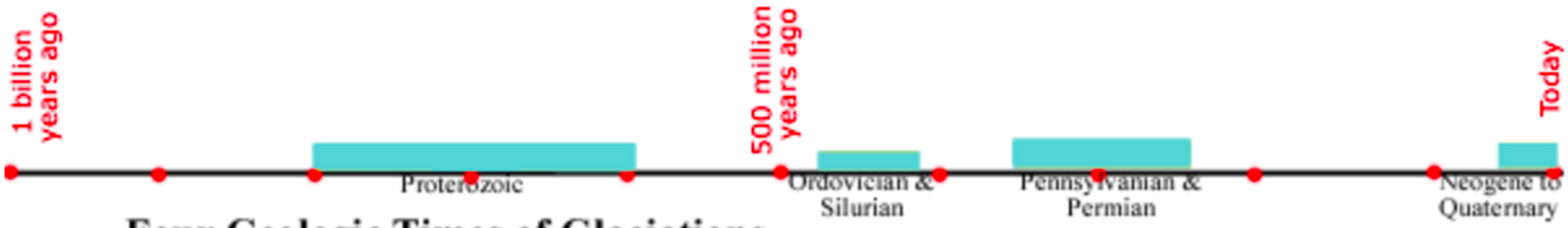
4961mi
Legend
Last Glacial Maximum Vegetation
Alpine tundra
Broadleaved temperate evergreen fores
Dry steppe
Forest steppe
Ice sheet or other permanent ice
Lakes and open water
Main Taiga
Monsoon or dry forest
Montane Mosaic
Montane tropical forest
Open boreal woodlands
Polar and alpine desert
Savanna
Semi-arid temperate woodland or scrub
Steppe-tundra
Subalpine parkland
Temperate desert
Temperate semi-desert
Temperate steppe grassland
Tropical extreme desert
Tropical grassland
Tropical rainforest
Tropical semi-desert
Tropical thorn scrub and scrub woodla
Tropical woodland
Tundra
Lakes
Continents



Four Geologic Times of Glaciations

SYSTÈME GLACIAIRE

OU RECHERCHES SUR

LES GLACIERS

LEUR MÉCANISME, LEUR ANCIENNE EXTENSION
ET LE RÔLE QU'ILS ONT JOUÉ DANS L'HISTOIRE DE LA TERRE,

PAR

MM. L. AGASSIZ, A. GUYOT & E. DESOR.

Première Partie.

NOUVELLES ÉTUDES ET EXPÉRIENCES
SUR LES GLACIERS ACTUELS,

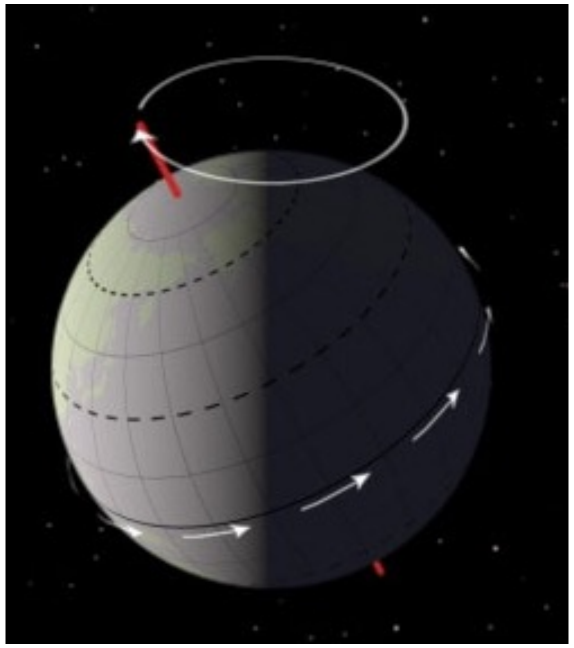
leur structure, leur progression et leur influence sur le sol;

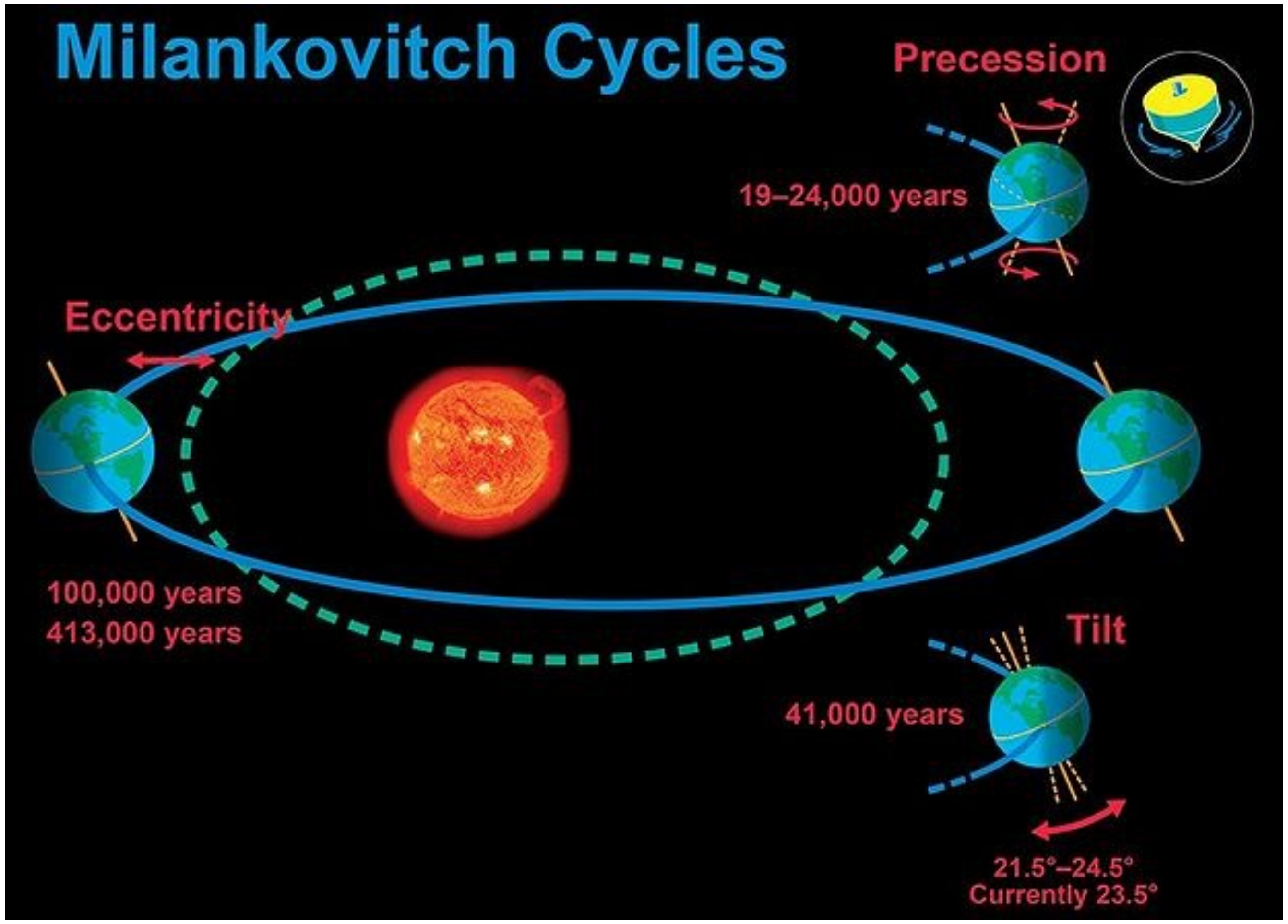
PAR L. AGASSIZ.

AVEC UN ATLAS DE 3 CARTES ET 9 PLANCHES.

PARIS,
VICTOR MASSON,
LIBRAIRE DES SOCIÉTÉS SAVANTES PRÈS LE MINISTÈRE DE L'INSTRUCTION PUBLIQUE,
Place de l'École de Medecine.
LEIPZIG, LÉOPOLD VOSS.
M DCCC XLVII

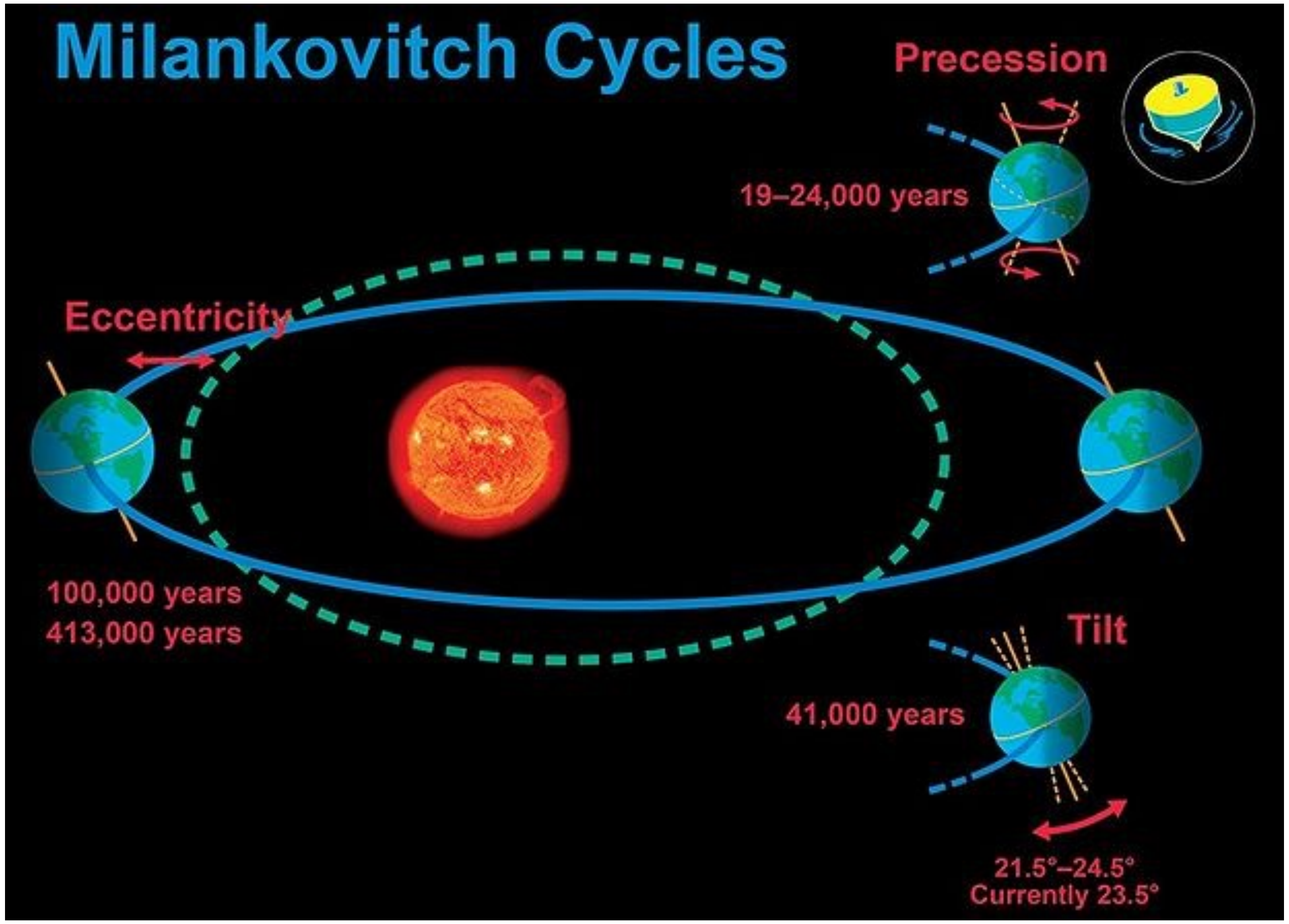
Adhemar 1842 βασισμένος στη μετάπτωση των ισημεριών (D’Alembert 1754 22kyr)

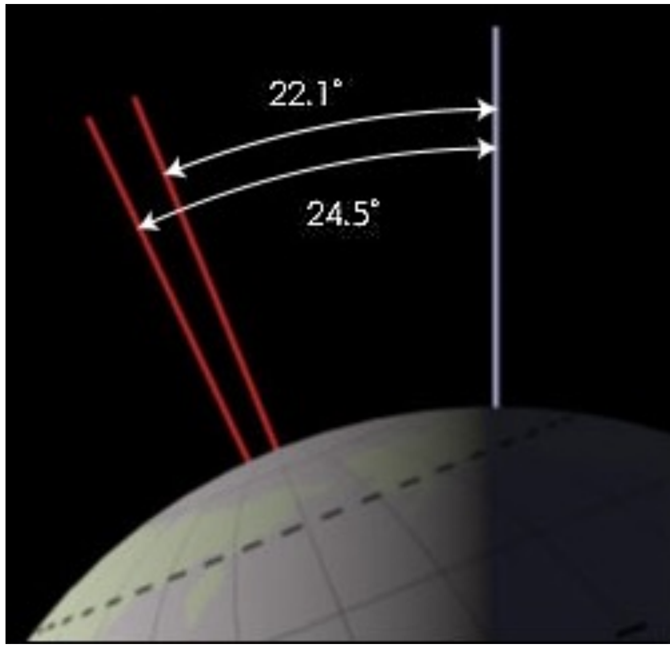




Λιγότερες ημέρες στο Ν ημισφαιριο απο το Β
Προβλέπει: παγετώνες εναλλάσονται μεταξύ Β και Ν ημισφαιρίου κάθε 11kyr

