Origin and significance of Late Cretaceous bioevents: Examples from the Cenomanian

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Palaeontological events, documented by widespread beds or thin intervals of strata with either unusual ("exotic") or acmes of common faunal elements are a characteristic feature of Upper Cretaceous epicontinental shelf sediments in NW Europe. Their importance in stratigraphic calibration has early been recognized and these "bioevents" are widely used as correlation tools. Furthermore, it appears that there is a genetic link between sequence and event stratigraphy as most of the "classic" bioevents developed during specific intervals of a 3rd-order depositional sequence. Early transgressive bioevents (ETBs) are subdivided into two subtypes, i.e., the lag and migration subtype. The lag subtype corresponds to the transgressive surface and develops in response to winnowing and relative enrichment of robust biogenic hardparts. Taphonomic alteration and time-averaging are important features. The migration subtype is related to the disappearance of physical or ecological barriers that triggered faunal migrations. Despite their onlapping character, most ETBs are quasi-isochronous, and their preservation potential is usually high. Thus, they are very useful stratigraphic markers. Maximum flooding bioevents (MFBs) represent autochthonous biogenic concentrations with relatively low shell densities. They are related to habitat stability and ecospace expansion, and develop by population blooms of taxa well adapted to the special maximum flooding conditions of the wide epicontinental shelf of NW Europe (e.g., low food availability). Cenomanian MFBs of NW Europe are not time-averaged and may comprise stratigraphically more expanded intervals with gradational lower and upper boundaries. Their often wide palaeogeographic extent associated with very high chances of preservation results in an excellent inter-basinal correlation potential. Late highstand bioevents (LHBs) are local to regional shell concentrations deposited as a result of increasing winnowing of fines and reworking by storms, currents and waves during late highstands. LHBs usually consist of pauci- or even monospecific skeletal concentrations with a high degree of fragmentation. Simple shell beds related to a single (storm) event, and composite (multiple-event) shell beds are recognized. LHBs share some features of ETBs, but lack of time-averaging, are laterally restricted and have low preservation potential. Thus, their importance in interbasinal correlation is poor. The time scales of Cenomanian bioevents range through several orders of magnitude (hours–days in LHB storm event concentrations to ~100 kyr in MFBs). In terms of position within sequences, the three bioevent types correspond to shell concentrations recognized in Mesozoic–Cenozoic formations around the world. Shell beds with similar positions within cycles as well as comparable sedimentologic and taphonomic characteristics have also been described from high-frequency sequences and parasequences, suggesting that the formational processes of shell beds operate in base-level controlled sedimentary cycles of different hierarchies (i.e., 3rd-up to 7th-order).

Key words: Palaeontological events, correlation, sequence stratigraphy, Cretaceous, Europe.

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Introduction

Palaeontological events, documented by widespread beds or thin intervals of strata that are characterized by either uncommon ("exotic") fossils or acmes of normally common faunal elements are a characteristic feature of Upper Cretaceous epicontinental shelf sediments of NW Europe (cf. Ernst et al. 1983, 1996; Dahmer and Ernst 1986; Kauffman and Hart 1995; Lehmann 1999; Wiese et al. 2004; Wilmsen 2003; Wilmsen and Voigt 2006; Wilmsen et al. 2007, 2010a; Wilmsen 2008; Wiese et al. 2009). They comprise short- to intermediate-term (days to ~100 kyr) evolutionary, ecologic and/or biogeographic responses of organisms to rapid environmental changes and may occur at local, regional and global scale (Kauffman and Hart 1995). Their importance for stratigraphic calibration was early recognized (e.g., Bower and Farmery 1910) and these so-called "bioevents" are widely used as high-resolution event stratigraphical correlation tools (e.g., Ernst et al. 1983, 1996; Wiese and Wilmsen 1999; Amédro and Robaszynski 2001a, b). However, only a few detailed

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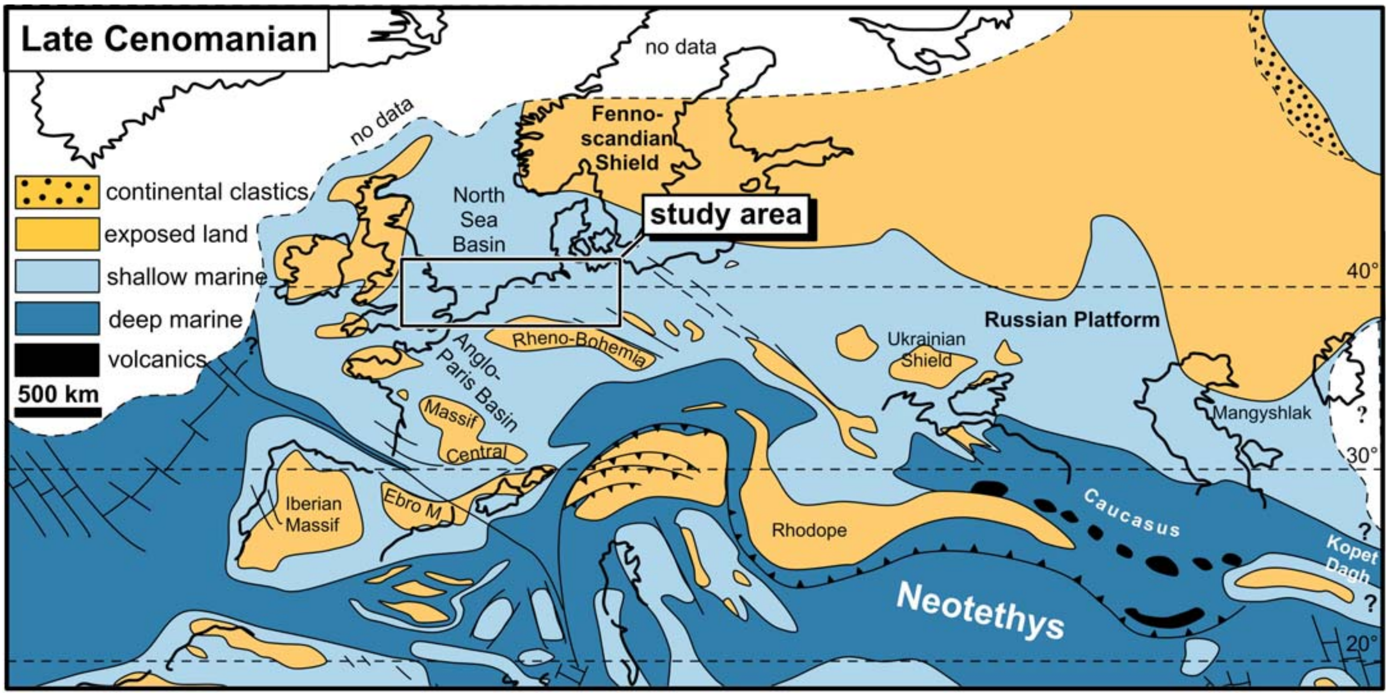

Fig. 1. Palaeogeography of the study area on the NW European epicontinental shelf (map modified after Philip and Floquet 2000).

studies on individual bioevents exist and the conceptual modes of bioevent formation often remained elusive because their correlation potential was the focus of interest (strictly speaking, an event is a process and cannot be a bed, it just produces a bed; thus, the term bioevent as a synonym for a bed produced by a palaeontological event is slightly misleading but it will be used in the following because it is deeply entrenched in the literature).

During an integrated sedimentological and sequence stratigraphical study of Cenomanian successions across northern Germany and into the Anglo-Paris Basin (Wilmsen 2003, 2007; Wilmsen et al. 2005) it appeared that most of the "classic" bioevents recognized in earlier stratigraphical studies occurred during specific intervals of the formation of depositional (i.e., 3^{rd}-order) sequences and, thus, they may be interpreted in a sequence stratigraphical context. The aim of the present paper is to demonstrate the genetic link between eustatic sea-level changes and bioevent formation, to compare Cenomanian bioevents with shell concentrations from Mesozoic–Cenozoic successions as reported in the literature, and to provide a generalized conceptual model for Upper Cretaceous bioevent formation.

Institutional abbreviations.—MMG, Museum für Mineralogie und Geologie Dresden; NK, Niedersachsen-Kreide; NWK, Nordrheinwestfalen-Kreide.

