An astronomical polarity timescale for the late middle Miocene based on cyclic continental sequences

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[1] We present an astronomically tuned polarity timescale for the late middle Miocene based on a cyclic shallow lacustrine/mudflat succession exposed in the Orera Composite Section (OCS; Calatayud basin, NE Spain). Spectral analysis and band-pass filtering of high-resolution carbonate and color reflectance records in the depth domain reveal cyclic changes with different cycle lengths, which correspond to lithological alternations observed in the field. An initial age model was constructed by calibrating the OCS magnetostratigraphy to the geomagnetic polarity timescale of Cand and Kent [1995]. Subsequent spectral analysis of the proxy records in the time domain reveals periodicities close to 23, 41, and 400 kyr and, to a lesser extent, 100 kyr, supporting an astronomical origin for the sedimentary cyclicity in the OCS. We established a new age model based on the astronomical calibration of the OCS to the Laskar et al. [1993] (La93) solution by tuning the cycles to the astronomical target curves. Cross-spectral analysis results of the tuned time series followed by band-pass filtering reveal a remarkably good and in-phase relation with precession and with obliquity despite a presumed uncertainty of 20–40 kyr in the tuning in some short intervals. Our tuning provides astronomical ages for sedimentary cycles and subsequently for polarity reversals in the interval between 12.9 and 10.6 Ma. Comparison with Cand and Kent shows that the OCS polarity reversal ages are older by 80 kyr. This age discrepancy decreases with increasing age to 50–60 kyr.

INDEX TERMS: 1035 Geochemistry; Geochronology; 1520 Geomagnetism and Paleomagnetism; Magnetostratigraphy; 8105 Tectonophysics: Continental margins and sedimentary basins; 9335 Information Related to Geographic Region: Europe; 9604 Information Related to Geologic Time: Cenozoic; KEYWORDS: geochronology, magnetostratigraphy, cyclostratigraphy, astronomical timescale, orbital forcing, Miocene


1. Introduction

[2] An astronomical polarity timescale (APTS) provides accurate ages for polarity reversals based on the tuning of cyclic sedimentary successions with a reliable magnetostratigraphy to astronomical time series of orbital or associated insolation change. The APTS is well established for the late Neogene and Pleistocene, and is based on marine successions from Ocean Drilling Program (ODP) sites [Shackleton and Crowhurst, 1997; Shackleton et al., 1999] and land-based sections in the Mediterranean [Hilgen et al., 1995; Krijgsman et al., 1999]. Although astronomically tuned marine successions are available for the middle Miocene [Shackleton and Crowhurst, 1997; Shackleton et al., 2000; Hilgen et al., 2000], the APTS lacks reversal ages in this interval due to the absence of reliable magnetostratigraphic records. This problem can be overcome by incorporating continental successions, which are known to record orbital-induced climate variations as well [Olsen et al., 1996; Van Vugt et al., 1998; Lu et al., 1999; Heslop et al., 2000; Steenbrink et al., 2000].

[3] One of the most promising continental sections covering the younger part of the middle Miocene is the Orera Composite Section (OCS) located in NE Spain [Abdul Aziz et al., 2000]. This section contains a shallow lacustrine-mudflat succession characterized by a remarkable regular alternation of dolomitic carbonate and mudstones. The calibration of the OCS magnetostratigraphy to the geomagnetic polarity timescale of Cand and Kent [1995] (hereafter referred to as CK95) provided an age range of 10.7 to 12.8 Ma for the entire section and hinted at an astronomical control for the cyclicity. In this paper, we will attempt (1) to substantiate the inferred astronomical origin of the sedimentary cyclicity in the late middle Miocene Orera Composite Section (OCS) in Spain by applying spectral analysis to detailed carbonate content and color records in the depth domain and, following magnetostratigraphic calibration to CK95, in the time domain and (2) to establish an astrochro-
nology for the OCS by tuning its sedimentary cycles to astronomical target curves, using inferred phase relationships between different scales of sedimentary cyclicity and the astronomical parameters. The resulting timescale will provide astronomical ages for polarity reversals in the interval between 12.9 and 10.6 Ma. The new ages will be compared with polarity reversal ages in CK95 and partly fill up the existing gap in the Miocene APTS.

2. Geological Setting and Section

The study area is located in the Valdelosterreros area near the village of Orera, ~15 km southeast of Calatayud (Figure 1). The shallow lacustrine/mudflat succession in that area forms part of a thick sediment pile that was deposited in the NW-SE elongated intramontane Calatayud basin during the Paleogene and Neogene. The exposed sediments are of late middle Miocene age. They were deposited in a shallow lake that formed in an interfan zone between two main alluvial fans, and display a remarkable and distinct alternation of mudstone and dolomitic carbonates [Abdul Aziz, 2001].

The Orera Composite Section (OCS) was constructed by selecting subsections (Figure 1) with the most prominent cyclicity [Abdul Aziz et al., 2000]. Correlations between partially overlapping subsections were established by fol-

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**Figure 1.** Geological setting and location map of the study area. The following subsections were, in a stratigraphical order, used to construct the Orera Composite Section (OCS): Orera Base (OB), Cementerio (CM), Orera Village (ORE), Valdelosterreros I (VTI), Overlap (LY), Valdelosterreros II (VTII), and Valdelosterreros-III (VTIII).

