

The timing of major climate terminations

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Abstract. A simple, untuned “constant sedimentation rate” timescale developed using three radiometric age constraints and eleven $\delta^{18}\text{O}$ records longer than 0.8 Myr provides strong support for the validity of the SPECMAP timescale of the late Quaternary [Imbrie *et al.*, 1984]. In particular, the present study independently confirms the link between major deglaciations (terminations) and increases in northern hemisphere summer radiation at high latitudes and shows that this correlation is not an artifact of orbital tuning. In addition, the excess ice characteristic of late Quaternary “100-kyr” climate cycles typically accumulates when July insolation at 65°N has been unusually low for more than a full precessional cycle, or >21 kyr, and once established does not last beyond the next increase in summer insolation. Thus, the timing of the growth and decay of large 100-kyr ice sheets, as depicted in the deep sea $\delta^{18}\text{O}$ record, is strongly (and semipredictably) influenced by eccentricity through its modulation of the orbital precession component of northern hemisphere summer insolation.

Introduction

For the past 20 years, the Milankovitch hypothesis, which holds that the Earth’s climate is controlled by variations in incoming solar radiation tied to subtle yet predictable changes in the Earth’s orbit around the Sun [Hays *et al.*, 1976], has been widely accepted by the scientific community. However, the degree to which and the mechanisms by which insolation variations control regional and global climate are poorly understood. In particular, the “100-kyr” climate cycle, the dominant feature of nearly all climate records of the last 900,000 years (e.g., Figure 1), has always posed a problem to the Milankovitch hypothesis [e.g., Hays *et al.*, 1976; Imbrie and Imbrie, 1980; Imbrie *et al.*, 1993]. The problem is threefold: First, while the eccentricity of the Earth’s orbit varies with a period near 100 kyr, the modulation of insolation at this period is insignificant (less than 1%); second, the 100-kyr cycle appeared for no obvious reason ~0.8 Myr ago, nearly 2 million years after the northern hemisphere ice ages started; and third, the climate cycles (in particular global ice volume) are highly nonlinear. As is obvious from the many $\delta^{18}\text{O}$ records plotted in Figure 1, the cycles are “saw tooth” shaped, with long periods of ice growth/cooling followed by rapid deglaciations, defined as “Terminations I-VII” (Figure 1) [Broecker, 1984]. These issues have been the focus of much theoretical research, most by investigators who accept the fundamental premise that the 100-kyr cycle is related to variations in the Earth’s eccentricity [Imbrie and Imbrie, 1980; De Blonde and Peltier, 1991; Lui, 1992; Saltzman and Verbitsky, 1994; Ledley, 1995; Imbrie *et al.*, 1993, and references therein].

In spite of these gaps in our understanding, a number of investigators in the late 1970s and early 1980s proceeded to develop timescales for the last 800 kyr based on the assumption that the climate cycles observed in deep-sea sediment records were driven by orbital parameters. This work culminated with

the SPECMAP timescale of Imbrie *et al.* [1984, p. 274], who succinctly describe the research strategy of their own and prior work:

All of the studies...make an initial assumption that the sediment accumulation function (depth-in-core vs. age) is linear between radiometric control points. All then relax this assumption to produce a satisfactory match between the adjusted isotopic curve and one or more astronomical curves that have been designated as targets of the tuning procedure.

The SPECMAP timescale, developed by “tuning” to an astronomical target curve, provided a chronology to which almost all paleoclimate records could be tied via their correlative and characteristic $\delta^{18}\text{O}$ record. This timescale has been the cornerstone of Quaternary paleoclimate studies for over 10 years. In addition, in the SPECMAP timescale, terminations are tightly linked to increases in summer 65°N radiation (i.e., deglaciations occur at times when northern high latitudes are warming [Broecker, 1984; Imbrie *et al.*, 1993]).

A number of investigators have challenged the validity of the SPECMAP timescale and, by extension, some of the underlying assumptions of the Milankovitch hypothesis. In the radiometrically dated groundwater $\delta^{18}\text{O}$ record from Devils Hole, Nevada, Winograd *et al.* [1992] present evidence suggesting that terminations do not consistently correlate with increases in 65°N summer radiation. Their dates for Terminations II, III, and V disagree significantly with SPECMAP ages and imply that major northern hemisphere deglaciations usually occur at or just prior to minima (rather than maxima) in northern hemisphere summer radiation. More recently, Muller and MacDonald [1995] question whether eccentricity plays any significant role in global ice volume variations and climate and propose that variations in the inclination of the Earth’s orbital plane relative to the invariant plane (the plane of symmetry of the solar system) drive the 100-kyr climate cycle. These investigators believe that spectral analyses of Quaternary $\delta^{18}\text{O}$ records which show strong Milankovitch frequencies have been biased by using a timescale which itself was tuned to these frequencies.

