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# Long-period astronomically-forced terrestrial carbon sinks

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ABSTRACT

Sequestration of organic matter by peat accumulation constitutes a primary sink for carbon in the global carbon cycle. The processes that control the formation and storage of peat at geological time scales are poorly understood but are of a non-solved issue of fundamental importance for understanding the global climate system. We analyzed a 7 million years long terrestrial record of Late Oligocene age from the As Pontes Basin in Northern Spain, which demonstrates that minima in the 405-kyr and 2.4-Myr eccentricity cycles play a key role in peat formation. Such nodes exhibit reduced precession amplitudes, thus avoiding extremes in seasons and seasonal contrast for a prolonged period of time. In the As Pontes Basin, this orbital configuration is associated with a decrease in siliciclastic sedimentation and enhanced peat formation. Feedbacks between equilibrium landscapes and ecosystem stability will lead to a deceleration of weathering and erosion rates in catchment areas and to minimum and stable sediment flux along the sediment routing system. Mid-latitude peat burial could contribute to disturb the carbon cycle by removing (atmospheric) carbon at times of minimum eccentricity.



## 1. Introduction

Very long-term orbital oscillations (>1 Myr) play an important role as triggers of irreversible changes in past climates (Zachos et al., 2001). Studies of long-period cyclicity as recorded in continental sediments are essential to disentangle the local, regional and global importance of the associated climate changes (e.g. Abels et al., 2012). The search for these signatures is, however, particularly challenging because of their inferred low preservation potential. Basic requirements for their development and study are stability of the basin depositional setting, sensitivity of the sedimentary environment to climate variations, and the preservation of a long stratigraphic record that preferably spans several cycles. A limited number of case studies exist that fully document long-period cyclicity in lacustrine systems (Olsen and Kent, 1999; Kashiwaya et al., 2001; Abels et al., 2010; Valero et al., 2014). However, recent studies show that these cycles can also be recognized in apparently less favourable continental settings such as fluvial systems (Abels et al., 2013; Hilgen et al., 2014), and that million-year scale climatic cycles can occur superimposed on the longterm tectonic signature of foreland basins (Valero et al., 2014). These results should stimulate debate on the various forcing factors that control sedimentation in different continental basins (Shanley and McCabe, 1994) and the timescales at which they operate (Miall, 2014).

Available numerical climate models help in understanding the sedimentary system response to climate change related to the short-period cycles of precession and obliquity (e.g., Bosmans et al., 2015). However, considerable uncertainty remains over the forcing mechanisms at million-year time scales such as that of the very long-period eccentricity cycle. Agreement exists in that the alteration of the hydrological cycle, summarized as the balance between precipitation and evaporation, must exert a prime control on sedimentary cyclicity (Abels et al., 2010). Nevertheless, climate can affect depositional settings through other processes, namely via their impact on vegetation cover, sediment production and (ground) water chemistry. In addition, sedimentary facies distribution is sensitive to erosional patterns in the catchment basin and the dynamics of sediment transfer systems, both intimately linked to vegetation cover and the morphology of the basin.

To understand how climate, by means of the million year-scale orbital oscillations, affects the sediment routing system and sedimentary facies distribution, we focused on a long coal-bearing stratigraphic record. Increase in clastic supply can lead to shrinking and obliteration of peatlands, thus making these systems excellent indicators of changes in vegetation and erosion in the catchment basin. Precession, obliquity and short eccentricity-related orbital forcing of coal-bearing sequences has already been documented (van Vugt et al., 2001; Large et al., 2003, 2004), and further correlated to marine climatic records

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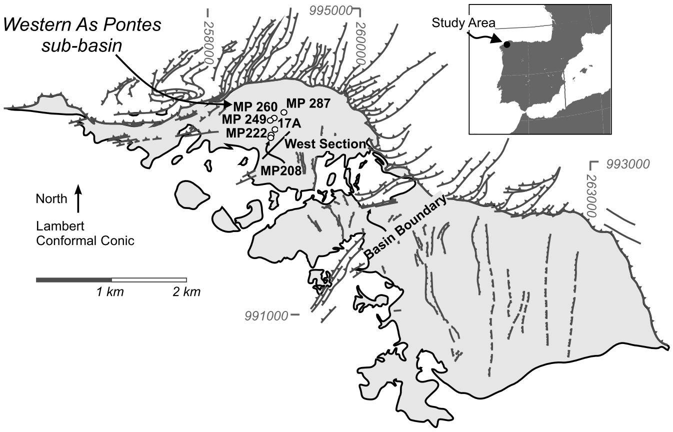


**Fig. 1.** Location map of the As Pontes Basin, NW Spain. The map shows the principal structures and the locations of the bore holes and West Section.

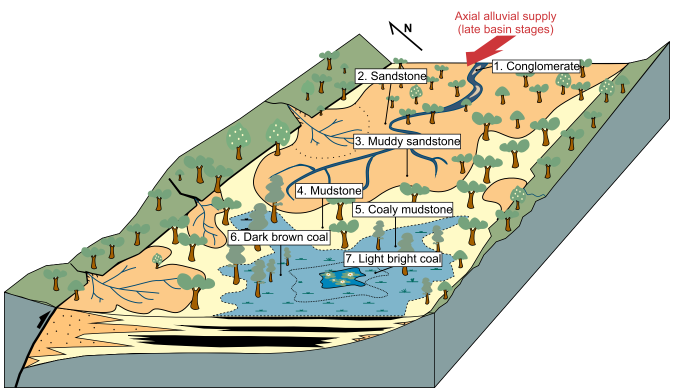


**Fig. 2.** Synthetic sedimentary facies model of the As Pontes Basin. Most of the terrigenous fraction was delivered from the North. Axial alluvial contributions became significant after the MSU deposition (see Fig. 3). In the distal and restricted areas deposition of fines or coals occurred. The vegetation cover likely played an important role in the sedimentation dynamics of the basin. The main facies are indicated with numbers. The details of the facies distribution are further explained in Table 1.