**Figure 2.** (opposite) Lithological column of the Orera Composite Section (OCS) with sedimentary cycle numbers [after Abdul Aziz et al., 2000]. (a) Carbonate (Ca%) and color reflectance (L*) records with their filtered components in the depth domain. Band-pass widths of the filtered carbonate records are $0.561 \pm 0.06 \text{ m}^{-1}$ (1.78 m) and $0.030936 \pm 0.0635 \text{ m}^{-1}$ (3.2 m). Of the color record, band-pass widths are $0.56613 \pm 0.06 \text{ m}^{-1}$ (1.77 m), and $0.2413 \pm 0.045 \text{ m}^{-1}$ (4.1 m). The middle part is the magnetostratigraphic record of the OCS correlated to CK95. (b) CK95-calibrated time series of the carbonate and color records and their filtered components. Band-pass widths of the filtered 25- and 47-kyr components of the carbonate record are $0.04 \pm 0.005 \text{ kyr}^{-1}$ (25 kyr) and $0.02128 \pm 0.00385 \text{ kyr}^{-1}$ (47 kyr). Band-pass widths of the filtered color records are $0.04 \pm 0.005 \text{ kyr}^{-1}$ (25 kyr), $0.02173 \pm 0.00325$ (46 kyr), and $0.00954 \pm 0.0018 \text{ kyr}^{-1}$ (105 kyr). Calibration points used for transforming the proxy records into time series are (stratigraphic level (m)-CK95 (kyr)): 0–12819; 5.33–12775; 9.22–12708; 11.43–12678; 35.53–12401; 51.64–12184; 58.8–12078; 67.3–11935; 101.29–11531; 104.57–11476; 129.85–11099; 131.35–11052; 136.58–10949.
lowing distinct beds in the field or by matching characteristics in the sedimentary cycle patterns [Abdul Aziz et al., 2000]. The position of polarity reversals was verified in stratigraphic overlaps, thus confirming cyclostratigraphic correlations between subsections.

[6] The OCS comprises at least 91 basic sedimentary cycles, which are arranged into larger cycles on different scales (Figure 2). Basic small-scale cycles, further referred to as S cycles, have an average thickness of 1.65 m and are characterized by an alternation of white carbonate beds and reddish and/or greenish gray mudstone. The carbonate beds are numbered in ascending order starting from the base of the section. Nineteen faintly developed carbonate beds, mostly intercalated in thick mudstone intervals, may
represent additional/extra cycles. These beds are denoted with the suffix “A” following the number of the preceding cycle. Large-scale cycles (L cycles) have an approximate thickness of 31 m and are characterized by an alternation of carbonate-poor intervals, in which S cycles are virtually absent or only weakly developed, and intervals with well-developed small-scale mudstone-carbonate cycles. Finally, two other types of cycles are distinguished. An intermediate-scale cycle (I cycle) is identified by thick and prominent carbonate beds in the lower part and by clusters of five well-developed S cycles in the upper part of the OCS. The last type of cyclicity, termed D cycle (after double), is characterized by alternating thick-thin carbonate beds in successive S cycles and is distinctly present in the middle part of the OCS [Abdul Aziz et al., 2000].

3. Material and Methods

3.1. Color Analysis

[7] Color measurements were taken in the field at an average of 16 levels per cycle, with steps of about 10 cm, using a portable photospectrometer (Minolta CM508i). The measurements are automatically converted into L*a*b*, 400 to 700 nm reflectance (%), and other color expression values. The L*a*b* (or CIELAB) value is a uniform color scale recommended by the Commission Internationale de l’Eclairage (CIE). This color scale utilizes an Adams-Nickerson cube root formula, adopted by the CIE in 1976 for use in the measurement of small color differences. When a color is expressed in CIELAB, L* defines lightness, a* denotes the red/green value and b* the yellow/blue value. The 550 nm reflectance record of the OCS is more or less similar to the L* reflectance record. However, we prefer to use the L* reflectance record because it slightly enhances the differences between mudstone and carbonate lithologies.

3.2. Carbonate Analysis

[8] From each mudstone-carbonate cycle, eight levels were sampled to determine the carbonate content. The samples were dried by deep freezing to −40°C and then ground in an agate mortar mill or in an automatic grinder. X-ray diffraction (XRD) measurements on selected samples indicated a high amount of dolomite and minor calcite in carbonate rich samples. Dolomite is a minor constituent in the mudstones in which illite and smectite mineralogies are dominant [Abdul Aziz, 2001]. Dolomite from all samples was brought into solution using the following procedure. Approximately 250 mg of dried sample was treated with 7.5 mL 1 M HCl and shaken for 12 hours. The solution was then preserved and the sample residue was treated again with 7.5 mL 1 M HCl. After 4 hours of shaking, the solution from the sample residue was added to the preserved solution. Major element (Ca and Mg) measurements were performed using an inductively coupled plasma emission spectrometer (ARL 34000). Analytical precision and accuracy were checked by replicate analysis of samples, and by an international and in-house standard. The relative errors were all less than 5% for the major elements. XRD measurements performed on dried residues showed that the dolomite was completely removed from the samples using the extraction procedure.

3.3. Statistical Analysis

[9] We used (cross) spectral analysis to investigate and evaluate the cyclicity in the color and carbonate records of the OCS. The Blackman-Tukey (BT) method was applied using the AnalySeries program [Paillard et al., 1996]. The BT method is based on the standard Fourier transform and requires evenly spaced time series. Therefore interpolation of unevenly spaced data sets is necessary before BT spectral analysis can be performed and hence this procedure may bias statistical results. We also applied the Lomb-Scargle Fourier transform method using the SPECTRUM program [Schulz and Stattegger, 1997], which is useful for unevenly spaced time series allowing analysis without interpolation. We found that the AnalySeries results did not differ significantly from SPECTRUM. Therefore the spectral analysis results presented in this paper are based on the BT method. The Gaussian band-pass filter used to extract the dominant spectral components was chosen such that it covers the maximum possible area of a peak in the power spectrum.

4. Results

4.1. Color and Carbonate Records

[10] The L* reflectance and Ca (%) records are presented in Figure 2 and will be termed color (reflectance) and carbonate record throughout the paper. Although the Mg (%), Ca (%), and Mg/Ca ratios do not differ significantly, we decided to use the Ca (%) record because it most clearly reveals the different scales of sedimentary cyclicity observed in the field. Our color record is derived from the same subsections that were used to construct the OCS [see Abdul Aziz et al., 2000] except for the interval between cycles 42 and 48, which was measured in another subsection because of the less weathered surface and therefore more distinct cyclicity.

[11] The different scales of cyclicity can be distinguished in the color and carbonate records (Figure 2). The S cycles are recognized because carbonate beds correspond to high values in both records. The L cycle is apparent in the color reflectance record in which intervals marked by low reflectance values and weakly developed S cycles alternate with intervals marked by high reflectance values and distinct S cycles. This L cycle is less evident in the carbonate record. However, the carbonate record clearly reflects the D cycle identified by alternating thick-thin carbonate beds in successive S cycles due to variations in bed thickness. This cycle is also discernible in the amplitude variation of the color record, especially in the interval covering cycles 28–50 (Figure 2).

