Early Aptian bay deposits at the southern margin of the Lower Saxony Basin: Integrated stratigraphy, palaeoenvironment and OAE 1a

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ABSTRACT:

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The present study establishes a lithostratigraphic subdivision, a bio- and chemostratigraphy and describes the sedimentology of the Alstätte Bay at the southern margin of the Lower Saxony Basin in northern Germany. The so-called Fischschiefer is developed in the lower part of the section, a 2.1 m thick laminated interval that shows TOC values of up to 2 % and is interpreted as local expression of the global Oceanic Anoxic Event 1a (OAE 1a). The basal part of the Fischschiefer is fairly continuously laminated, whereas its upper part is characterized by an alternation of laminated and non-laminated beds. Stable carbon isotopes ($\delta^{13}C_{carb}$) show a characteristic pattern for the Fischschiefer interval that can be correlated with sections from the Tethyan Realm. Immediately above the Fischschiefer, however, the studied section might reveal a diagenetic overprint as indicated by very negative carbon stable isotope values. The remaining part of the section is characterized by a rather monotonous claystone succession, terminated by a greenish layer rich in glauconite overlain by glacial till of Pleistocene age.

The fauna is typically Boreal in the lower part of the section, but changes around 2 m above the Fischschiefer towards an assemblage indicating a distinct Tethyan influx. The faunal shift is considered to be due to the maximum flooding of the continuous, long-term sea level rise of the Early Aptian which led also to a supposed shift from a restricted to open bay environment.

Key words: Early Cretaceous; Aptian; Biostratigraphy; Chemostratigraphy; Facies; NW-Germany; OAE 1a.

INTRODUCTION

Marine deposits of the Late Barremian–Aptian allow us an insight into a substantial turning point in ocean circulation, which had a major impact on marine and terrestrial ecosystems (e.g. Leckie *et al.* 2002; Heimhofer *et al.* 2005). At that time, a long-term change in the Mesozoic was initialized, resulting in a more sluggish oceanic circulation that became prone to low-oxygen conditions at the sea floor. Eventually, this led to the massive accumulation of organic-rich intervals, including the major Oceanic Anoxic Events of the mid-Cretaceous (e.g., Leckie *et al.* 2002; Schlanger and Jenkyns 1976). This is why the Late Barremian–Aptian time interval is

among the most intensively studied stratigraphic periods of the past few years (e.g. Ando *et al.* 2008; De Gea *et al.* 2008; Méhay *et al.* 2009; Herrle *et al.* 2010; Bover-Arnal *et al.* 2011; Mahanipour *et al.* 2011). Particularly the Oceanic Anoxic Event 1a (OAE 1a; Schlanger and Jenkyns 1976) has become a geological spotlight, representing a low-oxygen event that is associated with an enhanced burial of organic carbon and a major shift in the global δ^{13} record of both marine and terrestrial environments (e.g. Coccioni *et al.* 1989; Menegatti *et al.* 1998; Gröcke *et al.* 1999; Jenkyns and Wilson 1999; Heimhofer *et al.* 2003; Huck *et al.* 2010; Malkoc *et al.* 2010; Vahrenkamp 2010; Vincent *et al.* 2010; Cvetko Tesovic *et al.* 2011). The initial negative shift in carbon isotopes associated with OAE 1a indicates a massive and rapid input of ^{12}C-rich carbon into the atmosphere and oceans during the Early Aptian. This shift in carbon isotope composition is explained by methane release (e.g., Gröcke *et al.* 1999; Ando *et al.* 2002, 2003; Beerling *et al.* 2002) or thermal metamorphism of C_{org}-rich rocks (Van Breugel *et al.* 2007). Alternative models are the recycling of CO_2 formed by mineralization of organic matter in a stratified ocean (Menegatti *et al.* 1998) or intensified volcanic activities that raised atmospheric pCO_2 and enhanced oceanic nutrient fluxes (Larson and Erba 1999; Erba and Tremolada 2004).
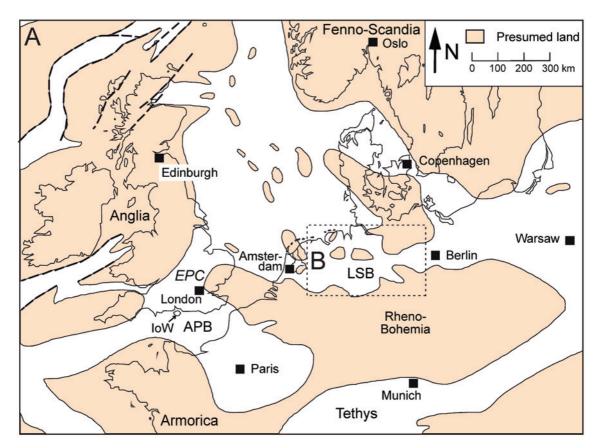
Apart from its characteristic carbon isotope signature, OAE 1a appears to be associated with a productivity peak, a crisis in carbonate-producing organisms and minor extinctions events, although these causalities are still under debate (Erbacher *et al.* 1996; Erba 2004; Heldt *et al.* 2008; Erba *et al.* 2010; Masse and Fenerci-Masse 2011). Unlike other Cretaceous OAEs (Leckie *et al.* 2002), however, initialisation is commonly tracked down to endogenic processes. In fact, an increased submarine volcanic exhalation in the Pacific ocean around the Ontong-Java Plateau is widely accepted as a major player (Larson and Erba 1999; Méhay *et al.* 2009; Tejada *et al.* 2009). Nevertheless, there is already some debate on the onset of these exhalations in the Late Barremian (Bodin *et al.* 2009), as indicated by strontium isotope values that are believed to be driven by mid-oceanic ridge production changes (Mcarthur *et al.* 2004). The consequences resulting from enhanced volcanism might trigger the Greenhouse effect and its manifold effects in causing changes in oceanic productivity by biolimiting metals (Larson and Erba 1999). This illustrates that the main biological reaction, a global impact on the productivity in all oceans, cannot be fully explained by CO_2 outgasing alone (Erba 2004). Furthermore, the terrestrial record does not prove a major climate shift and a CO_2 increase, at least not in a part of the Tethys (Heimhofer *et al.* 2004)
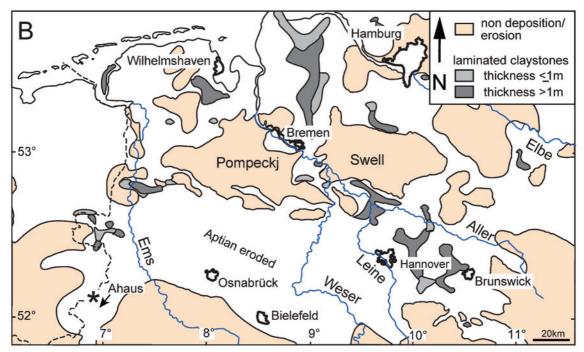
Most of the studies on OAE 1a and its palaeoenvironmental implications are based on oceanic or hemipelagic sections (Leckie *et al.* 2002, and references herein). Marginal sections are less commonly preserved and mostly associated with carbonate platforms in the Tethyan realm or the transitional area to the Boreal (Luciani *et al.* 2006; Wilmsen 2005). In the Boreal realm marginal sections are uncommon, apart from the classical Lower Greensand successions on the Isle of Wight in southern England (e.g. Casey *et al.* 1998; Gröcke *et al.* 1999). In the latter, the exact position and facies equivalent of OAE 1a has not yet been identified and, thus, its impact on proximal settings is poorly understood. Boreal sections of the River Volga area in Russia allow a better insight. There, a black shale interval in the basin, representing OAE 1a is correlating with sandy claystones in the more marginal position (*D. volgensis* Zone of the middle part of the Lower Aptian; Baraboshkin and Mikhailova 2002; Gavrilov *et al.* 2002).

Any further Boreal OAE 1a-bearing succession that is located at or close to the ancient coast line can provide important information to understand the impact of this event in shallow-marine settings. Such an example is the Alstätte Bay in northern Germany, a small proximal extension of the main Lower Saxony Basin that cut into the northern rim of the Rheno-Bohemian Massif during the Late Jurassic to Early Cretaceous (Text-fig. 1; e.g. Ziegler 1990). A series of former fossiliferous clay pits in the Alstätte district of the city of Ahaus and the nearby Barler Berg made this area a classic realm for Early Cretaceous geology and palaeontology in Germany since the 19th century (e.g., Ewald 1861; Hilbck 1867; Ziegler 1873). Kemper (1963, 1964, 1967, 1971) did fundamental biostratigraphic work on fossil invertebrates in this area, but did not log the Aptian succession in detail. Modern geological methodology could not be applied to this marginal part of the Lower Saxony Basin until recently due to the lack of suitable exposures. However, in 2009, a new excavation for a waste disposal site in Ahaus-Alstätte has been excavated, providing the possibility to describe the succession in the Alstätte Bay in greater detail.

GEOLOGICAL SETTING

The fill of the Lower Saxony Basin in Northern Germany (LSB in the following) is part of the North Atlantic depositional cycle, a 1st order transgressive-regressive sequence covering sediments of a time span of about 80 million years, throughout the Cretaceous period (Jacquin *et al.* 1998; Jacquin and De Graciansky 1998). Its limits are the Late Cimmerian and the Laramide unconformities.

