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A radiometric calibration of the SPECMAP timescale

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Abstract

The astronomical theory of climate change asserts that Earth's climate is affected by changes in its orbit, which vary the seasonal and latitudinal distribution of solar radiation. This theory is the basis of the orbitally tuned SPECMAP timescale. A key constraint for this important chronology was the mid-point of the Penultimate Deglaciation, initially dated to 127,000 years ago. Recent work suggests this event may be considerably older, casting doubt on the astronomical theory, the SPECMAP timescale, and the accuracy of orbitally tuned chronologies. Difficulties with U/Th coral dating of sea-level events have impeded progress on this problem, because most corals are not closed systems. Here, we use a new approach to U/Th dating that corrects for open-system behavior and produces a sea-level curve of sufficient resolution to confidently correlate with SPECMAP over the last 240,000 years, permitting a reassessment of both this critical chronology and a central tenet of climate change theory. High-precision ages for 24 oxygen isotope events provide a 240,000-year chronology for marine $\delta^{18}O$ records that is independent of orbital tuning assumptions. Although there appear to be significant differences between the radiometric and orbitally tuned timescales near the lastglacial maximum and at the Marine Isotope Stage 7/6 boundary, a comparison of radiometric and SPECMAP ages for identical isotope events suggest that the SPECMAP timescale is quite accurate and that its errors were, in general, overestimated. Despite suborbital complexity, orbital cyclicity is clearly evident in our record. High-amplitude sea-level oscillations at periods greater than ~20,000 years are very close in phase to summer insolation in the Northern Hemisphere. Although sea-level changes cannot be uniquely tied to a specific season or latitude of insolation forcing, the simplest explanation is that long-period, high-amplitude sea-level change is linked to Northern Hemisphere insolation forcing. These results validate the principles of orbital tuning and suggest such timescales are generally robust.

1. Introduction

The long and continuous sedimentary records available from deep-sea cores are rich geological archives, for which an accurate chronology is essential. These records, which may span ranges of hundreds of thousands to several million years, cannot be directly dated beyond the ~40 ka range of radiocarbon. The changing oxygen isotope composition ($\delta^{18}O$) of seawater, which is recorded in fossil shells of tiny marine organisms, is a key stratigraphic tool for global correlation of marine cores (Pisias et al., 1984), and a proxy for continental ice volume, sea level, ocean temperature, and climate. Marine core chronologies between 40 and 800 ka are calibrated by correlation with the benchmark $\delta^{18}O$ records of SPECMAP. Two such references exist, a 300-ka high-resolution chronology (Martinson et al., 1987) and a longer timescale extending to 800 ka (Imbrie et al., 1984). A strategy of 'orbital tuning' was used to develop these chronologies, and is used to generate chronologies for longer records e.g., Lisiecki and Raymo (2005). This technique is based on the astronomical theory of climate change, which was first proposed by Croll (1864) and later refined by Milankovitch (1941), and is supported by a substantial body of evidence. The similarities between $\delta^{18}O$ records and curves of summer insolation at high northern latitudes were pointed out in the early days of $\delta^{18}O$ research (Emiliani, 1955). Early dating of coral terraces (Mesolella et al., 1969), spectral analysis of $\delta^{18}O$ time series (Hays et al., 1976), and estimates of marine core sedimentation rates (Broecker and van Donk, 1970), all appeared to support a robust

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connection between changes in earth's orbit and its climate. The SPECMAP chronology was developed using several tuning approaches which all lead to nearly identical results. However, a key step was estimating the lag between orbital forcing and δ^{18}O response. In nearly every case, this estimate was based either directly or indirectly on an age of 127 ka for the midpoint of the Marine Isotope Stage (MIS) 7/6 boundary, also known as Termination II (TII) (Broecker and van Donk, 1970). Recent evidence suggests this climate event may be considerably older: 140 ka (Winograd et al., 1992), 135 ka (Henderson and Slowey, 2000), and >135.8 ka (Gallup et al., 2002), casting serious doubt on the accuracy of the SPECMAP timescale. Not only does the age of a key SPECMAP constraint appear to be in error, but the climate response appears to precede the peak in Northern Hemisphere summer insolation, leading some investigators (Winograd et al., 1992; Henderson and Slowey, 2000; Gallup et al., 2002) to question the fundamental basis for orbital tuning.