4.2. Spectral Analysis in Depth Domain

[12] Spectral analysis and Gaussian band-pass filtering were performed in the depth domain on the total color and carbonate record and on three discrete intervals, which were selected on the basis of their characteristic cycle patterns as observed in the field. These intervals comprise the cycles 1–28, 28–51, and 51–91. The results for the total records reveal significant peaks, which correspond to cycle lengths...
of 1.77 and 3.2 m for the carbonate and of 1.78 m for the color record (Figure 3a). The prominent peaks at 1.77 and 1.78 m correspond to the S cycles with their average thickness of 1.65 m because the filtered components follow the successive maxima and minima in the color and carbonate records related to the S cyclicity (Figure 2a). Also the carbonate and color spectra for the three separate intervals reveal a dominant 1.77 m peak.

The 3.2-m cycle in the total carbonate record is about twice the average thickness of the S cycles and reflects the D cycle (Figure 3a). Indeed, the filtered 3.2-m component follows this cycle, which is present in the middle part and, to a lesser extent, in the lower part of the OCS (Figure 2a). This observation is consistent with the 3.2-m peaks in the carbonate spectra for the individual intervals (Figure 3a). Also the color spectrum for the middle part of the section reveals a broad peak at 3.9 m that corresponds with the D cycle as well.

Finally, low-frequency peaks at 8.2 and 50 m and at 7.6 and 31 m are present in the spectra of the total and lower part of the color record, respectively (Figure 3a). The filtered 8.2-, 31-, and 50-m components follow the I and L cycles in the OCS (see Figure 4a).

4.3. Spectral Analysis in the Time Domain

The calibration of the OCS magnetostratigraphy to CK95 provided an age range of 10.7 to 12.8 Ma for the entire section [Abdul Aziz et al., 2000]. We transformed the color and carbonate depth records into time series using linear interpolation between and extrapolation beyond age control points provided by the calibration to CK95 (see Figure 2 and caption for age control points). The data were resampled at intervals of 2 kyr to obtain an equally spaced data set necessary for signal processing by the BT method.

The color and carbonate spectra reveal dominant peaks which correspond to periods of 28, 25, and 20 kyr (Figure 3b). The 25-kyr components extracted from the color and carbonate time series closely follow the S cycles, suggesting an orbital control by precession for this type of cyclicity (Figure 2b). Carbonate spectra of the total and middle part of the OCS record further reveal a relatively
broad peak centered around 47 kyr (Figure 3b). A similar peak, although less obvious, is found in the color spectra. The filtered components follow the D cycle, suggesting that it corresponds to the 41-kyr obliquity cycle.

[17] Spectral peaks in the low-frequency range are mainly registered in the color reflectance spectra. Although not well resolved, the most prominent peak in the total color record arrives at around 590 kyr (Figure 3b). Low-frequency peaks are better resolved at 438 and 336 kyr in the color spectra for the lower and upper part of the OCS, respectively. The extracted 590- and 438-kyr components follow the dark intervals with weakly developed mudstone-carbonate cycles and, hence, the L cyclicity in the OCS (not shown in Figure 2b). The periods of these peaks suggest that the L cyclicity corresponds to the 400-kyr eccentricity cycle. Finally, a less obvious peak in the total color spectrum corresponds to a 105-kyr period, whereas a significant 94-kyr component is present in the color spectrum for the lower part of the section. These components may be related to the 100-kyr eccentricity cycle. The filtered 105-kyr component follows the I cycle and is restricted to the lower and upper parts of the OCS (Figure 2b).

5. Phase Relations With the Astronomical Parameters

[18] The results of the spectral analysis suggest that the sedimentary cycles in the OCS are astronomically controlled with precession as the dominant orbital parameter. The logical next step is to tune these cycles to astronomical target curves. However, the phase relations with the orbital cycles have to be determined before the sedimentary cycles of the OCS can be astronomically tuned. Such phase relationships should meet several requirements to make them consistent with astronomical forcing by the eccentricity-precession syndrome and with known paleoclimate data from the marine and continental records.

5.1. Eccentricity

[19] Eccentricity modulates the amplitude of insolation changes driven by precession [Imbrie et al., 1993]. The effect of the modulation of precession by the 400-kyr eccentricity cycle in a hypothetical sedimentary record can be envisaged as follows. During 400-kyr eccentricity maxima precession controlled sedimentary cycles will be distinct and regular because of the enhanced amplitude of the forcing and the dominance of the 23-kyr precession component [Imbrie et al., 1984], respectively. Conversely, small-scale sedimentary cycles will be less distinct and irregular at times of 400-kyr eccentricity minima because of the low amplitude of the forcing and because precession cycles may have variable durations between 14 and 29 kyr. As a consequence, intervals in the OCS marked by a regular and well-developed S cyclicity will correspond to 400-kyr eccentricity maxima. The dark colored intervals, labeled I to V in Figure 4a, with their irregular and less distinct cyclicity will correspond to 400-kyr eccentricity minima. Thus the phase relation between the L cycles and eccentricity is established.

[20] It can be assumed that a similar phase relation will hold for the I cycle relative to the 100-kyr eccentricity cycle. Hence protruding thick carbonate beds and clusters of five well-developed S cycles of the I cycle will correspond to 100-kyr eccentricity maxima.

5.2. Precession

5.2.1. Marine Record

[21] To establish the phase relation between the S cycles and precession, the cyclicity in the marine record of the Mediterranean has to be taken into account. In late Neogene marine sequences, cyclic alternations of marls and sapropels occur on different scales and their phase relations with the orbital parameters are known. Small-scale marl.sapropel cycles are precession controlled, the sapropels corresponding to precession minima and hence to summer insolation maxima [Rossignol-Strick, 1983; Hilgen, 1991a; Lourens et al., 1996]. Climate conditions at times of sapropel formation are marked by an enhanced seasonality with increased precipitation [Lourens et al., 1992; Foucault and Mélières, 2000]. In contrast, reduced seasonality and precipitation favoring more arid climate conditions occurred during marl deposition. Summarizing, the marl-sapropel cycle reflects precession-induced dry-wet climate oscillations, an oscillatory system that remained essentially unchanged over the last 12 Myr [Schenau et al., 1999; Hilgen et al., 2000], i.e., well into the time interval covered by the OCS.