Kroll 1864 λαμβάνει υπόψη του μεταβολές εκκεντρότητας
Le Verrier 1843





Παγετώνες σχηματίζονται στο ΒΗ όταν το αφήλιο συμπίπτει με μεγάλη εκκεντρότητα (η τελευταία παγετωνική περίοδος άρχισε -250kyr και τερμάτησε -80kyr)

Εισήγαγε έννοια ανάδρασης πάγου στη λευκαύγεια και υποστήριξε ότι ευννοούνται οι παγετώνες όταν η κλίση τιυ άξονα είναι μικρότερη

Οι γεωλόγοι όμως αρχίζουν να έχουν συγκεντρώσει αρκετά στοιχεία που συνηγορούσαν ότι η τελευταία παγετωνική περίοδος τερμάτισε -15kyr

Παγετώνες φαίνεται ότι εμφανίζονταν συγχρόνως

Milanković το 1911 αρχίζει να υπολογίζει τη μεταβολή της κατανομής της ηλιοφάνειας

Η ετήσια ολική ενέργεια από τον ήλιο εξαρτάται μόνο από την εκκεντρότητα

$$\approx 1 + e^2/2 \quad (\delta e = 0.06 \rightarrow\ 0.18\%)$$

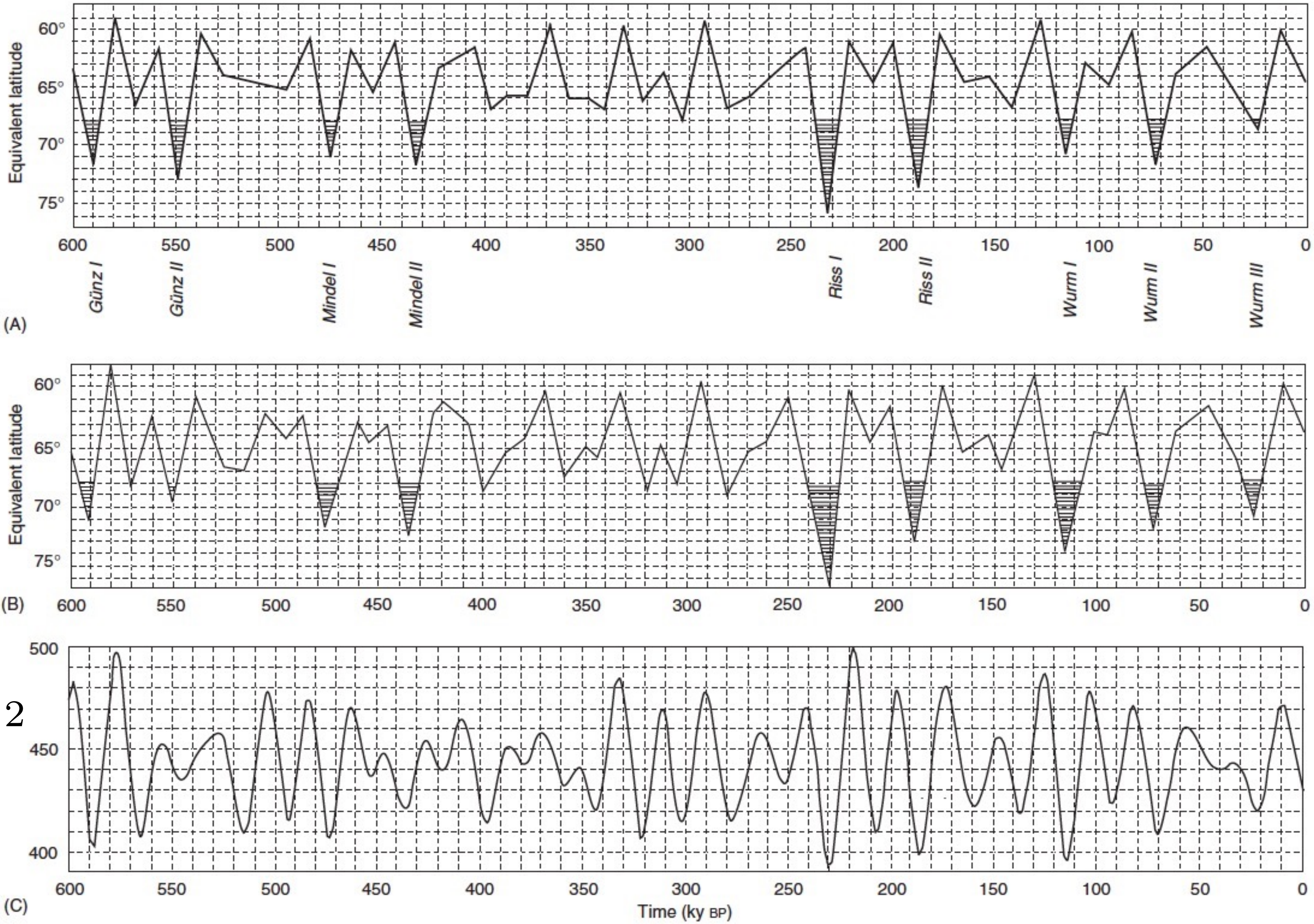
Υπόθεση Milanković σε συνεργασία με Koppen1920 : Κρίσιμη ποσότητα που ρυθμίζει τον σχηματισμό παγετώνων είναι το μέτρο της ηλιοφάνειας στο θερινό ηλιοστάσιο του ΒΗ (που όμως; στα 55, 60 ή 65 Β)

Μέγιστη ηλιοφάνεια στο θερινό ηλιοστάσιο όταν η κλίση είναι μέγιστη και το θερινό ηλιοστάσιο συμβαίνει στο περιήλιο

Μεταβολή στη κλίσης του άξονα περιστροφής οδηγεί σε μεταβολή στην εισερχόμενη ακτινοβολίας σε μεγάλα γεωγραφικά πλάτη $\approx 15\ \%$

Η μετάπτωση των ισημεριών σε συνδυασμό με την εκκεντρότητα $\approx e \sin \Lambda$ οδηγεί και αυτή σε μεταβολή στην εισερχόμενη ακτινοβολίας σε μεγάλα γεωγραφικά πλάτη

$$\approx 15\ \%$$


Equivalent latitude
60°
65°
70°
75°
600
550
500
450
400
350
300
250
200
150
100
50
0
Günz I
Günz II
Mindel I
Mindel II
Riss I
Riss II
Wurm I
Wurm II
Wurm III
(A)
Equivalent latitude
60°
65°
70°
75°
(B)
600
550
500
450
400
350
300
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200
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100
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0
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450
400
350
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250
200
150
100
50
0
(C)
Time (ky BP)

$\mathrm{W\ m^{-2}}$

A&A 532, A89 (2011)
DOI: 10.1051/0004-6361/201116836

Astronomy & Astrophysics

La2010: a new orbital solution for the long-term motion of the Earth★

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Received 5 March 2011 / Accepted 3 May 2011

ABSTRACT

We present here a new solution for the astronomical computation of the orbital motion of the Earth spanning from 0 to –250 Myr. The main improvement with respect to our previous numerical solution La2004 is an improved adjustment of the parameters and initial conditions through a fit over 1 Myr to a special version of the highly accurate numerical ephemeris INPOP08 (Intégration Numérique Planétaire de l'Observatoire de Paris). The precession equations have also been entirely revised and are no longer averaged over the orbital motion of the Earth and Moon. This new orbital solution is now valid over more than 50 Myr in the past or into the future with proper phases of the eccentricity variations. Owing to the chaotic behavior, the precision of the solution decreases rapidly beyond this time span, and we discuss the behavior of various solutions beyond 50 Myr. For paleoclimate calibrations, we provide several different solutions that are all compatible with the most precise planetary ephemeris. We have thus reached the time where geological data are now required to discriminate between planetary orbital solutions beyond 50 Myr.

Key words. chaos – methods: numerical – celestial mechanics – ephemerides – planets and satellites: dynamical evolution and stability – Earth

1. Introduction

Owing to gravitational planetary perturbations, the elliptical elements of the orbit of the Earth are slowly changing in time, as is the orientation of the planet's spin axis. As described by Milankovitch (1941) these changes induce variations in the insolation received on the Earth's surface that are at the origin of large climatic changes. Since the work of Hays et al. (1976), which established a correlation between astronomical forcing and the δ^{18}O records over the past 500 kyr, there has been a increasing need for a precise long-term ephemeris for the Earth orbital and rotational evolution (see Laskar et al. 2004 for a more detailed historical account).

For paleoclimate studies, the most widely used orbital solutions are nowadays either the averaged solution of Laskar (1988) and Laskar et al. (1993b) or the numerical solution of Laskar et al. (2004).

The first long-term direct numerical integration (without averaging) of a realistic model of the Solar System, together with the precession and obliquity equations, was performed by Quinn et al. (1991) over 3 Myr. Over its range, this solution presents only small differences with the secular solutions of Laskar (1988, 1990) (see Laskar et al. 1992). The orbital motion of the full Solar System was computed over 100 Myr by Sussman & Wisdom (1992) using a symplectic integrator with mixed variables (Wisdom & Holman 1991), confirming the chaotic behavior found by Laskar (1989, 1990). Following the improvement of computer technology, long-term integrations of realistic models of the Solar System have improved (Varadi et al. 2003; Laskar et al. 2004), but the main limitation remains the exponential divergence of nearby orbits resulting from the chaotic motion of the Solar System (Laskar 1989, 1990, 1999). Although it is now possible to integrate the motion of the Solar System over time periods of more than 5 Gyr, which is comparable to its age or expected lifetime (Laskar & Gastineau 2009), it is clear that the chaotic behavior of the solution will still limit its validity to a few tens of Myr.

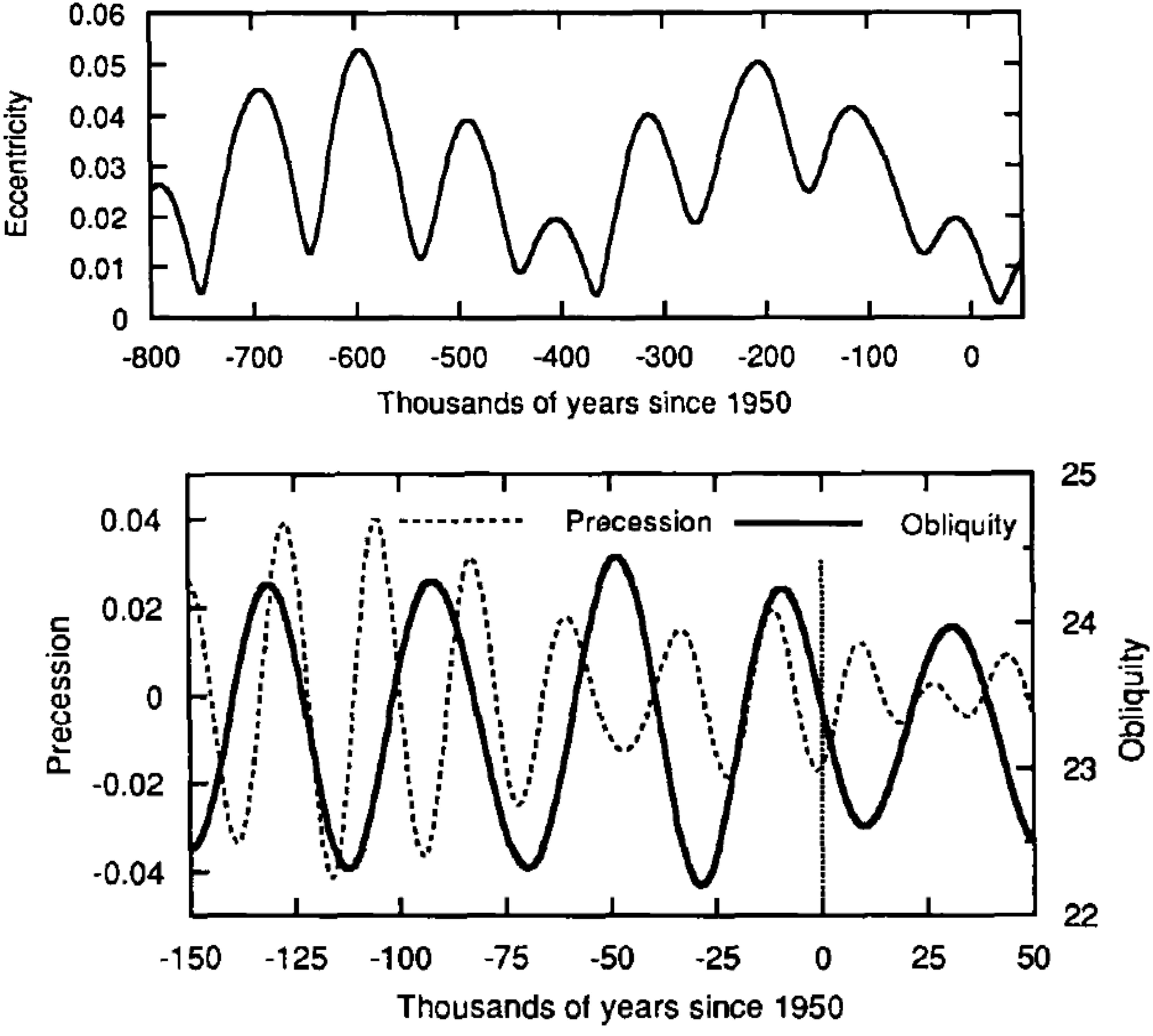
The present paper is a continuation of the work that has been conducted for decades in our group to obtain the most precise solution for the past evolution of the orbit and rotational state of the Earth, specifically aimed to paleoclimate studies.

