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A high-resolution carbon-isotope record of the Turonian stage correlated to a siliciclastic basin fill: Implications for mid-Cretaceous sea-level change

D. Uličný [a,*], I. Jarvis [b], D.R. Gröcke [c], S. Čech [d], J. Laurin [a], K. Olde [b], J. Trabucho-Alexandre [c], L. Švábenická [d], N. Pedentchouk [e]

[a] Institute of Geophysics, Academy of Sciences of the Czech Republic, 141 31 Prague, Czech Republic
[b] School of Geography, Geology and Environment, Kingston University London, Kingston upon Thames KT1 2EE, UK
[c] Department of Earth Sciences, University of Durham, Durham DH1 3LE, UK
[d] Czech Geological Survey, 118 21 Prague, Czech Republic
[e] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK

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ABSTRACT

Turonian strata of the Bohemian Cretaceous Basin, Central Europe, preserve a basin-scale record of shoreline transgressions and regressions, previously interpreted to have been strongly influenced by short-term eustatic cycles. Here, nearshore siliciclastic strata in two separate sub-basins are correlated to a multi-stratigraphic dataset generated from a new research core (Bch-1) drilled in offshore marine sediments of the central basin. A high-resolution $\delta^{13}C_{org}$ record from Bch-1 is presented along with major- and minor-element proxies, TOC, carbonate content, terrestrial to marine palynomorph ratios, and detailed macro- and microfossil biostratigraphy. The 400 m thick Turonian through Lower Coniacian interval permits correlation to the highest-resolution C-isotope curves available: all carbon-isotope events demonstrated by $\delta^{13}C_{carb}$ studies in the British Chalk, NW Germany and other reference sections in Europe are recognized in the $\delta^{13}C_{org}$ curve from Bch-1. A number of short-term, basin-wide regressions in the Bohemian Cretaceous Basin, most likely reflecting eustatic falls, show a recurrence interval of 100 kyr or less. This is an order of magnitude shorter than the timing of sea-level falls inferred from the New Jersey margin and the Apulian platform, interpreted to be driven by glacioeustasy. The estimated magnitude of the Bohemian Basin sea-level falls, typically 10–20 m and generally <40 m, indicates that the 2.4 Myr period suggested by others to generate 3rd-order cycles, is too long to be the principal cycle generating unconformities in rapidly-subsiding basins, where the rate of eustatic fall must exceed the subsidence rate. Unconformities in low-accommodation settings such as passive margins most likely represent amalgamated records of multiple cycles of sea-level fluctuations of 100 kyr scale, recognizable only in high-resolution datasets from expanded successions.

Comparison of the $\delta^{13}C$ excursions to the interpreted sea-level record has not yielded a clear causal link. A long-term 'background' $\delta^{13}C$ cycle shows a duration close to the 2.4 Myr long-eccentricity cycle, and shorter-term (1 Myr scale) highs and lows in $\delta^{13}C$ appear to broadly correspond to intervals characterised by more pronounced short-term sea-level highs and lows, respectively. However, on the scale of intermediate to short-term $\delta^{13}C$ fluctuations, no systematic relationship between $\delta^{13}C$ and sea-level change can be demonstrated.

1. Introduction

Late Cenomanian through Early Coniacian time included a global long-term sea-level maximum near the Cenomanian–Turonian (C–T) boundary, as well as a long-term sea-level low in the Middle Turonian (e.g. Haq et al., 1988; Kominz et al., 2008). Superimposed, high-frequency relative sea-level changes, with recurrence intervals within the Milankovitch band, have been reported from this time interval of mid-Cretaceous greenhouse (Plint, 1991; Gardner, 1995; Gale et al., 2002; Immenhauser and Matthews, 2004; Laurin and Uličný, 2004; Immenhauser, 2005; Laurin and Sageman, 2007; Varban and Plint, 2008; Uličný et al., 2009; Zhu et al., 2012). Cycles of similar frequency have been used in stratigraphic forward models (Sømme et al., 2009). The exact age and duration of such sea-level fluctuations, however, have not been resolved, and cannot be established without high-resolution inter-basinal correlation. The importance of this task is underlined by the current debate on potential greenhouse glacioeustasy during the Cretaceous (Miller et al., 2003, 2005; Moriya et al., 2007;

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* Corresponding author.
E-mail address: ulicny@ig.cas.cz (D. Uličný).