[22] On a larger scale, sapropel clusters correspond to eccentricity maxima, both for the 100- and 400-kyr eccentricity cycle, whereas sapropels are poorly developed or lacking during eccentricity minima [Hilgen, 1991a, 1991b]. The lack (or near absence) of sapropel deposition points to prolonged periods of relatively dry climate conditions at times of eccentricity minima [Rossignol-Strick, 1983, 1987; Rohling and de Rijk, 1999; Wehausen and Brümsack, 2000]. Consequently, sapropel clusters can best be explained by a series of precession-induced humid episodes linked to high amplitudes of successive precession minima at times of eccentricity maxima.

5.2.2. Continental Record

[23] According to our depositional model for the small-scale mudstone-carbonate cycle, mudstones accumulated on subaerially exposed, vegetated distal alluvial fan mudflats at times of lake level lowstands and relatively dry climate conditions [Abdul Aziz, 2001]. Carbonate precipitated from a shallow lake that extended over the mudflats at times of lake level highstands and relatively humid but probably also evaporative climate conditions. Given this link between the S cycles and climate, we can deduce their phase relation with precession by comparing the climate conditions that prevailed at times of sapropel formation and the known phase relation of these sapropels with precession. It follows that the carbonate beds of the S cycles in the OCS correspond to precession minima and that the mudstones correspond to precession maxima. This inferred phase relation is consistent with the interpretation of lignite-marl cycles in Pliocene lacustrine successions from the Ptolemais basin in northwestern Greece [Van Vugt et al., 1998; Kloosterboer-van Hoeve, 2000]. The latter cycles reflect lake level oscillations with higher lake levels resulting from enhanced winter precipitation during precession minima.

[24] The paleoclimatic interpretation of the S cycles and their phase relation with precession can now be combined with the previously established phase relations between the L cycle and 400-kyr eccentricity. This implies that the dark
colored intervals I–V correspond to relatively dry climate conditions and lake level lowstands. Conversely, carbonate beds in intervals with regular and distinct S cycles indicate punctuated wetter climate conditions and lake level highstands. Such conditions are linked to high-amplitude precession minima, which occur at times of eccentricity maxima. This phase relation is consistent with the interpretation of cyclic patterns observed in Pliocene marine sediments from drill holes located in the Gulf of Cadiz [Sierro et al., 2000]. They found that prolonged periods of relatively dry climate conditions occurred during 400-kyr eccentricity minima and punctuated wet episodes during eccentricity maxima. Again the same will hold for the I cycle with respect to the 100-kyr eccentricity and climate.

5.3. Obliquity

[25] Finally, even though obliquity is supposed to be less effective at low latitudes [Van Woerkum, 1953; Berger, 1978], its influence is recorded through interference with precession in the D cycle. The phase relation of the S cycles with precession in combination with seasonal changes in insolation (i.e., maximal seasonal contrast at times of obliquity maxima) implies that the thick carbonate beds of this cycle correspond to obliquity maxima and the intervening thinner beds to obliquity minima.

6. Late Middle Miocene APTS

[26] Now that we have established the phase relations between the sedimentary and orbital cycles we can continue with the tuning procedure. The initial age model is based on calibrating the OCS magnetostratigraphy to CK95. For the astronomical calibration we use the La93(1,1) solution with present-day values for the dynamical ellipticity of the Earth and tidal dissipation by the moon [Laskar et al., 1993] (La93). We selected this solution because it agrees very well with the sedimentary cycle patterns in marine sequences from the Mediterranean Plio-Pleistocene [Lourens et al., 1996, 2000]. The tuning approach follows the same procedure as used in the marine realm, which is based on tuning cycles with successively shorter periods to the astronomical curves [Hilgen et al., 1995]. The 400-kyr eccentricity cycle is considered the most secure basis for extending the astronomical timescale back in time [Shackleton et al., 2000] and, hence, the first-order tuning involves correlation of the L cycle to the 400-kyr eccentricity curve. Independent confirmation of the first-order tuning can be obtained from characteristic patterns in the astronomical and sedimentary cycle records such as interference between precession and obliquity. Finally, each S cycle is tuned to the precession and summer insolation time series.

6.1. Tuning to 400-kyr Eccentricity

[27] The first-order tuning involves the calibration of the dark colored intervals of the L cycle to 400-kyr eccentricity minima. These intervals comprise S cycles 14–17, 29–33, 44–50, 61–66, and 79–85, and they are labeled I–V (Figure 4). No direct correlation between these intervals and the eccentricity minima is found when we start from the ages provided by the magnetostratigraphic calibration to CK95. The minimal adjustment necessary for a consistent correlation between carbonate-poor intervals and eccentricity minima is shifting the ages of the calibration points toward older levels by 50–100 kyr. Such a shift is consistent with new astrobiological age estimates for polarity reversals in middle Miocene marine records, which indicated that the reversals may be about 50 kyr older than the ages in CK95 [Shackleton and Crowhurst, 1997; Hilgen et al., 1995, 2000].

[28] Alternative calibrations involved shifting intervals I–V to 400 kyr younger or older levels implying that the ages of the polarity reversals would become either 350 kyr younger or 450 kyr older than in CK95. Both calibration efforts do not result in a convincing correlation because precession-obliquity interference patterns support the initial first-order calibration shown in Figure 4a. Interference patterns in the OCS identified by thick-thin alternations of carbonate beds in successive S cycles are prominent in the interval which comprises cycles 29 to 50 and includes 400-kyr eccentricity minimum intervals II and III. Interference between precession and obliquity is expected during eccentricity minima related to the long-period 2.35 Myr cycle [Hilgen et al., 2000]. Such a minimum is reached between 12.5 and 12.2 Ma and coincides with cycles 16–28 (Figure 4a). However, also obliquity is marked by a long-term 1.2 Myr cycle [Lourens and Hilgen, 1997] whereby maximum amplitude variations occur in the interval between 11.6 and 12.2 Ma, which coincides with cycles 28–50. Because of the combined effects of these two long-period cycles, precession-obliquity interference in our insolation target is particularly strong in the interval between 11.6 and 12.2 Ma, which corresponds with the middle part of the OCS hence confirming the first-order tuning to the 400-kyr eccentricity cycle presented in Figure 4a. Moreover, discrepancies between the CK95 reversal ages and astronomical ages of 350 kyr (younger) or 450 kyr (older) are considered unlikely. A last exercise involved shifting the carbonate-poor intervals to 100 kyr older or younger levels, but this adjustment did not result in a consistent relation of the L cycle with 400-kyr eccentricity.

