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Integrated stratigraphy of the upper Lower – lower Middle Cenomanian of northern Germany and southern England

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ABSTRACT

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A high-resolution stratigraphic calibration of the upper Lower (upper *Mantelliceras dixoni* Zone) and lower Middle Cenomanian (*Cunningtoniceras inerme* Zone and lower *Acanthoceras rhotomagense* Zone) based on an integrated analysis of macrofossil biostratigraphy, event, cyclo-, stable-isotope and sequence stratigraphy of northern German and southern England key sections is presented. Classic event stratigraphy has a good potential in refining biostratigraphic correlations as most of the classic bioevents are isochronous within the integrated stratigraphy. Many lithological event beds such as marker marls can be incorporated into the cyclo- and sequence stratigraphic framework, explaining their significance in interregional correlation. The best stratigraphic resolution provides the cyclostratigraphy based on the typical Cenomanian marl-limestone couplets and their stacking pattern, inferred to reflect orbital forcing of the Milankovitch frequency band: detailed bed-by-bed correlation of couplets (precession cycle, ca. 20 kyr) allows a stratigraphic calibration within ~10 kyr time slices. Conspicuous marker marl beds embrace bundles of ~five couplets and are related to the short eccentricity (100 kyr) cycle. However, for the upper Lower Cenomanian (*dixoni* Zone) it appears that the existing couplet scale is incomplete. Sequence stratigraphic analysis demonstrates that the investigated interval comprises the maximum flooding and highstand interval of an Early Cenomanian sequence, capped by a significant late *dixoni* Zone sequence boundary, followed by uppermost Lower to Middle Cenomanian lowstand and transgressive deposits grading into a Middle Cenomanian maximum flooding zone ("calcimetry break"). Carbon stable-isotope values are stable around 2 ‰ vs. V-PDB within the mid- and late *dixoni* Zone, related to equilibrium conditions during maximum flooding and highstand conditions of sea-level. The latest Early to earliest Middle Cenomanian sea-level fall and lowstand was accompanied by a negative $\delta^{13}C$ excursion of ca. 0.4 ‰ in couplets B34-B40 (Lower-Middle Cenomanian boundary isotope Event, LMCE, new name) followed by a rise of 0.4–0.6 ‰ $\delta^{13}C$ in couplets B41-C2 during the early transgressive systems tract (Middle Cenomanian $\delta^{13}C$ excursion MCE 1). These observations support the interpretation that the $\delta^{13}C$ signal is a good proxy for (eustatic) sea-level changes. The LMCE is suggested as a proxy marker for the base of the Middle Cenomanian Substage.

Key words: Cretaceous, Stable-isotopes, Cyclostratigraphy, Stratigraphic events, Sequence stratigraphy, Correlation.

INTRODUCTION

Marine epicontinental sediments of the Cenomanian Stage in NW Europe can be subdivided using a super high-resolution integrated stratigraphy of bio-, event, sequence, stable-isotope and cyclostratigraphy (e.g. ERNST *& al.* 1983; GALE 1995; KAPLAN *& al.* 1998; ROBASZYNSKI *& al.* 1998; LEHMANN 1999; WILMSEN 2003; WILMSEN *& al.* 2005). However, despite this integrated stratigraphic framework, there are still several open questions concerning the correlation between northern Germany and southern England. In particular, the positions of certain marker beds and key surfaces within the Lower-Middle Cenomanian boundary interval remained controversial (e.g. the latest Early Cenomanian sequence boundary and the succeeding early Middle Cenomanian transgressive surface).

The scope of the present paper is thus a detailed integrated stratigraphic calibration of the upper Lower (upper *Mantelliceras dixoni* Zone) and lower Middle Cenomanian (*Cunningtoniceras inerme* Zone and lower *Acanthoceras rhotomagense* Zone) of four North German and southern England key sections (Hoppenstedt, Baddeckenstedt, Wunstorf, Southerham Grey Pit) in order to elucidate and date the sequence of the geological events. Sea-level changes as well as palaeontological and palaeoceanographical events are compared within a tightly constrained stratigraphic framework.

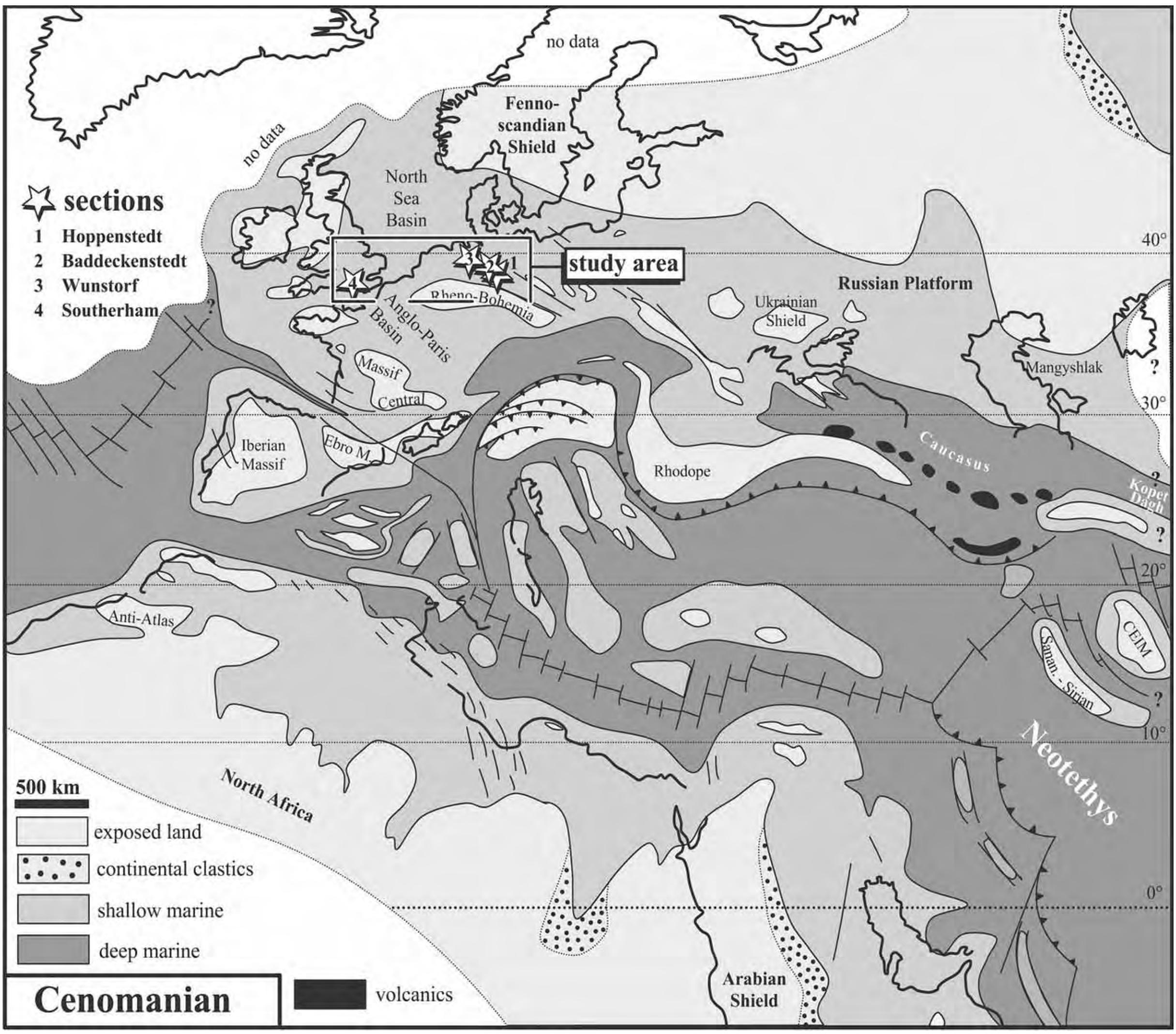


Fig. 1. Palaeogeography of the Cenomanian in the western Tethyan Realm (modified after PHILIP & FLOQUET 2000). The positions of the sections investigated are indicated by numbered asterisks within the rectangle

METHODS

Stratigraphic correlation is based on an integrated approach of detailed bed-by-bed logging and sampling, facies analysis, macrofossil biostratigraphy, event stratigraphy, stable-isotope, cyclo- and sequence stratigraphy. Limestones were investigated by hand-lens in the field and classified according to depositional fabric. Furthermore, selected samples were taken for optical microscope-based microfacies analysis with special emphasis on key surfaces such as hardgrounds and macrofossil concentrations (ca. 120 thin sections). Macrofossils were collected largely *in situ* and prepared using vibratools and needles. The sequence stratigraphic interpretation follows the guidelines published by ERNST *& al.* (1996), ROBASZYNSKI *& al.* (1998) and WILMSEN (2003) for epicontinental, mainly vertically accreted (hemi-)pelagic "chalks". The cyclostratigraphic analysis is based on the couplet scale for the Cenomanian Stage developed by GALE (1995).