The numerical integrator is the same symplectic integrator of Laskar & Robutel (2001) that was used in the La2004 solution (Laskar et al. 2004), but it was entirely rewritten in C in order to access the extended precision of the Intel architecture. The tidal model has been largely modified, and is now similar to the one used in the JPL planetary ephemeris DE405 (Standish 1998b) or in our new planetary ephemeris INPOP (Fienga et al. 2008, 2009). The precession equations for the evolution of the spin axis of the Earth are also new (Boué & Laskar 2006). We no longer average over the orbital motion of the planets, which allows a precise computation of the evolution of the Earth spin axis that can be compared to the most precise model adopted by the IAU (Soffel et al. 2003) (see Fienga et al. 2008).

In previous long-term solutions (Laskar 1988; Quinn et al. 1991; Laskar et al. 1993a; Varadi et al. 2003; Laskar et al. 2004), the initial conditions of the solutions were obtained either directly from a high precision planet ephemeris, or by performing a fit over its full time span (as in La2004) that was still limited to a few thousands of years. It was also difficult to monitor the real uncertainty in the adopted ephemeris.

★ The solutions are available at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/532/A89`

5 d -> 3Myr



Berger & Loutre (1991)

Ισοτοπικές διαφορές μας πληροφορούν για τη θερμοκρασία της Γής και την ποσότητα του πάγου

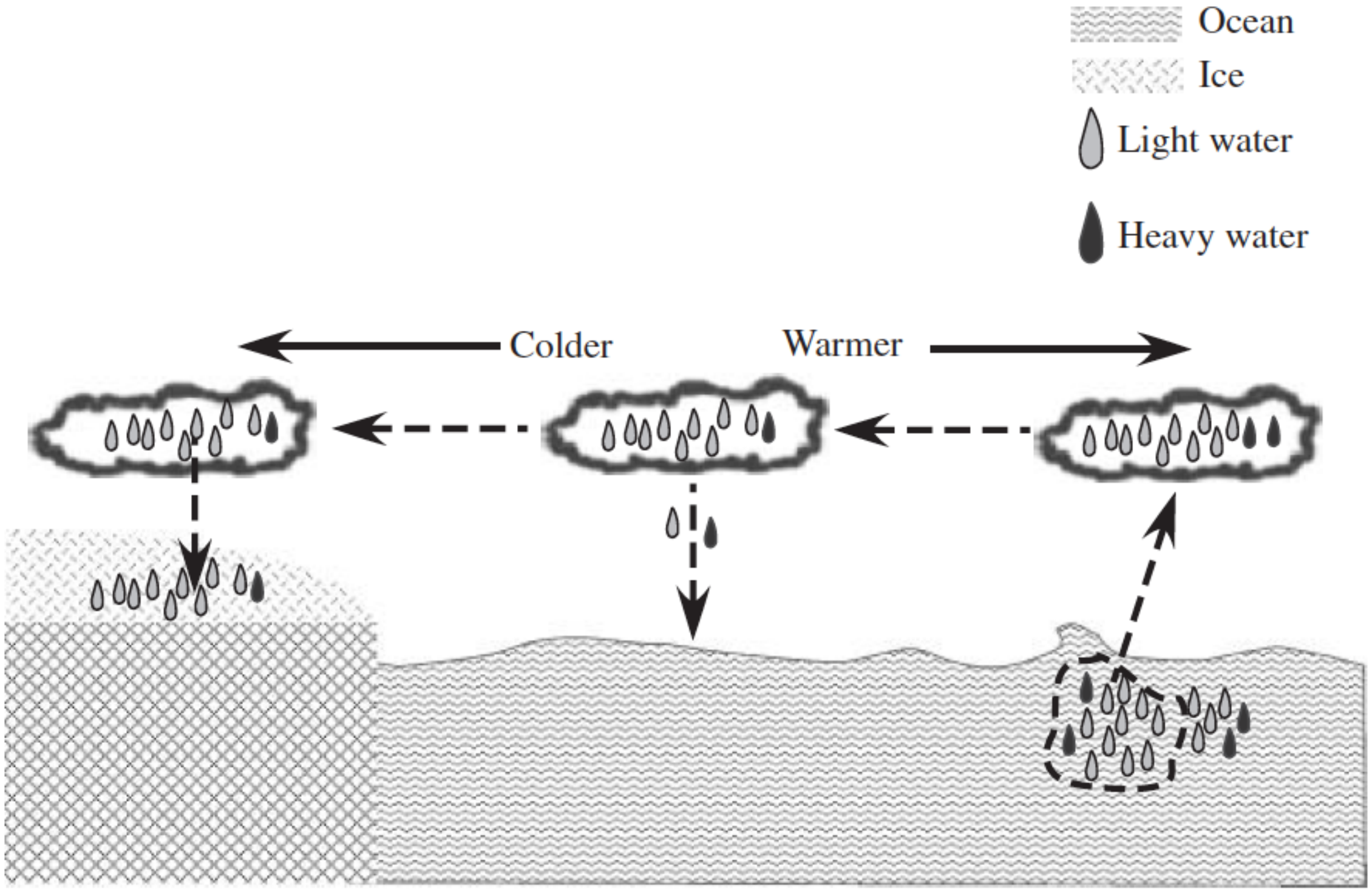
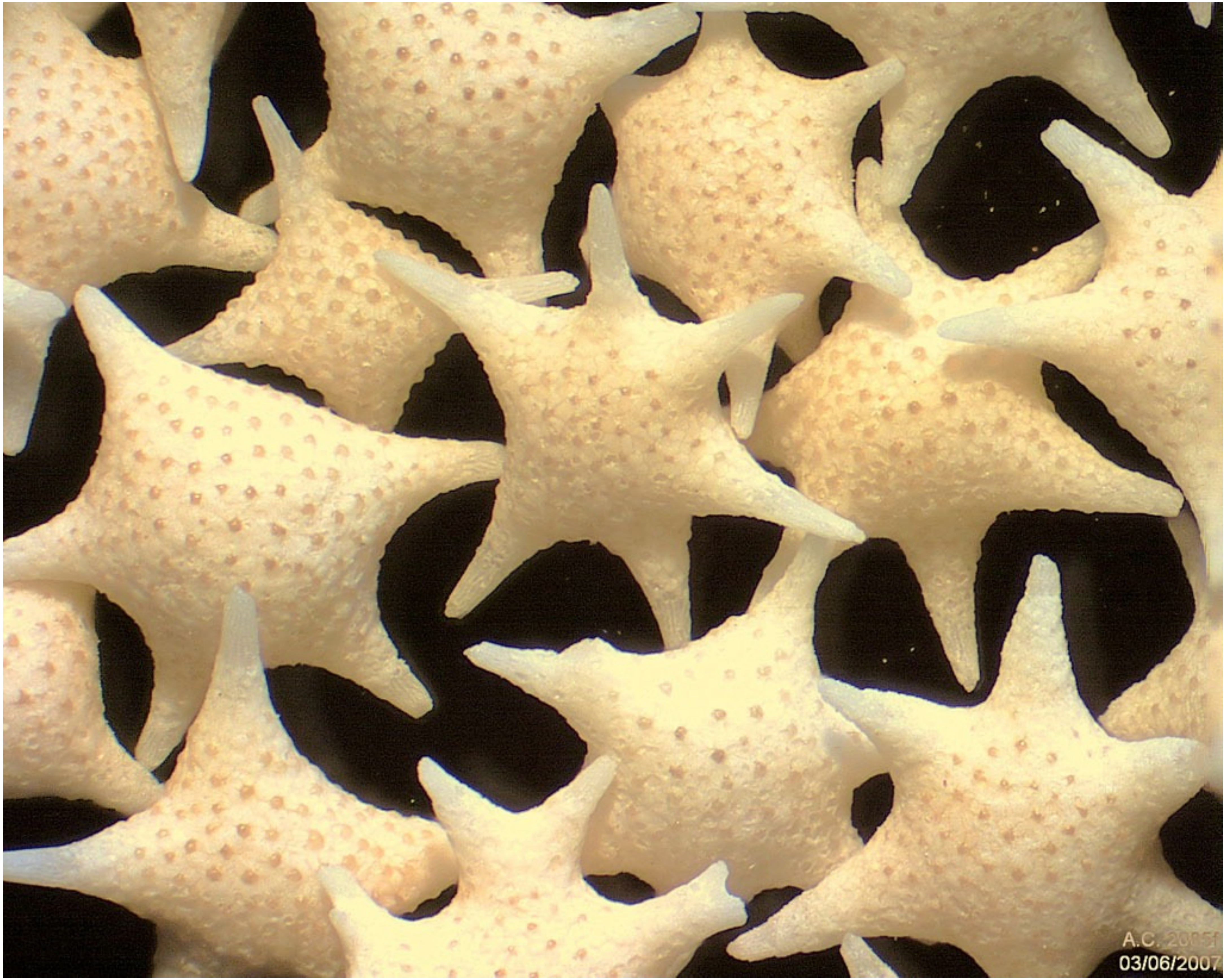


Figure 1.5 Sketch showing how the growth of ice sheets on land affects the isotopic composition of ocean water. The water vapor which evaporates from the ocean is enriched in lighter forms of water, and becomes more isotopically light as the heavy forms of water preferentially rain or snow out before the remainder is deposited on the glacier. This process systematically transfers isotopically light water to the glacier, leaving the ocean isotopically heavy.

και Foraminifera (forams) καταγράφουν τον όγκο των πάγων



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

For more than a century the cause of fluctuations in the Pleistocene ice sheets has remained an intriguing and unsolved scientific mystery. Interest in this problem has generated a number of possible explanations (*1, 2*). One group of theories invokes factors external to the climate system, including variations in the output of the sun, or the amount of solar energy reaching the earth caused by changing concentrations of interstellar dust (*3*); the seasonal and latitudinal distribution of incoming radiation caused by changes in the earth's orbital geometry (*4*); the volcanic dust content of the atmosphere (*5*); and the earth's magnetic field (*6*). Other theories are based on internal elements of the system believed to have response times sufficiently long to yield fluctuations in the range 10^4 to 10^6 years. Such features include the growth and decay of ice sheets (*7*), the surging of the Antarctic ice sheet (*8*); the ice cover of the Arctic Ocean (*9*); the distribution of carbon dioxide between atmosphere and ocean (*10*); and the deep circulation of the ocean (*11*). Additionally, it has been argued that as an almost intransitive system, climate could alternate between different states on an appropriate time scale without the intervention of any external stimulus or internal time constant (*12*).

Among these ideas, only the orbital hypothesis has been formulated so as to predict the frequencies of major Pleistocene glacial fluctuations. Thus it is the only explanation that can be tested geologically by determining what these frequencies are. Our main purpose here is to make such a test.

Previous work has provided strong suggestive evidence that orbital changes induced climatic change (*13–20*). However, two primary obstacles have led to continuing controversy. The first is the uncertainty in identifying which aspects of the radiation budget are critical to climatic change. Depending on the latitude and season considered most significant, grossly different climatic records can be predicted from the same astronomical data. Milankovitch (*4*) followed Koppen and Wegener's (*21*) view that the distribution of summer insolation (solar radiation received at the top of the atmosphere) at 65°N should be critical to the growth and decay of ice sheets. Hence the curve of summer insolation at this latitude has been taken by many as a prediction of the world climate curve. Kukla (*19*) has pointed out weaknesses in Koppen and Wegener's proposal and has suggested that the critical time may be September and October in both hemispheres. However, several other curves have been supported by plausible arguments. As a result, dates estimated for the last interglacial on the basis of these curves have ranged from 80,000 to 180,000 years ago (*22*).

The second and more critical problem in testing the orbital theory has been the uncertainty of geological chronology. Until recently the inaccuracy of dating methods limited the interval over which a meaningful test could be made to the last 150,000 years. Hence the most convincing arguments advanced in support of the orbital theory to date have been based on the ages of 80,000, 105,000, and 125,000 years obtained for coral terraces first on Barbados (*15*) and later on New Guinea (*23*) and Hawaii (*24*). These structures record episodes of high sea level (and therefore low ice volume) at times predicted by the Milankovitch theory. Unfortunately, dates for older terraces are too uncertain to yield a definitive test (*25*).

More climatic information is provided by the continuous records from deep-sea cores, especially the oxygen isotope record obtained by Emiliani (*26*). However, the quasi-periodic nature of both the isotopic and insolation curves, and the uncertain chronology of the older geologic records, have combined to render plausible different astronomical interpretations of the same geologic data (*13, 14, 17, 27*).

