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ORIGINAL ARTICLE

Facies pattern and sea-level dynamics of the early Late Cretaceous transgression: a case study from the lower Danubian Cretaceous Group (Bavaria, southern Germany)

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Abstract The facies development and onlap pattern of the lower Danubian Cretaceous Group (Bavaria, southern Germany) have been evaluated based on detailed logging, subdivision, and correlation of four key sections using an integrated stratigraphic approach as well as litho-, bio-, and microfacies analyses. Contrary to statements in the literature, the transgressive onlap of the Regensburg Formation started in the Regensburg–Kelheim area already in the early Early Cenomanian *Mantelliceras mantelli* ammonite Zone and not in the Late Cenomanian. In the Early Cenomanian, nearshore glauconitic-bioclastic sandstones prevailed (Saal Member), followed by Middle to lower Upper Cenomanian mid-shelf siliceous carbonates intercalated with fine-sandy to silty marls (Bad Abbach Member). Starting in the mid-Late Cenomanian (*Metoicoceras geslinianum* ammonite Zone), a considerable deepening pulse during the Cenomanian–Turonian Boundary Event (CTBE) initiated the deposition of the deeper shelf silty marls of the Eibrunn Formation, which range into the early Early Turonian. During the CTBE transgression, also the proximal Bodenwöhrer Senke (ca. 40 km NE of Regensburg) was flooded, indicated by the onlap of the Regensburg Formation onto Variscan granites of the Bohemian Massif, overlain by a thin tongue of lowermost Turonian Eibrunn Formation. A detailed record of the positive δ^{13}C excursion of the global Oceanic Anoxic Event (OAE) 2 has been retrieved from this shallow-water setting. An integrated approach of bio-, event-, carbon stable isotope and sequence stratigraphy was applied to correlate the sections and to decipher the dynamics of this overall transgressive depositional system. The Cenomanian successions show five prominent unconformities, which correlate with those being known from basins in Europe and elsewhere, indicating their eustatic origin. The rate of sea-level rise during the CTBE suggests glacio-eustasy as a driving mechanism for Late Cenomanian sea-level changes. The Regensburg and Eibrunn formations of the lower Danubian Cretaceous Group are highly diachronous lithostratigraphic units. Their regional distribution and northeast-directed onlap pattern onto the southwestern margin of the Bohemian Massif can readily be explained by the lateral movements of roughly coast-parallel (i.e., NW/SE-trending) facies belts of a graded shelf system transgressing on a northeastward-rising substrate. It took the Cenomanian coastline ca. 6 Ma to transgress from southwest of Regensburg to the topographically elevated granite cliffs southeast of Roding in the Bodenwöhrer Senke (=60 km distance).

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Introduction

During the early Late Cretaceous, one of the most pronounced eustatic sea-level rises of the Phanerozoic Eon occurred (e.g., Hancock and Kauffman 1979; Hallam 1992), resulting in the flooding of vast shelf areas across Europe and elsewhere. The Bohemian Massif as a part of the WNW/ESE-trending Mid-European Island remained emergent throughout this transgressive period, but widespread shallow-marine deposits onlapped its margins. At the southwestern margin of the Bohemian Massif, this diachronous onlap is documented by the age, paleogeographic distribution, and facies pattern of the condensed Cenomanian–Lower Turonian Regensburg and Eibrunn formations (lower Danubian Cretaceous Group; Niebuhr et al. 2009; cf. Fig. 1).

The scope of the present paper is the analysis of the facies pattern and stratigraphic architectures developing during the Cenomanian and Early Turonian based on a bed-by-bed logging of a section transect roughly perpendicular to the southwestern margin of the Bohemian Massif. Furthermore, the onlap patterns in the proximal positions of the Bodenwöhrer Senke (Fig. 1) allow a quantification of the eustatic sea-level rise of the Cenomanian–Turonian Boundary Event (CTBE) with significant implications for the dynamics of mid-Cretaceous sea-level changes.

Methods

The study applies an integrated stratigraphy (bio-, cyclo-, event, carbon stable isotope and sequence stratigraphy) along with an analysis of the litho-, bio-, and microfacies. In total, four sections have been logged bed-by-bed at the centimeter scale, and 85 thin-sections have been analyzed. Furthermore, several smaller outcrops have been included in the study. The biostratigraphy of the Danubian Cretaceous Group was based on macrofossils (see below). For sequence stratigraphic reconstructions, emphasis was placed on the sequence bounding unconformities which are well expressed due to the inner to mid-shelf setting of the study area and usually comprise significant stratigraphic gaps ("Lückenstratigraphie" *sensu* Ernst et al. 1996). Due to the lack of accommodation space during falling and low sea level, only transgressive and highstand deposits (i.e., TST–HST sequences) are developed. Event stratigraphy based on widely traceable stratigraphic events follows Ernst et al. (1983, 1996). Cyclostratigraphy is based on the recognition and correlation of stacking pattern of bedding cycles of different hierarchies (cf. Gale 1995; Wilmsen 2003; Voigt et al. 2008). Absolute ages are from the GTS 2004 (Gradstein et al. 2004). For carbon stable isotope analyses, the Bad Abbach, Grub and Obertrübenbach sections were sampled equidistantly in 0.20-m intervals or less based on their stratigraphic thicknesses. The bulk rock samples were powdered and carbonate powders were reacted with 100% phosphoric acid (density >1.9, Wachter and Hayes 1985) at 75°C using a Kiel III online carbonate preparation line connected to a ThermoFinnigan 252 mass spectrometer at the GeoZentrum Nordbayern (lab of M. Joachimski). All 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 is better than ±0.05 for $\delta^{13}C$ and ±0.06 for $\delta^{18}O$ (1σ).

Geological setting

The study area is located in Bavaria (southern Germany) and the investigated strata are part of the Danubian Cretaceous Group of Niebuhr et al. (2009). The formations of the group represent non-marine to neritic environments, comprising conglomerates, sands and sandstones, clays, marls and marlstones, calcarenites, siliceous opoka and limestones with a thickness of 300–500 m. The deposition of the sediments took place in a peri-continental setting at the northern margin of the Neotethys (Fig. 2). Terrestrial sediments were deposited during the Early Cretaceous (Schutzfels Formation) and in the Turonian to Santonian (Hessenreuth Formation). Marine units start with the Lower Cenomanian and persist into the Coniacian (Niebuhr et al. 2009; Tröger et al. 2009; Wilmsen et al. 2009a; Wilmsen and Niebuhr 2010). The complete succession documents a nearly symmetrical trans-/regressive mega-cycle with a maximum flooding interval during the late Middle to early Late Turonian.

The Regensburg, Eibrunn, and Winzerberg formations are marine lithostratigraphic units of the lower Danubian Cretaceous Group (Fig. 3). The Cenomanian to lowermost Turonian Regensburg Formation unconformably overlies various older rock units, in the southwest (i.e., Regensburg–Kelheim area) mainly Upper Jurassic carbonates or the Lower Cretaceous terrestrial Schutzfels Formation; in proximal (i.e., northeastern) positions the substrate is formed by older Mesozoic strata or by the Variscan basement of the Bohemian Massif. The Regensburg Formation is characterized by strong terrigenous input and by mixed glauconitic-bioclastic sediments with a shallow-water fauna of bivalves, brachiopods, and siliceous sponges

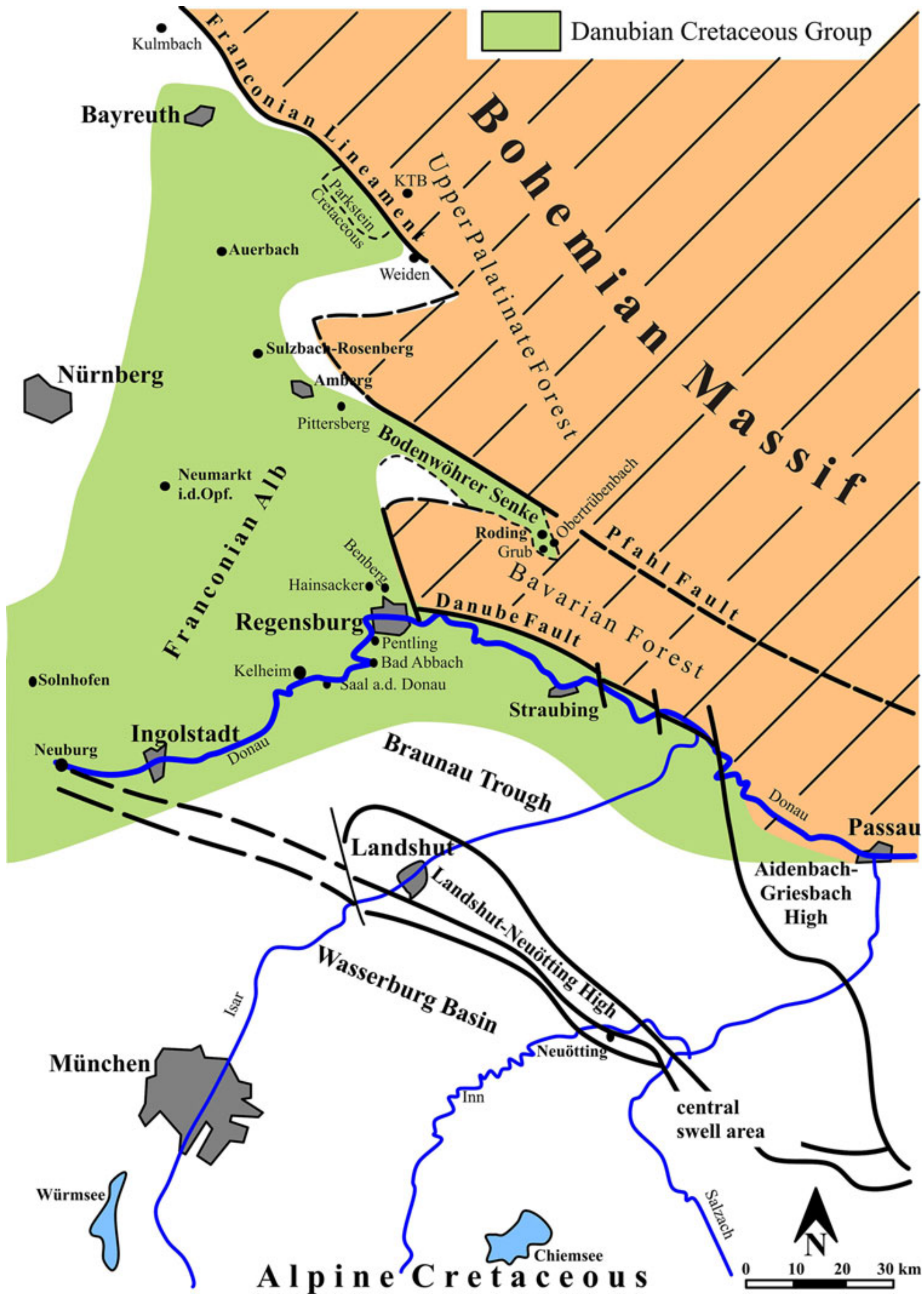


Fig. 1 Approximate distribution and structural setting of the Danubian Cretaceous Group (*green*). Sections and localities mentioned in the text are indicated

(Trusheim 1935; Kauffman et al. 2000; Niebuhr et al. 2009). It is subdivided into a lower Saal Member consisting of thickly bedded glauconitic sandstones and an upper Bad Abbach Member of interbedded sandy-silty marls and siliceous limestones. This bipartition corresponds to the subdivision in the old literature, where a lower "Grünsandstein" and an upper "Kalksandstein" have been separated (e.g., Trusheim 1935; Dacqué 1939). The uppermost Cenomanian–lower Lower Turonian silty marls of the Eibrunn Formation document a first maximum flooding interval during the early Late Cretaceous transgression and their faunal content (cephalopods, inoceramid bivalves and planktic foraminifera) was the subject of the papers by Förster et al. (1983), Hilbrecht (1986), and Röper and Rothgaenger (1995). The Eibrunn Formation is overlain by the spiculitic silt- and marlstones (Reinhausen Member) and sandstones (Knollensand Member) of the Lower Turonian Winzerberg Formation, which grades into coarse-grained sandstones of the so-called "Hornsand facies" (see Niebuhr et al. 2009). A conspicuous unconformity in the