For carbon and oxygen stable-isotope analyses, the sections were sampled equidistantly in 0.5-1 m intervals based on their stratigraphic thicknesses. For the considerably condensed Hoppenstedt section, a closer spaced sampling grid was applied. The bulk rock samples were powdered and carbonate powders were reacted with 100% phosphoric acid (density >1.9, WACHTER & HAYES 1985) at 75°C using a Kiel III online carbonate preparation line connected to a ThermoFinnigan 252 mass-spectrometer. All samples were processed in the stable-isotope lab of M. JOACHIMSKI (Erlangen University) and values are reported in per mil (‰) relative to V-PDB by assigning a $\delta^{13}C$ value of +1.95‰ and a $\delta^{18}O$ value of -2.20‰ to NBS19. Reproducibility was checked by replicate analysis of laboratory standards and was better than ± 0.03 for $\delta^{13}C$ and 0.04 for $\delta^{18}O$ (1σ).

GEOLOGICAL SETTING

Marine sediments of the Cenomanian stage (ca. 99.6–93.5 Ma according to the GTS 2004 of GRADSTEIN *& al.* 2004), deposited in a wide epicontinental shelf sea covering most of NW Europe at palaeo-latitudes of around 40°N, are widely distributed in northern Germany and southern England (see Text-fig. 1). The predominant lithologies are glauconitic sandstones (Essen Grünsand Formation), (silty) marls (Herbram Formation), fossiliferous marl-limestone alternations (Baddeckenstedt Formation), and calcare-

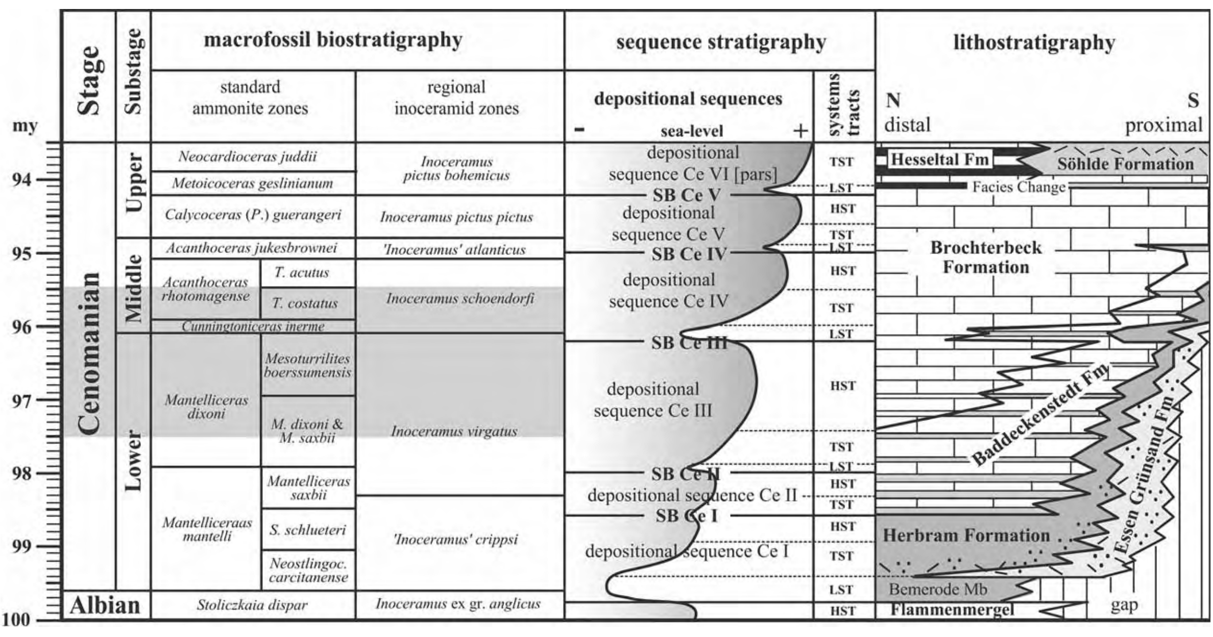


Fig. 2. Stratigraphic framework of the Cenomanian in northern Germany. The stratigraphic interval studied is shaded in grey. Biozonation after KAPLAN *& al.* (1984, 1998) and GALE (1995). Geochronological scale according to GRADSTEIN *& al.* (2004). Sequence stratigraphy after ROBASZYNSKI *& al.* (1998) and WILMSEN (2003); abbreviations: Ce = Cenomanian; LST = lowstand systems tract; TST = transgressive systems tract; HST = highstand systems tract; SB = sequence boundary

ous nannofossil limestones (Brochterbeck Formation), broadly reflecting the proximal-distal arrangement of inner, mid- and outer shelf facies belts (WILMSEN *&* *al.* 2005). These facies units also form the basis for the lithostratigraphic subdivision of the Cenomanian in northern Germany which was recently formalized (*http://www.stratigraphie.de/LithoLex/index.html*; NIEBUHR *&* *al*. 2007; Text-fig. 2).

The Cenomanian age was characterized by a general stepwise transgression culminating in the early Late Cenomanian [*Calycoceras (Proeucalycoceras) guerangeri* Zone]. This transgressive development is documented in a succession of inner shelf sediments (Essen Greensand and Herbram formations) overlain by mid-shelf marl-limestone alternations (Baddeckenstedt Formation) and outer shelf pelagites (Brochterbeck Formation) (Text-fig. 2). This facies development reflects the general retrogradational trend during the "Cenomanian transgression" of authors. During the Early-Middle Cenomanian boundary interval, all four sections were characterized by the deposition of fossiliferous marl-limestone alternations (Baddeckenstedt Formation). Hoppenstedt occupied a relatively proximal position in the Subhercynian subbasin of the North German shelf; Baddeckenstedt, in the southeastern part of the Lower Saxony subbasin, was intermediate, and Wunstorf was situated near the centre of the Lower Saxony subbasin (see WILMSEN & NIEBUHR 2002; WILMSEN 2003; WILMSEN & WOOD 2004 and WILMSEN *&* *al.* 2005, for details). The Southerham Grey Pit was located in the northern part of the Anglo-Paris Basin with a considerable distance to the surrounding emergent massifs (Text-fig. 1). It is part of the Southern Province of the British Chalk depositional and faunal provinces (see MORTIMORE *&* *al.* 2001, pp. 239-253, for details).

STRATIGRAPHY

The stratigraphic interval under discussion comprises approximately 2 Myr according to the GTS 2004 (GRADSTEIN *&* *al.* 2004). The integrated stratigraphic subdivision of the succession is displayed in Text-fig. 2.

Biostratigraphy. The macrofossil biostratigraphy is based mainly on ammonites and inoceramid bivalves (e.g. KAPLAN *&* *al.* 1984, 1998; GALE 1995) and is readily applicable owing to the fossiliferous nature of the succession. The succession comprises the upper part of the *Mantelliceras dixoni* Zone, the *Cunningtoniceras inerme* Zone and the lower *Acanthoceras rhotomagense* Zone (*Turrilites costatus* Subzone) of the Cenomanian standard ammonite biostratigraphy. The corresponding inoceramid bivalve zones are the upper part of the *Inoceramus virgatus* Zone and the lower part of the *Inoceramus schoendorfi* Zone.

Event stratigraphy. Event stratigraphy based on lithological or palaeontological events is of considerable importance for the correlation of lower Upper Cretaceous successions of NW Europe (ERNST *&* *al.* 1983). The following stratigraphic events are important within the interval under discussion (Table 1).

Cyclostratigraphy. The orbitally-forced cyclostratigraphy of the Cenomanian Stage was established by GALE (1990, 1995) and GALE *&* *al.* (1999). It is based on the ubiquitous Cenomanian marl-limestone couplets and their stacking into bundles and sets of bundles inferred to reflect the precession, short and long eccentricity of the Milankovitch band. The couplets were grouped into five parts (A–E) that are numbered from base to top (GALE 1995). The investigated stratigraphic interval comprises couplets B11–B45 and C1–C15. Boundaries between short eccentricity cycles (i.e. 100 kyr cycles) are often marked by conspicuous marker marls (WILMSEN & NIEBUHR 2002; WILMSEN 2003).

Isotope stratigraphy. Carbon stable-isotope curves for the upper Lower and lower Middle Cenomanian were published by PAUL *&* *al.* (1994), MITCHELL *&* *al.* (1996) and JARVIS *&* *al.* (2001, 2006). The most important feature is the double-spiked early Middle Cenomanian positive $\delta^{13}C$ excursion (MCE1a and 1b; cf. PAUL *&* *al.* 1994; MITCHELL *&* *al.* 1996). It is an excellent chemostratigraphic marker which is associated with the *arlesiensis* Bed and the *primus* Event.

