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Facies and integrated stratigraphy of the Upper Turonian (Upper Cretaceous) Großberg Formation south of Regensburg (Bavaria, southern Germany)

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ABSTRACT:

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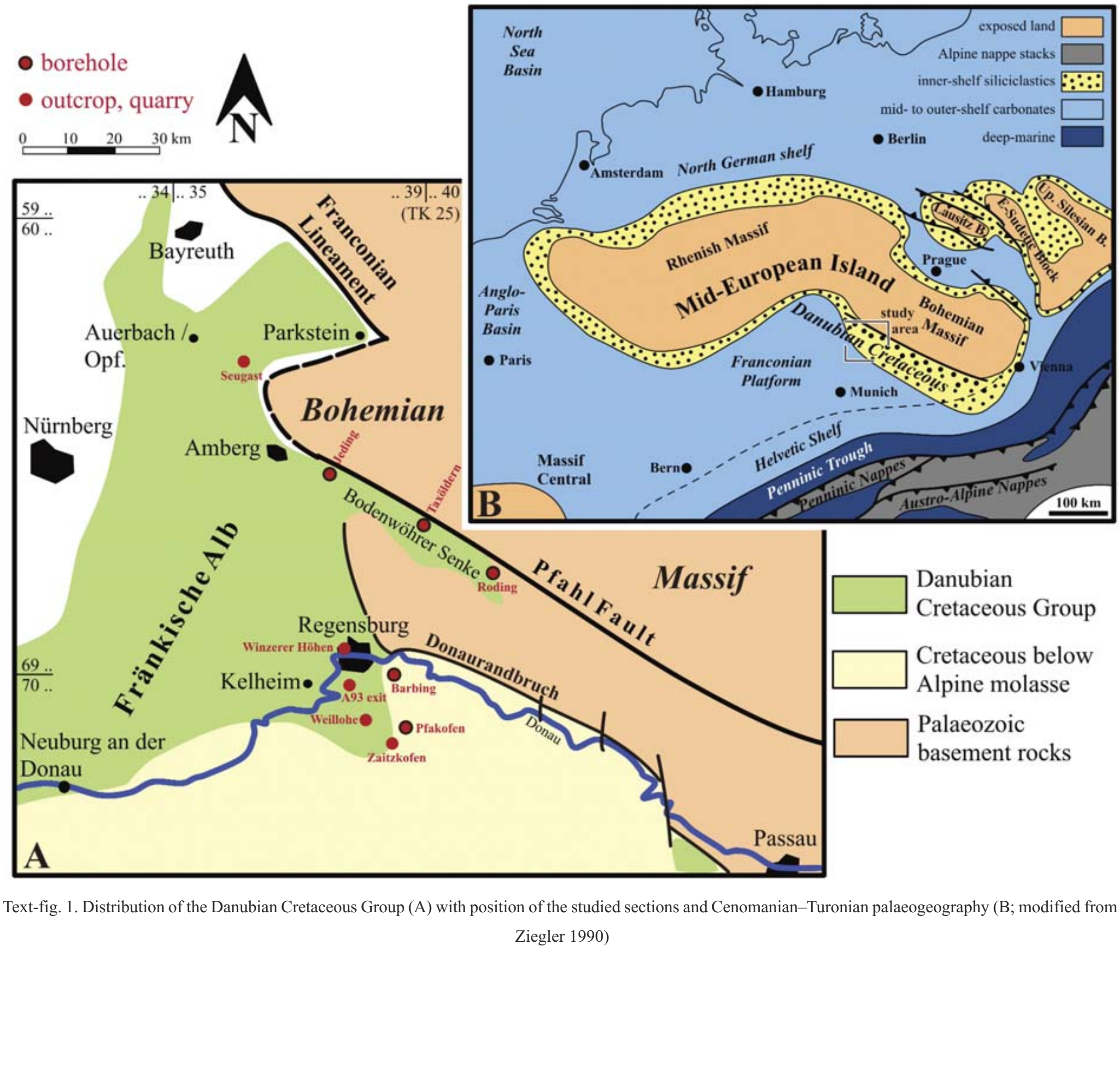
The Upper Turonian Großberg Formation of the Regensburg area (Danubian Cretaceous Group, Bavaria, southern Germany) has a mean thickness of 20–25 m and consists of sandy bioclastic calcarenites and calcareous sandstones which are rich in bryozoans, serpulids and bivalves (oysters, rudists, inoceramids). Eight facies types have been recognized that characterize deposition on a southward dipping homoclinal ramp: the inner ramp sub-environment was characterized by high-energy sandwave deposits (sandy bioclastic rud- and grainstones, bioclastic sandstones) with sheltered inter-shoal areas. In mid-ramp settings, bioturbated, glauconitic, calcareous sand- and siltstones as well as bioturbated, bioclastic wacke- and packstones predominate. The carbonate grain association of the Großberg Formation describes a temperate bryomol facies with indicators of warm-water influences. An inferred surplus of land-derived nutrients resulted in eutrophic conditions and favoured the heterozoan communities of the Großberg Ramp. Carbon stable isotope geochemistry cannot significantly contribute to the stratigraphic calibration of the Großberg Formation due to the depleted and trendless bulk-rock $\delta^{13}C$ values, probably resulting from a shallow-water aquafacies with depleted $\delta^{13}C_{DIC}$ values and low $\delta^{13}C$ values of syndepositional and early diagenetic carbonate phases. However, strongly enriched skeletal calcite $\delta^{13}C$ values support a correlation of the Großberg Formation with the mid-Late Turonian positive Hitch Wood isotope event (*Hyphantoceras* Event of northern Germany). This interpretation is supported by biostratigraphic data and a range from the *Mytiloides striatoconcentricus* Zone into the lower *My. scupini* Zone is indicated by inoceramid bivalves. Both the base and top of the Großberg Formation are characterized by unconformities. Sequence boundary SB Tu 4 at the base is a major regional erosion surface (erosional truncation of the underlying Kagerhöh Formation in the Regensburg area, fluvial incision at the base of the Seugast Member of the Roding Formation in the Bodenwöhr area towards the north and northeast). It is suggested that this unconformity corresponds to a major sea-level drop recognized in many other Cretaceous basins below the Hitch Wood or *Hyphantoceras* Event. The transgression and highstand of the Großberg Formation is concomitant to the deposition of the fluvial Seugast Member and the onlap of the marginal-marine "Veldensteiner Sandstein" onto the Fränkische Alb. The unconformity at the top of the Großberg Formation (late Late Turonian SB Tu 5) is indicated by a ferruginous firm-/ hardground and an underlying zone of strongly depleted $\delta^{13}C$ values. The abrupt superposition by deeper marine marls of the lower Hellkofen Formation (uppermost Turonian–Lower Coniacian) may be connected with inversion tectonics at the southwestern margin of the Bohemian Massif.

Key words: Danubian Cretaceous Group; Turonian; Großberg Formation; Integrated stratigraphy; Sedimentary unconformities; Depositional environment.

INTRODUCTION

Marine lower Upper Cretaceous strata document one of the strongest eustatic sea-level rises in the Phanerozoic (e.g., Hancock and Kauffman 1979; Hallam 1992), and their regional distribution can be used to track the numerous individual transgressions that occurred during that time interval. The WNW/ESE-trending Mid-European Island (MEI) remained emergent throughout this epoch, but widespread shallow-marine deposits of early Late Cretaceous age onlapped its peripheral zones and analyses of these strata have provided clues for the reconstruction of contemporaneous sea-level changes (e.g., Wilmsen 2003; Voigt *et al.* 2006a; Zítt *et al*. 2006, 2010; Wilmsen *et al*. 2010a; Richardt *et al*. in press). In northeastern Bavaria (Germany), at the southwestern margin of the Bohemian Massif (i.e., the southeastern part of the MEI), the early Late Cretaceous transgression *sensu lato* is documented by the onlap, palaeogeographic distribution, and facies pattern of the Danubian Cretaceous Group (Niebuhr *et al*. 2009; Text-fig. 1A, B). The integrated analyses of the Danubian Cretaceous Group greatly enhanced the knowledge of the facies development and sea-level changes in an area that mediates between the classic temperate northwest European Cretaceous sites and the Tethyan Alpine Cretaceous (e.g., Wilmsen *et al*. 2010a; Wilmsen and Niebuhr 2010; Niebuhr *et al*. 2011; Richardt *et al*. in press). The scope of the present paper is the analysis of the depositional environments and integrated stratigraphy of the Upper Turonian Großberg Formation based on detailed bed-by-bed logging of several sections, outcrops and one borehole in the area south of Regensburg, the type area of the Danubian Cretaceous Group (Text-fig. 2). Based on bio-, litho- and sequence stratigraphic considerations, detailed correlations with the terrestrial to marginal marine Seugast Member of the Roding Formation, ca. 50 km to the north (Niebuhr *et al*. 2011) as well as other peripheral sections around the MEI are suggested.