In this study, the SPECMAP timescale and the timing of major deglaciations is reevaluated using 15 years of accumulated $\delta^{18}\text{O}$ data provided by ocean drilling. In particular, can support

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for the SPECMAP timescale be found in the geologic record independent of any assumptions of orbital control and tuning? Are terminations tied to eccentricity-modulated increases in northern hemisphere radiation? My starting premise is that orbital control of ice-volume fluctuations is best evaluated by examining the relationship between the two using radiometrically constrained age models.

Data and Methods

This study uses 11 deep sea sediment $\delta^{18}\text{O}$ records (Figure 1 and Table 1) which extend beyond the Brunhes-Matuyama boundary. All records exhibit the typical sequence of oxygen isotope stages with no obvious hiatuses, drilling disturbance, or large swings in sedimentation rates (data described in this study are available electronically from the NOAA Geophysical Data Center, Boulder, Colorado, at paleo@mail.ngdc.noaa.gov). Two records are from piston cores (V28-239 and MD900963), while the others are spliced composite records recovered by the Deep Sea Drilling Project (DSDP) or the Ocean Drilling Program (ODP). None of these records were used in the development of the SPECMAP timescale [Imbrie *et al.*, 1984]. Not included in this study are cores with unspliced core breaks, low sampling resolution, drilling disturbance, hiatuses, and/or poorly resolved

or missing isotopic events. Included records come from three oceans, high and low latitudes, and eastern and western equatorial regions, and include data from both planktonic and benthic foraminifera (Figure 2 and Table 1). Mean sedimentation rates vary from less than 1 cm/kyr to more than 4 cm/kyr. Because significant variations in sedimentation rates can occur on glacial-interglacial (G-I) timescales (caused by variations in productivity or dilution by aeolian or ice-rafted material, etc.), this study focuses on dating the midpoint of terminations, events rapid enough to be considered as "instantaneous" events within the context of this study. The midpoint depths of terminations I-VII are listed for each core in Table 2a. Note also that Terminations III and VI are not terminations in the true sense of the word, which is defined as a rapid and abrupt shift from extreme glacial to extreme interglacial conditions [Broecker, 1984].

As a first step toward deriving a common chronology for these data, each core is put on a simple radiometric timescale pinned at the midpoint of stage 19 (arrow in Figure 1) and the midpoints of the last two deglaciations (Terminations I and II) with constant sedimentation rates assumed in between. The age of Termination I is assigned to be 13.5 kyr based on the estimated ^{14}C age of the midpoint of the Imbrie *et al.* [1992] $\delta^{18}\text{O}$ stack converted to calendar years (and plotted in Figure 16 of that paper). For Termination II, Th-230 and Pa-231 data