Text-fig. 1. A – Simplified palaeogeography of the Early Aptian in northern Europe with area under investigation. The rectangle indicates the position of the map in B. APB=Anglo-Paris Basin, LSB=Lower Saxony Basin, EPC = English Proto-Channel, IoW=Isle of Wight. B – Detailed palaeogeography of the southwestern boundary of the LSB, illustrating the restricted position of the Alstätte Bay with the position of the Alstätte locality in the Ahaus district (asterisk). A is modified after various sources, mainly Schott *et al.* 1969 and Ziegler 1990, B simplified after Mutterlose and Böckel 1998. Note that the English name Brunswick for the city of Braunschweig is used in the text

The LSB contains a sedimentary succession with a thickness of several thousand meters, spanning a time interval from the latest Jurassic to the Late Cretaceous. In the late Early Cretaceous, the basin was differentiated and subdivided by small swells and islands into subbasins, but generally it constituted a large epicontinental sea extending to the Proto-North Sea area (Kemper 1979). During the Early Aptian, the LSB was connected by passages with the rising Atlantic Ocean in the southwest and northwest. In the deeper subbasins, mainly shales were deposited in the Early Aptian, whereas towards the basin margin, silty to sandy dark-grey claystones predominated which are, however, underrepresented in the sedimentary record (Mutterlose and Böckel 1998). These proximal sediments are preserved only as relicts, giving evidence for the sedimentation of erosional debris by a northward transporting river system established on the Brabant-Rhenish Massif (Oakman and Partington 1998; Jeremiah *et al.* 2010).

THE ALSTÄTTE SECTION

The section focused upon here is located in the Alstätte district of the city of Ahaus, North Germany, a couple of kilometers east of the German-Dutch border. It is a temporary section for a waste disposal site by the "Entsorgungsgesellschaft Westmünsterland" (EGW) north of Alstätte (Text-fig. 2).
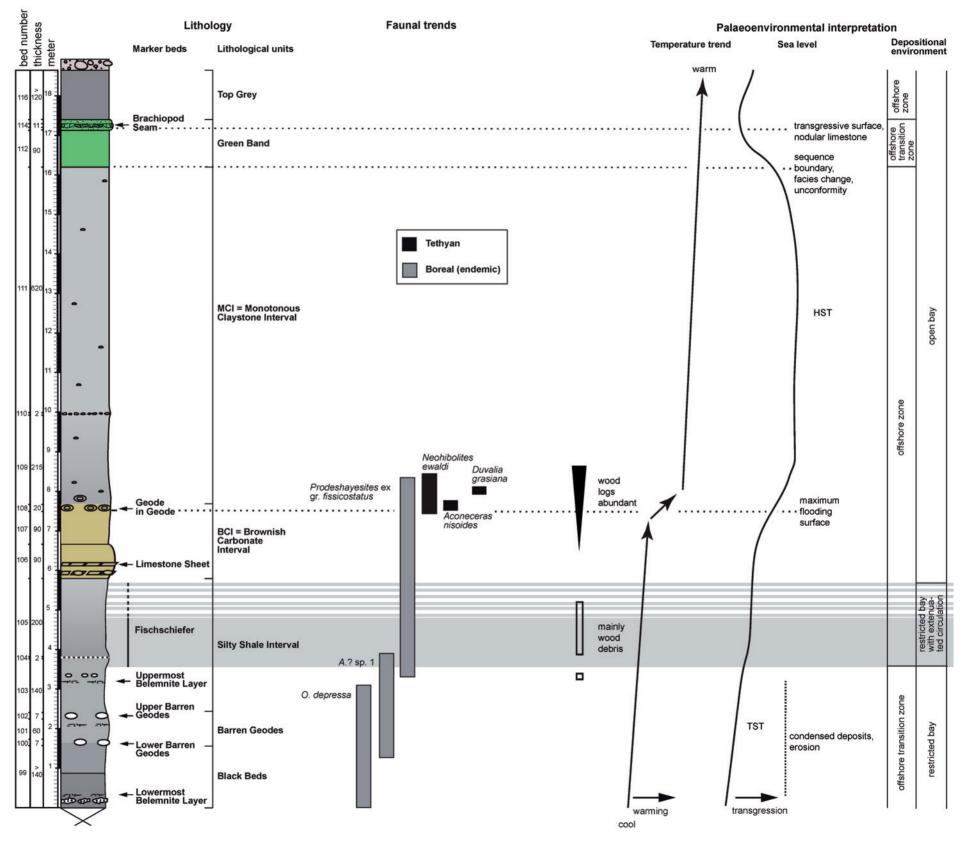
Text-fig. 3 is an overview of the complete sequence available for study, with the main profile measured at N52°09′04.8″, E006°54′39.5″. All geochemical samples and the major part of the macrofossils have been collected at these coordinates. Due to an extension of the section, a few additional fossils were sampled in the immediate vicinity of this spot, within a maximum distance of less than 50 m.

The top of the succession shows an unconformity between the Aptian sediment and the Pleistocene overburden. The latter is a till of the ground moraine that is dated as Drenthe stage of the Saale glacial period (Hiss *et al.* 1997). The ground moraine is unusually thick at this locality, reaching up to 8 m in contrast to a normal thickness of around 3m in thickness (Speetzen in Skupin *et al.* 1993), and contains frequently erratic boulders with Aptian as well as Neogene fossils including shark teeth (Lehmann and Rohe 2011). In the following, only the Aptian sediments are described.

The lithostratigraphic units represented in the investigated EGW section are indicated in Text-fig. 3, the core interval with the most relevant units and index beds is shown in Text-fig. 2. They are defined in Table 1 as follows (from the base to the top):

Text-fig. 2. Field aspects of the Alstätte section, EGW pit, with some key beds and lithostratigraphic intervals. Marker beds abbreviated: UBG – Upper Barren Geodes, LS – Limestone Sheet, GiG – Geode in Geode. View from the southeastern corner of the claypit to the North, photo taken at GPS coordinates N52°09′03.6″, E006°54′41.5″, ± 3m, June 2011

Text-fig. 3. Overview of the overall Alstätte sequence available for study, introducing a lithostratigraphic subdivision of the Lower Aptian as well as a palaeoenvironmental and depositional interpretation. Belemnites layers are lense-like accumulations of rostra that occur between the two limits indicated. *A. nis.* = *Aconeceras nisoides*. Legend see Text-fig. 5

The belemnite accumulations of the Barren Geodes- and Silty Shale intervals are here called Belemnite Layers. "Belemnite battlefields", and the corresponding German terms have been used in the literature to refer to these belemnite accumulations of various genesis (Doyle and Macdonald 1993; Urlichs 1971), but these terms are inappropriate for what is a natural concentration deposit.

The term Fischschiefer in the upper part of the Silty Shale Interval corresponds to the German term translated to "Fish Shale"; e.g. Keupp and Mutterlose 1994; Hild and Brumsack 1998; Mutterlose and Böckel 1998; Rückheim and Mutterlose 2002), and is a local expression of OAE 1a (Malkoc et al. 2010).

The Limestone Sheet of the BCI (Text-figs 3, 4.10) is very stable in thickness (5–7 cm). A thin section indicates a mudstone with minute wood debris, very few quartz grains; macroscopically, bioturbation is visible.

The unusual preservation of articulated star fishes can be explained by an early diagenetic lithification, as indicated by the three-dimensional preservation of asteroids as well as the virtual lack of any distortion by vertical, tube-like burrows and scavengers. This fits furthermore to a conspicuous, non-distorted preservation of bioturbation on bedding planes in the middle of bed 106 (Text-fig. 4.2). A further possible hint on the possibly exceptional diagenetic history of this bed and the whole BCI comes also from the stable isotope data (see CHEMOSTRATIGRAPHY below).

The Green Band is a very conspicuous interval within the Lower Aptian succession. Based on its green colour only, these beds might correspond to three green horizons (Vergrünungshorizonte), respectively 5 and 11 cm in thickness, reported by Heydemann (1995) from the late Early Aptian of the Wiechendorf drilling core, north of Hannover. Macroscopically observed glauconite of the

Interval	Etymology	Approximate thickness in cm
Black Beds	These claystones are darker than the superjacent beds, with a blackish lower half and a dark-greyish upper part. Conspicuous is a bed with abundant Chondrites isp. at the base of the unit (Text-fig. 4.5).	>70
Barren Geodes Interval	Two layers of large concretions are barren of macrofossils, the Lower Barren Geodes and the Upper Barren Geodes. Contains thin horizons with accumulations of partly reworked belemnites (Oxyteuthis, Neohibolites), details see BIOSTRATIGRAPHY and Text-fig. 8. These concretions are called geodes due to frequent cavities that are partly refilled with calcite.	215
Silty Shale Interval	A series of mm thin silt lenses and layers are characteristic for this interval (Text-fig. 2). In the lower part, thin horizons with accumulations of partly reworked belemnites occur as in the subjacent interval. In the upper part, bedding planes are even and laminated, representing the Fischschiefer. The onset of the Fischschiefer is fairly sharp, with the lower part laminated throughout, whereas it is a rather homogenous claystone with thin laminated layers intercalated in the upper part (Text-fig. 2).	200
Brownish Carbonate Interval (BCI)	A brownish claystone interval with a couple of carbonate layers (Text-fig. 2). Articulated star fishes occur in an almost continuous, platy limestone bed in the lower part that is named Limestone Sheet (Text-fig. 3, 4.2, 4.10). The top is formed by Geode in Geode, a limestone geode layer with geode cores.	90
Monotonous Claystone Interval (MCI)	Claystones, occasionally containing small phosphoritic concretions (Text-fig. 2).	850
Green Band	A sequence of glauconitic marlstones, limestones, partly containing intraclasts and indicating condensation.	40-130
Siltstone Interval	Dark clayey siltstones.	>100

Table 1

1cm

5cm

1cm

2cm

2cm

5mm

1cm

5mm

5mm

2cm

1cm

Green Band is a plausible explanation for the greenish colour, whereas the Vergrünungshorizonte are stained by berthierine according to Heydemann (1995).

