Z. Dt. Ges. Geowiss. (Int. J. Reg. Geol.)
Published online March 2020

PrePub Article

Chemostratigraphy and stratigraphic distribution of keeled planktonic foraminifera in the Cenomanian of the North German Basin

Jochen Erbacher[1], André Bornemann[1], Maria Rose Petrizzo[2] & Stefan Huck[3]*

Erbacher, J., Bornemann, A. & Petrizzo, M.R. & Huck, S. (2020): Chemostratigraphy and stratigraphic distribution of keeled planktonic foraminifera in the Cenomanian of the North German Basin. – Z. Dt. Ges. Geowiss.

Abstract: The record of keeled planktonic foraminifera during the Cenomanian in boreal epicontinental basins is discontinuous. Micropalaeontologic and bulk carbonate carbon and oxygen isotope investigations from two cores in the centre of the North German Basin (NGB, Wunstorf, Lower Saxony) showed keeled praeglobotruncanids and rotaliporids to exclusively appear during three stratigraphic intervals of varying duration in the lower and middle Cenomanian. Our new high-resolution carbon isotope ($\delta^{13}C_{carb}$) composite curve shows that keeled foraminifera are absent during the Mid-Cenomanian Event (MCE) I. In the aftermath of MCE I, keeled planktonic foraminifera are present throughout. The data are correlated to previously published sequence stratigraphic models for the NGB. The presence/absence of keeled planktonic foraminifera in the epicontinental NGB is believed to be controlled by sea level and according environmental conditions in the epicontinental basin.

Kurzfassung: In den Cenoman-zeitlichen Abfolgen der epikontinentalen Becken der borealen Kreide lassen sich gekielte planktonische Foraminiferen nicht durchgehend nachweisen. Neue Untersuchungen an zwei Bohrungen aus dem Norddeutschen Becken bei Wunstorf in Niedersachsen zeigen, dass sich die Vorkommen von gekielten Praeglobotruncanen und Rotaliporiden auf drei stratigraphisch klar abtrennbare Intervalle des Untercenomaniums und Mittelcenomaniums beschränken. Die hier präsentierte neue und hochauflösende Kohlenstoffisotopenkurve ($\delta^{13}C_{carb}$) belegt außerdem ein Fehlen gekielter planktonischer Foraminiferen während der positiven C-Isotopen-Exkursion des Mid-Cenomanian Event (MCE) I. Oberhalb des MCE I ist das Vorkommen gekielter planktonischer Foraminiferen kontinuierlich. Die Korrelation unserer Daten mit etablierten sequenzstratigraphischen Untergliederungen für das Cenomanium Norddeutschlands weist auf einen Zusammenhang zwischen Meeresspiegelschwankungen und dem Vorkommen gekielter Formen hin. Offensichtlich ermöglichten die Umweltbedingungen während hoher Meeresspiegelstände das Leben gekielter Formen in den Randbecken.

Keywords: planktonic foraminifera, carbon isotope stratigraphy, Boreal Cretaceous, Lower Saxony Basin, Germany

Schlüsselwörter: Planktonische Foraminiferen, Kohlenstoffisotopenstratigraphie, boreale Kreide, Niedersächsisches Becken, Wunstorf, Deutschland

1. Introduction

In the Cretaceous Tethyan and Atlantic oceans, some of the Late Albian to Cenomanian planktonic foraminiferal species are excellent stratigraphic marker fossils, often present throughout long intervals of successions, resulting in frequently applied biostratigraphical zonations (e.g. Robaszynski & Caron 1979, 1995; Caron 1985; Coccioni & Premoli Silva 2015). Over the years however, taxonomic revisions of planktonic foraminiferal taxa, especially of the polyphyletic *Rotalipora* group (*Rotalipora* Brotzen, 1942; *Thalmanninella* Sigal, 1948; *Pseudothamanninella* Wonders, 1978; *Parathalmanninella* Lipson-Benitah, 2008), have resulted in the re-interpretation of the morphologic plasticity and species variation within the lineages (Robaszynski et al. 1994; Petrizzo & Huber 2006; Gonzales-Donoso et al. 2007; Lipson-Benitah 2008), which of course, has influences on the classic planktonic foraminiferal biozonations (e.g. discussions in Ando et al. 2010; Petrizzo et al. 2015; Falzoni et al. 2018). In contrast to the Tethys, unkeeled and globular forms, predominantly muricohedbergellids (Huber & Leckie 2011) dominate the lower to lowermost Upper Cretaceous of

*Addresses of the authors:
[1]Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, 30655 Hannover, Germany (jochen.erbacher@bgr.de / andre.bornemann@bgr.de)
[2]Dipartimento di Scienze della Terra „A. Desio“, Università degli Studi di Milano, via Mangiagalli 34, 20133 Milano, Italy (mrose.petrizzo@unimi.it)
[3]Institut für Geologie, Leibniz Universität Hannover, Callinstraße 30, 30167 Hannover, Germany (huck@geowi.uni-hannover.de)

www.schweizerbart.de
DOI: 10.1127/zdgg/2020/0211
1860-1804/0211 $ 6.30

the Boreal epicontinental basins (Hecht 1938; Carter & Hart 1977; Weiss 1997; Rückheim et al. 2006; Weiss 2012). First keeled rotaliporids appear in the latest Albian, but mostly as single specimen or in low numbers (Weiss 1997). Stratigraphic patchiness of keeled planktonic rotaliporids and praeglobotruncanids continues in the lower to middle Cenomanian (Carter & Hart 1977; Koch 1977; Weiss 1982; Premoli Silva & Sliter 1999). This changes in the upper Cenomanian following the so-called "P/B break" in Boreal successions, a level marking a sudden increase in total number of planktonic foraminifera versus benthic foraminifera above the "mid-Cenomanian non-sequence" first described by Carter & Hart (1977) (see also Dahmer & Ernst 1986). As potential factors controlling the stratigraphic patchiness, palaeotemperatures (Carter & Hart 1977), ingressions of Tethyan water masses (Carter & Hart 1977; Weiss 1997), sea-level variations (Hart & Bailey 1979; Dahmer & Ernst 1986), the presence of a layered water column versus vertical mixing (Mitchell & Carr 1998) and changes in nutrient supply have been discussed. In the light of this patchiness, an application of the standard Tethyan planktonic foraminiferal zonation is obviously difficult, especially in the lower to middle Cenomanian (comp. Carter & Hart 1977; Weiss 1982; Bornemann et al. 2017).

The North German Basin as part of the Southern Permian Basin is one of the southernmost epicontinental basins of the Cretaceous Boreal realm with varying connections to the Tethys via potential gateways in the west and southeast (summary in Voigt et al. 2008b; Fig. 1). In the central Lower Saxony Basin (LSB), a subbasin of the North German Basin, the Cenomanian is represented by an up to 170 m thick succession of hemipelagic marly claystones and marly limestones. For details on the palaeogeographic evolution and depositional environment of the Cenomanian North German Basin see Voigt et al. (2008b) and Wilmsen (2003, 2012).

Over the past 15 years, detailed $\delta^{13}C$ records have allowed for a comprehensive chemostratigraphic correlation of upper Albian to upper Cenomanian successions between Tethyan basins, the Central Atlantic, and the Boreal realm (e.g. Jarvis et al. 2006; Petrizzo et al. 2008; Gambacorta et al. 2015; Giorgioni et al. 2015; Bornemann et al. 2017; Gyawali et al. 2017). Positive and negative excursions of carbon isotope records in the upper Albian to Turonian are frequently used to correlate sedimentary successions and have been interpreted as global carbon cycle perturbations (e.g. Jenkyns et al. 1994; Erbacher et al. 1996; Jarvis et al. 2006). For the upper Albian to middle Cenomanian, however, the resolution of the Boreal records from England (Mitchell et al. 1996; Jarvis et al. 2006) and Northern Germany (Mitchell et al. 1996; Wilmsen 2007) are rather low, hampering a detailed correlation to sections elsewhere. While the high-resolution record of Bornemann et al. (2017) focused on the Albian-Cenomanian transition, our study presents the first high-resolution $\delta^{13}C_{carb}$ record for the lower to upper Cenomanian of the Boreal realm. Globally or supra-regionally occurring carbon isotope excursions during the stratigraphic interval investigated herein are: the lower Cenomanian excursions belonging to LCE 1 to 3 (Jarvis et