Text-fig. 1. Distribution of the Danubian Cretaceous Group (A) with position of the studied sections and Cenomanian–Turonian palaeogeography (B; modified from Ziegler 1990)

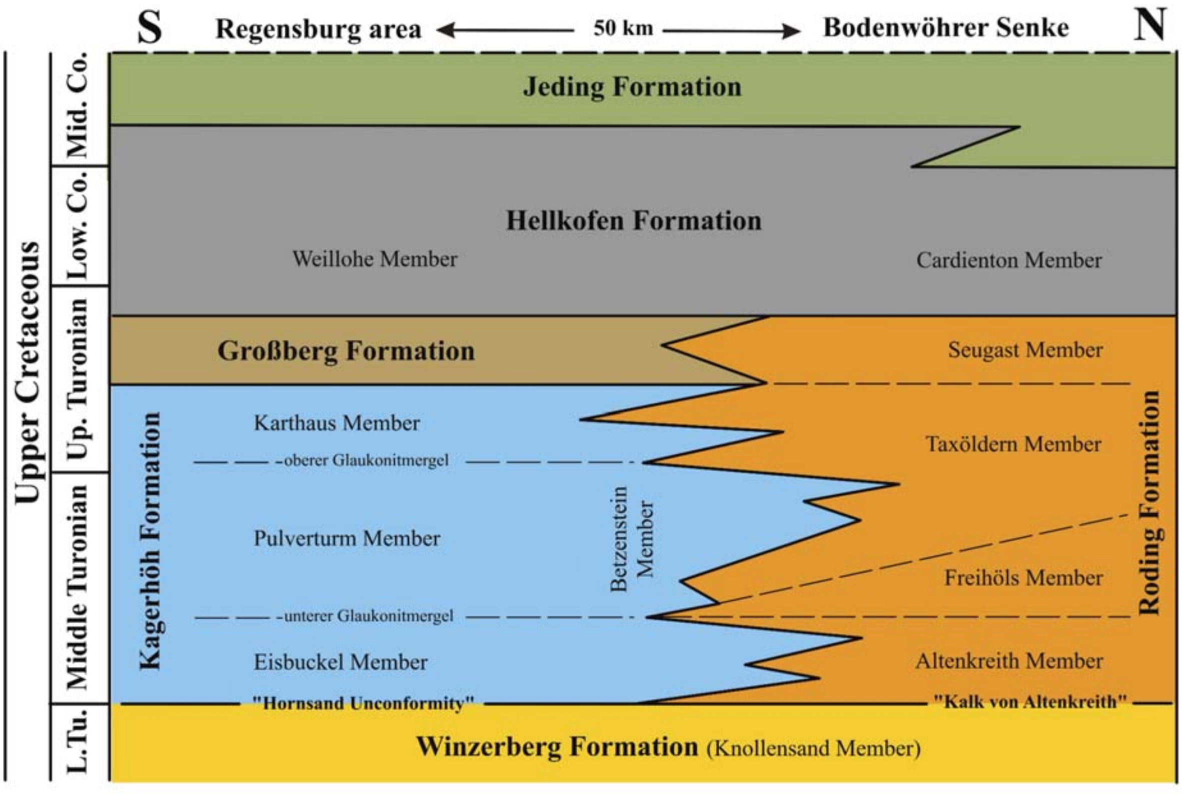
METHODS

All measured sections were logged bed-by-bed; the rocks were investigated by hand-lens and classified according to depositional fabrics (Dunham 1962; Embry and Clovan 1972). 29 thin-section samples were taken from facies types identified in the field in order to fully characterize them by microfacies analysis using a Leica M125 stereo microscope. Macro- and trace fossil occurrences have been plotted against the graphic logs.

For stable isotope stratigraphy, the borehole Pfakofen LAM B2/09 and the Zaitzkofen quarry were sampled at 0.50 m intervals; the section on the motorway A93 (exit Regensburg-Süd) was sampled at 0.20–0.50 m intervals. Stable isotope ratios of powdered bulk sediment were measured with a carbonate preparation line (Carbo-Kiel I) connected on-line to a Finnigan Mat 252 mass-spectrometer at the Geozentrum Nordbayern, Universität Erlangen-Nürnberg (lab of M. Joachimski). All isotopic values are reported in the standard δ-notation relative to V-PDB. Calcite palaeo-temperature values were calculated using the equation of Anderson and Arthur [1983: $t(°C) = 16 - 4.14(\delta_c - \delta_W) + 0.13(\delta_c - \delta_W)^2$], assuming a Late Cretaceous sea-water oxygen isotopic composition (δ_W) of –1 ‰ SMOW for an non-glacial world (e.g., Shackelton and Kenneth 1975). External precision was checked by multiple analyses of an internal laboratory standard and is better than 0.05 (± 1 σ) for $\delta^{18}O$ and $\delta^{13}C$.

GEOLOGICAL SETTING

The study area is located in Bavaria (southern Germany; Text-fig. 1) 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 depositional environments and consist of conglomerates, sands and sandstones, greensands, clays, marls and marlstones, calcarenites, siliceous opoka and limestones. The thickness of the group reaches 300–500 m and deposition took place in a peri-continental shelf setting at the northern margin of the Neotethys (Text-fig. 1B). Terrestrial sediments were deposited during the Early Cretaceous (Schutzfels Formation) and in the Turonian to Santonian (Hessenreuth Formation); marine deposition started in the Early Cenomanian and persisted into the Coniacian (Niebuhr *et al.* 2009, 2011; Niebuhr 2011; Tröger *et al.* 2009; Wilmsen *et al.* 2009, 2010a; Wilmsen and Niebuhr 2010; Richardt *et al.* in press). The complete succession of the Danubian Cretaceous Group documents a nearly



Text-fig. 2. Lithostratigraphy of the middle and upper part of the Danubian Cretaceous Group (modified after Niebuhr *et al.* 2009). Colours differentiate individual formations (the Großberg Formation is coloured in brown) symmetrical trans-/regressive mega-cycle with a maximum flooding interval during the late Middle Turonian (Niebuhr *et al*. 2009, 2011). The Großberg Formation was deposited during the regressive hemi-cycle in the Late Turonian.

The Großberg Formation is a shallow-marine lithostratigraphic unit in the middle part of the Danubian Cretaceous Group (Text-fig. 2) and consists of glauconitic sandstones, calcareous sandstones and calcarenites. In the Regensburg–Kelheim area it erosionally overlies the marls and limestones of the Middle to lower Upper Turonian Kagerhöh Formation. The Kagerhöh Formation is subdivided into three members which are separated by conspicuous glauconitic marl layers ("unterer" and "oberer Glaukonitmergel"). The lower Eisbuckel Member consists of thick-bedded, silty–spiculitic marlstones. The middle Pulverturm Member has the highest carbonate contents and the lowest terrigenous input of all formations of the Danubian Cretaceous Group. The light-grey limestones are fossil-rich and represent a maximum flooding interval. The upper Karthaus Member has sandy–silty glauconitic marls and marly clays intercalated with nodular siliceous limestones. Locally, especially in the northern part of the study area, the upper Karthaus Member is completely missing due to erosional truncation and, therefore, the Großberg Formation rests directly on the Pulverturm Member. Northeast of Nürnberg the "Veldensteiner Sandstein" (Lehner 1935), a lateral equivalent and synonym of the Großberg Formation, was deposited directly on top of the Upper Jurassic dolomites of the Fränkische Alb (Franconian Alb; Lehner 1935 already discussed a significant "early Late Turonian erosional episode"; see below).

The Middle to Upper Turonian Roding Formation of the Bodenwöhrer Senke, situated in front of the uplifted granites of the Bohemian Massif, is subdivided into four members (Niebuhr *et al.* 2009, 2011). The uppermost of them, the Seugast Member, is time-equivalent to the Großberg Formation and consists of terrestrial arkosic sandstones and conglomerates as well as mixed marine-terrestrial arkosic sandstones, intercalated with grey silts and clays. Both the Großberg Formation of the Regensburg–Kelheim area and the Roding Formation of the Bodenwöhrer Senke are overlain by silty marls and clays of the Hellkofen Formation. Both members of this formation, the Weillohe Member of the Regensburg–Kelheim area and the Cardienton Member of the Bodenwöhrer Senke as well as the Marterberg Member of the Sandbach Formation of the Ortenburg area near Passau (see Schneider *et al.* 2011) are differentiated from older marl units of the Danubian Cretaceous Group by a conspicuous content of white mica flakes (Niebuhr *et al.* 2009).

RESULTS

Sections

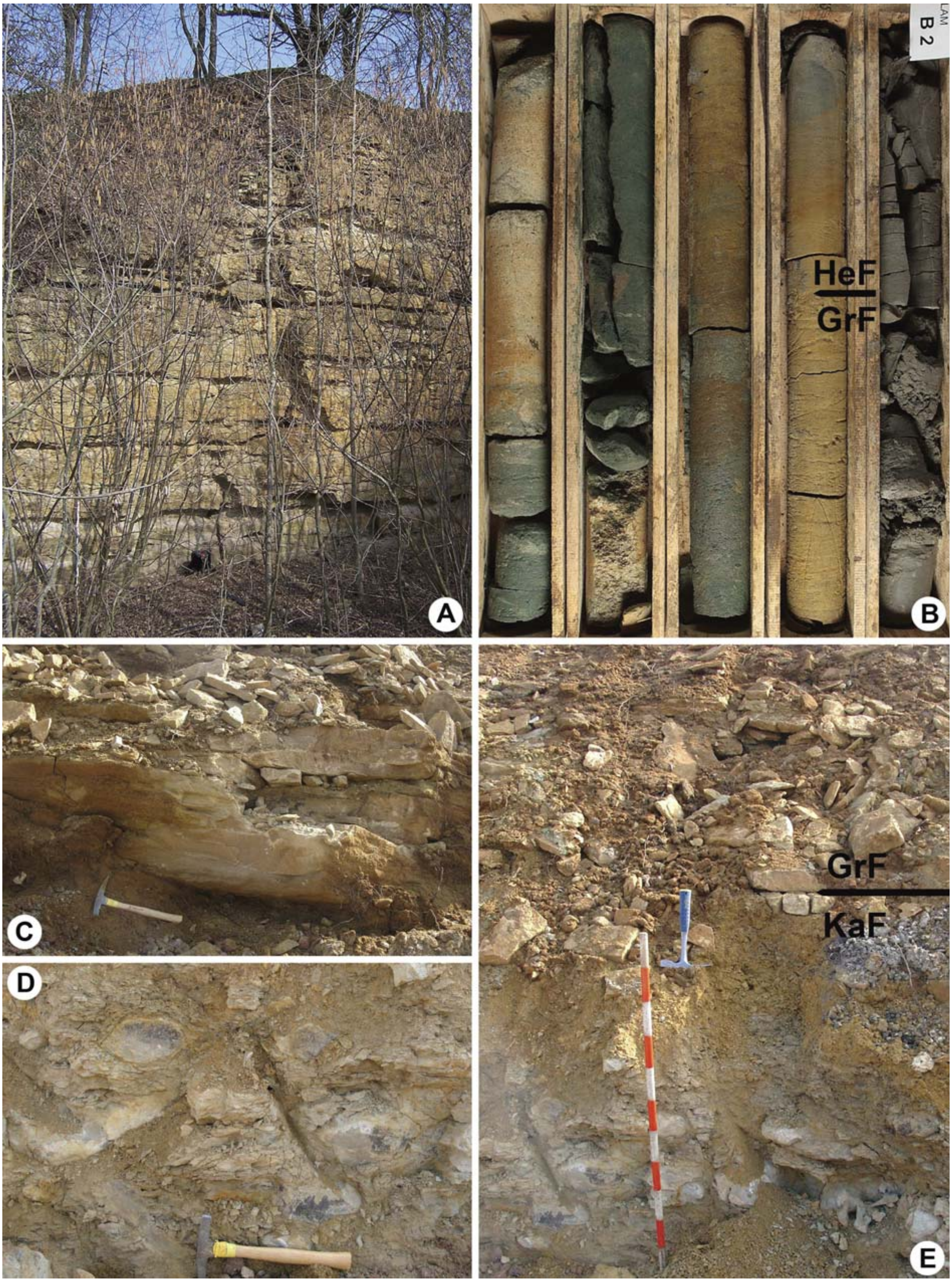
"Kühbuckel" and "Birkenberg"

At the "Winzerer Höhen", the steep northern riverside of the river Donau, east of Regensburg (topographic mapsheet TK 25: 6938 Regensburg, R 45 03 704/H 54 33 347), the Großberg Formation forms the youngest Cretaceous sediments between 425 and 446 m above sea-level. The marly Karthaus Member of the upper Kagerhöh Formation is missing here, and the platy sandstones and calcarenites of the Großberg Formation rest directly on the Pulverturm Member of the middle Kagerhöh Formation. No section could be measured here, but samples for thin-section analyses and thickness data were taken.