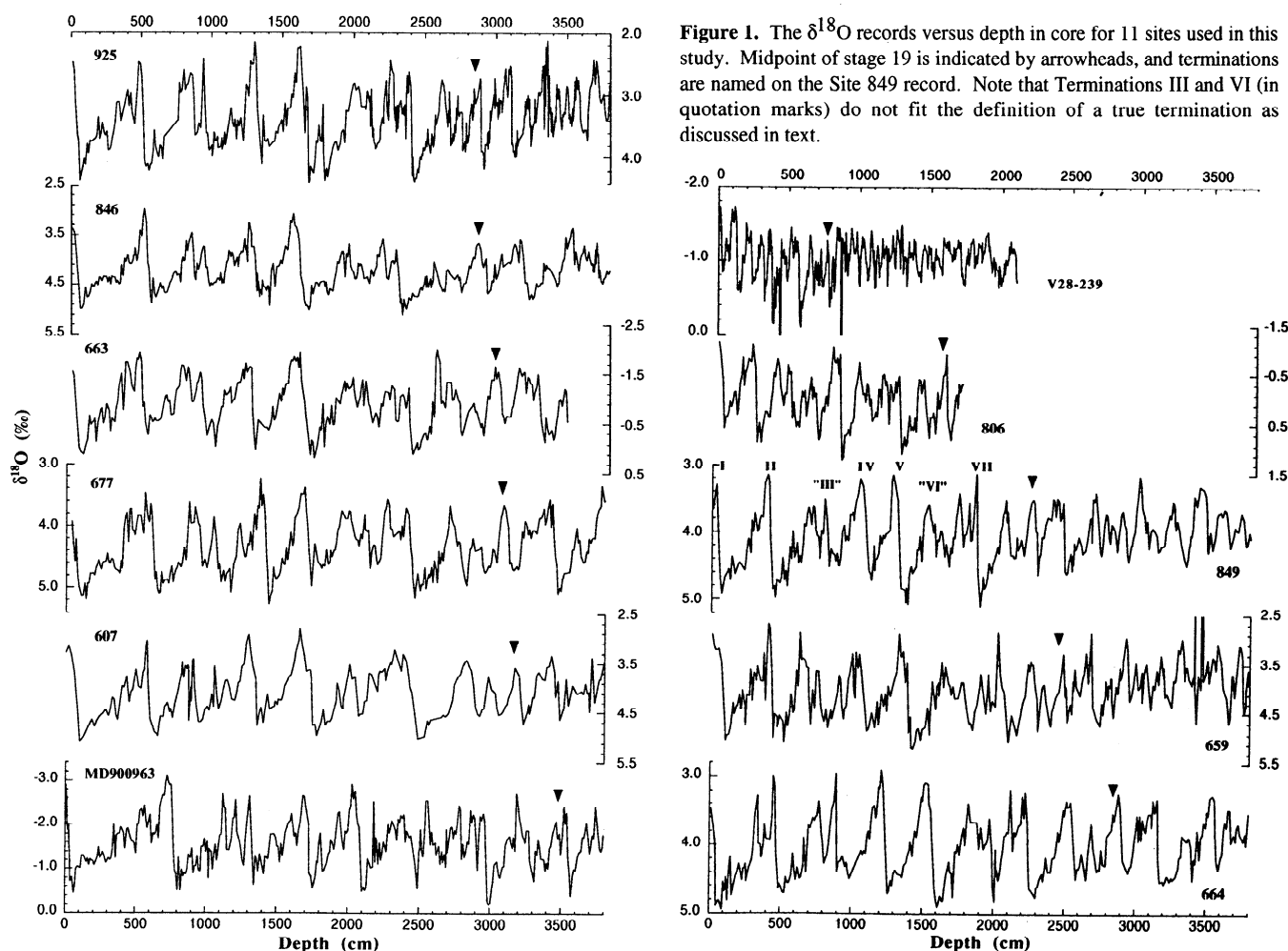


Figure 1. The $\delta^{18}\text{O}$ records versus depth in core for 11 sites used in this study. Midpoint of stage 19 is indicated by arrowheads, and terminations are named on the Site 849 record. Note that Terminations III and VI (in quotation marks) do not fit the definition of a true termination as discussed in text.

Table 1. Site Information

Site	Latitude	Longitude	Depth, m below sea level	Sedimentation Rate, * cm/kyr	Type†	Regional Environment	Reference‡
DSDP 607	41°00'N	32°58'W	3427	4.1	B	temperate/subpolar North Atlantic	1
ODP 659	18°05'N	21°02'W	3070	3.1	B	subtropical eastern Atlantic	2
ODP 663	01°12'S	11°53'W	3706	3.9	P	eastern equatorial Atlantic	3
ODP 664	00°06'N	23°14'W	3806	3.7	B	central equatorial Atlantic	4
ODP 677	01°12'N	83°44'W	3461	4.0	B	eastern equatorial Pacific	5
ODP 806	00°19'N	159°22'E	2520	2.0	P	western equatorial Pacific	6
ODP 846	03°06'S	90°49'W	3307	3.7	B	eastern equatorial Pacific	7
ODP 849	00°11'N	110°31'W	3851	2.9	B	eastern equatorial Pacific	8
ODP 925	04°12'N	43°29'W	3041	3.7	B	western equatorial Atlantic	9
V28-239	03°15'N	159°11'E	3490	0.9	P	western equatorial Pacific	10
MD900963	05°03'N	73°53'E	2446	4.6	P	central equatorial Indian	11

*Sedimentation rate estimated between Termination I and midpoint of stage 19.

†P, planktonic record; B, benthic record.

‡References are 1, *Ruddiman et al.* [1989]; 2, *Tiedemann et al.* [1994]; 3, P. de Menocal et al. (unpublished data, 1996); 4, this study; 5, *Shackleton et al.* [1990]; 6, *Berger et al.* [1994]; 7, *Mix et al.* [1995a]; 8, *Mix et al.* [1995b]; 9, *Bickert et al.* [1997]; 10, *Shackleton and Opdyke* [1976]; 11, *Bassinot et al.* [1994].

reported by *Cheng et al.* [1996] show that the last interglacial maximum, or stage 5e, fell between 120 and 125 kyr B.P., narrowing the window for stage 5e previously published by that lab (e.g., 120 to 130 kyr [*Gallup et al.*, 1994]). In addition, *Henderson and Slowey* [1996] conclude that stage 5e occurred between 118 and 130 kyr and that Termination II occurred no earlier than 131 kyr B.P. Using these radiometric constraints (older than 125 kyr but younger than 131 kyr), 128 kyr is the assigned age of Termination II. Finally, because the lock-in depth of magnetic reversals can vary in deepsea sediments and because paleomagnetic records are not available for some of these records, I follow the study of *de Menocal et al.* [1990] which demonstrated that the midpoint of stage 19 was 6 kyr younger than the Brunhes-Matuyama geomagnetic polarity reversal radiometrically dated at 778 ± 3.5 kyr [*Tauxe et al.*, 1996].