Strategy

All versions of the orbital hypothesis of climatic change predict that the obliquity of the earth's axis (with a period of about 41,000 years) and the precession of the equinoxes (period of about 21,000 years) are the underlying, controlling variables that influence climate through their impact on planetary insolation. Most of these hypotheses single out

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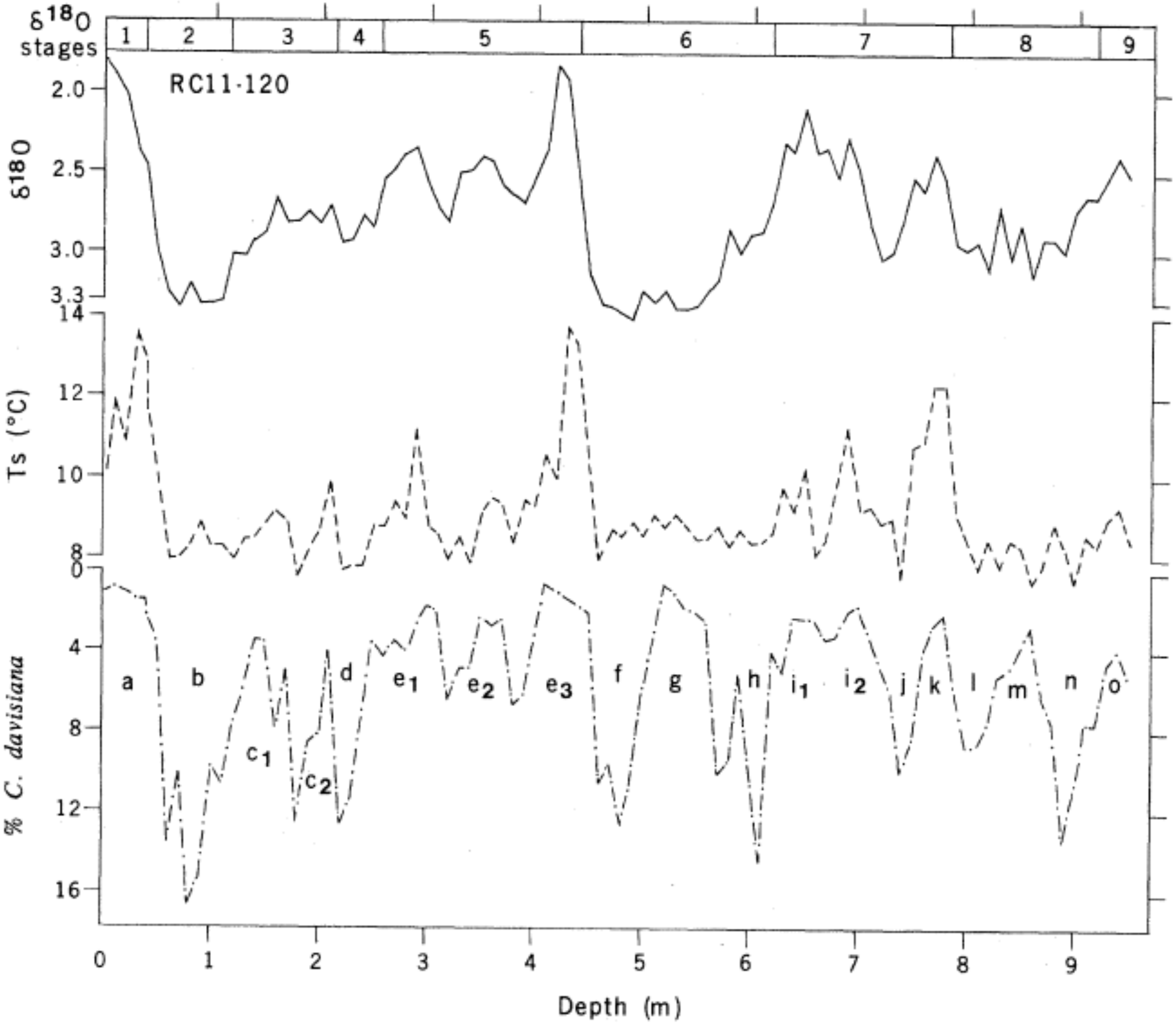


Fig. 2. Depth plots of three parameters measured in core RC11-120: $\delta^{18}O$ (solid line), *Ts* (dashed line), and percentage of *C. davisiana* (dash-dot line). Letter designations of peaks on the latter curve are informal designations of various parts of the record.

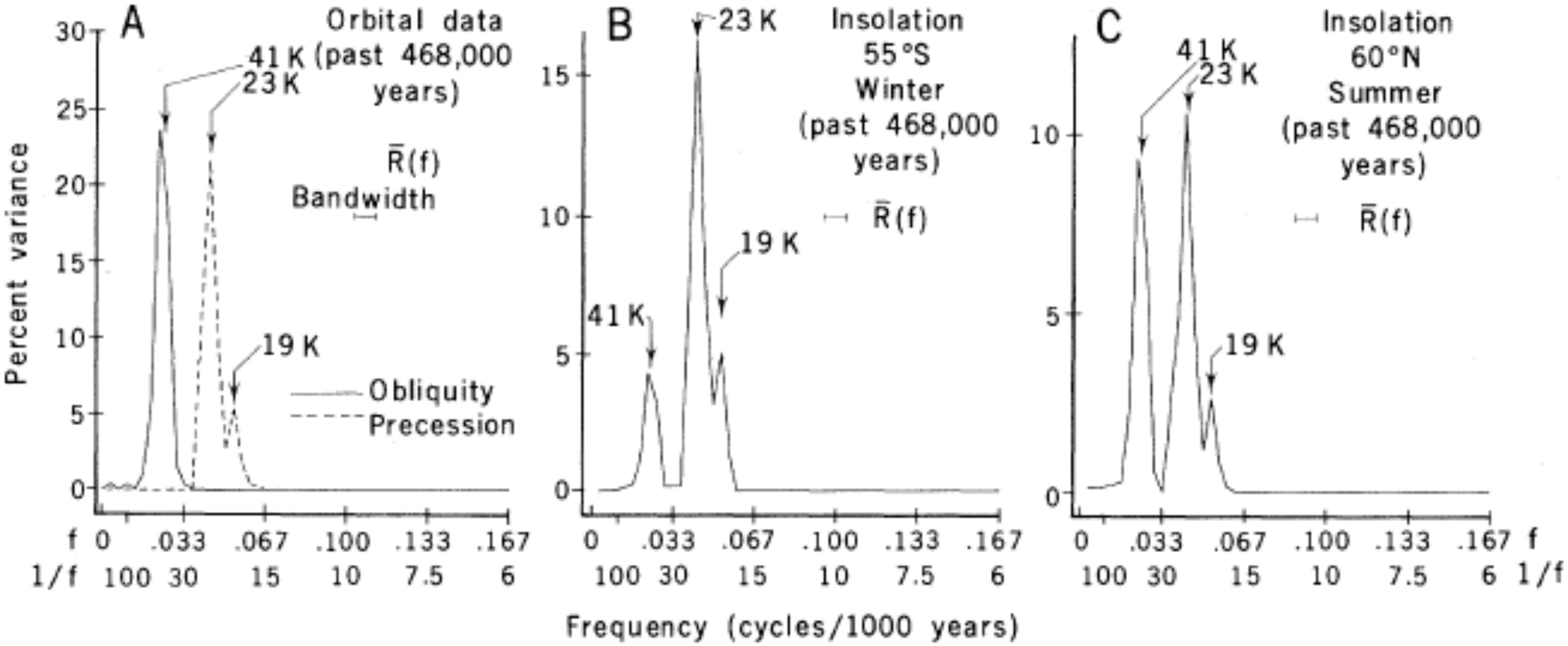


Fig. 4. High-resolution spectra of orbital and insolation variations over the past 468,000 years. Variance (as percentage of total variance per unit frequency band) is plotted as a function of frequency (cycles per thousand years). Arrows indicate weighted mean cycle lengths of spectral peaks (in thousands 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*)]

$a \approx 100kyr$, $b \approx 41\ kyr$, $c \approx 21\ kyr$

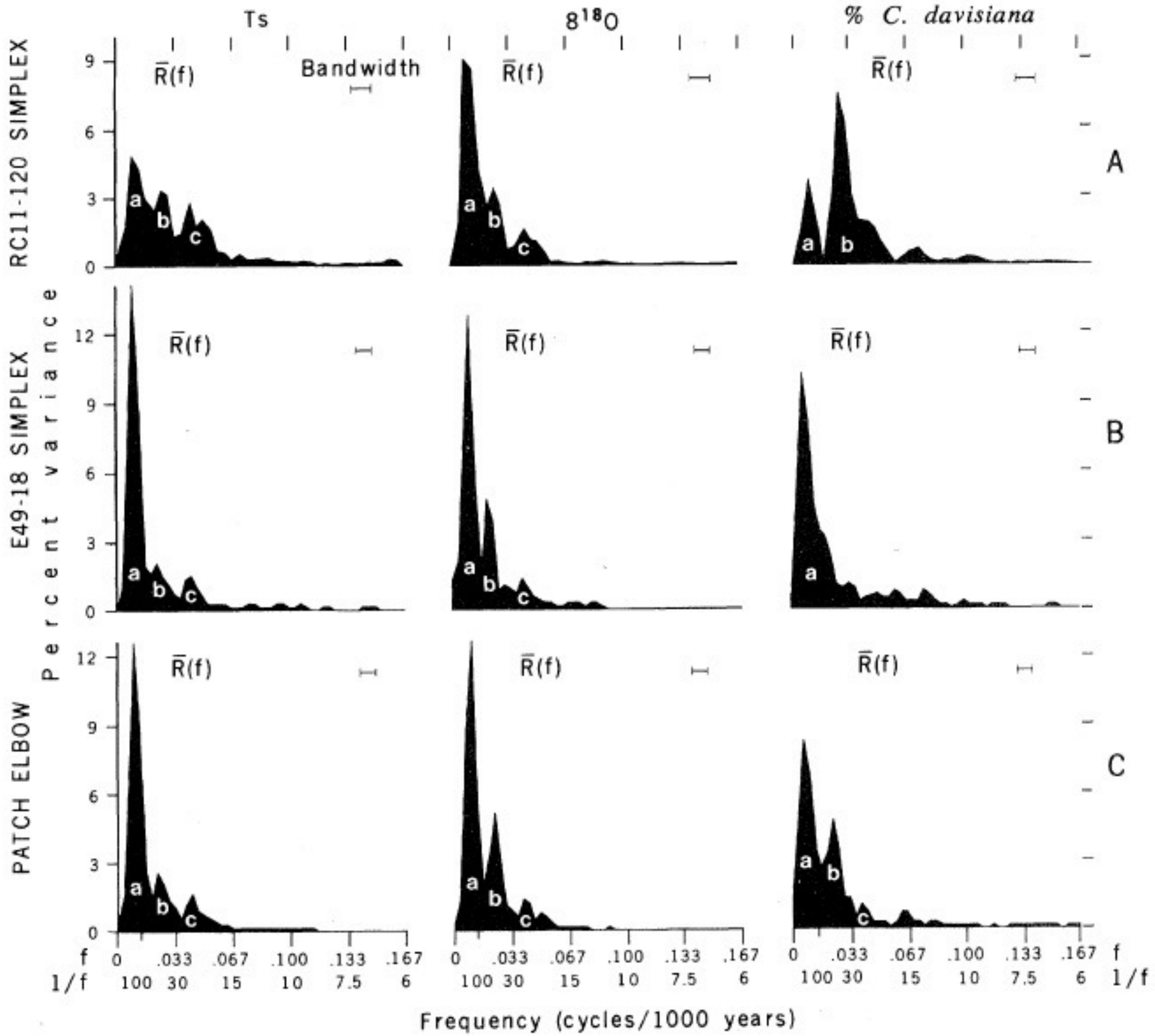
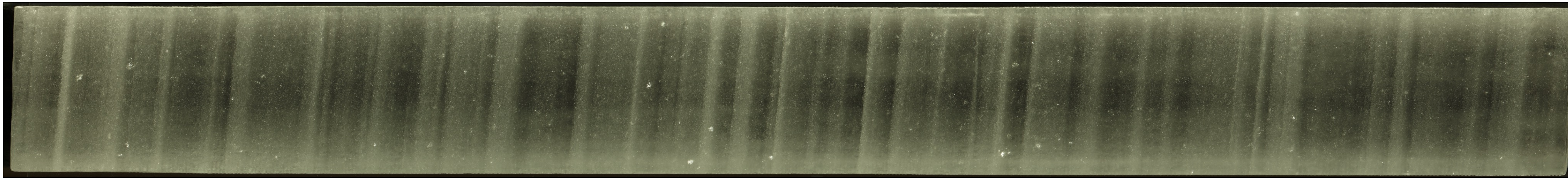