Motorway A93 exit Regensburg-Süd

During road construction of the motorway A93 exit Regensburg-Süd (TK 25: 7038 Bad Abbach, R 45 04 846/H 54 26 467) in the year 2008, the contact of the Karthaus Member of the Kagerhöh Formation, erosionally overlain by sandstones and sandy calcarenites of the Großberg Formation at a topographic height of 439 m above sea-level, was temporarily exposed (Text-figs 3C–E, 4A; the contact is still visible today). The topmost 4 m of the Karthaus Member of the Kagerhöh Formation ("Karthauser Baculitenmergel" of Brunhuber 1917) consist of silty marls with large nodules of siliceous limestones. Up to 20 cm long and 1–3 cm thick *Thalassinoides* burrows are very common. With a sharp contact, brownish, quartz granule-bearing, sandy bioclastic calcarenites of the lower Großberg Formation follow in medium- to thick-bedded strata. Intraformational

Text-fig. 3. Sections of the Großberg Formation (KaF = Kagerhöh Formation, GrF = Großberg Formation, HeF = Hellkofen Formation). **A** – Zaitzkofen quarry north of the road R1 between Unterdeggenbach and Zaitzkofen. Note cyclic sedimentation pattern of the Großberg Formation. **B** – core segments of the Pfakofen LAM B2/09 borehole between 39 m (lower left corner) and 34 m depth (upper right corner), photographs: M. Kling, 2010. The Großberg Formation between 39–35.45 m depth consists of bryozoan calcarenites (yellow) and glauconitites (green). Above the formation and sequence boundary SB Tu 5 at 35.45 m depth, dark grey to yellowish marls of the lower Hellkofen Formation appear. **C**–**E** – motorway A93 exit Regensburg-Süd. **C** – litho- and bioclastic, low-angle cross-bedded sandstones and calcarenites of the basal Großberg Formation cut into silty marls of the Karthaus Member of the Kagerhöh Formation. **D** – topmost 4 m of the Karthaus Member consisting of silty marls with large nodules of siliceous limestones. **E** – Kagerhöh/Großberg formational boundary, matching sequence boundary SB Tu 4


A
LAM
B 2
HeF
GrF
B
C
D
GrF
KaF
E

pebbles may characterize the bases of thicker beds. Macrofossils are represented by fragmented bivalve remains and bryozoans. Large-scale planar to weakly trough-shaped foresets within the lower Großberg Formation (four metres have been exposed) dip at 20° degrees towards 110–130° (ESE–SE), more or less parallel to the margin of the Bohemian Massif.

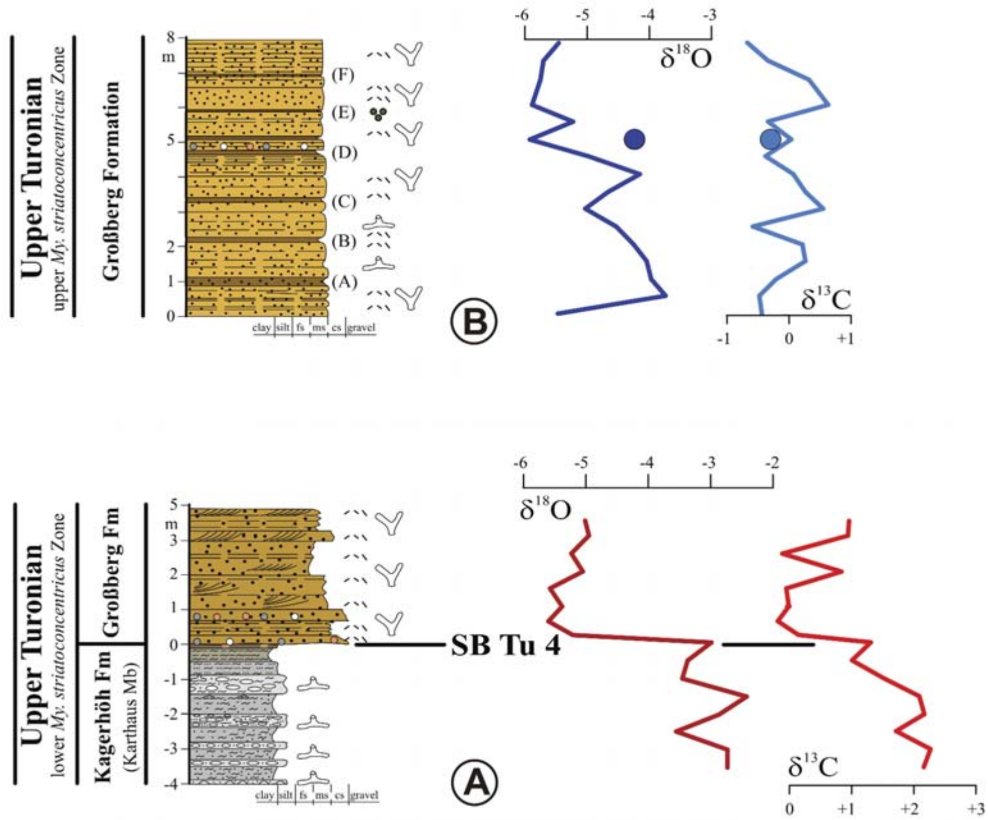
Small pits east of Großberg

300–500 m south of the motorway exit A93 Regensburg-Süd, the basal ca. 5 m of the Großberg Formation have been quarried in several small pits (TK 25: 7038 Bad Abbach, R 45 04 617/H 54 25 983). The lower part of the formation is likewise characterized by sandy bioclastic calcarenites showing large-scale foresets dipping at 20° towards ESE. Small current ripples have been observed on some of these foresets. On the western side of the federal road B16 road-cutting, the erosional base of the Großberg Formation is exposed at a topographic height of 437 m above sea-level. The lowermost beds are dm-thick, sandy bioclastic limestones. No section was measured here, but samples for thin-section analyses as well as palaeo-current and thickness data were taken.

Zaitzkofen quarry north of local road R1 between Unterdeggenbach and Zaitzkofen

In the old quarry 4 km south-southeast of the Pfakofen borehole (TK 25: 7139 Aufhausen, R 45 14 500/H 54 11 072), eight metres of the lower to middle part of the Großberg Formation are exposed between 372 m and 380 m above sea-level and were logged and sampled in detail (Text-figs 3A, 4B). The succession consists of brownish, medium-grained, sandy and partly glauconitic calcarenites with abundant bryozoan remains. One to three centimetres-thick, distinct burrows (*Thalassinoides* isp.) occur predominantly in the lower part. However, the fabric in general is strongly bioturbated, explaining the lack of primary sedimentary structures. The section shows a conspicuous cyclicity characterized by 1.10–1.40 m thick, internally stratified packages of brownish calcarenites, separated by distinct soft marls (Text-fig. 3A). Six of those marls have been identified, labelled A–F in Text-fig. 4B.

From the field brash in the fields ca. 1 km west of Zaitzkofen, immediately south of the road R1 and the quarry, the Großberg Formation has been mapped up to a topographic height of 392 m above sea-level (M. Kling, pers. comm. 2011). From these fields, Röper and



Text-fig. 4. Lithological sections and stable isotopes (carbon, oxygen) of bulk sediment (curve) and oyster shells (dots). **A** – section at motorway A93 exit Regensburg-Süd; **B** – Zaitzkofen quarry section. Log colours correspond to the natural colouration of strata. For key to symbols see Text-fig. 11

Neumeier (1995) mentioned more than 1,600 fossil specimens belonging to 71 taxa, mainly bryozoans, bivalves, sponges and serpulids. Some new species have also been described from that area (Voigt 1995; Löser 1996). The Großberg Formation is one of the most fossiliferous lithounits of the Danubian Cretaceous Group (e.g., Dacqué 1939).