The range charts presented and specimens figured here incorporate fossils from the EGW locality only. For a better understanding of the taxonomy and some stratigraphic considerations, however, additional material has been incorporated from a commercial clay pit of the Hagemeister GmbH & Co. KG company in the Alstätte district, ESE of Alstätte. This section is located 4 km SE of the EGW pit (N52°07´16.2´´, E006.56´30.5´´) and has a total thickness of less than five meters. Exposed sediments probably correspond to beds 106 to 109 in the EGW pit.

MATERIAL AND METHODS

The ranges of macrofossils given are based on excavation campaigns between 2009 and 2011, revealing a total number of more than 450 specimens (1 nautiloid, 120 deshayesitid ammonites, 35 aconeceratid ammonites, 53 ancyloceratid ammonites, 75 belemnites, 12 teleost remains, 1 chondrichthyan tooth, 2 crustaceans, >50 bivalves, 7 gastropods, 21 brachiopods, 1 asteroid, more than 30 ferns and 54 wood pieces). The macrofossil samples are all housed in the Geowissenschaftliche Sammlung der Universität Bremen in Bremen, Germany (GSUB).

Geochemical analyses were performed on the fossiliferous part of the section (0 to approximately 11 m). Bulk sediment samples were freeze-dried and homogenized to acquire geochemical data. For $CaCO_3$ and TOC, pulverized samples were measured using a LECO CS 300 instrument at University of Bremen. Total carbon content (TC) of the samples was determined first, followed by measurement of total organic carbon (TOC) content after removal of inorganic carbon with 12.5 % HCl. $CaCO_3$ content was calculated by the following equation: $CaCO_3$ [wt%]=(TC [wt%]-TOC [wt%])*8.33. Duplicate measurements were made every tenth sample. The analytical precision for the performed LECO analyses is ±3%.

Stable oxygen and carbon isotopes on bulk rock material were performed at Goethe-University Frankfurt (Germany) using a ThermoFinnigan MAT253 mass spectrometer equipped with a Gas Bench II. Isotope data are given in the usual delta-notation as ‰ versus the Vienna PeeDee Belemnite isotope standard (VPDB). Analytical precision (1σ) was better than 0.03 ‰ for $\delta^{13}C_{carb}$ and 0.07 ‰ for $\delta^{18}O_{carb}$.

FOSSIL RECORD

The lower part of the Alstätte section (0 to approximately 11 m) is very fossiliferous and thus we give detailed range charts for all groups of organisms obtained (Text-fig. 5). The fauna is largely dominated by nektonic organisms such as ammonites and belemnites. Nevertheless benthic molluscs, such as small bivalves and gastropods, occur also in the Fischschiefer interval (Text-fig. 4.7, 4.8, 4.11). The benthic associations of the lowermost 1.5 m of the section contain brachiopod clusters (*Cyclothyris* sp.; Text-fig. 4.4).

Undeterminable teleost scales and single bones occur particularly in the Fischschiefer, but except for a skeleton collected 1 m below the Fischschiefer (Text-fig. 4.1, 5) these findings are not articulated despite the fact that the Fischschiefer represents a fossil conservation deposit (Shields 1998). Similar observations have been made in the OAE 1a equivalent in Italy, the Selli Level (Coccioni *et al.* 1989) and in the Niveau Goguel in the Vocontian Basin in France (Bréhéret 1997).

An unexpected and extraordinary find constitutes the record of articulated asteroids from the platy limestone layer (Limestone Sheet) in the Brownish Carbonate Interval (Text-figs 4.10, 5).

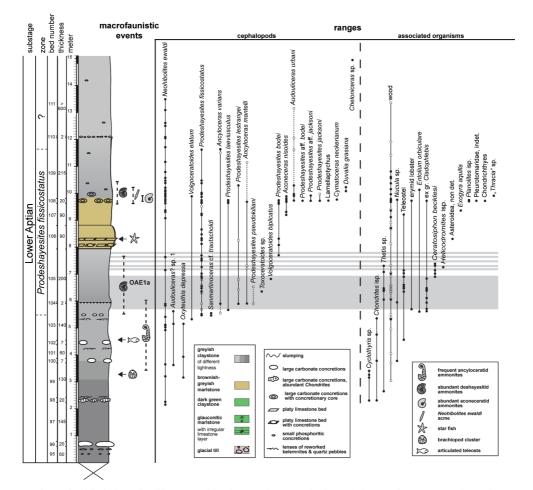In the following, taxonomic notes are given on the macrofossils obtained as far as necessary.

Ammonites

Aconeceras nisoides (Sarasin, 1893); Text-figs 6.5, 6.6

The moderately and well-preserved specimens referred to *A. nisoides* show very faint growth lines. Apart from the fact that this species is used as an lump species (Casey 1961), our specimens show more numerous and more distinct ornament in comparison to the Late Aptian *A. nisus* Sarasin 1893.

Text-fig. 4. Associated macrofauna of the Alstätte section. 1 – Fish fossil, non det., GSUB V2536, basal part of bed 103. 2 – Trace fossils on an extraordinary even bedding-plane in the middle part of the Limestone Sheet that might represent a firmground, GSUB I81, middle part of bed 106. 3 – Erymid lobster, possibly *Palaeastacus*; GSUB A186, bed 108. 4 – Brachiopod cluster with *Cyclothyris* sp., GSUB B2778, 30 cm below the top of bed 99. 5 – *Chondrites* isp., GSUB I67, basale nodule layer of bed 99. 6 – Indeterminable terrestrial plant fragment, typical for the lower part of the section; GSUB P1402, bed 103, 30 cm below the upper limit of bed 103. 7 – Mactromyid bivalve, *Thetis* sp. from the upper part of the Fischschiefer, GSUB L8986, upper part of bed 105. 8 – '*Thracia*' sp.; GSUB L8963, 10 cm above the base of bed 109. 9 – *Cladophlebis*-like fern; GSUB P1414, bed 104. 10 – Starfish, non det., a completely articulated specimen from the Limestone Sheet, GSUB E3195, middle part of bed 106. 11 – Aporrhaid gastropods, *Ceratosiphon becklesi*, from the upper part of the Fischschiefer, GSUB G10538, upper part of bed 105. All specimens from the EGW pit

Text-fig. 5. Ranges of macrofossils in the lower, fossiliferous part of the Alstätte section, EGW pit. The *Prodeshayesites fissicost*atus Zone is a total range zone. Note that the upper part of the section is not shown, since it is barren of macrofossils to a great extent. Legend (to all sections figured herein): Large carbonate concretions are up to a maximum length of 25 cm, small phosphoritic concretions are usually in between 1 and 3 cm of total length. Full circles are definite records of the taxa indicated, open circles indicate an uncertain assignment. In case of the wood records a full circle indicates massive wood logs and open circles small detritic wood fragments

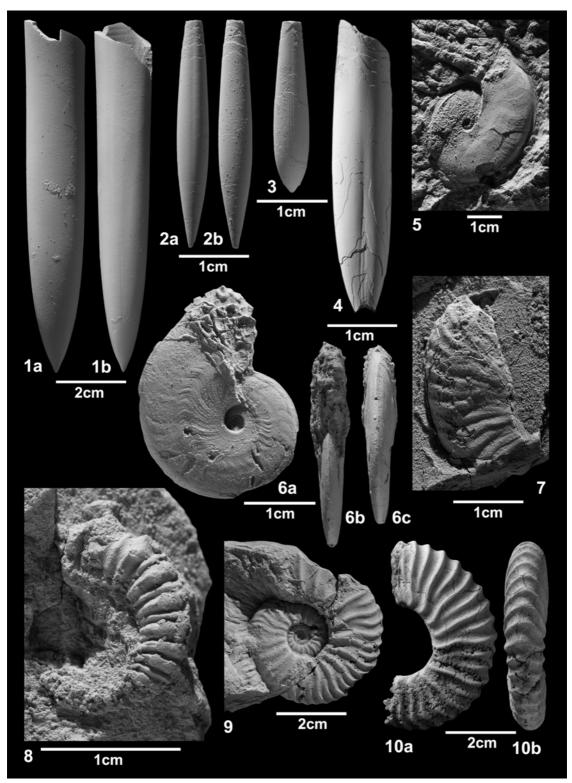*Ancyloceras mantelli* Casey, 1960; Text-figs 6.8, 7.2, 7.4

This is a medium- to small-sized representative of the genus and those of our specimens representing the inner whorls show fairly consistently trituberculate ribs with only one non-tuberculated interstitial rib as is typical in the holotype (Casey 1960).