6.2. Tuning to Precession

[29] The next logical step in the tuning would involve the 100-kyr eccentricity cycle. The related I cyclicity, however, is not very distinct in the OCS and is restricted to short intervals that are insufficiently long to establish a second-order calibration for the entire OCS. The same is true for the obliquity-related cycle. We therefore continue with the tuning of the small-scale mudstone-carbonate cycles to precession (Figure 4b).

6.2.1. Tuning of Cycles 1–28

[30] A straightforward correlation is achieved for the well-developed S cycles 1–13 and 16–27. However, due to several weakly developed carbonate beds in 400-kyr eccentricity minimum interval I, S cycles 1–13 could be tuned one or two precession cycles older (Figure 4b).

6.2.2. Tuning of Cycles 28–51

[31] The result of the tuning is a satisfactory and straightforward astronomical calibration of the S cycles 28–51 to precession (Figure 4b). The S cycles in the 400-kyr eccentricity minimum interval II are more regular and well developed than in other 400-kyr eccentricity minimum intervals. This may be explained by the fact that eccentricity does not reach extreme minimum values in this interval in
which regular precession cycles with 19- and 23-kyr periods dominate. Obliquity exerted a strong influence as evidenced by the dominance of the D cycle. On the basis of the phase relation with obliquity and precession, thick carbonate beds correlate to high-amplitude insolation maxima while the intervening thinner carbonate beds correlate to low-amplitude insolation maxima (Figure 4b).

6.2.3. Tuning of Cycles 51–91

[32] Apart from some uncertainties in the uppermost part, the correlation to precession is rather well constrained, especially for cycles 51–71 (Figure 4b). The imprint of the 100-kyr eccentricity cycle is obvious in this interval as evidenced by clusters of five S cycles between cycles 67 and 75 with a less pronounced cycle (71 and 77) separating each 100-kyr cluster (Figure 4b). The uncertainties involve (1) the correlation of cycle 72 which may possibly be tuned one precession cycle younger and (2) the complex cyclic pattern between cycles 80 and 91. Nevertheless, a correlation is achieved for cycles 80–91 if we use the average cycle thickness as an additional constraint. However, the tuning presented for this uppermost part should not be considered definite.

6.3. Evaluation of the Tuning

[33] Except for the uppermost part, a good correspondence between the OCS cycles and the astronomical record is observed (Figures 4a, 4b, and 5). The tuning of the L cycle to the 400-kyr eccentricity cycle appears convincing and robust. Also the detailed tuning of the S cycles in the well-developed mudstone-carbonate intervals to precession and insolation is straightforward although an uncertainty of one or possibly two precession cycles in the tuning cannot be excluded in some intervals. In contrast, the correlation of S cycles in some of the 400-kyr eccentricity minimum intervals to precession is hampered due to the weak or even lack of expression of the S cyclicity. Nevertheless, our astronomical tuning is supported by the precession-obliquity interference patterns as can be observed by the good correspondence between alternating thick-thin carbonate beds and amplitude variations in the insolation maxima of the insolation curve (Figure 4b).

[34] An age model for the OCS can now be constructed by assigning astronomical ages of the correlative precession minima to the midpoints of the carbonate beds. The quality of the astronomical tuning can be tested by spectral analysis of the carbonate and color reflectance records and by cross-spectral analysis between the tuned records and the orbital parameters (Figures 3c and 6). The spectral results for the three separate intervals of the OCS show dominant peaks in the precession band at 23 and 19 kyr (Figure 3c), which is not unexpected in view of the tuning of the carbonate beds to precession. Also obvious is the 41-kyr obliquity related peak in the spectra for the middle part of the section. Low-frequency 400- and 100-kyr eccentricity related peaks are present in the color spectra for the lower and upper part of the OCS (Figure 3c).

[35] Spectral and cross-spectral results of the total carbonate and color reflectance records reveal the dominance of precession and, not surprisingly, a high significant coherence and in-phase relation with ETP in the precession band (Figure 6). This also holds for the signal in the obliquity band. Since the OCS is tuned to precession, the good coherence and in-phase relation with obliquity (Figure 6) suggest that the tuning is reliable. The filtered 41-kyr components indeed show a good fit and in-phase relation of especially the filtered carbonate component with obliquity (Figure 5). However, also this outcome is not unexpected because the interference pattern observed in the insolation target curve has been taken into account during the tuning of the S cycles to precession. Unfortunately, it is not clear at present whether the precession/obliquity interference is still reliably resolved in the La93(1,1) solution for the interval between 10.5 and 12.5 Ma [Laskar, 1999].

[36] A good coherency is, as expected, found for the L cycles of the OCS and the 400-kyr eccentricity cycle (Figures 5 and 6). According to Shackleton et al. [1999], the accuracy of the astronomical tuning depends on counting 400-kyr eccentricity cycles back from the present, an approach that we followed when we started our tuning from the first-order calibration of the L cycles. Finally, the link between the intermediate cycle and 100-kyr eccentricity is less convincing which can be due to small errors in the tuning, the poor expression of the 100-kyr eccentricity cycle in the proxy records (Figure 5) or small uncertainties in the La93 solution.

