High-resolution terrestrial record of orbital climate forcing in coal

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ABSTRACT

Pre-Quaternary terrestrial climate records in which time has been calibrated using astronomical cycles are, with the exception of lacustrine proxies, poorly represented in the geological record. This omission is a significant gap in our knowledge of ancient climate systems. Here we present new evidence of orbital periodicities in an 18.3-m-thick late Paleocene coal and conclude that coal has the potential to provide continuous time-calibrated terrestrial climate data. Spectral analysis of changes in the relative proportions of vitrinite to inertinite, two environmentally sensitive coal macerals, reveals several characteristic frequencies, some of which display evidence of amplitude modulation every five to six cycles. Combining this observation with depositional time limitations derived from present-day rates of carbon accumulation in mires, we interpret the characteristic frequencies as resulting from precession and obliquity and their influence on oxidation and decay. Using the inferred precession component of the data to derive an internal time scale, we estimate that the Wyodak coal was deposited over a period of ~414 k.y. with a long-term carbon sequestration rate of 29 g m^{-2} yr^{-1}. The identification of an internal astronomical time scale in coal is an important step toward realizing the potential for coal to extend our high-resolution knowledge of Earth's terrestrial climate back to the formation of the first peat deposits at 360 Ma.

Keywords: Paleocene, coal, climate, carbon.

INTRODUCTION

Astronomically calibrated pre-Quaternary terrestrial records of climate, with the exception of lacustrine proxies (e.g., Olsen and Kent, 1999), are not generally present in the geological record. This omission results in a significant gap in our knowledge of ancient climate systems. Holocene high-resolution terrestrial climatic records have been obtained from peat deposits (Blackford, 2000), the precursors to coal. These records appear to indicate that peat composition responds to climatic change driven by minor (<1%) shifts in insolation related to sunspot activity (Blackford and Chambers, 1995). From estimated Holocene long-term rates of carbon accumulation (Clymo et al., 1998; Neuzil, 1997; Sorensen, 1993), it can be concluded that 10–100-m-thick coal seams probably formed from peat deposited over ~0.1–3.0 m.y. This indicates that coal deposition within an individual seam may be more than short-lived, a conclusion that is consistent with biostratigraphically constrained periods of coal deposition, e.g., the 0.5–2.8 m.y. intervals of Eocene to Miocene lignite deposition in Australia (Holdgate and Clarke, 2000). Thick coal seams should therefore show a clear imprint of the terrestrial response to the 5%–25% insolation changes (Laskar et al., 1993) that result from orbital cycles. To test for the presence of orbital cycles we undertook spectral analysis of a high-resolution maceral record derived from a thick late Paleocene coal in the Powder River Basin, Wyoming.

GEOLOGICAL SETTING AND TIME LIMITATIONS

An 18.3 m core of subbituminous coal was collected from the Wyodak coal zone in the upper Paleocene Tongue River Member of the Fort Union Formation, Powder River Basin, Wyoming, USA. This coal formed in raised mires between the channels of a braided river system in an intermontane continental basin (Flores, 1993) at a paleolatitude of 40–50°N (Davies-Vollum, 1997).

Limitations on the period of coal deposition may be calculated using either total carbon content in conjunction with estimated long-term rates of carbon accumulation or thickness in conjunction with estimated rates of peat accumulation. The latter requires an estimate to be made of the degree of compaction; the former does not. Because estimates of the degree of compaction during the transition from peat to coal vary considerably (Nadon, 1998), we have chosen the former method. Limitations on the duration of peat accumulation during formation of the Wyodak seam were obtained from estimated rates of carbon accumulation in Holocene boreal and tropical peatland. The validity of applying Holocene carbon accumulation rates to a Paleocene coal depends on whether the balance between productivity and decay in the late Paleocene is within the set of values that characterize the Holocene. Major controls on rates of decay are temperature (Clymo et al., 1998) and vegetation type. Mean annual temperatures in this region during the late Paleocene are estimated from floral assemblages to have been 12–16 °C (Wing et al., 2000), well within the global Holocene range. Members of the Taxodiaceae family were the dominant vegetation type in the coal-forming environment, and members of this family are in swamp environments today (Nichols, 1995, 1999). The carbon stored in the vegetation biomass during the late Paleocene, including the CO_2-rich Paleocene–Eocene thermal maximum in central North America, is estimated to be 1–6 kg C m^{-2} (Beerling, 2000), a value within the present global range of 0–20 kg C m^{-2} (White et al., 2000). With quantities of vegetation and vegetation type similar to those of the Holocene, it seems unlikely that Paleocene productivity in the Powder River Basin will not be encompassed by the present-day global range. From this it can be concluded that carbon accumulation rates during Paleocene coal formation probably are within the Holocene range.