Because δ^{18}O is a proxy for sea level, U/Th dated sea-level reconstructions from the ages and elevations of fossil corals should provide key constraints for the δ^{18}O events of SPECMAP. Indeed, much of the evidence both for and against SPECMAP's accuracy comes from such sea-level estimates. Conventional closed-system equations for U/Th age determination (Broecker, 1963) require that loss or gain of U and Th has not occurred except by radioactive decay since coral death. This criterion is violated in most fossil corals as a result of the alpha-recoil mobility of U-series nuclides (Fruijtier et al., 2000), and many investigators consider an initial coral ^{234}U/^{238}U ratio substantially different from modern seawater to be evidence of open-system behavior and an unreliable age (Gallup et al., 1994). These effects degrade both the accuracy and resolution of sea-level reconstructions (Thompson and Goldstein, 2005). Based on earlier attempts to correct for open-system behavior in marine sediments (Henderson and Slowey, 2000), new decay equations have been developed to correct coral ages for these effects (Thompson et al., 2003). Isochron methods (Villemant and Feuillet, 2003; Potter et al., 2004; Scholz et al., 2004), while potentially useful, do not permit age corrections for individual corals.

Extending our previous work (Thompson and Goldstein, 2005), we present a sea-level reconstruction for the last 240 ka that is of sufficient resolution to be correlated with a high degree of confidence to the marine δ^{18}O record (Fig. 1, Supplementary Table 1).

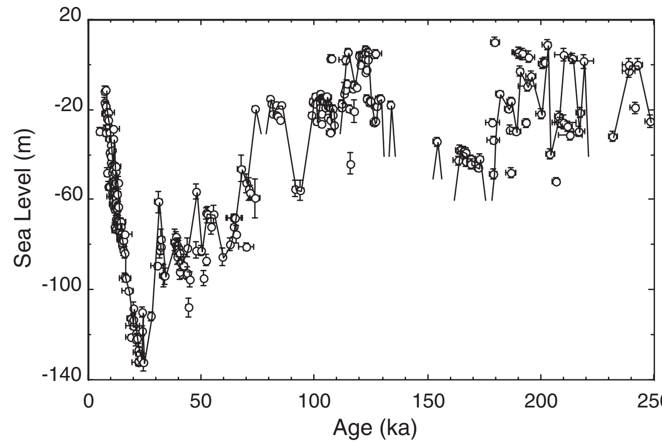

Fig. 1. A high-resolution sea-level reconstruction. Corrected coral ages have been calculated from published U and Th isotope ratio data (Bard et al., 1990a,b; Edwards et al., 1993; Gallup et al., 1994; Bard et al., 1996; Chappell et al., 1996; Cutler, 2000; Yokoyama et al., 2001; Gallup et al., 2002; Cutler et al., 2003; Thompson et al., 2003; Speed and Cheng, 2004). Error bars are 2-σ and those not visible are smaller than plot symbols.

2. Methods

2.1. U-series age calculation

U/Th isotope ratio data were selected from the coral dating literature. In cases where more than one set of isotope ratio measurements were made on the same coral, replicate ages were averaged. Here, we use a new method to recalculate U-series coral ages from published U/Th isotope ratios that corrects ages for the bias imposed by open-system behavior. While details of this method are published (Thompson et al., 2003), a short discussion of the equation's principles is given here.

A strong positive correlation between ^{234}U and ^{230}Th for corals from the same terrace demonstrates that corals have experienced the addition of these isotopes in a systematic manner (Gallup et al., 1994). This coupled addition is best explained by the adsorption of the thorium isotopes ^{234}Th (which rapidly decays to ^{234}U) and ^{230}Th, which are produced by the radioactive decay of ^{238}U and ^{234}U, respectively. ^{234}Th and ^{230}Th may be directly mobilized from the reef matrix by alpha-recoil, or produced in pore waters from the decay of dissolved U. To account for this redistribution of U-series daughters, a new system of decay equations was derived from first principles (Thompson et al., 2003). The equations assume that all reef carbonate initially had a seawater ^{234}U/^{238}U ratio and that ^{234}Th and ^{230}Th produced by the decay of ^{238}U and ^{234}U in the reef matrix has been added to (or lost from) the measured coral. These equations suggest that U-series compositions of coeval corals should fall on 'addition lines' whose slopes change as a function of time, and the skill of the equations in predicting empirical data trends suggests that the observed open-system behavior is well represented. The advantage of this dating method is the ability to calculate accurate corrected ages for all samples, regardless of the degree of ^{234}U and ^{230}Th addition, dramatically increasing the number of reliable data points available for sea-level reconstruction.