Ancyloceras varians (d'Orbigny, 1842); Text-fig. 7.5

Another medium- to small-sized representative of *Anycloceras* (BUSNARDO in Gauthier 2006), with a more compressed whorl height than the *A. mantelli* specimens in our material. There are trituberculate main ribs and associated tubercles that are stout and high on the hook. Earlier, they are less prominent, with comparatively thin interstitial secondary ribs, numbering one to three.
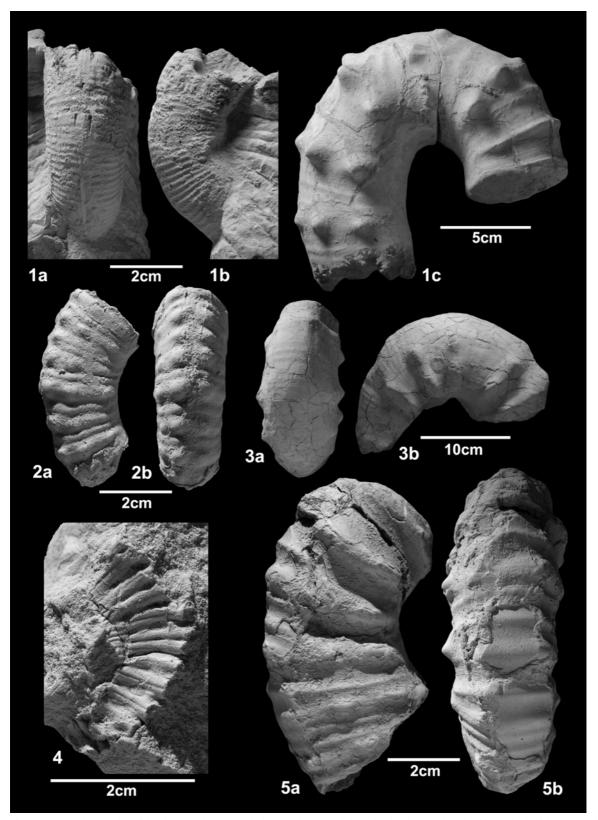
Audouliceras urbani (Neumayr and Uhlig, 1881); Text-fig. 7.1

This typical ancyloceratid is mostly known from the middle and late growth stages. The species is characterized by strong trituberculate ribs and consequently has been placed into *Ancyloceras* s. str. The type material of Neumayr and Uhlig (1881) shows a strong variability of the ornament of the last whorl of the spiral; the innermost whorls are not recorded according to their description on p. 190. The last whorl of the spiral of their specimen figured on plate 49, fig. 3 shows tubercles on each 3rd to 5th rib, whereas the specimen figured on pl. 50, fig. 1 varies from displaying no tubercles to being trituberculate on each second rib. Three specimens with hook and initial spiral in situ are to hand (GSUB C5765 from the EGW pit, Text-fig. 7.1; GSUB C5884 and C5960 from the Hagemeister clay pit in Al-
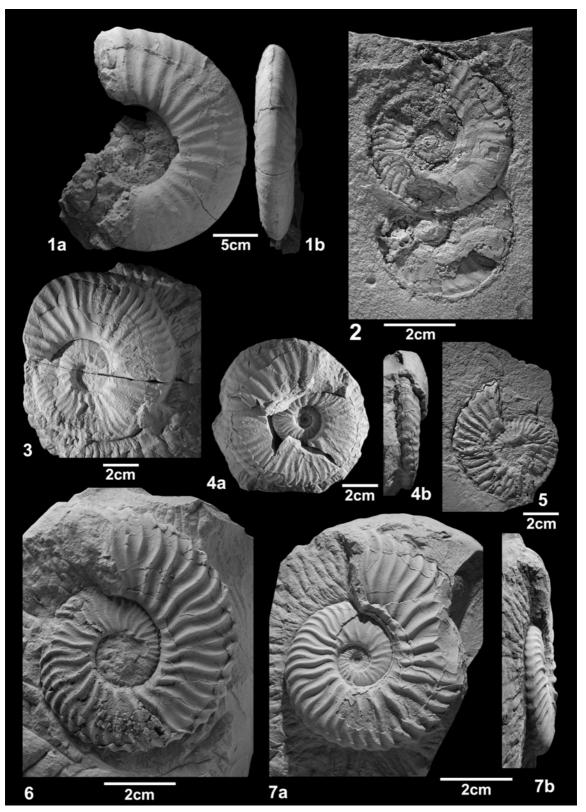
Text-fig. 6. Belemnites and ammonites of the Alstätte section. 1 – *Oxyteuthis depressa*, GSUB C5668, about 10 cm above the *Chondrites* nodule at the base of bed 99. 2 – *Neohibolites ewaldi*, GSUB C5672, 60 cm above the base of bed 99. 3 – *Neohibolites ewaldi*, a small-size specimen with stout and short tip, club shaped that is unusual for this species, GSUB C5902, 40 cm above the base of bed 103. 4 – *Duvalia grasiana*, GSUB C6173, from the basal part of bed 109. 5 – *Aconeceras nisoides*, GSUB C5928, bed 108. 6 – *Aconeceras nisoides*, GSUB C5818, probably bed 108 or 109. 7 – *Sanmartinoceras* (*Sinzovia*) cf. *trautscholdi*, GSUB C5681, 40 cm below the top of bed 103. 8 – *Ancyloceras mantelli*, GSUB C5829, bed 108. 9 – *Prodeshayesites fissicostatus*, GSUB C5913, bed 108. 10 – *Prodeshayesites fissicostatus*, GSUB C5708, bed 106, 15 cm above the Limestone Sheet. All specimens from the EGW pit

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Text-fig. 7. Heteromorph ammonites of the Alstätte section. 1 – *Audouliceras urbani*, 1a and 1b are showing the non-tuberculated inner whorls of the mature spiral, GSUB C5765, base of bed 109. 2 – *Ancyloceras mantelli*, GSUB C5683, about 3 m above bed 106. 3 – *Audouliceras*? sp. 1, GSUB C5823, around bed 103. 4 – *Ancyloceras mantelli*, GSUB C5726, bed 108. 5 – *Ancyloceras varians*, GSUB C5626, bed 104. All specimens from the EGW pit

Text-fig. 8. Deshayesitid ammonites of the Alstätte section. 1 – *Prodeshayesites lestrangei*, GSUB C5735, bed 50 cm above the base of bed 109. 2 – *Prodeshayesites lestrangei*, GSUB C5690, bed 104. 3 – *Prodeshayesites fissicostatus*, GSUB C5731, bed 108. 4 – *Prodeshayesites laeviusculus,* GSUB C5909, bed 108. 5 – *Prodeshayesites fissicostatus* from the lower part of the Fischschiefer bed, GSUB C5971, lower part of bed 105. 6 – *Prodeshayesites bodei*, GSUB C5728, bed 108. 7 – *Prodeshayesites fissicostatus*, GSUB C5922, bed 108. All specimens from the EGW pit

Text-fig. 9. Bedding plane of the Uppermost Belemnite Layer in the upper part of bed 103 of the Alstätte section (EGW pit) in oblique view. An accumulation of re-worked belemnites (B), several dozen quartz pebbles (largest one pointed: QuP), small to large plant debris with one larger wood log as well as very poorly preserved ammonites (the rib of an ancyloceratid is indicated). Photo taken at GPS coordinates N52°09'04.3″, E006°54'41.6″, ± 3m, June 2011

stätte). They confirm that the initial part of the spiral (whorl height 17 mm) is ornamented by trituberculate ribs in some cases, but also that the species loses tubercles on the ultimate whorl of the spiral that is ornamented by fine and low ribs only (whorl height around 22 mm). This places the species in *Audouliceras* (treated by some authors as a subgenus of *Ancyloceras*), since there is at least a stage with non-tuberculated main ribs (compare Thomel 1965; Wright 1996). This species is recorded from Bulgaria (Dimitrova 1967), southeastern France (Ropolo *et al.* 1999, 2000), Italy (Rodighiero 1919) and Poland (Szymakowska 1965, 1977), but all of these records are doubtful (pers. comm. L. Bulot).

Audouliceras? sp. 1; Text-fig. 7.3

A large ancyloceratid characterized by an expanded body chamber hook with distant major ribs, each with a row of inner and outer, laterally fairly indistinct bullae and a broadly rounded venter (Text-fig. 7.3). Apart from the specimens collected bed-by-bed, man specimens have been collected loosely from the interval between the upper part of bed 99 and 104. The inner whorls are unknown. An example recently figured by

Kakabadze and Hoedemaeker (2010) as *Audouliceras* cf. *urbani* on pl. 86 is probably conspecific.

Volgoceratoides biplicatus (von Koenen, 1902)

Ancyloceras biplicatum, described by Von Koenen (1902), is placed into *Volgoceratoides* following Mikhailova and Baraboshkin 2002. Typical is the biplicate ribbing on the flank. The ventral side shows a row of faint tubercles on each rib and a dense ribbing of fine ribs with interspaces usually thinner than the ribs.

Among the material quite a number of specimens cannot be referred to a species or even to the genus *Volgoceratoides* with certainty (e.g. GSUB C5813, C5807, C5972, C5973, C5701, C5689, C5809, C5930, C5932). Despite the poor preservation, these specimens, coming mostly from the Fischschiefer interval, demonstrate that small heteromorphic ammonites are an important part of the ammonite fauna in the OAE 1a interval.

Volgoceratoides elatum (von Koenen, 1902)

The ornament consists of fine, prosoradiate ribs that all bear tubercles, with ventrolateral tubercles and mid-lateral tubercles that are located slightly above mid-

flank. There are about four ribs for the corresponding whorl height. Klein *et al.* (2007) refer to the species as a possible subspecies of *Ancyloceras matheronianum*, but due to its open, bow-like coiling lacking a regular spiral it should be rather placed into *Volgoceratoides*.