Other abbreviations.—ETB, early transgressive bioevent; LHB, late highstand bioevents; MFB, maximum flooding bioevent; FSST, falling stage systems tract; HST, highstand systems tract; and LST, lowstand systems tract

Geological setting of the Cenomanian in NW Europe

Marine Cenomanian sediments are widely distributed in NW Europe due to the transgressive onlap during the course of the stage (e.g., Wilmsen 2003; Wilmsen et al. 2010b). Deposition took place in a wide epicontinental shelf sea covering most of NW Europe at palaeo-latitudes around 40°N (Fig. 1). The predominant lithologies are glauconitic sandstone ("greensands") and (silty) marl, fossiliferous marl-limestone alternations, and calcareous nannofossil limestone, broadly reflecting the proximal-distal arrangement of inner, mid- and outer shelf facies belts. Related to the strong transgressive onlap, Cenomanian successions typically consist of inner shelf glauconitic sandstone and silty marl overlain by mid-shelf marl-limestone alternations and outer shelf calcareous mudstone (see Wilmsen et al. 2005, for a synopsis). The gradients of the depositional profiles were very low (mostly less than 0.1°), and water depth ranged from above fair-weather wave-base in nearshore to at most 100 m to (at maximum) 200 m in outer shelf settings (Wilmsen 2003). Inner shelf water masses were unstable (well mixed), turbid, and eutrophic, whereas more stable, meso- to oligotrophic mid and outer shelf water masses showed a seasonal thermal stratification (Wilmsen et al. 2005). Mid- and outer shelf deposition was governed by vertical accretion of fines, predominantly pelagic carbonate particles ("planktonic rain") with subordinate contribution of terrigenous silt and clay (mid-shelf marl-limestone alternations). Deposition was orbitally forced, with a predominance of the 20 kyr precession signal (marl-limestone couplets), often grouped into bundles

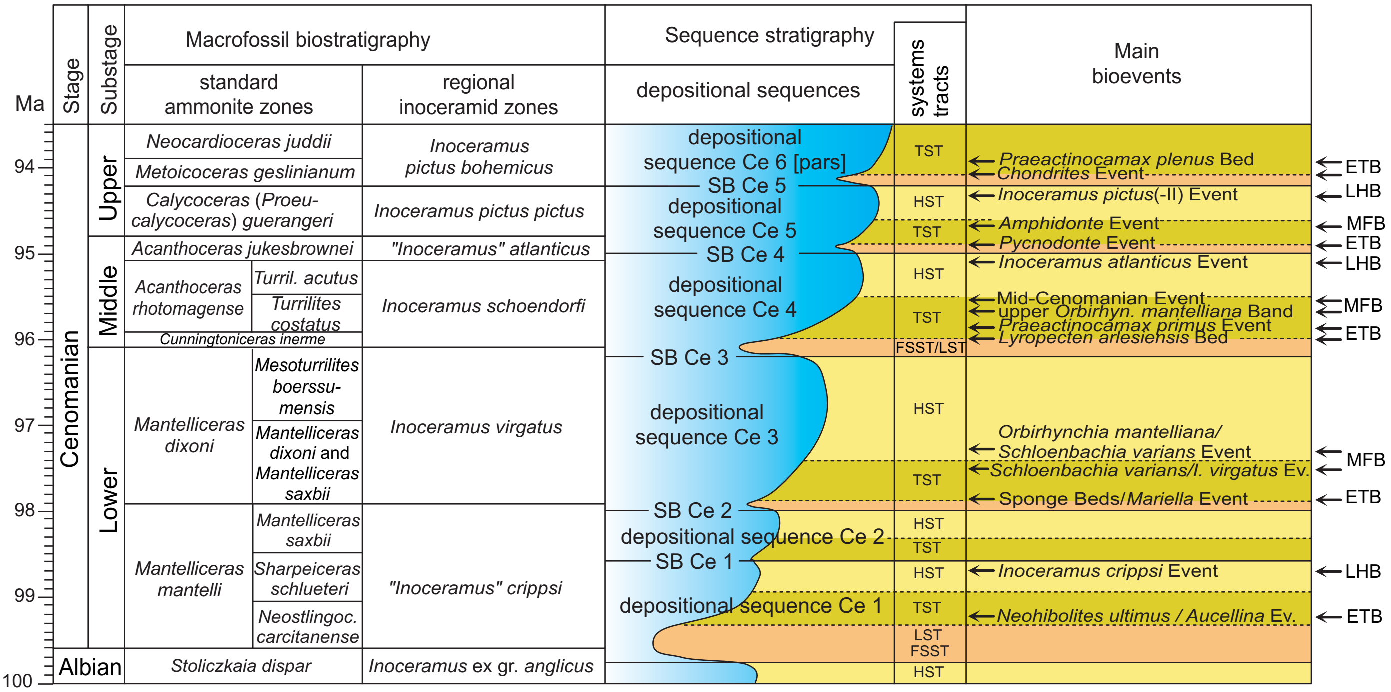

Fig. 2. Synoptic bio-, event and sequence stratigraphy of the Cenomanian stage in NW Europe. Absolute ages after Gradstein et al. (2004). Abbreviations: ETB, early transgressive bioevent; FSST, falling stage systems tract; HST, highstand systems tract; LHB, late highstand bioevent; LST, lowstand systems tract; MFB, maximum flooding bioevent; SB, sequence boundary; TST, transgressive systems tract. The coloured fields differentiate systems tracts.

of four to six couplets (100 kyr short eccentricity) and sets of four bundles (400 kyr, long eccentricity (Gale 1990, 1995; Gale et al. 1999; Wilmsen and Niebuhr 2002; Wilmsen 2003, 2007). 3rd-order sea-level changes are well documented, indicating five retrogradationally stacked depositional sequences and the lower part of a sixth sequence ranging into the Turonian (DS Ce 1–6; see Fig. 1; Robaszynski et al. 1998; Wilmsen 2003). The high resolution macrofossil biostratigraphy is based on ammonites and inoceramid bivalves, fine tuned by numerous stratigraphic event beds. A synoptic representation of all stratigraphic data is provided in Fig. 2.

Cenomanian bioevents and sequence stratigraphy

When plotted against the sequence stratigraphic subdivision of the stage (Fig. 2), nearly all important Cenomanian bioevents obviously formed during specific intervals of 3rd-order depositional sequences and may thus be interpreted in a sequence stratigraphical context (Fig. 3). According to their preferential sequence stratigraphical position, early transgressive, maximum flooding, and late highstand bioevents are distinguished (cf. Wilmsen 2003). During Cenomanian falling stage and lowstand intervals, no correlatable bioevents have been recorded.

Early transgressive bioevents (ETB).—Early transgressive bioevents ("onlapping bioevents" sensu Ernst et al. 1996) are confined to the transgressive surface or lower parts of the transgressive systems tract. The formation of these marker beds is related to two general, fundamentally different processes, (i) the accumulation and relative enrichment of robust biogenic hard parts due to winnowing of fines during initial transgression (as transgressive lags) and (ii) the disappearance of physical or ecological barriers (opening of marine connections, incursion of water masses of "unusual" phy-

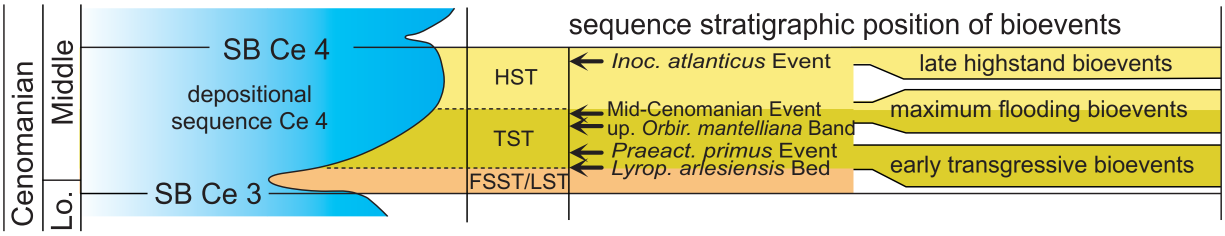

Fig. 3. Principal positions of Cenomanian bioevents in a 3rd-order depositional sequence exemplified by depositional sequence (DS) Ce 4. Abbreviations: FSST, falling stage systems tract; HST, highstand systems tract; Lo., Lower; LST, lowstand systems tract; SB, sequence boundary; TST, transgressive systems tract. The coloured fields differentiate systems tracts.