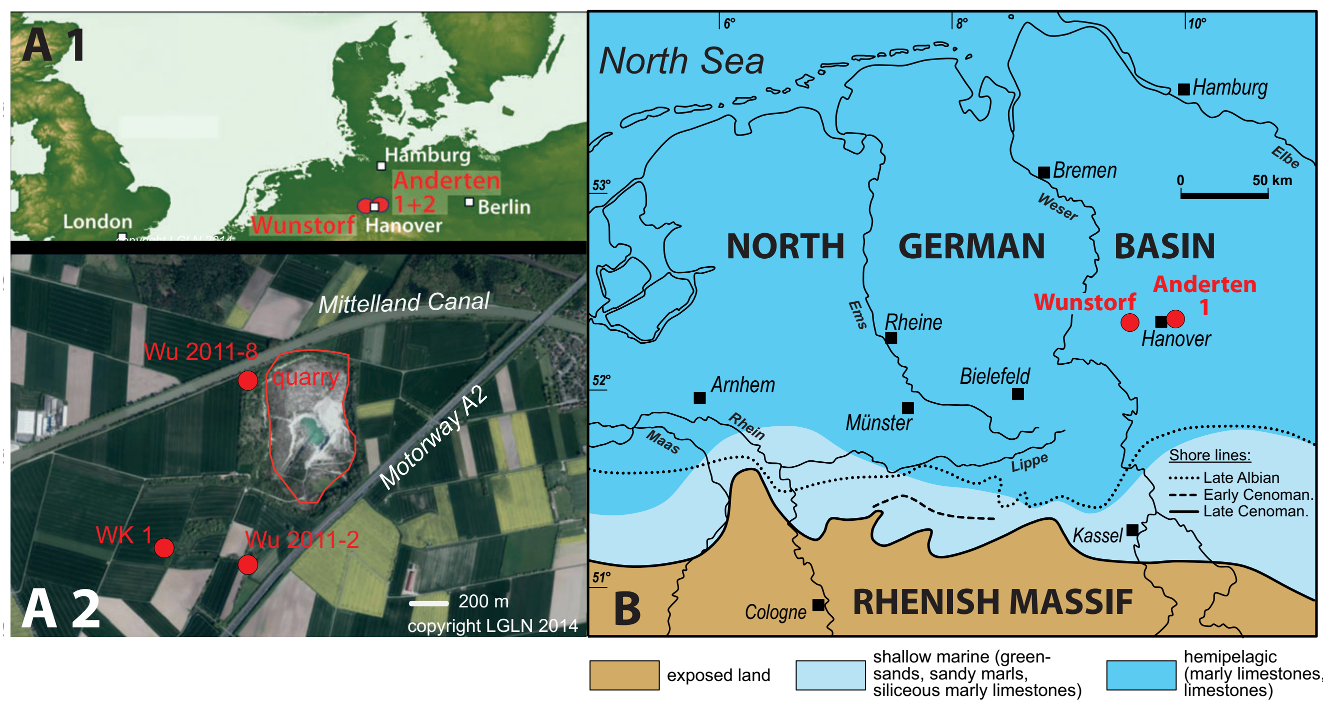

Fig. 1: (**A1**) Locality map of the Wunstorf quarry near Hanover with position of cores Wunstorf 2001-2 and Wunstorf 2011-8 as well as core WK1. (**A2**) Locality map of Northern Germany with position of Wunstorf and cores Anderten 1 and 2 near Hanover. (**B**) Palaeogeographic map of Northern Germany during Albian and Cenomanian times with position of locations discussed herein (modified after Hiss 1995).

al. 2006); the Mid-Cenomanian Event (MCE) I (Paul et al. 1994; Mitchell et al. 1996; Jarvis et al. 2006) and Oceanic Anoxic Event 2 (Arthur et al. 1985; Tsikos et al. 2004; Erbacher et al. 2005; Voigt et al. 2008a; Jenkyns 2010, among many others).

Our dataset includes a new composite record documenting the carbon and oxygen isotopes as well as the presence/absence of keeled planktonic foraminifera, spanning large parts of the Cenomanian. This is based on two recently cored commercial boreholes that have been drilled close to Wunstorf, 25 km west of Hanover, Germany (cores Wunstorf 11/8 and 11/2; Fig. 1). Our record is stratigraphically correlated and partly stratigraphically overlapping with core Anderten 1, east of Hanover, yielding an upper Albian to lower Cenomanian succession (see Bornemann et al. 2017) and with core WK1, close to Wunstorf and stratigraphically covering the upper Cenomanian to lower Turonian (Voigt et al. 2008a; Figs. 1 and 2). Our data is complemented with published data from the upper Cenomanian of Wunstorf (Weiss 1982: planktonic foraminifera; Voigt et al. 2008a: carbon and oxygen isotopes).

The upper part (uppermost Lower Cenomanian to Cenomanian–Turonian Boundary Interval) of the herein studied succession has been described by several authors based on a 110 m thick succession cropping out in the Wunstorf quarry (Weiss 1982; Meyer 1990; Zügel 1994; Mitchell et al. 1996; Wilmsen 2007; Wilmsen et al. 2007) and the scientific drill core WK1 (Fig. 1; Erbacher et al. 2007; Voigt et al. 2008a; Blumenberg & Wiese 2012; van Helmond et al. 2015). Wilmsen (2003) and Wilmsen & Niebuhr (2002) established a well-documented multi-stratigraphic, sedimentological and sequence-stratigraphic scheme of the succession. According to them, the succession in Wunstorf was situated on the outer shelf with high sedimentation rates of up to 100 m/Ma in the lower and middle Cenomanian and 4 to 6 times lower sedimentation rates in the upper Cenomanian. Regardless of the expanded character of the section, hiatuses of potentially limited extend might be present at the sequence boundaries.

The aim of this paper is to document and investigate the stratigraphic patchiness of keeled planktonic foraminifera in the lower to middle Cenomanian of the North German Basin. Potential reasons responsible for this patchiness are discussed and the first high-resolution carbonate carbon isotope record spanning the entire Cenomanian of the North German Basin is presented. Planktonic foraminiferal events in the North German Basin are stratigraphically constrained by this detailed chemostratigraphic record.

2. Material and methods

Cores Wunstorf 2011/2 and Wunstorf 2011/8 are located 1 km south of Wunstorf (approx. 25 km west of Hanover, Germany) near a semi-active quarry, owned by Lafarge-Holcim, north of the Autobahn A2. The two holes are situated ca. 800 m apart (Wunstorf 2011/2: UTM 32532994.75 E, 5805234.25 N; Wunstorf 2011/8: UTM 32532837.55 E, 5806131.47 N; Fig. 1). Each core covers a 100 m thick succession spanning the lower Turonian to upper part of the lower Cenomanian (Wunstorf 2011/2) and upper part of the lower Cenomanian to the lower part of the lower Cenomanian (Wunstorf 2011/8). Lithostratigraphically, the two cores comprise the uppermost Herbram (Bemerode Member), Baddeckenstedt and Brochterbeck formations. The upper part of the cored succession, including the Cenomanian–Turonian Boundary Event (CTBE) is intensively discussed in Voigt et al. (2008a), Wilmsen (2003) and Weiss (1982). Therefore, we focus on the lower 57 m of core Wunstorf 2011/2 and the lowermost 80 m succession of Wunstorf 2011/8, i.e. the lower part of the upper Cenomanian to lower Cenomanian (Fig. 2) herein. Our data, however, is complemented with the datasets from Voigt et al. (2008a) and Weiss (1982). See Figs. 3 and 4.

Micropalaeontology sample spacing ranges from 5 to 100 cm. All samples were crushed into small pieces (1 to 2 cm in diameter), dried, gently disaggregated using an 85 % water, 15 % hydrogen peroxide solution and soaked in a solution of 80 % acetic acid and water modified after the method suggested by Lirer (2000). After soaking, the samples were washed with warm water over a 63-µm mesh sieve and dried at 50 °C. The fraction >63 µm was then dry-sieved into fractions >315 µm, 315 to 200 µm, 200 to 125 µm and 125 to 63 µm. From each fraction, planktonic foraminifera and ostracods were picked in slides. Planktonic foraminifera and the ostracod *Physocythere steghausi* were qualitatively (present/absent) and semi-quantitatively documented for biostratigraphic purposes. Keeled planktic foraminifera and *P. steghausi* were only retrieved from fractions >125 µm. Taxonomic concepts for planktonic foraminiferal genera and species identification follow their original descriptions and illustrations, the taxonomies by Caron & Spezzaferri (2006), Petrizzo & Huber (2006), Ando & Huber (2007), Gonzales Donoso et al. (2007), Huber & Leckie (2011), Petrizzo et al. (2015), and the online taxonomic database for Mesozoic Planktonic Foraminifera available at http://www.mikrotax.org/pforams/index html (Huber et al. 2016). Type material is stored in the Collection of Micropalaeontology (Micro-Unimi) of the Department of Earth Sciences, University of Milan. As mentioned above, we used data documented and described by Weiss (1982) to complement our dataset by correlating his data from the nearby Wunstorf quarry to our dataset (see Fig. 5). Weiss (1982) focused on the middle to upper Cenomanian part of the succession, leading us to sample the lower part of the section at higher resolution.