Using the above tie points, the ages of the remaining terminations were determined in each record (Table 2a). For each termination, a wide range of estimated ages is obtained, reflecting inherent natural variability of sediment accumulation through time as well as disturbance (stretching/compression) during the core recovery process [e.g., *Ruddiman et al.*, 1986]. No obvious correlation between termination age and sedimentation rate is observed (Tables 1 and 2a and Figure 3). Assuming that random variations in sedimentation rates average out when using many records from many regions, the mean age of each termination, termed the "global stratigraphic synthesis" (GSS97) age, is calculated and compared to the SPECMAP and

Devils Hole (DH) timescales (Table 2b). Note that the exact values of the GSS97 and DH timescales would be sensitive to errors in the radiometric data, while the SPECMAP timescale would change slightly if more recent astronomical solutions were used as the tuning target (such as *Laskar et al.* [1993]).

Timescale Evaluation

The GSS97 ages calculated for each termination are in close agreement with SPECMAP ages, with all but Termination III agreeing to within 1.0%. By contrast, relatively poorer agreement is observed with the DH timescale. To test whether this result is due to the age assignment of 128 kyr to Termination II, termination ages were recalculated assuming that Termination II was at 131 kyr. This value, at the error limit of the *Henderson and Slowey* [1996] study, falls closer to the proposed Devils Hole age for Termination II (140 kyr; note that *Winograd et al.* [1996] suggest that Termination II may occur as young as 134 kyr). The recalculated ages (Table 2b) show better agreement with DH ages at Termination III but show much poorer agreement with DH ages relative to SPECMAP ages at Terminations V (SPECMAP and DH ages for Termination IV are the same). The same result (Table 2b) is obtained if one eliminates the constraint at Termination II altogether (the reason not to do this is discussed below).

It is important to ask whether any systematic errors could invalidate the constant sedimentation rate assumption in each core and bias the GSS97 ages. Such errors could include (1) long-term secular variations in ocean input-output fluxes (e.g., a lower global river flux in the Mid-Brunhes) and related chemistry changes (Mid-Brunhes dissolution cycle); (2) systematic sediment disturbance (stretching/compression) during core recovery; or (3) natural dewatering and compaction of sediments as they are buried. While the first possibility cannot be ruled out, all of these sites are located above the lysocline over the last 800 kyr [e.g. *Bassinot et al.*, 1994; *Farrell and Prell*, 1991], so variable carbonate preservation is unlikely to have biased long-term sedimentation rates or GSS97 ages.

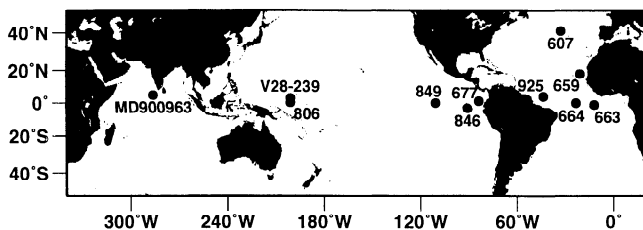


Figure 2. Map showing location of sites used in this study.

Table 2a. Termination Depths and Age Estimates

Site	Termination														stage 19	
	I		II		III		IV		V		VI		VII			
	Depth	Age	Depth	Age	Depth	Age	Depth	Age	Depth	Age	Depth	Age	Depth	Age		
607	0.72	13.5	5.88	128.0	9.22	(210.9)*	13.51	317.4	17.41	414.2	20.57	492.7	24.45	589.0	31.83	772.2
659	0.87	13.5	4.31	128.0	7.69	234.8	10.76	331.8	13.88	430.4	17.92	558.0	20.64	643.9	24.70	772.2
663	0.40	13.5	5.08	128.0	9.42	240.3	12.92	330.9	16.57	425.4	21.03	540.8	23.95	616.4	29.97	772.2
664	0.45	13.5	4.69	128.0	8.95	242.5	12.37	334.4	15.73	424.7	19.89	536.5	22.44	605.0	28.66	772.2
677	0.73	13.5	6.20	128.0	10.74	246.4	14.17	335.9	17.13	413.1	21.38	523.9	24.36	601.6	30.90	772.2
806	0.40	13.5	2.70	128.0	5.21	249.8	6.99	336.1	8.68	418.1	10.69	515.6	12.91	623.3	15.98	772.2
846	0.46	13.5	5.42	128.0	9.64	244.6	13.09	340.0	16.23	426.7	20.60	547.5	23.16	618.3	28.73	772.2
849	0.45	13.5	4.08	128.0	8.12	269.3	10.84	364.4	13.16	445.6	16.32	556.1	18.63	636.9	22.50	772.2
925	0.38	13.5	5.12	128.0	9.54	249.7	13.22	351.1	ambiguous		21.24	572.0	24.01	648.3	28.51	772.2
V28-239	0.21	13.5	1.29	128.0	2.34	242.5	3.20	336.2	3.77	398.3	4.78	508.4	5.67	605.4	7.20	772.2
MD900963	0.30	13.5	7.70	128.0	13.26	259.4	17.26	354.0	20.87	439.3	24.64	528.5	29.74	649.0	34.95	772.2

Depth values are in meters, and age values are in kiloyears. The error on picking termination midpoints appears to be a few centimeters between investigators.

*This value is not included in the calculation of mean age in Table 2b, since it fell more than 2σ away from mean calculated with all data.

