Orbital tuning and correlation of 1.7 m.y. of continuous carbon storage in an early Miocene peatland

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ABSTRACT

Peatland is an important terrestrial carbon reservoir that contains >25% of soil carbon and accounts for 25%–38% of natural methane emissions. Most of this carbon is contained in postglacial boreal peat. Our understanding of the carbon cycle within this reservoir and its links to the atmosphere is therefore restricted to periods of <10 k.y. A record of the longer-term behavior of the peatland carbon reservoir under nonglacial conditions does, however, exist in thick lignite deposits formed over periods of >1 m.y. Spectral analysis of varying lignite color reveals that 120 m of early Miocene lignite from the Gippsland Basin, Australia, contains a 1.7 m.y. record of orbitally paced climate oscillations dominated by the response to obliquity. Use of the regular orbital signal indicates that the average long-term rate of peatland carbon accumulation recorded in the lignite is 27.5 g·m^{-2}·yr^{-1}. This rate is constant over periods of >100 k.y. and is independent of shorter-term, <10 k.y., fluctuations in climate and hydrology. Matching the lignite record to the theoretical insolation curve indicates that the lignite formed between 22.5 and 20.8 Ma. Contemporaneous long-term changes in lignite color and the $^{13}C/^{12}C$ ratios of marine foraminifera may relate to changing peatland methane flux and thus point to a link between terrestrial and marine carbon dynamics.

Keywords: Miocene, lignite, carbon cycle, methane, astronomical calibration.

INTRODUCTION

Peatland is an important terrestrial carbon reservoir that contains >25% of soil carbon. The potential for the peatland carbon reservoir to influence the global carbon cycle and global climate is high. Currently, peatland accounts for 25%–38% of natural methane emissions (Christensen et al., 2003) at a rate of 0.046 Gt/yr, equivalent to 50%–61% of the carbon fixed by peatland per annum (Gorham, 1991). This rate of methane emission is highly significant when compared to the minimum, 0.112 Gt/yr, invoked to have caused the Paleocene–Eocene thermal maximum (Dickens et al., 1997), particularly given that the area occupied by peatland may have been as much as three times greater than the present area (Beerling, 2000). The fact that most peatland carbon, 455 Gt, is contained within postglacial boreal and subarctic peatland (Gorham, 1991) restricts our understanding of peatland in the carbon cycle to periods of <10 k.y. (Kremenetski et al., 2003; Vitt et al., 2000). However, the longer-term behavior of the peatland carbon reservoir under nonglacial conditions is recorded in thick lignite deposits formed over periods of >1 m.y. In this paper we use evidence of orbitally forced oscillations in lignite color to explore the long-term evolution of an early Miocene peatland and its relationship with other global carbon reservoirs.

GEOLOGIC SETTING AND DATA PROCESSING

The lower Miocene Morwell lignite was deposited in ombrotrophic peatland in an ocean-margin setting in the Gippsland Basin, Victoria, Australia (Holdgate et al., 1995), at a paleolatitude of ~50°S (Lawver and Gahagan, 2003). Biostratigraphy places the base of the Morwell lignite in the early Miocene within biozone N4 (Holdgate et al., 1995). The absence of active faulting and the presence of drape structures in the lignite over pre-Tertiary faulted blocks (Holdgate et al., 1995) indicate that the basin was undergoing postrift subsidence. To establish a record of carbon storage in this lignite, a measure of time is required. We use evidence of orbitally paced climate oscillations in lignite color to erect the temporal framework. Lignite color is considered to reflect the depth of the water table (Holdgate et al., 1995; Sluiter et al., 1995): paler lignite accumulated in a wetter, expanding, raised peatland (Sluiter et al., 1995). As peatland hydrology is strongly influence by climate (Fraser et al., 2001), lignite color has the potential to record orbital climate forcing. Lignite color data (Mackay et al., 1985) from four 80–110 m cores of the Morwell seam, spaced 1.5 km apart (Mackay et al., 1985), were correlated and converted to a common depth scale (see Data Repository[1]) (Fig. 1). Correlation of the color records from each core was achieved by aligning the contact between the Morwell 1A and Morwell 1B subdivisions of the Morwell seam as a reference datum, described by Holdgate et al. (1995). The four records were then combined and averaged to produce a single 120 m record with increased signal to noise ratio (Fig. 1).