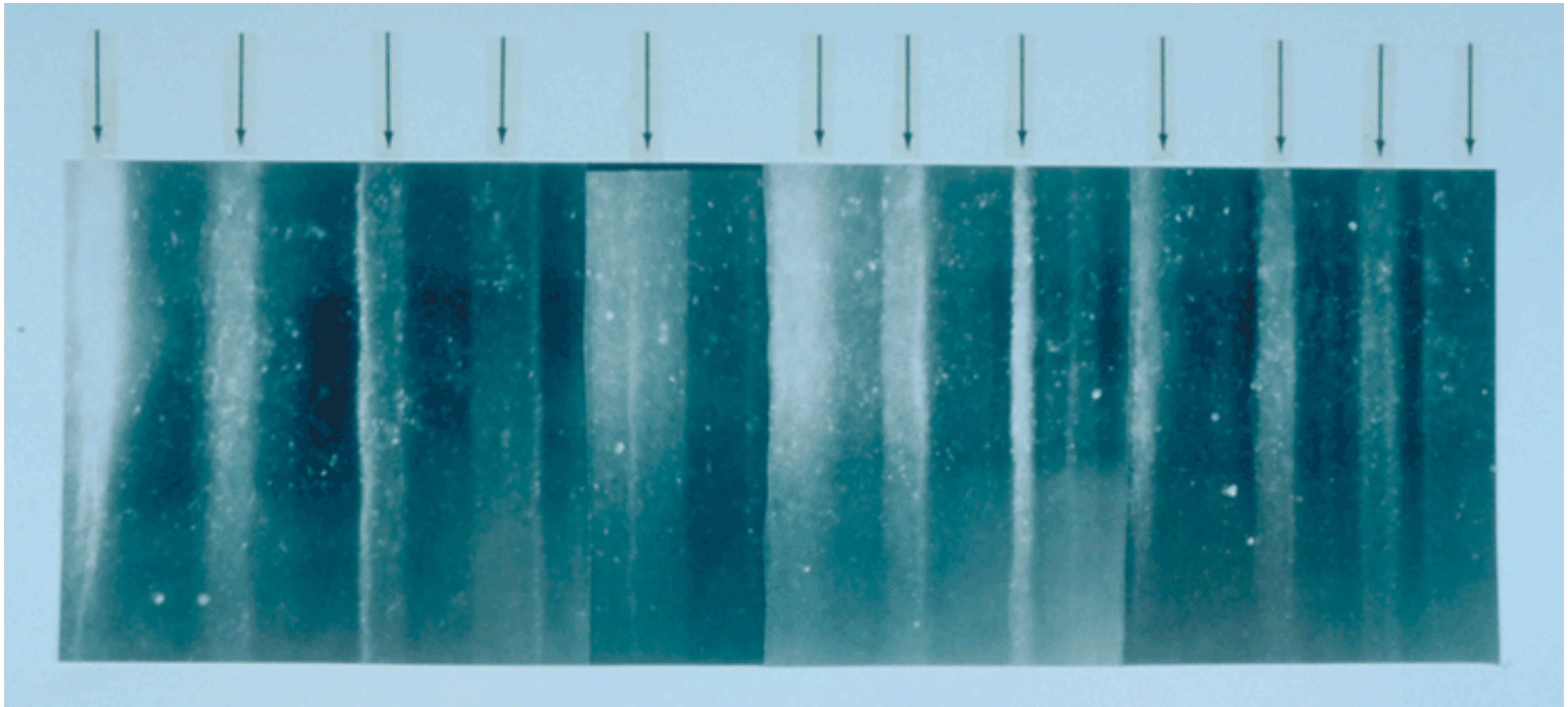
Fig. 5. High-resolution spectra of climatic variations in *Ts*, $\delta^{18}O$, and percentage of *C. davisiana*. Variance (as percentage of total variance per unit frequency band) is plotted as a function of frequency (cycles per thousand years). Prominent spectral peaks are labeled *a*, *b*, and *c*. 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.

AURORA AUSTRALIS
P&O

Κολώνες πάγου από την Ανταρκτική

Τμήμα της κολώνας πάγου 3308 μ που εξορύχθηκε το 1993 από το GISP2






Ronne Ice Shelf
90°W
Siple Station
South Pole
Dome A
90°E
3500
Vostok
Transantarctic Mountains
3000
Ross Ice Shelf
Law Dome
Dome C
Taylor Dome
70°S
2000
1000

Article

Nature **429**, 623-628 (10 June 2004) | doi:10.1038/nature02599; Received 27 February 2004; Accepted 22 April 2004

Eight glacial cycles from an Antarctic ice core

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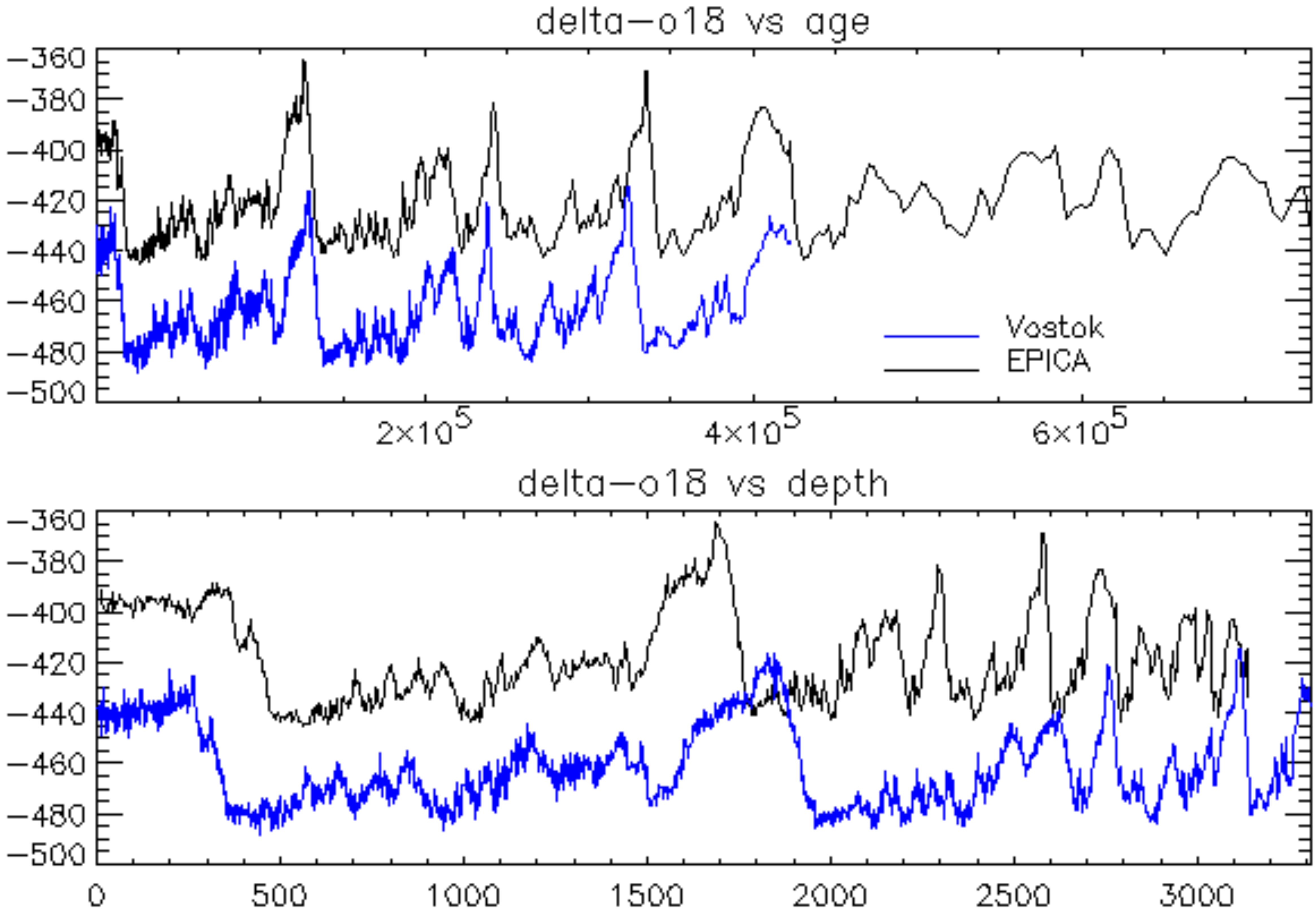
Top

The Antarctic Vostok ice core provided compelling evidence of the nature of climate, and of climate feedbacks, over the past 420,000 years. Marine records suggest that the amplitude of climate variability was smaller before that time, but such records are often poorly resolved. Moreover, it is not possible to infer the abundance of greenhouse gases in the atmosphere from marine records. Here we report the recovery of a deep ice core from Dome C, Antarctica, that provides a climate record for the past 740,000 years. For the four most recent glacial cycles, the data agree well with the record from Vostok. The earlier period, between 740,000 and 430,000 years ago, was characterized by less pronounced warmth in interglacial periods in Antarctica, but a higher proportion of each cycle was spent in the warm mode. The transition from glacial to interglacial conditions about 430,000 years ago (Termination V) resembles the transition into the present interglacial period in terms of the magnitude of change in temperatures and greenhouse gases, but there are significant differences in the patterns of change. The interglacial stage following Termination V was exceptionally long—28,000 years compared to, for example, the 12,000 years recorded so far in the present interglacial period. Given the similarities between this earlier warm period and today, our results may imply that without human intervention, a climate similar to the present one would extend well into the future.


delta−o18 vs age
−360
−380
−400
−420
−440
−460
−480
−500
2×10^5
4×10^5
6×10^5
Vostok
EPICA
delta−o18 vs depth
−360
−380
−400
−420
−440
−460
−480
−500
0
500
1000
1500
2000
2500
3000