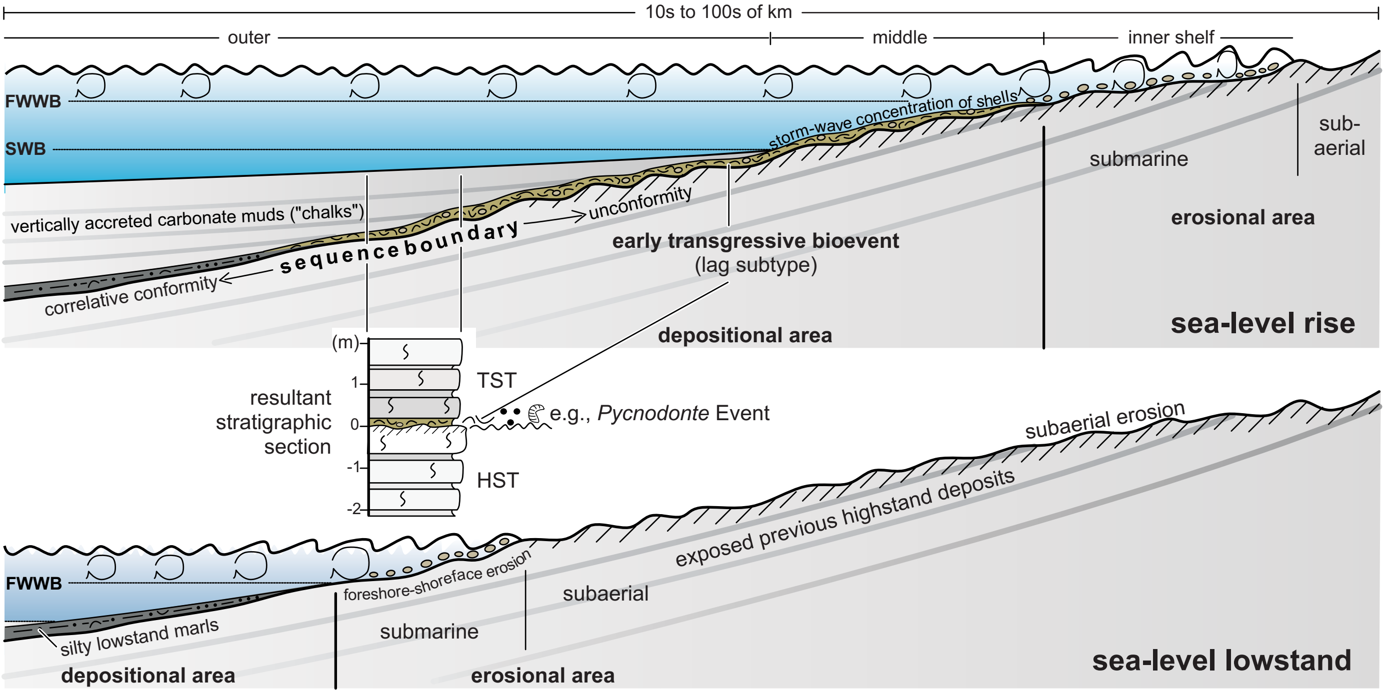

Fig. 4. Sketch (strongly vertically exaggerated) explaining the formation of early transgressive bioevents of the lag subtype with resultant stratigraphic section in Cenomanian epicontinental shelf settings of NW Europe. Abbreviations: FWWB, fair-weather wave-base; HST, highstand systems tract; SWB, storm wave-base; TST, transgressive systems tract. For key of symbols see Fig. 9.

sico-chemical properties such as salinity, temperature and associated ”exotic” faunal elements). The late Middle Cenomanian *Pycnodonte* Event is a good example of the former type (see Wilmsen and Voigt 2006 for full details), the *Praeactinocamax primus* and *P. plenus* (belemnite) events represents the latter type (e.g., Wiese et al. 2009; Wilmsen et al. 2010a). The above-mentioned ETBs will be briefly described in some more detail below.

The *Pycnodonte* Event of the upper Middle Cenomanian *Acanthoceras jukesbrownei* Zone (Ernst et al. 1983) represents a concentration of the small oyster *P.* (*Phygraea*) *vesicularis vesiculosa* at the base of the transgressive systems tract of Cenomanian depositional sequence 5 (Robaszynski et al. 1998; Wilmsen 2003). It usually occurs in a marl band that thins from 30 centimetres in proximal sections such as Zilly to just a few centimetres in distal sections such as Misburg near Hannover (Wilmsen and Voigt 2006). The oyster shells show considerable abrasion and sorting of size and shapes (mainly left valves of similar size are present) as well as the presence of borings and epibionts such as encrusting serpulids. The matrix of the shell bed is a dark, slightly glauconitic, clayey-silty to fine sandy bioclastic marl with plant remains which rests on an erosion surface (Wilmsen and Voigt 2006). All these observations suggest physical reworking by storm waves in a relatively shallow-marine, eutrophic environment as the major process of event bed formation (concentration of shells; Fig. 4). Species diversity of the event bed is low (environmental instability) and the presence of authigenic matrix glauconite and epibionts suggests that low accumulation rates prevailed during event bed formation (winnowing of fines). The *Pycnodonte* Event is thus not an instantaneous event but comprises an unknown, but geologically relatively short-term interval of time. The bed can be correlated from northern Germany into the Anglo-Paris and Cleveland basins (Wilmsen and Niebuhr 2002) and was first identified in the Chalk of eastern England by Bower and Farmery (1910) as the “*Gryphaea* Band”.

The *Praeactinocamax primus* and *P. plenus* events represent geologically medium-term (tens of thousands of years) migration events of belemnite species’ with more extended

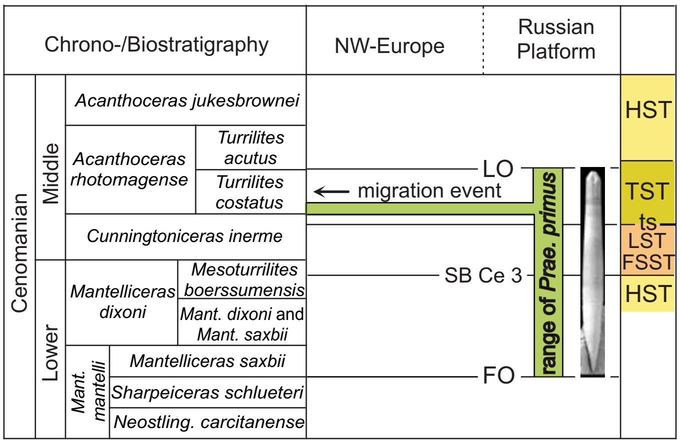

Fig. 5. Stratigraphic framework and lateral extent of the *Praeactinocamax primus* Event as an example of an early transgressive bioevent of the migration subtype. Abbreviations: FO, first occurrence; FSST, falling stage systems tract; HST, highstand systems tract; LO, last occurrence; LST, lowstand systems tract; SB, sequence boundary; ts, transgressive surface; TST, transgressive systems tract; *Mant.*, *Mantelliceras*; *Neostling.*, *Neostlingoceras*. The coloured fields differentiate systems tracts.