To define the minimum period of deposition of the Wyodak, a mean long-term rate of carbon accumulation for tropical forest peat was used. Values of long-term carbon accumulation rates in tropical peat range from 59 to 145 g m^{-2} yr^{-1} (Neuzil, 1997; Sorensen, 1993), and the rate chosen was a mean value of 99.5 g m^{-2} yr^{-1}. Because rates of carbon accumulation tend to decrease from middle to high latitudes (Clymo et al., 1998; Diessel et al., 2000), the average long-term rate of carbon accumulation in boreal peat from higher than 60°N should provide a reasonable lower rate of carbon accumulation. The lower value chosen for the average rate of long-term carbon accumulation was 19.9 g m^{-2} yr^{-1}, the value for high-latitude Finnish peat from 60–70°N (Korhola et al., 1995). Using these carbon accumulation rates, it can be calculated that the 18.3-m-thick Wyodak seam, having a dry bulk density of 1.1 g cm^{-3} and 60% carbon, was deposited between 121 and 607 k.y. Because carbon loss continues throughout the period of peat formation (Clymo et al., 1998) and during coalification, these limiting periods of deposition have probably been underestimated.

CLIMATE PROXY

The quotient of two macerals, vitrinite/inertinite, is used as a climate proxy. This is similar to a quotient known as the gelification index (Lamberson et al., 1991) that is considered to reflect the degree of dryness of the depositional environment (Diessel, 1992). The difference between the vitrinite/inertinite quotient and the gelification index is that the gelification index includes an oxidized humic gel known as macrinite, an inertinite maceral, that is added to total vitrinite when calculating the gelification index. Macrinite, however, is a scarce constituent of the Wyodak seam (0.7% of total inertinite), produced by aerobic oxidation of humic gel (Diessel, 1992), so we have chosen to include it in the total inertinite. Vitrinite is produced by the coalification of humified plant matter that has been hydrolyzed below the water table (Diessel, 1992). Inertinite is derived from plant matter, either pristine or humified, that has undergone severe oxidation (mainly by fire and fungal decay) or desiccation and therefore has lost the capacity to become hydrolyzed (Diessel, 1992). Inertinite is easily distinguished from vitrinite by its higher reflectance. During dry periods, oxidation, particularly by fire, is more likely (Scott, 2000), and the peat becomes enriched in inertinite. In contrast, during wet periods the peat remains enriched in vitrinite precursors. The quotient of vitrinite/inertinite may therefore be interpreted as a representation of the probability of aerobic oxidation. Inertinite can also be enriched by selective decay because it decays more slowly than vitrinite precursors (Scott, 2000). The rate of decay of peat is linked to temperature (Clymo et al., 1998), therefore it can be concluded that the quotient of vitrinite/inertinite will reflect both water availability and temperature. Inertinite can also be transported by wind and water (Scott, 2000). The presence of externally derived inertinite could be inferred from its association with clastic detritus or from deposits of very fine grained, potentially wind-blown, inertinite, but there is no clear evidence that such inertinite has contributed significantly to the Wyodak seam.

The core was sectioned into 0.04–0.05 m intervals. A subsample 0.01–0.02 m thick was then collected from each sectioned interval for maceral analysis. Although the subsample will not necessarily represent the mean maceral composition in a 0.05 m interval, this random error will contribute to high-frequency noise and spectral leakage, but will not inhibit the detection of low-frequency, meter-scale, maceral trends. The vitrinite/inertinite quotient was measured in every sample by point counting 500 points. Each block was counted by traversing perpendicular to the stratigraphic layering. This ensured a minimum resolvable frequency of 10.0 m^{-1}. A disadvantage of point counting is that the amplitude estimate obtained from a probabilistic quotient of the number of vitrinite points to inertinite points can be infinite in extremis. To eliminate infinite values, samples in which no inertinite was recorded were deemed to contain one inertinite point (0.2%).