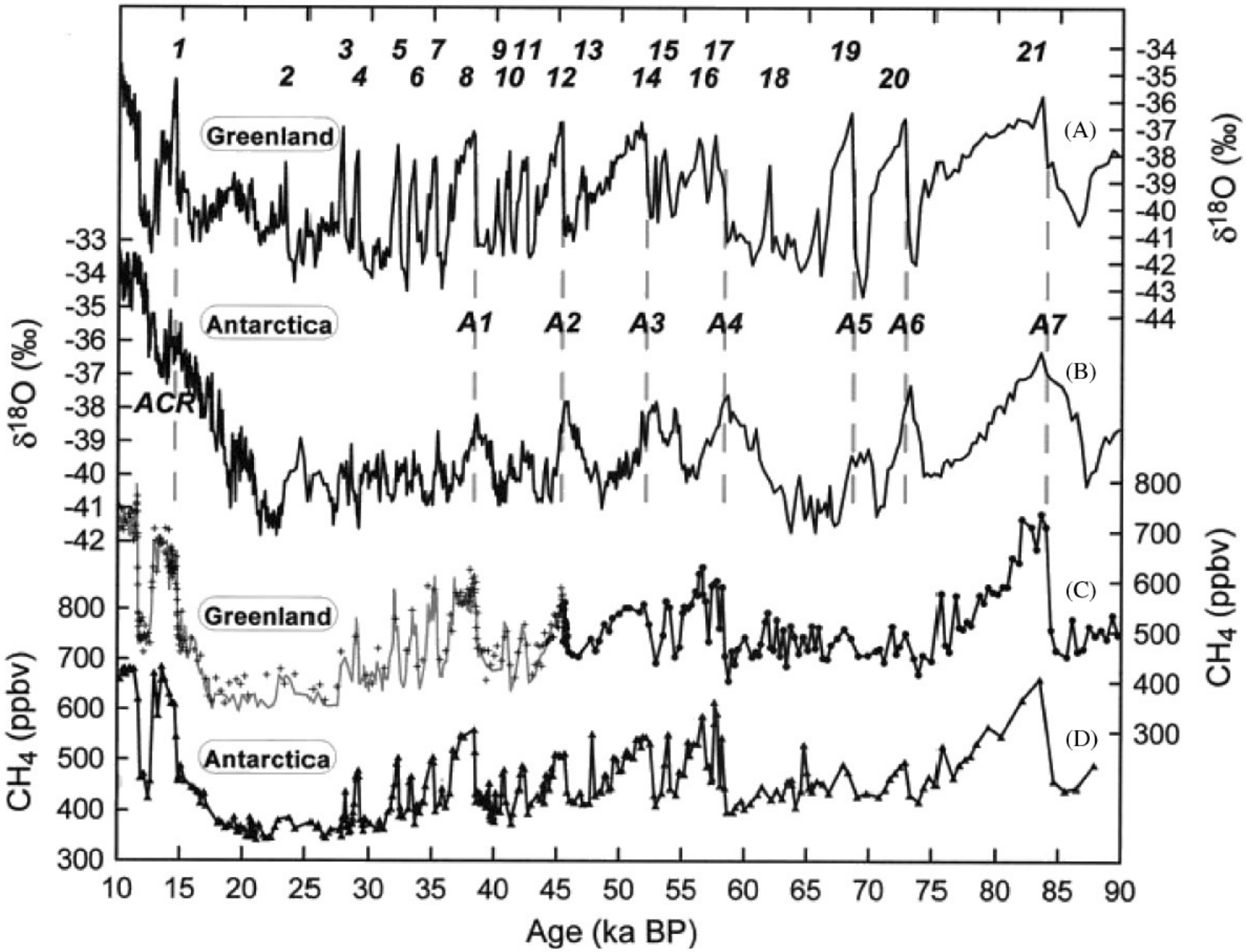
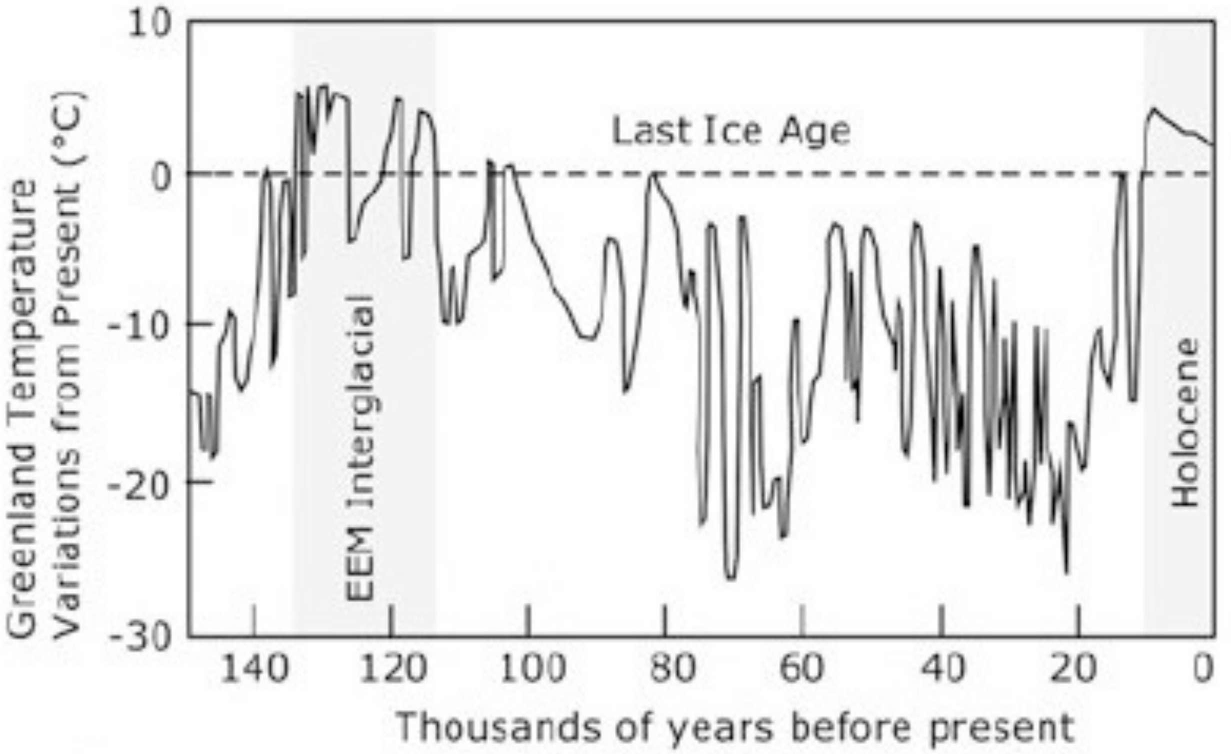
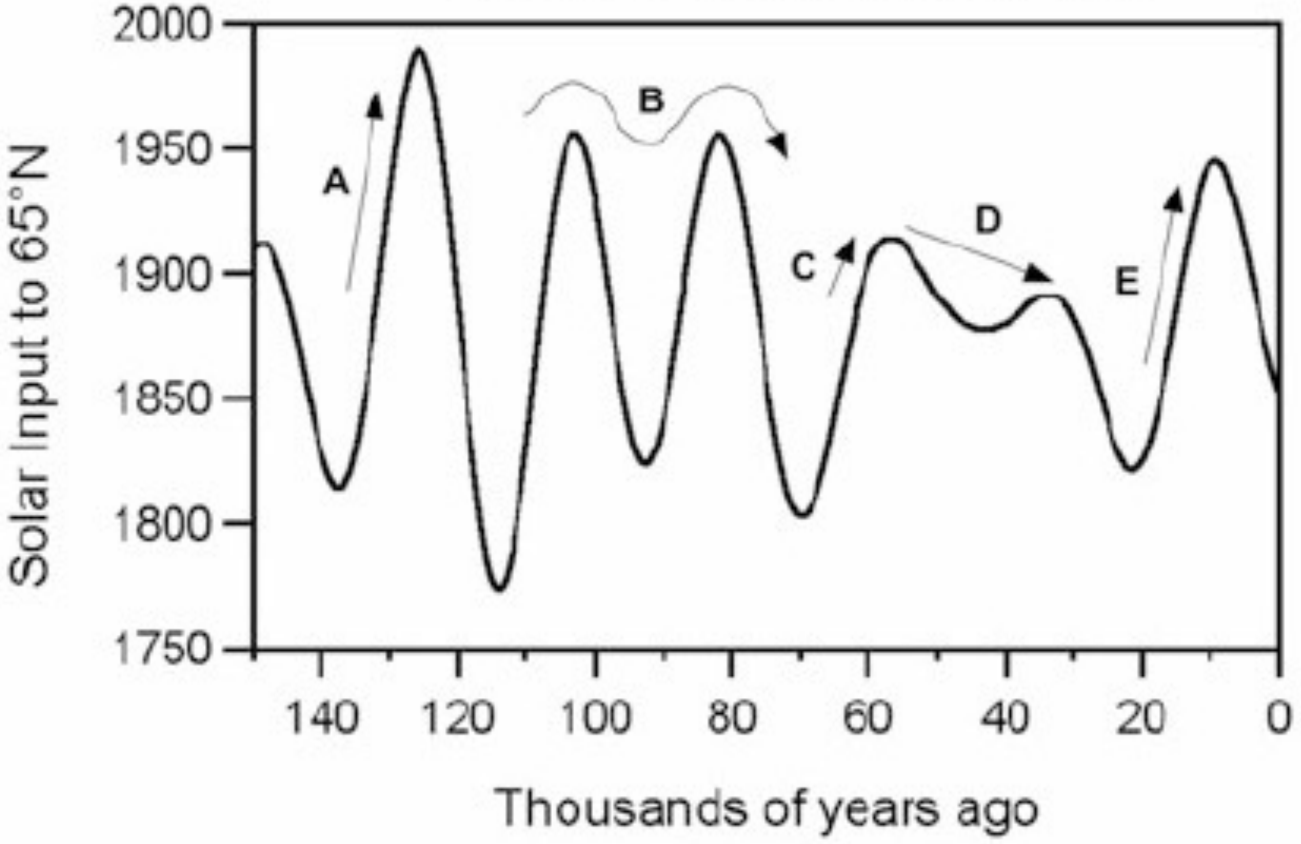
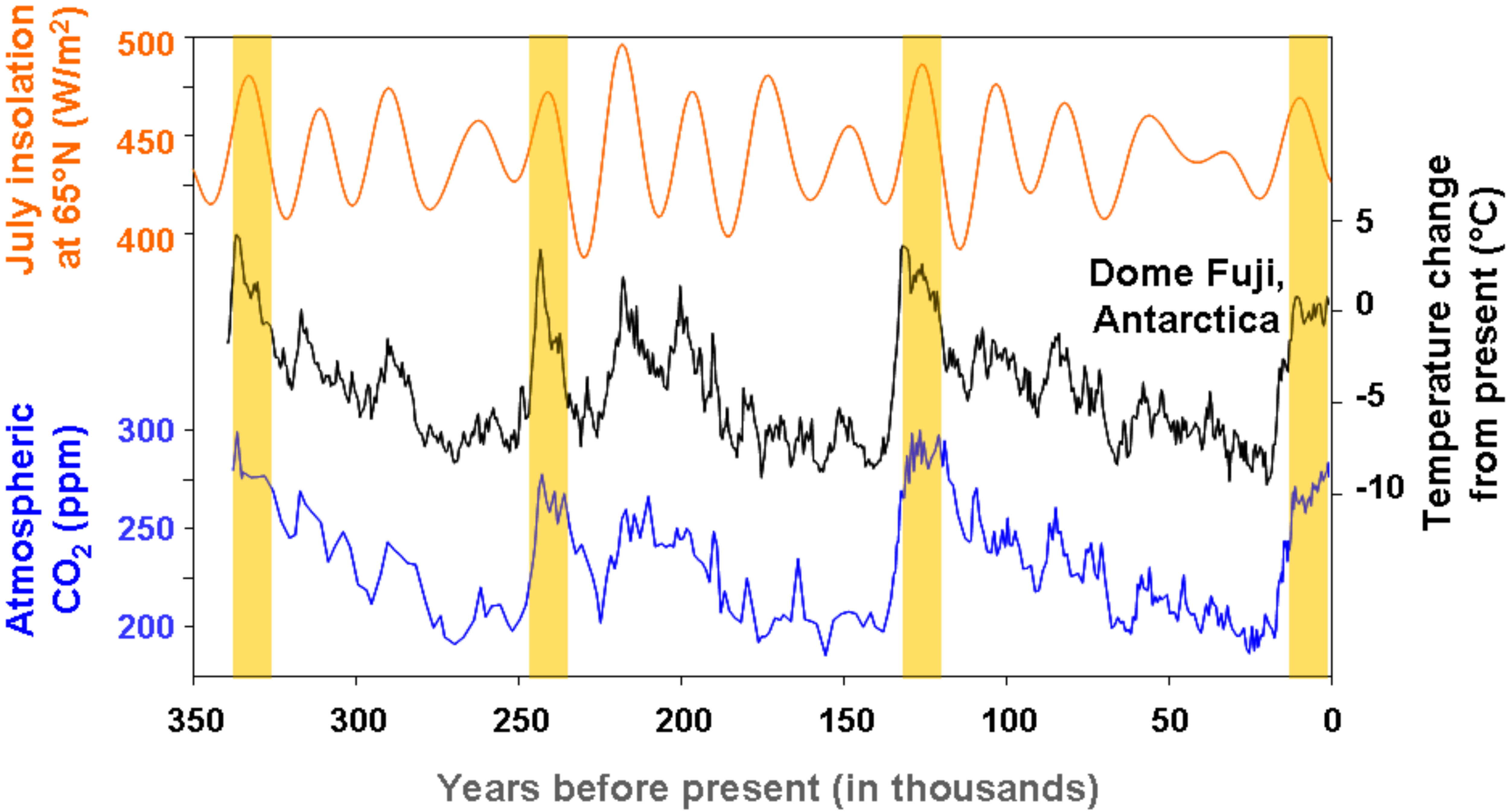


Fig. 1. Taken from Blunier and Brook (2001). Upper curve (A) is the δ^{18}O in the GISP2 Greenland ice-core; curve (B) is the δ^{18}O in the Antarctic Byrd core, with time scale adjusted to the GISP2 estimated methane. Curves (C), (D) are the methane data in the cores (for Greenland, data are from both GRIP and GISP2 cores). Dashed vertical lines indicate warm events in the Antarctic core. Numerals at top label Dansgaard–Oeschger events in Greenland. Note that time runs from right-to-left here.


Greenland Temperature Variations from Present (°C)
10
0
-10
-20
-30
Last Ice Age
EEM Interglacial
Holocene
140
120
100
80
60
40
20
0
Thousands of years before present


Solar Input to 65°N
2000
1950
1900
1850
1800
1750
A
B
C
D
E
140
120
100
80
60
40
20
0
Thousands of years ago


July insolation at 65°N (W/m²)
500
450
400
Atmospheric CO₂ (ppm)
300
250
200
Dome Fuji, Antarctica
Temperature change from present (°C)
5
0
-5
-10
350
300
250
200
150
100
50
0
Years before present (in thousands)