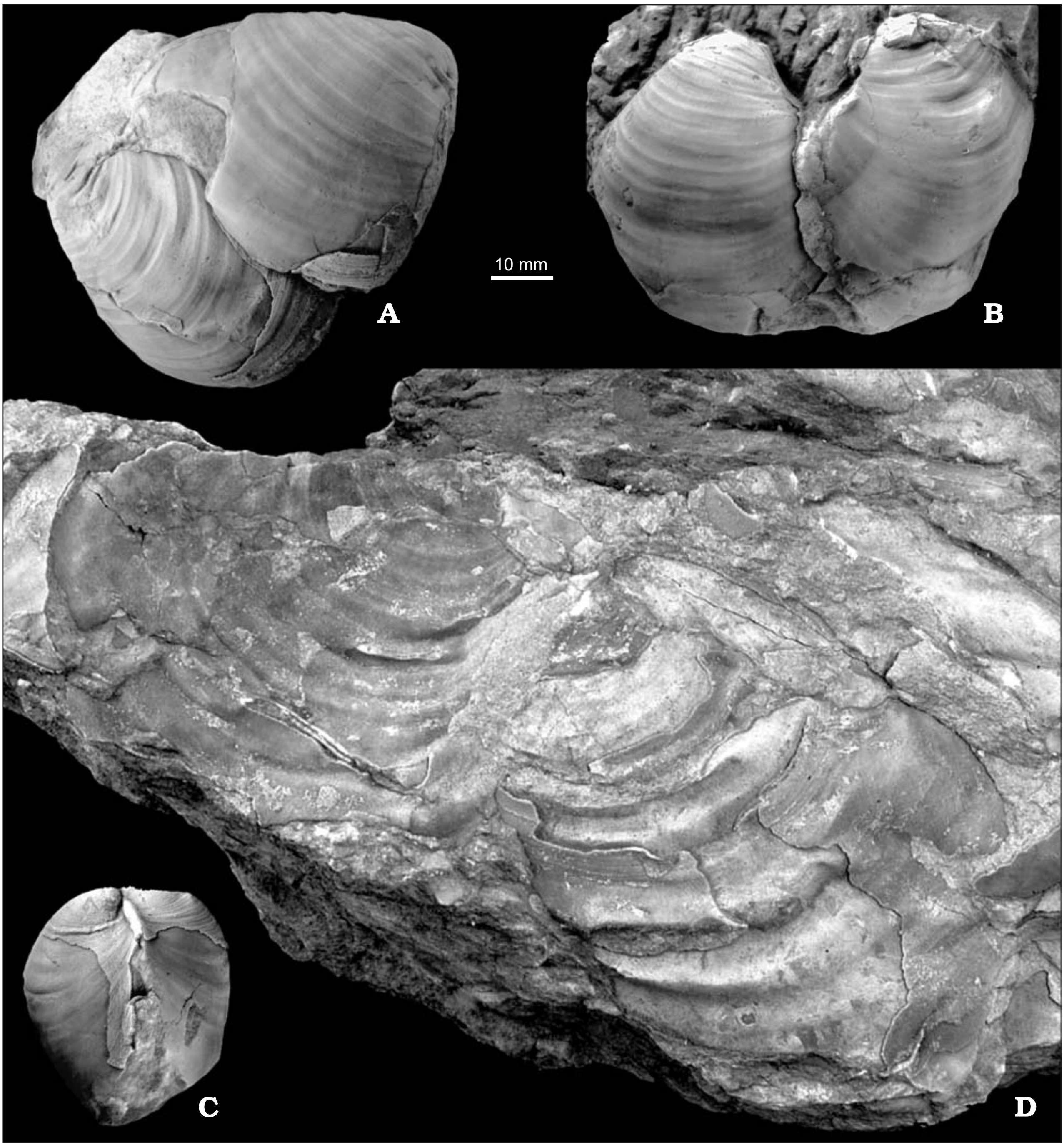

Fig. 6. Inoceramid bivalves from maximum flooding (**A**–**C**) and late highstand bioevents (**D**). All specimens are in the collection of the Senckenberg Naturhistorische Sammlungen Dresden (MMG) and illustrated in natural size. **A**–**C**. Specimens of *Inoceramus* ex gr. *virgatus* Schlüter, 1877 from the Early Cenomanian *Schloenbachia*/*Inoceramus virgatus* Event. Note the excellent preservation (**A**) as well as butterfly (**B**) and bivalved (**C**) specimens (repository NK). **D**. Slab of the Early Cenomanian "*Inoceramus*" *crippsi* Event (repository NWK) from the Ascheloh quarry (near Halle/Westfalen, northern Germany) as an example of an amalgamated (multiple-event) late highstand bioevent (cf. Fig. 8). Note shelly bioclastic fabric and convex-up position of shells.

stratigraphic ranges in their "homegrounds" (i.e., the Russian Platform; Fig. 5; see Christensen 1997 and Košťák 2004 for details). Such migration events appear to occur not during the initial transgressive development (i.e., associated with the transgressive surface) but during succeeding flooding events within the early transgressive systems tract: both, the *P. primus* and *P. plenus* events, happened ca. 100 kyr after the beginning of the onlap of depositional sequences Cenomanian 4 and 6, respectively (Wilmsen et al. 2007, 2010a). Based on their stratigraphic position, physical reworking and taphonomic alteration is not as important as in the lag bioevents, and species diversity may be high due to favourable environmental conditions (see Wilmsen et al. 2007 for a detailed account and palaeoecological interpretation of the *P. primus*

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Event fauna from the type locality in Wunstorf, northern Germany).

Further examples of ETBs are the Early Cenomanian *Neohibolites ultimus*/*Aucellina* Event of depositional sequence Cenomanian 1 (DS Ce 1; Niebuhr et al. 2001), the Sponge Bed and *Mariella* events of DS Ce 3 (Ernst and Rehfeld 1997) and the Late Cenomanian *Chondrites* Event (DS Ce 6). The preservation potential of ETBs is high according to their position at the bases of onlap cycles.

Maximum flooding bioevents (MFB).—Maximum flooding bioevents are rather rare in the Cenomanian of northern Germany. The scarcity of bioevents around the maximum flooding of depositional sequences is related to the fact that, during this interval, a sedimentary system fed mainly by pelagic carbonate "rain" will be characterized by continuous accumulation of carbonate mud; sedimentologic and taphonomic processes such as winnowing and condensation, usually responsible for the development of shell beds (cf. Kidwell 1991; Fürsich and Oschmann 1993; Fürsich 1995), are largely excluded. This also explains why maximum flooding surfaces are difficult to detect in pelagic carbonate systems and the interval of maximum flooding (the maximum flooding zone) is commonly represented by a succession of inconspicuous ("normal") chalks (e.g., Ernst et al. 1996). Only migration events, or blooms of specialist taxa adapted to maximum flooding conditions characterized by low-energy and probably more mesotrophic to oligotrophic conditions with low food supplies for benthic faunas, are to be expected. The resultant event beds are usually more poorly defined and thicker than in the case of early transgressive and late highstand bioevents (see below) and may comprise an interval ranging from late transgressive to early highstand conditions of a depositional sequence (the "maximum flooding zone" of Wiese and Wilmsen 1999). However, due to their development during maximum flooding, they are often very widespread and their preservation potential should be high. The *Schloenbachia*/*Inoceramus virgatus* Event of the late Early Cenomanian *Mantelliceras dixoni* Zone (DS Ce 3) may be a good example for this type of bioevent (see Wilmsen et al. 2001 and Wilmsen 2008 for full details). The commonly bivalved or butterfly preservation (Fig. 6A–C) of the inferred very efficient filter-feeding inoceramid bivalves and rare fragmentation suggest low-energy conditions, absence of post-mortem transport, and lack of time-averaging (cyclostratigraphic considerations; Wilmsen 2008). The event formed a low-density, autochthonous skeletal concentration of 1–8 m thickness with poorly defined lower and upper boundaries. The accompanying fauna is of moderate diversity, which is attributed to the low food supply for the benthos during more meso-/oligotrophic maximum flooding conditions (Wilmsen 2008).

A further example of a Cenomanian maximum flooding bioevent is the stratigraphically superimposed *Orbirhynchia*/*Schloenbachia* Event (likewise DS Ce 3). Brachiopods are, similar to epifaunal filibranchs such as the inoceramids, efficient filter-feeders under unfavourable low-nutrient conditions, and in this case superior to other bivalves (Tomasovych 2006). In the event bed, brachiopods of the genus *Orbirhynchia* form low-density skeletal concentrations in a stratigraphic interval of 1–3 m with diffuse lower and upper boundaries. The event correlates with the "lower *Orbirhynchia* Band" of England (Jeans 1980). The lower Middle Cenomanian "upper *Orbirhynchia* Band" (Jeans 1980) is associated with the post-*P. primus* Event succession in the later part of the transgressive systems tract of DS Ce 4. It forms a low-density, near-monospecific skeletal concentration that markedly is in contrast to the high-diversity *P. primus* Event fauna (cf. Wilmsen et al. 2007). It is very well developed in England (e.g., Mortimore et al. 2001) and a similar mode of formation as for the *Orbirhynchia*/*Schloenbachia* Event is assumed. The Mid-Cenomanian Event (MCE, Ernst et al. 1983, capping the "upper *Orbirhynchia* Band") and the Upper Cenomanian *Amphidonte* Event (Ernst et al. 1983) are also shown as maximum flooding bioevents herein (Fig. 2) due to their position at, or close to, the maximum floodings of DS Ce 4 and 5. However, the taphonomic attributes of the former (glauconitization, reworking) and the similarity of the latter with the *Pycnodonte* Event cast some doubt on this interpretation. A potential explanation for these contradictory observations is the fact that Cenomanian depositional (i.e., 3rd-order) sequences are composed of stacked high-frequency sequences (400 kyr cycles of the long-eccentricity Milankovitch periodicity; Wilmsen 2003), and both event beds occur at the base of such cycles. It may thus be that both events in fact represent early transgressive lag bioevents developing in response to a high-frequency cyclicity (see discussion below). For the Mid-Cenomanian Event this interpretation is supported by the detection of the maximum flooding surface of DS Ce 4 in the so-called p/b-Break (Carter and Hart 1977) or the "calcimetry-break" (Jarvis et al. 2001) a short distance above the MCE.