Table 2b. Termination Ages in GSS97 Timescale and Comparison to Other Timescales

	Termination							stage 19
	II	III	IV	V	VI	VII		
Number of cores with age estimate		10	11	10	11	11		
GSS97 mean age, kyr		247.9	339.3	423.6	534.5	621.6		
Standard deviation		10.0	12.8	13.6	23.6	20.6		
Median age, kyr		245.5	336.1	425.0	536.5	618.3		
If Termination II equals 131 kyr	131.0	250.4	341.3	425.2	535.7	622.3		
If timescale pinned at Termination I only, kyr	135.7	249.4	343.0	429.5	538.7	624.1		
SPECMAP age*, kyr	128.0	245.0	339.0	423.0	538.1	625.3		
Devils Hole age*, kyr	140.0	253.0	339.0	417.0	--	--		
GSS97 age relative to SPECMAP*, %		+1.2%	same	+0.1%	-0.7%	-0.6%		
GSS97 age relative to Devils Hole, %		-2.0%	same	+1.6%	--	--		
Glacial-interglacial cycle length, kyr	II-I: 114.5	III-II: 119.9	IV-III: 91.4	V-IV: 84.3	VI-V: 110.9	VII-VI: 87.1	19-VII 150.6	

*Ages for Terminations VI and VII taken from revision of lower half of SPECMAP timescale published by Shackleton *et al.* [1990]. This revision was based on astronomical tuning of the Site 677 oxygen isotope record. GSS97 ages which are within 0.1% of SPECMAP or Devils Hole ages are shown as "same." Note that recent work by Winograd *et al.* [1996] suggests that the Devils Hole age for Termination II may be closer to 134 kyr.

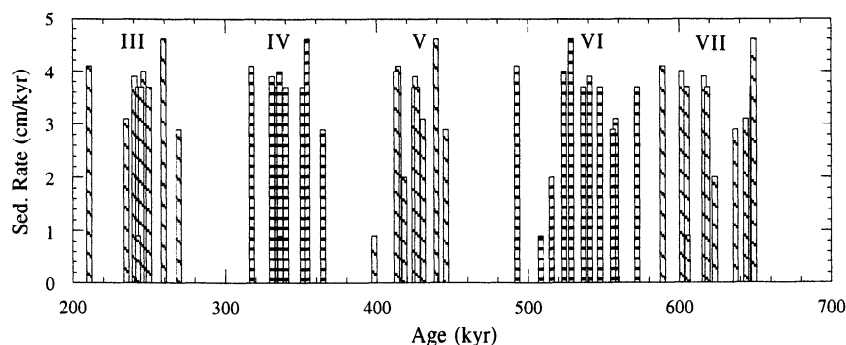


Figure 3. Sedimentation rate plotted versus age (from Table 2a) for each core at each termination examined. Any systematic bias of age with sedimentation rate would skew the distribution of the data.

Long-term productivity variations, however, cannot be ruled out, especially as seawater $\delta^{87}\text{Sr}$ variations [Farrell *et al.*, 1995] suggest that river fluxes may have decreased slightly in the last 0.5 Myr. If such a bias occurred, it would make the GSS97 ages systematically too young, especially in the deeper sections.

As to coring disturbance, the most typical problems are loss of the sediment-water interface, stretching near the top of cores, and compression at the bottom of very long piston cores. In the ODP/DSDP records, no single cored section is longer than 10 m. Further, the process of building a composite sequence from offset holes helps to randomize where potentially compressed sections fall in the age domain. On the other hand, in core MD900963, stage 19 falls 35 m deep in a single cored section, and indeed, this record has the shortest duration for the interval between stage 19 and Termination VII, consistent with possible compression in the lower portion of the core.

Last, deep-sea cores typically show downcore decreases in water content and porosity and increases in dry and wet bulk density [e.g., Curry *et al.*, 1995]. These changes are due to the natural compaction that occurs in sediments as they are buried and result in sedimentation rates being artificially high at the tops of cores, decreasing with depth. Such a bias would make GSS97 ages systematically too old, especially near the top of the core. In addition, core top extension may occur in the top few meters or so of ODP/DSDP piston cores when they are placed horizontally on deck. The core tops are typically quite watery and are rarely as cohesive as sediment only 10 m downhole. The data in Table 2a suggest that indeed some sort of relaxation (or slumping) is systematically occurring in the top few meters of these cores. Comparing the sedimentation rate for the interval between Terminations I and II to that for each record as a whole (Table 1) would lead one to the conclusion that ~10% stretching (on average) had occurred in the top few meters of sediment (values range from 3% compression to 41% extension).