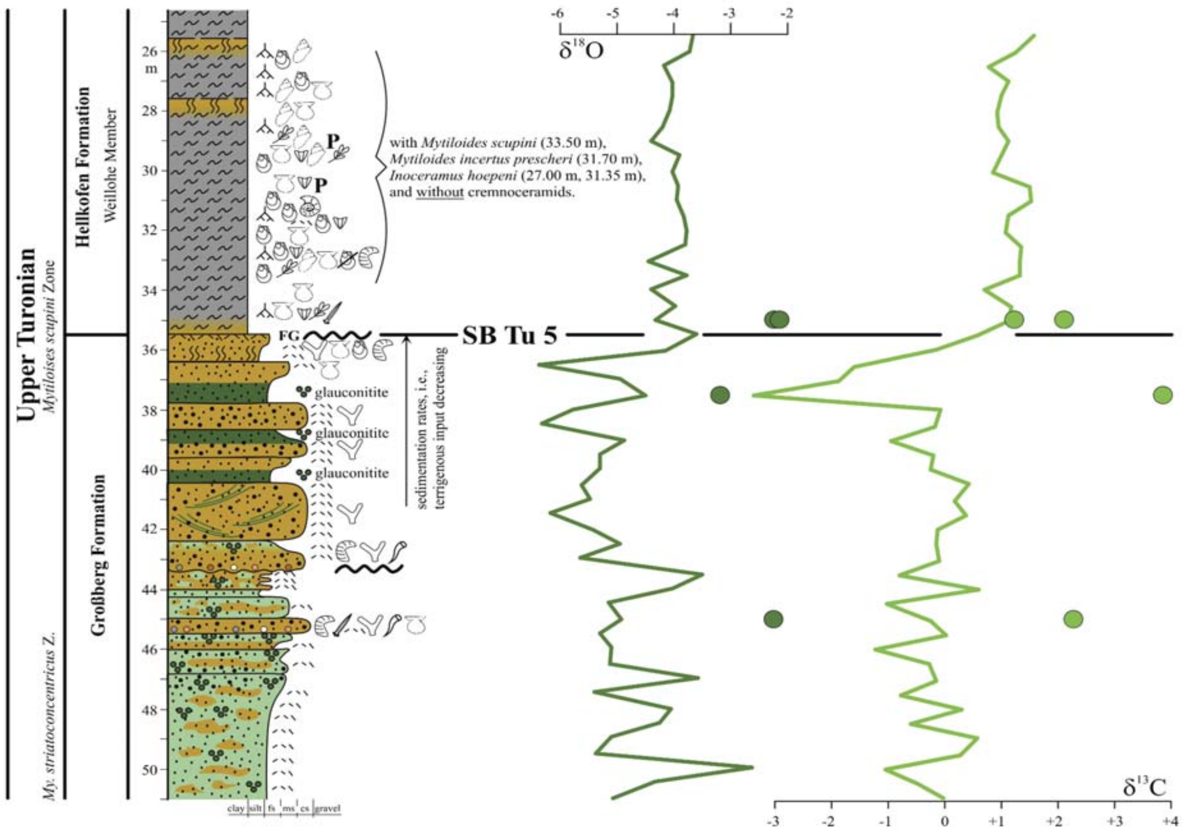
Borehole Pfakofen LAM B2/09

The Pfakofen borehole was drilled in 2009 by the Bayerisches Landesamt für Umwelt (LfU), ca. 20 km south of Regensburg (TK 25: 7139 Aufhausen, R 45 17 010/H 54 14 210) at a topographic height of 380 m above sea-level. It cored ca. 33 m thick silty marls of the lower Hellkofen Formation (2–35.50 m depth), followed by 15.50 m of the Großberg Formation (35.50–51 m depth; Niebuhr 2011). The top of the Großberg Formation is located at 344 m above sea-level and the base was not reached in the core.

The succession of the Pfakofen LAM B2/09 borehole (Text-figs 3B, 5) is characterized by bioturbated, fine- to medium-grained bioclastic–glauconitic sandstones up to an erosional level at 43.30 m depth. A coarse bioclastic bed at 44.95–45.50 m depth yielded oysters, spines of regular echinoids, bryozoans, serpulids and bivalves. In the upper part of the Großberg Formation, coarse-grained, partly cross-bedded sandy calcarenites and fine-grained glauconitites alternate. Bryozoan remains are the most conspicuous faunal element in this part. The uppermost bed also yielded several bivalves (oysters, inoceramids) and is capped by a firmground. The lowermost part of the Hellkofen Formation (Weillohe Member) is very fossiliferous. It yielded (among other inoceramids) the index fossil *Mytiloides scupini* (Heinz), indicating that the boundary between the Großberg and Hellkofen formations is late Late Turonian in age (Niebuhr 2011).

Type locality of the "Weilloher Mergel"

9.5 km west-northwest of the Pfakofen borehole (TK 25 7038 Bad Abbach, R 45 08 410/H 54 18 380), the topmost Großberg Formation is exposed in a karst depression, sharply overlain by 1.70 m of silty marls of the lowermost Weillohe Member of the Hellkofen Formation. The top of the Großberg Formation is located here at 407 m above sea-level. The planktonic foraminifera indicate (Weidich 1987) that the boundary between the "Weillohe-Mergel" and the



Text-fig. 5. Lithological section and stable isotopes (carbon, oxygen) of bulk sediment (curve) and oyster shells (dots) of the borehole Pfakofen LAM B2/09. Log colours correspond to the natural colouration of strata. For key to symbols see Text-fig. 11

"Großberg-Sandstein" lies in the *Marginotruncana primitiva* Zone (Lower Coniacian according to Caron 1985 and Korsitzke 1995). A sample for thin-section analysis was taken here from the uppermost Großberg Formation.

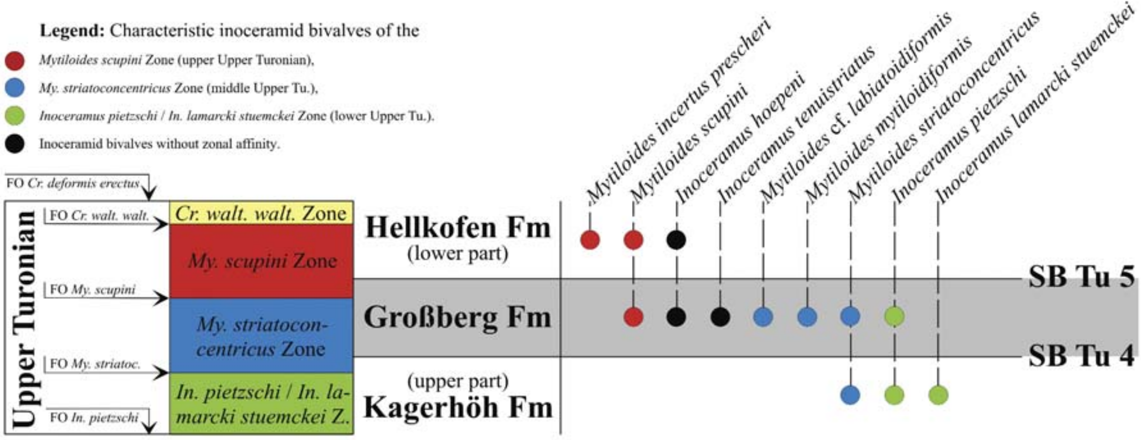
Biostratigraphy

The biostratigraphic subdivision of the Danubian Cretaceous is mainly based on inoceramid bivalves (Tröger *et al*. 2009), ammonites and belemnites (Wilmsen *et al*. 2009, 2010b; Wilmsen and Niebuhr 2010; Niebuhr 2011; Schneider *et al*. 2011). Eleven inoceramid bivalves of the genera *Inoceramus* and *Mytiloides* belonging to seven taxa are known to date from the Großberg Formation (Tröger *et al.* 2009). Both *Inoceramus pietzschi* Tröger and *Mytiloides striatoconcentricus* (Gümbel) also occur in the underlying Kagerhöh Formation (Text-fig. 6), which shows that the base of the Großberg Formation and, therefore, sequence boundary SB Tu 4 of Niebuhr *et al*. (2011), is located within the lower part of the middle Upper Turonian *My. striatoconcentricus* Zone, defined by the first occurrence of the zonal index (Text-fig. 6). Additional characteristic inoceramids of this zone that are found in the Großberg Formation are *My.* cf. *labiatoidiformis* (Tröger) and *My. mytiloidiformis* (Tröger). The boundary between the Großberg and Hellkofen formations and, therefore, sequence boundary SB Tu 5, lies within the upper Upper Turonian, indicated by the occurrence of the zonal index *Mytiloides scupini* (Heinz) and *Inoceramus hoepeni* (Heinz) in both formations (Tröger *et al.* 2009; Niebuhr 2011). It must be emphasized that there are no records of the uppermost Upper Turonian zonal index cremnoceramid [*Cremnoceramus waltersdorfensis* (Andert)] from either the Großberg or the Hellkofen Formation.

Carbon and oxygen stable isotopes

Most of the carbon stable isotope values of the bulk-rock samples from the Großberg Formation are relatively low and vary between -1.0 ‰ and +1.0 ‰ $\delta^{13}C$ vs. V-PDB (Text-fig. 7). Furthermore, the uppermost 2 m of the Pfakofen section is strongly depleted (up to -3.4 ‰ $\delta^{13}C$; Text-fig. 7). This is in contrast to the carbon stable isotope values of the underlying Kagerhöh Formation and the overlying Hellkofen Formation, which constantly vary between +1.0 ‰ and +2.0 ‰ $\delta^{13}C$. The shift at the formational boundaries is abrupt in both cases. Moreover, the carbon isotope composition of the complete Großberg Formation shows no trend from base to top (Text-fig. 7). In the upper Kagerhöh Formation, a weak decrease in $\delta^{13}C$ values is indicated, followed by a 1.0 ‰ negative shift at the base of the Großberg Formation. Ignoring the extremely depleted $\delta^{13}C$ values at the top of the Großberg Formation, a positive shift of comparable magnitude (+1.5 ‰) occurred at the contact with the Hellkofen Formation. The carbon isotope curve of this formation is again fairly straight.