Sequence stratigraphy. The sequence stratigraphy of the Cenomanian Stage is well established (see ROBASZYNSKI *&* *al.* 1998; JARVIS *&* *al.* 2001; WILMSEN 2003). Even if the position of certain sequence boundaries may slightly vary according to different authors (e.g. the base of the 4th Cenomanian sequence, see below), most studies recognized five (ROBASZYNSKI *&* *al.* 1998; WILMSEN 2003) or six depositional sequences. JARVIS *&* *al.* (2001) proposed an additional Upper Cenomanian

Name	Characteristics and remarks	References
Mid-Cenomanian Event (MCE, *sensu* Ernst *& al.* 1983)	enrichment of fossils [typically abundant *Sciponoceras baculoide* (Mantell), large and partly fragmented *Acanthoceras rhotomagense* (Brongniart), *Parapuzosia* (*Austiniceras*) sp., and *Holaster subglobosus* (Leske)] in rather coarse-grained, nodular limestones near the summit of the *Turrilites costatus* Subzone (middle of the *rhotomagense* Zone, couplet C10); followed by a conspicuous increase in the content of carbonate = "calcimetry break", Jarvis *& al.* 2001)	Jeans (1980), Ernst *& al.* (1983), Dahmer & Ernst (1986), Lehmann (1999), Wilmsen *& al.* (2005)
Upper *Orbirhynchia* band (Jeans 1980)	concentration of *Orbirhynchia mantelliana* (J. de C. Sowerby) in couplets C6–C10	Jeans (1980), Paul *& al.* (1994)
Praeactinocamax primus Event (Ernst *& al.* 1983)	characterized by a sudden appearance of the belemnite *Praeactinocamax primus* (Arkhangelsky) in marl-limestone couplet C1 (usually the marl) of the lowermost *Acanthoceras rhotomagense* Zone. It is accompanied by a highly diverse invertebrate fauna. The event corresponds to the "Cast Bed" of Price (1877)	Ernst *& al.* (1983), Christensen (1990), Paul *& al.* (1994), Gale (1995), Lehmann (1999), Wilmsen & Niebuhr (2002), Wilmsen *& al.* (2007)
arlesiensis Bed	represents a fossiliferous lower Middle Cenomanian (*Cunningtoniceras inerme* Zone) marker horizon in the Anglo-Paris Basin succession (i.e. the marl of couplet B41), characterized by the occurrence of the small bivalve *Lyropecten* (*Aequipecten*) *arlesiensis* (Woods)	Paul *& al.* (1994), Gale (1995), Mitchell *& al.* (1996), Wilmsen *& al.* (2007)
Middle *Orbirhynchia* band (Jeans 1980)	concentration of *Orbirhynchia mantelliana* (J. de C. Sowerby) around the Lower-Middle Cenomanian boundary	Jeans (1980), Gale (1995)
Marl M Ia (Badaye 1986)	marker marl defined in the Baddeckenstedt section	Badaye (1986), Ernst & Rehfeld (1997), Wilmsen & Niebuhr (2002)
Marl M Ib (Badaye 1986)	marker marl defined in the Baddeckenstedt section	Badaye (1986), Ernst & Rehfeld (1997), Wilmsen & Niebuhr (2002)
Turrilites scheuchzerianus bed (Badaye 1986)	intra-*dixoni* Zone shell concentration with abundant *T. scheuchzerianus* Bosc	Ernst & Rehfeld (1997), Wilmsen & Niebuhr (2002)
Marl M II (Badaye 1986)	conspicuous marker marl defined in the Baddeckenstedt section	Badaye (1986), Ernst & Rehfeld (1997), Wilmsen & Niebuhr (2002)
"double limestone" (Badaye 1986)	prominent bipartite limestone between marker marls M III and M II, named in the Baddeckenstedt section	Badaye (1986), Gale (1995), Ernst & Rehfeld (1997), Wilmsen & Niebuhr (2002)
Marl M III (Badaye 1986)	conspicuous marker marl defined in the Baddeckenstedt section	Badaye (1986), Ernst & Rehfeld (1997), Wilmsen & Niebuhr (2002)
Orbirhynchia/ Schloenbachia Event (Ernst *& al.* 1983)	characterized by the small rhynchonellid brachiopod *Orbirhynchia mantelliana* (J. de C. Sowerby) ("lower *Orbirhynchia* band" of Jeans 1980) associated with *S. varians* and a moderately diverse association of macrobenthic and nektobenthic invertebrates	Jeans (1980), Ernst *& al.* (1983), Lehmann (1999)
Schloenbachia/I. virgatus Event (Ernst *& al.* 1983)	five rather calcareous marl-limestone couplets of the *dixoni* Zone, characterized by an abundance of *Inoceramus* ex gr. *virgatus* Schlüter and *Schloenbachia varians* (J. Sowerby)	Ernst *& al.* (1983), Lehmann (1999), Wilmsen *& al.* (2001), Wilmsen (subm.).
"The rib" (Gale 1995)	prominent limestone in the lower *dixoni* Zone (limestone of couplet B11)	Gale (1995)

Table 1. Important late Early and early Middle Cenomanian stratigraphic events (in ascending order)

sequence 5b. A completely different approach was presented by GALE *& al.* (2002) who regarded high-frequency (4th-order) sequences as depositional (i.e. 3rd-order) sequences.

This study follows the concept of five depositional (3rd-order) sequences (DS Ce I–V) for the Cenomanian, each capped by a sequence boundary (SB Ce I–V). A sixth sequence ranges into the Turonian, capped by an intra-Turonian sequence boundary. The interval under consideration comprises the maximum flooding and highstand interval of DS Ce III and the lowstand and transgressive systems tract of DS Ce IV. Sequence boundary SB Ce III, defining the boundary of both sequences, is of latest Early Cenomanian age (upper *Mantelliceras dixoni* Zone) and of comparably great magnitude (see WILMSEN 2003, for a discussion of absolute magnitudes of Cenomanian eustatic sea-level changes).

RESULTS

Sections

The sections investigated represent a ca. 600 km E–W transect, from the proximal Subhercynian area (Hoppenstedt) via the medial Baddeckenstedt and the distal Wunstorf section near the centre of the Lower Saxony subbasin, to the Southerham section in the northern Anglo-Paris Basin (Text-figs 3, 4). Despite these great distances, lithology and fossil content are similar. Thicknesses, however, vary considerably.

Hoppenstedt

The abandoned limestone quarry "Kalkwerk Nordharz" is situated 4 km west of Osterwiek at the northern exit of Hoppenstedt [topographic map TK 25 Vienenburg (scale 1:25,000), no. 4029, Gauß-Krüger co-ordinates R: 4408000, H: 5763350], north of the Harz Mountains, ca. 25 km WNW of Halberstadt. Structurally, it belongs to the southern limb of the Fallstein, a narrow, NW/SE-trending anticline with a core of Triassic sediments. The Cenomanian succession of Hoppenstedt, from the base of the *dixoni* Zone to the mid-Upper Cenomanian "Facies Change" (see ERNST *& al.* 1983), is ca. 40 m thick (HORNA 1996; WILMSEN & WOOD 2004). The section (Text-fig. 4) was measured from the northern quarry wall (Text-fig. 3A) along the eastern quarry wall. The interval from "the rib" (limestone of couplet B11 of GALE 1995) to the Mid-Cenomanian Event measures 11 m.