2.2. Accuracy and precision of ages

In keeping with reporting practices for uncorrected U/Th coral ages, reported precision is propagated from analytical uncertainties and does not include potential error from the failure of model assumptions. It is well known that the accuracy of uncorrected coral ages depends directly on the range of initial $^{234}U/^{238}U$ deemed 'acceptable' by the individual investigator (Gallup et al., 1994). For a commonly used criterion of modern seawater $^{234}U/^{238}U \pm .008$, the error imposed is approximately ± 3200 years (Thompson et al., 2003). Additional uncertainty of ~800 years arises from the analytical error in determining the corals initial $^{234}U/^{238}U$ ratio. This 4000-year total uncertainty has never been included in formally quoted errors for uncorrected coral ages. The model used here corrects for this uncertainty, although other error may be introduced in the process. The theoretically predicted $^{230}Th/^{234}Th$ addition ratio is a potential source of error for the age correction equations. However, sensitivity analysis suggests that any potential natural variability in the predicted $^{230}Th/^{234}Th$ addition ratio, which determines the slope of the addition lines, is similar to or less than typical measurement uncertainties (Thompson et al., 2003). Empirical evidence supports this conclusion (Thompson et al., 2003) and suggests any variability in the addition ratio is too small to be detected. The dominant source of error from analytical uncertainty is different for conventional (the ^{230}Th measurement) and corrected (the ^{234}U measurement) ages. Therefore, analytical uncertainty for corrected ages can be smaller than conventional analytical errors, particularly for older corals.

The most significant source of potential error for both corrected and conventional ages is the assumption of a constant $^{234}U/^{238}U$ seawater ratio over time. Mass balance constraints and modelling of the ^{234}U ocean budget suggest that the maximum variability of this ratio is constrained to 1% over glacial/interglacial cycles (Richter and Turekian, 1993). In this worse case scenario, both corrected and conventional ages could be systematically offset from the true age by as much as 4 ka during times when the actual seawater $^{234}U/^{238}U$ was 1% different from the assumed value. Fortunately, the actual range of seawater $^{234}U/^{238}U$ is reasonably well constrained. Empirical evidence suggests that seawater $^{234}U/^{238}U$ has been constant to within 0.2% during interglacial periods out to the dating limits of the U/Th system (~600 ka) (Gallup et al., 1994; Stirling et al., 1995, 2001; Thompson et al., 2003; Andersen et al., 2005), indicating a maximum systematic age offset of 0.8 ka during interglacials, which comprise a large portion of our curve. However, there is some evidence to suggest seawater $^{234}U/^{238}U$ may have been as much as 0.7% lower during the lastglacial maximum (LGM) (Robinson et al., 2004). To take the apparent shift of seawater $^{234}U/^{238}U$ to lower values during this period into account we have adopted, for the period 17–35 ka, the lower value of 1.1406 recently suggested by the radiocarbon calibration group (Hughen et al., 2004). Evidence suggests seawater $^{234}U/^{238}U$ was close to modern at 35 ka (Chiu et al., 2005). The sensitivity of the corrected ages to the accuracy of decay equation constraints is shown in Table 1. It must be emphasized that normalizing open-system ages to a constant initial $^{234}U/^{238}U$ will place ages in accurate chronological order even if there is some uncertainty about the absolute ages, because the potential rate of change of ^{234}U in the ocean is quite low. Corals that are the same age can be identified and distinguished from adjacent ages with a degree of confidence that is determined primarily by analytical precision. Furthermore, it must be remembered that uncorrected ages will be equally biased by variable initial $^{234}U/^{238}U$, because they are screened with a modern seawater $^{234}U/^{238}U$ criterion. Standard screening criteria, rejecting any samples that were reported to have >2% calcite, >2 ppb ^{232}Th, or U concentrations substantially different from modern corals of the same species (see Thompson and Goldstein, 2005) for species-specific U criteria), were adopted to eliminate samples that had suffered recrystallization, and U or Th loss or gain, which degrade the accuracy of both conventional and corrected ages. Quoted uncertainties (Table 1) are 2-σ and ages were calculated using the most recently determined decay constants for ^{234}U and ^{230}Th (Cheng et al., 2000).

2.3. Data interpretation—the sea-level curve

Original elevations of fossil corals were calculated by subtracting an uplift correction, based open-system ages and local uplift rate, from the measured elevations. Local uplift rates were determined from the present elevation of the last interglacial terrace top at each site, assuming sea levels were 5 m above modern at 122 ka, which is consistent with data from the Bahamas (Chen et al., 1991), a tectonically stable site, where open-system *A. palmata* ages from the reef crest zone (2–2.5 m elevation) are 118–122 ka, agreeing extremely well with *A. palmata* terrace top ages from Barbados. Uplift rates for the deglacial sequence were those given by the authors, except for Cutler (2000), where we used the author's method of adjusting the uplift rate to yield the best match to the Barbados record (Bard et al., 1990a,b). Sea-level uncertainty is propagated from a 1 m uncertainty in the measured elevation, an estimated ±2% error in the uplift rate, and open-system age errors. The curve from 250 to 70 ka is identical to that in Thompson and Goldstein (2005). The 70–10 ka portion of the curve was constructed in a similar manner. The sea-level curve is drawn through the highest corals of any given age, because corals grow over some depth range and are easily transported down slope. Adjacent peaks must be distinguishable outside the 2σ errors in the ages. Corals may also be transported to higher elevations by wave action (Thompson and Goldstein, 2005). For this reason, three corals (two near 109 ka and one near 127 ka) whose elevation was in serious conflict with the bulk of the data in that age range were excluded from the sea-level curve. Corals identified by the authors as beach cobbles (Gallup et al., 1994) were also excluded. This excluded data is plotted in Fig. 1 along with the resulting curve. The sea-level curve is defined by the minimum number of coral ages necessary to produce a curve that satisfies these criteria.