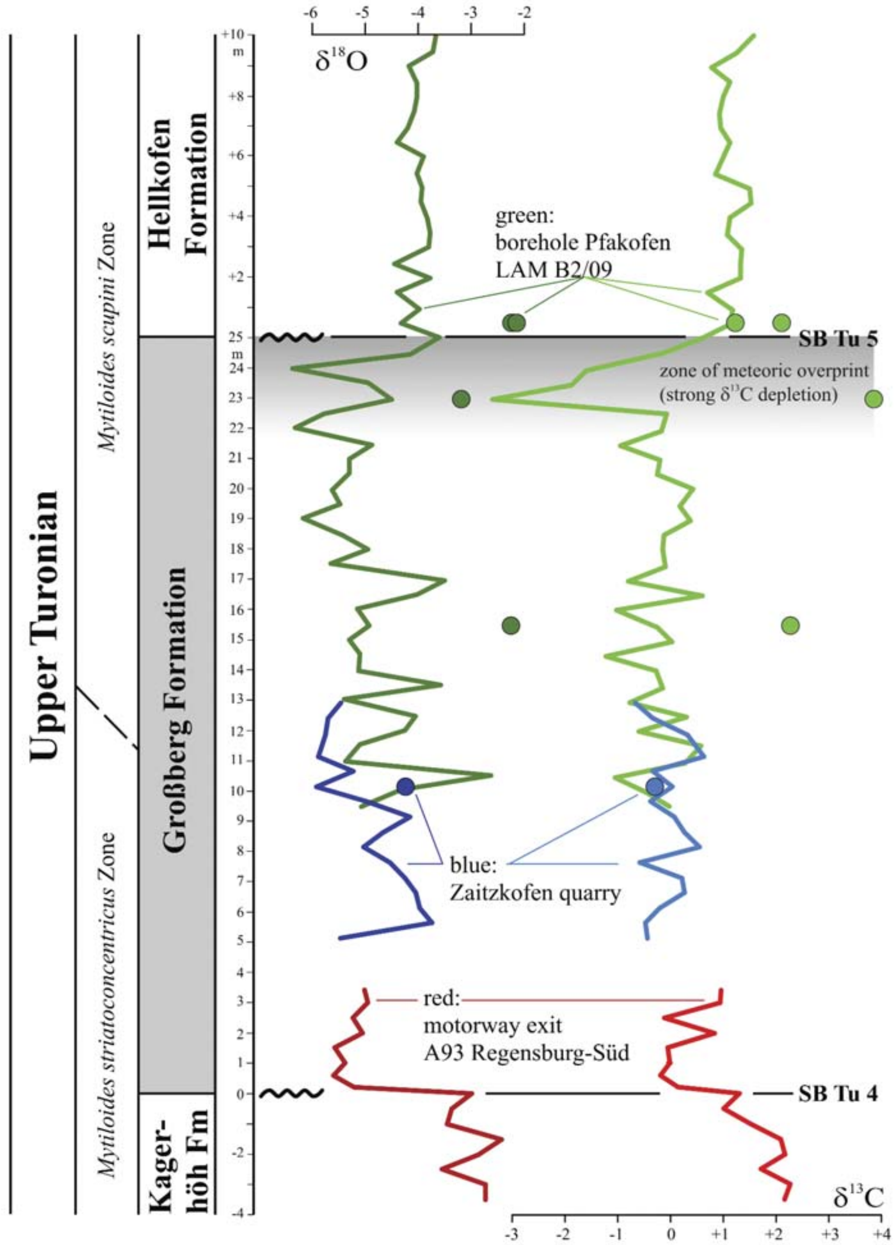
$\delta^{18}O$ values of the Großberg Formation are likewise depleted and vary between -2.5 ‰ and -6.4 ‰ vs. V-PDB. Furthermore, their scatter is much greater (up to 4.0 ‰) than in the under- and overlying formations. Therefore, their use in correlation and reconstruction of $\delta^{18}O$ sea-surface palaeo-temperatures is not advisable. At the boundary between the Kagerhöh and Großberg formations, an abrupt negative shift of -2.0 ‰ occurs. A reverse shift of +1.0 ‰ occurs at the top contact of the Großberg Formation, followed by relatively uniform values around -4.0 ‰ $\delta^{18}O$ in the lower Hellkofen Formation. Crossplots of $\delta^{18}O/\delta^{13}C$ show a correlation coefficient of $R^2 = 0.58$ for the lower Großberg Formation of the A93 exit Regensburg-Süd section, while at Zaitzkofen and the Pfakofen borehole, R^2 is ≤ 0.01.



Text-fig. 6. Biostratigraphy of the Großberg Formation based on bulk-formational occurrences (dots) of inoceramid bivalves

Skeletal calcite values of oyster shells (Text-fig. 7, coloured dots) of both carbon and oxygen stable isotopes are strongly enriched compared to the bulk-rock samples. This does not so much apply to the single sample from the Zaitzkofen quarry, but to the two samples from the Pfakofen borehole. Here, the offset may be as large as +3.0 ‰ in $\delta^{18}O$ (lower sample) and +5.0 ‰ in $\delta^{13}C$ (upper sample with +3.8 ‰ $\delta^{13}C$ vs. V-PDB). For the lower part of the Hellkofen Formation, the differences are reduced, being in the order of +2.0 ‰ in $\delta^{18}O$ and ≤ 1.0 ‰ in $\delta^{13}C$ (Text-fig. 7). Isotope palaeo-thermometry for the skeletal calcite samples of the Pfakofen borehole (minimum -3.15 ‰ $\delta^{18}O$, maximum -2.18 ‰ $\delta^{18}O$) results in a range of palaeo-temperatures of ca. 4°C between 22 and 26°C.

It is difficult to judge the potential correlation of the Zaitzkofen quarry and Pfakofen borehole sections using only the isotope curves. However, considering that in the surroundings of the quarry, the top of the Großberg Formation is 12 m above the measured section, the curves can be overlapped by placing the top of the Zaitzkofen curve exactly this distance below the top boundary of the



Text-fig. 7. Synoptic carbon and oxygen stable isotope curve (bulk rock) and skeletal calcite values (dots) of the upper Kagerhöh, Großberg and lower Hellkofen formations. See text for further explanations

Großberg Formation in the Pfakofen curve (Text-fig. 7). This approach resulted in a reasonable fit of both curves and suggests that, based on a mean thickness of the Großberg Formation of 20–25 m in the study area (e.g., Brunhuber 1917; Oschmann 1958; Bauberger *et al.* 1969), 1–2 m are missing between the base of the quarry section and the A93 exit Regensburg-Süd section.

Microfacies

The sedimentary facies of the Großberg Formation is characterized by thin- to medium-, rarely thick-bedded bioclastic calcareous sandstones and sandy calcarenites of medium-brown colour. Grain-sizes of siliciclastic components vary from fine to coarse; glauconite contents are variable and in the upper part, glauconitites with glauconite contents of 20–40 % occur. Quartz grains are the most common siliciclastic component and usually well to moderately well rounded, but feldspar may also occur locally. The most conspicuous macrofossils are bryozoans and serpulids as well as small corals and rudists. Bivalves are also common but rarely preserved as complete valves (most of the biogenic components are more-or-less fragmented and abraded bioclasts). Large-scale planar foresets have been observed especially in the lower and upper parts of the formation, dipping moderately steeply (10–20°) constantly towards the ESE–SE. These cross-bedded units disintegrate at the individual cm-thick foresets, resulting in a thin-bedded fabric of the rock. Thin-section analyses resulted in the recognition of eight characteristic (micro-)facies types (FT) that are briefly described below (Text-figs 8, 9).

FT 1 – Quartz-bearing bioclastic rudstones

Bioclastic rudstones are the most common facies type in the lower part of the formation (e.g., A93 exit Regensburg-Süd, small pits at Großberg; Text-fig. 8A–D). They are well washed (no micrite) and contain fragments of bryozoans, colonial serpulids, bivalves (mainly oysters and strongly recrystallized, thin-shelled fragments, rare rudists) and echinoderms (e.g., cidaroid spines). Benthic foraminifera, calcareous algae (some encrusting red algae, rare dasycladaleans), punctate brachiopods and sponge fragments are accessory components. All bioclasts are variably strongly altered taphonomically (abraded, Fe-stained, some are bored, micritic envelopes around primarily aragonitic components are common; Text-fig. 8D). Quartz grains are well to moderately well rounded and vary in size from granules to fine sand-size. Small rounded lithoclasts may occur as well. Based on the amount of quartz, transitions to bioclastic sandstones exist. Between the grains, there is a ferruginous blocky calcite. Cross-bedding with planar, 1–5-cm-thick foresets is common (Text-fig. 8C). Individual foresets are graded, with poorly sorted, quartz granule-bearing bioclastic rudstones at the base and well sorted, fine-grained sandy bioclastic grainstones/bioclastic sandstones at the top.

FT 2 – Intraclast-bearing bioclastic rudstones

The intraclast-bearing bioclastic rudstones are similar to the bioclastic rudstones described above, but additionally contain cm-sized, poorly rounded intraclasts of reworked grey marly–argillaceous wackestone. They usually constitute only thin layers at the base of cross-bedded units.