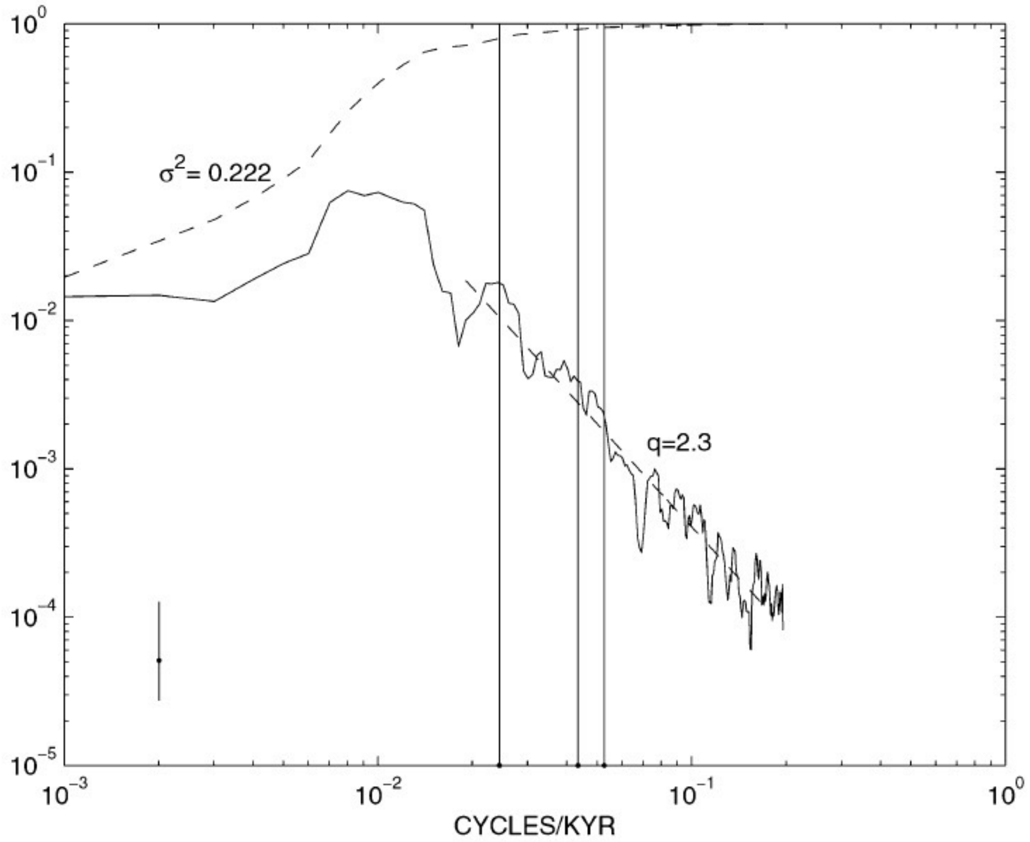


Fig. 3 Power spectrum, $\Phi(s)$, (*solid line*) normalized to sum to unity, for the record in Fig. 2, with an approximate 95% confidence interval. Dotted line is the accumulating sum, $I(s)$, of $\Phi(s)$ as a function of frequency. A least-squares fit to the power spectrum over the range of frequencies indicated by the short dashed line, of a simple power law at shorter periods results in $q = 2.3$ as shown. At low frequencies, a transition to near white noise occurs. σ^2 is the record variance in δ^{18}O units squared. Notice that both scales are logarithmic, permitting power laws to plot as *straight lines*, and the use of a constant confidence interval. Vertical lines denote periods of 41, 23 and 19 ky as a rough guide to the Milankovitch periods. The 100 ky maximum is treated here as distinct from the Milankovitch frequencies. All spectral estimates shown here are from D. Thomson's multitaper method (see Percival and Walden 1993)

of a general red-noise process at high frequencies, on which is superimposed some weak spectral structures whose significance needs to be assessed. ("Red noise" is a stochastic time series whose energy density generally increases with decreasing frequency; it need *not* be an autoregressive process. Blue noise has an energy density increasing with frequency, and white noise has an energy density independent of frequency. The phase relationships in the Fourier transforms are random, distinguishing the behavior from

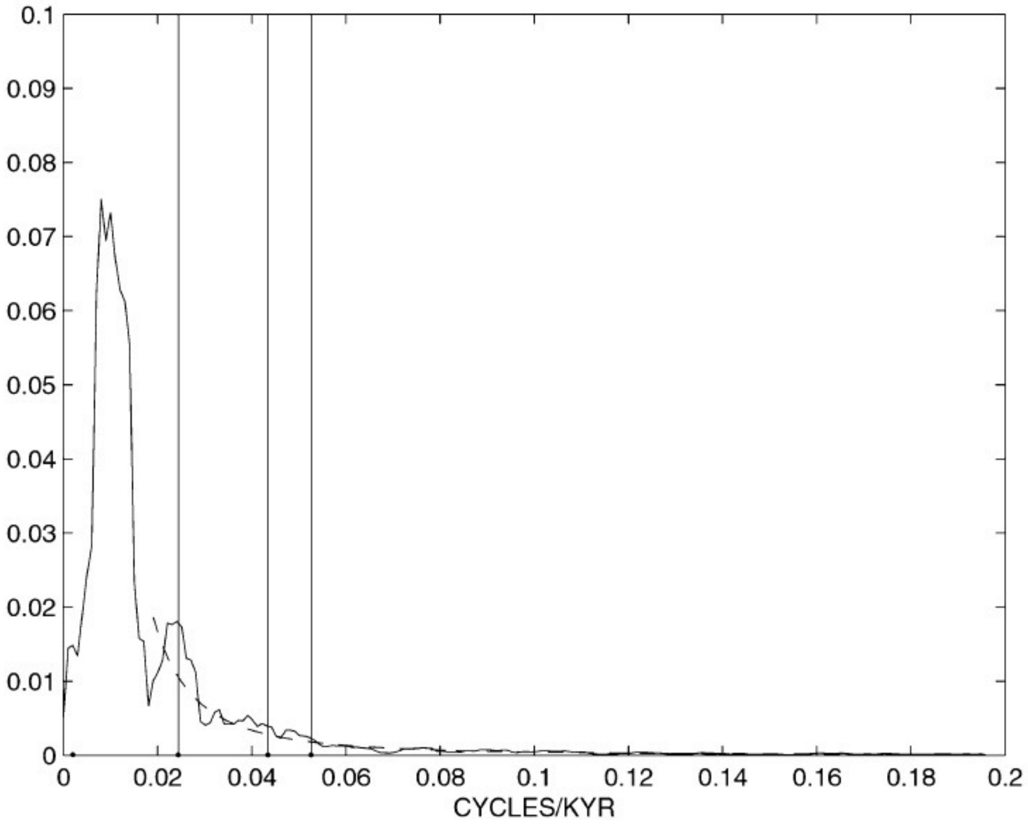
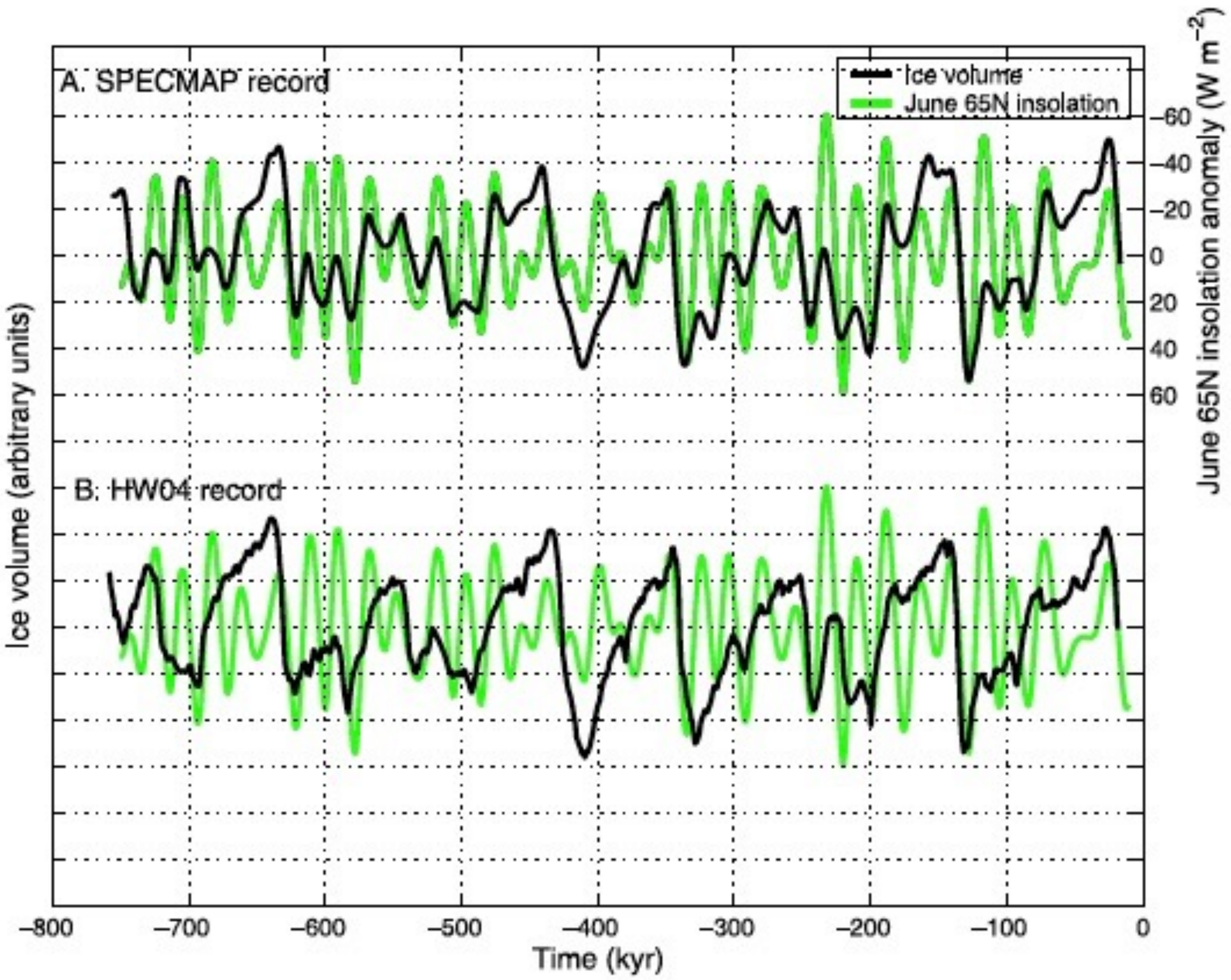


Fig. 4 Same result as in Fig. 3 except plotted on linear scales (and with the high frequencies omitted to render visible the low frequency structure). This presentation tends to emphasize the spectral peaks relative to the background continuum values, which are far more numerous, but of lower relative intensity. The 100 ky maximum is now very conspicuous. The power law plots as a *curve* on these scales

An upper bound on the importance of the Milankovitch periodicities can be obtained by assigning to them *all* of the energy lying at the Milankovitch periods, including energy more properly belonging to the background continuum. We find that,

$$\frac{\int_{M\text{-}bands}\Phi(s)\mathrm{d}s}{\int_0^{s_{\max}}\Phi(s)\mathrm{d}s} < 0.15 \ . \tag{3}$$

Here "*M-bands*" refers to the frequency range in $\Phi(s)$ containing the bulk of the Milankovitch precessional (here taken to be everything from 26 to 18 ky periods) and obliquity (55 to 33 ky periods) energy. The bands are based upon a generous, visual, estimate of the possible region of excess energy and not upon the spectrum of insolation, which has small, but finite energy at all frequencies. Separately, the obliquity band accounts for less than 11% and the precessional band for less than 0.5% of the total variance. Recall that the record variance is, by Parseval's Theorem,



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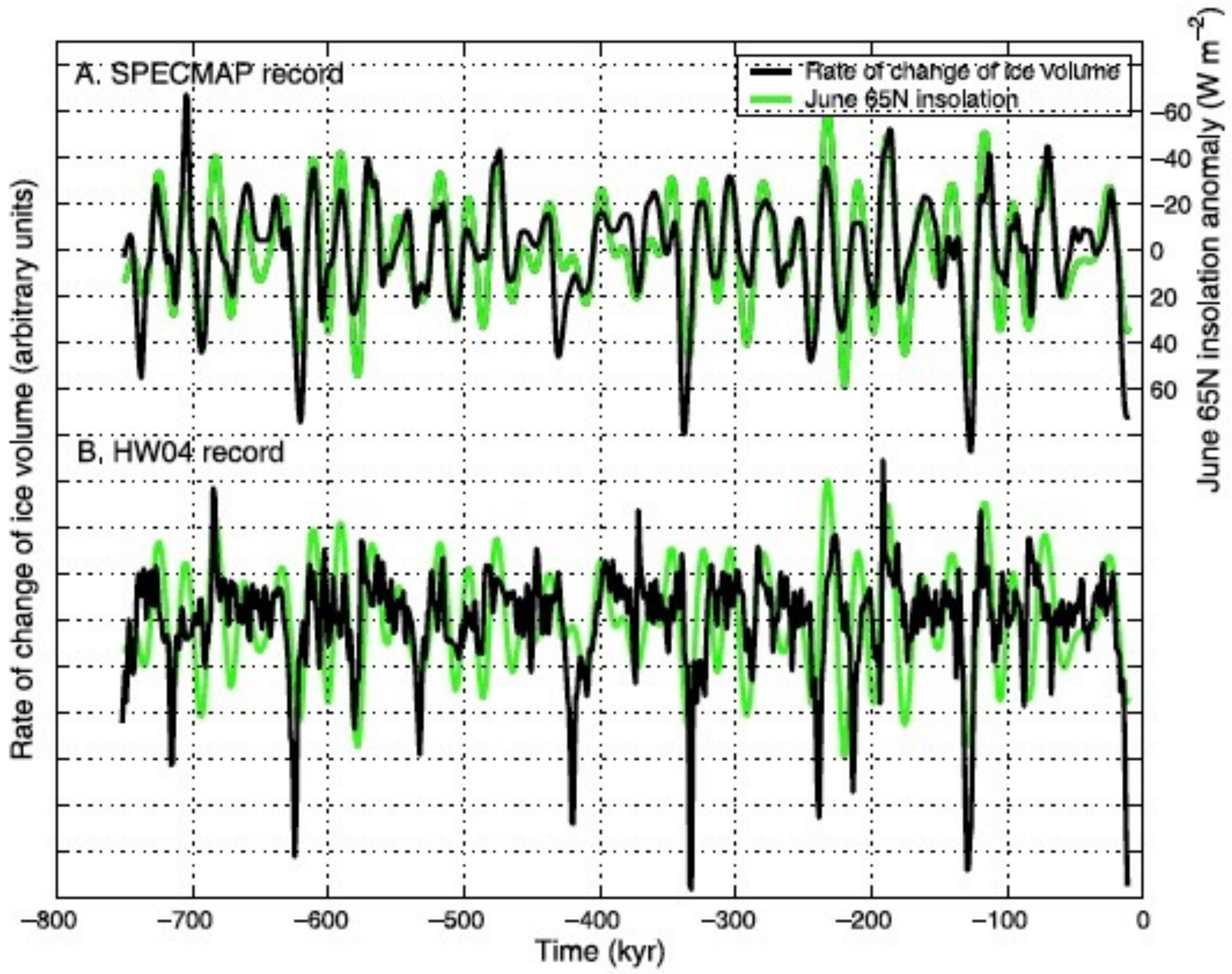