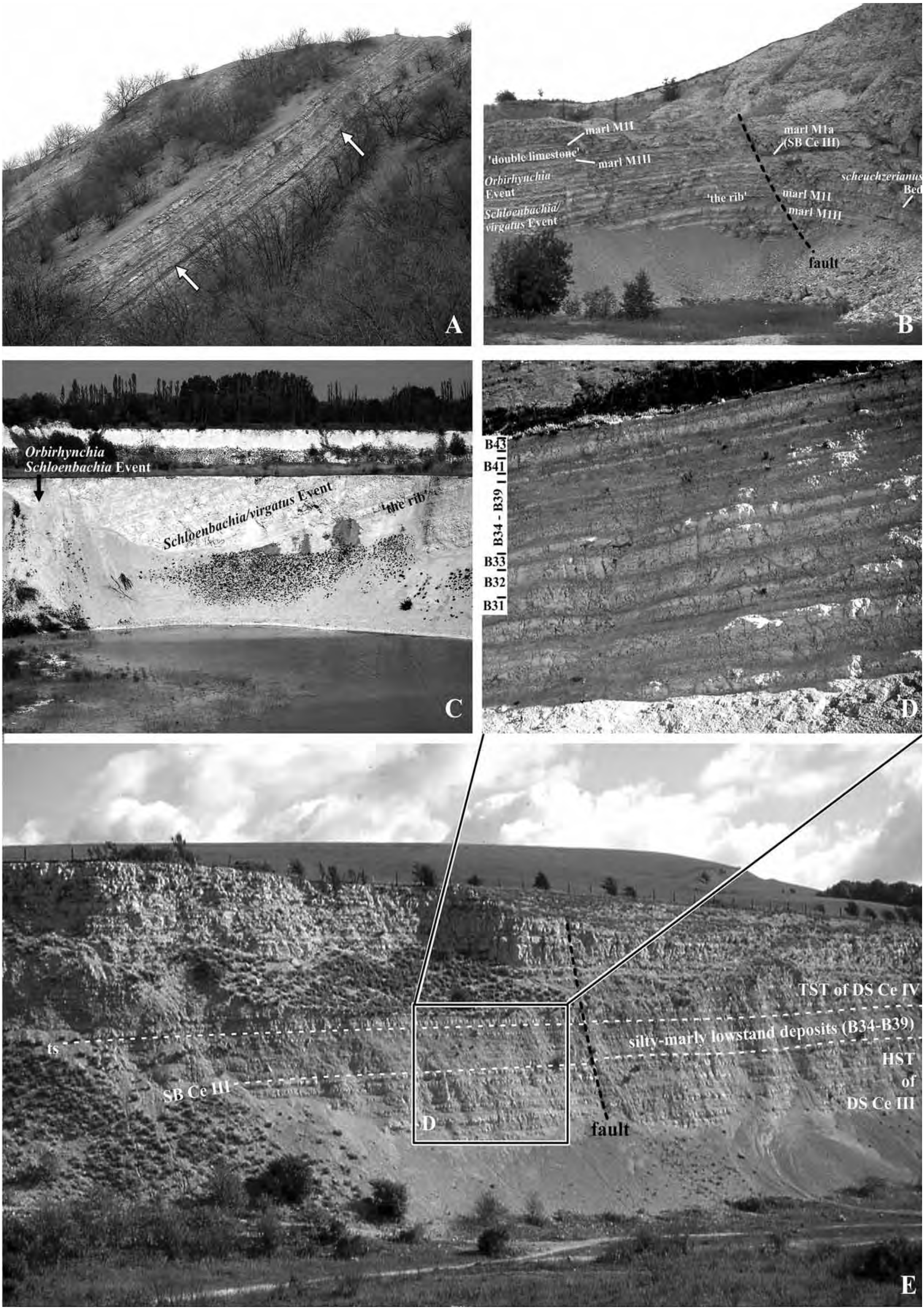
Baddeckenstedt

The abandoned limestone quarry at Baddeckenstedt is located near Salzgitter on the southern slope of the Raster Berg at the NW margin of the village of Baddeckenstedt, east of the Federal Road B6 from Hildesheim to Goslar (TK 25 Ringelheim, no. 3927, R: 3584000, H: 5774000). Structurally, it represents the NW part of the Innerste Syncline and exposes a ca. 41.5 m thick fossiliferous succession of marl-limestone alternations and limestone ranging from the lower *dixoni* Zone up to the Facies Change (see BADAYE 1986; ERNST & REHFELD 1997; WILMSEN & NIEBUHR 2002). The succession from "the rib" to the Mid-Cenomanian Event is nearly 17 m thick (Text-figs 3B, 4).

Wunstorf

The abandoned Wunstorf quarry is situated ca. 25 km west of Hannover in the Wunstorf Cretaceous Syncline, immediately north of the A2 motorway (TK 25 Wunstorf, no. 3522, R: 3533360, H: 5807750). The succession exposed today on a lower and an upper floor of the quarry (Text-fig. 3C) has a thickness of 110 m from near the base of the *dixoni* Zone up to the Facies Change, followed by several metres of black shales (MEYER 1990; WILMSEN 2003). The much expanded succession from "the rib" to the Mid-Cenomanian Event measures 59.5 m (Text-fig. 4).

Fig. 3. Field aspects of the sections investigated. A – Hoppenstedt, northern quarry wall in the central part of the pit. The conspicuous marl (arrowed) is the equivalent of marker marl M III in Baddeckenstedt and overlain by the "double limestone". B – Baddeckenstedt, central part of the quarry with Lower Cenomanian marker beds indicated (cf. WILMSEN & NIEBUHR 2002). C – Wunstorf, mid-*Mantelliceras dixoni* Zone (upper Lower Cenomanian) succession of the lower quarry floor. "The rib", the *Schloenbachia/I. virgatus* and *Orbirhynchia/Schloenbachia* events are indicated. D – Southerham Grey Pit, Lower/Middle Cenomanian boundary interval. Marl-limestone couplets B31-B43 are indicated. Note the conspicuous facies change from thick, limestone-dominated couplets to thin, marl-dominated couplets with couplet B33. E – Southerham Grey Pit, overview of the upper Lower and Middle Cenomanian succession. The marly uppermost Lower to lowermost Middle Cenomanian boundary strata (couplets B34–B39/40) are interpreted as a lowstand systems tract (LST)


A
marl M1I
'double limestone'
marl M1II
Orbirhynchia Event
Schloenbachia/ virgatus Event
marl M1a (SB Ce III)
scheuchzerianus Bed
'the rib'
marl M1I
marl M1II
fault
B
Orbirhynchia Schloenbachia Event
Schloenbachia/virgatus Event
'the rib'
C
B43
B41
B34 - B39
B33
B32
B31
D
TST of DS Ce IV
silty-marly lowstand deposits (B34-B39)
HST of DS Ce III
ts
SB Ce III
D
fault
E

Southerham

The Southerham Grey Pit quarry (Text-fig. 3D, E) is located northeast of Lewes (Sussex, southern England) on the southern side of the A27 road from Lewes to Eastbourne, east of the river Ouse, near the Cliffe Industrial Estate (UK Ordnance Survey grid reference TQ 428 090 in 1:25,000 scale; see also MORTIMORE *& al.* 2001). It is the southern of two now abandoned quarries called the "Grey Pit" in the past (the second one is located a few hundred metres to the NNE and is called the "Machine Bottom Pit"). Both quarries exposed a ca. 75 m thick Cenomanian succession from near the base of the Cenomanian up to the "sub-*plenus* erosion surface", the equivalent of the North German Facies Change. The succession from "the rib" to the Mid-Cenomanian Event is ca. 26 m thick (Text-fig. 4).

Stable-isotope stratigraphy

The carbon and oxygen stable-isotope curves are displayed in the integrated correlation diagram (Text-fig. 4). In this figure, the *Praeactinocamax primus* Event (cf. Table 1) is used as a datum. The lowermost isotope sample in all sections comes from "the rib" (limestone of couplet B11 of GALE 1995), the topmost samples derive from an interval comprising strata from couplet C5 to above the Mid-Cenomanian Event of ERNST *& al.* (1983).

Carbon stable-isotopes

The δ^{13}C values of the upper Lower Cenomanian in all four sections are relatively constant and generally below 2.0‰ vs. V-PDB (only in Wunstorf does the curve vary around 2.1‰ vs. V-PDB). The variation is in the order of <0.2‰ vs. V-PDB, resulting in more-or-less straight curves. Small peaks and excursion seem to be of minor or no importance for stratigraphic calibration as they often cannot be reproduced in other sections (e.g. the *Schloenbachia/virgatus* and *Orbirhynchia/Schloenbachia* events are marked by minor positive excursions in Baddeckenstedt but these signatures are not recorded at the other localities). However, there is a correlatable negative peak between the *Schloenbachia/virgatus* and *Orbirhynchia/Schloenbachia* events, and a minor positive excursion in marl M III and correlative beds (Text-fig. 4). Furthermore, in the couplets below B34 there is a conspicuous trough between two minor peaks, the upper one of which occurring in couplet B33. This signature is correlatable from Southerham to Baddeckenstedt but seems to be cut out at Hoppenstedt, where only the lower peak and the trough are present.

A major change in the δ^{13}C signatures occurs in the uppermost Lower Cenomanian above couplet B33 in Southerham and the correlative levels in Wunstorf [MEYER's (1990) bed 901] and Baddeckenstedt (marl MIa), initiating a negative excursion of ca. 0.3–0.4‰ δ^{13}C, culminating in a minimum in couplet B36 at Southerham. This minimum can be correlated from Southerham via Wunstorf into the thin marl bed MIa in Baddeckenstedt, but again, it seems to be absent from Hoppenstedt. From B36, values rise stepwise towards a double-spiked positive excursion of ~0.8‰ δ^{13}C, known as MCE 1a and MCE 1b (PAUL *& al.* 1994; MITCHELL *& al.* 1996). δ^{13}C values as high as prior to the negative excursion on the rise to MCE 1a are not reached in Southerham and Wunstorf before couplets B39/B40. Thus, the negative pre-MCE 1 excursion comprises the couplets from B34 to B40. The two peaks of positive excursion MCE are associated with two important biovents known as the *arlesiensis* Bed and the *primus* Event (cf. Table 1). The MCE corresponds roughly to couplets B41–C3. The positive double spike is also recorded in Hoppenstedt (but without the earlier negative excursion). At Baddeckenstedt, however, only one spike was identified. Above the MCE, values drop again slightly but not to values as low as during the late Early Cenomanian (generally above 2.0‰ δ^{13}C). A small peak is recorded from the Mid-Cenomanian Event (*sensu* ERNST *& al.* 1983; cf. Table 1) at Southerham and Baddeckenstedt.