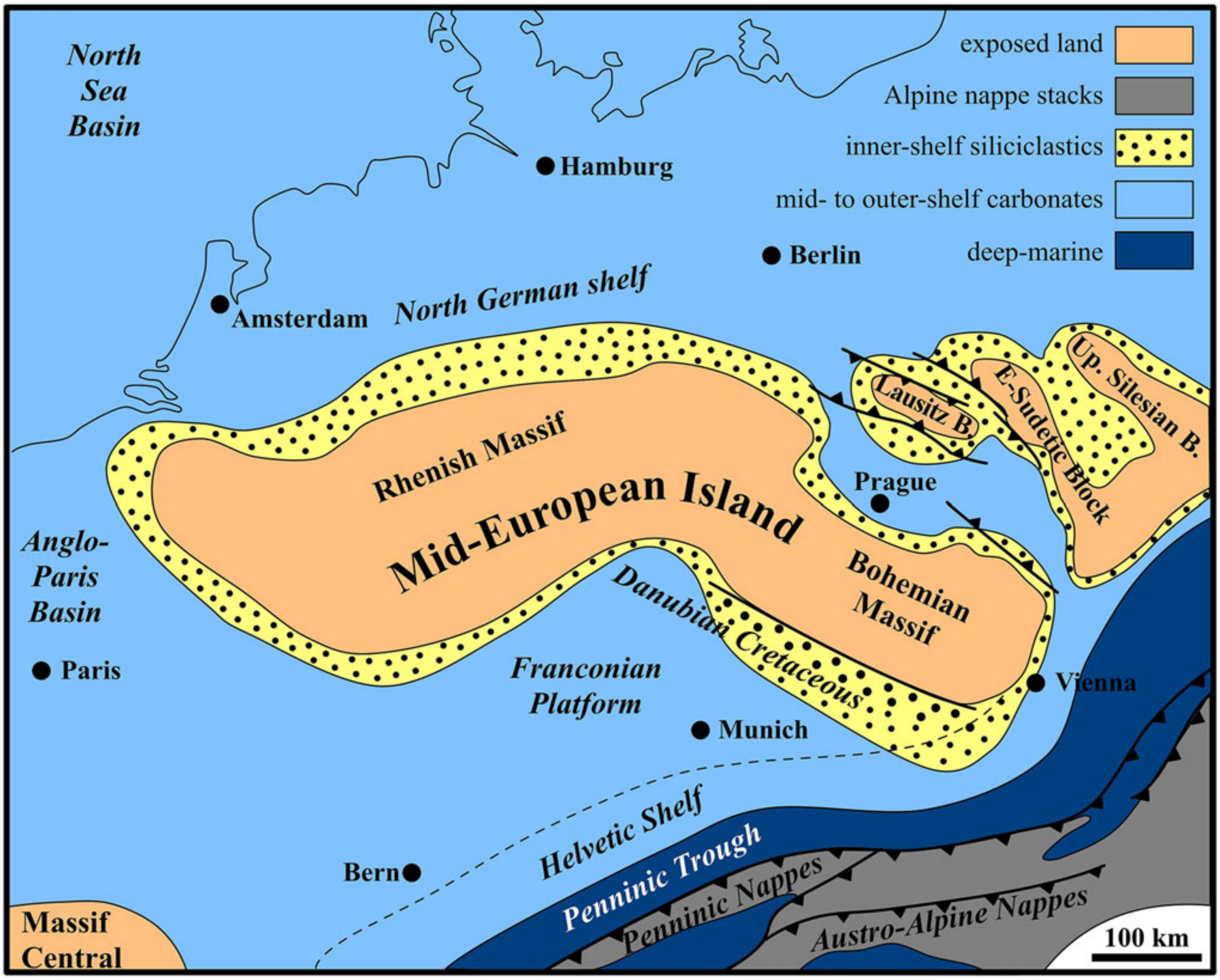


Fig. 2 Paleogeography of the Cenomanian–Turonian in central Europe (after Ziegler 1990) with indication of the depositional area of the Danubian Cretaceous Group to the southwest of the Bohemian Massif

Lower–Middle Turonian boundary interval terminates this first (i.e., Cenomanian–Early Turonian) trans-/regressive cycle of the Danubian Cretaceous Group. The lithostratigraphic succession of the lower Danubian Cretaceous Group in the Bodenwöhrer Senke is identical to that of the Regensburg–Kelheim area. However, the Regensburg and Eibrunn formations are considerably reduced in thickness and the Winzerberg Formation may consist entirely of the Knollensand Member (Fig. 3).

The biostratigraphy of the Danubian Cretaceous Group is based on inoceramid bivalves and ammonoids (Dacqué 1939; Förster et al. 1983; Hilbrecht 1986; Röper and Rothgaenger 1995; Hilbrecht et al. 1996; Tröger et al. 2009; Wilmsen et al. 2009a; Wilmsen and Niebuhr 2010). Data on the planktic foraminifera of the Eibrunn Formation are also present (Risch 1983; Förster et al. 1983). Contrary to former interpretations (Upper Cenomanian), the onset of transgressive onlap started during the Early Cenomanian as the *Mantelliceras mantelli* and *Mantelliceras dixoni* ammonite zones have been proven for the Saal Member of the Regensburg–Kelheim area (see Wilmsen and Niebuhr 2010 for a synopsis). Middle Cenomanian index fossils are rare but Upper Cenomanian cephalopods (ammonoids, belemnites) and Upper Cenomanian to Lower Turonian inoceramid bivalves are common, providing the basis for detailed biostratigraphic subdivision and correlation (Tröger et al. 2009; Wilmsen et al. 2009a, 2010).

Sections

Four sections have been logged bed-by-bed, forming a SW–NE transect roughly perpendicular to the southwestern margin of the Bohemian Massif (Fig. 1). They are grouped

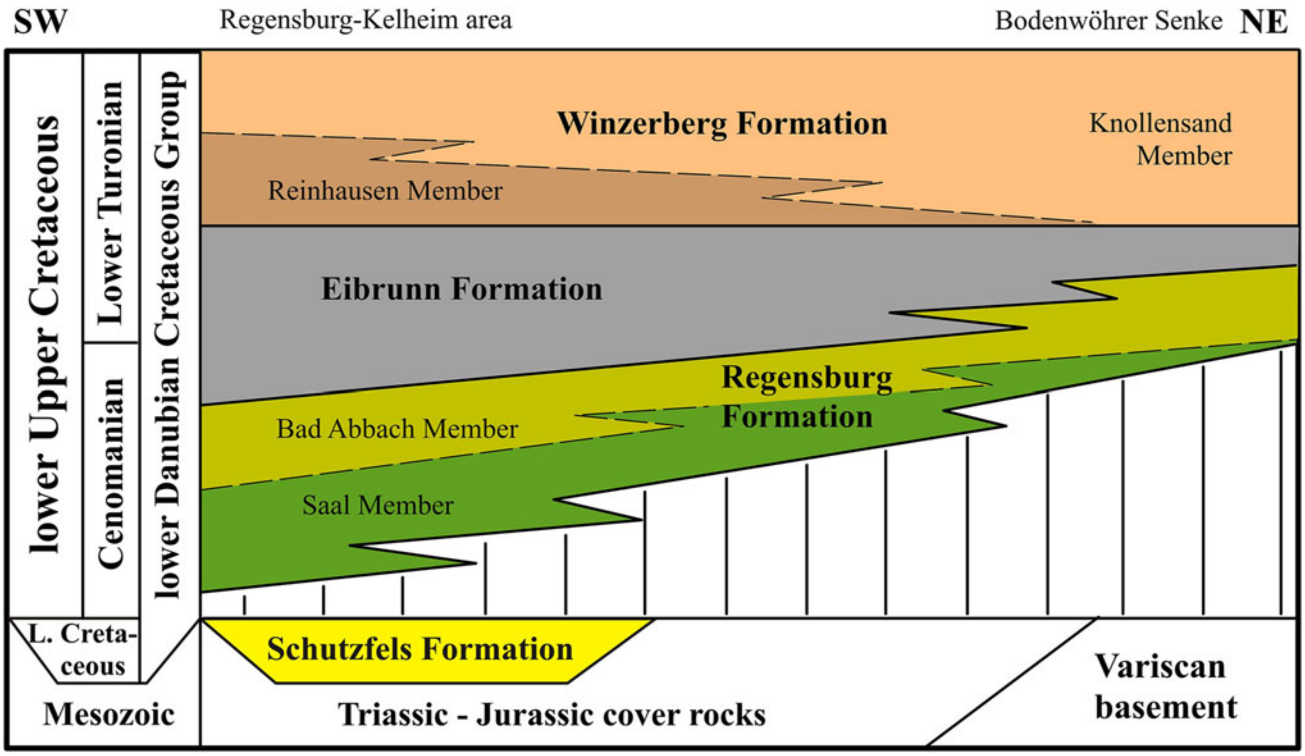


Fig. 3 Lithostratigraphy of the lower Danubian Cretaceous Group in a SW–NE transect from the Regensburg–Kelheim area to the Bodenwöhrer Senke (cf. Niebuhr et al. 2009)

into two pairs, i.e., Saal an der Donau and Bad Abbach, which characterize the type region of the Danubian Cretaceous Group in the Regensburg–Kelheim area, as well as Grub and Obertrübenbach in the Bodenwöhrer Senke near Roding, which reflect deposition in proximal parts of the basin, close to the elevated topography of the Bohemian Massif. Other outcrops such as the Schutzfelsen near Pentling, Hainsacker and Benberg north of Regensburg as well as temporary exposures during road construction (e.g., at the B85 near Pittersberg, a few kilometers east of Amberg) have also been included in the study (see Fig. 1 for locations).

The Saal section is located in the active quarry of the Felswerke AG in Saal an der Donau, ca. 15 km southwest of Regensburg (Figs. 1, 4a, 5). It exposes the Schutzfels Formation in a karst depression overlain by a ca. 8-m-thick succession of the lower Regensburg Formation and is the type section of the Saal Member.

The Bad Abbach section is located on the southern flank of the Mühlberg near the Dantschermühle, south of Bad Abbach, ca. 10 km south-southwest of Regensburg (Fig. 1). In an abandoned quarry, it exposes a ca. 25-m-thick succession of the lower Danubian Cretaceous Group, including the Regensburg, Eibrunn and lower Winzerberg formations (Figs. 4b, 5). The Bad Abbach section is the type section of the Regensburg Formation and likewise that of the upper Bad Abbach Member of the formation (Niebuhr et al. 2009).

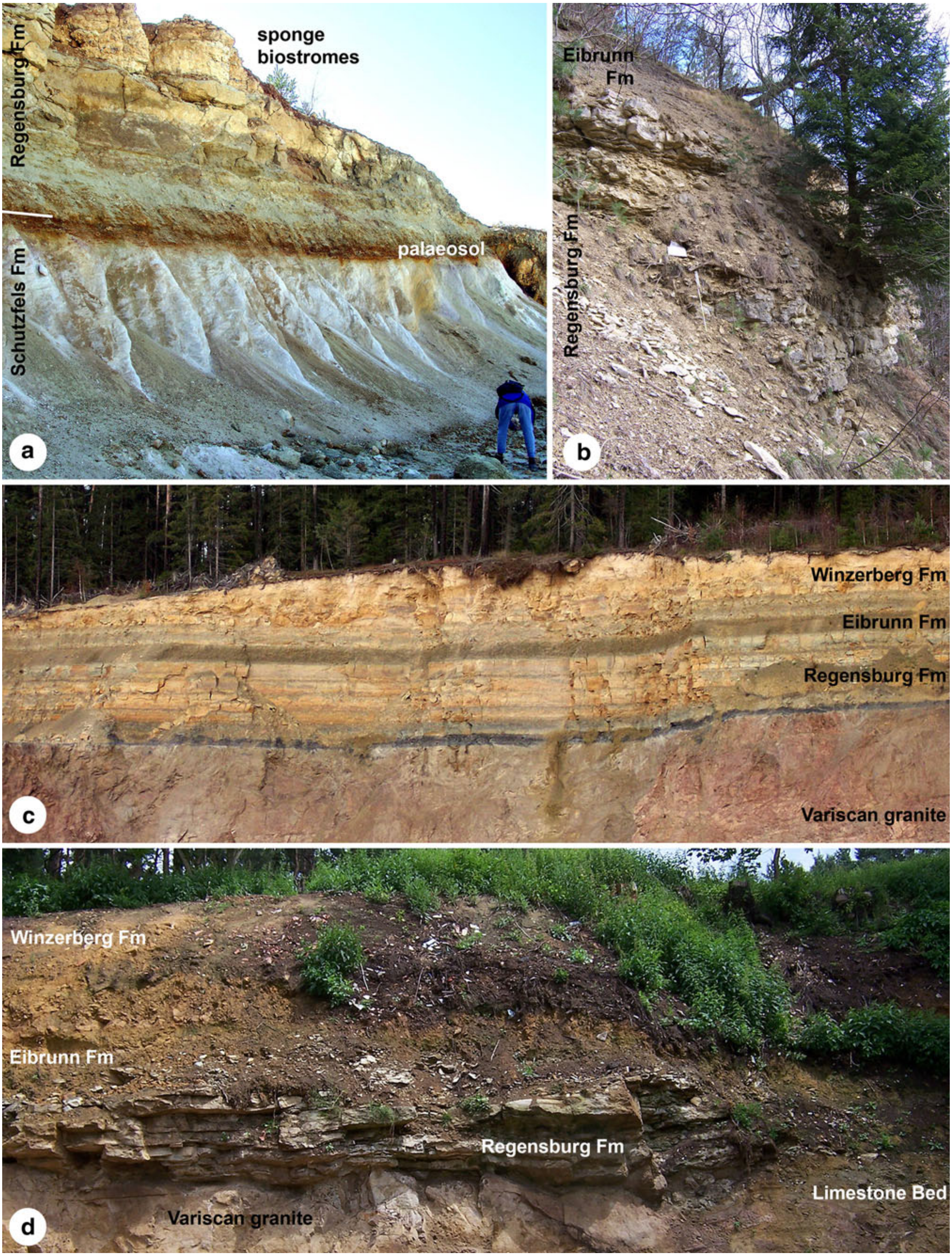
The Grub section is located in the active quarry of the Haimerl gravel works, ca. 5 km south of Roding (Bodenwöhrer Senke). It exposes a ca. 10-m-thick succession of the Regensburg, Eibrunn, and lower Winzerberg formations, which rests on a flat-topped Variscan granite (Figs. 4c, 7).

The Obertrübenbach section is located 3.5 km south-southeast of Roding in an abandoned quarry near the small road connecting Unter- and Obertrübenbach. It exposes a thin succession of the Regensburg, Eibrunn, and Winzerberg formations resting on a Variscan granite that shows significant paleotopography in outcrop scale (Figs. 4d, 7, 8), and it is classified as Geotop No. 75 of the 100 most important geological heritage sites of Bavaria. It is the last preserved site of several small quarries formerly located in close vicinity (Trusheim 1935).