For carbon and oxygen isotope the two drill cores were sampled at a spacing between 20 and 100 cm resulting in a total of 319 samples that were analysed for $CaCO_3$ and total organic carbon (TOC) using a Leco device (Leco Corporation, St Joseph, MI, USA) at the BGR in Hanover. Analyses for bulk-rock stable isotopes ($\delta^{13}C$, $\delta^{18}O$) were conducted using a Thermo Scientific GasBench II carbonate device connected to a Thermo Scientific Delta 5 Advantage IRMS (Thermo Fisher Scientific, Waltham, MA, USA) at the Institute of Geology, Leibniz University of Hanover. The GasBench uses viscous water-free (98 g mol^{-1}) orthophosphoric acid at 72 °C to

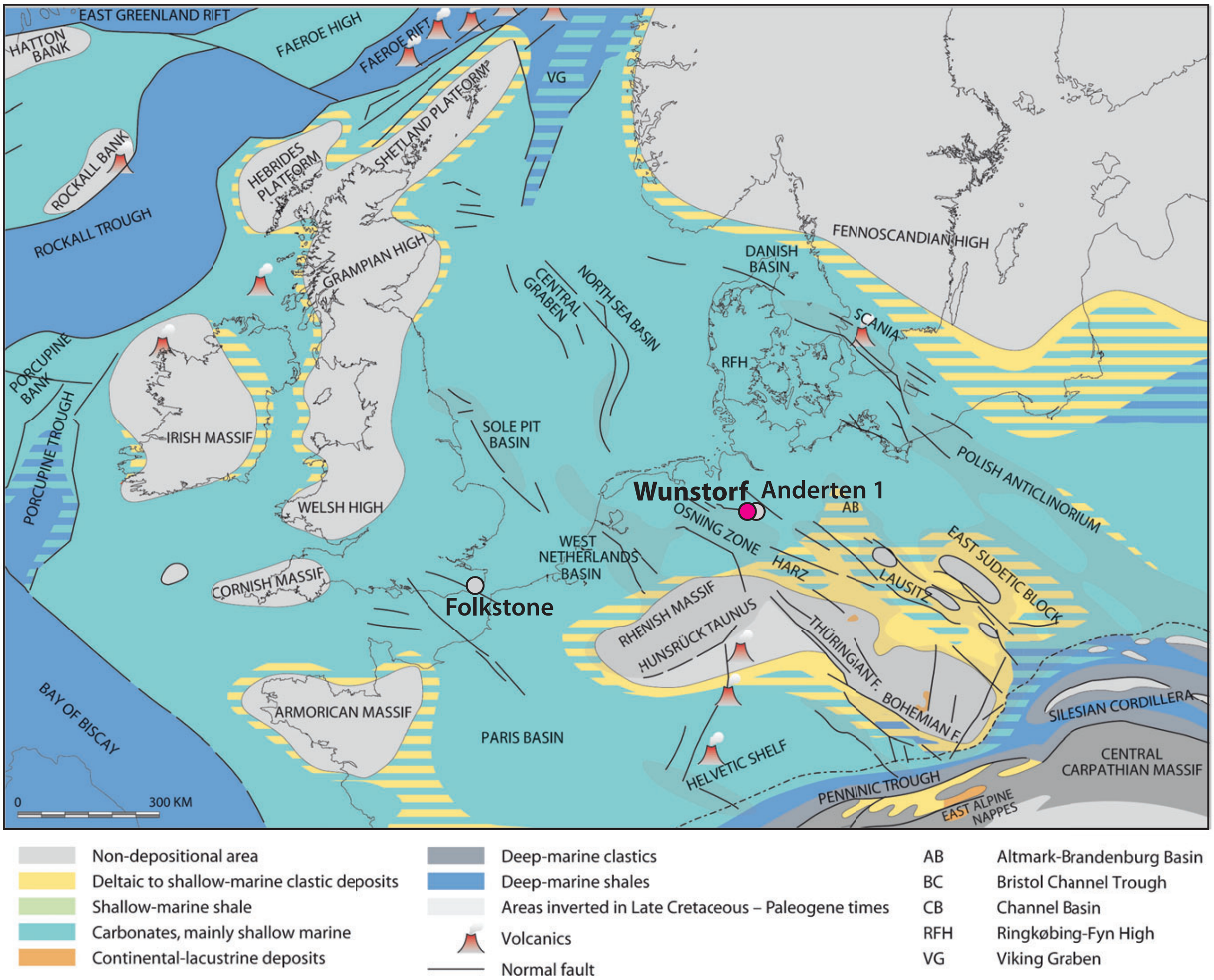

Fig. 2: Palaeogeographic map of Europe for the Upper Cretaceous; modified after Vejbaek et al. (2010).

release CO_2 of the calcite 1 h before the start of the measurement. Values are expressed in the delta notation relative to Vienna Pee Dee Belemnite (VPDB) in per mill. Repeated analyses of certified carbonate standards (NBS 19, IAEA CO-1 and CO-8) show an external reproducibility of <0.06 ‰ for $\delta^{13}C$ and <0.08 ‰ for $\delta^{18}O$. As mentioned above, we used data documented and described by Voigt et al. (2008a) to complement our dataset by correlating their data from the nearby core WK 1 to our dataset (see Fig. 3).

3. Results

3.1 Stable isotope stratigraphy and $CaCO_3$ values

The $\delta^{13}C$ values of cores Wunstorf 11/2 and 11/8 are remarkably stable and vary around 2 per mill between 145 and 45 mcd (meter composite depth; Fig. 3). A 1.5-‰ positive excursion with maximum values of up to 3 ‰ is evident between 49 and 30 mcd, followed by a short trough and another increase between 20 and 14 mcd. The $\delta^{18}O$ values are more variable than the $\delta^{13}C$ data. Most negative excursions are documented between 145 and 130 mcd (around -3.8 ‰). Upsection, the oxygen isotope record shows a long-term cyclicity between 2 and 3 ‰ and whereas $CaCO_3$ values show a gradual long-term increase from 60 to 90 wt% between the base of the succession and the top. However, a step in $CaCO_3$ content is observed at 70 mcd, values below this level show a meter-scale high variability of 15 wt% reflecting marl and limestone alternations, values above 70 m are more uniform.

3.2 Planktonic foraminifera (Fig. 4)

Planktonic foraminifera, mostly muricohedbergellids, are present in all samples in varying abundances (see also Weiss 1982). Below 117 mcd of the composite section, planktonic foraminiferal faunas are dominated by muricohedbergellids.

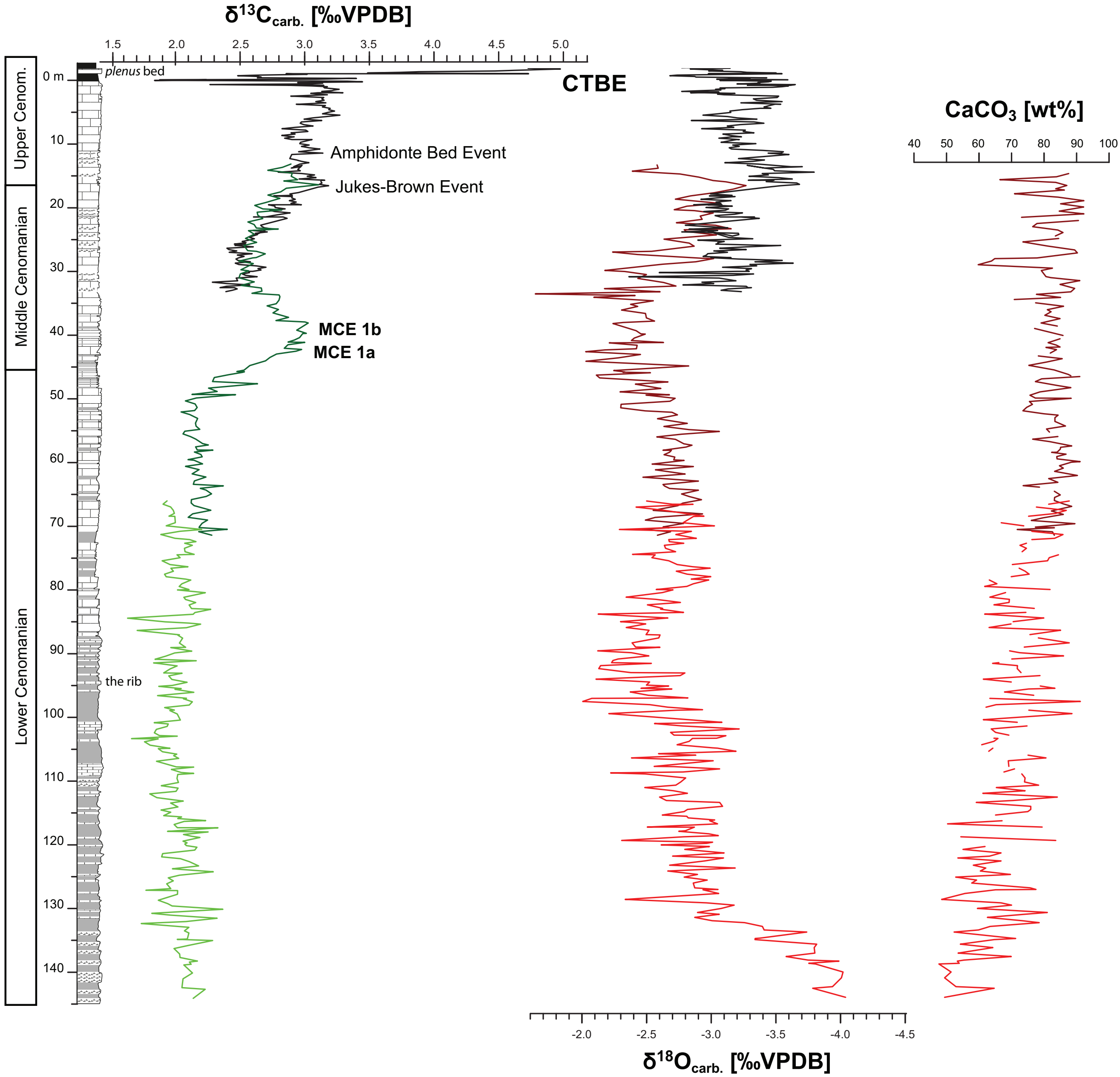

Fig. 3: Composed section for Wunstorf cores (WK1, Wunstorf 2011-2 and Wunstorf 2011-8) and Wunstorf quarry (Wilmsen 2003; Erbacher et al. 2007; Voigt et al. 2008a) showing schematic lithology, stable carbon and oxygen isotope records and $CaCO_3$ values. Names indicate key chemostratigraphic events following the terminology of Jarvis et al. (2006). $\delta^{13}C$ record: light green line from core Wunstorf 2011-8, dark green line from core Wunstorf 2011-2, black line from core WK 1 (Voigt et al. 2008a). $\delta^{18}O$ record: red line from core Wunstorf 2011-8, brown line from core Wunstorf 2011-2, black line from core WK 1 (Voigt et al. 2008a). $CaCO_3$ values: red line from core Wunstorf 2011-8, brown line from core Wunstorf 2011-2. The "facies change", which marks the lithologic base of the Cenomanian Turonian Boundary Event (CTBE), has been taken as 0 m on the depth scale.

