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Climatic instability before the Miocene Climatic Optimum reflected in a Central European lacustrine record from the Most Basin in the Czech Republic

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ABSTRACT

The work investigates the extensive freshwater lacustrine deposits of the Most Formation, which formed in the period between 17.7 Ma and ca. 15.9 Ma, in order to describe climate changes just before the Miocene Climatic Optimum (MCO). The Most Basin, an incipient rift within the European Cenozoic Rift System, exhibited a sedimentary environment that was sufficiently stable to preserve orbital signatures of environmental changes. Changes in the mineral composition of the sediments were characterised in terms of variations in their elemental composition, particularly their Al/Si and K/Ti element ratios and Fe, Sr, and Zr elemental abundances, which were efficiently obtained using X-ray fluorescence spectroscopy with a density of 3–4 samples per metre of core (approximately 15–20 samples per precession cycle). The sediments are distinguished by the presence of distinct and correlated horizons (1–10 cm thick) containing Sr, Ba-rich crandallite, a mineral from the aluminium-phosphate-sulphate (APS) group. Chemo-, magneto-, and cyclostratigraphy were used to correlate eight cores with lengths up to 240 m and to date the sediment; discrepancies at scales of up to two precession cycles (each ca. 20 kyr, typically ~4 m per cycle) were observed. The primary age model was based on magnetic polarity analysis (5 reversals) and later refined at the metre scale using cyclostratigraphy. We interpret the onset of the basin-wide lacustrine phase in the Most Basin as being a consequence of the enhanced input of fluvial clastic sediment to the former peat swamps during the high-eccentricity period at 17.7–17.55 Ma, i.e., immediately after the initial decay of the East Antarctic ice sheet according to Levy et al. (2016). The most important environmental change recorded by the lacustrine interval in the Most Basin occurred at 16.44 Ma during an eccentricity maximum and is nearly coeval with further shrinkage of the East Antarctic ice sheet. The second stage of monotonous lacustrine deposition, which exhibited enhanced precession-controlled compositional variability in 16.1–16.0 Ma witnessed the onset of the MCO. Sediments younger than 15.9 Ma are missing due to erosional removal after subsequent basin inversion. The sediments of the Most Formation represent an archive of environmental change in central Europe during the early stages of the MCO and have a temporal resolution ca. 5 kyr.

1. Introduction

Deep marine sedimentary records are considered stable but their temporal resolution is limited by slow deposition. Continental clastic sedimentary archives may exhibit good temporal resolution if they have been formed by fast and continuous deposition (examples can be found in Hao and Guo, 2007; Li et al., 2013; Prokopenko et al., 2001; Wang et al., 2016; and Zeng et al., 2014). However, confident interpretation of the archives requires knowledge of the mechanisms of the environmental changes occurring at a specific site. For example, both tectonic processes and climate create accommodation space, modify paleogeography, and drive sediment production in the source area; climate is the main control on transport pathways to the sediment sink (Clift et al., 2014; Li et al., 2013; Valero et al., 2017; Zeng et al., 2014). Fundamental components of this complex picture may, however, be poorly known. Paleontological reconstructions of past climates may appear more straightforward (Eronnen et al., 2011; Utescher et al., 2012), but their temporal resolution and "calibration" (that is, the calculation of conventional climatic parameters using biogenic proxies) may be a challenge for more ancient times. Additionally, taphonomic issues may hinder their interpretation. Uneven recovery of fossils from individual parts of climate cycles is another crucial problem for paleontological reconstructions (Eronnen et al., 2011). There are cases in which the

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strengths of sedimentological and paleontological approaches cannot be combined, particularly in fossil-poor sedimentary series, as is the case in the sediments discussed in this paper.