Results

Facies types

Based on litho-, micro-, and biofacies analyses, 20 facies types (FT, including two subtypes) have been recognized


Regensburg Fm
sponge
biostromes
palaeosol
Schutzfels Fm
a
Eibrunn
Fm
Regensburg Fm
b
Winzerberg Fm
Eibrunn Fm
Regensburg Fm
Variscan granite
c
Winzerberg Fm
Eibrunn Fm
Regensburg Fm
Limestone Bed
Variscan granite
d

◀ **Fig. 4** Field aspects of the studied sections. **a** Saal section, Felswerke quarry in Saal an der Donau southwest of Regensburg. The terrestrial Schutzfels Formation is overlain by the Saal Member of the Regensburg Formation. Both formations are separated by a brownish paleosol ("Braunhorizont"). *Person* for scale. **b** Bad Abbach section at Mühlberg near Dantschermühle, south of Regensburg. The Bad Abbach Member of the Regensburg Formation is overlain by the Eibrunn Formation. Exposed thickness ca. 10 m. **c** Grub section south of Roding/Bodenwöhrer Senke. Transgression of the Regensburg Formation onto a Variscan granite. The Regensburg Formation is overlain by the Eibrunn Formation and the lower part of the Winzerberg Formation. Width of the landscape in the photograph is ca. 50 m. **d** Obertrübenbach section southeast of Roding/Bodenwöhrer Senke. Transgression of the Regensburg Formation onto a Variscan granite (note onlap towards the *left*). The Regensburg Formation is overlain by the Eibrunn Formation and the lower part of the Winzerberg Formation. Width of the landscape in the photograph is ca. 15 m

(Table 1). They usually characterize the successive lithostratigraphic units and are thus briefly described according to their stratigraphic provenance (see also Figs. 6, 9, 10).

The Saal Member of the Regensburg Formation is characterized by relatively coarse-grained facies types, strong siliciclastic input and high glauconite contents. In total, twelve facies types have been recognized (Table 1). Stratification is dominated by thick beds of fairly uniform fabric and lithology. Macrofossils are not uncommon but often concentrated in certain levels. Bioturbation is pervasive. The Saal Member ("Grünsandstein" of the older literature) was formerly quarried as freestone for constructional and ornamental purpose.

The Bad Abbach Member (formerly often termed "Kalksandstein") of the Regensburg Formation is characterized by relatively fine-grained, uniform facies types as well as weak to moderate siliciclastic and glauconite contents. Four facies types have been recognized (Table 1). The Bad Abbach Member is thin- to medium-bedded and weathers softly. Macrofossils are rare, bioturbation is common.

The Eibrunn Formation has a fairly uniform lithology dominated by soft marls with variable contents of silt and (fine) sand combined in two facies types (Table 1). Macrofossils are generally rare, only in the lower part of the formation in the Regensburg–Kelheim area, cephalopods and bivalves (inoceramids, pectinids) were recorded. Microfossils (especially planktic foraminifera), however, are common (e.g., see Förster et al. 1983; Risch 1983). Bioturbation is dominated by the ichnogenus *Chondrites*.

The Winzerberg Formation has a lower Reinhausen Member (siliceous-silty marlstones) and an upper Knollensand Member (bioturbated, fine- to coarse-grained calcareous sandstones). The facies of the Reinhausen Member is fairly similar to that of the Bad Abbach Member of the Regensburg Formation, likewise comprising two facies types (Table 1).

Facies development

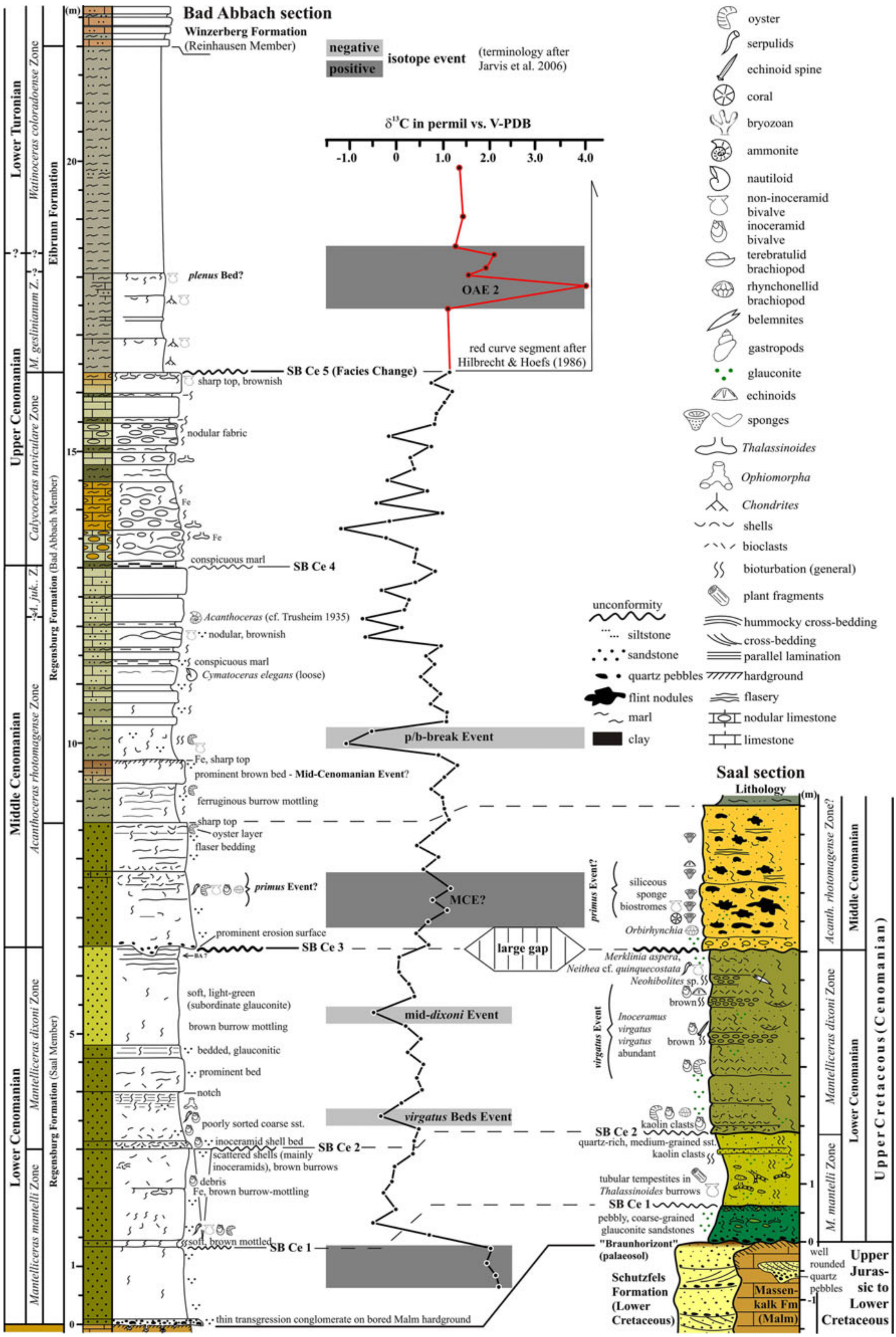
In the following, the regional variation and stratigraphic context of the facies development of the lower Danubian Cretaceous Group in the two principal areas, i.e., Regensburg–Kelheim and Bodenwöhrer Senke, is described.

Regensburg–Kelheim area

In the Saal and Bad Abbach quarries, the Regensburg Formation rests unconformably either on Upper Jurassic carbonates ("Massenkalkfazies") or on cross-bedded, pebbly sandstones of the Schutzfels Formation (Figs. 4a, 5). The latter occurs in decameter-scale karst depressions (e.g., Saal, Schutzfelsen at Pentling) and is capped by a conspicuous ferruginous horizon ("Braunhorizont"). The Saal Member of the Regensburg Formation commences with a thin lag of quartz granules and oyster shells (FT 1), overlain by strongly glauconitic, medium- to coarse-grained bioclastic sandstones (FT 3 and 4). In Saal, *Thalassinoides* burrows are filled by coarse-grained sandstones and represent tubular tempestites (FT 10). Granule layers of kaolinite clasts may be interspersed.

The Saal Member continues with a unit of light green, fine- to medium-grained, moderately glauconitic, bioclastic sandstones (FT 6 and 7). The bioclasts are concentrated in thin layers or small scours (FT 8), and bioturbation is common. Common fossils include small exogyrine oyster (*Ceratostreon* sp.) and frequently double-valved inoceramid bivalves (*Inoceramus virgatus virgatus*), associated by pectinid bivalves (*Merklinia aspera, Neithea* sp.), rhynchonellid brachiopods (*Orbirhynchia* sp.), spines of regular echinoids, serpulids, and fragments of belemnite guards (*Neohibolites* sp.). Weakly accentuated nodular, slightly more calcareous horizons display a poorly developed cyclicity. The Saal section is more fossiliferous in this interval compared to Bad Abbach, and two subordinate unconformities (SB Ce 1 and 2) can be correlated between both sections (Fig. 5).

Above a major erosion surface (SB Ce 3) at the 5-m level (Saal) and 6.5-m level (Bad Abbach), a thin lag of medium-grained, glauconitic sandstones with small lithoclasts (FT 1) occurs in Saal, followed by fine-grained, poorly glauconitic sandstones with siliceous sponge biostromes in two beds of a combined thickness of 2.50 m (FT 11; see Kauffman et al. 2000 for details and Fig. 5). Small solitary corals as well as *Orbirhynchia* sp., pectinid bivalves and small irregular echinoids (*Discoides subuculus*) occur within the sponge frameworks. The sponge biostromes are dated as Middle Cenomanian (Kauffman et al. 2000), and the integrated stratigraphy of this study supports this interpretation (see below). In Bad Abbach, the erosion surface cuts into fine-grained, poorly glauconitic



Bad Abbach section
Winzerberg Formation
(Reinhausen Member)
negative
positive
isotope event
(terminology after Jarvis et al. 2006)
δ13C in permil vs. V-PDB
-1.0
0
1.0
2.0
3.0
4.0
OAE 2
red curve segment after Hilbrecht & Hoefs (1986)
SB Ce 5 (Facies Change)
sharp top, brownish
nodular fabric
Fe
conspicuous marl
SB Ce 4
Acanthoceras (cf. Trusheim 1935)
nodular, brownish
conspicuous marl
Cymatoceras elegans (loose)
p/b-break Event
Fe, sharp top
prominent brown bed - Mid-Cenomanian Event?
ferruginous burrow mottling
sharp top
oyster layer
flaser bedding
primus Event?
MCE?
prominent erosion surface
SB Ce 3
large gap
soft, light-green (subordinate glauconite)
brown burrow mottling
mid-dixoni Event
bedded, glauconitic
prominent bed
notch
poorly sorted coarse sst.
virgatus Beds Event
inoceramid shell bed
SB Ce 2
scattered shells (mainly inoceramids), brown burrows
debris
Fe, brown burrow-mottling
soft, brown mottled
SB Ce 1
thin transgression conglomerate on bored Malm hardground
plenus Bed?
(m)
0
1
5
10
15
20
Lower Turonian
Upper Cenomanian
Middle Cenomanian
Lower Cenomanian
Watinoceras coloradoense Zone
M. geslinianum Z.
Calycoceras naviculare Zone
A. juk. Z.
Acanthoceras rhotomagense Zone
Mantelliceras dixoni Zone
Mantelliceras mantelli Zone
Eibrunn Formation
Regensburg Formation (Bad Abbach Member)
Regensburg Formation (Saal Member)
oyster
serpulids
echinoid spine
coral
bryozoan
ammonite
nautiloid
non-inoceramid bivalve
inoceramid bivalve
terebratulid brachiopod
rhynchonellid brachiopod
belemnites
gastropods
glauconite
echinoids
sponges
Thalassinoides
Ophiomorpha
Chondrites
shells
bioclasts
bioturbation (general)
plant fragments
hummocky cross-bedding
cross-bedding
parallel lamination
hardground
flasery
nodular limestone
limestone
unconformity
siltstone
sandstone
quartz pebbles
flint nodules
marl
clay
Saal section
Lithology
siliceous sponge biostromes
Orbirhynchia
primus Event?
Merklinia aspera,
Neithea cf. quinquecostata
Neohibolites sp.
brown
Inoceramus virgatus virgatus abundant
virgatus Event
brown
kaolin clasts
SB Ce 2
quartz-rich, medium-grained sst.
kaolin clasts
tubular tempestites in Thalassinoides burrows
SB Ce 1
pebbly, coarse-grained glauconite sandstones
"Braunhorizont" (palaeosol)
Schutzfels Formation (Lower Cretaceous)
Massenkalk Fm (Malm)
well rounded quartz pebbles
Acanth. rhotomagense Zone?
Mantelliceras dixoni Zone
M. mantelli Zone
Middle Cenomanian
Lower Cenomanian
Upper Cretaceous (Cenomanian)
Upper Jurassic to Lower Cretaceous

◀ **Fig. 5** Graphic logs of the Bad Abbach and Saal sections including carbon stable isotope curve for Bad Abbach (cf. Borota 2007). The legend also applies for the other figures. Abbreviations: *M.* = *Mantelliceras*; *Acanth.* = *Acanthoceras*; *A. juk.* Z. = *Acanthoceras jukesbrownei* Zone; *M. geslinianum* Z. = *Metoicoceras geslinianum* Zone (all zones have ammonite indices); *MCE* Mid-Cenomanian positive carbon stable isotope excursion

calcareous sandstones and is overlain by coarse-grained, strongly glauconitic, bioclastic sandstones (FT 3) yielding serpulids, oysters, inoceramids, pectinids, brachiopods, and bryozoans. The top of the Saal Member is sharp in both sections and marked by an oyster layer in Bad Abbach.

The overlying Bad Abbach Member is 7.60 m thick at the type section and consists of an intercalation of bioturbated, silty to fine-sandy marls (FT 13) and silty, spiculitic limestones, the fabric of which becomes more nodular up-section (FT 14 and 15). Macrofossils are comparatively rare and comprise oysters and thin-shelled pectinids as well as occasional nautilids and ammonoids. A limestone bed with a strongly bioturbated, ferruginous omission surface occurs at 9.70 m of the section and a conspicuous marly siltstone bed (FT 16) at 13 m caps a thickening-upward trend commencing above the omission surface. The Regensburg Formation is sharply terminated by another ferruginous and bioturbated omission surface at 16.30 m (SB Ce 5; Fig. 5).