Globigerinelloides is present but rare throughout this lower part of the succession. Favusellids only occur in very few samples. At 116.20 mcd and 1.18 m above the HO (highest occurrence) of *P. steghausi*, lies the LO (lowest occurrence) of rotaliporids in core Wunstorf 11/8, which are represented by *Thalmanninella globotruncanoides* and *Thalmanninella* cf. *reicheli*. Strikingly large forms (>200 µm) dominate these faunas. Rotaliporids disappear above 114.2 mcd and reappear in low numbers between 105 and 104 mcd. Specimens in the latter interval are small and mainly represented by the species *Thalmanninella globotruncanoides* and *Thalmanninella brotzeni*. Weiss (1982) documented praeglobotruncanids in the same stratigraphic level of the nearby Wunstorf quarry. No keeled planktonic foraminifera (with exception of

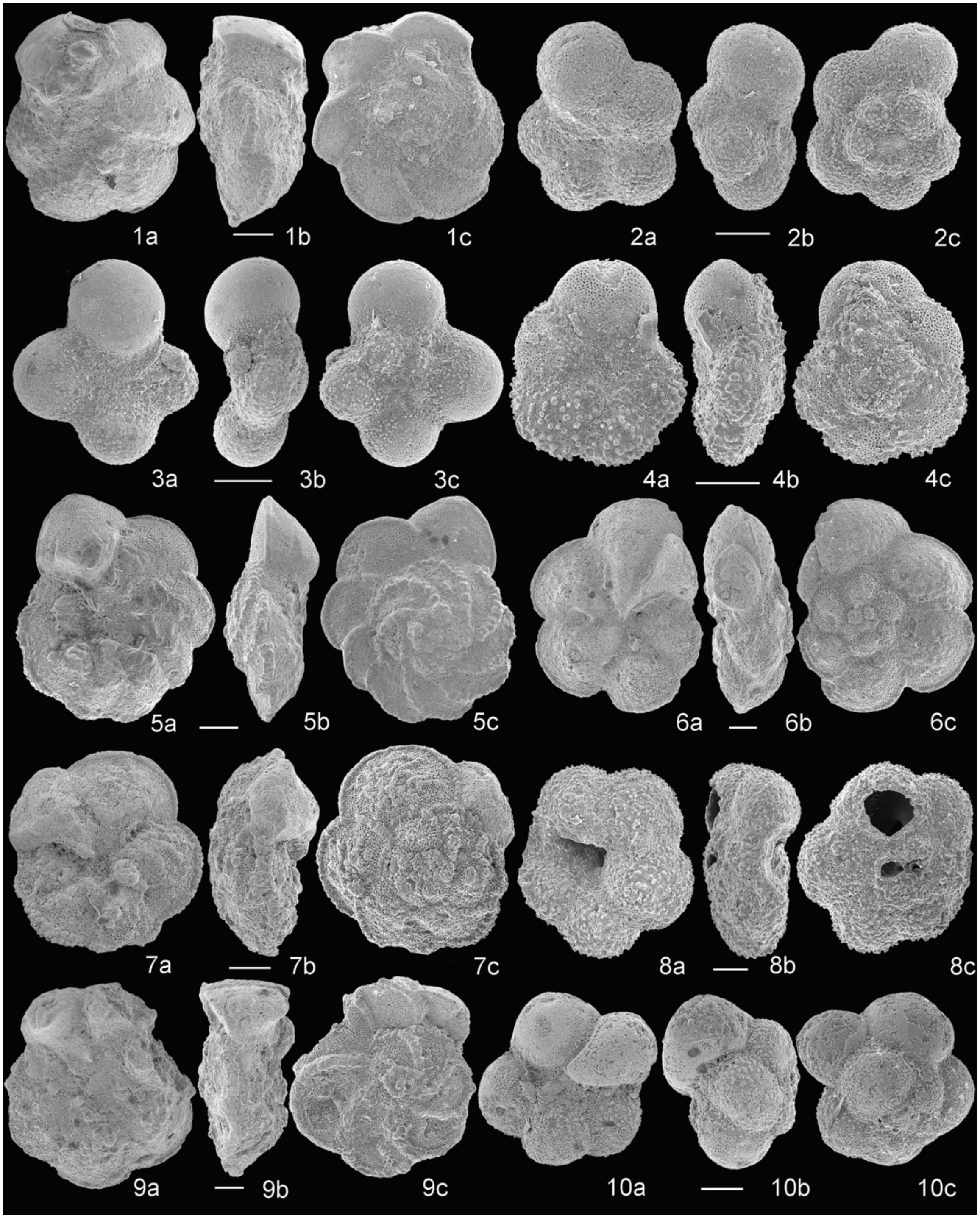

Fig. 4: (**1a–c**) *Thalmanninella gandolfi*, sample 11/8-31.00–31.05. (**2a–c**) *Muricohedbergella delrioensis*, sample 11/8-31.00–31.05. (**3a–c**) *Clavihedbergella simplicissima*, sample 11/8-31.00–31.05. (**4a–c**) *Praeglobotruncana delrioensis*, sample 11/8-56.10–56.15. (**5a–c**) *Thalmanninella globotruncanoides*, sample 11/2-57.44–57.50. (**6a–c**) *Rotalipora montsalvensis*, sample 11/2-50.00–50.05. (**7a–c**) *Rotalipora* cf. *cushmani*, sample 11/2-50.00–53.05. (**8a–c**) *Whiteinella archaeocretacea*, sample 11/2-76.22–76.78. (**9a–c**) *Thalmanninella reicheli*, sample 11/2-50.00–53.05. (**10a–c**) *Muricohedbergella portsdownensis*, sample 11/2-50.00–50.05. Scale bars 100 µm. SEM images acquired at the Department of Earth Sciences, University of Milan using Jeol JSM-IT500.

one single *Praeglobotruncana delrioensis* specimen at 97.11 mcd) occur until 87.88 mcd. Between 87.88 and 75 mcd keeled planktonic foraminifera belonging to the species *Th. globotruncanoides*, *Th. brotzeni*, *Thalmanninella gandolfi* are present albeit usually in small numbers. The assemblages in this interval are composed by abundant muricohedbergellids (*Muricohedbergella delrioensis*, *Clavihedbergella amabilis*, *Clavihedbergella simplicissima*, *Muricohedbergella portsdownensis*) characterised by a high variability in the arrangement of the chambers. Rare *Rotalipora montsalvensis* are identified at 79 mcd. No keeled forms are present between 70 and 74 mcd. Between 70 and 45 mcd keeled planktonic foraminifera such as *Th. globotruncanoides*, *Th. gandolfi*, *R. montsalvensis* and *Praeglobotruncana delrioensis* are mostly present. Rare specimens resembling *Thalmanninella reicheli* and *Thalmanninella greenhornensis* are recorded at 49.52 mcd. Few metres above, at 45.95 mcd, *Thalmanninella deeckei* and *Whiteinella archaeocretacea* are recorded although very rare. Muricohedbergellids and especially the species *M. delrioensis* and *M. portsdownensis* are common in this interval. A striking lack of keeled forms is evident between 44 and 32 mcd. Weiss (1982) documented one single sample at approx. 38 mcd from this interval with a few praeglobtruncanids. Above 30 mcd, keeled planktonic foraminifera are present and usually common in all samples investigated. Remarkable are the occurrence of common *R. montsalvensis*, which shows a high morphologic variability in the shape and number of chambers in the last whorl, and the presence of many specimens transitional to *Rotalipora cushmani*.

A detailed and taxonomic study/review on the planktonic foraminifera observed will be the focus of another study (Petrizzo & Erbacher in prep.).

3.3 Stratigraphy and correlation of the sections investigated

The base of our composite succession lies in the lowermost lower Cenomanian. The uppermost positive excursions of the Albian-Cenomanian Boundary Event, well documented in core Anderten 1 (see Bornemann et al. 2017), is not reached, which gives us a good estimate for the maximum age of our succession.