Hindrances to the reconstruction of climate from basin sediments include the action of other driving factors. Local tectonic and autocyclic processes, such as sediment reworking and river network reorganisation can distort (Alonso-Zarza et al., 2012) or even erase climate signatures (Valero et al., 2017) unless a sufficiently detailed understanding of the basin environment is available. However, the older the basins are, the less well known their paleogeography and tectonic evolution will be. One of the simplest ways to "isolate" a climate signal from non-climatic disturbances is to perform stratigraphic correlation across a basin and examine the depositional environments in detail (Ezquerro et al., 2014; Pla-Pueyo et al., 2015; Valero et al., 2014, 2016). Correlation with other (reference) regional and global climate records may also be efficient, but while it is nearly obligatory for Quaternary sediment archives (Baumgarten et al., 2015; Cukur et al., 2014; Prokopenko et al., 2001), in older sediments the reference curves are rarely available. In more ancient continuous sediment archives, magneto- and cyclostratigraphy are powerful tools for establishing temporal scale and identify external (climatic) forcing (Baumgarten et al., 2015; Li et al., 2013; Pla-Pueyo et al., 2015; Prokopenko et al., 2001; van Vugt et al., 2001; Valero et al., 2014, 2016). The most robust way to exclude possible tectonic influences on local sedimentary environments is to compare them with coeval records from remote (tectonically independent) basins (Ied et al., 2011).

Major climatic changes in the Miocene comprised the onset of the Miocene Climatic Optimum (MCO; sometimes denoted the Middle Miocene Climatic Optimum, MMCO) and its termination and the subsequent substantial global cooling (Clift et al., 2014; Holbourn et al., 2015; Zachos et al., 2001), the latest being called the Miocene climatic transition. The MCO was one of the major episodes of transient warming during the otherwise persistent Cenozoic cooling trend, but its triggers and impacts are still debated. The MCO included a temporal retreat or even disappearance of the East Antarctic ice sheet (Gasson et al., 2016; Levy et al., 2016; Passchier et al., 2013; Pekar and DeConto, 2006), perturbation of the carbon cycle (Beerling and Royer, 2011; Gasson et al., 2016; Holbourn et al., 2015), and strengthening of the East Asian summer monsoon (Clift et al., 2014), but the paleontological evaluation of its impacts in the middle latitudes of the European and North American continents remains controversial (Böhme et al., 2011; Eronnen et al., 2011; Kotthoff et al., 2014; Larsson et al., 2011; Utescher et al., 2012). The question is whether the impact of the MCO on the continents was weak, or if the available records have some intrinsic problems. More work is also needed to identify and model the actual triggers of the MCO (Gasson et al., 2016; Goldner et al., 2014; Krapp and Jungclaus, 2011). According to Holbourn et al. (2015), one of the current hypotheses involves a combination of orbital forcing and extensive eruptions of flood basalt in the northwestern part of what is now the United States (the Columbia River Basalt Group, CRBG). The idea of the volcanic cause of the MCO is older (Courtillot and Renne, 2003) but has not yet been verified. Formation of the CRBG was practically coeval with the early stages of the MCO: The Steens Basalt is dated to 17.2–16.7 Ma, the Imnaha Basalt is dated to 16.7–16.5 Ma, and the Grande Ronde Basalt (the most voluminous of the three) is dated to 16.0–15.6 Ma (Bary et al., 2010). The latter age range nearly overlaps with the reconstructed Miocene maximum of atmospheric CO_2 (Beerling and Royer, 2011). However, the estimated amount of CO_2 released to the atmosphere by the CRBG was thought to be insufficient to explain the MCO before very recent adjustment of climate models (Gasson et al., 2016). There is still no definite explanation for the substantial shoaling of the carbonate compensation depth that occurred between 18.5 and 16.0 Ma (Pälike et al., 2012). The first episode of East Antarctic ice sheet decay at 17.8 Ma (Levy et al., 2016; Passchier et al., 2013) also seems to predate the CRBG. After the initial pre-MCO warming pulses, the carbon cycle partly recovered, but then a more persistent disruption (the MCO) followed, which was coeval with the eruption of the major flood basalts of the CRBG. Holbourn et al. (2015) identified the carbon perturbation at approximately 17.0 Ma as the onset of the MCO. The East Antarctic ice sheet was substantially and persistently reduced between approximately 17 and 16 Ma (Levy et al., 2016; Passchier et al., 2013; Pekar and DeConto, 2006). The impacts of the East Asian summer monsoon on weathering and erosion in the source area were strengthened in the period 17.2–15.5 Ma (Clift et al., 2014) showing the global impact of the MCO on continental climates. Another change that could possibly have impacted the global environment was the uplift of the Qinghai-Tibetan Plateau approximately 17 Ma (Wang et al., 2016; Zeng et al., 2014).