Late highstand bioevents (LHB).—Late highstand bioevents are shell concentrations deposited as a result of winnowing of fines and reworking by storm activity, currents, and waves. They are often associated with relatively coarse-bioclastic and carbonate-rich sediments deposited during decreasing accommodation rates of late highstands of 3rd- (and 4th-order high-frequency) sequences, prior to increased input of terrigenous material during falling stage and lowstand systems tracts into the basin or the development of stratigraphic gaps at the basin margins. Late highstand bioevents usually consist of skeletal concentrations with a high degree of fragmentation and convex-up orientation of shells (Fig. 6D). They are usually pauci- or even monospecific and share some features of early transgressive lag bioevents (see above). However, authigenic minerals such as glauconite as well as bored and encrusted shells are less common, suggesting limited time-averaging. Furthermore, LHBs are laterally more restricted than ETBs because their accumulation is controlled by local to regional processes (such as storm

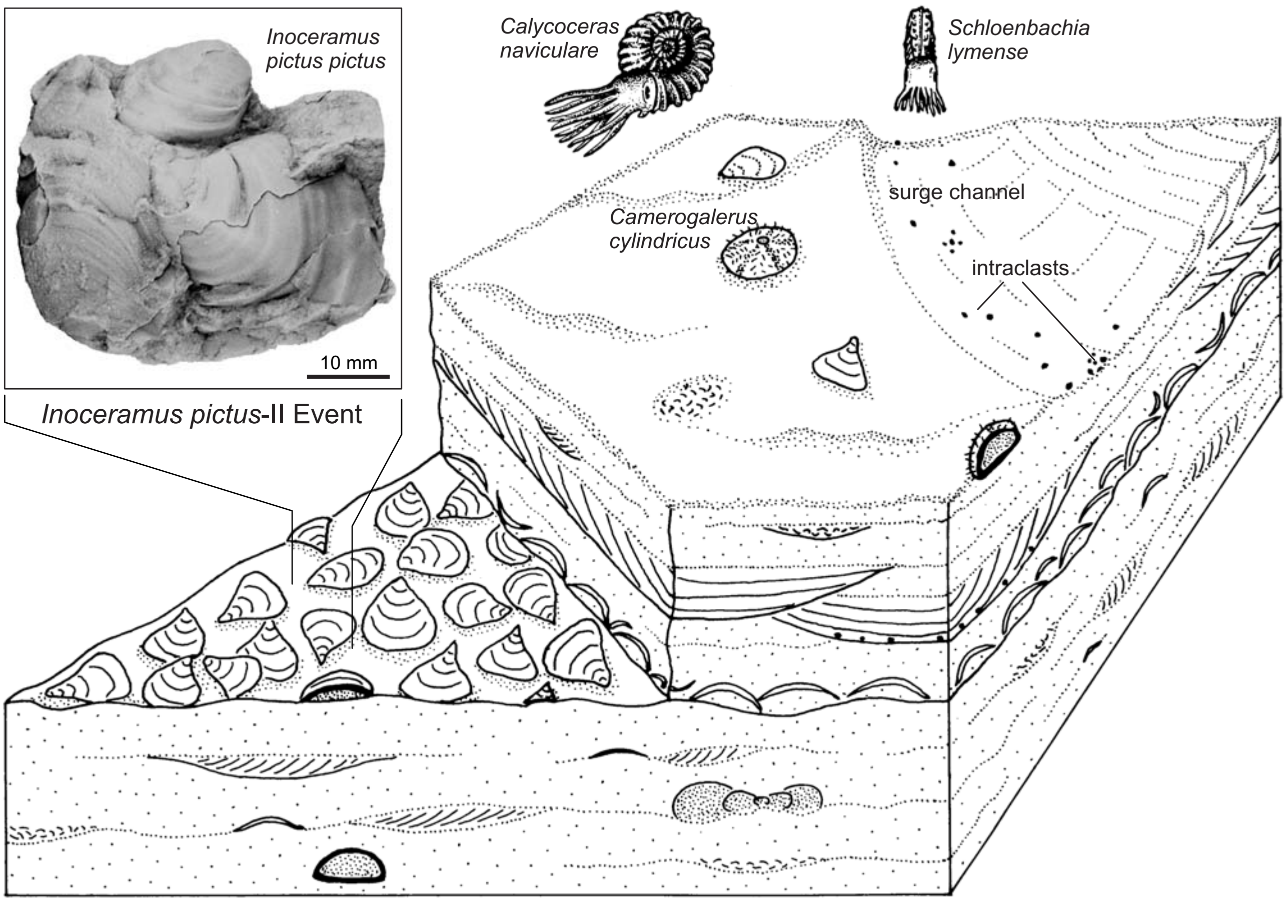


Fig. 7. Palaeoecologic reconstruction of the Late Cenomanian *Inoceramus pictus*-II Event as an example for a single-event late highstand bioevent based on analysis of the Wunstorf section (northern Germany, Hannover area).

flows, winnowing related to topography, etc.). Moreover, their preservation potential is not as high as in ETB and MFB because of frequent reworking and erosion at the succeeding sequence boundary. Thus, their importance in interbasinal correlation is rather poor.

Two subtypes of LHBs may be distinguished: (i) simple shell beds consisting of a relatively thin concentration of shells, and (i) amalgamated shell beds which comprise thicker units characterized by a more-or-less densely packed, bioclastic shelly fabric, often capped by a terminal sequence boundary. Examples of the latter subtype of LHBs are the early Early Cenomanian "*Inoceramus*" *crippsi* Event and the Middle Cenomanian "*I.*" *atlanticus* Event (late highstands of Cenomanian 3rd-order depositional sequences DS Ce 1 and 4), whereas the Late Cenomanian *Inoceramus pictus* events (DS Ce 5) represent the former (Figs. 7, 8).

The *I. pictus* events are documented by up to three thin inoceramid shell beds with inferred correlation from the Münsterland to the Lower Saxony subbasins of northern Germany (Ernst et al. 1983; Kaplan and Best 1985; however, only one, the inferred middle layer has been recorded in Lower Saxony; Wilmsen 2003). The *I. pictus*-II Event has been studied in detail at the Wunstorf section (Fig. 7). It is represented by a thin, monospecific shell bed of densely

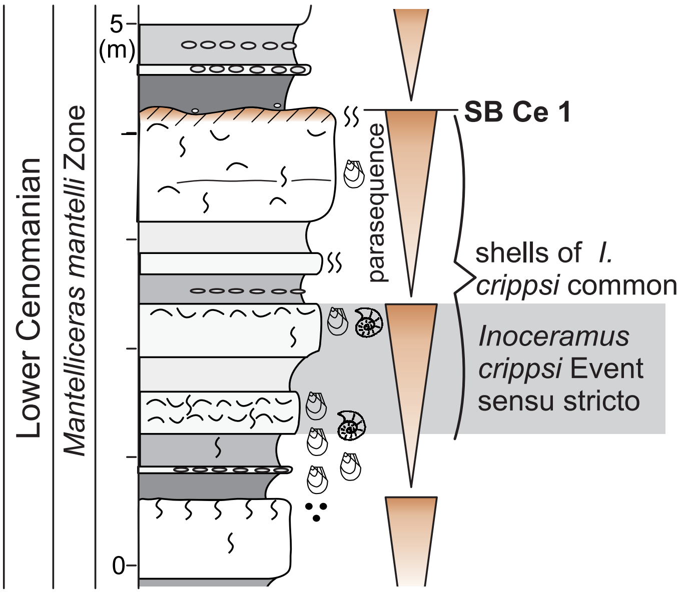


Fig. 8. Stratigraphic log of the Early Cenomanian "*Inoceramus*" *crippsi* Event in the Ascheloh quarry (near Halle/Westfalen, northern Germany) as an example for a composite late highstand bioevent (modified after Richardt 2010). SB Ce 1, sequence boundary Cenomanian 1. For key of symbols see Fig. 9.

packed inoceramid valves in convex-up position. It probably results from the backflow of a major storm event transporting numerous shells into this distal setting, thus representing a tempestite and being of very short-term duration (hours to days). Support for this interpretation is the presence of small (dm-scale) surge channels with intraclast lags and hummocky cross-bedding in strata above the event, below the terminal sequence boundary SB Ce 5 (Fig. 6; Wilmsen 2003).