**Table 1**
Description of depth ranks including the core codes, lithologic equivalence of the depth ranks, location within the basin, and rank values.

| Core description | Lithology | Location Fig. 2 | Rank value |
|---|---|---|---|
| PP | Light bright coal | 7 | 6 |
| PP..a | Light bright coal with very low mud content | 7 | 6 |
| PP.a | Light bright coal with low mud content | 7 | 7 |
| PP′a | Mud bearing Light bright coal | 7 | 8 |
| PPa | Muddy Light bright coal | 7 | 9 |
| L | Dark brown coal | 6 | 10 |
| L..a | Dark brown coal with very low mud | 6 | 11 |
| L.a | Dark brown coal with low mud content | 6 | 12 |
| L′a | Dark brown coal with mud | 6 | 13 |
| La | Muddy dark brown coal | 6 | 14 |
| LX | Xyloid Lignite | 6 | 15 |
| LX..a | Xyloid Lignite with very low mud | 6 | 16 |
| LX.a | Xyloid Lignite with low mud | 6 | 17 |
| LX′a | Xyloid Lignite with mud | 6 | 18 |
| LXa | Muddy Xyloid Lignite | 6 | 19 |
| L + A | Mudstones and Lignites | 6 | 20 |
| Ac | Coaly Mudstone | 5 | 21 |
| A′c | Mudstone with coal | 5 | 22 |
| A.c | Mudstone with low coal content | 5 | 23 |
| A..c | Mudstone with very low lignite content | 5 | 24 |
| A | Mudstone | 4 | 25 |
| A..ar | Mudstone with very low sand | 3 | 26 |
| A.ar | Mudstone with low sand | 3 | 27 |
| A′ar | Sandy Mudstone | 3 | 28 |
| Aar | Sandy Mudstone | 3 | 29 |
| S | Silt | 3 | 30 |
| AR′a | Sandstone with abundant mud | 2 | 31 |
| ANa | Muddy sandstone | 2 | 32 |
| AN.a | Sandstone with low mud content | 2 | 33 |
| AR..a | Sandstone with very low mud content | 2 | 34 |
| AN | Sandstone | 2 | 35 |
| AR′q | Quarzitic Sandstone | 2 | 35 |
| GRar | Sandy gravel | 1 | 36 |
| GRa | Muddy gravel | 1 | 36 |
| GR | Gravel | 1 | 36 |
| CG | Conglomerate | 1 | 36 |
| Q | Quartzite | 0 | *x* |
| P | Hercynian basement | 0 | *x* |

(Van Vugt et al., 1998; Briggs et al., 2007). However, compelling evidence for a relationship between coal formation in mid-latitude swampy environments and long-period Milankovitch cycles has not yet been found. As peatlands are significant contributors to the carbon cycle (Large et al., 2004), understanding the climatic controls on coal formation is critical to a better understanding of forcing and feedbacks in Earth's climate system.

In this paper, a cyclostratigraphic analysis of the Upper Oligocene coal-bearing sequence of the As Pontes Basin in NW Spain is carried out. The long time span of ca. 7 Myr of this record is essential for the investigation of recurrent basin-wide coal expansions. Magnetostratigraphic data from earlier studies (Huerta et al., 1997) have been revised and integrated in this study in order to provide the necessary temporal framework. Spectral analysis was applied on selected borehole data with the aim of statistically testing the orbital forcing hypothesis for sedimentary cyclicity, before comparing the cycle record with orbital target curves. The significance of the cyclicity and the mechanisms through which orbitally forced insolation changes are transmitted to the sedimentary record are discussed.

## 2. Geological setting and section/cores

The As Pontes Basin developed along a NW–SE-oriented dextral strike-slip fault system associated with convergence between the Iberian and European plates (Santanach et al., 2005). The northern basin margin is structurally complex, characterized by a vertical stack of numerous southward directed thrusts sheets coeval with N–S directed extensional faults derived from the major fault system (Fig. 1). The basin is divided into two fault-bounded sub-basins and the basin infill consists of a 400 m thick coal-bearing sedimentary record. A detailed basin stratigraphy is based on high-resolution basin-wide correlations, using the core database of the mining company. The bedrock of the catchment area consists mostly of Paleozoic slate and Precambrian meta-graywackes. Small-sized alluvial fan deposits accumulated in the proximal areas, interfingering basinwards with metric and decametric-scale peat deposits (Fig. 2). Shifts of the facies belts led to the organization of the sedimentary fill into basin-wide decameter-scale sequences. Such sequences consist of a coal-rich clayey lower unit overlain by a clastic unit, which was mainly fed from alluvial fans along the northern basin margin (Fig. 2, Fig. 3). This cyclic stacking pattern is interrupted by a major clastic episode (Middle Sandstone Unit) in the middle of the sequence, which marks the complete connection between the two sub-basins during the late stage of the basin fill. The Middle Sandstone Unit onlaps onto the structural high bounding the western and eastern sub-basins, and is associated with a rearrangement of the alluvial network following the connection of the sub-basins (Ferrús, 1998). Cyclic aggradation of the coal/clastic sequences is resumed after this episode. Finally, basin overfilling is marked by a coarsening trend, representing alluvial progradation due to a reduction of the accommodation space.

The paleobotanical record suggests a semitropical swamp forest environment (Cavagnetto, 2002), where warm and humid con-