The succession continues with silty-clayey marls (FT 17) of the Eibrunn Formation, which is ca. 6.50 m thick. In its lower part, bioturbation by *Chondrites* is common and thin-shelled pectinids ("paper pecten") occur. Approximately 1.60 m above the base of the formation, a slightly more calcareous, 1 to 2-dm-thick nodular horizon ("Kalkmergelbank" of Förster et al. 1983) occurs (FT 18), which yielded the belemnite *Praeactinocamax plenus* and, slightly below, a mid-Upper Cenomanian (*Metoicoceras geslinianum* zonal) ammonite fauna (Förster et al. 1983; Röper and Rothgaenger 1995). The appearance of fine-grained siliceous limestone beds (FT 19 and 20) at 22.50 m mark the base of the Winzerberg Formation, the lower few meters of which are exposed at the top of the section (Fig. 5).

Bodenwöhrer Senke

In the Bodenwöhrer Senke, the Danubian Cretaceous Group starts upon a peneplained surface of older Mesozoic strata or granitic basement rocks of the Bohemian Massif (Fig. 7).

In Grub, a flat-topped granite is overlain by a 0.80-m-thick black clay (FT 2) at the base of which patchily distributed granules and pebbles of reworked Liassic iron ores may occur (FT 1). The clay contains sponge spicules, benthic foraminifera, and in its upper part, the belemnite *Praeactinocamax plenus* (Chellouche 2008; Wilmsen et al. 2010). Furthermore, it yielded a fully marine, diverse assemblage of dinoflagellates and calcareous nannoplankton as well as some glauconite grains. The clay is unconformably overlain along an irregular erosion surface by a 0.80–0.90-m-thick, medium- to coarse-grained glauconitic-bioclastic sandstone bed (FT 5) with a basal lag of phosphatic and poorly, rounded orange alkali feldspar granules as well as fragments of belemnite guards (Lower Greensand Bed; Fig. 7). Furthermore, the bed contains oysters, pectinids, siliceous sponges, brachiopods, and also plant remains. It is heavily bioturbated and fines up-section, grading into the overlying silty, siliceous limestones of the Bad Abbach Member, which contain shark teeth and relatively abundant fish remains. The Bad Abbach Member is 4.60 m thick and consists of bioturbated, poorly fossiliferous siliceous limestones (FT 14) capped by another glauconitic sandstone bed (Upper Greensand Bed; FT 4). In the lower part of the member, *Chondrites* layers are common and small oysters [*Pycnodonte* (*Phygraea*) *versicularis vesiculosa*] occur. In the upper part of the member at the 4.20-m level, the inoceramid bivalve *Inoceramus pictus* aff. *concentricoundulatus* was found (Tröger et al. 2009). Silty marl seams 5–10 cm thick (FT 13) subdivide the Bad Abbach Member into three internally stratified bedding bundles of ca. 1-m thickness. The member is terminated by the Upper Greensand Bed, the base of which is clearly erosional and contains lithoclasts of up to 50 mm in diameter ripped-up from the underlying strata. Except for rare pectinid and inoceramid bivalves, the bed is poorly fossiliferous. It grades into the overlying Eibrunn Formation, which is only 1.50 m thick and consists of dark-grey, silty to fine-sandy marls. The section is terminated by a few meters of siliceous, marly siltstones of the lower Winzerberg Formation (Fig. 7).

In Obertrübenbach, the top surface of the underlying granite shows a strong relief (Figs. 7, 8). In the southern part of the small quarry, the succession starts with the ca. 0.15-m-thin Limestone Bed of bioclastic floatstone yielding solitary and colonial (i.e., microsolenid) corals, siliceous sponges, oysters, spines of regular echinoids, serpulids, terebratulid brachiopods, bryozoans, and shark teeth (FT 12). At the base of this bed, granules of quartz and alkali feldspar occur, along with isolated larger pebbles and small cobbles of rounded granite. The Limestone Bed is erosionally overlain by a several dm-thick unit of immature, pebbly sandstone, which thins towards the northern part of the outcrop (Fig. 8), where it is directly onlapping the granite and forming a distinct basal conglomerate (FT 1; Fig. 9c). Interspersed into that unit are rounded granite cobbles and boulders up to 0.80 m in diameter. The succession continues with a siliceous sponge biostrome (FT 11: Sponge Bed; Fig. 9a), likewise pinching out towards the north, followed by a graded, hummocky cross-stratified, glauconitic, fine- to medium-grained lithoclastic sandstone bed of laterally variable thickness and a strongly bioturbated, somewhat marlier top (FT 9; Fig. 9b).

Table 1 Facies types (FT) recognized in the lower Danubian Cretaceous Group

FT	Name	Short description	Interpretation, remarks
Saal Member of the Regensburg Formation			
1	Basal conglomerate	Predominantly clast-supported granule-pebble-cobble conglomerates with poorly to very well rounded components and variable sorting; matrix sandy-glauconitic; clast spectrum strongly depending on local sources (e.g., Fig. 9c)	High-energy transgressive lags
2	Black clay	Nearly pure calcareous clay with only subordinate silt and fine-sand as well as authigenic glauconite; fully marine fossils (belemnites, dinoflagellates, coccoliths) present	Marine quiet water deposit (below storm-wave base)
3	Coarse-grained glauconitic-bio- and/or lithoclastic sandstones	Poorly sorted coarse-grained, bioclastic quartz sandstones often with fine-grained sandy-silty matrix; quartz grains are usually well rounded and glauconite occurs as small pellets within the matrix (but rarely exceeds 10%); bioclasts are mainly oyster shells and may be dispersed, imbricated or nested; lithoclasts small (granules to small pebbles) of local provenance; color dirty brownish-green (Fig. 6b, c)	High-energy nearshore deposit with infiltrated matrix during calm conditions
4	Glauconite sandstones	Often homogenous (bioturbation!) quartz sandstones with grain size variable from fine to coarse and changeable contents (usually 10–30%) of predominantly allochthonous glauconite grains which are sometimes larger than the co-occurring quartz grains; rare scattered bioclasts and lithoclasts; color usually green to dark olive-green (Fig. 10f)	Marine inner shelf sediments of variable water energy and low to moderate accumulation rate
5	Glauconitite	Glauconite sandstones with more than 50% of usually well rounded, medium-grained glauconite; fine-grained quartz, shell debris and matrix present; color dark olive-green (Fig. 10g)	Shelf sediments with very low accumulation rate
6	Fine- to medium-grained shelly sandstones	Fine- to medium-grained, bioturbated quartz sandstones with 10–30% glauconite (small grains and pellets, also authigenic glauconite in the matrix) rich in shells of mainly oysters, inoceramids and pectinids; many shells are broken, but entire shells may occur; inhomogeneous fabric due to bioturbation; color light green	Shelf sediment with moderate water energy at the transition inner to mid-shelf
7	Fine-grained sandstones with glauconite	Fine-grained quartz sandstones with less that 10% small glauconite grains and very homogenous fabric due to intense bioturbation; small bioclasts are rare but larger quartz grains may be scattered in the fine sandstone matrix (mixed into it by bioturbation of formerly discrete coarser layers); color light-green to yellowish (Fig. 6a, e)	Shelf sediment with moderate to low water energy at the transition inner to mid-shelf
8	Oyster and inoceramid float- to rudstones	Thin (usually cm-scale) more-or-less densely packed float- and rudstones with sandy-glauconitic matrix; upwards grading into shell-poor glauconitic sandstones; occur both as graded beds or in lenses (scours and gutters) (Fig. 6d)	Tempestitic shell beds which escaped re-mixing by bioturbation
9	Graded bio- and lithoclastic sandstones	Coarse- to fine-grained and variably glauconitic quartz sandstones with bioclasts and lithoclasts usually concentrated in undulating, i.e., hummocky-stratified laminae; sharp bases and normal grading into fine-grained sandstones with post-event bioturbation; amalgamation common (Figs. 9b, 10d, e)	(amalgamated) proximal tabular tempestites

Table 1 continued

FT	Name	Short description	Interpretation, remarks
10	Coarse-grained burrow fills	Coarsely filled crustaceous burrows, usually containing mixtures of coarse quartz and glauconite grains as well as shell debris (mainly oysters)	Tubular tempestites formed by storm-infilling of open burrow systems
11	Siliceous sponge biostromes	Siliceous sponge biostrome are predominantly built by lithistids within fine-grained calcareous sandstone matrix. Two subtypes occur: (a) biostromes dominated by erect and knobby forms (see Kaufman et al. 2000 for details). (b) biostromes dominated by encrusting forms (Figs. 9a, 10c)	Autochthonous primary biogenic structures formed during periods of decreased terrigenous input (transgressions) in distal inner to proximal mid-shelf settings
12	Bioclastic float- to packstones	Floatstones contain corals (solitary forms and microsolenids) in micritic matrix with variable amounts of smaller bioclasts; laterally microfacies changes without sharp boundary to bioclastic packstones with recrystallized mollusc fragments, serpulids and echinoderm debris (mainly spines of regular echinoids) as well as small allochthonous glauconite grains and occasional quartz; dissolution vugs are filled with vadose silt and sparry calcite; color light-grey (Fig. 10a, b)	Shallow-water carbonates accumulating in nearshore settings sheltered from clastic input (Obertrübenbach cliff)
Bad Abbach Member of the Regensburg Formation			
13	Silty to fine-sandy marls	Fissile silty to fine-sandy marls contain small glauconite pellets, sponge spicules and weather soft; bioturbation is common (in part by *Chondrites* isp.), but mainly indifferent; color is dark grey with a greenish touch	Mid-shelf sediments in times of increased terrigenous input
14	Bioturbated siliceous wacke- to packstones	Siliceous limestones are predominantly microbioclastic, spiculitic wacke- to packstones with dispersed larger bioclasts (oyster debris, rare echinoid fragments) with a micritic-clayey matrix; the fabric is often inhomogeneous due to bioturbation; color light greenish-grey to yellow-grey (Figs. 6f, 10h)	Biogenic mid-shelf sediments, low terrigenous input
15	Nodular siliceous limestones	Similar to FT 13 in terms of microfacies but with a nodular fabric due to stronger bioturbation (*Thlassinoides* isp.); color more brownish due to higher Fe contents	Biogenic mid-shelf sediments, low terrigenous input and low accumulation rate
16	Silty marlstones to marly siltstones	Fine-grained microbioclastic wackestones-siltstones with variable contents of subangular to moderately rounded silt grains (5–50%); bioclast are predominantly oyster debris and smooth-shelled ostracods; bioturbation common (*Chondrites* isp.; *Planolites* isp.); color medium- to dark grey with a greenish touch	Mid-shelf sediments with variably high terrigenous input
Eibrunn Formation			
17	Clayey-silty marls	Microbioclastic wackestones with small planktic foraminifera, thin- and smooth-shelled ostracods, roveacrinid remains and a few percent of matrix glauconite (often filling foraminifera shells) and pyrite; bioturbation indistinct, but *Chondrites* isp. occurs frequently; color dark grey with a touch of dark olive-grey (Fig. 6g)	Muddy outer shelf sediment deposited below storm-wave base

Table 1 continued

FT	Name	Short description	Interpretation, remarks
18	Nodular clayey marlstone	Similar to FT 17 but with higher content of microbioclasts and/or micrite; *Chondrites* isp. common; similar color as in FT 17 but a touch lighter	Outer shelf sediment deposited below storm-wave base, higher biogenic sediment contribution
Lower Winzerberg Formation (Reinhausen Member)			
19	Siliceous limestones	Spicule wackestones with microbioclasts in a micritic matrix; spicules are predominantly monaxones and chert concretions (often filling crustaceous burrows) are common; color medium grey, yellow to brownish (Fig. 6h)	Outer shelf sediment deposited below storm-wave base
20	Silty siliceous limestones	Similar to FT 19 but with increasing siliciclastic content (mainly subangular to moderately well rounded quartz silt and occasional quartz sand grains)	Outer to mid-shelf sediment with increasing terrigenous influence