Toxoceratoides sp.

GSUB C5976 bears two rows of tubercles on the hook and thus is assigned to *Toxoceratoides*.

Prodeshayesites Casey, 1961

It is widely recognized that the taxonomic value of this genus is doubtful. We provisionally follow the classical concept for Northern Germany to separate *Prodeshayesites* from *Deshayesites*. Since this group is not monographed herein, we do not have substantial arguments at hands for the complex discussion if *Prodeshayesites* should be better regarded as a synonym of *Deshayesites* (as proposed by Kemper 1995; García Mondéjar *et al.* 2009) or *Paradeshayesites* and *Obsoleticeras* (see Bogdanova and Mikhailova 1999; Bogdanova and Mikhailova 2004) or alternatively if the latter two genera are subjective synonyms of *Deshayesites* (García-Mondéjar *et al.* 2009).

Prodeshayesites bodei (von Koenen, 1902); Text-fig. 8.6

Among the comprehensive *Prodeshayesites* material at hand, we only 12 specimens belong to *P. bodei*, confirming Kemper (1967) and others that this is a very rare species. It appears likely that *P. bodei* is not more than an extreme morphological variant of *P. fissicostatus* as already suggested by Casey (1964), but we stay with the conventional taxonomy as long as no statistical data exists on this matter.

Prodeshayesites fissicostatus (Phillips, 1829); Text-figs 6.9, 6.10, 8.3, 8.5, 8.7

A total number of more than 60 specimens is referred to this species, thus it is the most common ammonite species recorded in the Alstätte section, showing a considerable morphological plasticity. We follow Casey (1980) in regarding *Prodeshayesites tenuicostatus* (von Koenen 1902) as a junior synonym of *P. fissicostatus*.

Prodeshayesites aff. *fissicostatus* (Phillips, 1829)

One single specimen, GSUB C5742, is clearly distinct from typical *P. fissicostatus* by a coarser ribbing on the inner whorls and thicker and lower ribs.

Prodeshayesites laeviusculus (von Koenen, 1902); Text-fig. 8.4

A couple of very large specimens from Alstätte show the typical reduced ornament and the tight, involute coiling as figured by Von Koenen 1902 and Kemper 1967 from Alstätte. Further research might indicate that the *P. laeviusculus* morphotype represents not more than a macroconch of one of the other *Prodeshayesites* species.

Prodeshayesites lestrangei Casey, 1964; Text-fig. 8.1, 8.2

A very large specimen (Text-fig. 8.1) shows less dense ribbing compared to the original of von Koenen (1902; pl. 39, fig. 3a, b, a copy is refigured by Casey 1964 as text-fig. 128), but with the same flexuous ribbing of slightly prosiradiate ribs with occasionally one intercalated secondary rib in between and with a smooth outline in lateral view. This contrasts with the wave-like outline of fully mature specimens of *Prodeshayesites jacksoni* (compare Casey 1980, pl. 112, fig. 1a, 1b) that is also distinguished by a more distinct ribbing, particulary across the venter. It is difficult to compare these growth stages with the inner whorls referred to *P. lestrangei*.

Belemnites

Neohibolites ewaldi (von Strombeck, 1861); Text-fig. 6.2, 6.3

The more than 60 specimens of *N. ewaldi* show a considerable variability, ranging from variants with stout and short apex to slowly tapering tips to very slender and craned. Club-shaped variants are more rare compared to *Neohibolites* of the Late Aptian that have been separated as *Neohibolites clava* by Stolley (1911). Furthermore, *Neohibolites ewaldi* reaches larger sizes compared to *N. clava*; this observation agrees with our material.

Bivalves

Thetis sp.; Text-fig. 4.7

The present material contains of very small-size bivalves, usually with a breadth less than 5 mm. Similar specimens were figured by Mordvilko (1932) and re-

ferred to as *Thetironia* spp., a genus synonymised with *Thetis* by Cox *et al.* (1969).

Gastropods

Ceratosiphon becklesi (Mantell, 1851); Text-fig. 4.11

The aporrhaid gastropods obtained from the section are characterised by two main carinae that are not tuberculated. None or up to two secondary carinae and five or more secondary carinae occur below the lower main carina and two secondary carinae, or even more occur above the upper main carina.

Crustaceans

Erymid lobster, non det.; Text-fig. 4.3

GSUB A186 is a crustacean claw. Its long and slender dactylus and propodus indicate strong affinities to the family Erymidae, most probably the specimen belongs to *Palaeastacus*.

Plants; Text-figs 4.6, 4.9

A large number of plant fossils occur in the lower part of the section, this includes *Cladophlebis*-like ferns and detritic wood fragments in the Fischschiefer interval. In bed 108 and the basal part of bed 109, large wood logs are present with a maximum size of up to several decimeters.

BIOSTRATIGRAPHY

For the Lower Aptian of northern Germany only a few studies applying of bed-by-bed collecting of macrofossils have been published (Neuss 1979; Malkoc *et al.* 2010; Mutterlose and Wiedenroth 2009; Mutterlose *et al.* 2009). Moreover, a significant number of the available data comes from a construction site near Brunswick in the eastern part of the Lower Saxony Basin. Until now, no bed-by-bed collection exists for the southeastern part of the basin. Here, earlier palaeontological work is not stratigraphically precise (e.g. Kemper 1963; 1964, 1967). Our material of a few hundred specimens constitutes the most extensive collection of this stratigraphic interval from Germany and thus provides a fairly solid basis for biostratigraphy based on ammonites and belemnites (Text-fig. 5).

Belemnites

The lowermost index cephalopod obtained is *Neo-*

hibolites ewaldi from the basal part of bed 99, as part of the Black Beds. This is a belemnite species ranging from a basal level in the Lower Aptian to the basal Upper Aptian and a *N. ewaldi* Zone has been proposed for the upper part of the Lower Aptian and the lowermost Upper Aptian of NW Europe (Mutterlose 1990).

In the middle part of bed 99, the belemnite species *Oxyteuthis depressa* occurs for the first time (Text-fig. 5, 6.1), a zonal index fossil mainly characterizing the uppermost Barremian and ranging into the lowermost Aptian (Mutterlose 1990). The lowermost record of *O. depressa* in our section is unequivocally an *in situ* occurrence of an excellently preserved rostrum in pure claystone sediment. It is important to mention that this is a large specimen with a maximum length of more than 100 mm, since Mutterlose (1990) reported this large species from the lowermost Lower Aptian but not above. Stolley (1925) records the genus in the Lower Aptian to Upper Aptian, but he separated a smaller species with a regular length of less than 50 mm as *Oxyteuthis senilis*. Our results are supported by the find of another large-size *O. depressa* with preserved phragmocone (indicating an unequivocal *in situ* occurrence) from the same bed that frequently contains the Lower Aptian ammonite *Prodeshayesites fissicostatus*, (clay pit Hagemeister in Alstätte, GSUB C2350). Reworked individuals of *O. depressa* occur in beds 101 to 103, associated with abundant quartz pebbles several mm in diameter (Text-fig. 9), and are probably derived from lowermost Aptian or even uppermost Barremian strata. Nevertheless, according to our observations and contrary to data from the Brunswick area (Mutterlose *et al.* 2009), *O. depressa* occurs in the Lower Aptian and even overlaps with *N. ewaldi*. Malkoc *et al.* (2010) did not report *Oxyteuthis* in their bed-by-bed collection from the eastern LSB albeit Mutterlose (1990) recorded it from the lowermost Lower Aptian.

Among the belemnite fauna, *Duvalia grasiana* is the rarest specimen in our section. It occurs in the basal part of bed 109 only (Text-fig. 6.1). Nevertheless, this is a long-ranging species that has been recorded in the Tethys from the Lower Barremian to the Upper Aptian (Combémorel 1973, Mutterlose 1990, Fischer and Combémorel 2006 in Gauthier 2006).

Ammonites

Deshayesitids are used as the major index fossils in the Lower Aptian (e.g. Sinzow 1898, Von Koenen 1902). Traditionally, the Lower Aptian interval in northern Germany is subdivided into a *Prodeshayesites*

bodei Zone at the base, a superjacent *Prodeshayesites tenuicostatus* Zone and a *Deshayesites deshayesi* Zone above (Kemper 1995), a concept that is followed until today (Mutterlose *et al.* 2009, Malkoc *et al.* 2010; Text-fig. 10). The biostratigraphical dating of the Fischschiefer and its limits, however, are still debated. The Fischschiefer is either interpreted as representing the middle part of the *D. deshayesi* Zone (Rückheim and Mutterlose 2002), roughly correlating with this zone (Mutterlose *et al.* 2009), or it is covering the transition of the *P. tenuicostatus* and *D. deshayesi* zones (Mutterlose 1998, Mutterlose and Wiedenroth 2009; Text-fig. 10). Most recently, Malkoc *et al.* (2010) assigned the Fischschiefer to the *P. tenuicostatus* Zone (Text-fig. 10).

Following the taxonomy of Casey (1980), who regards the first as a junior synonym (see FOSSIL RECORD), the *P. tenuicostatus* Zone as used in the German literature, has been replaced by the *Prodeshayesites fissicostatus* Zone in this study. At Alstätte, the first occurrence of *P. fissicostatus* predates the first occurrence of *P. bodei*, but not vice versa as indicated by the traditional zonal scheme of northern Germany. Furthermore, as explained in the taxonomic notes above, *P. bodei* is probably an extreme morphological variant of *P. fissicostatus* and thus we dismiss to use the former as a zonal index any longer.