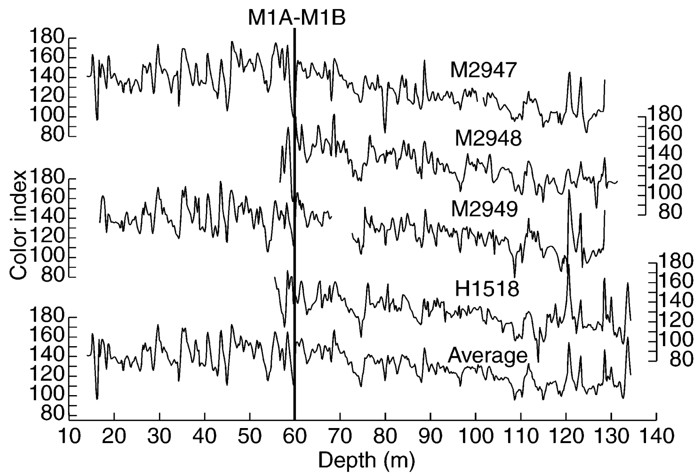

Figure 1. Color index data from colorimeter logs of cores M2947, M2948, M2949, and H1518 (Mackay et al., 1985). Higher color index value corresponds to paler lignite. All four curves are plotted on common depth scale and were aligned by wiggle matching. Position of boundary between Morwell 1A and Morwell 1B (M1A-M1B) seam subdivisions was used as common datum to help position curves prior to wiggle matching. Lowest curve is mean of those above.

SPECTRAL ANALYSIS

Spectral analysis of this record was undertaken by using the singular spectrum analysis–multitaper method Toolkit 4.1 (Dettinger et

[1]GSA Data Repository item 2004145, correlated color index data, is available online at www.geosociety.org/pubs/f2004.htm or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

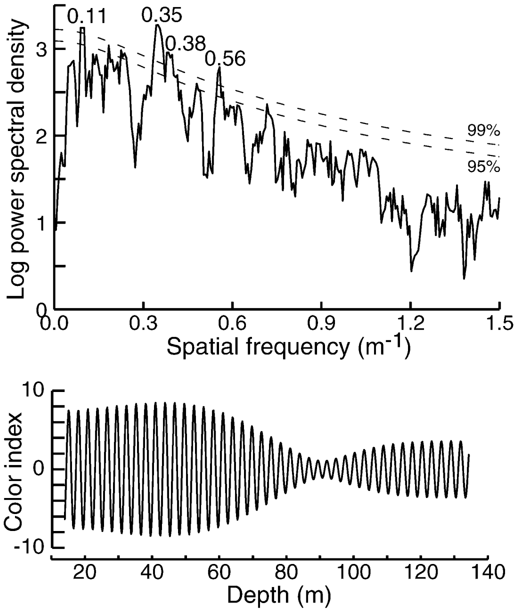

Figure 2. Power spectrum of mean detrended color index record showing 95% and 99% significance levels. Spectrum was produced by using multitaper method with robust estimation of background noise (Mann and Lees, 1996). Frequencies of peaks >99% significance shown. Reconstruction of 0.35 m^{-1} spatial frequency in power spectrum using method of Ghil et al. (2002) displays amplitude modulation on scale of 30–40 cycles.

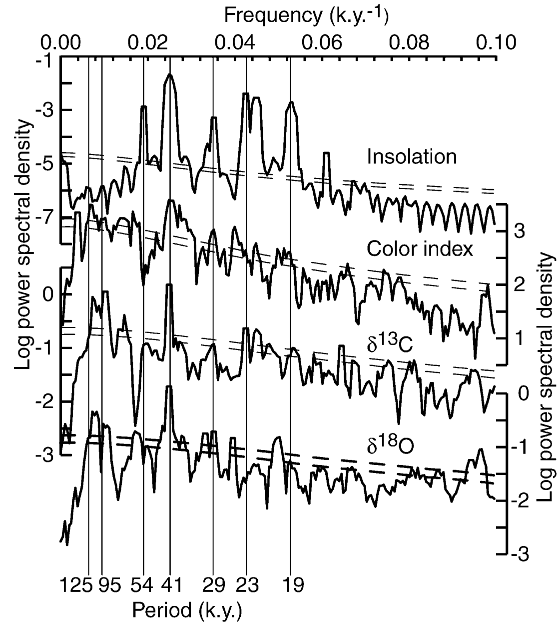

Figure 3. Power spectra calculated by using same multitaper technique for theoretical insolation record (Shackleton et al., 1999), benthic foraminifera δ^{13}C and δ^{18}O records (Zachos et al., 2001), and tuned lignite color index record. All records are for period 22.56–20.858 Ma and were resampled at 1 k.y. intervals by using constrained cubic spline prior to analysis; 99% and 95% significance levels are indicated.