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Bornemann et al., 2008; Kominz et al., 2008; Ando et al., 2009; Flögel et al., 2011).

Glacioeustasy is particularly controversial for the Turonian, which represents arguably the warmest climate for the entire period (Bice et al., 2003; Friedrich et al., 2012; MacLeod et al., 2013). Significant uncertainties in biostratigraphic dating, the long duration of hiatuses in many key sections, as well as the fact that the duration of the suspected high-frequency sea-level fluctuations is below biostratigraphic zonal resolution, have so far prevented correlation of short-term Milankovitch band sea-level events between basins with any certainty.

Carbon isotope stratigraphy has been developed as a powerful correlation tool in the Cretaceous and other intervals of geological history (e.g. Scholle and Arthur, 1980; Gale et al., 1993; Jenkyns et al., 1994; Voigt and Hilbrecht, 1997; Jarvis et al., 2006; Voigt et al., 2008a; Wendler, 2013), with much finer resolution than is afforded by biostratigraphy, and a unique capability to link marine and terrestrial records (Gröcke et al., 1999; Gröcke, 2002; Hesselbo and Pienkowski, 2011; Takashima et al., 2011). Due to the short mixing time of carbon in the ocean–atmosphere system, in the order of 10^3 yr (Siegenthaler and Sarmiento, 1993), correlation of δ^{13}C variations among sites on kyr time scales has been demonstrated, to a point where it has been suggested that chemostratigraphy might substitute for biostratigraphy in some intervals of the geological record (e.g. Herrle et al., 2004).

Causal links between carbon isotope fluctuations and eustatic sea-level variations have been suggested, with a positive correlation between sea level and δ^{13}C initially being proposed based on low-resolution studies focusing on the long-term maximum flooding near the Cenomanian/Turonian boundary (Scholle and Arthur, 1980). An underlying assumption is that an increase in organic C production and deposition will result in an increase in δ^{13}C value of the remaining dissolved C in the oceanic reservoir. Later work, utilizing progressively higher-resolution datasets, resulted in interpretations of the covariance between global sea level and carbon isotope events (CIEs) on a Myr timescale (Gale, 1996; Mitchell et al., 1996; Jarvis et al., 2002, 2006), and potentially even 100 kyr (Uličný et al., 1997). Other authors have suggested, however, that some positive CIEs in the Cretaceous correlate to relative sea-level falls (Gröcke et al., 1999, 2006), including those of the Middle and Late Turonian (Voigt, 2000; Wiese and Voigt, 2002), with Bornemann et al. (2008) and Takashima et al. (2010) explicitly interpreting the positive δ^{13}C excursion of the late Middle Turonian 'Pewsey' CIE to correlate to a short-term glacioeustatic fall.

Quantitative modelling of carbon burial during sea-level rise can, under certain conditions, simulate limited positive excursions in δ^{13}C (Bjerrum et al., 2006), but although sea-level rise and organic-C deposition may react to the same forcing, they need not have a direct causal link. Recent studies of Mesozoic and Cenozoic datasets that demonstrate orbitally-driven, climatic control of δ^{13}C fluctuations (Cramer et al., 2003; Pälike et al., 2006; Voigt et al., 2007; Giorgioni et al., 2012) do not interpret direct links to sea-level change.

In areas where a eustatic component of base-level change can be interpreted from a transgressive–regressive (T–R) record of a particular sedimentary basin fill, a comparison of the T–R history to the δ^{13}C record in the same basin will contribute significantly to an understanding of the potential relationship between sea-level change and the carbon cycle. Most published Turonian δ^{13}C curves originate from pelagic or hemipelagic successions that lack direct physical correlation to shallow-water nearshore successions, which provide a record of shoreline movement through time. Correlation to presumed global eustatic sea-level has typically been made by using either the Haq et al. (1988) cycle charts (e.g. Stoll and Schrag, 2000; Voigt, 2000), or by comparison with shallow-water records studied elsewhere (e.g. Jarvis et al., 2006 referring to Sahagian et al., 1996). One notable exception is that of Gale (1996) who derived the sea-level trends from stratal geometries of the Chalk that also provided his δ^{13}C record.