Oxygen stable-isotopes

The oxygen stable-isotope curves do not show any clear trends throughout the late Early or early Middle Cenomanian; δ^{18}O values range from -2.0 to -4.5‰ vs. V-PDB and show a relatively large scatter. A slight general fall and rise during the *dixoni* Zone, observed in Baddeckenstedt (WILMSEN 2003), cannot be reproduced in the other sections. There may be a vague correlation between bundles of couplets (100 kyr cycles) and

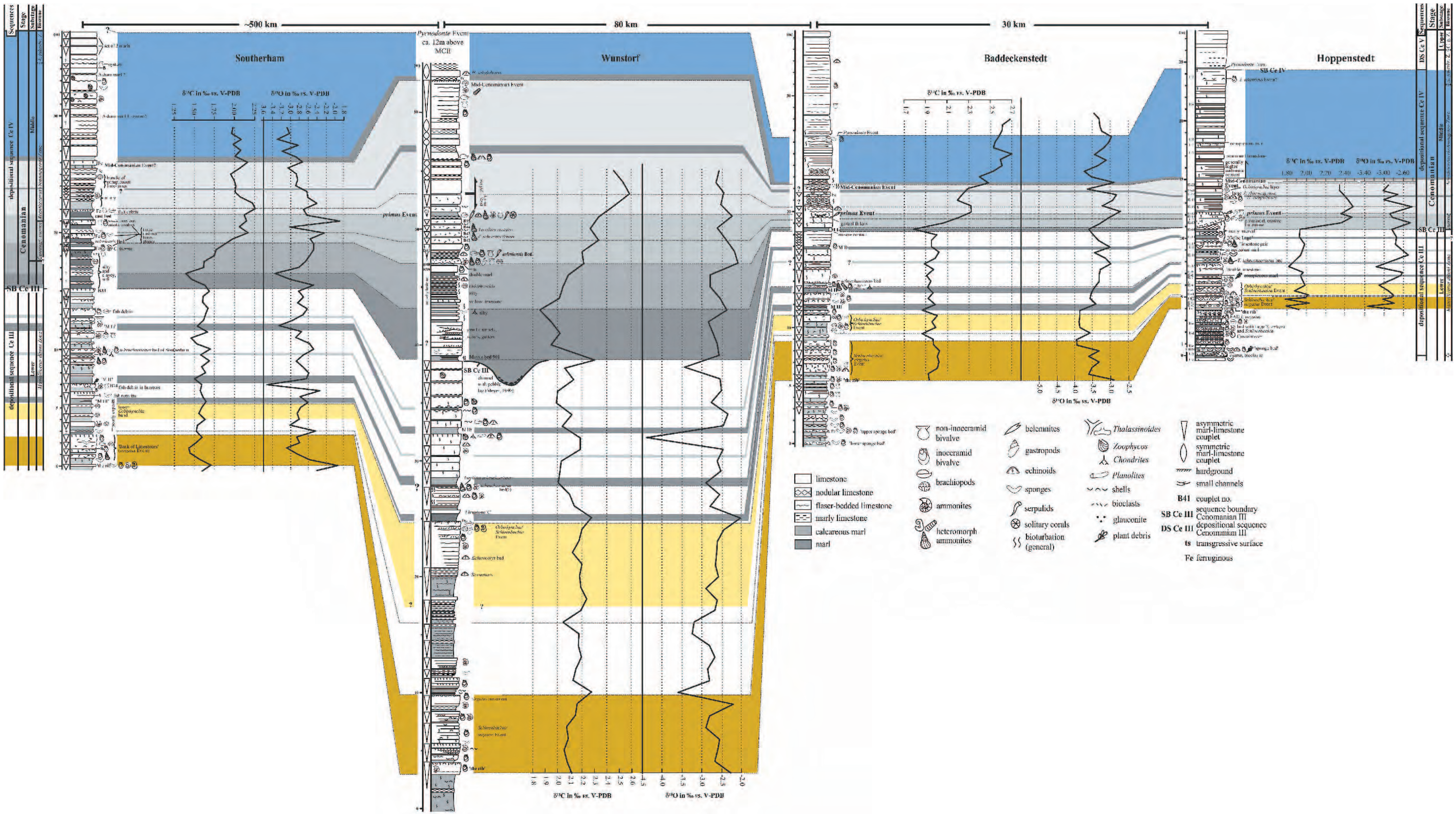


Fig. 4. Integrated stratigraphic correlation of the upper Lower (upper *Mantelliceras dixoni* Zone) and lower Middle Cenomanian (*Cunningtoniceras inerme* Zone and lower *Acanthoceras rhotomagense* Zone) in northern Germany (Hoppenstedt, Baddeckenstedt and Wunstorf) and southern England (Southerham). The *Praeactinocamax primus* Event (marl of couplet C1) is used as the datum plane. The legend applies to all figures. See text for discussion

$\delta^{18}O$ values in some cases (more negative towards the top; e.g. *Schloenbachia/virgatus* Event bundle, bundles below sequence boundary SB Ce III in Wunstorf). However, the overall correlation is very poor.

Event stratigraphy

The marker bed of "the rib" (limestone of couplet B11 of GALE 1995) appears in all four sections as a prominent limestone. It is generally thin (0.1-0.2 m), only in Wunstorf does it attain a thickness of 0.9 m. "The rib" yields the ammonite zonal index *Mantelliceras dixoni* and marks the entry of common inoceramid bivalves of the group of *Inoceramus virgatus* SCHLÜTER. The mid-*dixoni* Zone *Schloenbachia/Inoceramus virgatus* Event consists of five calcareous marl-limestone couplets rich in commonly bivalved inoceramid bivalves of the *virgatus* group (cf. WILMSEN *& al.* 2001, WILMSEN, in press). The event is represented by a bundle of five couplets that varies in thickness from nearly 7 m in Wunstorf, to slightly more than 1 m at Hoppenstedt. The succeeding *Orbirhynchia/ Schloenbachia* Event ("lower *Orbirhynchia* band") is less conspicuous, being related to an interval comprising couplets B19–B22. In Hoppenstedt, it directly overlies fossiliferous couplets of the *Schloenbachia/Inoceramus virgatus* Event, suggesting either a significant stratigraphic gap or considerable condensation (in Wunstorf, both events are separated by more than 10 m of relatively marly sediments).

The "double limestone", a conspicuous, bipartite limestone of the mid-*dixoni* Zone (comprising couplets B23–B24, Text-fig. 3A, B), can now be correlated to the proximal Hoppenstedt quarry (WILMSEN & WOOD 2004) and, with some certainty, to the 25.5-27.8 m interval at Wunstorf (Text-fig. 4). It also corresponds to two strong limestones between the 5.8 and 7 m levels at Southerham. The under- and overlying conspicuous marls correlate, in northern German terminology, to the marker marls M II and M III, respectively. The succeeding *Turrilites scheuchzerianus* bed, formerly recognized in Baddeckenstedt (BADAYE 1986; ERNST & REHFELD 1997), is related to a weak limestone following marl M II. It can now be correlated from Hoppenstedt via the type locality Baddeckenstedt to Wunstorf. However, the *T. scheuchzerianus* bed of Southerham is slightly younger, being clearly related to a prominent limestone bed of a higher couplet (Text-fig. 4).

The upper *dixoni* Zone is poor in interregional palaeontological marker beds. The only significant marker beds are conspicuous marls, the stratigraphic significance of which is discussed below. The next bioevent above the *Turrilites scheuchzerianus* bed is the "middle *Orbirhynchia* band" around couplet B39, low in the Middle Cenomanian. It is recognized only in Wunstorf and Southerham. In Baddeckenstedt and Hoppenstedt, it is missing due to a extreme condensation (in marl M Ia) or a stratigraphic gap (see carbon stable-isotopes). The first significant Middle Cenomanian bioevent is the *arlesiensis* Bed. It is marked by a conspicuous, dark marl bed in Southerham and Wunstorf yielding a fairly diverse and diagnostic invertebrate fauna (see PAUL *& al.* 1994; WILMSEN *& al.* 2007). Furthermore, it is associated with the lower peak 1a of the Middle Cenomanian carbon stable-isotope excursion MCE (PAUL *& al.* 1994; MITCHELL *& al.* 1996; Text-fig. 4). This lower peak allows correlation of the *arlesiensis* Bed to the more proximal sections of Baddeckenstedt and Hoppenstedt, where the event is represented by bioclastic inoceramid prism limestone (Text-fig. 4).