Table 1
Ages of SPECMAP δ^{18}O events

SPECMAP[a] event #	SPECMAP age (ka)	±	Sample	Ref.[b]	Corrected age (ka)[c]	±[d]	Mean age (ka)	±	Δage[e] (ka)	Sensitivity tests: Ratio[f] (ka)	Sea[g] (ka)	Point[h] (ka)
2.2	17.9	1.4	13 130	2	23.1	0.5			−5.2	0.0	1.2	−0.3
2.21	19.2	1.4	KNM 50	3	23.7	0.5			−4.5	0.0	1.2	0.3
3.1	25.4	5.9	Kanz U16	9	31.1	1.6			−5.7	0.0	1.2	1.3
None	35.6	7.3	KNMT2	3	38.6	0.6			−3.0	0.0	1.2	−0.1
3.3	50.2	3.9	KAND-4	3	47.8	0.6			2.4	0.0	1	−3.0
3.31	55.5	5	KWAK-1	3	52.2	0.6	53.8	0.75	1.7	0.0	1	−1.2
	55.5	5	Kanz-4	9	55.4	0.9				0.0	1	
4.23	68.8	4.2	Sial-U2	1	67.7	1.7			1.1	0.1	1	2.3
5.1	79.3	3.6	NU 1483	8	80.5	0.9			−1.2	0.0	0.8	0.2
None	84.1	6.2	NU 1482	8	85.3	1.2			−1.2	0.0	0.8	−2.0
5.2	91	6.4	KWAS-1	3	91.3	0.8			−0.3	0.0	1	2.6
5.31	96.2	5.1	0C-2	4	100.3	0.9			−4.1	0.1	0.8	−0.9
5.33	103.3	3.4	AEG 36	8	104.0	0.8			−0.7	0.0	0.8	−0.4
5.4	110.8	6.3	AEG 2	8	108.5	0.7	110.1	0.8	2.3	0.0	1	0.1
			OC-1	4	111.8	0.9				0.1	1	
5.51	122.6	2.4	UWIW93-1	4	122.6	1.4			0.0	0.0	0.8	0.1
6.0	129.8	3.1	NU 1473	4	129.3	1.0			0.5	0.1	1	−1.1
None	132.8	3.4	NU 1471	4	133.5	1.1			−0.7	0.0	1	np
6.4	152.6	9.9	NU 1511	6	153.9	1.2			−1.3	0.4	1.2	np
6.41	161.3	8.9	NU 1464	4	164.0	1.6			−2.7	0.0	1.2	1.6
None	168.9	9.2	UWI-103	4	169.1	1.7			−0.2	0.0	1.2	0.0
6.5	175.1	9.8	NU 1465B	4	172.9	1.8			2.2	0.7	1.2	−0.3
7.0	189.6	2.3	NU 1467	4	179.2	1.7			10.4	0.0	1	−0.1
7.1	193.1	2	164	7	190.8	1.4	193.5	2.4	−0.4	0.3	0.8	−0.3
			WAN C 1	5	194.0	3.7				0.1	0.8	
			WAN E 1	5	195.6	2.2				0.2	0.8	
7.3	215.5	1.4	141	7	214.1	1.8			1.4	5.1	0.8	−4.1
7.5	240.2	6.3	AKF 3	8	239.0	2.9	241.0	2.5	−0.8	3.8	0.8	−2.0
			AKD 3	8	243.0	2.1				0.6	0.8	

[a]SPECMAP ages, event numbers, and error estimates from Martinson et al. (1987).

[b]References: (1) Chappell et al. (1996), (2) Cutler (2000), (3) Cutler et al. (2003), (4) Gallup et al. (2002), (5) Gallup et al. (1994), (6) Speed and Cheng (2004), (7) Thompson and Goldstein (2005), (8) Thompson et al. (2003), (9) Yokoyama et al. (2001).

[c]Ages recalculated from published U-series isotope ratio data using the age correction equation of Thompson et al. (2003) and the decay constants of Cheng et al.(2000).

[d]Error estimates are 2-σ and propagated from the analytical uncertainties.

[e]Difference between the SPECMAP and radiometric ages. A negative number indicates the SPECMAP age is younger.

[f]Sensitivity of ages to the assumed ^{234}Th/^{230}Th addition ratio: the addition age uncertainty that might be introduced by the maximum estimated natural range of the addition ratio. (Constraints: $f_{234} = 0.975 \pm 0.75$, $f_{recoil} = 0.5 \pm 0.5$, δ^{234}U of source $= 145 \pm 20$; see Thompson et al., 2003 for details).