Therefore *P. fissicostatus* is the critical index species in our section and has a long range from the upper part of bed 103 to the upper part of bed 109, including the Fischschiefer interval (Text-Fig. 5). The lower part of our *P. fissicostatus* Zone is almost correlating with the Fischschiefer interval which accords with Malkoc *et al.* (2010). The upper part of the *P. fissicostatus* Zone, as defined here, is characterized by a more common occurrence of *P. bodei*. This interval is interpreted here rather as a biohorizon rather than a zone because *P.*

bodei is showing close affinities to *P. fissicostatus* and is hardly to separate.

In the *P. fissicostatus* Zone (Text-fig. 5) a couple of *Prodeshayesites* species are associated with the zonal index, all originally described from the *P. fissicostatus* Zone, *P. bodei* Subzone of northern Germany (Von Koenen 1902). *Prodeshayesites laeviusculus* (Text-fig. 8.4), together with *Prodeshayesites lestrangei*, occurs in southern England at a similar level (Casey 1964). In our section both range well above the Fischschiefer (beds 108 and 109) and well into the *P. fissicostatus* Zone. *Prodeshayesites lestrangei* is apparently rare in Alstätte; our lowermost record is from the lower part of the Fischschiefer. Malkoc *et al.* (2010) collected *P. lestrangei* associated with *P. fissicostatus* in a bed directly below the Fischschiefer in the Brunswick area, an occurrence representing the ammonite abundance peak in this section. This might indicate that the limits of the Fischschiefer are not synchronous in the LSB. Another unequivocally identified *Prodeshayesites* species is *P. jacksoni*, collected from bed 108. This species is recorded from the *Deshayesites forbesi* Zone, *Deshayesites fittoni* Subzone, of southern England yet (Casey, 1964). This could possibly indicate that the geode in geode level (bed 108) of the Alstätte profile correlates with the basal-most Atherfield Clay Formation of the Lower Greensand Group on the Isle of Wight in southern England.

Compared to deshayesitid ammonites, heteromorphs are of limited biostratigraphic use in the Aptian (e.g. Mitchell and Underwood 1999, Hoedemaeker *et al.* 2003, Moreno-Bedmar *et al.* 2010). Although there are no zones defined by heteromorphic species in the Boreal Realm, some species appear to be of stratigraphic relevance. *Audouliceras*? sp. 1 is occurring in a limited interval of the basal Al-

Sub-stage	Spain M.-B et al. 2009	Spain G.-M. et al. 2009 / M. et al. 2009	South England Casey 1961, Casey et al. 1998 (zone)	(detail)	North Germany Kemper 1995 South	Kemper 1995 North	Mu.1998	Rück. & Mu. 2002	Mu. et al. 2009	Mu. & Wiedenroth 2009	Malkoc et al. 2010	present paper
Lower Aptian	Du. furcata	Du. furcata	T. bow.	C. meyendorffi	T. bow. & Du. furcata	Aconeceras nisus (pars)	T. bow.	T. bow.	T. bow.	T. bow.	T. bow.	?
		D. d.-Du. f.		Du. transitoria								
	D. desh.	D. desh.	D. desh.	D. grandis	D. desh. ?		D. desh.	D. desh.	D. desh.	D. desh.	D. desh.	
				C. parinodum								
	D. weissi	D. weissi	D. forbesi	D. annelidus			P. tenuic.	P. tenuic.	P. tenuic.	P. tenuic.	P. tenuic.	P. fissic.
				D. callidiscus								
				D. kiliani								
				D. fittoni								
	D. oglanl.	D. oglanl.	P. fissic.	P. obsoletus	P. bodei	?	P. bodei	P. bodei	P. bodei	P. bodei	P. bodei	
				P. bodei								?

Text-fig. 10. Schematic ammonite zonation of North Germany compared to South England. Note different stratigraphic position of the Fischschiefer interval indicated by bars according to different authors. Abbreviations as far as not clear from the chart: *A.* = *Aconeceras*, *C.* = *Cheloniceras*, *D.* = *Deshayesites*, *Du.* = *Dufrenoyia*, *D. d./Du. f.* = *Deshayesites deshayesi-Dufrenoyia furcata* transition zone, *P.* = *Prodeshayesites*, *T. bow.* = *Tropaeum bowerbanki*, *desh.* = *deshayesi*, *fissic.* = *fissicostatus*, *tenuic.* = *tenuicostatus*, *G.-M.* = García-Mondéjar, *M.* = Millán, *Mu* = Mutterlose, *M.-B* = Moreno-Bedmar, *Rück.* = Rückheim. Note that we regard *P. tenuicostatus* as a synonym of *P. fissicostatus* (details see BIOSTRATIGRAPHY)

stätte section (Text-fig. 7.3; taxonomy see FOSSIL RECORD). A few examples of this very large ancyloceratid have been collected bed-by-bed from the upper part of bed 99 to the upper part of bed 103, but seven loosely collected specimens (GSUB C5823, C5921, C5819 to C5822, C5888) together with others left in the field, indicate that this species is frequent and probably even has a slightly more extended range (Text-fig. 5).

Volgoceratoides elatum and *V. biplicatus* have been described from the *Hoplites weissi* Zone sensu Von Koenen (1902) of Kastendamm only. This corresponds to a level above the *P. fissicostatus* Zone in the sense used here, possibly to the *D. deshayesi* Zone (Kemper 1995). We record *V. elatum* from beds 103 and 109 and *V. biplicatus* from bed 105, each of our *P. fissicostatus* Zone.

Ancyloceras varians and *Ancyloceras mantelli* range from bed 104 to 108 respectively top of bed 109 in our section. Their biostratigraphic value is probably limited, since both have been recorded from younger horizons elsewhere. The first one is recorded from the *D. deshayesi* and *T. bowerbanki* Zones of France (Casey 1960, Busnardo in Gauthier 2006) and the latter is recorded from a level above our records in England, the *D. forbesi* Zone, *D. callidiscus* to *D. annelidus* Subzones (Casey 1960, referring to the revised zonation by Casey *et al.* 1998).

Audouliceras urbani (Text-fig. 7.1; taxonomy see FOSSIL RECORD) is a species that is associated with *P. bodei* according to Von Koenen (1902). Our records from bed 108 and basal bed 109 confirm this; nevertheless, von Koenen (1902) also recorded the species from his *Hoplites weissi* and *H. deshayesi* Zones. Thus it probably ranges significantly higher (*D. deshayesi* Zone in the modern sense, see Kemper 1995).

Aconeceratid ammonites are generally of limited stratigraphic value compared to other ammonite groups (e.g. Riccardi *et al.* 1987), probably because of more complex ecological preferences. Nevertheless, a few species of this group have been used as zonal markers in North Germany in the past (Kemper 1995, Text-fig. 10). We record *Aconeceras nisoides*, a Lower Aptian species (Casey 1961, Kennedy and Klinger 1979), not below the middle part of bed 107 in our section and thus use it as indicating a biohorizon only (Text-fig. 5). A further aconeceratid is *Sanmartinoceras* cf. *trautscholdi* that occurs in the Lower Aptian of the former USSR, England and Germany (Kemper 1971, Kennedy and Klinger 1979; Text-fig. 6.7). An Upper Aptian record from South Africa (Kennedy and Klinger 1979) is doubtful, since the single evidence better matches
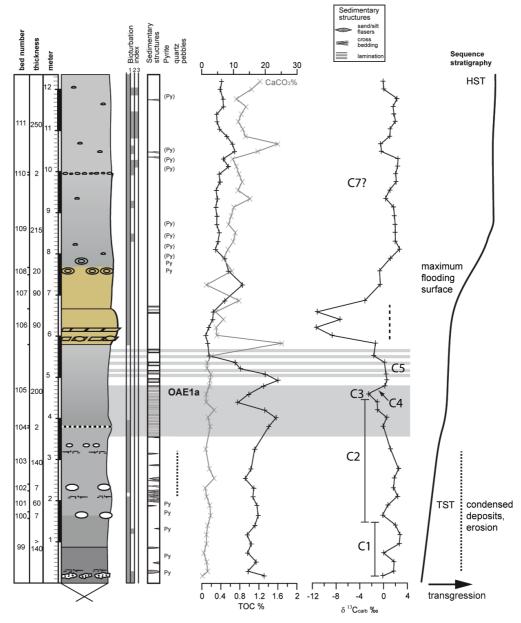
with *S.* (*S.*) *stolleyi* Casey, 1961 following Riccardi *et al.* (1987).

A single representative of *Cheloniceras* (*Cheloniceras*) sp. from the upper part of bed 111 indicates an upper Lower Aptian stratigraphic position for the upper part of the MCI (Text-fig. 3, 5; e.g. Casey *et al.* 1998).
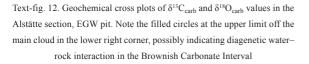
CHEMOSTRATIGRAPHY

For the past decades chemostratigraphy based on stable carbon isotopes has become a powerful tool for stratigraphic correlation (Jarvis *et al.* 2006, Weissert *et al.* 2008). For the Lower Aptian, a classification of the stable carbon isotope perturbation introduced by Menegatti *et al.* (1998) has been applied by many succeeding authors (e.g., Dumitrescu and Brassell 2006; Heldt *et al.* 2008; Kuhnt *et al.* 2011). Chemostratigraphy is particularly important for the sections of the northern Tethys where this reference curve has been developed, since deshayesitids are missing here, although they are generally present in the Mediterranean Tethyan Belt stretching from Spain to the Kopet Dagh. However, in many reference curve sections calcareous nannofossils and planktonic foraminifera are used for calibration only (Malkoc *et al.* 2010). This lack of integrated carbon isotope and ammonite data in many areas significantly enhances the relevance of the present contribution and makes it possible to compare with e.g. the La Bedoule section in southeastern France that provides a combination of both data sets (Moullade *et al.* 1998, Renard *et al.* 2005, Renard *et al.* 2009).