al., 1995; Ghil et al., 2002). In undertaking spectral analysis we assume that the rate of peat accumulation was approximately constant and that sudden changes in this rate or periods of erosion, if present, were sufficiently minor not to disrupt a continuous orbital pattern. This inference is not in agreement with the sequence stratigraphic interpretation of the Morwell seam in which a 3.5 m.y. hiatus is placed between the M1B and M1A subseams (Holdgate et al., 1995). The inferred hiatus is unproved and arises from the suggestion that the coal subseams formed during sea-level highstands and therefore can be correlated with coastal onlap charts. In the Morwell mine coal there is no evidence for a break in coal deposition, and the position of the subseam boundary is placed at a regionally recognized transition from light to dark lignite (Holdgate et al., 1995).

Prior to calculating a power spectrum, an underlying data trend was identified by using singular spectrum analysis (Ghil et al., 2002) and subtracted from the data. The most significant peak in the power spectrum of the detrended lignite color record (Fig. 2) occurs at a spatial frequency of 0.35 m^{-1}. When the 0.35 m^{-1} signal is reconstructed (Fig. 2), it displays long-period amplitude modulation on a scale of ~30–40 cycles (Fig. 2). This modulation is also apparent in the raw color index data (Fig. 1). Modulation on this scale is similar to the 1.2 m.y. amplitude modulation of the obliquity cycle (Zachos et al., 2001).

To test whether the 0.35 m^{-1} component of the spectrum is due to obliquity we produced a floating tuned record, by converting depth to time under the assumption that that each 0.35 m^{-1} oscillation represents 40 k.y. By comparing the power spectrum of the tuned record to the power spectrum of an insolation record of similar length (Fig. 3), we see a significant spectral response at frequencies corresponding to eccentricity and precession. This spectral response to orbital frequencies not used to tune the data indicates that the frequency corresponding to obliquity has probably been correctly identified.

As an additional check on the identification of obliquity we positioned the lignite within the astronomically calibrated stratigraphy for the Miocene (Shackleton et al., 1999) and compared the inferred obliquity record in the lignite with the theoretical obliquity record (Fig. 4). Marine sediment at the base of the Morwell seam is of early Miocene age. Planktonic foraminifera indicate that these sedimentary deposits are in biozone N4, close to the N4a-N4b boundary (Gallagher et al., 2001; Holdgate et al., 1995). The estimated age of the N4a-N4b biozone boundary is 0.6 m.y. above the base of N4 (Berggren et al., 1995), ca. 22.4 Ma in the revised astronomical time scale (Shackleton et al., 1999). Confidence in this age estimate comes from the 22–21 Ma radiometric age of the Thorpdale Volcanics, which are contemporaneous with the Morwell 1B subseam (Birch, 2003). The approximate age was then used to position the color record in an approximate time interval. When the base of the color record is placed at 22.4 Ma, comparison with the astronomical record reveals closely matching obliquity-amplitude minima at 21.8 Ma in the color record and 22.0 Ma in the theoretical record. Both records also display similar changes in amplitude. On the basis of these similarities we conclude that the lignite formed over a period of 1.7 m.y. and obliquity exerted a strong influence on the peat accumulation.

DISCUSSION

If lignite color reflects changes in peatland hydrology, then spectral analysis indicates that obliquity exerted control on the hydrological cycle, a conclusion that is consistent with evidence that obliquity influences poleward transport of atmospheric water (Raymo and Nisancioglu, 2003; Vimeux et al., 1999) and precipitation (Tuenter et al., 2003). Methane emission rates are also primarily controlled by the hydrological influence on the depth of the aerobic layer in the peatland (Macdonald et al., 1998). This interpretation therefore provides a mechanism whereby astronomical forcing can influence the water budget of boreal peatland and associated terrestrial methane emissions.