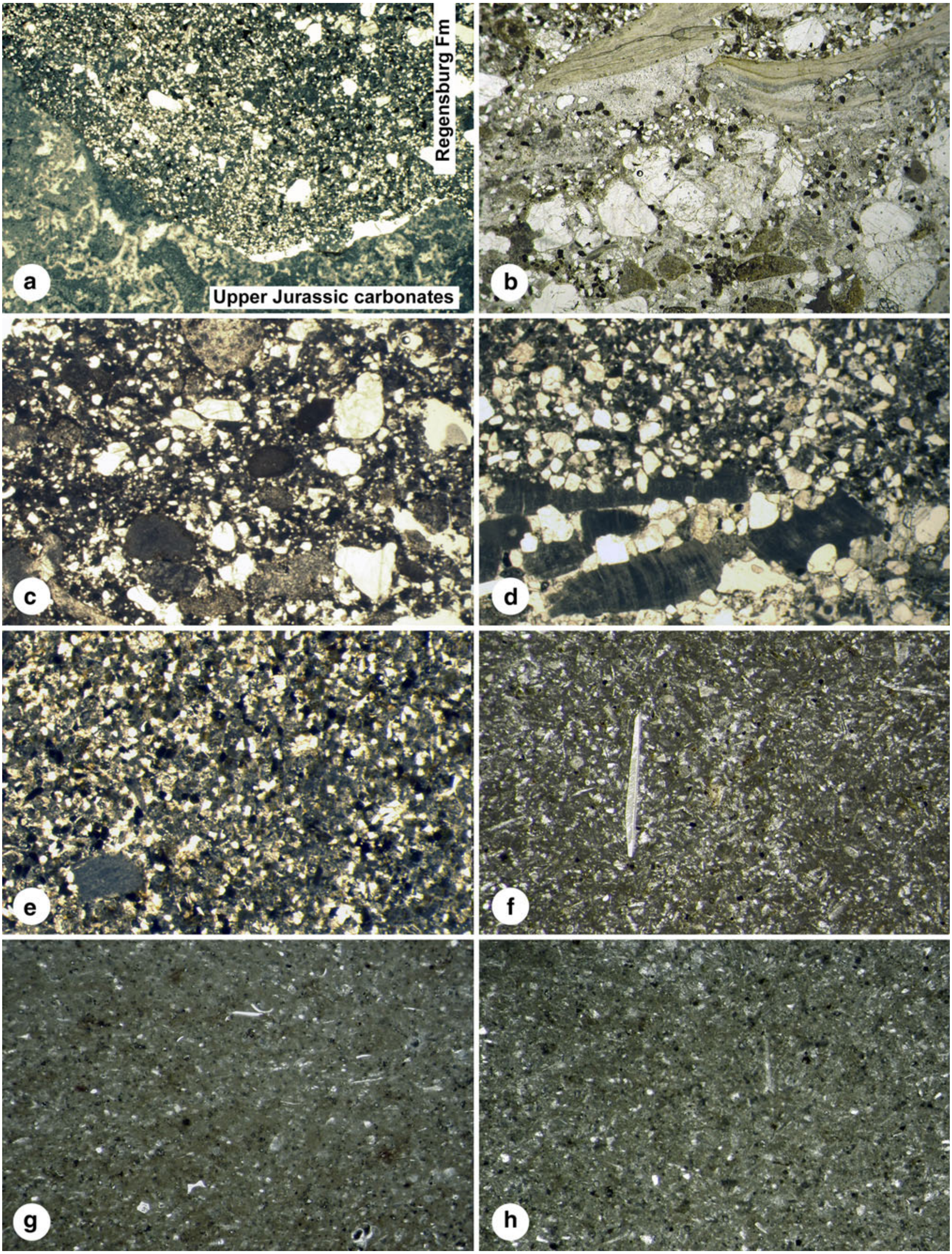
Fig. 6 Microfacies of the lower Danubian Cretaceous Group in the Regensburg area. **a** Hainsacker c. 8 km north of Regensburg. Transgression of glauconitic, fine-grained sandstones of the Regensburg Formation onto Upper Jurassic carbonates. Width of photomicrograph is 18 mm. **b** Saal section. Bioclastic, coarse-grained sandstones of the lowermost bed of the Saal Member of the Regensburg Formation. Bioclasts are mainly oyster fragments while small dark grains are glauconite. Note bimodal distribution of quartz grains (*light-colored*). Width of photomicrograph is 10 mm. **c** Schutzfelsen near Pentling. Poorly sorted, lithoclastic coarse-grained sandstones, lower part of the Saal Member of the Regensburg Formation. Width of photomicrograph is 10 mm. **d** Bad Abbach section. Graded, inoceramid debris-bearing, coarse- to medium-grained sandstone of the lower part of the Saal Member, 3 m above the base of the Regensburg Formation. Width of photomicrograph is 10 mm. **e** Bad Abbach section. Fine-grained, glauconitic sandstone of the middle part of the Saal Member, 5 m above the base of the Regensburg Formation. Note homogenous fabric and bioclast (probably echinoderm remain) in *lower left*. Width of photomicrograph is 5 mm. **f** Bad Abbach section. Bioclast-bearing spiculitic packstone from the upper part of the Bad Abbach Member, 15.5 m above the base of the Regensburg Formation. Small dark grains are glauconite. Width of photomicrograph is 5 mm. **g** Bad Abbach section. Microbioclastic wackestone with ostracods and planktic foraminifera (*lower right*) from the lower part of the Eibrunn Formation (at 18 m). Width of photomicrograph is 5 mm. **h** Bad Abbach section. Spiculitic wackestone from the lowermost part of the Reinhausen Member of the Winzerberg Formation (at 22.7 m). Width of photomicrograph is 5 mm ▶

Up-section, a unit of dm-thick, parallel-laminated and/or hummocky cross-bedded, calcareous, fine-grained sandstones with glauconite and oyster debris follows (FT 9), terminating the Regensburg Formation. When logged and correlated in cm-detail, the strata of the Regensburg Formation show conspicuous onlap patterns from S to N within the quarry with a minimum relief of 2 m in a distance of ca. 25 m (Fig. 8). The transition into the only 0.80-m-thin silty Eibrunn Formation is gradual and the lower Winzerberg Formation, consisting of medium- to coarse-grained sandstones of the Knollensand Member, terminates the Obertrübenbach section (Fig. 7).

Stratigraphy

Bio- and event stratigraphy

Based on the occurrence of the ammonite *Mantelliceras mantelli* from the lower part of the Saal Member in the now-abandoned Kapfelberg quarry near Saal, the lower strata of the Saal Member in the Regensburg–Kelheim area can be assigned to the early Early Cenomanian *Mantelliceras mantelli* Zone (Wilmsen et al. 2009a; Wilmsen and Niebuhr 2010). The succeeding fossiliferous middle part of the member can be dated as late Early Cenomanian *Mantelliceras dixoni* ammonite Zone based on the presence of abundant *Inoceramus virgatus virgatus* (Tröger et al. 2009; Wilmsen and Niebuhr 2010). This interval likewise represents the level of the mid-*dixoni* zonal *Inoceramus*


Regensburg Fm
Upper Jurassic carbonates
a
b
c
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e
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h

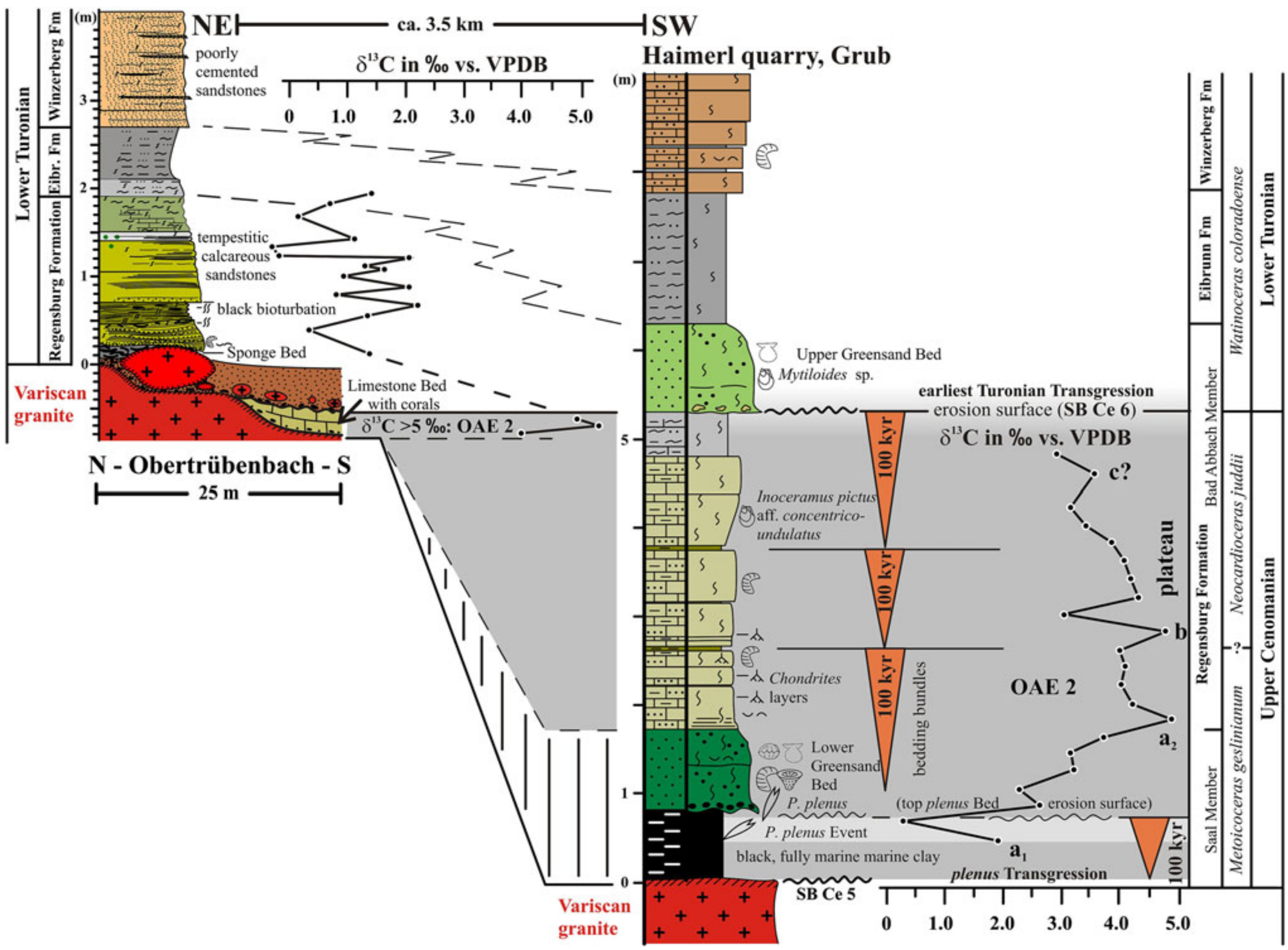


Fig. 7 Graphic logs of the Grub and Obertrübenbach sections including carbon stable isotope curves (cf. Chellouche 2008; Niebuhr 2008). For key of symbols see Fig. 5. Abbreviations: *Fm* Formation; *Eibr. Fm* Eibrunn Formation

virgatus Event (see Wilmsen 2008 and discussion below). The presence of a characteristic invertebrate fauna in coarse-grained bioclastic and glauconitic sandstone, above a major erosion surface in the upper part of the Saal Member indicates the early mid-Cenomanian *Praeactinocamax primus* Event (Ernst et al. 1983; see Wilmsen et al. 2007 for synopsis). The "Kalkmergelbank" of Förster et al. (1983) yielded the belemnite *Praeactinocamax plenus* and, slightly below, a mid-Upper Cenomanian (*Metoicoceras geslinianum* zonal) ammonite fauna (Förster et al. 1983; Röper and Rothgaenger 1995). The belemnite level corresponds to the mid-Upper Cenomanian *Praeactinocamax plenus* Event (see Wilmsen et al. 2010 for details).

In the Bodenwöhrer Senke, the occurrence of the inoceramid bivalve *Inoceramus pictus* aff. *concentricoundulatus* indicates a Late Cenomanian age for the Bad Abbach Member of the Regensburg Formation of Grub (Tröger et al. 2009). The proof of the mid-Upper Cenomanian *Praeactinocamax plenus* Event in the underlying black clay horizon capping the granite suggests a considerable delay in transgressive onlap between the Regensburg–Kelheim and Bodenwöhr areas (see discussion below and Wilmsen et al. 2010 for details).

Carbon stable isotopes

The carbon stable isotope curve of the Regensburg Formation at Bad Abbach (cf. Borota 2007) is characterized by a relatively flat signature with low values between −1.0 and +1.0‰ $\delta^{13}C$ vs. V-PDB (Fig. 5). Merely in the lowermost part, values of +2.0 to +2.2‰ $\delta^{13}C$ are recorded. The lower part of the section up to the erosional surface at 6.50 m shows mean values of c. 0.0 to +0.2‰ $\delta^{13}C$ whereas there is a slight shift towards heavier values of +0.5 to +1.0‰ $\delta^{13}C$ above that level up to ca. 11.50 m with a major negative peak in the marl above the brown omission surface at 10 m. The succession from 12 m to the top of the formation is characterized by relatively strong fluctuations. For the lower Eibrunn Formation, the curve of Hilbrecht and Hoefs (1986) was adopted. It is characterized

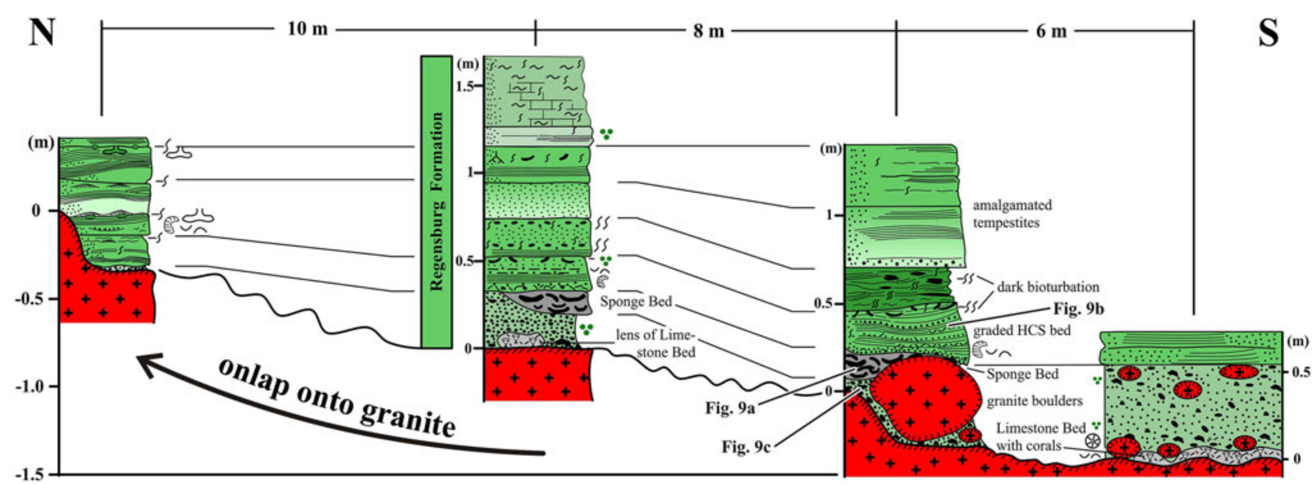


Fig. 8 Onlap pattern and bed-by-bed correlation in the Obertrübenbach quarry (cf. Niebuhr 2008). For key of symbols see Fig. 5

by a major positive excursion up to +4.0‰ δ^{13}C between 1.10 m and 2.20 m above the formational boundary.

The carbon stable isotope curve of the Regensburg Formation at Grub (cf. Chellouche 2008; Fig. 7) is characterized by a major positive excursion reaching values of up to +5.0‰ δ^{13}C. Values start to increase within the Lower Greensand Bed from relatively low values at the top of the underlying black clay to reach a first maximum at the transition into the Bad Abbach Member 1.70 m above the base of the section. A second maximum occurs 2.75 m above the base of the section. The δ^{13}C values stay high (above +3‰ δ^{13}C) up to the 5 m-level, below the Upper Greensand Bed. Samples from above had too low carbonate contents for δ^{13}C analysis.