In DSDP/ODP holes, sediment relaxation or expansion of cored sections is much less of a problem downcore for three reasons: (1) Sediment water content decreases, (2) full cores are taken, unlike the topmost core which typically recovers a few meters of overlying water in the core liner, and (3) all deeper soupy or disturbed looking sections, including the uppermost sections of recovered cores, are omitted from the composite record, which is built up by taking the best sections of the two or three identical holes drilled right next to each other [Ruddiman *et al.*, 1986]. Thus, while it is unlikely that any pronounced disturbance is occurring below the core top sediments, it is

highly likely that some residual amount of the ~10% stretching is extending below Termination II (and is hence not corrected for by radiometric constraints). For instance, a core with 10% stretching between Terminations I and II could have 5% stretching between Terminations II and III. This would affect the GSS97 timescale by making Termination III slightly older than its actual age, with the age bias on each deeper termination falling off by approximately half. Unfortunately, in the absence of additional radiometric age constraints, such a correction is almost impossible to make, as the degree of stretching apparent in these cores between Termination II and the core top is highly variable and the depth to which stretching extends (either above or below Termination II) is uncertain.

In summary, it is unclear whether any systematic errors bias the GSS97 ages. Core top stretching is largely, but probably not completely, corrected for by the radiometric constraint used at Termination II. The other two possible biases, long-term changes in river fluxes or compaction at depth, are in opposite directions. Systematic increases or decreases in sedimentation rates deeper in the core are not predictable or recognizable at this time. Accepting the GSS97 timescale at face value, I conclude that an analysis of the timing of major climate terminations, using a simple sedimentation rate model independent of any assumptions about tuning targets or climate forcing mechanisms, provides strong support for the SPECMAP dating of deglaciations over the last 800 kyr. All GSS97 ages fall within 1.5% of SPECMAP ages. The largest offset, at Termination III, is consistent with the most probable bias in this study (core top relaxation) as discussed above.

More relevant to understanding the mechanisms of climate change is that this study provides independent support for the correlation of terminations to increases in summer insolation at high northern latitudes. Comparison of benthic $\delta^{18}\text{O}$ data from Pacific ODP Site 849 (plotted using the GSS97 chronology) to mid-July insolation at 65°N shows that all termination midpoints except for Termination III fall on increases in insolation (shown by vertical lines on Figures 4 and 5). A deep Pacific record was chosen for this comparison to minimize the temperature overprint on the isotope record and most closely reflect the true ice volume history. Termination IV falls early in an insolation rise, while Termination V falls late in an insolation increase. Terminations I (not shown), II (radiometrically dated), VI, and VII are centered on insolation increases. Termination III appears to have begun too early relative to the insolation increase, an offset consistent with the possible age bias for this termination