The "*I.*" *crippsi* Event has been studied in some detail by Wilmsen (2003) and recently by Richardt (2010). It consists of an interval of strata up to a few metres in thickness below sequence boundary SB Ce 1 (Fig. 8). The nearly monospecific inoceramid shells are loosely to densely packed, disarticulated, often fragmented and/or in stable convex-up position (Figs. 6D, 8), suggesting amalgamation by multiple reworking phases (storm waves?). However, the absence of authigenic glauconite and lack of significant taphonomic alteration (boring, encrusting) argues against significant time-averaging.

It appears that fossils are also concentrated towards the tops of some 4th- and 5th-order (long- and short-eccentricity) cycles in the Cenomanian of NW Europe (cf. Wilmsen 2003): loosely packed shells tend to occur in relatively coarse host rock towards such cycle tops. This suggests that the processes inferred to control the development of late highstand bioevents (storm winnowing and reworking, amalgamation) may also operate in higher frequency cycles (see also Banerjee and Kidwell 1991; Kondo et al. 1998; Archuby 2009; Archuby et al. 2011).

Discussion

Shell beds and shell concentrations have been widely recognized as valuable tools in basin analysis and sequence stratigraphic interpretation, and they have been used in Mesozoic–Cenozoic successions around the world (e.g., Banerjee and Kidwell 1991; Kidwell 1991; Fürsich and Oschmann 1993; Fürsich 1995; Abbott 1997, 1998; Kondo et al. 1998; Fürsich and Pandey 1999, 2003; Wilmsen 2003; Cantalamessaa et al. 2005; Parras and Casadio 2005; Fürsich et al. 2009; Archuby and Fürsich 2010; Archuby et al. 2011). Upper Cretaceous bioevents are well known for their facies-breaking correlation potential and the possibility to calibrate biostratigraphic schemes of widely separated regions (e.g., the Cenomanian belemnite events; Mitchell 2005). However, the modes of bioevent formation as well as their relationship to sequence stratigraphy and shell concentrations from other (Mesozoic–Cenozoic) ages have not yet been discussed in full detail.

Three main types of bioevents are recognized within a conventional 3rd-order depositional sequence (Fig. 9), termed "early transgressive" (ETB), "maximum flooding" (MFB) and "late highstand bioevents" (LHB). In terms of position within 3rd-order sequences (i.e., early transgressive systems tract [TST], maximum flooding zone [MFZ], late highstand systems tract [HST]), these bioevent types correspond to shell concentrations recognized by Kidwell (1991) in siliciclastic sequences and by Fürsich and Pandey (1999, 2003) in Upper Jurassic–Cretaceous sedimentary cycles of Kachchh and the Cauvery Basin, India. At a higher frequency (i.e., high-frequency to parasequence) scale, a similar subdivision of molluscan shell beds was presented by Banerjee and Kidwell (1991) for the Lower Cretaceous Mannville Group of the Alberta Foreland Basin, Canada, and by Kondo et al. (1998) for late Neogene cycles of Japan and New Zealand. Abbott (1997, 1998) described onlap and midcycle shell beds from the mid-Pleistocene of New Zealand. Banerjee and Kidwell (1991) recognized hydraulic, event-concentrated "base of parasequence shell beds", laterally extensive hiatal "mid-sequence shell beds" (hiatal concentrations of dispersed shells), and thick, amalgamated "top of parasequence shell beds", representing composite, multiple event concentrations of local shells, capped by flooding surfaces. This suggest that the formational processes of shell beds operate in base-level controlled sedimentary cycles of different hierarchies (i.e., 3rd- to 7th-order; cf. Fig. 9).

Early transgressive bioevents (ETB) are subdivided into two subtypes, i.e., the lag and migration subtypes. The lag subtype is associated with reduced accumulation rates (winnowing, authigenic glauconite and associated minerals such as phosphate granules which are common in the Early Cenomanian *Neohibolites ultimus*/*Aucellina* Event), relative enrichment of robust hard-parts, and their taphonomic alteration by abrasion, sorting, boring, and encrustation. The Late Cenomanian *Pycnodonte* Event is a classic example (see Wilmsen and Voigt 2006). Time-averaging and condensation (Fürsich and Aberhan 1990) may thus be important processes in this subtype of bioevent.

The migration subtype is related to the disappearance of physical or ecological barriers. Physical barriers are removed by flooding of landmasses and opening of marine connections in the course of transgression. Ecological barriers break down due to the incursion of water masses of "unusual" physico-chemical properties such as salinity and temperature which enable or facilitate the migration of associated "exotic" faunal elements ("pulse faunas" of Jeans 1980). The Late Cenomanian "*plenus* cold event" of Gale and Christensen (1996) is a good example for this subtype as the belemnite migration is inferred to have occurred during a short-term cooling of NW European shelf water masses. The migration of the belemnite *Neohibolites ultimus* to northern Cantabria during the early Middle Cenomanian transgression of DS Ce 4 was associated with the opening of a marine connection and a warm-water incursion (Wilmsen 1999). The migration subtype of ETBs is a diversification bioevent by immigration sensu Kauffman and Hart (1995) or an incursion epibole sensu Brett and Baird (1997). In the shell bed classification of Fürsich and Oschmann (1993), the lag subtype of ETBs is a transgressive lag formed by storm wave and current concentration. In 3rd-order sequences, they match the onlap shell bed of Kidwell (1991) and the base of TST shell beds of Fürsich and Pandey (2003). In high-fre-