SPECTRAL ANALYSIS OF THE MACERAL RECORD

The maceral data show marked oscillations in the vitrinite/inertinite quotient (Fig. 1). Spectral analysis of the vitrinite/inertinite quotient is improved by approximately equalizing spread about the mean and by giving sufficient weight to relative changes in small values. Both of these objectives were achieved by applying a logarithmic transformation, $\log_{10}(x)$, to the quotient. A positive skewness in the histogram of the data (Fig. 1) after the logarithmic transformation may be a result

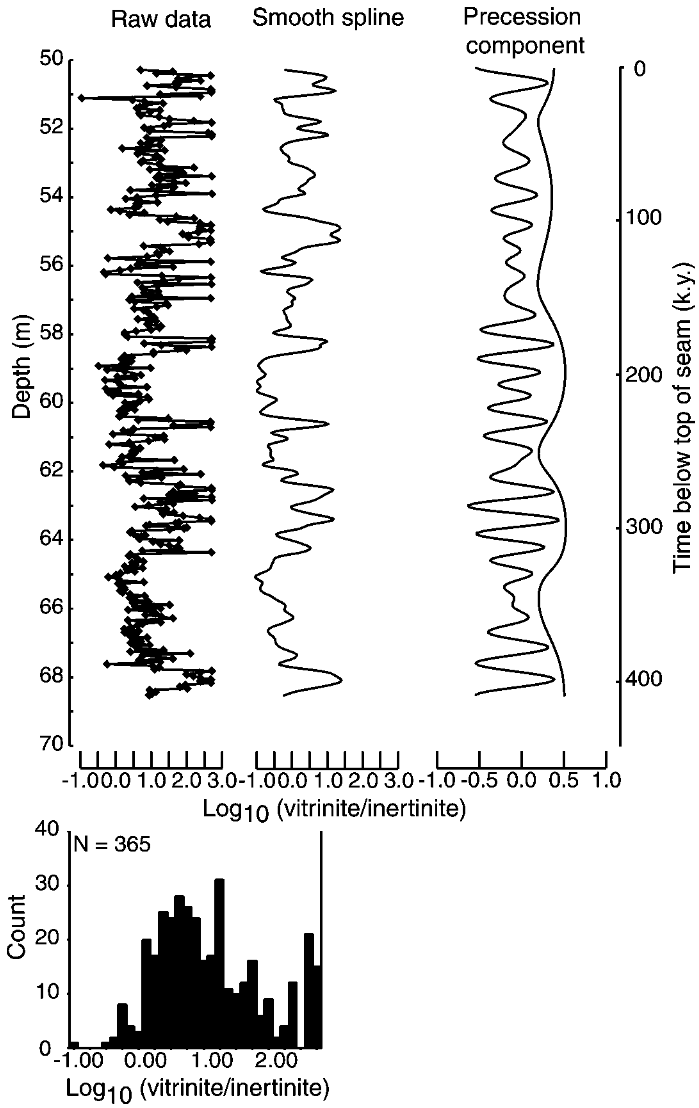

Figure 1. Comparison of $\log_{10}$(vitrinite/inertinite) vs. depth profile with same data after smooth spline interpolation, and band-pass filtering to isolate precession component. Chosen width of band-pass filter was 1.26 m^{-1} ± 25%. Evidence of five- to six-fold amplitude modulation is highlighted by means of envelope to right of precession component. Histogram illustrates positively skewed distribution of $\log_{10}$(vitrinite/inertinite). Peak on right of histogram is consequence of maximum vitrinite/inertinite value generated by point counting.

of lower accumulation rates during periods of inertinite enrichment. The use of the quotient also results in a low signal to noise ratio, so to improve the signal and to compensate for unevenness in the sampling interval, a smooth spline was fitted to the data. The resulting fit has an r^2 of 0.69, improves visualization of the low frequencies, and when compared to an unsmoothed spline fit does not change the power spectrum in the frequency range of interest.

Inherent to the spectral analysis are the assumptions that no major hiatus occurs in the data and that the long-term rate of carbon accumulation was approximately constant. An unconformity is locally reported between the Fort Union and Wasatch Formations, but no major erosion surfaces have been noted within the Wyodak coal or the Tongue River Member of the Fort Union Formation (Ellis et al., 2002). These observations confirm our assumption that there is no major hiatus in the data. By making these assumptions the depth series can be treated as a time series and Fourier spectral analysis can be applied to