Stable carbon isotopes show an interval of relatively stable values for the lowermost 2.5 m of the studied section, followed by a negative shift into the Fischschiefer interval (Text-fig. 11). The lowest value of this negative shift occurs at the top of the lower, continuously laminated part of the Fischschiefer in the Silty Shale Bundle. The upper part of the Fischschiefer is characterized by an increase in $\delta^{13}C_{carb}$ values followed by fairly stable values (a plateau *sensu* Menegatti *et al.* 1998). Following the stratigraphic scheme of Menegatti *et al.* (1998), five dsegments of the above described $\delta^{13}C_{carb}$ record are distinguished as C1 to C5 (see Text-fig. 11). Above the Fischschiefer interval, da distinct trend towards extremely negative $\delta^{13}C_{carb}$ values corresponds to the lower half of the Brownish Carbonate Interval. dSamples showing these very negative $\delta^{13}C_{carb}$ values also dshow a pronounced positive trend in corresponding

Text-fig. 11. Geochemistry data in the lower, fossiliferous part of the Alstätte section, EGW pit. Bioturbation index according to Miller and Smail (1997). Legend see Text-fig. 5. The pyrite content is high throughout the section, abundant pyrite concretions or pyritic burrows indicated by Py, less common occurrence in brackets. The dashed line at the negative $\delta^{13}C_{carb}$ excursion might indicate an interval that has been diagenetically altered

$\delta^{18}O_{carb}$ values, clearly separating this interval from the rest of the section (Text-fig. 12). Given the extreme values for both carbon and oxygen isotopes and their good correlation for this interval in contrast to other parts of the section, the lower part of the Brownish Carbonate Interval might be interpreted to be influenced by diagenetic processes. This might be supported by the fossil preservation as explained above (chapter THE ALSTÄTTE SECTION), but dalso by preliminary $\delta^{13}C_{org}$ ddata. A $\delta^{13}C_{org}$ curve in progress is showing a positive, but no negative spike as in the $\delta^{13}C_{carb}$ values in the critical interval. These dobservations are in accordance with a clear positive trend in the $\delta^{13}C_{carb}$ values (segment C6 of Menegatti et al. 1998), which was recorded by isotope data of belemnite carbonate from the LSB (Malkoc et al. 2010). In our section, a slight positive trend in the upper part of the Brownish Carbonate Interval is followed by fairly stable $\delta^{13}C_{carb}$ values to the top of our geochemical record. Thus, data of slightly above bed 109 to bed 111 probably correspond to segment C7 of Menegatti et al. (1998).

Text-fig. 12. Geochemical cross plots of $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ values in the Alstätte section, EGW pit. Note the filled circles at the upper limit off the main cloud in the lower right corner, possibly indicating diagenetic water–rock interaction in the Brownish Carbonate Interval

STRATIGRAPHIC CORRELATION OF OAE 1a

For the Boreal realm, a discussion of OAE 1a and its correlation with the ammonite and carbon isotope stratigraphy is hardly possible without its comparison to the Tethyan record, since it is well-recorded from the latter realm (e.g. Erbacher *et al.* 1996). In many Tethyan sections, however, ammonites are rare particularly within the OAE 1a interval, hindering the correlation between macrofossil biostratigraphy and stable isotope data (Landra *et al.* 2000; Bernaus *et al.* 2003; Lehmann *et al.* 2009). Recently, Malkoc *et al.* (2010) compared both faunal realms, mainly discussing results by Moreno-Bedmar *et al.* (2009) from northeastern Spain, who attributed OAE 1a to an interval in the upper *Deshayesites weissi* Zone and the positive $\delta^{13}C_{carb}$ excursion to the *D. deshayesi* Zone (compare also Reboulet *et al.* 2011). In contrast, sections described by García-Mondéjar *et al.* (2009) and Millán *et al.* (2009) in the Aralar mountains in north central Spain infer an age for OAE 1a that is *D. weissi* to earliest *D. deshayesites-D. furcata* transition Zone (Text-fig. 10). Since OAE 1a is not expressed in the lithology (i.e., lack of laminated marlstones or black shales), chemostratigraphy can be used to locate the OAE 1a interval. The typical negative isotope signature of segments C3 and C4, indicating the onset of OAE 1a
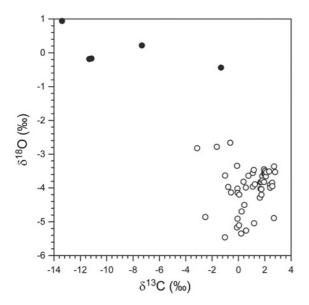
in the northern Tethys (Menegatti *et al.* 1998), is present in the lowermost part of the section of García-Mondéjar *et al.* (2009, composite section in fig. 23; uppermost Barremian) and in the *D. weissi* Zone following Millán *et al.* (2009). The isotope shift C6, close to the upper limit of OAE 1a in the northern Tethys, is located in the lower *D. deshayesi-D. furcata* transition Zone of both sections. At least a part of these discrepancies in the Spanish successions can be partly explained by a different taxonomic and zonal approach used by these authors.

A correlation of ammonite biostratigraphy between the Boreal and the Tethys is difficult on the base of ammonites. Until today *D. deshayesi* is missing in all bed-by-bed-studied Fischschiefer sections in the LSB, including the comprehensive material at hand. Furthermore the index species of the subjacent *D. weissi* Zone was originally described from North Germany, but is not recorded recently in sections of this area. However, it is recorded from the Bedoulian type section in southern France (Ropolo *et al.* 2006, 2009). This species may be regarded as of uncertain systematic affinities, and therefore it should not be used (Reboulet *et al.* 2006). Recently the species name has been retained to define an assemblage zone of various ammonites in the Tethys of which some occur in the Boreal *D. forbesi* Zone (Text-fig. 10; e.g. García-Mondéjar *et al.* 2009).

In our study the Fischschiefer, covering the upper half of the C2 to C5 segments (Text-fig. 11), is represented in the *P. fissicostatus* Zone. According to the correlation of segments as defined by Menegatti *et al.* (1998), this correlates with the *D. weissi* Zone of Moreno-Bedmar *et al.* (2009) and the *D. oglanlensis* to basalmost *D. deshayesi-D. furcata* transition Zone of García-Mondéjar *et al.* (2009). We agree with several papers (De Gea *et al.* 2003; Moreno-Bedmar *et al.* 2009; Malkoc *et al.* 2010) that the positive excursion of the carbon isotope curve (segment C7 of Menegatti *et al.* 1998) occurs above OAE 1a. Based on the pronounced positive $\delta^{13}C_{carb}$ excursion, we correlate the lower *D. deshayesi-D. furcata* transition Zone of García-Mondéjar *et al.* (2009) with the unzoned interval above the *P. fissicostatus* Zone of the present scheme. This might correlate with the lower *D. deshayesi* Zone sensu Moreno-Bedmar *et al.* (2009).

PALAEOBIOGEOGRAPHY

The Alstätte area belongs to the temperate province of the Boreal faunal realm of the European Creta-

ceous, contrasting the low-latitude Tethyan Province with more thermophilic biota (e.g. Wiedmann 1979; Kemper *et al.* 1981; Mutterlose 1992). For the pre-Aptian period, faunal separation between both provinces was distinct (Rawson 2006). Nevertheless, several episodes of faunal exchange occurred in the Early Cretaceous of Western and Central Europe. One of these episodes corresponds to the Early Aptian transgression. The Early Aptian transgression is a part of the long-lasting mid-Cretaceous sea level rise that culminated in the Turonian (Haq *et al.* 1988; Hardenbol *et al.* 1998). In parts of Europe, the environmental impact of this sea level rise was dramatic, demonstrated for example by a change from terrestrial flood plains of the Barremian to Early Aptian marine conditions in southern England (Gröcke *et al.* 1999). In fact, southern England is a key area for the palaeobiogeographical development of Europe in the Aptian. New migration routes for Tethyan elements were opened by the ingression, including that via the English Proto-Channel (Text-fig. 1; Rawson 1992; Mutterlose 1998). In North Germany this new palaeogeographic and palaeoceanographic situation in the Aptian can be visualized by a southward extension of the LSB with its limits along the northern rim of the Rhenish massif (Text-fig. 1; Schott *et al.* 1969). As a consequence, the distinct marine provinces of the Barremian slowly began to disappear (Mutterlose 1992). For the initial transgression in the earliest Aptian, a faunal and floral turnover is postulated that is followed by the invasion of Tethyan elements during the sea level peak in the late Early Aptian (Mutterlose 1992; Mutterlose and Wiedenroth 2009).