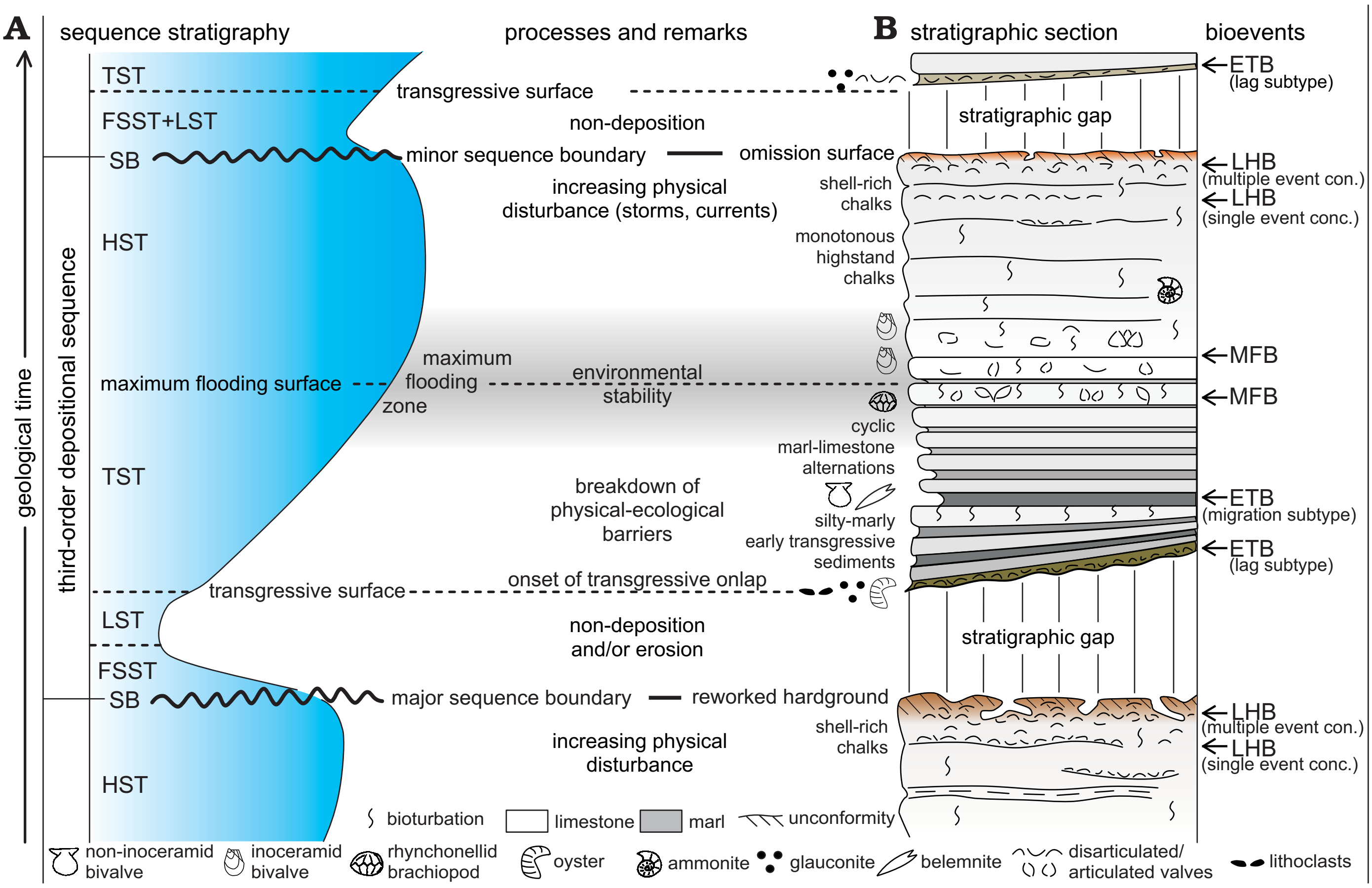
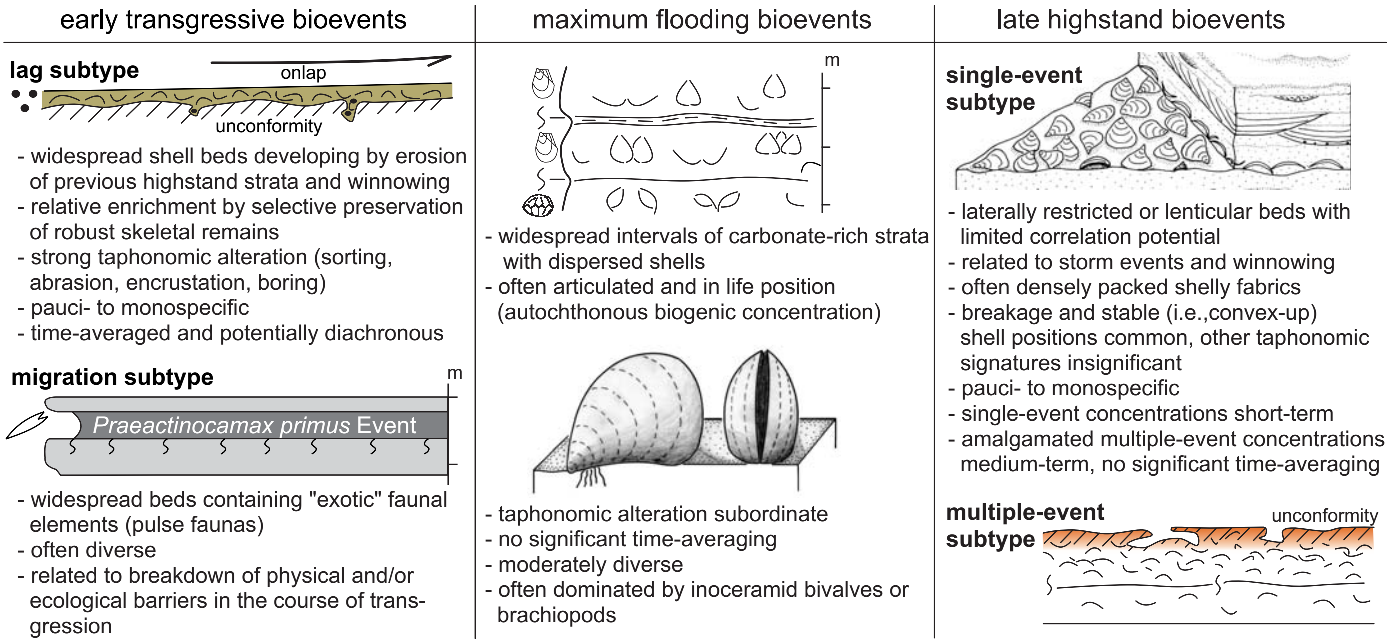


Fig. 9. Conceptual model of bioevent formation in a Cenomanian depositional sequence. **A**. Sea-level curve and sequence stratigraphic subdivision. **B**. Resultant stratigraphic section and bioevents. Note that in high-frequency sequences, genetically similar bioevents may develop on shorter time-scales. Not to scale. Abbreviations: ETB, early transgressive bioevent; FSST, falling stage systems tract; HST, highstand systems tract; LHB, late highstand bioevent; LST, lowstand systems tract; MFB, maximum flooding bioevent; SB, sequence boundary; TST, transgressive systems tract.

quency sequences and parasequences, the lag subtype correspond to "base of parasequence shell beds" of Banerjee and Kidwell (1991), the onlap shell bed of Abbott (1998) and the type 4a and 5 shell beds of Archuby (2009) and Archuby and Fürsich (2010). The preservation potential of ETBs is usually good as they form during a phase of increasingly rapid creation of accommodation space and are thus not very prone to post-depositional erosion (cf. Kidwell 1991). They are, thus, very useful stratigraphic marker beds.

The conceptual model of early transgressive marker beds implies a certain degree of diachronism (i.e., onlap) during their development, specifically for the lag subtype (Fig. 4). However, carbon stable isotope and cyclostratigraphic correlations suggest that most ETBs are quasi-isochronous (e.g., Wilmsen 2007; Wilmsen et al. 2007; Wilmsen and Rabe 2008; Wiese et al. 2009), a fact probably related to the minimal gradients of the Cenomanian epicontinental shelf sea and resultant rapid advance of transgressions. Also, faunal migrations may occur very rapidly, as shown by studies of the dispersal of benthic molluscs across modern oceans (e.g., Scheltema 1977). Therefore, migration bioevents usually occur beyond the resolution of any stratigraphic method, even more so if nektonic organisms such as belemnites are involved (cf. Wilmsen et al. 2010a). Cyclostratigraphic considerations suggest that the migration of *P. primus* to NW Europe and its persistence there lasted not more than 10 kyr (Wilmsen et al. 2007).

Maximum flooding bioevents from the Cenomanian epicontinental shelf setting of NW Europe (which is dominated by the vertical accretion of pelagic carbonate mud; see Wilmsen et al. 2005) differ from most of the shell concentrations recognized from the maximum flooding zones of other basins in that they are not associated with condensation and time-averaging. In siliciclastic-dominated shelf settings, reduced accumulation rates (i.e., condensation) during maximum flooding are related to the landward shift of depocentres and may thus result in a relative enrichment of shells (e.g., Kidwell 1991; Fürsich and Pandey 1999, 2003; Fürsich et al. 2009). This process, however, does not play any role in pelagic carbonate systems as continuous settling of pelagic carbonate mud occurs during this stage of a depositional sequence (Wilmsen 2003; Wilmsen et al. 2005). This also explains the fact that maximum flooding bioevents are comparatively rare in the Cenomanian of NW Europe. Furthermore, MFBs are stratigraphically less well defined than ETBs or LHBs, which usually form individual beds, as their lower



early transgressive bioevents

lag subtype

- widespread shell beds developing by erosion of previous highstand strata and winnowing
- relative enrichment by selective preservation of robust skeletal remains
- strong taphonomic alteration (sorting, abrasion, encrustation, boring)
- pauci- to monospecific
- time-averaged and potentially diachronous

migration subtype

- widespread beds containing "exotic" faunal elements (pulse faunas)
- often diverse
- related to breakdown of physical and/or ecological barriers in the course of transgression

maximum flooding bioevents

- widespread intervals of carbonate-rich strata with dispersed shells
- often articulated and in life position (autochthonous biogenic concentration)

- taphonomic alteration subordinate
- no significant time-averaging
- moderately diverse
- often dominated by inoceramid bivalves or brachiopods

late highstand bioevents

single-event subtype

- laterally restricted or lenticular beds with limited correlation potential
- related to storm events and winnowing
- often densely packed shelly fabrics
- breakage and stable (i.e.,convex-up) shell positions common, other taphonomic signatures insignificant
- pauci- to monospecific
- single-event concentrations short-term
- amalgamated multiple-event concentrations medium-term, no significant time-averaging

multiple-event subtype

Fig. 10. Synoptic representation of Cenomanian bioevents summarizing their main features and genetic processes. For key of symbols see Fig. 9.

and upper boundaries may be gradational (Wilmsen 2008). However, their often wide palaeogeographic extent during maximum flooding conditions, associated with very high chances of preservation in mid-sequence stages (maximum creation of accommodation space; cf. Kidwell 1991), results in an excellent interbasinal correlation potential.