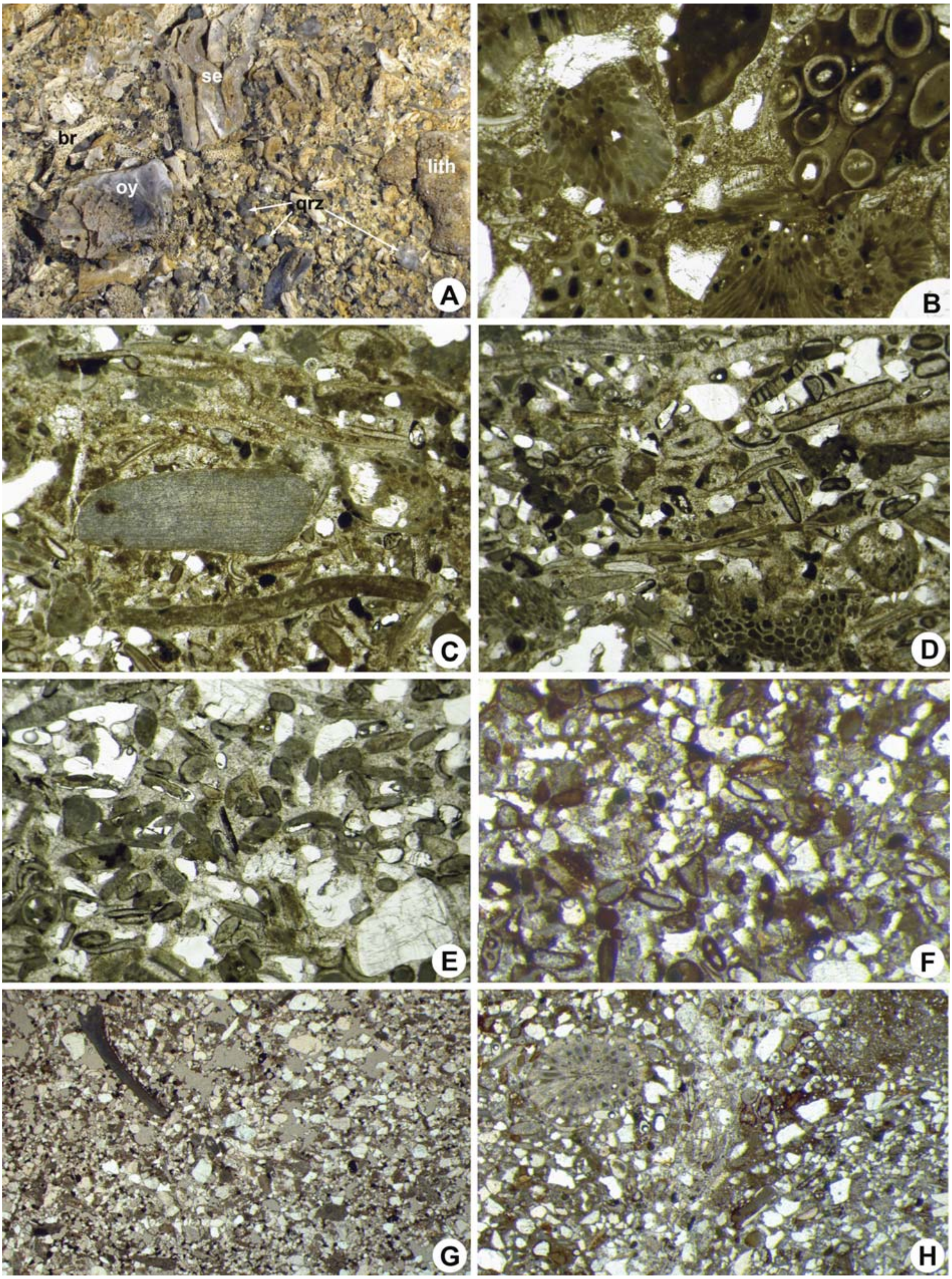
FT 3 – Bioclastic sandstones

This facies type groups all sediments with predominantly siliciclastic fabrics (Text-figs 8G, 9H, I) and transitions exist to sandy bioclastic grainstones (Text-fig. 8F) and quartz-bearing bioclastic rudstones. The bioclasts are commonly better rounded than in the other facies types and often characterized by micritic envelopes (small cortoids). Recognizable (larger) bioclasts are again dominated by bryozoans, serpulids and oyster fragments. Planar cross-bedding has also been observed in the field in this facies type, usually in the coarse varieties. As in FT 1, blocky sparite cements the grains but, in the finer varieties, micrite is additionally present, associated with rare peletoidal glauconite grains. Shelter porosity filled by dog tooth-like rim cements and blocky sparite has also been observed (Text-fig. 9H, I).

FT 4 – Sandy bioclastic grainstones

This facies type differs from the quartz-bearing bio-

Text-fig. 8. Microfacies aspects of the Großberg Formation (plane polarized light, except A). **A** – macroscopic bedding-plane view of weathered surface of a quartz-bearing bioclastic rudstone of the lower Großberg Formation at motorway A93 exit Regensburg-Süd section (oy = oyster, br = bryozoan, se = serpulids, qrz = quartz, lith = lithoclast; field of view: 36 mm). **B** – quartz-bearing bioclastic rudstone at motorway A93 exit Regensburg-Süd section (1 m above the formational base; field of view: 8 mm). **C** – quartz-bearing bioclastic grain- to rudstone from the small pits near Großberg (field of view: 6 mm). Note oblique cross-section of a cidaroid spine (centre) and recrystallized bivalve fragments tracing foresets. **D** – quartz-bearing bioclastic grain- to rudstone from the small pits near Großberg (field of view: 6 mm). Note the poorly sorted fabric and the dark micritic envelopes around many grains. **E** – sandy bioclastic grainstone from the small pits near Großberg (field of view: 5 mm). Note the relatively good sorting and rounding of carbonate components (many with micritic envelopes). **F** – transition from sandy bioclastic grainstone to bioclastic sandstone (Zaitzkofen quarry, field of view: 4 mm). Note dark envelopes around nearly all carbonate grains. **G** – bioclastic sandstone (Zaitzkofen quarry, field of view: 15 mm). Note poor textural maturity. **H** – bioturbated calcareous sandstone (Zaitzkofen quarry, field of view: 7.5 mm). Note micritic matrix, some dark glauconite grains and bryozoan cross-section (centre-left)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clastic rudstones mainly in smaller grain size and better sorting of all components (bioclasts and quartz; Text-fig. 8E). The bioclasts are very well rounded, and most are internally recrystallized with micritic envelopes. Their biological affinities are consequently often difficult to evaluate. Larger bioclasts occur scattered within this facies type and are mainly fragments of bryozoans, serpulids and oysters. Quartz grains vary between silt- and medium sand-size and are subrounded to subangular in shape. A dirty blocky calcite occurs between all the grains.

FT 5 – Calcareous siltstones to fine-grained sandstones

This facies type combines relatively well sorted and fine-grained siliciclastic sediments with a micritic matrix (Text-figs 8H, 9A). Fabrics are usually grain-supported, but bioturbation has resulted in an inhomogeneous distribution of components in one sample (Text-fig. 8H). Small bioclasts (shell fragments) and glauconite grains are present. The quartz fraction is moderately rounded to subangular. This facies type is common in the middle part of the Großberg Formation (e.g., Zaitzkofen quarry).

FT 6 – Bioturbated spiculitic–bioclastic wacke- to packstones

The spiculitic–bioclastic wacke- to packstones contain up to 10 % angular to subrounded silt- to fine sand-sized quartz grains and are heavily bioturbated (Text-fig. 9B). The biogenic components are unidentifiable microbioclasts, sponge spicules, ostracods, echinoderm fragments (thin echinoid spines), bryozoan remains and small textulariid foraminifera. Glauconite is common.

FT 7 – Glauconitites

The glauconitites contain up to 40 % largely authigenic glauconite which developed in the pore spaces of a siltstone to fine-grained sandstone (Text-fig. 9C). The bioclasts are predominantly dendroid bryozoans. The quartz grains are subangular to subrounded and the non-glauconitic pore space is filled with a patchily distributed micritic matrix or fine-grained calcite spar. Glauconitites occur only in the upper part of the Großberg Formation (e.g., Pfakofen borehole).

FT 8 – Glauconitic bryozoan rudstones

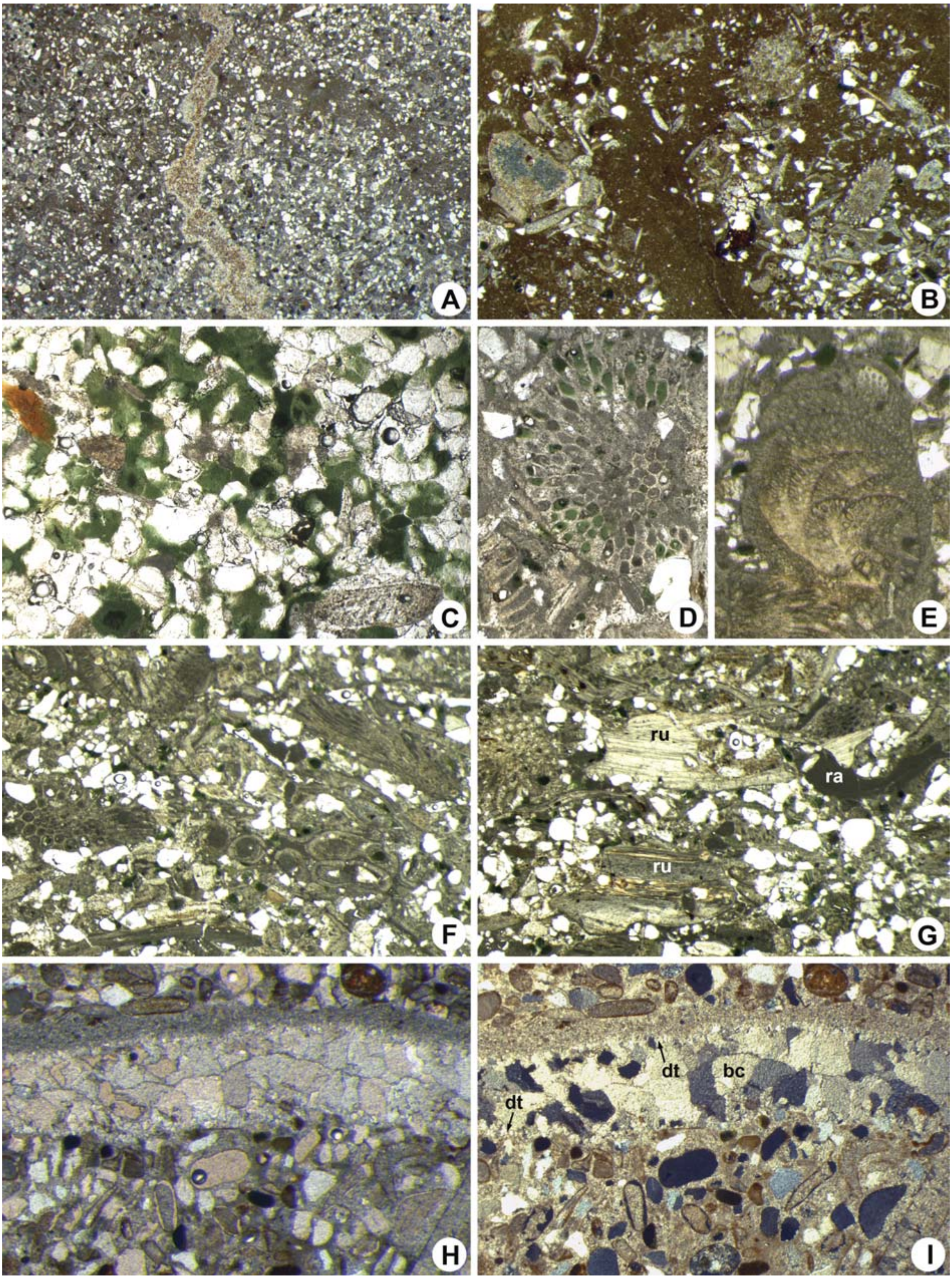
Associated with glauconitites in the upper part of the Großberg Formation in the Pfakofen borehole are sand-bearing, micritic bryozoan rudstones (Text-fig. 9D–G). They contain abundant and only poorly fragmented bryozoans with many different growth forms (erect branching, hemispherical encrusting, foliate, leaf-like). Accessory biogenic components are fragments of bivalves, serpulid fragments and red algae. Glauconite occurs as infill within bryozoan chambers (Text-fig. 9D) and as scattered peletoidal grains. The quartz grains are silt- to sand-sized, poorly sorted but well to moderately well rounded.