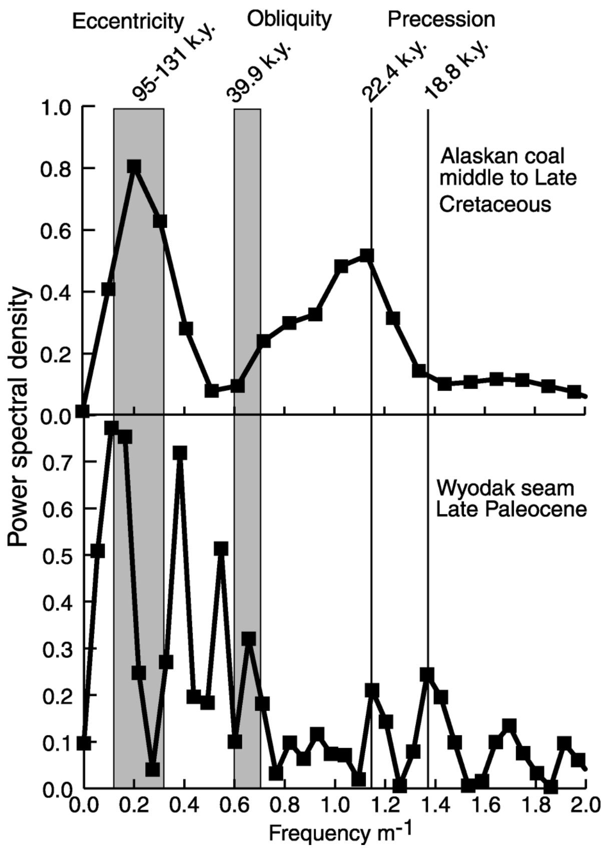

Figure 2. Comparison of positions of precession, obliquity, and eccentricity bands relative to peaks in power spectrum of frequencies derived from $\log_{10}$(vitrinite/inertinite) of Wyodak Seam and from Cretaceous coal from Alaska (Rao and Walsh, 1999). Values chosen for precession and obliquity frequencies are estimated values at 50 Ma (Berger et al., 1992). Eccentricity and obliquity bandwidths were calculated relative to inferred precession frequencies. Bandwidth was set at frequency range about median frequency ± one frequency bin.

the $\log_{10}$(vitrinite/inertinite) versus depth profile (Fig. 1). Conversely, only if this assumption is correct will regular periodicities emerge from the Fourier spectral analysis.

To investigate characteristic frequencies, a power spectrum (Fig. 2) was obtained from the data using Fourier analysis with a Hamming $\cos^2$ window. The band in which the orbital frequencies should occur can be deduced from the time limitations on the period of coal deposition. During the Paleocene the shortest orbital cycle was the 18.8 k.y. precession cycle (Berger et al., 1992); given that the maximum period of coal deposition is 607 k.y. and the minimum period 121 k.y., the precession frequency would be expected to be in the frequency range 1.76–0.35 m^{-1}. Within this interval distinct high-amplitude peaks in the power spectrum occur at 1.16, 1.37, 0.54, and 0.67 m^{-1} (Fig. 2). If these peaks result from orbital forcing, then the peaks at 1.16 and 1.37 m^{-1} must correspond to the 18.8 and 22.4 k.y. precession cycles, because either obliquity or eccentricity at these frequencies would result in a depositional period greatly in excess of the 607 k.y. constraint. The ratio of these two frequencies (1.18) is also close to the expected ratio between the precession frequencies (1.20). If the peaks at 1.16 m^{-1} and 1.37 m^{-1} result from precession, then the relative position of the 95–131 k.y. eccentricity and 39.9 k.y. obliquity frequency bands can be calculated (Fig. 2). The possible eccentricity peak in the data from 0.1 to 0.19 m^{-1} is poorly resolved due to its low frequency. As a consequence of its low frequency its exact position is sensitive to choice of data window; however, when a range of data windows is applied this peak is consistently in the range 0.1–0.27 m^{-1}. If the peaks at 1.16 and 1.37 m^{-1} are not the result of orbital forcing, then the peaks at 0.54 and 0.67 m^{-1} could be due to the precession signal. However, if this were the case, then no spectral power exists at 0.31 m^{-1}, the expected obliquity frequency. The peaks at 0.54 m^{-1} and 0.67 m^{-1} may therefore result from modulation of the obliquity signal within the data set. The additional peak at 0.38 m^{-1} probably results from a combination of eccentricity and obliquity.