The presence of regular orbital cycles in lignite is noteworthy because pollen and color records (Holdgate et al., 1995; Sluiter et al., 1995) indicate short-term variability in environmental conditions and

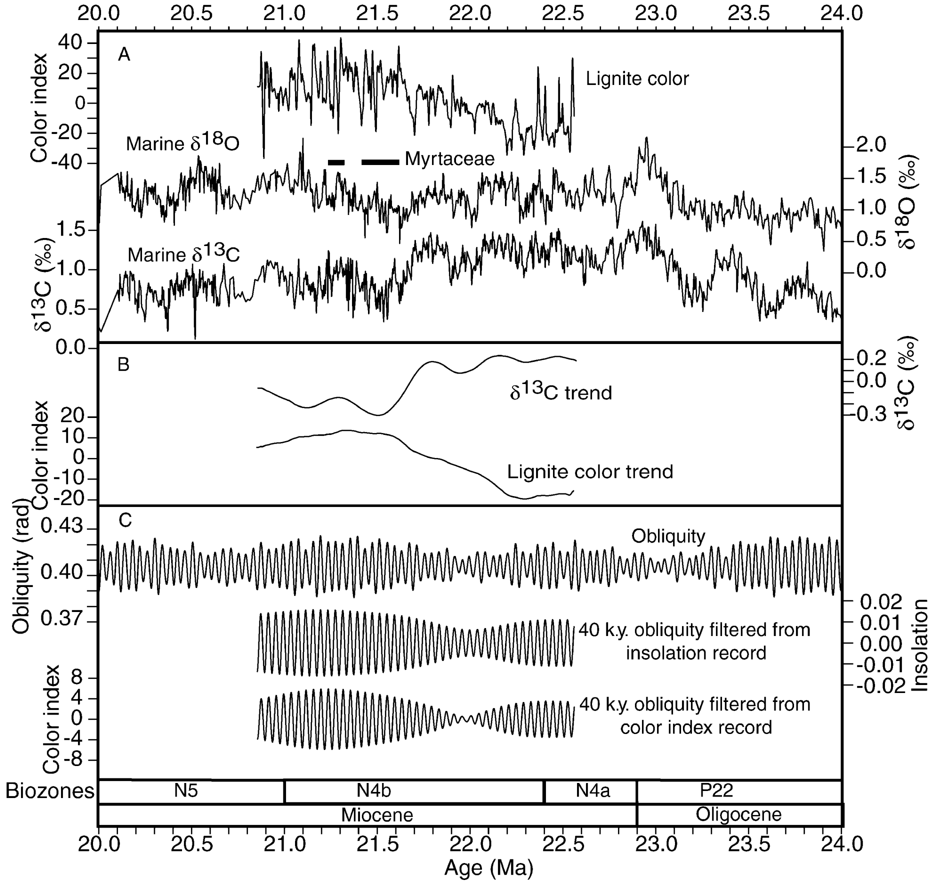

Figure 4. A: Comparison of marine isotope records (Zachos et al., 2001) with lignite color record. Periods of Myrtaceae pollen enrichment (Holdgate et al., 1995) are indicated. B: Background trends for marine $\delta^{13}C$ values and lignite color identified and plotted by using singular spectrum analysis (Ghil et al., 2002). C: Long-period amplitude modulation in obliquity records derived from insolation curve (Shackleton et al., 1999) and lignite color record compared to predicted obliquity (Shackleton et al., 1999). Obliquity records were reconstructed by using combined singular spectrum analysis and multitaper methods to isolate 40 k.y. component of obliquity (Ghil et al., 2002). P22 to N5 refer to planktonic foraminiferal biozones (Berggren et al., 1995) plotted on revised astronomical time scale (Shackleton et al., 1999).

vegetation type, both of which are expected to influence rates of peat accumulation. The carbon concentration in the lignite varies little, ranging on a dry-mass basis from 67.8% in the pale lignite to 66.4% in the darker lignites (George and Mackay, 1991). Therefore, the presence of regular orbital cycles requires that long-term rates of carbon accumulation on scales of 100–1000 k.y. are constant and independent of short-term variability on the scale of an individual cycle, ~10 k.y. or less. The average air-dried density of the Morwell seam is 0.802 g/cm^3, the average air-dried carbon concentration is 67.15%, and shrinkage during air drying is 28.4% (George and Mackay, 1991); therefore, the long-term rate of carbon accumulation in the Morwell seam is 27.5 $g \cdot m^{-2} \cdot yr^{-1}$, well within the 19.9–99.5 $g \cdot m^{-2} \cdot yr^{-1}$ global range for modern peatland (Large et al., 2003). What determines this rate also needs to be considered. If the long-term rate is independent of climate, hydrology, and associated decay path, then the rate must reflect the primary productivity, and, on average at a given latitude and in a given paleogeographic setting, this rate must be approximately constant. This conclusion is certainly feasible as mire systems are never short of water (peat containing ~95 wt% water), and, if the system is ombrotrophic, the primary source of nutrients will be air fall. The main variables will then be atmospheric CO_2 and available sunlight.