[g]Sensitivity of ages to assumed ^{234}U/^{238}U of seawater is 0.4 ka for every 0.1% uncertainty in the ^{234}U/^{238}U ratio.

[h]Sensitivity of ages to drawing of sea-level curve and selection of individual data points: Initially selected correlation points were deleted from the dataset, the curve was redrawn, and new sea level peaks selected. The difference in age between the new peak ages and the original peak ages is given. A negative number indicates the original age was younger. Peaks that disappear entirely are indicated by np.

Where there was a choice between several data points that were identical within error, the datum with the smallest error was chosen. The sea-level curve in Fig. 1 is not a unique interpretation of the data, as any number of smoother curves could be drawn without violating the fundamental constraint that the sea level must be above the highest coral data. However, the reproducibility of detailed sub-orbital period variability in portions of the curve from independent data sets and differing locations, well as the good agreement with independent speleothem constraints, validates our methodology (Thompson and Goldstein, 2005).

Caution must be used when combining sea-level data from different locations, because differences in uplift rates or global glacio-isostatic response might produce artifacts in the resulting sea-level curve. To minimize these problems, data for large portions of the curve are from single locations. Corals for MIS 5, 6, and 7 are from Barbados (Gallup et al., 1994, 2002; Thompson et al., 2003; Speed and Cheng, 2004). Corals for MIS 3 are primarily from the Huon Peninsula of Papua New Guinea (Chappell et al., 1996; Yokoyama et al., 2001; Cutler et al., 2003). Deglacial corals are from Barbados (Bard et al., 1990a,b), Tahiti (Bard et al., 1996), Huon (Edwards et al., 1993), and Vanuatu (Cutler, 2000). For the deglacial interval, individual sea-level curves were first constructed for each location, and then a composite curve was drawn including only variability that was common to all curves in the intervals where they overlapped. This procedure was adopted to avoid potential artifacts that could arise from the combining of data from widely separated locations. Although care must be taken in interpreting the transitions between the Barbados, Huon Peninsula, and composite curve data at ~24 and ~70 ka, the good agreement of sea-level reconstructions from the Huon Peninsula and Barbados for the last interglacial (Thompson and Goldstein, 2005) and deglacial (Edwards et al., 1993) suggests that artifacts from transitions between data locations is small, if any.

2.4. *Correlation of oxygen isotope and sea-level events*

The following procedure was used to correlate sea level and $\delta^{18}O$ events. The equivalent of MIS boundaries were first identified in the sea-level record, and then the major sub-stage sea-level peaks were correlated. Finally, isotope events within sub-stages were correlated. In almost all cases, the correlation was unequivocal. However, a few exceptions are noted. In MIS 7, there appear to be four major sea-level high stands but three major $\delta^{18}O$ events. Correlation was made on the basis of the large positive $\delta^{18}O$ excursion between MIS 7.3 and 7.5 that was assumed to correspond with the clear gap in coral ages at ~230 ka. During the MIS 6/5 transition (TII), we correlate the earliest peak in sea level with the negative $\delta^{18}O$ event at the beginning of the 6/5 transition, and the second peak with a slight pause near the mid-point the $\delta^{18}O$ transition. We base these correlations on prominent $\delta^{18}O$ excursions evident in the high-resolution record of V19-30, which is part of the SPECMAP stack. V19-30 had an average sedimentation rate of 6.4 cm/ka and an average sampling interval of 3.3 cm, for a sampling resolution of 500 years. The $\delta^{18}O$ events we identify in the record of V19-30 are not evident in every record because the resolution of such short-lived events is dependent on sedimentation rate, sampling interval, and the effects of mixing by bioturbation. In MIS 3, correlation of the first and last sea-level events with the SPECMAP record is clear, but alternate correlations are possible for events in between. Again, we base our correlations on the most prominent features of V19-30. The age of event 3.31 was calculated as the mean of two ages, 5.4 was the mean of 2, 7.3 the mean of 3, and 7.5 the mean of 2. In some cases there appear to be events in the sea-level record that cannot be correlated with a $\delta^{18}O$ event.

3. Results

The compiled and corrected data provide a relatively continuous set of sea-level constraints for the last 240 ka.