The highest occurrence (HO) of the ostracod species *Physocythere steghausi* is regarded as a useful stratigraphic marker in the North German Basin (Frieg et al. 1989; Witte et al. 1992). The HO of *P. steghausi* in core Wunstorf 11/8 at 73.38 m (117.38 mcd) is very close to the lowest occurrence (LO) of rotaliporids at 72.69 m (116.2 mcd; Fig. 5). Bornemann et al. (2017) described the same succession of biostratigraphic events, which we call the “*steghausi-Thalmanninella*-Event”, and even the same vertical distance between these events from core Anderten 1. This suggests similar sedimentation rates in both successions and underlines the solid applicability of the *steghausi-Thalmanninella*-Event at least in the North German Basin. Bornemann et al. (2017) related a pronounced positive $\delta^{13}C$ excursion immediately below this event to one of the Lower Cenomanian Events (LCEs) sensu Jarvis et al. (2006). Although sampled at high resolution, this carbon isotope peak cannot be identified in Wunstorf 11/8. Whether this questions the completeness of Wunstorf 11/8 or interpretation in Bornemann et al. (2017) remains open.

Above approx. 105 mcd, the succession recovered in Wunstorf 11/8 overlaps with the record formerly cropping out in the Wunstorf quarry, which was described in detail by Wilmsen (2003). This allows for a correlation of the recently developed and well-established bio- and lithostratigraphic scheme for the North German Cenomanian (e.g. Wilmsen 2003; Wilmsen et al. 2005; Wilmsen 2007; Wilmsen 2008) with the succession discussed herein (Figs. 2 and 3).

We interpret the pronounced positive carbon isotope excursion between 49 and 30 mcd to be the local expression of the MCE I. Mitchell et al. (1996) and Wilmsen (2007) both described the presence of the MCE I at Wunstorf. As described in Mitchell et al. (1996), MCE I may be subdivided in two distinct positive peaks, MCE 1a and MCE 1b (Fig. 3). Above approx. 30 mcd, the succession recovered in Wunstorf 11/2 overlaps with the succession described by Erbacher et al. (2007) and Voigt et al. (2008a) (core WK1; Figs. 1 and 2). This allows us to tying our data to a stable isotope record reaching up to the lower Turonian, including the positive carbon isotope excursion related to the Cenomanian-Turonian Boundary Event (Fig. 3).

4. (Sequence-) Stratigraphic distribution of keeled planktonic praeglobotruncanids and rotaliporids in the North German Basin

Fig. 4 shows the stratigraphic distribution of intervals yielding keeled planktonic foraminifera. Four of these intervals (Intervals I to IV) may be discriminated. Interval I, in the lower part of the lower Cenomanian was first described in core Anderten 1 (Bornemann et al. 2017). It is the first, albeit stratigraphically short interval, with abundant and diverse keeled planktonic foraminifer faunas in the North German Basin. Stratigraphically older findings are confined to single and mostly rare specimen of *Th. appeninica* in upper Albian successions (Koch 1977; Weiss 1997). A comparison with the relative sea-level curve and sequence stratigraphic scheme for the North German Basin by Wilmsen (2012) shows Interval I lying above Sequence Boundary Ce1 and correlating with the according transgressive systems tract (TST).

Interval II in the middle lower Cenomanian is not as pronounced as Interval I, as keeled planktonic foraminifera do occur but are not as common as in Interval I. It is striking, however, that the interval lies once again above a sequence boundary (SB Ce2) and, thus, falls into a TST.

In contrast to Intervals I and II, the upper lower Cenomanian Interval III is of much longer duration. As Interval II, it belongs to depositional sequence Ce III (Wilmsen 2003).

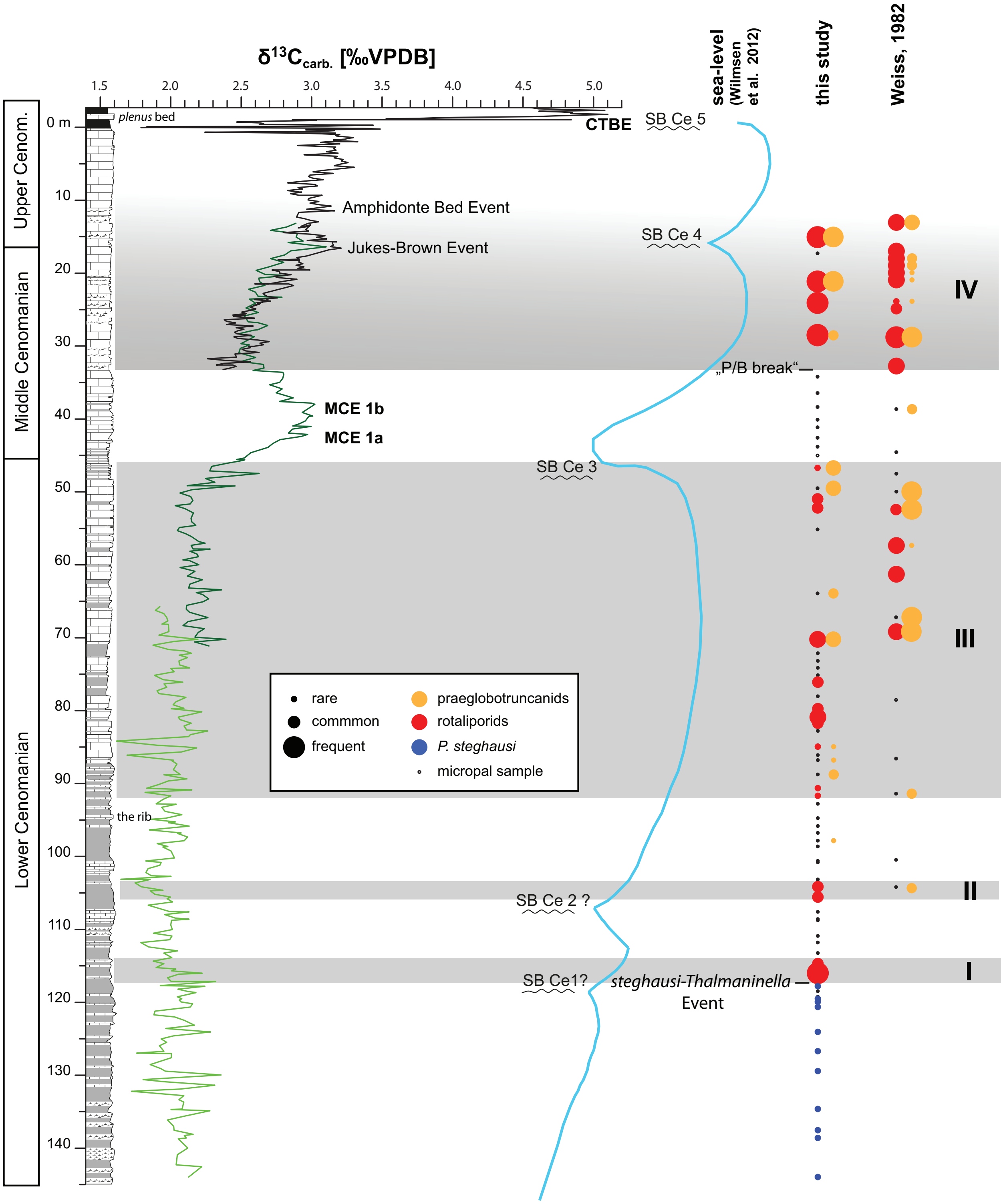

Fig. 5: Composed section for Wunstorf cores (WK1, Wunstorf 2011-2 and Wunstorf 2011-8) and Wunstorf quarry showing schematic lithology and $\delta^{13}C$ record (see figure caption 4). Dots indicate micropalaeontologic results from this study (left column) and Weiss (1982) (right column). Sequence boundaries (SB Ce) are from Wilmsen (2003) and Bornemann et al. (2017). Sea-level curve from Wilmsen (2012). Grey shaded horizons mark intervals with keeled planktonic foraminifera.

While Interval II correlates with the lower part of the TST, Interval III comprises the maximum flooding zone as defined by Wilmsen (2003).

Interval IV begins at the end of the MCE I and its base correlates with the "P/B break" (sensu Carter & Hart 1977). The upper limit of this interval is not defined, as keeled planktonic foraminifera are present throughout the mid middle to upper Cenomanian succession in Northern Germany (Koch 1977; Weiss 1982; Dahmer & Ernst 1986).

5. Planktonic foraminiferal intervals and controlling factors – a discussion

Based on the results presented above, the occurrence of keeled planktonic foraminifera in the North German Basin seems to be related to sea level. A rising sea level would allow keeled planktonic foraminifera to migrate into the Cenomanian North German Basin via gateways potentially existing in the northwest (North Sea) and southeast (Polish Basin) (Voigt et al. 2008b; Fig. 2). Several authors already suggested this being a potential cause for the base of Interval IV (Carter & Hart 1977; Dahmer & Ernst 1986), but for the earlier Intervals I to III, this observation has not been documented yet.

