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TEX$_{86}$ and stable δ^{18}O paleothermometry of early Cretaceous sediments: Implications for belemnite ecology and paleotemperature proxy application

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ABSTRACT

Recent studies have cast doubt on the unadjusted usage of Jurassic and Cretaceous δ^{18}O paleotemperature data derived from belemnites, since the latter data often reflect cooler paleotemperature estimates than would be expected. In this study we address this problem by analysing rocks of Barremian to early Aptian age from two outcrops in northern Germany using TEX$_{86}$ paleothermometry, along with 142 belemnite guards studied for their stable isotope (δ^{13}C, δ^{18}O) and trace element composition (magnesium, strontium, iron, and manganese). Both TEX$_{86}$ and δ^{18}O$_{Bel}$ indicate very warm water temperatures for a distinctive black shale sequence of late early Barremian age ("Hauptblätterton") with temperatures of up to 29 °C and 23 °C, respectively. We observe a constant offset of TEX$_{86}$ temperatures versus the 4 to 5 °C cooler δ^{18}O belemnite signal for this interval. The late Barremian sequence shows an increase of the δ^{18}O$_{Bel}$ values from −1‰ to 0‰ reflecting temperatures around 16 to 12 °C, while the contemporaneous TEX$_{86}$ temperatures vary between 26 and 32 °C. The common occurrence of belemnites in the anoxic sediments of the early Barremian implies, however, clearly a nektonic way of life similar to that of recent teuthids, rather than a nektobenthic one like *Sepia*. This in turn suggests that the belemnites investigated here (genera *Praeoxyteuthis*, *Aulacoteuthis, Oxyteuthis, and Neohibolites*) were active swimmers, which inhabited a deeper habitat below the thermocline in an epicontinental sea of perhaps 100 to 250 m water depth. The offset of the TEX$_{86}$ and δ^{18}O$_{Bel}$ data is therefore interpreted to reflect temperature signals from two different depth habitats, i.e. the TEX$_{86}$ is selectively derived from warm sea-surface waters, and the belemnites likely occupied deeper and cooler waters with relative increasing salinities in the late Barremian. This study stresses the importance that the taxonomy, paleobiology and ecology of the belemnite taxa (genera, species) used for paleotemperature reconstructions must be considered before the δ^{18}O$_{Bel}$ signal can be further interpreted. The variation of the δ^{18}O signature gained from one belemnite population of 22 specimens by 1.1‰ suggests that the δ^{18}O data of individual belemnites should be used with caution for reconstructing long termed paleotemperature trends.

1. Introduction

The oxygen isotope composition of calcareous shells of marine fossils has been used as a paleothermometer as early as by Urey et al. (1951) and Epstein et al. (1951). With a growing interest in paleoclimatic and paleoceanographic questions this paleotemperature proxy was successfully established over the last decades. In particular the low-Mg-calcitic guards of belemnites supplied temperature estimates for Jurassic and Cretaceous seas (e.g., Podlaha et al., 1998; Price et al., 2000; Schootbrugge van de et al., 2000; McArthur et al., 2004, 2007; Wierzbowski and Joachimski, 2007; Mutterlose et al., 2009). In more recent publications some of these data sets, however, turned out to be contradictory or not consistent (McArthur et al., 2004, 2007; Wierzbowski and Joachimski, 2007), e.g., paleotemperatures reconstructed from one boreal species showed a variation of up to 1.3‰ in their δ^{18}O$_{Bel}$ signatures (equivalent to about 6 °C) within the same stratigraphic horizon (Malkoc and Mutterlose, 2010). This may be partly contributed to the poor understanding of the belemnite biology, which makes the interpretation of these stable isotope data sets difficult. While the taxonomy of belemnites is relatively well known, hardly any data concerning the paleoecology are available. It is unknown, for example, what water depth specific belemnite taxa inhabited, whether they were bottom dwellers or active swimmers, and whether the ontogeny involved seasonal migration. Consequently, it is unclear to which extent the isotope data derived from

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belemnites reflect a signal from the sea-surface or from below the thermocline, neither is it known whether the lifestyle and/nor the ecologic niche of belemnites changed during ontogeny.

The more recent application of the TEX_{86} paleothermometer offers the possibility to gain paleotemperature data independent of $\delta^{18}O$ data determined on belemnites. TEX_{86} is an organic geochemical paleotemperature proxy based on the composition of membrane lipids derived from a ubiquitous component of marine plankton, the *Crenarchaeota* (Schouten et al., 2002). It can generally be applied to thermally immature Cretaceous sediments (Schouten et al., 2003, 2004). So far, a limited number of sea-surface temperature data based on TEX_{86} have been published for the early Aptian to early Turonian (Schouten et al., 2003), the Maastrichtian (Jenkyns et al., 2004), the early Aptian (Dumitrescu et al., 2006), the Cenomanian (Forster et al., 2007a) and the Albian to Santonian (Forster et al., 2007b). The latter study has shown that TEX_{86} temperature estimates generally agree well with those of $\delta^{18}O$ of well preserved “glassy” planktonic foraminifera.

Stratigraphically well dated Barremian to early Aptian anoxic sediments rich in organic carbon and belemnites from the northwest German Basin offered the opportunity to study both paleotemperature proxies (TEX_{86} and $\delta^{18}O$ of belemnites) collected bed-by-bed from the same horizons from the two outcrops. With a well known sedimentological and paleontological background these sediments enabled us to compare and evaluate both proxies in order to get a better understanding of the nature and relevance of the $\delta^{18}O$ signal of specific groups of belemnites (genera *Praeoxyteuthis*, *Aulacoteuthis, Oxyteuthis, and Neohibolites*). These findings serve to gain insight into the so far unknown lifestyle (nektonic versus nektobenthic) and the habitat (shallow versus deep) of these specific belemnite genera.