Band-pass filtering was applied to isolate the inferred precession signal and determine if this frequency displayed the characteristic amplitude modulation every 5–6 cycles that results from precession being modulated by the 95–131 k.y. eccentricity cycle (Laskar et al., 1993) (Fig. 1). The result is a signal with some evidence of modulation every 5–6 cycles (Fig. 1). This frequency is therefore interpreted as the precession frequency.

If the precession frequency is correctly identified, then it should also be observed in other coal seams. To test this, spectral analysis was applied to the vitrinite/inertinite quotient calculated from published total inertinite and total vitrinite data (Rao and Walsh, 1999) obtained every 0.15 m from three cores through a 5-m-thick bituminous, gymnosperm-bearing coal from the middle to Late Cretaceous Corwin Formation of northern Alaska. Two peaks were observed in the average power spectrum of the data from the three Alaskan cores; an underlying trend at 0.19 m^{-1} and another peak at 1.12 m^{-1} (Fig. 2). Given the lower resolution of the Alaskan data, these frequencies are close to the inferred precession (1.16 and 1.37 m^{-1}) and eccentricity frequencies (0.19–0.27 m^{-1}) in the Wyodak seam (Fig. 2). Recognition of similar characteristic frequencies in two widely separated coal seams supports the assertion that these frequencies may result from orbital climate forcing. Distinct frequencies have also been reported from an isotopic study of Miocene lignite at 0.08–0.12 m^{-1} and 0.25–0.32 m^{-1} (Jones et al., 1997). Because lignite is a lower rank coal, characteristic frequencies related to orbital forcing should also be lower; therefore, these frequencies probably represent eccentricity and obliquity cycles.

DISCUSSION

If our interpretation is correct, there must also be a reason for the vitrinite/inertinite quotient to respond to orbital forcing. Both temperature and changes in the hydrological cycle will influence the vitrinite/inertinite quotient. Of these two factors it is predicted that orbital forcing, in particular precession, should have greatest influence on the hydrological cycle (Valdes and Glover, 1999), a prediction supported by the observed link between precession, precipitation, and the timing of sapropel deposition (Vazquez et al., 2000). Attempts to model the influence of precession on the level of the Eocene Lake Gosiute (Morrill et al., 2001) reveal that the exact nature of the link between the water budget of a lake and orbital forcing involves much more than a direct link between orbital forcing and precipitation. In particular, Morrill et al. (2001) demonstrated that precession may modify the seasonal pattern of precipitation but not the annual precipitation, and precession-induced changes in short-wave radiation may have a greater influence on the local hydrological cycle than either temperature or precipitation. Because peat contains as much as 95% water, similar factors may be equally important in determining the water budget and decay processes operating in a mire.

There are 20 probable precession cycles in the Wyodak coal seam (Fig. 1) and the precession period in the Paleocene ranges from 22.6 to 18.8 k.y. (Berger et al., 1992); therefore the period in which it was deposited is ~414 k.y. In the Alaskan coal there are 5 precession cycles, indicating a depositional period of ~100 k.y. These values are close to the duration of the 100 and 400 k.y. eccentricity cycles and this may indicate that these cycles influence the accumulation of thick peat deposits.

The internal time frame also allows an estimate to be made of the rate of carbon sequestration in late Paleocene mires. Given that coal from the Wyodak averages 60% carbon and a dry bulk density of 1.1 g cm^{-3}, the long-term rate of carbon accumulation is 29 g m^{-2} yr^{-1}. The estimated global area of ''coaly clastics'' in the late Paleocene is 5.6×10^6 km^2 (Sloan et al., 1992), so the annual rate of long-term carbon storage in peatland at that time may have been on the order of 0.16 Gt C yr^{-1}. This value is about half the inferred rate of carbon release (0.3 Gt C yr^{-1}) into the atmosphere used in models of late Paleocene global warming (Dickens et al., 1997). Peatland may therefore have been an important long-term carbon sink during the late Paleocene.

The observation that orbital cycles are recorded in coal not only demonstrates that peat responds to orbital climate forcing, but is also a significant step toward interpreting the ancient terrestrial climatic record and correlating the climatic response of terrestrial and marine systems. Peat has periodically accumulated on Earth's surface from the Late Devonian to the present, a period of 360 m.y. Over that period peat has formed in a wide range of environments, from inner continental to ocean margin, polar to equatorial (Diessel, 1992). The internal climatic time frame provided by orbital periodicities is therefore a key to unlocking high-resolution snapshots of Earth's ancient terrestrial climate in a wide range of environments.

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Notes