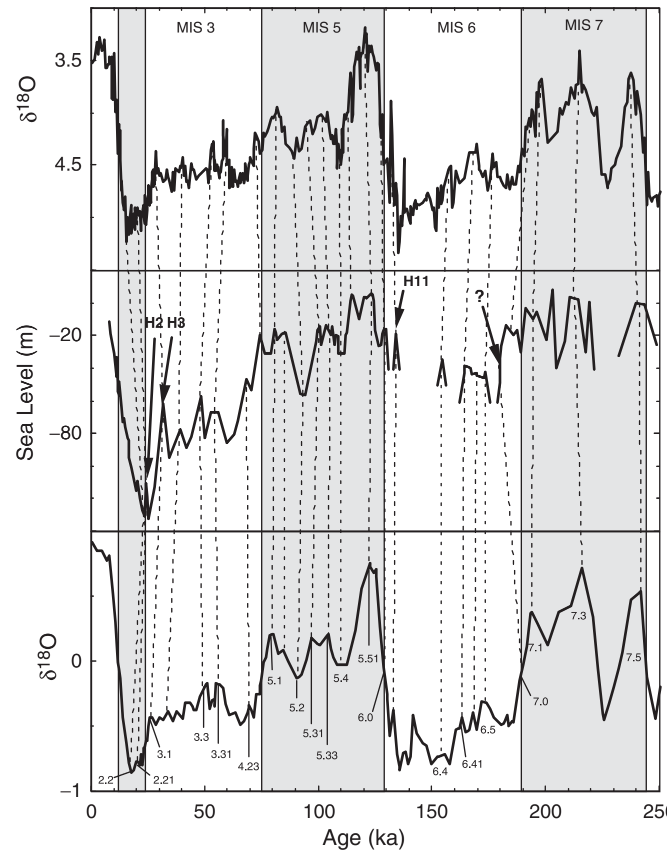

Fig. 2. Correlation of sea level and $\delta^{18}O$ events. Dotted lines indicate correlation between records. Marine Isotope Stage boundaries indicated are those of SPECMAP. (a) The benthic $\delta^{18}O$ record from core V19-30 (Shackleton et al., 1983), the best-resolved record in the SPECMAP stack. All $\delta^{18}O$ scales are reversed so that negative isotopic events are peaks for ease of comparison with the sea-level record. (b) Our high-resolution coral sea-level reconstruction. Three sea-level highstands potentially associated with Heinrich events and discussed in the text are labelled. The question mark and arrow indicate an anomalous event discussed in the text. (c) The stacked SPECMAP benthic $\delta^{18}O$ record (Pisias et al., 1984) on the SPECMAP timescale (Martinson et al., 1987) with selected $\delta^{18}O$ events (Martinson et al., 1987) labelled.

There are only eight gaps between ages that exceed 3 ka. The correspondence between our high-resolution sea-level record and the SPECMAP record is striking (Fig. 2), and in most cases, the correlation of sea-level events with $\delta^{18}O$ excursions is unequivocal. Based on this correlation, we match specific isotope events in the SPECMAP record with corrected U/Th ages of individual corals, assigning high-precision radiometric ages to 24 events for the first time, providing a timescale that is independent of orbital tuning assumptions (Table 1). To test the sensitivity of these results to the drawing of the curve and assess the robustness of the age picks, we deleted the chosen data points, redrew the curve, and compared the new ages to our first choices (Table 1). Although two single-point peaks are eliminated entirely, the average difference in ages was 1.1 ka. With few exceptions, the agreement between the corrected ages and SPECMAP is startling (Fig. 3); and suggests that the average uncertainty (5 ka) quoted for

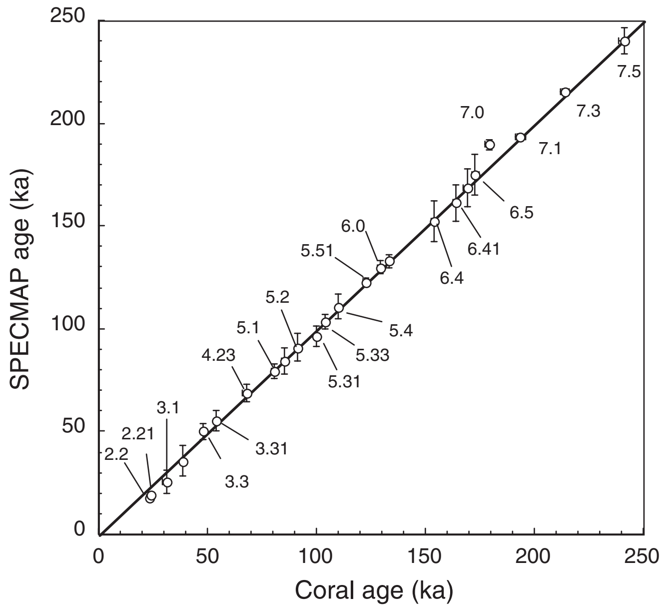

Fig. 3. A comparison of SPECMAP's orbitally tuned age estimates (Martinson et al., 1987) and open-system U/Th coral ages. Data points that correspond to numbered SPECMAP events are labelled. The solid line is a 1–1 line and ages that agree will plot on this line. Error bars are 2-σ and those not visible are smaller than plot symbols.