The classic model for depth habitats of Cretaceous planktonic foraminifera goes back to a modern analogue model, where species with small, simple and globular tests would be shallow dwellers and large, complex tests often disc-shaped with keels would be deep dwellers. Accordingly, muricohedbergellids are interpreted as shallow dwellers and keeled species, such as rotaliporids, as deep dwellers resulting in a dominance of muricohedbergellids in epicontinental basins (e.g. Hart & Bailey 1979; Hart 1980; Caron & Homewood 1983; Leckie 1987; Premoli Silva & Sliter 1999). Modern depth-habitat reconstructions based on carbon and oxygen isotope investigations of diagenetically uncompromised tests, however, demonstrated that such models are too simplistic (e.g. Hart 1999; Abramovich et al. 2003; Bornemann & Norris 2007; Ando et al. 2009, 2010; Falzoni et al. 2013, 2016). Planktonic foraminifera seem to be far more adaptive to varying environmental conditions than formerly expected and water depth seems to be only one potential factor controlling the presence or absence in ecological niches. Other ecological factors are the thickness of the mixed-layer, position and stability of the thermocline, trophic conditions and salinity, as well as surface water circulation (see Hart 1999; Abramovich et al. 2003; Ando et al. 2009, 2010; Falzoni et al. 2013, 2016; Petrizzo et al. 2017 and discussions therein).

The spatial distribution of planktonic organisms in epicontinental seas is mainly depending on ocean circulation patterns (e.g. currents) and boundaries between different water masses (Schiebel & Hemleben 2017). For the case of the North German Basin this means Tethyan or Atlantic water-masses needed to have flown into or through the basin in order to enable planktonic foraminifera to invade. An increase of sea level alone would not bring e.g. Tethyan planktonic foraminifera to the North German Basin. This sounds trivial but needs to be taken into account when discussing the factors responsible for the presence or absence of keeled planktonics in an epicontinental basin.

Intervals I to IV: While a correlation of Intervals III and IV with high sea level is obvious as both of these intervals correlate perfectly with the maximum flooding zones defined by Wilmsen (2003, 2008), the correlation of Intervals I and II is not as straightforward. Both of these events are much shorter in duration and rather correlate with phases of rising but not highest sea level (Fig. 5). This might be explained by a sample resolution too low to document the presence/absence of foraminifera sophisticatedly. Another possible explanation is a lack of precision of Wilmsen's sea-level curve for the lower lower Cenomanian part of the succession. Certainly, his observations for this stratigraphic interval are based on a rather limited number of sections, leaving space for a re-interpretation of the sea-level curve for this stratigraphic part (see question mark behind the position of SB Ce2 in e.g. Wilmsen 2003). A third possibility could be, ocean currents connecting the North German Basin during the initial transgression, only and being redirected, elsewhere, during further sea-level rise. This interpretation is supported by the presence of large rotaliporid tests in Interval I and a lack of small, potentially juvenile forms. One potential explanation for this interpretation was given by Retailleau et al. (2009). These authors have observed a lack of small tests in planktonic foraminifer cohorts on the modern continental shelf in the Bay of Biscay. The authors interpreted theses faunas as being expatriated from the open ocean. Environmental conditions on the shelf (river discharge affecting salinity and trophic conditions) allowed a further growth of the foraminifer individuals but no reproduction.

Keeled planktonic foraminifera in the Cenomanian of southern England: A comparison with the planktonic foraminiferal record of the Cenomanian in Southern England shows a rather comparable evolution, although continuous records are lacking. Apparently, keeled species are present from the base of the Lower Cenomanian onward (*Thalmanninella appenninica* and *Praeglobotruncana stephani*) (Carter & Hart 1977) but their stratigraphic appearance seems to be patchy and a continuous presence of keeled forms is not observed before the late Early Cenomanian, i.e. during our late Interval III (Carter & Hart 1977; Paul et al. 1994; Hart & Harris 2012).

MCE 1: In contrast to Wunstorf and Baddeckenstedt, a more proximal section to the southeast of Wunstorf (Bartels, unpubl.), keeled planktonic foraminifera are present in Southern England during the MCE 1 positive carbon isotope excursion (Paul et al. 1994; Mitchell & Carr 1998). Mitchell & Carr (1998) explained the occurrence of *Th. reicheli* in Folkestone to be controlled by the 100 ka eccentricity cycle with *Th. reicheli* only being present during the transgressive phase of a cycle and disappearing thereafter and *R. montsalvensis* and praeglobotruncanids being present throughout the MCE. Generally, however, MCE 1 is paralleled by a low sea level (Wilmsen 2012; Gebhardt et al. 2004) and a potential ingression of cool water masses from the Boreal Sea (e.g.

Zheng et al. 2016). The environmental conditions during MCE 1, obviously did not allow keeled planktonic species to survive in the North German Basin. As they were described from southern England, however, temperature can be ruled out as a factor controlling the absence. Other factors such as water depth, salinity, the availability of prey or the connection of the North German Basin by open ocean currents thus have to be considered. Batenburg et al. (2016), based on astronomical age models for sections from the Western Interior Seaway, dated the base of the MCE 1 excursion to 96.57 ± 0,12 Ma and the end of the excursion to 96.36 ± 0,12 Ma, resulting in a duration of 200 ka for MCE 1 and the absence of keeled planktonic foraminifera in Northern Germany, respectively.

6. Summary

Micropalaeontologic and carbon and oxygen isotope investigations from two new cores in the centre of the North German Basin (Wunstorf, Lower Saxony) showed keeled praeglobotruncanids and rotaliporids to appear during three stratigraphic intervals of varying duration in the Lower and Middle Cenomanian. The last interval without keeled planktic foraminifera is during the Mid-Cenomanian Event (MCE 1). Above MCE 1 and starting with the "P/B-break" (Carter & Hart 1977), keeled planktonic foraminifera are present throughout. Our new high-resolution stable carbon isotope record allowed tying the micropalaeontologic record to sequence stratigraphic models and sea-level curves for the North German Basin published by Wilmsen (2012). Obviously, high sea level connected the North German Basin to Tethyan and/or Atlantic water masses during the intervals yielding keeled planktonic foraminifera. Planktonic foraminifera were able to adapt to the environmental conditions in the North German Basin. Whether or not they were thriving in the same ecological niches as in their "original" habitat remains open.

7. Acknowledgements

We thank Michaela Berensmeier and Holger Gebhardt for insightful comments and suggestions to improve the manuscript. Our gratitude is expressed to Brian Huber, Markus Wilmsen, Malcolm B. Hart and Silke Voigt for hints, discussions, etc., which helped getting this project finished. Eckbert Seibertz and Bernd Reupke (Holcim/Lafarge) provided access to cores Wunstorf 2011-2 and Wunstorf 2011-8 and to internal technical reports. Without their help, this study would not have been possible. Gabriele Grützner and Sabine Stäger are thanked for SEM imaging and sample preparation.

8. References

Abramovich, S., Keller, G., Stüben, D. & Berner, Z. (2003): Characterization of late Campanian and Maastrichtian planktonic foraminiferal depth habitats and vital activities based on stable isotopes. – Palaeogeogr., Palaeoclimatol., Palaeoecol., 202: 1–29.

Ando, A. & Huber, B.T. (2007): Taxonomic revision of the late Cenomanian planktic foraminifera *Rotalipora greenhornensis* (Morrow, 1934). – J. Foramin. Res., 37: 160–174.

Ando, A.B., Huber, B.T., MacLeod, K.G., Ohta, T. & Khim, B.-K. (2009): Blake Nose stable isotopic evidence against the mid-Cenomanian glaciation hypothesis. – Geology, 37: 451–454.

Ando, A.B., Huber, B.T. & MacLeod, K.G. (2010): Depth-habitat reorganization of planktonic foraminifera across the Albian/Cenomanian boundary. – Paleobiology, 36: 357–373.

Arthur, M.A., Dean, W.E. & Schlanger, S.O. (1985): Variations in the global carbon cycle during the Cretaceous related to climate, volcanism, and changes in atmospheric CO_2. – In: Sundquist, E.T. & Broecker, W.S. (ed.): The carbon cycle and atmospheric CO: Natural variations Archean to Present. – Geophys. Monogr., 32: 504–529.

Batenburg, S.J., De Vleeschouwer, D., Sprovieri, M., Hilgen, F.J., Gale, A.S., Singer, B.S., Koeberl, C., Coccioni, R., Claeys, P. & Montanari, A. (2016): Orbital control on the timing of oceanic anoxia in the Late Cretaceous. – Clim. Past, 12: 1995–2009.

Blumenberg, M. & Wiese, F. (2012): Imbalanced nutrients as triggers for black shale formation in a shallow shelf setting during the OAE 2 (Wunstorf, Germany). – Biogeosciences, 9: 4139–4153.

Bornemann, A. & Norris, R.D. (2007): Size-related stable isotope changes in Late Cretaceous planktic foraminifera: Implications for paleoecology and photosymbiosis. – Mar. Micropaleontol., 65: 32–42.

Bornemann, A., Erbacher, J., Heldt, M., Kollaske, T., Wilmsen, M., Lübke, N., Huck, S., Vollmar, N.M. & Wonik, T. (2017): The Albian-Cenomanian transition and Oceanic Anoxic Event 1d – An example from the Boreal Realm. – Sedimentology, 64: 44–65.

Brotzen, F. (1942): Die Foraminiferengattung *Gavelinella* nov. gen. und die Systematik der Rotaliiformes. – Sver. Geol. Unders., Ser. C, No.451, 36 (8): 1–60.

Caron, M. (1985): Cretaceous planktonic foraminifera. – In: Bolli, H., Saunders, J. & Perch-Nielsen, K. (ed.): Plankton stratigraphy: 17–86; Cambridge (Cambridge Univ. Pr.).

Caron, M. & Homewood, P. (1983): Evolution of early planktonic foraminifera. – Mar. Micropaleontol., 7: 453–462.