6.4. Ages of the Reversal Boundaries

[37] Astronomical ages can be assigned to the polarity reversal boundaries and are compared with the polarity reversal ages of CK95. Starting with subchron C5n.2n (o) to C5An.1n (y), the ages of the polarity reversal boundaries are consistently older by about 80 kyr (Table 1). This age discrepancy decreases to 50–60 kyr from subchron C5An.1n (o) to C5Ar.2n (o). Apart from the youngest astronomically dated age control point used in CK95, uncertainties in the ages of older tie points are fairly large [see Cande and Kent, 1992]. The next older calibration point, C5Bn (y), is assigned an age of 14.8 Ma, which is the average of two radioisotopic ages namely 14.6 ± 0.4 Ma [Tsuchi et al., 1981] and 15.0 ± 0.3 Ma [Andreeff et al., 1976]. The third calibration point is at the Oligocene-Miocene boundary, which is assumed to correspond to C6Ch.2n (o) and assigned an age of 23.8 Ma according to Harland et al. [1990]. However, the error of that estimation is ±1 Myr [Harland et al., 1990]. Considering the uncertainties of the calibration ages, we see no reason to

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Figure 4. (opposite) (a) First-order calibration of the dark, carbonate-poor intervals of the large-scale cycles (shaded) in the Orera Composite Section (OCS) to 400-kyr minima of the eccentricity curve of La93(1,1) [Laskar et al., 1993]. The filtered components of the color record in the depth domain have band-pass widths centered at 0.122 ± 0.0285 m⁻¹ (8.2 m), 0.032475 ± 0.005 m⁻¹ (31 m), and 0.02011 ± 0.005 m⁻¹ (50 m). (b) Detailed tuning of the OCS small-scale cycles to precession and to 65°N summer insolation curves of La93(1,1). The thick carbonate beds of the thick-thin interference pattern in the OCS are tuned to enhanced peaks of maximum insolation (extended solid lines). The right column shows the geomagnetic polarity timescale (GPTS) of Cande and Kent [1995].
Figure 6. Cross spectra and coherency results of the carbonate and color records with ETP (equal to the sum of normalized orbital parameters of precession, multiplied by $-1$, tilt and eccentricity). (top) Blackman-Tukey variance spectra for proxy records (thick solid line) and ETP (thin solid line) plotted on a log scale. The bandwidth (= 0.00667) and upper and lower confidence intervals (80%) are shown in the lower left corner of the spectra. (middle) Coherency spectra with 80 and 95% significance levels of nonzero coherency. (bottom) Phase angle spectra with (80%) confidence interval (dashed lines). The AnalySeries program of Paillard et al. [1996] was used for all the calculations.

Figure 5. (opposite) Filtered records of the carbonate (Ca%) and color reflectance time series ($L^*$) after astronomical tuning of the Orera Composite Section and their comparison with the astronomical curves of $La93_{1,1}$ [Laskar et al., 1993]. The 41-kyr obliquity related filters for the carbonate and color records (dashed lines) are centered at $0.02439 \pm 0.0059$ kyr$^{-1}$ and $0.02439 \pm 0.005$ kyr$^{-1}$, respectively, and show a good fit with the obliquity curve of $La93_{1,1}$ (solid lines). The thick carbonate beds of the D cycle are shown by the stretched dashed lines. A good fit can also be observed between the 409-kyr color reflectance filter centered at $0.002445 \pm 0.0005$ kyr$^{-1}$ and the 400-kyr eccentricity filter of $La93_{1,1}$ centered at $0.0025 \pm 0.0001$ kyr$^{-1}$. In contrast, the filtered 92-kyr component of the carbonate record, centered at $0.010865 \pm 0.002$ kyr$^{-1}$, does not agree with the 100-kyr eccentricity curve of $La93_{1,1}$.
Table 1. Stratigraphic Position of Polarity Transitions of the Subchrons in the Orera Composite Section (OCS), Their Astronomical (APTS OCS) and Spreading Rate (SR-OCS) Ages, and Comparison With Other Age Models

<table>
<thead>
<tr>
<th>Chron</th>
<th>Lithology and Cycle</th>
<th>Stratigraphic Level, m</th>
<th>APTS-OCS, Ma</th>
<th>SR-OCS, Ma</th>
<th>CK95, Ma</th>
<th>Δ OCS-CK95, Ma</th>
<th>ODP Site 845, Age 1, Ma</th>
<th>Δ OCS-Age 1, Ma</th>
</tr>
</thead>
<tbody>
<tr>
<td>C5n.2n (o)</td>
<td>top C 74 (or in M 73)</td>
<td>135 (or 136.12)</td>
<td>11.043 (or 11.023)</td>
<td>11.030</td>
<td>11.049</td>
<td>0.094 (or 0.074)</td>
<td>10.998 ± 0.020</td>
<td>0.085 ± 0.025</td>
</tr>
<tr>
<td>C5r.1n (y)</td>
<td>M 69</td>
<td>131.35</td>
<td>11.122</td>
<td>11.122</td>
<td>11.052</td>
<td>0.070</td>
<td>11.071 ± 0.020</td>
<td>0.051 ± 0.020</td>
</tr>
<tr>
<td>C5r.2n (o)</td>
<td>M 74 (or in M 73)</td>
<td>135 (or 136.12)</td>
<td>11.043 (or 11.023)</td>
<td>11.030</td>
<td>11.049</td>
<td>0.094 (or 0.074)</td>
<td>10.998 ± 0.020</td>
<td>0.085 ± 0.025</td>
</tr>
<tr>
<td>C5r.1n (y)</td>
<td>M 51 (or M 52)</td>
<td>101.29 (or 99.67)</td>
<td>11.618 (or 11.650)</td>
<td>11.630</td>
<td>11.531</td>
<td>0.087 (or 0.119)</td>
<td>11.673 ± 0.013</td>
<td>-0.055</td>
</tr>
<tr>
<td>C5Ar.2n (o)</td>
<td>M 27</td>
<td>51.64 ± 0.4</td>
<td>12.214 ± 0.005</td>
<td>12.220</td>
<td>12.184</td>
<td>0.03 ± 0.010</td>
<td>12.105 ± 0.030</td>
<td>0.013 ± 0.020</td>
</tr>
<tr>
<td>C5Ar.1n (y)</td>
<td>M 18</td>
<td>35.53</td>
<td>12.447</td>
<td>12.447</td>
<td>12.401</td>
<td>0.046</td>
<td>-0.004 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>C5An.2n (o)</td>
<td>M 7</td>
<td>9.22</td>
<td>12.770</td>
<td>12.770</td>
<td>12.708</td>
<td>0.062</td>
<td>-0.004 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>C5An.2n (o)</td>
<td>M 3</td>
<td>5.1 ± 0.3</td>
<td>12.825 ± 0.005</td>
<td>12.830</td>
<td>12.775</td>
<td>0.047</td>
<td>-0.004 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>C5An.2n (o)</td>
<td>Below C 1</td>
<td>0</td>
<td>12.881</td>
<td>12.881</td>
<td>12.819</td>
<td>0.062</td>
<td>-0.004 ± 0.010</td>
<td></td>
</tr>
</tbody>
</table>

*OCS is after Abdul Aziz et al. [2000]. For each polarity reversal, the type of lithology (C, carbonate, and M, mudstone), its corresponding cycle number, and stratigraphic position are shown. In some cases the polarity reversal is unclear and possible positions are indicated between parentheses or as an error.