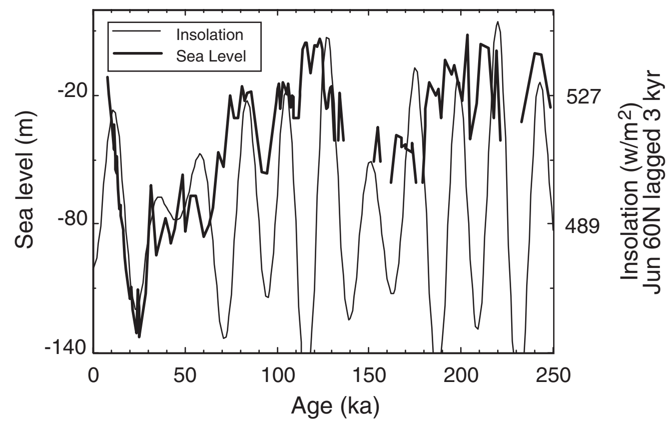

Fig. 4. Sea level and Northern Hemisphere insolation. Thin line is insolation variability at 60°N that is a result of changes in the Earth's orbit (Berger and Loutre, 1991). Thick line is our high-resolution sea-level curve.

SPECMAP timescale was overestimated. Excluding SPECMAP ages younger than 35 ka, which were linked to uncalibrated radiocarbon ages, and a clear anomaly at the MIS 7/5 boundary, the average difference between radiometric and SPECMAP ages is 1.3 ka. Our results strongly support the accuracy of the SPECMAP chronology, suggesting that the astronomical theory of climate change provides a robust basis for orbital tuning strategies. Indeed, the orbitally driven component of sea-level fluctuation is clearly evident in our record (Fig. 4), consistent with the findings of many previous investigators, e.g. Broecker et al. (1968), Mesolella et al. (1969), Edwards et al. (1987), Stirling et al. (2001), Bard et al. (2002), Robinson et al. (2002), Andersen et al. (2005). There is also considerable suborbital sea-level variability (Chappell, 2002; Siddall et al., 2003; Potter et al., 2004; Thompson and Goldstein, 2005) that may be unrelated to Northern Hemisphere insolation change. However, it is quite clear that: (1) high-amplitude sea-level change at periods greater than 20 ka is nearly in phase with summer insolation in the Northern Hemisphere (Fig. 4), (2) the majority of sea level change between colder and warmer climates is due to the waxing and waning of large Northern Hemisphere ice sheets (Peltier, 2002), (3) summer insolation at high latitudes provides the strongest insolation signal (Berger and Loutre, 1991). Although sea-level change cannot be uniquely tied to isolation at a specific season and latitude, and the apparent sensitivity of ice volume to insolation change requires substantial amplification, the simplest explanation for these observations is that long-period high-amplitude ice volume change is linked to variability in Northern Hemisphere high latitude insolation.

4. Discussion

There are only two instances where the corrected U/Th and SPECMAP chronologies differ significantly (Fig. 3): from the end of Marine Isotope Stage (MIS) 3 to the lowest sea levels of the Last Glacial Maximum (LGM) and at the MIS 7/6 transition (Fig. 2). These discrepancies may represent either problems with SPECMAP's timescale or our sea-level reconstruction. The MIS 3/2 transition is poorly resolved in our record (Fig. 1). The LGM is better resolved, with 18 ages between 19.6 and 24.6 ka, but the exact shape of the sea-level curve is somewhat dependent on uplift assumptions. As previously discussed, there is some uncertainty regarding seawater $^{234}U/^{238}U$ at this time. However, the brief sea-level high stand at a U/Th age of 23.7 ka (Fig. 2b) may be related to Heinrich event 2 (H2). The age of H2 has been independently determined to be ~24 ka (Hemming, 2004), suggesting our bracketing U/Th ages of 23.1 and 24.6 ka for the lowest sea levels of the LGM are quite accurate, and that SPECMAP's age of 17.9 for event 2.2 (Fig. 2c) is ~5 ka too young. The same case can be made for event 3.1, the last negative $\delta^{18}O$ excursion in MIS 3, which is contemporaneous with H3 in several records (e.g., Labeyrie et al., 1999). Our U/Th age of 31.1 ka agrees with the ~31 ka age of H3 (Hemming, 2004), but ~6 ka older than SPECMAP's age of 25.4 ka for event 3.1. Much of the discrepancy between the SPECMAP and U/Th timescales near the LGM is very likely due to the use of uncalibrated radiocarbon ages in this interval as initial tuning constraints for SPECMAP.

At the MIS 7/6 transition, the mid-point of falling sea-level (Fig. 2b) has a U/Th age of 179.2 ka, occurring ~10 ka later than the $\delta^{18}O$ shift in the SPECMAP record at 189.6 ka (Fig. 2b and c). The early enrichment of $\delta^{18}O$ may suggest deep ocean temperature change substantially leads sea-level change on this transition. However, if this difference between the SPECMAP and U/Th timescales is real, it represents a significant problem for orbitally tuned ages in this interval (Henderson, pers. comm.).