The carbon stable isotope curve of the Regensburg Formation at Obertrübenbach (cf. Niebuhr 2008; Fig. 7) is characterized by very high values of +3.8 to +5.4‰ δ^{13}C only in the thin Limestone Bed resting directly on the granite in the southern part of the quarry. Above the erosion surface, the parallel-laminated/hummocky cross-bedded calcareous fine-grained sandstones yielded relatively low values between −1.0 and +2.3‰ δ^{13}C. Samples from the Eibrunn Formation provided no data due to their low carbonate contents.

Discussion

Integrated stratigraphy

The integrated data set of bio-, event, stable isotope, and sequence stratigraphic data allows a very precise reconstruction of the onlap pattern of the Regensburg and Eibrunn formations during the Cenomanian and Early Turonian (Fig. 11). As the biostratigraphic data are documented elsewhere (Tröger et al. 2009; Wilmsen et al. 2009a; Wilmsen and Niebuhr 2010), only event, stable isotope, and sequence stratigraphy will be discussed below. The biostratigraphic data clearly show that the Saal Member of the Regensburg Formation in the Regensburg–Kelheim area has an Early to early Middle Cenomanian age, and that the Bad Abbach Member is older than the mid-Late Cenomanian (Wilmsen and Niebuhr 2010). Biostratigraphic information for the Bodenwöhrer Senke is sparse (see Tröger et al. 2009), but the event and carbon stable isotope data indicate that the base of the Regensburg Formation is diachronous on short distances, being not older than mid-Late Cenomanian.

Event stratigraphy

Three important stratigraphic events can be recognized in the Regensburg and Eibrunn formations of the lower Danubian Cretaceous Group. The first one is the so-called *Schloenbachia/I. virgatus* Event in the mid-*Mantelliceras dixoni* Zone of the late Early Cenomanian (Fig. 5; see Ernst et al. 1983; Wilmsen 2008). Albeit the characteristic Boreal ammonite *Schloenbachia varians* is not known from the Danubian Cretaceous Group, the abundant occurrences of frequently double-valved *Inoceramus virgatus virgatus* in the middle Saal Member of the Regensburg–Kelheim area can be correlated with the event (Wilmsen and Niebuhr 2010). The stratigraphic position within a maximum flooding interval of the mid-*Mantelliceras dixoni* ammonite Zone (see below) is in good accordance with the sequential setting of the *Schloenbachia/I. virgatus* Event in NW Europe (see Wilmsen 2008 for synopsis).

The second important event, the lower Middle Cenomanian *Praeactinocamax primus* Event, is not evident from the eponymous marker belemnite *P. primus*, but its presence is indicated by a conspicuous invertebrate fauna consisting of small solitary corals, *Orbirhynchia* sp.,


a
b
2 cm
c

◀ **Fig. 9** Lithofacies specimens from the Regensburg Formation in the Obertrübenbach quarry (natural size, *scale bar* for all figures). **a** Sponge Bed with siliceous sponges in situ (*lower part*) capped by two bio- and lithoclastic layers rich in alkali feldspar. **b** Bio- and lithoclastic, glauconitic, hummocky cross-stratified, medium- to coarse-grained sandstone tempestite. Bioclasts are predominantly oyster shells (many in convex-up position). Lithoclasts are orange alkali feldspars and marly limestones (*center right*). Note swelling of bed towards *left* (bed immediately above the Sponge Bed). **c** Poorly sorted basal transgression conglomerate with pebbles and granules of crystalline basement rocks (mainly vari-colored metaquartzites, milky quartz, and metatexites) in a weakly glauconitic, coarse-grained sandy matrix. Note only moderate rounding of components

pectinid bivalves, serpulids and small irregular echinoids (*Discoides subuculus*) in coarse-grained transgressive sediments of the upper Saal Member from the Regensburg–Kelheim area above a prominent erosion surface (Figs. 5, 11). This fits very well the sequence stratigraphic setting of the *primus* Event, which is a transgressive bioevent low in the *Acanthoceras rhotomagense* ammonite Zone following a major sea-level drop and lowstand in the Lower–Middle Cenomanian boundary interval (Wilmsen 2003, 2007; Wilmsen and Wood 2004; Wilmsen et al. 2007; Wilmsen and Rabe 2008). The superposition of the sequence boundary and the *primus* Event suggest the presence of a significant stratigraphic gap at the unconformity.

The third bioevent, the mid-Late Cenomanian (*Metoicoceras geslinianum* ammonite zonal) *Praeactinocamax plenus* Event (Fig. 11), is well known from the lower part of the Eibrunn Formation in the Regensburg–Kelheim area where it occurs in the so-called Kalkmergelbank and is associated with a positive carbon stable isotope excursion (Förster et al. 1983; Hilbrecht et al. 1986; Hilbrecht and Hoefs 1987; Röper and Rothgaenger 1995; Wilmsen et al. 2010). In the Bodenwöhrer Senke (Grub section), the *plenus* Event occurs in the lower part of the Regensburg Formation. Interestingly, the *plenus* Event in Grub is subdivided along an erosional surface at the base of the Lower Greensand Bed into two levels (Chellouche 2008; Wilmsen et al. 2010). This fits very well the stratigraphic pattern of the *plenus* Event in northern Germany and the Anglo-Paris Basin (Wiese et al. 2009; Wilmsen et al. 2010), and a correlation with the erosion surface at the top of the *plenus* Bed in northern Germany and at the base of Jeffries Bed 4 of the *plenus* Marls in the Anglo-Paris Basin is suggested.

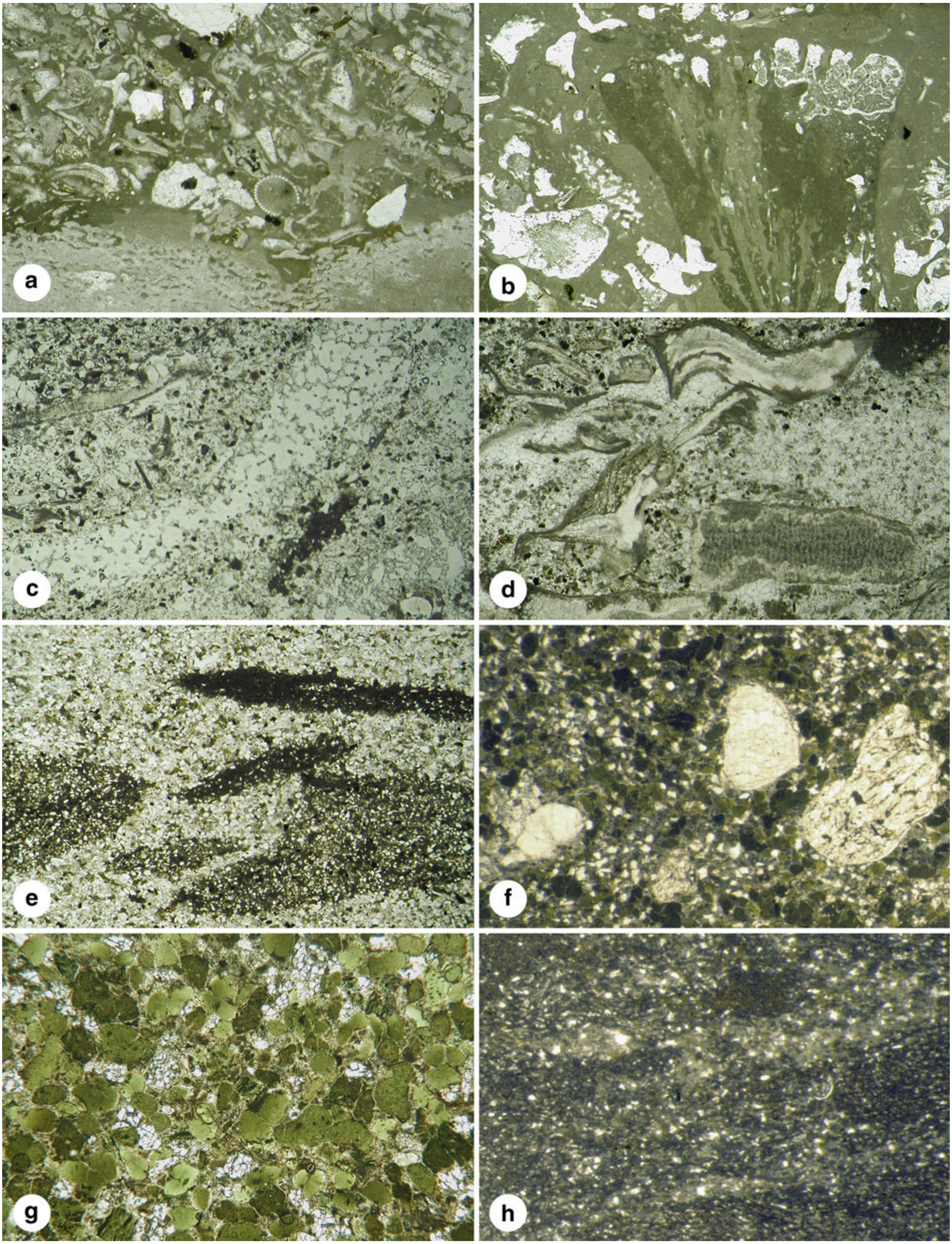
Carbon stable isotope stratigraphy

The carbon stable isotope curve of the Regensburg Formation at Bad Abbach is difficult to interpret. The relatively flat signature of the Lower Cenomanian is punctuated by two negative excursions in the *Mantelliceras dixoni* Zone which may be correlated with the *virgatus* Beds and mid-*dixoni* Event of Jarvis et al. (2006). The shift to slightly heavier values in the lower Middle Cenomanian is also observed in NW Europe (Wilmsen and Niebuhr 2002; Jarvis et al. 2006; Wilmsen 2007) albeit the positive excursion MCE (Mitchell et al. 1996) around the *primus* Event is not well expressed. The negative peak at ca. 11 m is in the stratigraphic position of the p/b-break Event of Jarvis et al. (2006) and would also fit a maximum flooding zone in a sequential framework (see below). The strong scatter of the $\delta^{13}C$ values up to the base of the Eibrunn Formation cannot be safely correlated with the reference curve of Jarvis et al. (2006).

The carbon stable isotope curve of the Eibrunn Formation is adopted from Hilbrecht and Hoefs (1986) because the marls of the Eibrunn Formation are in the meantime too deeply weathered for a meaningful analysis (a fresh core section would be needed). Unfortunately, the existing curve is of low resolution. However, it shows at least a part of the positive excursion of the OAE 2 that can be used to correlate the section to the Bodenwöhrer Senke and elsewhere.

In the Grub section of the Bodenwöhrer Senke, the positive $\delta^{13}C$ excursion of the OAE 2 is well represented and allows to correlate the standard biozonation into the succession (Figs. 7, 11). Similar to the situation in Wunstorf, northern Germany (Voigt et al. 2008), at least a part of the a-peak of the OAE 2 excursion (see Jarvis et al. 2006 for terminology) is located above the *plenus* Event and shows the highest positive values. The b-peak correlates with the positive peak at 2.70 m and the c-peak is tentatively placed at 4.60 m. The high values up to the 5-m level suggest that the strata below the erosional base of the Upper Greensand Bed are still Late Cenomanian in age, belonging to the *Metoicoceras geslinianum* and *Neocardioceras juddii* ammonite zones (see Voigt et al. 2007, 2008). This isotope stratigraphic interpretation is supported by the occurrence of *Inoceramus pictus* aff. *concentricoundulatus* ca. 4.20 m above the base of the Grub section (Tröger et al. 2009). The presence of poorly preserved *Mytiloides* sp. (non *hattini*) in the Upper Greensand Bed at the ca. 5.80-m-level suggests already an Early (but not basal) Turonian age.

The presence of $\delta^{13}C$ values of >+5.0 ‰ only in the thin Limestone Bed resting on the granite substrate in the southern part of the Obertrübenbach quarry can only be explained as a signature of the OAE 2 and suggest that the section represented an island or coastal cliff that was only marginally flooded during the Cenomanian–Turonian Boundary Event (i.e., the *Metoicoceras geslinianum* and *Neocardioceras juddii* ammonite zones). The low values of the strata above the erosional surface capping the isotopically heavy Limestone Bed strongly suggest that they are already Early Turonian in age (see, e.g., Voigt et al. 2008 for detailed isotope stratigraphy of the OAE 2 and the


a
b
c
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◀ **Fig. 10** Microfacies of the Regensburg Formation in the Bodenwöhrer Senke (Obertrübenbach and Grub sections). **a** Obertrübenbach section. Limestone Bed at the base of the Regensburg Formation, CTBE Transgression. Microsolenid coral (*below*) overlain by bioclastic packstone. Bioclasts are dominated by recrystallized mollusc fragments and echinoderm debris (mainly spines of regular echinoids). Dark grains are allochthonous glauconite. Width of photomicrograph is 10 mm. **b** Obertrübenbach section. Limestone Bed at the base of the Regensburg Formation, CTBE Transgression. Bioclastic floatstone with fragments of solitary corals. Note vugs filled by vadose silt and sparry calcite. Width of photomicrograph is 10 mm. **c** Obertrübenbach section. Strongly silicified, spiculitic wackestone with lithistid siliceous sponge, Sponge Bed in the lower part of the Regensburg Formation, earliest Turonian Transgression. Width of photomicrograph is 10 mm. **d** Obertrübenbach section. Sandy, bio- and lithoclastic pack- to rudstone with oyster and echonoderm debris (fragment in lower left preserves the vesicular shell structure typical of pycnodonteines such as *Pycnodonte* (*Phygraea*) *vesicularis*). Lower part of the Regensburg Formation, earliest Turonian Transgression. Width of photomicrograph is 10 mm (in macroscopic view, hummocky cross-stratification is presents, cf. Fig. 9b). **e** Obertrübenbach section. Spiculitic, fine-grained sandstone with sub-horizontal *Chondrites* bioturbation. Upper part of the Regensburg Formation. Width of photomicrograph is 10 mm. **f** Grub section. Glauconitic sandstone, base of the Lower Greensand Bed of the Regensburg Formation. Note dispersed large alkali feldspar clasts. Width of photomicrograph is 6 mm. **g** Grub section. Quartz-bearing glauconitite, upper part of the Lower Greensand Bed of the Regensburg Formation. Note that glauconite grains are conspicuously larger than quartz grains. Width of photomicrograph is 10 mm. **h** Grub section. Fine-grained, silty wackestone, lower part of the Bad Abbach Member of the Regensburg Formation. Note inhomogeneous fabric due to bioturbation (mainly *Chondrites* isp.). Width of photomicrograph is 6 mm

Lower Turonian) and link the unconformity to the erosional surface at the base of the Upper Greensand Bed in the Grub section (see below).