Recognition of orbital cycles and a constant rate of carbon accumulation in this lignite casts doubt on the current sequence stratigraphic interpretation. In particular the inference that the M1A subseam accumulated at half the rate of the M1B subseam, a consequence of a sequence stratigraphic interpretation (Holdgate et al., 1995), becomes untenable. There is no particular need to link changes in peatland hydrology to changes in sea level as, even in paralic settings, peatland hydrology is determined mainly by climate, not sea level.

By using orbital cycles it is also possible to compare the long-term evolution of coeval terrestrial and marine systems. To achieve such a comparison, the lignite record was tuned to the astronomical time scale by assuming that the obliquity-amplitude minima are the same in both the theoretical and lignite color records and then by matching individual obliquity cycles in both curves. This final stage of tuning places the lignite record between 22.56 and 20.86 Ma (Fig. 4). Tuning to one orbital cycle is not ideal but, in this case, is the only option, as the 100 k.y. and 400 k.y. eccentricity cycles used to tune the marine record (Shackleton et al., 1999) are not well expressed in the lignite.

Comparison of the lignite power spectrum with the power spectra of the composite marine benthic foraminifera carbon and oxygen isotope records (Zachos et al., 2001) highlights the similar quality of the lignite record but the much stronger response of the marine system to eccentricity (Fig. 3). This comparison indicates that even in an ocean-margin setting, the responses of terrestrial and marine systems to eccentricity are not strongly coupled.

Comparison with the marine oxygen isotope record (Zachos et al., 2001) (Fig. 4) indicates that the oxygen isotope minimum at 21.6 Ma indicative of warming (Zachos et al., 2001) corresponds closely to the position of the boundary between the Morwell 1A and Morwell 1B at 21.5 Ma. Concentrations of Myrtaceae pollen (Fig. 4), indicative of warmer climatic conditions, peak within an interval of ±8 m (~100 k.y.) on either side of this boundary (Holdgate et al., 1995). This evidence of near-simultaneous warming in both the terrestrial and marine records increases confidence in the orbital tuning and implies general global warming at that time.

Comparison with the marine carbon isotope record (Zachos et al., 2001) (Fig. 4) reveals a 0.3‰ decrease in $\delta^{13}C$ from 22.1 to 21.5 Ma that corresponds to the lignite becoming paler between 22.3 and 21.5 Ma. This relationship is most clearly observed when the underlying antithetic trends in marine $\delta^{13}C$ and lignite color are compared (Fig. 4). It is possible that these records are linked through the carbon cycle. In particular, wetter conditions associated with paler lignite should also favor increased methane flux (Nykanen et al., 1998) from peatland to the atmosphere. Peatland methane is isotopically light; its δ^{13}C values are −60‰ (Bellisario et al., 1999; Hornibrook et al., 1997; Nakagawa et al., 2002), similar to the values of methane clathrates (Dickens et al., 1997). To produce a 2.3‰ decrease in marine carbonate δ^{13}C due to clathrate-derived methane with a δ^{13}C of −60‰ requires an addition of 1120 Gt of methane over 10 k.y. (Dickens et al., 1997). If linear behavior is assumed, a 0.3‰ decrease over 10 k.y. would require an increase in the annual flux of methane by 0.015 Gt, equivalent to a 13% increase in the 0.115 Gt of methane released from natural wetlands today (Wuebbles and Hayhoe, 2002). Given that natural methane fluxes from peatland can range over two orders of magnitude (Nykanen et al., 1998; Segers, 1998), a 13% increase is not an unreasonable proposition. The areal extent of early Miocene peat formation is indicated by the extensive mid-latitude peatland that gave rise to thick lignite in both the Northern (Bechtel et al., 2002; Crosdale et al., 2002) and Southern Hemispheres (Holdgate and Clarke, 2000). This correlative lignite suggests that the lignite of the Gippsland Basin is a manifestation of a larger-scale phenomenon.

The identification of a 1.7 m.y. record of orbital cycles in Miocene lignite reveals the potential of thick lignite and coal for investigation of the link between the oceanic and terrestrial carbon reservoirs. The as much as 430 m of lignite in the Gippsland Basin gives a potential 6.9 m.y. late Oligocene to middle Miocene record that may be correlated at high resolution with the marine record to reveal how variations in carbon sequestration and methane release in peatland might influence global climate.

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