The Middle Cenomanian *Praeactinocamax primus* Event is the best-known event stratigraphical marker of the Middle Cenomanian (see ERNST *& al.* 1983; CHRISTENSEN 1990; LEHMANN 1999; WILMSEN 2003; WILMSEN & WOOD 2004; WILMSEN *& al.* 2007; WILMSEN & RABE in press). It is now also proved for Baddeckenstedt and Hoppenstedt by *in-situ* finds of the index belemnite (KRÜGER 2003; WILMSEN & RABE in press) and used as the datum plane in Text-fig. 4 due to its widespread (overlapping) character. It is associated with a small trough within mid-Cenomanian carbon stable-isotope excursion MCE 1, just below peak 1b. The last event stratigraphical marker discussed herein, the Mid-Cenomanian Event *sensu* ERNST *& al.* (1983; see Table 1), can be correlated across all four sections and is marked by iron-staining and glauconitization as well as synsedimentary lithification and reworking (WILMSEN *& al.* 2005). The beds below the terminal surface are in part relatively fossiliferous (e.g. in Wunstorf), containing, among other fossil groups, abundant specimens of the rhynchonellid brachiopod *Orbirhynchia mantelliana* ("upper *Orbirhynchia* band"). The Mid-Cenomanian Event is marked by a small positive $\delta^{13}C$ excursion (Text-fig. 4). Above this event, high-carbonate sediments were deposited in all sections (the "calcimetry break" of JARVIS *& al.* 2001).

Cyclostratigraphy

In order to refine the stratigraphic resolution, the orbitally-tuned cyclostratigraphy of GALE (1995) was applied, including the use of his couplet numbers. Detailed bed-by-bed (i.e. couplet correlation) is possible in some intervals (e.g. in the *Schloenbachia/virgatus* Event and from below the *arlesiensis* Bed to the Mid-Cenomanian Event *sensu* ERNST *& al.* 1983), and small-scale gaps (beyond the resolution of any other stratigraphic method) can be recognized (e.g. the absence of couplets B44–B45 in Southerham; PAUL *& al.* 1994). However, there are also problems in some parts of the succession, e.g. in the interval from the "double limestone" (equivalent to couplets B23–B24) up to couplet B33 of GALE (1995). It appears that there are, in fact, more marl-limestone pairs (couplets) than expected from the couplet scale of GALE (1995, nine couplets, B25–B33); 11–13 in Southerham (depending on the inclusion of weak limestones) and 11 in Wunstorf and Baddeckenstedt. Hoppenstedt shows only eight couplets but is potentially incomplete (see below). However, from B39 (a couplet characterized by a strong limestone in Southerham and Wunstorf), a detailed couplet correlation is possible up to couplet C10, the level of the Mid-Cenomanian Event *sensu* ERNST *& al.* (1983). The interval between couplets B33 and B39 [which includes the first appearance datum (FAD) of *Cunningtoniceras inerme* (PERVINQUIÈRE) and, thus, the base of the Middle Cenomanian Substage in couplet B38; PAUL *& al.* 1994] is marly and weakly cyclic in Southerham.

Good correlations can be achieved using bundles of couplets and marker marls (see also WILMSEN & NIEBUHR 2002). Most of the "classic" marker marls of the Baddeckenstedt section (M III, M II, M Ib, M 1a) have their counterparts in conspicuous marls in the other sections (Text-fig. 4). M III, M II and M Ib correlate with conspicuous, thick marls in Southerham and Wunstorf, as well as with thin, dark marls in Hoppenstedt. Marl M Ia equates with a facies change to marly sediments in Southerham, and with bed 901 of MEYER (1990) in Wunstorf, which grades laterally into a thick, erosional channel. Two additional thinner marker marls are recognized in Southerham and Wunstorf (stratigraphically between M III and M II and M Ib and M 1a, respectively; Text-fig. 4).

Bundles of five to six couplet are best developed in the thick section of Wunstorf, especially between M II and M Ib as well as M Ib and bed 901 (=M 1a). The marker marls of the *arlesiensis* Bed and the *primus* Event (marls of couplets B41 and C1) characterize the more expanded Wunstorf and Southerham sections, grading into inoceramid prism-rich limestone towards Baddeckenstedt and Hoppenstedt. They define a bundle (couplets B41–B45), which is complete only in Wunstorf. The *primus* Event and a marly to nodular bed five couplets higher up, and a marly bed above the Mid-Cenomanian Event, delimit the two succeeding bundles (couplets C1–C5 and C6–C10).

Sequence stratigraphy

The interregionally correlatable cyclicity and the high-carbonate content of the strata of the middle-late *dixoni* Zone from the *Schloenbachia/virgatus* Event to couplet B33 indicate widespread undisturbed deposition. In (hemi-)pelagic "chalk" settings, this typically occurs during maximum flooding and sea-level highstands (cf. ERNST *& al.* 1996; NIEBUHR & PROKOPH 1997; ROBASZYNSKI *& al.* 1998; WILMSEN 2003). A major change is recorded above couplet B33: the lithofacies changes to silty marl and/or bioclastic limestone in Southerham and Wunstorf, the cyclic signal is either nearly lost or couplets are very thin up to couplet B40, and extreme condensation and/or gaps occur in Baddeckenstedt and Hoppenstedt. These observations are consistent with a rapid and significant lowering of sea-level followed by lowstand deposition in distal sections and non-deposition and/or erosion in proximal sections (lack of accommodation space). Thus, a sequence boundary is placed at the top of couplet B33. It should be noted here that the inferred lowstand deposits in Wunstorf and Southerham show a conspicuous negative carbon stable-isotope excursion, the trough of which comprises couplets B34–B40 (see above).

The renewed onset of cyclic deposition in the basinal areas and the onlap of marine deposits onto the basin margins are contemporaneous with the couplet bundle starting with the *arlesiensis* Bed (couplets B41–B45) and the lower peak 1a of the positive $\delta^{13}C$ excursion MCE. Consequently, the transgressive surface after the sea-level lowstand across the Lower-Middle Cenomanian boundary is placed at the junction of couplets B40 and B41. The *primus* Event, followed by the second peak 1b of the positive $\delta^{13}C$ excursion MCE, marks a second transgressive pulse within the transgressive systems tract (TST). The Mid-Cenomanian Event *sensu* Ernst *& al.* (1983) suggests a short-lived erosional episode within the TST, indicated by evidence by of reworking and the occurrence of coarse-grained sediments. It is followed by a conspicuous increase in carbonate content in all sections, interpreted as the maximum flooding signal. It coincides with the the "calcimetry break" of Jarvis *& al.* (2001), i.e. the onset of deposition of carbonate-rich sediments. Furthermore, this level is also an important lithostratigraphic boundary, marking the base of the traditional Grey Chalk of British terminology and the base of the Brochterbeck Formation (formerly "Arme *rhotomagense*-Kalke") in northern Germany.

DISCUSSION

The integrated stratigraphic correlation presented in Text-fig. 4 enables a very high resolution calibration of upper Lower and Lower Middle Cenomanian successions from northern Germany to southern England. The easiest and most rapid approach to stratigraphic calibration is event stratigraphy. Most of the classic bioevents (cf. Ernst *& al.* 1983), such as the *Schloenbachia/virgatus* and *primus* events or the *Orbirhynchia* bands and the *arlesiensis* Bed, are easily recognized during logging due to their diagnostic fossil contents. They are isochronous within the integrated stratigraphy, with the exception of the *scheuchzerianus* bed, which is younger in Southerham (southern England) than in northern Germany. Many of the lithological event beds such as the marker marls M III, M II, M 1b and M 1a can be incorporated into a cyclo- and sequence stratigraphic framework, explaining their obvious isochrony and significance for interregional correlation (see below).

The most powerful tool for stratigraphic resolution is the couplet stratigraphy developed by Gale (1995) and Gale *& al.* (1999). The marl-limestone couplets and their stacking into bundles of four to six couplets and sets of four bundles are inferred to reflect orbital forcing of the Milankovitch frequency band (precession, short and long eccentricity, respectively). These high-frequency (6^{th}- to 4^{th}-order) cycles are superimposed on the long-term 3^{rd}-order sea-level trend. Accepting a Milankovitch control (which is, however, not yet rigorously statistically tested), cyclostratigraphy may result in a temporal resolution of 20, 100 and 400 kyr. Correlation of individual beds of marl-limestone couplets may provide a stratigraphic resolution down to ca. 10 kyr (Text-fig. 5).