2. Geological background

2.1. Geological setting

During the early Cretaceous, northwest Europe was composed of a number of marine basins including the northwest German Basin, which had a paleolatitude of ~33° N. These formed the southernmost extension of the Boreal Arctic Sea that was located further to the north. In contrast to the Valanginian – Hauterivian and Aptian – Albian, when seaways extended towards the Tethys in the south, the Barremian sea was restricted, semi-enclosed and marginal (Fig. 1). As a consequence of the paleogeographic location of northwest Europe between the Boreal and the Tethyan Realms throughout the early Cretaceous, paleoceanographic changes should be more obvious in this area than elsewhere because these basins, which were bordering the two realms, were extremely sensitive to changes of sea-level, paleogeography and paleoclimate.

Throughout the Barremian and early Aptian anoxic conditions were caused by a stable stratification of the surface water, which initiated the deposition of TOC-rich laminated mudstones rich in total organic carbon (TOC). With the deposition of the most prominent black shale horizon in the late early Barremian (Hauptblätterton facies) anoxic conditions were established throughout the basin extending well into the Barremien Proto-North Sea. Organic geochemical studies show that these laminated sediments have a higher portion of marine organic matter compared to the coeval black clays (Littke et al., 1998; Mutterlose and Böckel, 1998), the total organic carbon (TOC) content varies from 1 to 5%. During the phase of organic-rich laminite sedimentation warm conditions caused a long lasting stable water stratification (Mutterlose et al., 2009).

Benthic organisms (foraminifera, macrofossils) are in general extremely rare in the Barremian laminites, while phytoplankton (calcareous nannofossils, calcispheres, dinoflagellates) and nektonic faunas (ammonites, belemnites) are quite common. A diverse and exceptionally well preserved fauna of teleosteid fishes has been described from these laminites (Brahms, 1913), supporting the absence of benthic organisms due to oxygen depletion of bottom waters. These observations go along with the absence of bioturbation and the preservation of the fine lamination. The most common macrofossils are belemnites, which allow for a detailed biostratigraphic zonation of these beds.

2.2. Belemnite paleobiology

The morphologic resemblance of belemnites (Naef, 1922; Stevens, 1965; Monks et al., 1996) to modern pelagic “teuthids” led to the assumption that belemnites were fast swimmers. This comparison is based on analogies of the skeleton morphology. Different lifestyles (nektonic versus nektobenthic) of belemnite genera with differently shaped guards are arguable. Specimens with short, thick guards (e.g., *Acroteuthis, Pachyteuthis*) would perhaps suggest a more nektobenthic lifestyle, while slender and elongated forms (e.g., *Hibolithes*) may have been fast swimmers, and taxa with laterally extremely flattened guards (e.g., *Duvalia*) may have had a benthic lifestyle. Following this view the extreme slender and elongate form of the *Aulacoteuthis* guards studied here would imply an active swimming lifestyle. These interpretations, which are purely based on the morphology, are, however, highly speculative if they are not supported by other data.

Recent teuthids (e.g., *Ancistrocheirus lesueuri*), which are permanent swimmers, use arm hooks to catch large, soft prey like fish. Arm hooks found along with preserved soft bodies of Toarcian belemnites (Reitner and Urlichs, 1983; Riegraf and Hauff, 1983) indicate a similar lifestyle for belemnites as active predators. Recent findings of Klug et al. (2009) of a late Jurassic *Hibolithes* guard preserved with beaks, arms and ink sac do suggest a fast swimming effective predator. The other two modern cephalopod groups (ocotopods, and sepioids), who specialise in feeding on nektonic prey like crustaceans, do not use arm hooks but suckers to catch their prey. The presence of a buoyancy mechanism in the form of a gas-filled phragmocone supports the assumption of an active swimming mode of life for belemnites. Modern “teuthids”, who have a reduced keratinous gladius, possess an enlarged and muscular mantle cavity making them fast and permanent swimmers.

Based on oxygen isotope data, Wierzbowski (2002) suggested a bottom-dwelling lifestyle at least for certain belemnite taxa of Oxfordian age. Most recently, Wierzbowski and Joachimski (2007), postulated a nektobenthic lifestyle for Bajocian to Bathonian belemnites (*Belemnopsis, Hibolithes*) based on their $\delta^{18}O$ values, which go well along with those of co-occurring bottom-dwelling oysters and trigonid bivalves. In both cases, the oxygen thermometry results of belemnite guards were interpreted as a temperature signal from below the thermocline. This view of a nektobenthic lifestyle is, however, contradicted by the common findings of *Aulacoteuthis* and *Oxyteuthis* guards, studied here, in the black shale sequence deposited under anoxic conditions (see Section 5.2 for details).

The Barremian of northwest Europe is dominated by the belemnite family *Oxyteuthididae* (suborder *Belemnitina*), a group which is restricted to the Boreal Realm. The species succession of the *Oxyteuthididae* underwent an endemic evolution in the North Sea area: *Praeoxyteuthis jasikofiana* (Hauterivian/Barremian boundary interval) – *Praeoxyteuthis pugio* (earliest Barremian) – *Aulacoteuthis* spp. (late early Barremian) – *Oxyteuthis brunsvicensis* (early late Barremian) – *Oxyteuthis germanica* (mid late Barremian) and *Oxyteuthis depressa* (latest Barremian). These taxa are restricted to the central and southern North Sea, excluding any major immigration from the Tethys or from the Boreal Arctic Sea further north. The early Aptian saw an abrupt change in the composition of the belemnite faunas, the Tethyan derived belemnopseid *Neohibolites*, which is the first belemnite genus to obtain a cosmopolitan distribution replaced the endemic *Oxyteuthididae*.