We have recently demonstrated that the Most Basin, which is located in the Ohře Rift in the Czech Republic (Figs. 1 and 2), hosts a valuable sedimentary archive covering the late Burdigalian, just before the MCO (Matys Grygar et al., 2014). We found that the chemical composition of lacustrine sediments in the Most Basin (specifically, the Libkovice Member of the Most Formation, which represents the first lacustrine stage) varied in response to orbital forcing. We also proposed that these sediments cover the end of chron C5Dn, all of chron C5Cr (between approximately 17.2 and 16.7 Ma), and the early part of chron C5Cn.3n, that is, the period just before the peak warmth of the MCO. The aim of the current study was to confirm and extend the existing age model for the Libkovice Member to the other members of the Most Formation and explain the observed geochemical changes in environmental terms. The extension of the age model was intended to cover the period including the first pulse of the Antarctic Ice Sheet loss and the carbon cycle perturbation at approximately 17.8 Ma (Holbourn et al., 2015; Levy et al., 2016; Passchier et al., 2013) and early MCO. We also intended to compare the Most Basin environmental changes with other recently established climatic records (Holbourn et al., 2015; Levy et al., 2016; Utescher et al., 2012) and examine the impact of the Antarctic Ice Sheet loss on central Europe.

2. Geological setting and local stratigraphy

The Most Basin (Fig. 1) is a part of the Ohře Rift, the north-eastern part of the European Cenozoic Rift System (ECRIS). It is situated in the Alpine foreland and has been active since the late Eocene. The Ohře Rift has been characterised as an incipient rift (Rajchl et al., 2009). The *syn*-rift period during the Oligocene and early Miocene was accompanied by mafic volcanism at the southeast of the basin (Ulrych et al., 2011). Subsidence of the Most Basin since the early Miocene was followed by basin inversion in the middle Miocene (Pešek et al., 2010; Rajchl et al., 2009). On one hand, this process caused erosional loss of part of the basin fill, in particular at the basin margins. On the other hand, the sediments were not buried by more than a few hundred metres and hence underwent only weak diagenesis. The Miocene basin fill was described from drill cores and outcrops in open cast mines during extensive geological surveys, exploitation of the coal seams and searches for possible raw materials for ceramics. Those activities produced basin-wide lithological descriptions and an informal stratigraphy covering the entire Most Basin, which have been described in technical reports and the local literature and comprehensively reviewed by Pešek et al. (2010). The formal stratigraphy of the Most Basin fill (Fig. 2) was proposed by Domácí (1975) and Váně (1987) and further corroborated by Rajchl et al. (2009) and Matys Grygar and Mach (2013a). Biostratigraphic markers are absent from the clastic sediments above the coal seam (Matys Grygar et al., 2014).

Subsidence of the Most Basin began with broadening of the alluvial plains, formation and expansion of mires, and accumulation of peat in swamp environment. This peat later became a coal seam, which is 20–60 m thick. Subsequent expansion of fluviodeltaic environments and flooding of the mire were caused by enhanced tectonic subsidence and peat compaction (Mach, 2003; Mach et al., 2013, 2014; Rajchl and Uličný, 2005; Rajchl et al., 2008, 2009); the major and final flooding