DISCUSSION

Depositional environment

The microfacies analysis of the Großberg Formation reveals a typical temperate carbonate shelf bryomol facies (e.g., Nelson 1988; Flügel 2004) with strong terrigenous input. The abundance and diversity of bryozoans, bivalves and serpulids as well as the occurrence of glauconite and red algae support this interpretation. However, there are also indications of warm-water influences, such as the presence of abundant cortoids (development of micritic envelopes) and the rare occurrence of rudists and corals. The sparse oxygen palaeo-temperature values of the skeletal calcite (22–26°C) would indicate a sub-tropical warm-water setting but the calcite may have been diagenetically altered. Palaeogeographic reconstructions (Text-fig. 1; see also Philip and Floquet 2000) place the study area at ca. 35° northern palaeo-latitudes at the northern margin of the Tethyan warm-water zone, separated from the warm-temperate Boreal shelf of northwestern Europe by the Mid-European Island. Voigt *et al.* (2004) reconstructed contemporaneous brachiopod palaeo-temperatures of 15–20 °C in the mid-latitude shelf sea of northwestern Europe. Thus, sea-water temperatures of the Großberg

Text-fig. 9. Microfacies aspects of the Großberg Formation (plane polarized light, except I). **A** – bioturbated calcareous siltstone to fine-grained sandstone (Zaitzkofen quarry, field of view: 14 mm); small dark grains are glauconite. **B** – bioturbated bioclastic wacke- to packstone (Zaitzkofen quarry, field of view: 4 mm). **C** – sandy glauconitite (Pfakofen borehole, field of view: 2.5 mm); note authigenic matrix glauconite. **D** – authigenic glauconite in the zooecia of a branched bryozoan (Pfakofen borehole, field of view: 1.25 mm). **E** – close-up of a hemi-spherical encrusting bryozoan form a bryozoan rudstone (Pfakofen borehole, field of view: 3 mm). **F** – glauconite-bearing sandy bioclastic rudstone with bryozoans and serpulids; Pfakofen borehole, field of view: 8 mm. **G** – glauconite-bearing sandy bioclastic rudstone with bryozoans, rudist fragments (ru) and encrusting red algae (ra) (Pfakofen borehole, field of view: 8 mm). **H** – bioclastic sandstone from the Pfakofen borehole with shelter porosity below bivalve shell filled with dog-tooth-like rim cement and blocky calcite (field of view: 4 mm). **I** – bioclastic sandstone from the Pfakofen borehole with shelter porosity below bivalve shell filled with dog-tooth-like rim cement (dt) and blocky calcite (bc; crossed nicols, field of view: 4 mm)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Formation should be somewhat higher than in typical temperate shelf carbonates (≥ 20°C). The formation of typical heterozoan carbonates (bryomol facies) may thus be also connected with a nutrient surplus in the depositional environment resulting in a suppression of photozoan facies (Carranante *et al.* 1988; Brasier 1995; James 1997). A strong input of land-derived nutrients can be regarded as certain given the enormous clastic influx from the emergent hinterland and the interfingering of the Großberg Formation with non- and marginal marine facies (Text-fig. 10; see also below).

The smooth transition of facies types and the absence of gravitationally redeposited sediments suggest that the Großberg Formation was deposited on a homoclinal, ramp-like surface dipping gently into deeper water (Text-fig. 10; cf. Burchette and Wright 1992). The planar cross-bedded bioclastic sediments represent submarine sandwaves migrating ESE–SE-wards parallel to the coastline of the Bohemian Massif (Text-fig. 10). Their uniform orientation reflects a coast-parallel current and may give clues for the reconstruction of palaeocirculation patterns at the northern Tethyan margin in the early Late Cretaceous. In sheltered inter-sandwave areas, fine-grained marly–silty sediments rich in bryozoans and serpulids accumulated that were episodically overridden and reworked by advancing sandwaves (basal intraclast-lag of cross-bedded units). Deeper parts of the Großberg Ramp (Text-fig. 10) are characterized by bioturbated glauconitic calcareous siltstones to fine-grained sandstones and bioturbated bioclastic wacke- to packstones. Glauconitites and diverse glauconitic bryozoan rudstones occur at the top of the Großberg Formation in the Pfakofen borehole, where they are associated with a shallowing trend below a terminal emersion surface (see below). They are associated with reduced accumulation rates in the late highstand (lack of accommodation space).

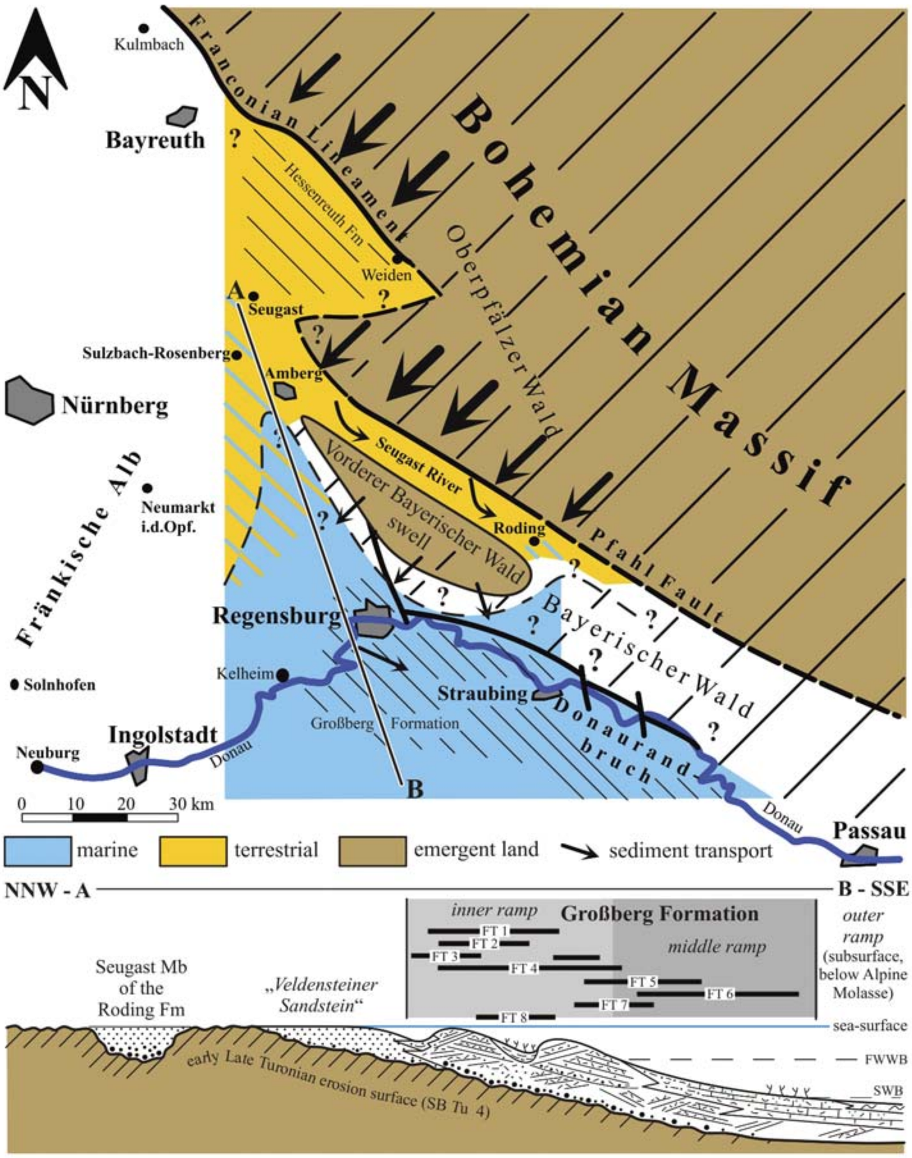
Chemostratigraphy

Carbon stable isotope stratigraphy is a very powerful tool for calibration and correlation of the stratigraphic record of marine carbonates (e.g., Jarvis *et al*. 2006). In this respect, the Upper Turonian is usually a very well suited interval as it is characterized by a conspicuous zig-zag trend of $\delta^{13}C$ values with a distinctive mid-Upper Turonian positive excursion (*Hyphantoceras* Event or Hitch Wood Event; Voigt and Hilbrecht 1997; Wiese 1999; Voigt *et al.* 2004; Jarvis *et al.* 2006; Wiese 2010; Richardt and Wilmsen 2012). However, the combined curve of the upper Kagerhöh, Großberg and lower Hellkofen formations is rather linear and shows no conspicuous $\delta^{13}C$ maximum albeit the succession straddles the relevant interval (Text-fig. 7). Furthermore, the offset of isotope values at the formational boundaries demands a careful evaluation.

As already noted by Voigt and Hilbrecht (1997, p. 52), the $\delta^{13}C$ values of proximal sections are generally lighter than in contemporaneous offshore equivalents and overall stratigraphic trends are linear. Also Immenhauser *et al.* (2008) observed clear $\delta^{13}C$ gradients with light values in nearshore and heavy values in open marine settings in several well documented case studies from the geological record. They explain this observation with the decoupling of shallow neritic and open marine seawater, resulting in different physico-chemical properties of water masses (shallow-water aquafacies with depleted $\delta^{13}C_{DIC \text{ (dissolved inorganic carbon)}}$ values). This gradient in $\delta^{13}C_{DIC}$ also occurs in modern settings (Patterson and Walter 1994) and transforms into depleted $\delta^{13}C_{carb \text{ (carbonate)}}$ values of shallow-water carbonates. This effect nicely explains the negative and positive shifts of $\delta^{13}C$ values at the lower and upper formational boundaries of the Großberg Formation: at sequence boundary SB Tu 4, the depositional environment shifted abruptly from hemipelagic into shallow-water settings, while at SB Tu 5, a rapid deepening at the base of the Hellkofen Formation is reflected by increased $\delta^{13}C$ values.

Furthermore, respiration of abundant organic matter may generate pore waters with strongly depleted $\delta^{13}C_{DIC}$ values, imparting low $\delta^{13}C$ values to syndepositional and early diagenetic carbonate (e.g., marine phreatic cements; Immenhauser *et al.* 2008). This effect is of course more important in coarse-grained sediments (e.g., Großberg Formation) than in fine-grained ones with little or no pore space (e.g., Kagerhöh and Hellkofen formations). That alteration by depleted pore waters played a significant role in the negative bulk-rock $\delta^{13}C$ values of the Großberg Formation is shown by the relatively high values of primarily calcitic (i.e., diagenetically stable) macro-invertebrates in comparison to bulk-rock values from the same sample which inevitably contains potentially altered unstable aragonitic components and early marine cements (see Text-figs 8, 9 and chapter Microfacies).