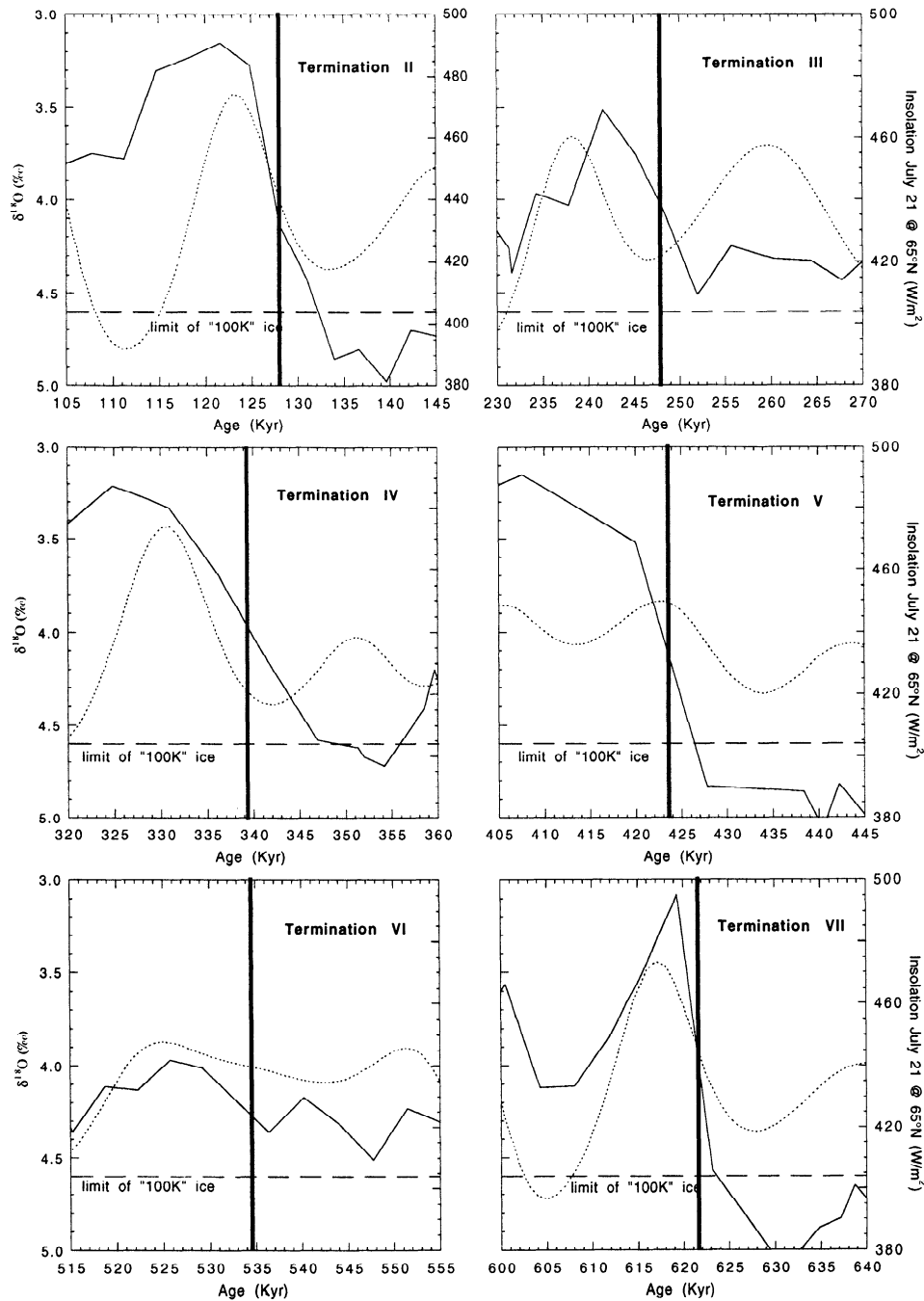


Figure 4. Terminations II through VII in the benthic $\delta^{18}\text{O}$ record from Site 849 plotted using the GSS97 timescale and compared with insolation received on July 21 at 65°N [after *Laskar et al.*, 1993]. The midpoints of terminations as defined in Table 2b are shown by vertical bold lines. Horizontal dashed lines define limit of 100-kyr ice as discussed in text.

discussed above. The fact that Terminations III and IV appear to start just before insolation begins to rise is probably due to some combination of four factors: (1) Errors/inaccuracies in the GSS97 timescale; (2) artificial lengthening of the apparent duration of the deglaciation event by the use of an age model pinned only at the midpoint of terminations; (3) deglaciations may be triggered by insolation earlier in the year (for instance, June insolation values begin to rise approximately 2000 years earlier, and ~4000 years earlier in May); and/or (4) the ice volume system has a very short (to nonexistent) lag to insolation forcing once a deglaciation is triggered.

The Origin of the 100-kyr Cycle

While terminations appear to be associated with increases in summer northern hemisphere radiation, they are not necessarily linked to the largest-amplitude insolation shifts. In fact, some terminations, in particular the stage 12-11 transition, occur in association with relatively weak insolation forcing (the problem of the disparity between forcing and response at stage 11 is reviewed by *Imbrie et al.* [1993]). Why do major deglaciations, or terminations, occur when they do? It is clear from the data shown in Figure 5 (and also Table 2b) that the time interval

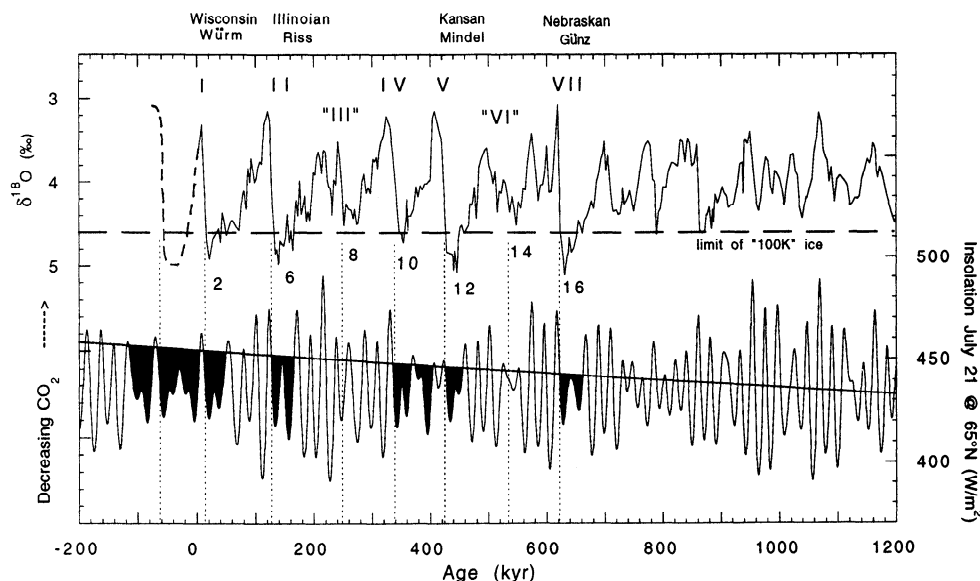


Figure 5. Benthic $\delta^{18}\text{O}$ data from Pacific Site 849 plotted to the GSS97 timescale. Insolation received on July 21 at 65°N is shown on lower half of figure [after Laskar *et al.*, 1993]. This site is representative of the pattern of ice volume change over the last 800 kyr and can be compared with other records plotted in Figure 1. The horizontal dashed line on the $\delta^{18}\text{O}$ record indicates the level below which 100-kyr ice is observed. Terminations and selected isotope stages are labeled, as well as the historical names of the glacial stages. On the insolation record, the fiducial level below which 100-kyr ice can nucleate and be stable (shaded regions) is indicated by the slanted horizontal line. The vertical dashed lines indicate the midpoint of terminations using the GSS97 timescale.