Maximum flooding bioevents are diversification bioevents sensu Kauffman and Hart (1995), mainly related to habitat stability and favourable ecospace expansion. In the terminology of Brett and Baird (1997), they are proliferation epiboles characterized by interregional population blooms. In the shell bed classification scheme of Fürsich and Oschmann (1993), MFBs represent primary biogenic concentrations with relatively low shell densities (e.g., lower and upper "*Orbirhynchia* bands"). They also correspond in sequence stratigraphic position to the backlap and downlap shell beds of Kidwell (1991), and the MFZ concentrations of Fürsich and Pandey (2003) and Fürsich et al. (2009). In high-frequency sequences and parasequences, MFBs correspond to the midsequence shell bed of Banerjee and Kidwell (1991), the mid-cycle shell bed of Abbott (1997), the backlap shell bed of Naish and Kamp (1997), and the type 4b+c shell beds of Archuby (2009).

Late highstand bioevents rarely form good marker beds. This is related to the fact that they are often laterally not as extensive as ETBs and MFBs, as their formational processes are more often of local to regional (storm flows, winnowing and amalgamation on topographic highs) than of an interregional nature. Furthermore, the preservation potential of LHBs is much lower than those of ETBs and MFBs because they are prone to reworking during the succeeding phases of reduced generation or even destruction of accommodation space (latest HST, FSST, and LST; cf. Kidwell 1991). LHBs share some sedimentologic features with ETBs of the lag subtype (e.g., the densely packed shelly fabric). However, the limited lateral extent and taphonomic features such as the absence of authigenic minerals and epibionts as well as a greater importance of shell breakage over abrasion and sorting separate the former from the latter. This shows that time-averaging plays a lesser role in LHB formation, and that short-term reworking and subsequent rapid deposition predominate (e.g., *I. pictus*-II Event). However, amalgamation of shell beds by multiple (storm) events or current winnowing over prolonged time intervals may result in composite late highstand shell beds characterized by local transport and modest time-averaging (e.g., "*I.*" *crippsi* Event).

In 3rd-order sequences, LHBs correspond to the toplap shell bed of Kidwell (1991) and the top highstand concentrations of Fürsich and Pandey (2003). In high-frequency sequences and parasequences, LHBs correspond to the top of parasequence shell beds of Banerjee and Kidwell (1991), the toplap shell bed of Naish and Kamp (1997), and the type 5 shell bed of Archuby (2009). In Fig. 10, the main features and genetic processes of Cenomanian (Upper Cretaceous) biovents are summarized.

During FSST and LST, no bioevents with any correlation potential have been recorded so far. The nearly complete absence of bioevents during these stages of a depositional sequence in the Cenomanian epicontinental shelf setting of NW Europe is related to the lack or even destruction of accommodation space in those time intervals. In proximal and medial parts of the relatively shallow-marine depositional system, erosion and non-deposition prevailed and stratigraphic gaps developed ("Lückenstratigraphie" of Ernst et al. 1996; see also Wilmsen 2003 and Wilmsen et al. 2005). Thus, sequences consist usually only of transgressive and highstand systems tracts (Figs. 4, 9). Only in deeper marine, small-scale intrashelf basins, did unfossiliferous silty-marly deposits accumulate during falling and low sea-level. This scenario is largely incompatible with the formation of widely correlatable (i.e., useful) bioevents.

The time scales of Cenomanian (Upper Cretaceous) bioevents vary in several orders of magnitude. Storm event concentrations of the LHB type may develop within hours to days (e.g., the *I. pictus*-II Event) whereas ETBs such as the belemnite migration events of *Praeactinocamax primus* and *P. plenus* may comprise 10–20 kyr (Wilmsen et al. 2007, 2010a; Wiese et al. 2009). MFBs may need up to 100 kyr for their formation (Wilmsen 2008).

In general, many of the differences between shell beds and shell concentrations of different formations, ages and basins can be related to differences in the time involved in their formation (3rd-order versus high-frequency sequences and parasequences), to their general time of formation (i.e., to evolutionary processes, e.g., oyster-dominated concentrations are common in Jurassic–Cenozoic times), and/or to characteristics of the individual basins influencing faunal habitats and taphonomic conditions (e.g., slope angles, water depth and energy, water temperature and salinity, mineralogy of the accumulated sediments).

Conclusions

Three main types of Cenomanian (Upper Cretaceous) bioevents are recognized within a conventional 3rd-order depositional sequence, termed “early transgressive”, “maximum flooding” and “late highstand bioevents”. Early transgressive bioevents (ETBs) are subdivided into two subtypes, i.e., the lag and migration subtype. The lag subtype corresponds to the transgressive surface and develops in response to reduced accumulation rates (winnowing, authigenic minerals) and relative enrichment of robust biogenic hardparts. Taphonomic alteration and time-averaging may be important features of this subtype. The migration subtype is related to the disappearance of physical (flooding of landmasses and opening of marine connections) or ecological barriers (the incursion of water masses of “unusual” physico-chemical properties with associated “exotic” faunal elements). The conceptual model of early transgressive marker beds implies a certain degree of diachronism (i.e., onlap) during their development, specifically for the lag subtype. However, integrated stratigraphic approaches suggest that most ETBs are quasi-isochronous, a fact probably related to rapid faunal migrations and/or the minimal gradients of the Cenomanian epicontinental shelf sea and resultant rapid progress of transgressions. The preservation potential of ETBs is usually good as they form during a phase of increasingly rapid creation of accommodation space. Thus, they are very useful stratigraphic markers.

Maximum flooding bioevents (MFBs) represent autochthonous primary biogenic concentrations with relatively low shell densities. They are related to habitat stability and ecospace expansion and develop by blooms of certain taxa (often inoceramid bivalves or brachiopods), which are well adapted to the special maximum flooding conditions of the wide epicontinental shelf of NW Europe (low food availability, low water energy and soft substrates, continuous vertical accretion of fine carbonate particles). Therefore, Cenomanian MFBs of NW Europe differ from most shell concentrations recognized in the maximum flooding zone of other basins and ages in that they are not time-averaged and not significantly taphonomically altered. Furthermore, they are comparatively rare and may comprise stratigraphically more expanded intervals with gradational lower and upper boundaries. However, the often wide palaeogeographic extent of MFBs during maximum flooding conditions associated with very high chances of preservation in mid-sequence stages results in an excellent inter-basinal correlation potential.

Late highstand bioevents (LHBs) are shell concentrations deposited as a result of winnowing of fines and reworking by storm activity, currents and waves during decreasing accommodation rates of the late highstands of 3rd-order (and high-frequency) sequences. LHBs usually consist of pauci- or even monospecific skeletal concentrations with a high degree of fragmentation and convex-up orientation of shells. As in ETBs, two subtypes are to be distinguished: (i) simple shell beds consisting of a thin concentration of shells related to a single (storm) event, and (ii) multiple-event shell beds which comprise densely packed, amalgamated bioclastic units, capped by a terminal sequence boundary. LHBs share some features of early transgressive lag bioevents. However, taphonomic data suggest that time-averaging is not as important as in ETBs. Furthermore, LHBs are laterally more restricted because their accumulation is controlled by local to regional processes. Additionally, their preservation potential is poor because of frequent reworking and erosion at the succeeding sequence boundaries. Thus, the importance of LHBs in interbasinal correlation is rather limited.

The time scales of Cenomanian bioevents vary in several orders of magnitude. Storm event concentrations of the LHBs type may develop within hours to days whereas ETBs such as the Cenomanian belemnite migration events may comprise thousands to tens of thousands of years. MFBs may last up to 100 kyr. The absence of bioevents during falling and lowstand of sea-level is explained by frequent hiatuses in these intervals at the basin margins and the locally restricted deposition of lowstands. In Upper Cretaceous monotonous (hemi-) pelagic shelf carbonates, bioevents are important tools for sequence stratigraphic analyses and long-distance correlation. In terms of position within sequences, the three bioevent types correspond to shell concentrations recognized by many authors in Mesozoic–Cenozoic formations around the world. Furthermore, also from high-frequency sequences and parasequences, shell beds with similar positions within the cycles (base, mid- and top of cycle) and with comparable sedimentologic and taphonomic characteristics have been recorded. This suggests that the formational processes of shell beds operate in base-level controlled sedimentary cycles of different hierarchies (i.e., 3rd- up to 7th-order). Many of the

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variations between shell beds and shell concentrations of different formations, ages and basins may be related to differences in the time involved in their formation (3rd-order versus high-frequency cycles), to their general time of formation (i.e., evolutionary processes), and/or to characteristics of the individual basins.

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