The astronomical ages of the OCS (APTS OCS) was determined by assigning astronomical ages of the corresponding precession minima of La93 [Laskar et al., 1993] to the midpoints of the carbonate beds. The method for constructing spreading rate ages (SR OCS) is described in the text. For a comparison with other timescales, the difference (Δ) between the APTS OCS ages and published ages according to the geomagnetic polarity time scale (GPTS) of Cande and Kent [1995] is shown. The magnetostratigraphy from ODP site 925 to site 845 of ODP Leg 138 from sedimentary records in the open ocean, which were tested and confirmed the new APTS CK95 ages.

To allow an expanded vertical scale in Figure 7, the distance measurement plotted in Figure 7 are reduced by subtracting a constant spreading rate prediction. The distance prediction is the product of the rate labeled in the figure margin and the age from the spreading rate (SR) column of Table 1. These ages are directly from the OCS tuning in cases where cycle ambiguity or gaps in the

doubt our APTS because of modest disagreement with the CK95 ages. [38] The OCS polarity reversal ages show a slightly better agreement with the polarity reversal ages estimated from sedimentary records in the open ocean, which were determined by exporting astronomical ages of nannofossil events from ODP site 925 to site 845 of ODP Leg 138 having a reliable magnetostratigraphy [Backman and Raffi, 1997; Hilgen et al., 2000]. In general, the OCS polarity reversal ages are about 40 kyr older than the combined Ceara Rise/eastern Pacific ages (Table 1). Age estimates for the most reliably dated reversals of subchron C5r.2n, associated with the calcarceous nannofossil Discoaster kugleri, are even 50 kyr older than the OCS ages. This discrepancy may partially result from an error (of 20 or 40 kyr) in the tuning of the OCS, but the tuning in the Ceara Rise (and of the Glibiscemi section in Sicily) might be prone to small errors as well. Also, the basic assumption of synchronous calcarceous nannofossil events and constant sedimentation rates at ODP Leg 138 site 845 might prove to be incorrect. Therefore the estimated ages of the reversal boundaries in the open ocean should not be considered as definitive, as they only represent a fair approximation of the true astronomical ages, as stated by Hilgen et al. [2000].

7. Testing and Confirming the New APTS Ages Using Seafloor Spreading Rates

[39] Additional evaluation of the magnetic reversal ages is possible by testing their implications for rates of seafloor spreading (Figure 7). Our technique closely follows that of Wilson [1993] and Krijgsman et al. [1999], who demonstrated that many plate pairs show constant spreading rates over intervals of 3–6 Myr duration according to the APTS for the last 10 Myr. We assume that simultaneous apparent rate changes of the same ratio on multiple plate pairs are artifacts of timescale errors, and that a successful calibration for older than 10 Ma will extend the pattern of common intervals of constant spreading rate. Instead of determining interval rates by measuring the widths of individual polarity intervals along ship tracks, we measure the total spreading distance by determining the finite rotation that reconstructs observed reversal positions on opposite plates to their original common location. Testing a set of total distances for constant rate according to a given timescale is a simple matter of testing for linearity of age versus distance. In a slight refinement of the technique of Wilson [1993] appropriate for large total spreading distances, we restrict the rotation pole search to one dimension by solving for an interpolation factor between two finite rotations that bound the time interval of interest.

[40] We found six plate pairs suitable for precise spreading distance measurement, and in all cases interpreted reversal positions from digital magnetic data obtained from NGDC (National Geophysical Data Center) or the scientists who collected the data. South America-Africa distances have been presented by Weiland et al. [1995] and Grindlay et al. [1995]. Pacific-Antarctic and Nazca-Antarctic distances are based on reanalysis of data presented by Cande et al. [1995] and Tebbens et al. [1997], respectively. Australia-Antarctic, Cocos-Pacific, and Nazca-Pacific distances are based on new compilations (D. Wilson, manuscript in preparation, 2002). For anomalies C3B to C4A, distance measurements overlap substantially with those presented by Krijgsman et al. [1999], and ages are from Hilgen et al. [1995]. To allow an expanded vertical scale in Figure 7, the distance measurements plotted have been reduced by subtracting a constant spreading rate prediction. The distance prediction is the product of the rate labeled in the figure margin and the age from the spreading rate (SR) column of Table 1. These ages are directly from the OCS tuning in cases where cycle ambiguity or gaps in the
South America-Africa

\[ R = 42.5 \text{ mm/yr} \]

\[ 31^\circ \text{S} \]

Pacific-Antarctic

\[ R = 40.4 \text{ mm/yr} \]

\[ 64.5^\circ \text{S} \]

Australia-Antarctic

\[ R = 65.0 \text{ mm/yr} \]

\[ 98^\circ \text{E} \]

Nazca-Antarctic

\[ R = 79.2 \text{ mm/yr} \]

\[ 64.5^\circ \text{S} \]

Cocos-Pacific

\[ R = 181.7 \text{ mm/yr} \]

\[ 6^\circ \text{N} \]

Nazca-Pacific

\[ R = 173.1 \text{ mm/yr} \]

\[ 18^\circ \text{S} \]