between terminations is not constant; it varies from 84 kyr between Terminations IV and V to 120 kyr between Terminations III and II. G-I climate cycles appear to be “quantum” in the sense that the length between subsequent terminations is either four or five precessional cycles long (Figure 5). It is further observed that true terminations, namely, rapid transitions from full glacial to full interglacial conditions as seen at Terminations I, II, IV, V, and VII, do not occur unless significant excess ice accumulates just prior to the deglaciation. Stage 16 is typically the first time that these heavier glacial $\delta^{18}\text{O}$ values are observed in deep-sea isotopic records; excess ice, or “surplus ice” of Berger and Jansen [1996], is also observed during glacial stages 2, 6, 10, and 12 (Figure 5; the horizontal dashed line at 4.6‰ defines the limit of this 100-kyr ice).

What controls the timing of large ice sheet growth and hence the timing of the subsequent terminations? Approximately 800,000 years ago, some boundary condition changed within the climate system that allowed larger ice sheets to grow. Here this change is assumed to be the long-term drawdown of atmospheric $p\text{CO}_2$ levels by tectonic processes [Raymo *et al.*, 1988; Raymo, 1994], depicted schematically by the solid horizontal line on the insolation curve in Figure 5. Over 1.2 Myr, the change in this fiducial line, intended to reflect a hypothesized decrease in the strength of the Earth’s greenhouse, is equivalent to about half the mean insolation change between June and July ($\sim 25 \text{ W m}^{-2}$). The placement of the line defines a proposed insolation (temperature) threshold below which a large ice sheet could become established given sufficient time. In other words, if the global greenhouse weakened over the past few million years, certain locations would become colder for a given insolation regime, promoting the expansion of ice sheets into regions where it was previously too warm (hence the fiducial line moves up as CO_2 falls).

The excess 100-kyr ice ($\sim 0.2\text{--}0.4\%$), equivalent to a 20- to 40-m sea level change, typically grows during unusually long intervals of low summer insolation (greater than one precession cycle) caused by the interaction of obliquity and the eccentricity modulation of precession (shaded areas on the insolation curve in Figure 5). Ten thousand years of cold summer temperatures is not long enough to grow a typical late Quaternary 100-kyr ice sheet and is the proposed reason why no large ice sheets are observed prior to 800 ka. It was never cold enough, for long enough, at boreal latitudes. The only exception to the above “rule” is observed between 385 and 400 ka when insolation was low for the requisite length of time (>21 kyr) but a large ice sheet did not develop. However, this interval also followed closely upon a termination and peak interglacial conditions and thus may not have provided enough time to go from full interglacial to full glacial conditions, given the slow time constant of ice sheet growth.

Once established, 100-kyr ice lasts only until the next increase in summer insolation. The first warming of any note causes the ice mass to melt catastrophically, triggering a global climate warming (e.g., terminations). This large ice sheet instability, the critical driving mechanism in most theoretical models of the 100-kyr climate cycle [e.g., Weertman, 1974; Pisias and Moore, 1981; Hughes, 1987; De Blonde and Peltier, 1991; Imbrie *et al.*, 1984], is consistent with the observed record of global ice volume changes relative to 65°N summer radiation.

In conclusion, it is proposed that the interaction between obliquity and the eccentricity-modulation of precession as it controls northern hemisphere summer radiation is responsible for the pattern of ice volume growth and decay observed in the late Quaternary. If one compared Site 849 to other insolation records (e.g., different latitudes or seasons), the correlation between “excess ice” and persistent low insolation is less striking

(although still present), requiring that one argue that the correlation shown in Figure 3 is either coincidentally the best or that midsummer insolation between 60° and 70°N exerts the strongest control on ice volume in the late Pleistocene. Likewise, the position of the sloping line on Figure 3 is as required by this model; the secular trend in the strength of the Earth's greenhouse could have had steps (use straight line segments with a step around 800 kyr B.P.) or have been constant (use a straight line). In either case, additional exceptions to this model would appear.

Extension of this model into the future predicts that the Holocene warm period is nearly over and that the cold substages typical of stages 5, 7, and 15 will not occur (for contrasting predictions see *Ledley* [1995] and *Berger and Loutre* [1997]). A 100-kyr ice sheet will grow, possibly larger than any observed previously, given the extended cool period predicted by the orbital insolation values, and the next termination will occur ~64 kyr from now. If the hypothesized secular decline in atmospheric CO₂ continued for the next million years, glacial cycles would probably increase in length, as the lowering of ambient CO₂ levels would be equivalent to raising the insolation threshold below which large ice sheets could grow and be stable (Figure 5). Reconstruction of secular trends in Plio-Pleistocene atmospheric pCO₂ would provide an important first test of this model.

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