Caron, M. & Spezzaferri, S. (2006): High-resolution stratigraphy of the Cenomanian–Turonian boundary interval at Pueblo (USA) and Wadi Bahloul (Tunisia): Stable isotope and bio-events correlation. – Geobios, 39: 171–200.

Carter, D.J. & Hart, M.B. (1977): Aspects of mid-Cretaceous stratigraphical micropaleontology. – Bull. Br. Mus. (Nat. Hist.), Geol., 29: 1–135.

Coccioni, R. & Premoli Silva, I. (2015): Revised Upper Albian-Maastrichtian planktonic foraminiferal biostratigraphy and magnetostratigraphy of the classical Tethyan Gubbio section (Italy). – Newsl. Stratigr., 48: 47–90.

Dahmer, D.-D. & Ernst, G. (1986): Upper Cretaceous event-stratigraphy in Europe. – In: Walliser, O. (ed.): Global bio-events. – Lect. Notes Earth Sci., 8: 353–362.

Erbacher, J., Thurow, J. & Littke, R. (1996): Evolution patterns of radiolaria and organic matter variations: A new approach to identify sea-level changes in mid-Cretaceous pelagic environments. – Geology, 24: 499–502.

Erbacher, J., Friedrich, O., Wilson, P., Birch, H. & Mutterlose, J. (2005): Stable organic carbon isotope stratigraphy across Oceanic Anoxic Event 2 of Demerara Rise, western tropical Atlantic. – Geochem., Geophys., Geosyst., 6 (6): 1–9; DOI: 10.1029/2004GC000850

Erbacher, J., Mutterlose, J., Wilmsen, M., Wonik, T. & Wunstorf Drilling Scientific Party (2007): The Wunstorf Drilling Project: Coring a global stratigraphic reference section of the Oceanic Anoxic Event 2. – Sci. Drilling, 4: 19–21.

Falzoni, F., Petrizzo, M.R., MacLeod, K.G. & Huber, B.T. (2013): Santonian–Campanian planktonic foraminifera from Tanzania, Shatsky Rise and Exmouth Plateau: Species depth ecology and paleoceanographic inferences. – Mar. Micropaleontol., 103: 15–29.

Falzoni, F., Petrizzo, M.R., Clarke, L.J., MacLeod, K.G. & Jenkyns, H.C. (2016): Long-term Late Cretaceous oxygen and carbon-isotope trends and planktonic foraminiferal turnover: A new record from the southern midlatitudes. – Geol. Soc. Am., Bull., 128: 1725–1735.

Falzoni, F., Petrizzo, M.R., Caron, M., Leckie, R.M. & Elderbak, K. (2018): Age and synchronicity of planktonic foraminiferal bioevents across the Cenomanian–Turonian boundary interval (Late Cretaceous). – Newsl. Stratigr., 51: 343–380.

Frieg, C., Kemper, E. & Baldschuhn, R. (1989): Mikropaläontologische Gliederung und Abgrenzung von Ober-Alb und Unter-Cenoman in Nordwestdeutschland. – Geol. Jb., A 113: 73–193.

Gambacorta, G., Jenkyns, H.C., Russo, F., Tsikos, H., Wilson, P.A., Faucher, G. & Erba, E. (2015): Carbon- and oxygen isotope records of mid-Cretaceous Tethyan pelagic sequences from the Umbria–Marche and Belluno Basins (Italy). – Newsl. Stratigr., 48: 299–323.

Gebhardt, H., Kuhnt, W. & Holbourn, A. (2004): Foraminiferal response to sea level change, organic flux and oxygen deficiency in the Cenomanian of the Tarfaya Basin, southern Morocco. – Mar. Micropaleontol., 53: 133–157.

Giorgioni, M., Weissert, H., Bernsconi, S.M., Hochuli, P.A., Keller, C.E., Coccioni, R., Petrizzo, M.R., Lukeneder, A. & Garcia, T.I. (2015): Paleoceanographic changes during the Albian-Cenomanian in the Tethys and North Atlantic and the onset of the cretaceous chalk. – Global Planet. Change, 126: 46–61.

Gonzales-Donoso, J.-M., Linares, D. & Robaszynski, F. (2007): The rotaliporids, a polyphyletic group of Albian–Cenomanian planktonic foraminifera: Emendation of genera. – J. Foramin. Res., 37: 175–86.

Gyawali, B.R., Nishi, H., Takashima, R., Herrle, J.O., Takayanagi, H., Latil, J.-L. & Iryu, Y. (2017): Upper Albian-upper Turonian calcareous nannofossil biostratigraphy and chemostratigraphy in the Vocontian Basin, southeastern France. – Newsl. Stratigr., 50: 111–139.

Hart, M.B. (1980): A water depth model for the evolution of the planktonic Foraminiferida. – Nature, 286: 252–254.

Hart, M.B. (1999): The evolution and biodiversity of Cretaceous planktonic Foraminiferida. – Geobios, 32: 247–255.

Hart, M.B. & Bailey, H.W. (1979): The distribution of planktonic Foraminiferida in the mid-Cretaceous of NW Europe. – In: Wiedmann, J. (ed.): Aspekte der Kreide Europas. – Int. Union Geol. Sci., Ser. A, 6: 527–542.

Hart, M.B. & Harris, C.S (2012): Albian-Cenomanian Foraminifera and Ostracoda from the Glynderbourne Borehole, Sussex, U.K. – N. Jb. Geol. Paläont. Abh., 266: 319–335.

Hecht, F.E. (1938): Standard-Gliederung der Nordwestdeutschen Unterkreide nach Foraminiferen. – Abh. Senckenb. Naturforsch. Ges., 443: 1–42.

Hiss, M. (1995): Kreide. – In: Geologisches Landesamt Nordrhein-Westfalen (ed.): Geologie im Münsterland: 41–63; Krefeld (Geol. Landesamt Nordrhein-Westf.).

Huber, B.T. & Leckie, R.M. (2011): Planktic foraminiferal species turnover across deep-sea Aptian/Albian boundary sections. – J. Foramin. Res., 41: 53–95.

Huber, B.T., Petrizzo, M.R., Young, J.R., Falzoni, F., Gilardoni, S.E., Bown, P.R. & Wade, B.S. (2016): Pforams@ microtax: A new online taxonomic database for planktonic foraminifera. – Micropaleontology, 62: 429–438.

Jarvis, I., Gale, A.S, Jenkyns, H.C. & Pearce, M.A. (2006): Secular variation in Late Cretaceous carbon isotopes: A new $\delta^{13}C$ carbonate reference curve for the Cenomanian–Campanian (99.6–70.6 Ma). – Geol. Mag., 143 (5): 561–608.

Jenkyns, H.C. (2010): Geochemistry of oceanic anoxic events. – Geochem., Geophys., Geosyst., 11: Q03004; DOI: 10.1029/2009 GC002788

Jenkyns, H.C., Gale, A.S. & Corfield, R.M. (1994): Carbon-isotope and oxygen-isotope stratigraphy of the English Chalk and Italian Scaglia and its paleoclimatic significance. – Geol. Mag., 131: 1–34.

Koch, W. (1977): Biostratigraphie in der Oberkreide und Taxonomie von Foraminiferen. – Geol. Jb., A 38: 11–123.

Leckie, R.M. (1987): Paleoecology of mid-Cretaceous planktonic foraminifera: A comparison of open ocean and epicontinental sea assemblages. – Micropaleontology, 33: 164–176.

Lipson-Benitah, S. (2008): Phylogeny of the middle Cretaceous (Late Albian-Late Cenomanian) planktonic foraminiferal genera *Parathalmanninella* nov. gen. and *Thalmanninella*. – J. Foramin. Res., 38: 183–9.

Lirer, F. (2000): A new technique for retrieving calcareous microfossils from lithified lime deposits. – Micropaleontology, 46: 365–369.

Meyer, T. (1990): Biostratigraphische und sedimentologische Untersuchungen in der Plänerfazies des Cenoman von Nordwestdeutschland. – Mitt. Geol. Inst. Univ. Hannover, 30: 1–114.

Mitchell, S.F. & Carr, I.T. (1998): Foraminiferal response to mid-Cenomanian (Upper Cretaceous) palaeoceanographic events in the Anglo-Paris Basin (Northwest Europe). – Palaeogeogr., Palaeoclimatol., Palaeoecol., 137: 103–125.

Mitchell, S.F., Paul, C.R. & Gale, A.S. (1996): Carbon isotopes and sequence stratigraphy. – In: Howell, J.A. & Aitken, J.F. (ed.): High resolution sequence stratigraphy: Innovations and applications. – Geol. Soc. London, Spec. Publ., 104: 11–24.

Paul, C.R.C., Mitchell, S.F., Marshall, J.D., Leary, P.N., Gale, A.S., Duane, A.M. & Ditchfield, P.W. (1994): Paleoceanographic events in the Middle Cenomanian of Northwest Europe. – Cretaceous Res., 15: 707–738.

Petrizzo, M.R. & Huber, B.T. (2006): Biostratigraphy and taxonomy of Late Albian planktonic foraminifera from ODP Leg 171b (western North Atlantic Ocean). – J. Foramin. Res., 36: 165–189.