In Text-fig. 3, the faunal trends are indicated for the Alstätte section. The macrofauna below the Fischschiefer is dominated by the belemnite *O. depressa* and the large ancyloceratid ammonite *Audouliceras*? sp. 1. *Oxyteuthis* characterises this interval indicating the Boreal faunal realm (Malkoc *et al.* 2010), *Audouliceras*? sp. 1 is, so far, recorded by Kakabadze and Hoedemaeker (2010) only. The latter authors figured it as *Audouliceras* cf. *urbani* from North Germany (see taxonomic notes in FOSSIL RECORD).

A general dominance of endemic faunas in the entire lower half of the section is, however, underlined by the abundant occurrence of *P. fissicostatus* and closely related forms between the top of bed 103 and the lower part of bed 109. *Prodeshayesites* species of this group are also recorded from Spain, the Alps, France and Iran (Masse and Thieuloy 1975; Collignon *et al.* 1979; Kaiser-Weidich and Schairer 1990; Delanoy 1991; Immel *et al.* 1997; García-Mondéjar *et al.* 2009). The Spanish record (Collignon *et al.* 1979) is certainly not representing

Prodeshayesites (H. G. Owen, personal communication), the French records are already indicated as doubtful (Delanoy 1995; Delanoy *et al.* 1997), including the non-figured records by Kakabadze and Kotetishvili (1995) that have been originally indicated as doubtful already. The core distribution of prodeshayesitids is therefore the European Boreal Realm, but it probably also occurs in North-East Iran (Raisossadat 2004).

A clear change in faunal composition is indicated in the interval between bed 108 and the basal part of bed 109 (Text-fig. 3). Here, the Tethyan belemnite *Neohibolites* (e.g. Mutterlose *et al.* 1983) occurs in high abundances, especially characterized by a peak of *N. ewaldi*. This species shows a fairly wide distribution from the European Boreal realm and Tethys (Swinnerton 1955; Wiedmann and Dieni 1968) to Azerbaijan (Ali-Zade *et al.* 1988), Caucasus and Crimea (Drushchits and Kudryavtsev 1960) as well as Mozambique (Doyle 1987). This shift from a rather endemic fauna to more thermophilic associations is also indicated by the occurrence of the Tethyan belemnite *Duvalia grasiana* (Mutterlose 1998; Text-fig. 6.4) and an abundance peak of *Aconeceras nisoides* that also is primarily a Tethyan species with records from Europe, Russia, central Asia, Colombia (Bogdanova and Hoedemaeker 2004) and Mozambique (Förster 1975), although records from the latter two countries might be doubtful (L. Bulot, pers. com.). For the same interval, a single specimen of the widely distributed nautiloid *Cymatoceras neckerianum* (Lehmann *et al.* 2009) has been obtained in the studied section.

The above-mentioned occurrences of specific macrofaunal elements show a distinct change from an endemic fauna typical for the Boreal Realm during the initial Early Aptian towards an increasing occurrence of Tethyan macrofaunas in the framework of the late Early Aptian sea level peak. This is in good accordance with increasing temperatures assumed by Mutterlose and Wiedenroth (2009) for this interval (Text-fig. 3).

PALAEOENVIRONMENT

The Lower Saxony Basin experienced some relevant climatic changes during the time interval of the Late Barremian to Lower Aptian (Mutterlose and Wiedenroth 2009; Malkoc and Mutterlose 2010). A cooling in the Late Barremian, with a peak around the Barremian/Aptian boundary, is followed by a warming trend in the Early Aptian. This climatic trend is accompanied by a prominent supraregional third-order sea level fluctuation in the latest Barremian and Early Aptian (Hardenbol *et al.* 1998).

A continuous transgression is interpreted for the lower interval of the profile, following Mutterlose and

Wiedenroth (2009). During this time interval, the depositional environment in the Alstätte Bay is believed to be an offshore transition zone (Coe and Church 2003), restricted but under fairly well-oxygenated conditions. The latter is indicated by a common bioturbation in this interval (Text-fig. 11, bioturbation index following Miller and Smail 1997) and the occurrence of *Cyclothyris* sp., a brachiopod that occurs partly in clusters in the lowermost part (about 1.5 metres) of the section, since brachiopods are filterers and whirlers they need a sufficient oxygen supply (Rudwick 1970).

A rising sea level might be indicated in the section by lense-like accumulations of belemnites (determined as *Neohibolites* and *Oxyteuthis*) that occur in several levels within the interval from the middle of the Barren Geodes interval to the lower part of the Silty Shale Interval (Text-fig. 3). These beds yield lenses of sand and small-size gravel with quartzitic pebbles up to a size of several cm. The rostra of *Neohibolites* are well-preserved and mostly complete. The rostra of *Oxyteuthis*, however, show strong mechanical damages and are often only fragmentary. Additionally, some of the oxyteuthid rostra are penetrated by boreholes that can be attributed to the activity of acrothoriacican cirripedia as recorded from Early Cretaceous belemnites (e.g. Seilacher 1968, 1969; Petriconi 1971 and Lukeneder 1999). These different lines of evidence suppose that the belemnites are accumulated by condensation and erosion, as also is indicated by the accompanying quartz pebbles (Text-fig. 9). Comparable reworked sediments rich in fossils are known from sections characterized by a low sediment supply during a Transgressive Systems Tract (TST; e. g. Coe and Church 2003). This agrees with the European sea level curves (Hardenbol *et al.* 1998). The succeeding interval that includes the Fischschiefer also agrees with a sequence stratigraphic interpretation as a TST. The Fischschiefer shows lamination that is particularly well-developed in the lower part. The lamination as well as the lack of bioturbation during most of the Fischschiefer interval (Text-fig. 11) indicates a generally low oxygen level. Small bivalves and gastropods are scattered in the whole lower part of the fossiliferous section, including the Fischschiefer. They attest to short episodes with at least moderate oxygen availability allowing benthic life to repopulate. This is in accordance with a restricted bay situation with extenuated circulation that can be supposed for the Fischschiefer interval.

Continuous transgression with a Maximum Flooding Surface (mfs) at the Geode in Geode marker bed is assumed. This level is characterized by a larger abundance of ammonites, with a number of more widely distributed species increasing the biodiversity. This conspicuous occurrence agrees with other examples in the geological record of a mfs without apparent sedimentological features such as condensation and taphonomic accumulation, but that are characterized by a shift to more oceanic faunal assemblages (Boardman *et al.* 1998: Palaeozoic of Kansas; Owen 1996, Lehmann 1999, *Mantelliceras dixoni* Event of Northern Germany). This development from a more restricted to open bay setting above the Fischschiefer interval is paralleled by a significant change in both $CaCO_3$ and TOC values (Text-fig. 11). Higher TOC values characterize the more restricted environment of the lower part, including OAE 1a. Improved connection to the open ocean in the upper part probably led to more oxygenated bottom-water conditions resulting in a decreasing preservation of organic matter at the sea floor. Paralleling the development of decreasing TOC values, the carbonate content increases up-section. Due to the more open-marine environment associated with the general sea level rise and the open bay setting, it can be speculated that an increase in calcareous nannoplankton, favouring more open-ocean conditions, led to the observed increase in $CaCO_3$. Numerous massive wood logs around the Geode in Geode marker bed (Text-figs 3, 5) might be an additional hint on the mfs. According to the model by Erbacher *et al.* 1996), the rise of sea level in the OAE 1a interval led to a leaching of nutrients by the flooding of coastal lowlands. The influx of wood debris recorded for the largest part of the Fischschiefer interval already might therefore indicate a first flooding event of lowlands as a precursor and the big trunks recorded mainly from the Geode in Geode marker bed and the basal part of bed 109 are caused by the main event. Similar settings of wood associated with a supposed maximum flooding interval are recorded for example from the Lower Jurassic of Sweden (Frandsen and Surlyk 2003).

In contrast to the rich macrofaunas at the mfs and slightly above, the fossil record gets distinctly poor in the overlying MCI. This cannot be explained by a change of the oxygen content in the water column or in the uppermost cm of the sediment column, as demonstrated by a regular level of bioturbation, generally low TOC values, and the occurrence of *N. ewaldi* in the lower part of the MCI (Text-fig. 5). Because of the poor fossil content in this interval, sedimentological criteria are used for the sequence stratigraphic interpretation. The conspicuous facies change between the MCI and the Green Band from pure claystone facies to an interval that contains larger amounts of glauconite is believed to represent a sequence boundary (Text-fig. 3). Glauconite is well-known to be associated with erosion and condensation at the margins of the LSB, but it is missing in the offshore zones (e.g. Seibertz 1979; Kaplan *et al.* 1998). Thus, the enrichment of glau-

conite is interpreted as the product of sediment by-passing and erosion in the offshore transition zone, an explanation supported by the observed unconformity associated with the facies change. This sequence stratigraphic interpretation is in agreement with accordant models (Coe and Church 2003). The top of the Green Band consists of a glauconitic marlstone with an irregular layer of limestone in the middle that is called Brachiopod Seam (Text-fig. 3). The limestone layer is composed of limestone nodules and contains accumulations of terebratulid brachiopods and belemnites. We interpret the Brachiopod Seam as related to a pause or decrease in the rate of sedimentation associated with a rise in sea level at the transgressive surface. In agreement with Coe and Church 2003, this might cause minor erosion and reworking from increased storm-induced activity in the offshore transition zone. The change from the Green Band to the Top Grey interval marks a further facies change to pure claystone sedimentation lacking any glauconite. This is interpreted as a sea level increase that shifts the depositional environment to the offshore zone again.

Acknowledgements

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