Demonstrating a direct record of eustatic change is not possible in nearshore stratigraphic successions (Burton et al., 1987) because the sea-level signal in the rock record is altered by the effects of tectonic subsidence, isostasy, sediment supply, and the intrinsic dynamics of depositional systems. Studies based on large datasets with high stratigraphic resolution have shown, however, that it is possible to differentiate tectonic and supply-driven changes in stratal geometries from those that were probably driven by eustasy (e.g. Varban and Plint, 2008). In order to accomplish this goal, it is necessary to carefully evaluate stratal geometries using regional, basin-scale, three-dimensional (3D) datasets. In such a case, it is possible to take advantage of the fact that tectonically subsiding basins offer expanded records with fewer, or less extensive, unconformities than carbonate platforms, shallow-water pelagic settings, or up-dip parts of passive margins.

Previous research in the Bohemian Cretaceous Basin of Central Europe (Uličný et al., 2009) has inferred eustatic forcing to have been a partial control on the transgressive–regressive history of siliciclastic deltaic and nearshore systems. On the basis of stratal geometries, it was possible to identify temporal and spatial variations in tectonic subsidence and supply rate in the basin fill, and proximal nearshore facies were correlated to distal offshore hemipelagic strata (Laurin and Uličný, 2004; Uličný et al., 2009).

The primary aim of the present paper is to compare regional T–R histories that suggest a short-term eustatic component, with a high-resolution bulk organic matter carbon isotope ($\delta^{13}C_{org}$) record, and to evaluate the potential for detailed correlations in Europe and worldwide. Additionally, the role of stratigraphic resolution in inferring relationships between sea-level change and δ^{13}C in this and other datasets are addressed. Finally, the timing of δ^{13}C fluctuations and their relationship to orbital frequencies are briefly discussed.

2. Data and methods

In 2010, a new research core was drilled through offshore marine sediments of late Cenomanian–Early Coniacian age in the Bohemian Cretaceous Basin (Bch-1, Fig. 1), at Běchary, east-central Czech Republic (coordinates N 50°18′54.2″; E 15°17′42.03″).

Fluctuations in $\delta^{13}C_{org}$, major- and minor-element proxies, palynological assemblages, and petrological composition, documented in the core, were correlated to the depositional histories of two depocentres of the Basin: the Lužice–Jizera sub-basin in the NW; and the Orlice-Žd'ár sub-basin in the SE (Fig. 1B). The two depocentres were part of the same seaway that developed along the reactivated Elbe Fault System, but their deposits were sourced from different blocks uplifted along separate faults. As a consequence, rates of subsidence and clastic influx differed between the two sub-basins. A basin-scale correlation grid was developed, based on well-log data (gamma-ray, resistivity, neutron porosity logs) from more than 700 boreholes. In most cases, the well logs were supplemented by either archive descriptions of cores or study of cores by the authors, and, where possible, calibrated by outcrop sedimentology and outcrop gamma-ray logging. For the NW depocentre, details of the sequence-stratigraphic framework and the types of genetic sequences were described by Uličný et al. (2009). Data from the SE depocentre, presented here, were treated in an analogous way. Genetic sequences, bounded by maximum transgressive surfaces, form a hierarchy of nested, composite sequences, interpreted to record a response to relative sea-level changes. Transgressive and regressive (T–R) histories were derived from tracking the maximum transgressive surfaces separating the sequences and the maximum regressive facies within composite genetic sequences, i.e. they are based on the genetic sequence concept of Galloway (1989), combined with elements of the T–R sequence *sensu* Embry (1995).

Correlation of the sequence framework shown in Fig. S1 was established over a total distance of c. 170 km. Because of the structural separation of the sub-basins, the correlation may be considered to be halfway between intra- to inter-basinal. Importantly, interpretations