Petrizzo, M.R., Huber, B.T., Wilson, P.A. & MacLeod, K.G. (2008): Late Albian paleoceanography of the western subtropical North Atlantic. – Paleoceanography, 23: PA1213; DOI: 10.1029/2007 PA001517

Petrizzo, M.R., Caron, M. & Premoli Silva, I. (2015): Remarks on the identification of the Albian/Cenomanian boundary and taxonomic clarification of the planktonic foraminifera index species *globotruncanoides*, *brotzeni* and *tehamaensis*. – Geol. Mag., 152: 521–536.

Petrizzo, M.R., Berrocoso, A.J., Falzoni, F., Huber, B.T. & Macleod, K.G. (2017): The Coniacian–Santonian sedimentary record in southern Tanzania (Ruvuma Basin, East Africa): Planktonic foraminiferal evolutionary, geochemical and palaeoceanographic patterns. – Sedimentology, 64: 252–285.

Premoli Silva, I. & Sliter, W.V. (1999): Cretaceous paleoceanography: Evidence from planktonic foraminiferal evolution. – In: Barrera, E. & Johnson, C.C. (ed.): Evolution of the Cretaceous ocean-climate system. – Geol. Soc. Am., Spec. Pap., 332: 301–328.

Retailleau, S., Howa, H., Schiebel, R., Lombard, F., Eynaud, F., Schmidt, S., Jorissen, F. & Labeyrie, L. (2009): Planktonic foraminiferal production along an offshore-onshore transect in the south-eastern Bay of Biscay. – Cont. Shelf Res., 29: 1123–1135.

Robaszynski, F. & Caron, M. (ed.) (1979): Atlas de foraminifères planctoniques du Crétacé moyen (Mer Boréale et Téthys). – Cahiers Micropaléont., 1: 1–185.

Robaszynski, F. & Caron, M. (1995): Foraminifères planctoniques du Crétacé: Commentaire de la zonation Europe-Méditerranée. – Bull. Soc. Géol. France, 166: 681–692.

Robaszynski, F., Caron, M., Amédro, F., Dupuis, C., Hardenbol, J., Gonzalez-Donoso, J.M., Linares, D. & Gartner, S. (1994): Le Cénomanien de la région de Kalaat Senan (Tunisie Centrale): Litho-biostratigraphie et interprétation séquentielle. – Rev. Paléobiol., 12: 351–505.

Rückheim, S., Bornemann, A. & Mutterlose, J. (2006): Planktonic foraminifera from the mid-Cretaceous (Barremian-Lower Albian) of the North Sea Basin: Palaeoecological and palaeoceanographic implications. – Mar. Micropaleontol., 58: 83–102.

Schiebel, R. & Hemleben, C. (2017): Planktonic foraminifera in the modern ocean: 358 p.; Berlin (Springer).

Sigal, J. (1948): Notes sur les genres de foraminifères *Rotalipora* Brotzen 1942 et *Thalmanninella*. Famille des Globorotaliidae. – Rev. Inst. Fr. Pétrole Paris, 3 (4): 95–103.

Tsikos, H., Jenkyns, H.C., Walsworth-Bell, B., Petrizzo, M.R., Forster, A., Kolonic, S., Erba, E., Premoli Silva, I., Baas, M., Wagner, T. & Sinninghe Damste, J.S. (2004): Carbon-isotope stratigraphy recorded by the Cenomanian-Turonian Oceanic Anoxic Event: Correlation and implications based on three localities. – J. Geol. Soc. London, 161: 711–719.

Van Helmond, N.A.G.M., Sluijs, A., Sinninghe Damsté, J.S., Reichart, G.-J., Voigt, S., Erbacher, J., Pross, J. & Brinkhuis, H. (2015): Freshwater discharge controlled deposition of Cenomanian–Turonian black shales on the NW European epicontinental shelf (Wunstorf, northern Germany). – Clim. Past, 11: 495–508.

Vejbaek, O.V., Andersen, C., Dusa, M., Herngreen, W., Krabbe, H., Leszczynski, K., Lott, G.K., Mutterlose, J. & van der Molen, A.S. (2010): Cretaceous. – In: Doornenbal, H. & Stevenson, A. (ed.): Petroleum geological atlas of the Southern Permian Basin Area: 195–209; Houten (EAGE Publ.).

Voigt, S., Erbacher, J., Mutterlose, J., Weiss, W., Westerhold, T., Wiese, F., Wilmsen, M. & Wonik, T. (2008a): The Cenomanian – Turonian of the Wunstorf section (North Germany): Global stratigraphic reference section and new orbital time scale for Oceanic Anoxic Event 2. – Newsl. Stratigr., 43: 65–89.

Voigt, S., Wagreich, M., Surlyk, F., Walaszczyl, I., Ulicný, D., Voigt, T., Wiese, F., Wilmsen, M., Niebuhr, B., Reich, M., Funk, H., Michalík, J., Jagt, J.W.M., Felder, P.J. & Schulp, A.S. (2008b): Cretaceous. – In: McCann, T. (ed.): The geology of Central Europe; vol. 2: Mesozoic and Cenozoic: 923–997; London (Geol. Soc.).

Weiss, W. (1997): Late Albian immigrations of planktonic foraminifera into the Boreal sea: Results from Kirchrode I borehole (Hannover, NW Germany). – Newsl. Stratigr., 35: 1–27.

Weiss, W. (1982): Planktonische Foraminiferen aus dem Cenoman und Turon von Nordwest- und Süddeutschland. – Palaeontographica, A 178: 49–108.

Weiss, W. (2012): Small planktonic foraminiferal assemblages from the Boreal Aptian Hoheneggelsen KB 9 core (Hannover, northern Germany) – Distribution, biostratigraphy and palaeoceanography. – N. Jb. Geol. Paläont. Abh., 266: 283–317.

Wilmsen, M. (2003): Sequence stratigraphy and paleoceanography of the Cenomanian Stage in northern Germany. – Cretaceous Res., 24: 525–568.

Wilmsen, M. (2007): Integrated stratigraphy of the upper Lower – lower Middle Cenomanian of northern Germany and southern England. – Acta Geol. Pol., 57: 263–279.

Wilmsen, M. (2008): A Lower Cenomanian (Late Cretaceous) maximum flooding bioevent in NW Europe: Correlation, sedimentology and biofacies. – Palaeogeogr., Palaeoclimatol., Palaeoecol., 258: 317–333.

Wilmsen, M. (2012): Origin and significance of Late Cretaceous bioevents: Examples from the Cenomanian. – Acta Palaeontol. Pol., 57: 759–771.

Wilmsen, M. & Niebuhr, B. (2002): Stratigraphic revision of the upper Lower and Middle Cenomanian in the Lower Saxony Basin (northern Germany) with special reference to the Salzgitter area. – Cretaceous Res., 23: 445–460.

Wilmsen, M., Niebuhr, B. & Hiss, M. (2005): The Cenomanian of northern Germany: Facies analysis of a transgressive biosedimentary system. – Facies, 51: 242–263.

Wilmsen, M., Niebuhr, B., Wood, C.J. & Zawischa, D. (2007): Fauna and palaeoecology of the Middle Cenomanian *Praeactinocamax primus* Event at the type locality, Wunstorf quarry, northern Germany. – Cretaceous Res., 28: 428–460.

Witte, L., Lissenberg, T. & Schuurman, H. (1992): Ostracods from the Albian/Cenomanian boundary in the Achterhoek area (eastern part of the Netherlands). – Scripta Geol., 102: 33–84.

Wonders, A.A.H. (1978): Phylogeny, classification and biostratigraphic distribution of keeled Rotaliporinae. – Proc. K. Ned. Akad. Wet., B 81: 113–44.

Zheng X.-Y., Jenkyns, H.C., Gale, A.S., Ward, D.J. & Henderson, G.M. (2016): A climatic control on reorganization of ocean circulation during the mid-Cenomanian event and Cenomanian-Turonian oceanic anoxic event (OAE 2): Nd isotope evidence. – Geology, 44: 151–154.

Zügel, P. (1994): Verbreitung kalkiger Dinoflagellaten-Zysten im Cenoman/Turon von Westfrankreich und Norddeutschland. – Cour. Forschungsinst. Senckenb., 176: 1–159.

Manuscript received: 26.09.2019
Revisions required: 18.11.2019
Revised version received: 22.01.2020
Accepted for publication: 27.01.2020

Electronic supplements

Supplementary material associated with this article is embedded in the pdf of this article. The online version of *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften – Journal of regional Geology* (*ZdGG*) is hosted at the journal's website www.schweizerbart.com/journals/zdgg. The publisher does not bear any liability for the lack of usability or correctness of supplementary material.

Supplementary Table 1: Stable isotope, TOC and $CaCO_3$ data, from Wunstorf composite, cores 2011/2 and 2011/8; m depth refers to specific cores; mcd = meter composite depth, refers to the composite section.

Supplementary Table 2: Stratigraphic distribution of praeglobotruncanids, rotaliporids and the ostracod *Physocythere steghausi* in Wunstorf composite cores 2011/2 and 2011/8; m depth refers to specific cores; mcd = meter composite depth, refers to the composite section.

Please save the electronic supplement contained in this pdf-file by clicking the blue frame above. After saving rename the file extension to .zip (for security reasons Adobe does not allow to embed .exe, .zip, .rar etc. files).