The isotope stratigraphy demonstrates that the Regensburg Formation of the Bodenwöhrer Senke ranges from the mid-Upper Cenomanian into the lowermost Turonian (Grub section) or is entirely of earliest Turonian age (northern part of the Obertrübenbach section). Furthermore, it places the Eibrunn Formation of that area entirely in the lower Lower Turonian and provides chronostratigraphic constrains for a not yet widely recognized unconformity near the Cenomanian–Turonian boundary (see below).

Sequence stratigraphy

The logged sections show a clear stacking pattern of unconformities (omission and/or erosional surfaces) and more-or-less conformable packages of strata that can be interpreted in terms of sequence stratigraphy (Fig. 11). The depositional sequences usually consist of only transgressive and highstand systems tracts (TST and HST), which is readily explained by the up-dip position of the sections and the lack (or even destruction) of accommodation space during falling and lowstand systems tracts (FSST and LST; for terminology see Coe 2003). Following the integrated stratigraphic revision of the (lower) Danubian Cretaceous Group (Niebuhr et al. 2009; Tröger et al. 2009; Wilmsen et al. 2009a; Wilmsen and Niebuhr 2010; this study), the successions of the Regensburg–Kelheim area and the Bodenwöhrer Senke can also be related to the well-studied successions of northern Germany and the Anglo-Paris Basin (Robaszynski et al. 1998; Wilmsen 2003).

The Lower to lower Upper Cenomanian is only present in the Regensburg–Kelheim area and, thus, the sequence stratigraphy is based on the Saal and Bad Abbach sections (Fig. 11). The Lower Cenomanian shows two relatively thin sequences and one slightly thicker depositional sequence with an overall retrogradational stacking pattern; the latter sequence is capped by a major unconformity. This sequential trend is identical to the situation in northern Germany and the Anglo-Paris Basin (Wilmsen 2003, 2007), and relates the three unconformities within the Saal Member to the inter-regional/global sequence boundaries SB Ce 1–3. Following a sea-level lowstand across the Lower–Middle Cenomanian boundary, the early Middle Cenomanian was characterized by a major eustatic sea-level rise (see Wilmsen 2007). This development is mirrored by the change from the Saal to the Bad Abbach Member of the Regensburg Formation and culminates in a thick marl bed interpreted as maximum flooding zone. Interestingly, this marl bed is characterized by a negative carbon stable isotope excursion interpreted as the p/b-break Event of Jarvis et al. (2006). Sequentially, this event also characterizes a maximum flooding interval in the Anglo-Paris Basin, giving strong support for the proposed correlation. The late Middle Cenomanian sequence boundary SB Ce 4 is tentatively placed at the base of a conspicuous marl bed at the 13-m level of the Bad Abbach section, which terminates a highstand unit (Fig. 11). Above, a retro- and progradational unit up to the top of the formation is interpreted as depositional sequence SB Ce 5. According to Walther's law of facies, a belt of shallow-water greensands (Saal Member facies) must have been present between the still emergent Bodenwöhrer Senke and the deeper Regensburg–Kelheim area (characterized by Bad Abbach Member facies) during the Middle and early Late Cenomanian. Evidence for this interpretation is provided by the Benberg section north of Regensburg where the Regensburg Formation is only 8 m thick, consists entirely of the Saal Member, and is overlain along SB Ce 5 by the Eibrunn Formation including the *plenus* Event (Förster et al. 1983; Wilmsen et al. 2010).

The top of the Regensburg Formation in the Regensburg–Kelheim area is sharp and marked by an omission surface. It correlates with the prominent mid-Late Cenomanian sequence boundary SB Ce 5 at the transition from the *Calycoceras naviculare* to the *Metoicoceras geslinianum* Zone (Robaszynski et al. 1998; Wilmsen 2003). This

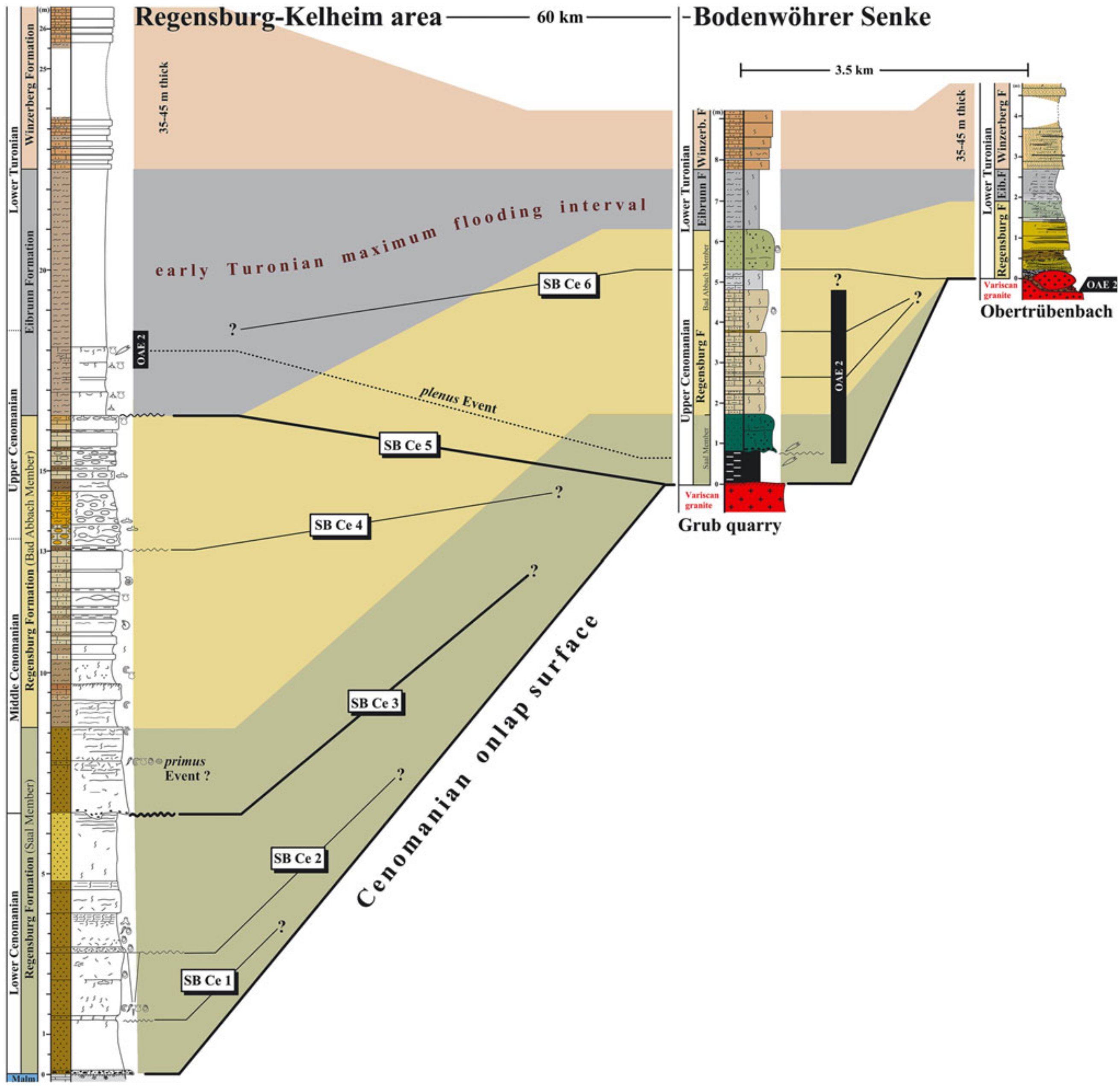

Fig. 11 Correlation diagram of the lower Danubian Cretaceous Group based on the Bad Abbach, Grub, and Obertrübenbach sections. Note the diachroneity of lithostratigraphic units (traced by their typical colors). Correlation lines are chronostratigraphic surfaces (sequence boundaries, stratigraphic events). For key of symbols see Fig. 5

surface is equivalent to the Facies Change in northern Germany ("Faziesgrenze" of Ernst et al. 1983). The following transgressive development of the Cenomanian–Turonian Boundary Event (CTBE) is associated with the *plenus* Event (*plenus* Transgression) and the positive carbon stable isotope excursion of the OAE 2. It led to the deposition of fine-grained sediments of the Eibrunn Formation in the Regensburg–Kelheim area and the onlap of the Regensburg Formation onto the proximal granite massifs of the Bodenwöhrer Senke (Fig. 11). The transgression was interrupted by a minor sea-level fall near the Cenomanian–Turonian boundary forming an unconformity, which is only well expressed in the shallow-water successions (base Upper Greensand Bed in Grub, top of Limestone Bed in Obertrübenbach with dissolution vugs overlain by coarse clastics; Figs. 7, 8, 10b). This event is not yet widely recognized, but it may correspond to the omission surface at the base of the Bila Hora Formation in the Bohemian Cretaceous Basin (Ulicný et al. 1993), the top of the Dölzschen Formation in the Saxonian Cretaceous

Basin (Wilmsen et al. 2009b), and the top-hardground of the Beer Head Limestone in the condensed Cenomanian successions in Devon, SW England (Carson and Crowley 1993), thus being of inter-regional importance. The name SB Ce 6 is proposed for this sequence boundary (Fig. 11).

The early Late Cretaceous transgression continued in the earliest Turonian, leading to the deposition of a thin tongue of the deeper marine Eibrunn Formation also in the Bodenwöhrer Senke, representing an early Early Turonian maximum flooding event which appears to be a truly global signal (Hardenbol et al. 1998; mfs K140 of Sharland et al. 2001). The base of the Winzerberg Formation already signals the beginning of shallowing and thus the transition into succeeding highstand deposition. The HST is capped by a prominent sequence boundary in the Lower–Middle Turonian boundary interval at the top of the Winzerberg Formation ("Hornsand unconformity" of Niebuhr et al. 2009).

The sequence stratigraphic analysis shows that the Cenomanian second-order transgression was punctuated by five prominent sea-level falls (plus one close to the C–T boundary). The resulting sedimentary unconformities in the Regensburg Formation (SB Ce 1–5) seem to correlate with those being known from basins in Middle Europe (Robaszynski et al. 1998; Wilmsen 2003) and elsewhere (e.g., Tunisia, Robaszynski et al. 1993), indicating their eustatic origin and, thus, chronostratigraphic significance.

CTBE sea-level rise

The sequence stratigraphic reconstructions and onlap patterns of the Upper Cenomanian–Lower Turonian strata in the Bodenwöhrer Senke combined with integrated high-resolution stratigraphy and estimates of water depth changes by means of detailed facies analysis (cf. Sahagian et al. 1996; Immenhauser 2005) offer the opportunity to quantify the sea-level rise of the Cenomanian–Turonian Boundary Event (CTBE, Fig. 12). The situation is similar to the condition in Saxony (eastern Germany) where Voigt et al. (2006) used the Upper Cenomanian succession around a paleo-cliff in Dresden to infer absolute sea-level changes. In both cases, the onlap pattern can be related to eustatic sea-level changes based on the tectonically stable regional settings and the inter-regional correlation of the sequence of events.

A prerequisite for quantification of geological processes, such as sea-level change, is the existence of a robust age model. For the successions in the Bodenwöhrer Senke, this age model is based on the correlation of the carbon stable isotope stratigraphy combined with the apparent cyclicity, which can be correlated to the orbitally fine-tuned CTBE section of Wunstorf in northern Germany (Voigt et al. 2008). In Wunstorf, the top of the *plenus* Bed is a sharp omission surface which can be isotopically and event-stratigraphically correlated to the erosional base of the Lower Greensand Bed in Grub (see above). Below the *plenus* Bed, there is a bundle of strata starting with the first significant black shale of the OAE 2, and this set represents a short eccentricity of the Milankovitch band (i.e., 100 ka) cycle (Voigt et al. 2008). The belemnite *Praeactinocamax plenus* occurs towards the top of the *plenus* Bed and the beds below show clear onlap patterns (Wiese et al. 2009). The transgressive black marine clay below the Lower Greensand Bed is thus inferred to have been formed during this onlapping short eccentricity cycle which was apparently deposited in a single cycle of sea-level rise.

Above the top-*plenus* Bed omission surface in Wunstorf, there are three more short eccentricity cycles, the top of the uppermost of which is a significant omission surface close to the Cenomanian–Turonian boundary followed by a significant deepening into the Early Turonian (Voigt et al.