The best cyclostratigraphic record comes from expanded distal sections such as Wunstorf (Text-figs 3, 4) which are potentially more complete than condensed proximal ones. Precession couplets (6^{th}-order cycles) are marly and thin in proximal settings such as Hoppenstedt and tend to disappear or to fuse with other couplets. In distal settings they are thick and limestone-dominated (e.g. Wunstorf). Marker marl beds such as M II, M Ib and M Ia as well as the *arlesiensis* Bed and the *primus* Event are most likely related to the 100 kyr short eccentricity (i.e. 5^{th}-order) cycle as they embrace bundles of ~five couplets. They are associated with small-scale sea-level change as indicated by offlap of strata below the terminal surfaces (e.g. in couplet bundle B41–B45). An estimation of the precise amount of sea-level change is difficult but it may be in the order of a few metres (see Wilmsen 2003, for a discussion). With those marker marls, a safe correlation of expanded and considerably condensed sections is possible (Text-fig. 4). Fourth-order cycle boundaries are significant erosion surfaces (e.g. the Mid-Cenomanian Event *sensu* Ernst *& al.* 1983). These reflect 400 kyr cycles of 4^{th}-order sea-level change (Wilmsen 2003). However, Gale *& al.* (2002) regarded these high-frequency sequences as depositional (i.e. 3^{rd}-order) sequences, a view not followed here.

From the correlation described above it appears that the couplet scale of Gale (1995) may be incomplete in some intervals, as there are a few more couplets in the upper *dixoni* Zone of Southerham, Wunstorf and Baddeckenstedt than proposed. This observation brings up an "old" problem: there is a very good correlation between absolute ages (derived from dating of bentonites in the Western Interior Basin) and the Middle and Late Cenomanian part of the couplet-based orbital time scale (Gale 1995, p. 195). For the Early Cenomanian, on the other hand, there are big discrepancies; the *Mantelliceras dixoni* Zone, for example, has a duration of ca. 1.6 my according to the GTS of GRADSTEIN *& al.* (2004) but contains only 38 couplets (B1–B38) equating to only ca. 800 kyr (cf. GALE 1995, based mainly on thin English successions). However, the expanded *dixoni* Zone succession of Wunstorf (more than 65 m, WILMSEN 2003, fig. 10) consists of at least 12 stacked, 4-7 m thick cycles inferred to reflect the short eccentricity signal (and the base of the zone may not even be exposed there). This underlines the inference of a considerable incompleteness of many Lower Cenomanian shallow-water succession across NW Europe (as already noted by NIEBUHR *& al.* 2001 and WILMSEN 2003) due to accommodation-controlled deposition, especially around sequence boundaries (WILMSEN 2007).

In contrast to former interpretations (ROBASZYNSKI *& al.* 1998; WILMSEN 2003), sequence boundary SB Ce III (upper *dixoni* Zone), separating Cenomanian depositional sequence 3 (DS Ce III, *dixoni* Zone) from depositional sequence 4 (DS Ce IV), is placed slightly lower at the top of couplet B33, where a significant facies change or channelling occurred in Southerham and Wunstorf (Text-figs. 3D, E, 4, 5). It is an important erosional surface in proximal settings and there it is always associated with a significant gap (Hoppenstedt). The amount of sea-level fall is difficult to estimate but it was sufficient to subaerially expose the inner and parts of the middle shelf areas (see WILMSEN 2003). Thus, a sea-level fall of 20-40 m is assumed (Text-fig. 5). Lowstand deposits in distal settings (uppermost *dixoni* to lower *inerme* Zone) consist of a few metres of non- to poorly rhythmic silty marls and marly limestones. Transgressive onlap onto the basin margins, associated with the resumption of cyclicity in the basin centre, increase in fossil content, iron and glauconite mineralization, and an increase in δ^{13}C values towards the positive early Middle Cenomanian δ^{13}C excursion MCE1, occurred from couplet B41. Thus, the transgressive surface (ts) of DS Ce IV has to be placed at the top of couplet B40 (as suggested by MITCHELL & CARR 1998 and WILMSEN 2003). This is in contrast to the interpretation of GALE (1995) and ROBASZYNSKI *& al.* (1998), who regarded the base of the *primus* Event as the transgressive surface. However, the base of the *primus* Event represents a flooding surface of a 5th-order short eccentricity cycle within the early transgressive systems tract of DS Ce IV (Text-fig. 5).

An important component of the integrated stratigraphic approach are carbon stable-isotopes. The absolute δ^{13}C values show a relatively large offset between sections. As all sections are of comparable lithology and weathering state, and all sample were processed in the same laboratory, these differences either reflect diagenetic overprint (e.g. by different maximum burial depth) or primary environmental signals (the proximal sections tend to have lighter δ^{13}C values; cf. IMMENHAUSER *& al.* 2007). However, carbon stable-isotopes are relative robust against diagenetic modifications, and, in homogenous lithologies, diagenesis will not selectively modify the curves. Thus, the trends of the curves can be used for stratigraphic correlations and reconstructions of past carbon cycle changes. It must also be emphasized that, due to the relatively coarse 0.5-1 m sample distance, the carbon stable-isotope curves may lack some details such as small scale Lower Cenomanian positive excursions as recorded by JARVIS *& al.* (2006), particularly in the reduced proximal sections. The trends and main events, however, are well displayed by the stable-isotope curves presented herein (Text-fig. 4).

Carbon stable-isotope values of the mid- and late *dixoni* Zone are constant around 2‰ vs. V-PDB, related to equilibrium conditions during maximum flooding and highstand of depositional sequence DS Ce III, with no major perturbation of the carbon cycle. The succeeding sea-level fall and lowstand (couplets B34–B40) is associated with a negative excursion of ca. 0.4‰ δ^{13}C vs. V-PDB, followed by a stepwise rise of 0.4-0.6‰ δ^{13}C vs. V-PDB during the early TST of DS Ce IV (couplets B41–C2, positive δ^{13}C excursion MCE 1a and 1b; Text-figs 4, 5). This observation supports the interpretation of a general coupling of the δ^{13}C signal and eustatic variations via preservation and erosion of C_{org}-rich shelf sediments during rises and falls of sea-level, respectively (MITCHELL *& al.* 1996; JARVIS *& al.* 2006).

The conspicuous latest Early to earliest Middle Cenomanian δ^{13}C trough (couplets B34–B40), initiated with the sequence boundary SB Ce III at the top of couplet B33 and associated with the lowstand of DS Ce IV in Southerham and Wunstorf, is missing or represented in a single marl bed in proximal settings (Baddeckenstedt, Hoppenstedt). Based on the isotope correlation with the complete sections (Wunstorf and Southerham), the gap at the Lower-Middle Cenomanian boundary at Hoppenstedt can be estimated to comprise ca. 200 kyr (couplets B31–B40). In Baddeckenstedt, this interval is condensed into marl M Ia. The presence or absence of this negative isotope event is a good indicator for the stratigraphic completeness of the Lower-Middle Cenomanian boundary interval and a new name (Lower-Middle Cenomanian boundary isotope Event, LMCE) is proposed (Text-fig. 5). Furthermore, it is a good proxy for the placement of the base of the Middle Cenomanian Substage, as the FAD of *Cunningtoniceras inerme*, the proposed biomarker, is only slightly higher (couplet B38 in Southerham; PAUL *&* *al.* 1994) than the minimum of the $\delta^{13}C$ trough (couplet B36; ca. 40 kyr, see Text-fig. 5).

The double-spiked early Middle Cenomanian positive $\delta^{13}C$ excursion (MCE 1a and 1b), associated with the *arlesiensis* Bed and the *primus* Event, is an excellent chemostratigraphic marker (cf. PAUL *&* *al.* 1994; MITCHELL *&* *al.* 1996; WILMSEN & NIEBUHR 2002; JARVIS *&* *al.* 2006). It is also present at Hoppenstedt in a calcarenitic limestone that overlies truncated *dixoni* Zone sediments unconformably (WILMSEN & WOOD 2004). At Baddeckenstedt, the double spike is either condensed into one peak or the lower one is missed due to a too wide sample spacing of 0.5 m.