Our sea-level record also provides some insight into the TII age controversy. It may be that the wide range of age estimates for TII is simply the result of previously unsuspected suborbital climate variability. Our first TII sea-level event occurs at 133.5 ka, which might be considered too early to be accounted for by orbital forcing because it precedes the ~128 ka peak in Northern Hemisphere insolation (Fig. 4). However, this brief highstand occurs ~6 ka after Northern Hemisphere insolation begins to increase, which does not exclude the possible influence of Northern Hemisphere insolation forcing. Furthermore, this sea-level event is simultaneous with Heinrich event 11, as inferred from accurately dated in speleothem records of the Asian Monsoon and northeast Brazil pluvial events (Cheng et al., 2005), and may be related to ice-sheet instabilities during the onset of the Penultimate Deglaciation. Based on the correlations we choose for TII, the sea-level chronology does not conflict with SPECMAP.

While our correlation of the 2 points on TII may be debated, this does not change our conclusion that the SPECMAP timescale is extremely accurate. Indeed, ages of the highest sea-level event and most negative δ^{18}O excursion during MIS 5, immediately following TII, are identical within error. In general, correlations between the sea level and oxygen isotope records are most clear for δ^{18}O peaks within isotope stages, and less clear during transitions between stages, possibly due the effects of to rapidly changing deep-sea temperatures, e.g. Skinner and Shackleton (2005). If changes in temperature and sea-level, which both affect δ^{18}O, are out of phase on the transitions, this would create differences in timing between sea-level and δ^{18}O events. For example, during major transitions to colder climates, deep-sea temperatures may have to cool before substantial ice can form on the continents. In this case, falling sea levels will lag the change in δ^{18}O. Similarly, during major transitions to warmer climates, substantial ice might have to melt before deep-sea temperatures can warm, so that δ^{18}O continues to rise after sea level is relatively high. Under these circumstances, the transition midpoints of the sea level and δ^{18}O records will have different ages, with sea-level highstands being somewhat longer lived than negative δ^{18}O excursions. These differences in timing, if real, do not invalidate the theory of orbitally driven climate or the general application of orbitally tuned chronologies. The ages of the peaks in the coral sea-level record provide a more robust age control than the ages of the transitions for a number of reasons: (1) the age of major marine δ^{18}O transitions may be different at widely spaced locations (Skinner and Shackleton, 2005), (2) the true ages of the transition midpoints may be different in the sea level and δ^{18}O records, (3) age estimates of key MIS stage boundaries, particularly TII, are still in conflict, and (4) the ages of the peaks in the coral sea-level record are generally better-constrained than the ages of the transitions. Therefore, the use of ages from sea-level peaks rather than transitions (Table 1) is recommended when using δ^{18}O stratigraphy to develop marine core chronologies.

5. Conclusions

Our results suggest that age correction equations (Thompson et al., 2003) alleviate many of the problems associated with uncorrected conventional U-series ages, producing sea-level reconstructions with improved accuracy and resolution. This new technique clarifies relationships between sea-level, δ^{18}O, and orbital forcing. There is no question that the sea-level curve presented here may change as new information becomes available. Much work remains to be done linking corrected coral ages and stratigraphic context. Further refinement and testing of age correction equations and constraints are likely to advance our understanding of U/Th coral geochronology. The chronology presented here is as accurate as is currently possible given our present understanding of U-series systematics in corals, the history of ocean δ^{234}U, and the currently available coral data, and is significantly more accurate and better-resolved than previous chronologies based on uncorrected conventional ages. We have identified 24 U/Th high-precision ages that may be used as tie points for a δ^{18}O stratigraphy that is independent of orbital tuning assumptions. With the exception of the LGM and the MIS 7/6 boundary, the average difference between radiometrically determined and orbitally tuned ages is 1.3 ka, suggesting that the uncertainty in the SPECMAP chronology (Martinson et al., 1987) was overestimated. While there is evidence for substantial suborbital sea-level variability, our results confirm the essential validity of both the SPECMAP chronology and orbital tuning strategies. Although sea-level changes cannot be uniquely linked to a specific insolation curve, high-amplitude sea-level changes with periods longer than ~20 ka are nearly in phase with high-latitude Northern Hemisphere insolation. While much work remains to be done to identify the latitudes, mechanisms and amplification of orbital forcing, it seems clear that there is a vital connection between orbital cyclicity and climate. Although there may be one or two climatically significant and chronologically important exceptions, orbital tuning of benthic δ^{18}O records will generate accurate chronologies for marine sediment cores.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online Version at doi:10.1016/j.quascirev.2006.02.007.

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