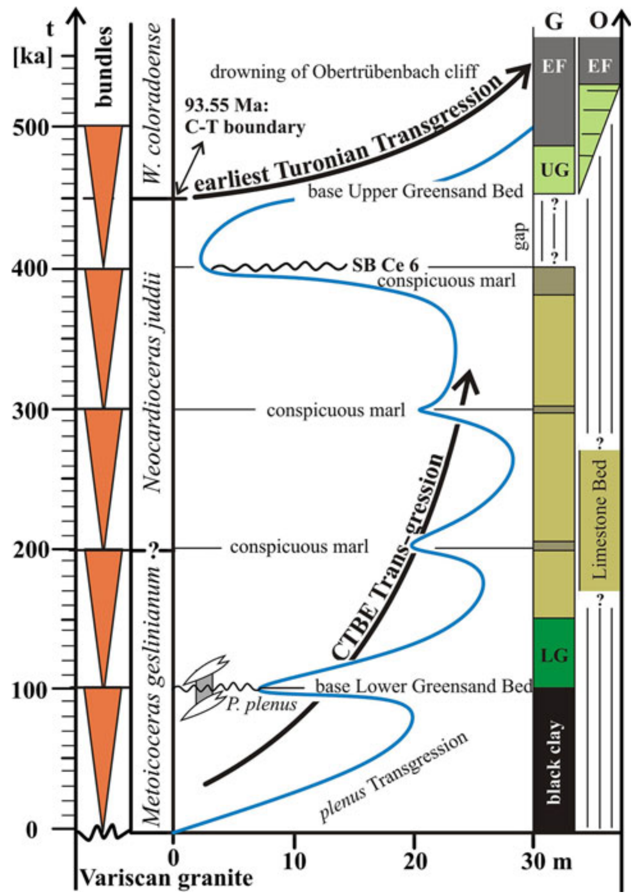

Fig. 12 Onlap pattern of the Regensburg and Eibrunn (*EF*) formations reconstructed from the successions in the Bodenwöhrer Senke (cf. Fig. 7; *G* Grub; *O* Obertrübenbach) and inferred absolute sea-level changes in meters (age model modified after Voigt et al. 2008, C–T boundary age after Gradstein et al. 2004). The rate of change suggests glacio-eustasy for the latest Cenomanian sea-level rise (see text for further explanations)

2008). The same pattern of Milankovitch-driven cyclicity and sea-level development can be inferred from the Grub and Obertrübenbach sections, albeit in a much more proximal position (Fig. 12). From the base of the Lower Greensand Bed (=top-*plenus* Bed omission surface), there are three Upper Cenomanian bundles of strata in the Bad Abbach Member of Grub bounded by thin conspicuous marls below the Upper Greensand Bed. These bedding bundles are easily recognized in the cliff face (cf. Figs. 4c, 7) and internally stratified. The bounding darker marl seams have higher silt/sand contents and characterize periods of increased siliciclastic input. Above the Upper Greensand Bed, a further deepening associated with a final submergence of the Obertrübenbach cliff in the earliest Turonian is recorded, providing strong evidence for short-term and rapid eustatic sea-level changes at the southern flank of the Mid-European Island during the CTBE. Given the short period of geological time involved (less than 500 ka) and the tectonically stable position of the sections, (minimal) regional subsidence is not considered in the following estimates of magnitudes and rates of CTBE sea-level change.

From the foregoing age constrains it follows that the onlap of the open-marine black clay onto the Variscan granite in Grub happened in the early *Metoicoceras geslinianum* Zone within 100 ka or less. The minimum water depth of deposition of this bed which certainly accumulated below storm-wave base is 20 m, resulting in a minimum rate of sea-level rise of 200 m/Ma. This rate of rise can only be explained by glacio-eustasy (e.g., Pitman and Golovchenko 1983; Miller et al. 2005) or a yet unknown process. The following unconformity at the base of the Lower Greensand Bed appears to be associated with a short-term sea-level fall which at least shifted the depositional environment above fair-weather wave base or even back into an emergent setting. The following rise within the next 100-ka cycle (still *Metoicoceras geslinianum* Zone) was likewise very rapid and shifted the Grub section back into a sub-storm wave base environment (>20 m of water depth). The presented estimates fit very well the data from the drowned paleo-cliff in Saxony at the northern margin of the Mid-European Island where Voigt et al. (2006) reconstructed a *Metoicoceras geslinianum* zonal sea-level rise of 22–28 m in less than 200 ka. During the two following (*Neocardioceras juddii* zonal) 100-ka cycles, the transgressive development continued, being terminated shortly before the Cenomanian–Turonian boundary (unconformity at the base of the Upper Greensand Bed). The following rapid rise into the earliest Turonian was again related to only one 100-ka cycle (see also Voigt et al. 2008), and the submergence of the Obertrübenbach cliff from above sea level to below storm-wave base again suggests a high magnitude of >20 m (Fig. 12).

This case study shows clearly the great potential of stratal and facies analyses within a high-resolution framework of integrated stratigraphy for the quantification of past sea-level change. It thus provides non-isotopic evidence for a glacio-eustatic control on mid-Cretaceous sea-level changes.

Paleogeography

The Late Cretaceous transgression started in the Regensburg–Kelheim area in the early Early Cenomanian with a patchily distributed basal conglomerate of the Regensburg Formation over a peneplained paleo-karst topography sealed by fluvial to limnic deposits of the Lower Cretaceous Schutzfels Formation. The flat-topped surface of the Upper Jurassic carbonates is often bored by bivalves (see also Trusheim 1935) and may represent wave-cut abrasion platforms. With further rise of sea level, base-level rose above the sea floor and accommodation space was created for the deposition of the Saal Member of the Regensburg Formation. The Saal Member represents the inner shelf facies of the transgressing Cenomanian Sea (Fig. 13), and the moderately diverse assemblage of shallow-water bivalves, brachiopods, serpulids, siliceous sponges and echinoids as well as pervasive bioturbation suggest favorable environmental conditions.

Associated with a further, significant sea-level rise in the Middle Cenomanian, sedimentation in the Regensburg–Kelheim area changed to fine-grained, glauconite-poor and more carbonate-rich spiculitic siltstones and silty siliceous limestones with marl interbeds (mid-shelf facies of the Bad Abbach Member; Fig. 13). The inner shelf greensand belt was north of Regensburg at that time. A conspicuous facies change, associated with signatures of omission, to silty marls of the Eibrunn Formation occurred in the middle part of the Upper Cenomanian (*Calycoceras naviculare*–*Metoicoceras geslinianum* zonal boundary) and is related to the transgressive development of the CTBE. Deposition of the Eibrunn Formation occurred below the storm-wave base in a paleo-waterdepth of a few tens of meters, representing the deeper shelf facies of the early Late Cretaceous Sea (Fig. 13).

In the Bodenwöhrer Senke, ca. 40 km NE of Regensburg, deposition of the Danubian Cretaceous Group started with the *plenus* Transgression of the CTBE in the early *Metoicoceras geslinianum* Zone (basal black clay horizon of Grub). Up-section, the Regensburg Formation shows the deepening associated with the CTBE by means of a facies change into the fine-grained mid-shelf Bad Abbach Member. In terms of macrobenthos, the upper Upper Cenomanian Regensburg Formation of the Bodenwöhrer Senke appears impoverished in contrast to the older units in the south despite a similar depositional environment, implying

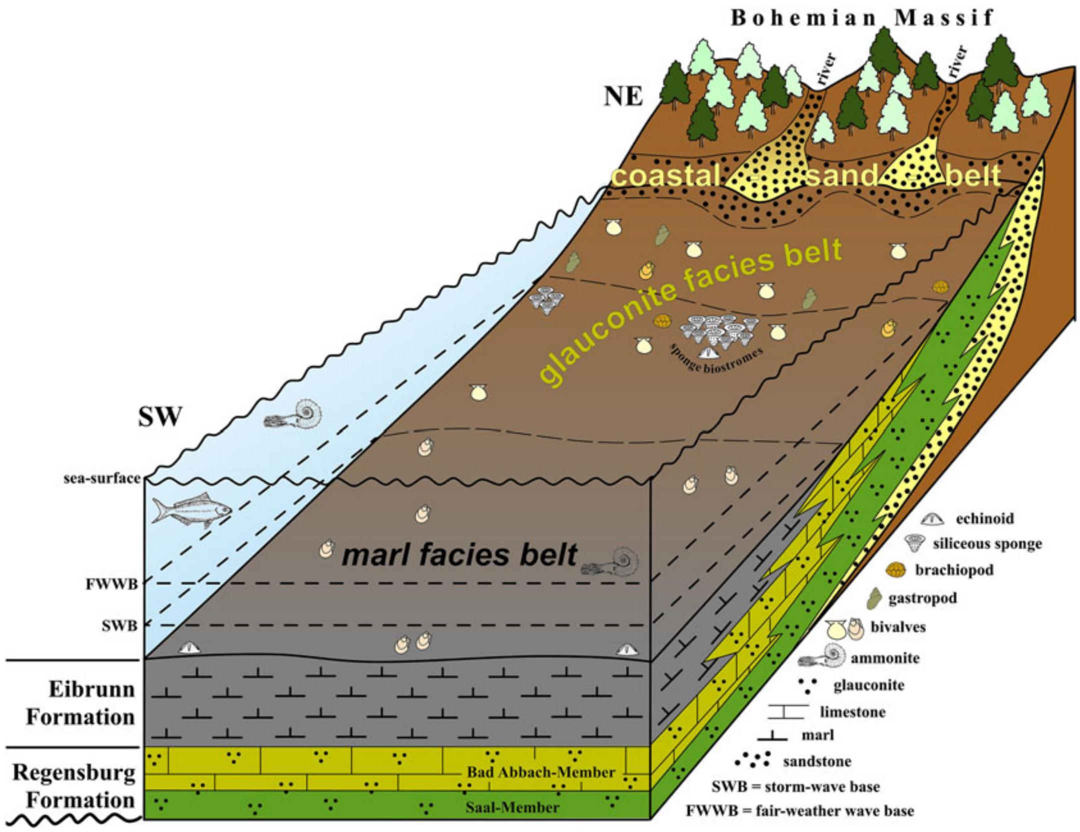

Fig. 13 Facies model and paleogeographic reconstruction for the lower part of the Danubian Cretaceous Group showing the transgressive onlap of the Regensburg and Eibrunn formations towards the NE onto the Bohemian Massif

an impact of OAE 2 also in relative shallow-water settings (cf. Ulicný et al. 1993; Hilbrecht et al. 1996). During that interval, coastal cliffs or emergent islands still persisted nearby (e.g., Obertrübenbach).

Following the short-term regression near the Cenomanian–Turonian boundary, a flooding of the Obertrübenbach cliff (or island) occurred during the earliest Turonian Transgression. The fabric (poor sorting and only moderate rounding) of the transgression conglomerate can only be explained by a very fast rise in sea level (rapid deposition and only limited time for high-energy maturation). The following set of hummocky cross-stratified tempestites shows small-scale onlap pattern towards the north (Bohemian Massif) and suggests a continued rise of base-level (fair-weather wave base rose above the cliff top), and finally a submergence below the storm-wave base (deposition of a thin tongue of the muddy Eibrunn Formation).

The Regensburg and Eibrunn formations of the lower Danubian Cretaceous Group highlight the diachronous nature of the lithostratigraphic units formed during the early Late Cretaceous transgression. Their northeast-directed onlap pattern can readily be explained by the lateral movements of roughly coast-parallel facies belts of a graded shelf system transgressing on an inclined surface formed by the southwestern margin of the Bohemian Massif (Fig. 13). It took the coastline ca. 6 Ma of geological time (ca. 99–93 Ma according to Gradstein et al. 2004) to transgress about 60 km from southwest of Regensburg to southeast of Roding (see Fig. 1).

Conclusions

The facies development and onlap pattern of the lower Danubian Cretaceous Group (Bavaria, southern Germany) have been evaluated based on detailed logging, subdivision and correlation of four key sections using an integrated stratigraphic approach as well as litho-, bio-, and microfacies analyses. The study results in a considerable revision of the stratigraphy and paleogeography of that area and has important consequences for sea-level dynamics during early Late Cretaceous times.

The transgressive onlap of the Regensburg Formation started in the Regensburg–Kelheim area already in the early Early Cenomanian *Mantelliceras mantelli* Zone (and not in the Late Cenomanian as frequently stated in the literature; e.g., Meyer 2000). In the Early Cenomanian, nearshore glauconitic-bioclastic sandstones prevailed (Saal

Member), followed by Middle to lower Upper Cenomanian mid-shelf siliceous carbonates intercalated with fine-sandy to silty marls (Bad Abbach Member). Starting in the *Metoicoceras geslinianum* Zone of the mid-Late Cenomanian, a considerable deepening pulse during the Cenomanian–Turonian Boundary Event (CTBE) led to the deposition of the deeper shelf silty marls of the Eibrunn Formation, which range into the early Early Turonian. During the CTBE transgression, also the proximal Bodenwöhrer Senke (ca. 50 km NE of the Regensburg–Kelheim area) was flooded, indicated by the onlap of the Regensburg Formation onto Variscan granites of the Bohemian Massif, overlain by a thin tongue of lowermost Turonian Eibrunn Formation. A detailed record of the positive δ^{13}C excursion of the global Oceanic Anoxic Event (OAE) 2 accompanying the CTBE has been recorded from this shallow-water setting. An integrated approach of bio-, event-, carbon stable isotope and sequence stratigraphy was applied to correlate the sections on a distal-proximal transect, and to decipher the dynamics of this overall transgressive depositional system. The sequence stratigraphic analysis shows that the Cenomanian transgression was punctuated by five prominent sea-level falls (and a sixth one close to the Cenomanian–Turonian boundary), and the resultant unconformities seem to correlate with those being known from basins in Europe and elsewhere, indicating their eustatic origin. The study of the onlap pattern of the CTBE in the Bodenwöhrer Senke onto basement rocks combined with a high-resolution age model suggests glacio-eustasy (or a yet unknown process causing rapid eustatic change) as a driving mechanism for the sea-level rise during the Late Cenomanian.

The Regensburg and Eibrunn formations of the lower Danubian Cretaceous Group are highly diachronous lithostratigraphic units that were deposited during the early Late Cretaceous transgressions. Their regional distribution and northeast-directed onlap pattern onto the southwestern margin of the Bohemian Massif can readily be explained by the lateral movements of roughly coast-parallel (i.e., NW/SE-trending) facies belts of a graded shelf system transgressing on an inclined surface. It took the coastline ca. 6 Ma to transgress from southwest of Regensburg (Kelheim) to the topographically elevated granite cliffs southeast of Roding in the Bodenwöhrer Senke (=60 km distance), resulting in a mean coastal shift of 10 km/Ma.

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