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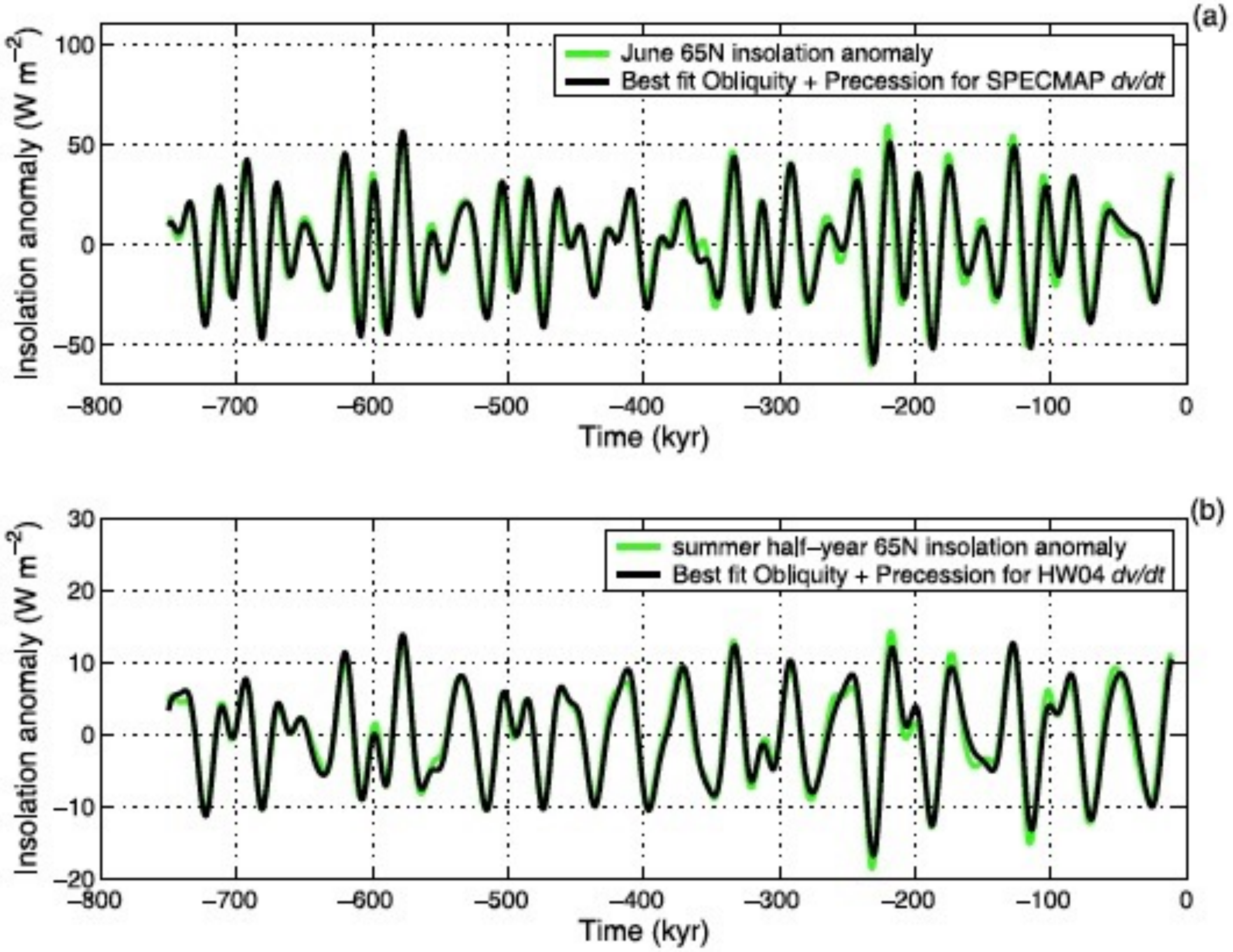

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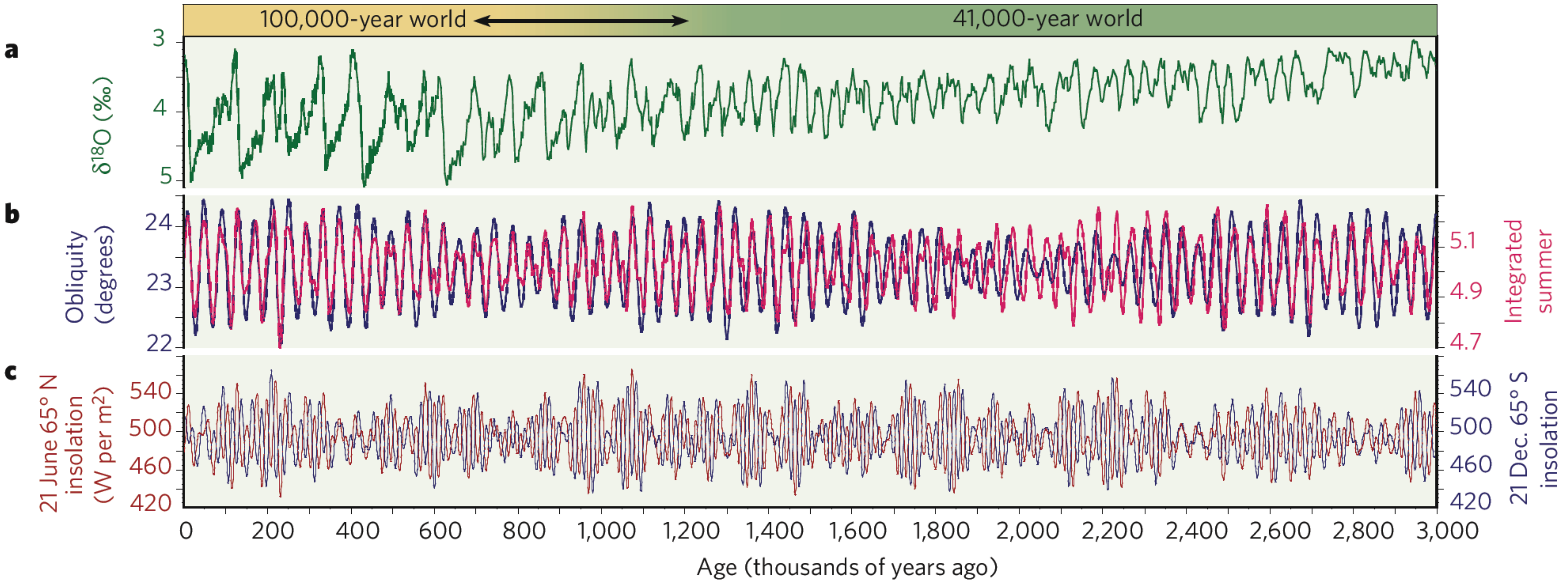

Figure 1 | Ice-age climate and solar variability. A 3-million-year record of δ^{18}O (ref. 8) (**a**); orbital obliquity (blue) compared with integrated summer insolation (red)[3] (**b**); and summer insolation for the Northern Hemisphere (on 21 June at 65° N; red) and the Southern Hemisphere (on 21 December at 65° S; blue)[6] (**c**). δ^{18}O is considered a proxy of global ice-volume change, which is assumed to occur mostly in the Northern Hemisphere over this interval. From 3 to 1 million years ago, δ^{18}O varies primarily a
year period characteristic of obliquity and integrated insolatio
1 million years ago to the present, longer cycles of climate char
roughly 100,000-year period, are more obvious. The double-h
indicates a transition more gradual than abrupt over the time i
GJ, gigajoule; W, watts.

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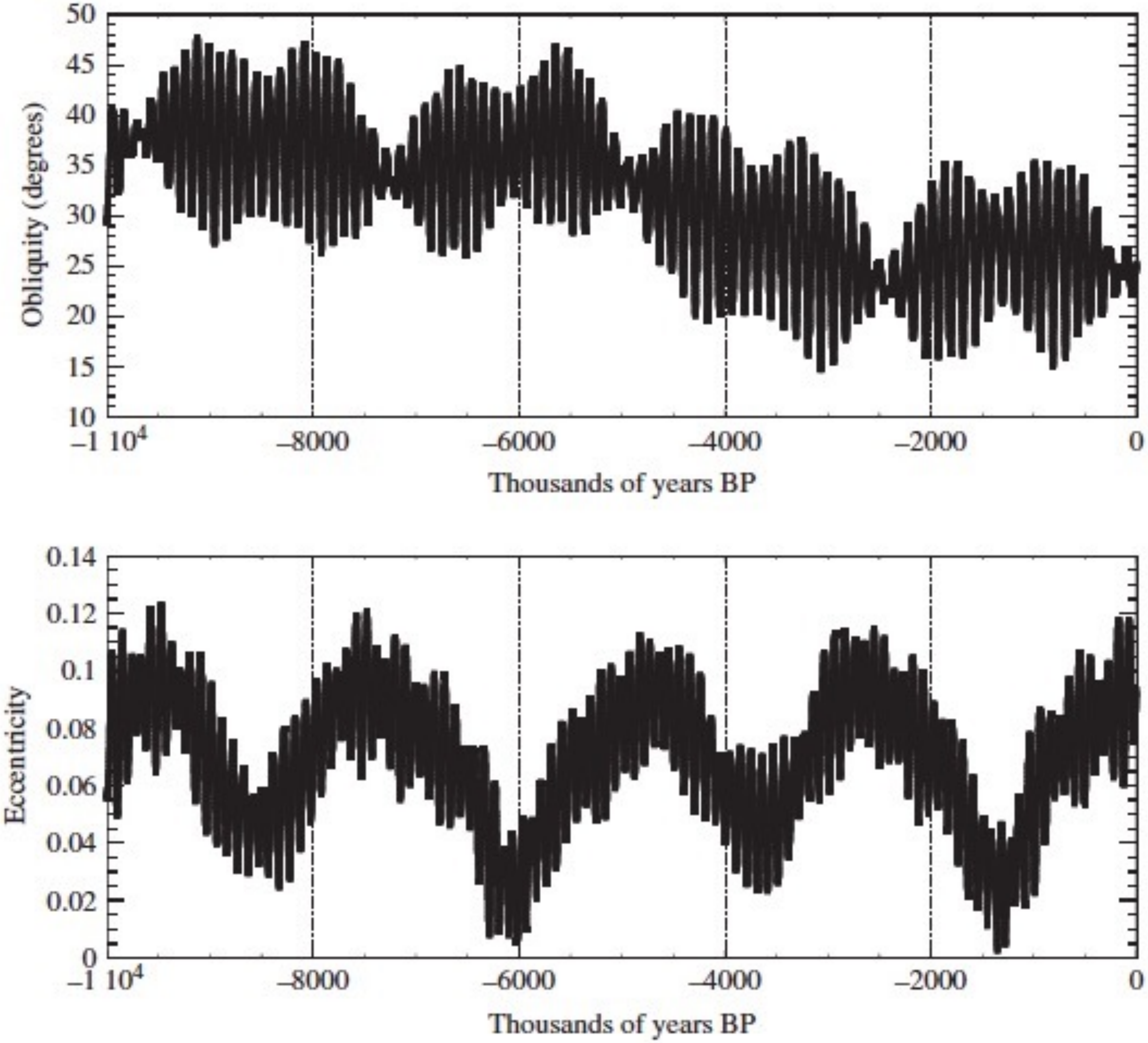

Figure 7.16 Evolution of Mars' obliquity and eccentricity. Data taken from Laskar *et al.* (2004).

Συμπεράσματα

- Η υπόθεση του Milanković δεν εξηγεί τις ταχύρυθμες και κατακλυσμιαίες εξόδους από τα παγετωνικά κλίματα.

- Η υπόθεση του Milanković δεν εξηγεί τη μετάβαση από τους παγετωνικούς κύκλους των 40000 χρονων στους παγετωνικούς κύκλους των 100000 χρόνων που συνέβη στο μέσο της Πλειστοκαινούς.

- Η υπόθεση του Milanković δεν εξηγεί το συνεχές φάσμα κλιματικών διακυμάνσεων στις περιόδους των 1000 χρόνων.

- Τα ευρήματα όμως δικαιώνουν την αρχική υπόθεση όπως διατυπώθηκε από τον Milanković αλλά και απο τους Koppen και Wegener ότι α) η ένταση της συνολικής θερινής ηλιοφάνειας είναι ο κύριος ρυθμιστής του όγκου των παγετώνων στους παγετωνικούς κύκλους και β) ο ρυθμός μεταβολής του όγκου των παγετώνων βρίσκεται σε φάση 180 μοιρών με τη ηλιοφάνεια στα υψηλά γεωγραφικά πλάτη η οποία μεταβάλλεται λόγω των αλλαγών της κίνησης της Γης.