Figure 7. Reduced distance tests for constant spreading rate. Observed spreading distance \((D)\) is plotted against age \((A)\), after subtracting predicted distance according to a constant spreading rate \((R)\) model. Distance scales are plotted inversely to the spreading rate so that for plate pairs spreading constantly at the reduction rate, timescale errors will plot as uniform vertical departures from the reduction line (0.1-Myr scale bar). Our revised ages (solid lines) indicate that plate pairs not including Cocos or Nazca plates are consistent with constant spreading rate older than 8 Ma; pairs including those are approximately constant older than 11 Ma, and each requires a rate change at 10.0–10.5 Ma.
magnetostratigraphic record introduce only negligible errors. In other cases, these SR ages are an attempt to use the spreading distance observations to refine the age determination within the uncertainties listed in the APTS age column of Table 1. Age adjustments in these cases are intended to bring as many distance observations as possible into consistency with the average rates defined by the better determined ages. For the very fast Cocos-Pacific and Nazca-Pacific plate pairs, full spreading rates above 170 km yr$^{-1}$ mean that the better determined distance measurements with 95% confidence intervals of ±1.5 km correspond to age uncertainties slightly less than ±0.01 Myr. Also, magnetic reversal ages separated by only 0.05 Myr correspond to polarity boundaries spaced greater than water depth (3.6–4.2 km), allowing separate resolution of the young and old boundaries of brief polarity intervals C5r.2n and C5An.1r.

Figure 8. Marine magnetic anomaly profiles from conjugate areas of the Pacific and Nazca plates formed at 10–13 Ma. Pacific profiles are from 15° to 20°S; Nazca profiles are from 18° to 23°S and include data previously published by Cande and LaBrecque [1974], Handschumacher [1976], and Lonsdale [1985] with comparable identifications. Synthetic anomalies at bottom are calculated from the reversal ages of Table 1 (SR) using an 86 mm yr$^{-1}$ half spreading rate and a 5-km transition width. Agreement between data and model is good to excellent, and the ages of subchron C5r.2r-1 directly from the OCS tuning successfully predict a tiny wiggle observed on most of the profiles.

For South America-Africa, Pacific-Antarctic, and Australia-Antarctic, our reversal ages are consistent with constant spreading rates over the age range bounded by 7–8 Ma at the young end and extending to the limit of anomaly coverage or reversal ages at 12–13 Ma. The steadiness of Australia-Antarctic spreading is especially striking, with no distances measurements deviating more than 2.0 km from the prediction of a 65.0 mm yr$^{-1}$ constant rate for the age range 7–13 Ma. The faster spreading rate pairs Nazca-Antarctic, Cocos-Pacific, and Nazca-Pacific all have a relatively constant rate for the 11.0–12.8 range of the Orera ages, but all require a rate change at 10.0–10.5 Ma. The eastern Pacific has long been recognized as having a tectonic reorganization at about this time [e.g., Herron, 1972; Wilson, 1996]. Because the rate changes are of different ratios, it is not possible for any alternative timescale to predict constant spreading rate for more than one of these pairs. In fact, we consider the implication that these plate pairs changed rates simultaneously to be good corroboration of our reversal ages.

[42] The spreading rate implications support the younger alternative in resolving the 100-kyr ambiguity in correlating interval V with the eccentricity model. An age 100 kyr older for C5n.2n (o) would introduce a 7-km departure in the case of Australia-Antarctic from the linear age-distance relation established by the other reversals. For at least five of the six plate pairs we consider, the older alternative would imply a 15% rate increase at subchron C5r.2n, followed in most cases by decrease to below the original rate near subchron C5n.2n (o), followed by another change by subchron C4Ar.2n, returning to the original rate in some cases.
simplicity of the younger alternative, with only a single rate change on half of the plate pairs, is preferable.

[43] Even though normal polarity interval C5r.2r-1 is not mentioned in the timescales of Cande and Kent [1992, 1995], it has been identified by Schneider [1995] in a core from ODP Leg 138, Site 845. Moreover, its existence as an event of comparable duration to C5r.1n (Table 1) is evident from marine magnetic anomaly profiles where fast spreading rate and satisfactory magnetic geometry allow resolution of these closely spaced, brief intervals. Magnetic anomaly profiles from the central part of the Nazca-Pacific plate pair (Figure 8) show two peaks of comparable amplitude in the younger half of the predominately reversed interval between C5n and C5r.2n. For this time interval, the fine structure of Cande and Kent timescales is derived from the timescale of Blakely [1974], who worked with profiles from the northeast Pacific formed at a half rate of 40 km Myr\(^{-1}\). At that rate, two brief polarity intervals separated by \(\sim 0.1\) Myr will be only marginally resolvable as distinct sea surface magnetic anomalies. The single polarity interval reported in these timescales appears to reflect this difficulty in resolving the two intervals we observe. The duration of the single interval approaches the sum of our two intervals and its age is intermediate between our two intervals (after normalizing for calibration differences). The marginal resolution of the northeast Pacific data set for the shortest polarity intervals is well illustrated by the differences between Blakely’s [1974] interpretation and that of Cande and LaBrecque [1974] using the same data. Blakely identified one correlatable positive anomaly between C5n and C5r.2n, and two during C5Ar, whereas Cande and LaBrecque correlated three in the former interval but only one in the latter.

8. Conclusions

[44] Spectral analysis results on high-resolution carbonate and color reflectance records in the depth and time domain, demonstrate that the various scales of sedimentary cyclicity observed in the shallow lacustrine and alluvial fan mudflat deposits of the Orera Composite Section (OCS) are related to the astronomical cycles of precession, obliquity and eccentricity and, thus, to astronomical induced oscillations in regional climate.

[45] The assumption of zero phase between the sedimentary cyclicity and the astronomical parameters, allows the cycles to be tuned to the eccentricity, precession and insolation time series of solution La93(1,1) with present-day values for the dynamical ellipticity and tidal dissipation by the Moon.

[46] The astronomical tuning of OCS may have an uncertainty of 20 or 40 kyr for certain intervals. Nevertheless, spectral analysis shows significant coherencies with the 41-kyr obliquity and with the 400-kyr eccentricity cycle. Less coherent is the relation with the 100-kyr eccentricity cycle. The cause of this inconsistency still remains to be explained.

[47] Finally, the astronomically tuned OCS cycles cover a period between 10.6 and 12.9 Ma and provide new ages for polarity reversals. The OCS reversal ages are about 80 kyr older than the ages of CK95. This age discrepancy decreases to 50–60 kyr with increasing age. The newly acquired astronomical ages for the polarity reversals in the OCS are in better agreement with seafloor spreading rates than CK95.

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