In contrast, the flat carbon stable-isotope signature of the upper Lower Cenomanian does not help much in refining the stratigraphic resolution. A

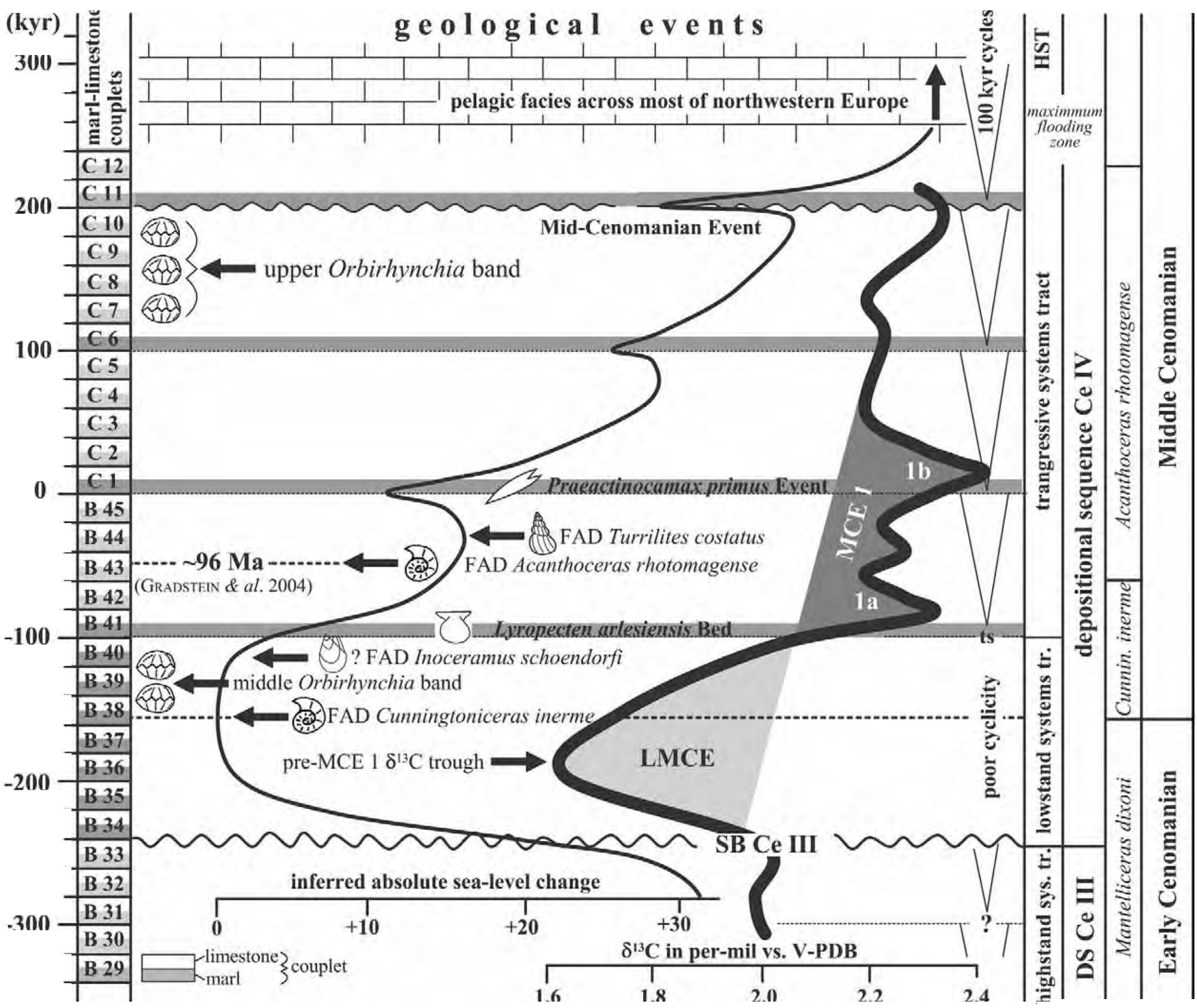


Fig. 5. Geochronological summary diagram highlighting the sequence of geological events across the Lower-Middle boundary interval in NW Europe. FAD = first appearance datum; LAD = last appearance datum; MCE = Middle Cenomanian carbon stable-isotope excursion with lower peak 1a and upper peak 1b (cf. MITCHELL *&* *al.* 1996). LMCE = Lower-Middle Cenomanian boundary negative carbon stable-isotope Event (new). *Cunnin.* = *Cunningtoniceras*; ts = transgressive surface

negative isotope event from the *Schloenbachia/virgatus* Event is reported by JARVIS *& al.* (2006; their "*Virgatus* Beds Event"). A negative excursion is seen at Southerham and Wunstorf from this level, but it is not represented in the profiles at Baddeckenstedt (where a positive excursion occurs) and Hoppenstedt (but this may be related to sample resolution). The small negative $\delta^{13}C$ excursion between the *Schloenbachia/virgatus* and the *Orbirhynchia/Schloenbachia* events is developed in all sections except Hoppenstedt (Text-fig. 4). However, it is not expressed in Lower Cenomanian isotope profiles published by JARVIS *& al.* (2006). There is another small negative $\delta^{13}C$ excursion some distance above the first *Orbirhynchia* band (*Orbirhynchia/Schloenbachia* Event) introduced by JARVIS *& al.* (2006). This "Mid-*dixoni* Event" may occur at the level of marl M II at Southerham and Wunstorf (see Text-fig 4). Furthermore, there are some minor positive excursions in marl M III, in the limestone(s) below marl M 1b and just below sequence boundary SB Ce III (the latter being cut out in Hoppenstedt) with some correlation potential (Text-fig. 4). However, all those small-amplitude $\delta^{13}C$ variations (≤0.25‰) are difficult to apply as stratigraphic markers as they may be influenced by local/regional factors, are easily missed by a too wide sample spacing, and difficult to find in strongly condensed sections (such as Hoppenstedt).

CONCLUSIONS

A very high resolution stratigraphic calibration of the upper Lower (mid-upper *Mantelliceras dixoni* Zone) and lower Middle Cenomanian (*Cunningtoniceras inerme* Zone and lower *Acanthoceras rhotomagense* Zone) of northern Germany and southern England is presented. Classic event stratigraphy shows its potential in refining biostratigraphic correlations as most of the classic bioevents such as the *Schloenbachia/virgatus, Orbirhynchia/Schloenbachia*, *Praeactinocamax primus* and Mid-Cenomanian events are easily recognized due to their fossil contents and are isochronous within the integrated stratigraphy. Many of the lithological event beds such as the German marker marls M III, M II, M 1b and M 1a can be incorporated into the cyclo- and sequence stratigraphic framework of the Cenomanian stage, demonstrating their significance for interregional correlation.

The highest stratigraphic resolution is provided by the cyclostratigraphy developed by GALE (1995). The marl-limestone couplets (precession cycle, ca. 20 kyr) and their organisation into bundles of four to six couplets (short eccentricity, ca. 100 kyr) and sets of four bundles (long eccentricity, ca. 400 kyr) are inferred to reflect orbital forcing of the Milankovitch frequency band. Detailed bed-by-bed couplet correlation is possible in some intervals, enabling the comparison of sections and the dating of geological events within 10 kyr time slices. Marker marl beds such as M II, M Ib and M Ia, as well as the *arlesiensis* Bed and the *primus* Event, which embrace bundles of ~five couplets are most likely related to the short eccentricity (100 kyr) cycle. The cyclostratigraphy allows the compilation of a detailed chronology of geological events across the Lower-Middle Cenomanian boundary into the lower Middle Cenomanian. However, for the upper Lower Cenomanian (*dixoni* Zone) it seems that the existing couplet scale is incomplete.

The sequence stratigraphic analysis shows that the investigated interval comprises the maximum flooding and highstand interval of an Early Cenomanian sequence (DS Ce III), capped by a late *dixoni* Zone sequence boundary (SB Ce III) at the top of couplet B33, followed by lowstand and transgressive deposits of sequence DS Ce IV (latest Early to Middle Cenomanian). The highstand is characterized by relatively carbonate-rich sediments and interregionally correlatable cyclicity. The latest Early to early Middle Cenomanian sea-level fall and lowstand was of relatively great magnitude and is recognized by the onset of marly-silty, poorly cyclic lowstand deposits in distal sections, and (erosional) gaps in proximal sections. It lasted ca. 140 kyr (couplets B34–B40). Coastal onlap of the succeeding transgressive systems tract started with the *arlesiensis* Bed (marl of couplet B41) and culminated in a Middle Cenomanian maximum flooding zone ("calcimetry break").

Carbon stable-isotope values are stable around 2‰ vs. V-PDB within the mid- and late *dixoni* Zone. This phenomenon is related to equilibrium conditions during maximum flooding and highstand of depositional sequence DS Ce III. There are some small-scale $\delta^{13}C$ variations (≤0.25‰), some of which have some correlation potential but peaks often cannot be reproduced between sections with confidence. However, this problem may be resolved in the future with closer sample distances.

The latest Early to earliest Middle Cenomanian sea-level fall and lowstand was accompanied by a negative $\delta^{13}C$ excursion of ca. 0.4‰ vs. V-PDB (Lower-Middle Cenomanian boundary isotope Event, LMCE, new name). The LMCE is followed by a rise of 0.4–0.6‰ $\delta^{13}C$ in couplets B41–C2 (ca. 140 kyr) during the early TST of DS Ce IV (positive Middle Cenomanian $\delta^{13}C$ excursion MCE 1). These observations support the interpretation that the $\delta^{13}C$ signal is a good proxy for (eustatic) sea-level changes (decreasing values during falling and low sea-level, increasing values especially during initial rises). The LMCE is suggested as a proxy marker for the base of the Middle Cenomanian Substage.

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