Early meteoric diagenesis may also significantly lighten the $\delta^{13}C$ values from an exposure surface downwards (Immenhauser *et al.* 2008). The depth of the altered zone is typically a few decimetres to metres thick and lowered $\delta^{13}C$ values result from interaction with soil-zone CO_2 from organic respiration, atmospheric CO_2 and dissolved metastable carbonate phases. The top 2–3 m of the Großberg Formation show exactly this signature of strongly depleted $\delta^{13}C$ values below sequence boundary Tu 5, thus supporting emersion at this level. The retention of heavy $\delta^{13}C$ values in stable calcitic shell



Text-fig. 10. Palaeogeography of the mid-Late Turonian in the area south and north of Regensburg (above) and facies model of the Großberg Formation (below; FWWB = fair-weather wave-base; SWB = storm-weather wave-base; see text for further explanations)

from that interval gives further evidence of alteration of an originally isotopically heavier sediment by early meteoric diagenesis.

In conclusion, the $\delta^{13}C$ curve of the upper Kagerhöh to lower Hellkofen Formation cannot be used to constrain the stratigraphic position of the Großberg Formation. However, the high skeletal $\delta^{13}C$ values of the Großberg Formation (up to +3.8 ‰) may indicate a relationship to the mid-Late Turonian (upper *Subprionocyclus neptuni* ammonite Zone) positive Hitch Wood Event (Voigt and Hilbrecht 1997; Voigt *et al*. 2004; Jarvis *et al*. 2006), as already assumed by Niebuhr *et al*. 2009 [a questionable *S. neptuni* (Geinitz) was reported from the underlying Karthaus Member by Wilmsen *et al*. 2009]. During this event, brachiopod $\delta^{13}C$ values may reach up to +4.2 ‰ $\delta^{13}C$, but typically vary between +2.6–3.8 ‰ (Voigt *et al*. 2004). This suggests that sequence boundary Tu 4 is of mid-*Subprionocyclus neptuni* ammonite zonal age (see below), i.e., lies within the *Mytiloides striatoconcentricus* inoceramid Zone (Text-fig. 6).

Sequence stratigraphy and palaeogeography

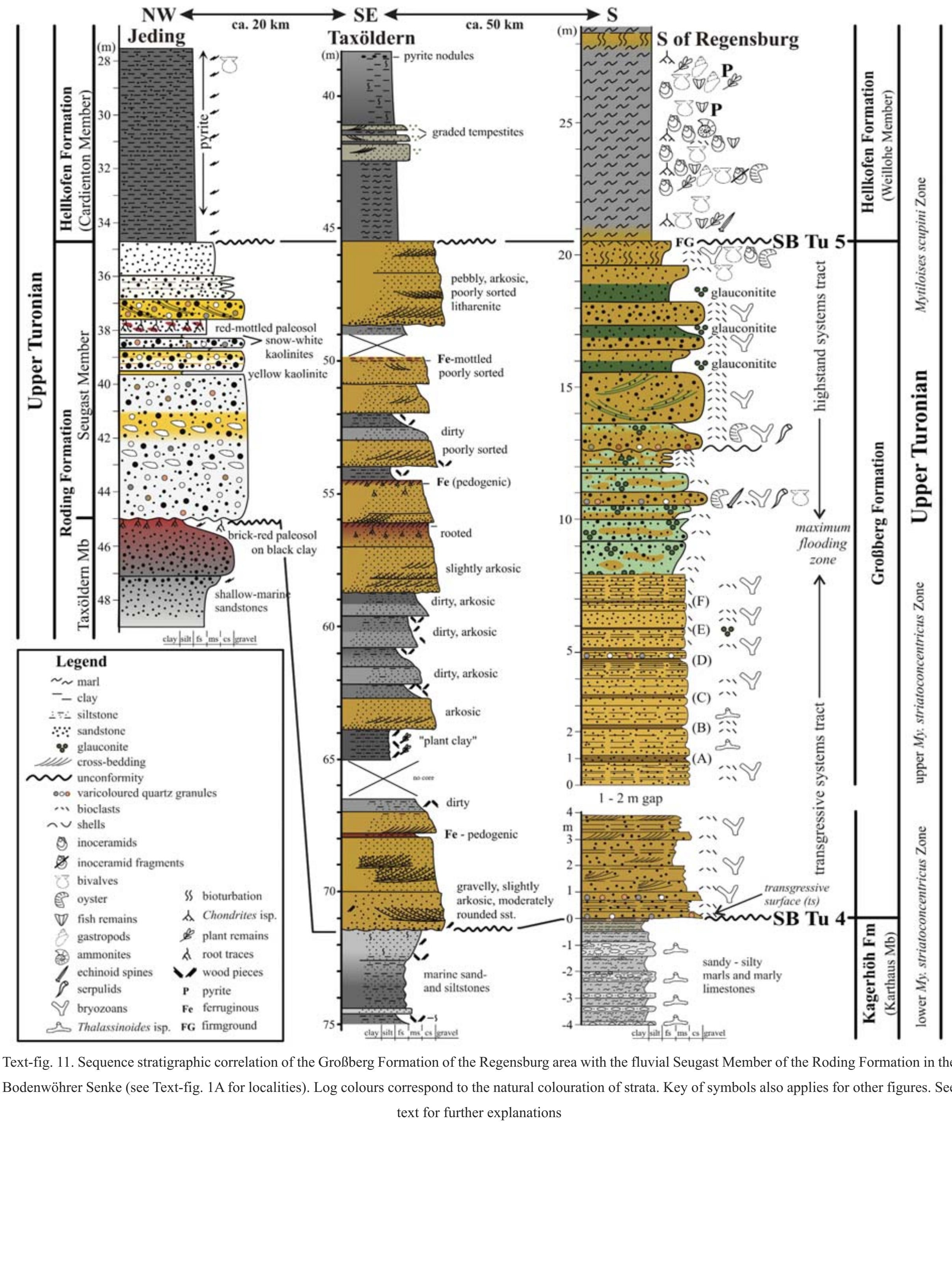
The Großberg Formation is bounded at its base (SB Tu 4) and top (SB Tu 5) by unconformities, thus corresponding to a depositional sequence. The abrupt shift from hemipelagic sediments at its base (Karthaus Member of the Kagerhöh Formation) to transgressive, shallow-marine, litho- and bioclastic calcarenites suggests a stratigraphic gap at this level (absence of falling stage and lowstand sediments). Correlations in the Regensburg area (Meyer 1996) indicate widespread erosion at this level with partial removal of the complete Karthaus Member. Biostratigraphic data indicate that the unconformity is mid-Late Turonian in age (*Mytiloides striatoconcentricus* inoceramid Zone; Text-fig. 6). Lehner (1935) already discussed a significant "early Late Turonian erosional episode" on the Fränkische Alb during which widespread shallow-marine equivalents of the Middle–lower Upper Turonian Kagerhöh Formation ("Betzensteiner Kreidekalk") and Lower Turonian sediments were eroded before the deposition of the "Veldensteiner Sandstein". The "Veldensteiner Sandstein" is a marginal marine equivalent of the Großberg Formation and transgressively onlaps the erosional surface, in many cases directly onto Upper Jurassic carbonates (Lehner 1935, p. 432). Lateral correlation into the proximal Bodenwöhrer Senke (Niebuhr *et al.* 2011; Text-fig. 1) shows that the base of the Großberg Formation corresponds to the erosional incision at the base of the fluvial conglomerates and sandstones of the Seugast Member of the Roding Formation, cutting into the shallow-marine sandstones of the Taxöldern Member (Text-figs 10, 11). As the incision of fluvial valleys occurs during the falling stage to early lowstand systems tracts and usually stops in late lowstand times, the infilling starts with the transgressive systems tract (addition of accommodation; e.g., Coe 2003; Catuneanu *et al.* 2011); thus, the deposition of the fluvial sediments of the Seugast Member is related to the transgression of the Großberg Formation farther south. Support for the existence of a stratigraphic gap below the Seugast Member comes from a palaeosol in the Jeding borehole (Text-fig. 11). The fluvial proximal–distal gradients in the Bodenwöhrer Senke from northwest to southeast indicate that the Seugast River was forced to discharge parallel to the structural elements of the Oberpfälzer Wald and the swell area of the Vorderer Bayerischer Wald, and that it entered the shallow-marine "Großberg Sea" northeast of the study area (Text-fig. 10; cf. Niebuhr *et al.* 2011). In the Münsterland Cretaceous Basin, Richardt and Wilmsen (2012) recognized a major mid-*S. neptuni* zonal unconformity (their SB Tu 4) at the base of the Soest Greensand Member of the Salder Formation. This sequence boundary is situated below the positive Hitch Wood isotope event (sensu Jarvis *et al.* 2006). The magnitude of sea-level fall is comparable in both cases (≥30 m), but the exact contemporaneity of both surfaces cannot be unequivocally proved yet. However, a major sequence boundary is also observed in the Bohemian Cretaceous Basin at the base of the Teplice Formation in a similar stratigraphic position (Wiese *et al.* 2004), and a correlation of these surfaces is suggested. Further work is in progress.

Sequence boundary SB Tu 5 capping the Großberg Formation can be precisely dated as intra-*Mytiloides scupini* Zone (late Late Turonian; Niebuhr 2011). It terminates the Middle–Late Turonian trans-/regressive 2nd-order cycle of the middle Danubian Cretaceous Group (Niebuhr *et al.* 2009). In the study area, SB Tu 5 is characterized by a ferruginous surface (firm- to hardground) and an abrupt shift into the hemipelagic marls of the lower Hellkofen Formation (Weillohe Member; Text-fig. 11). Subaerial exposure at this level is supported by the strongly depleted carbon isotope values in a 2–3-m-thick zone immediately below the surface (cf. Immenhauser *et al*. 2008; see above). In the Bodenwöhrer Senke, a likewise very abrupt facies shift occurs at the contact of the Roding and Hellkofen formations: along a sharp surface, the fluvial sediments of the Seugast Member are replaced by deeper marine silty clays of the Cardienton Member without transition (Text-fig. 11). This observation suggests a very rapid deepening pulse, maybe associated with a stratigraphic gap. SB Tu 5 was first reported as a shallowing event within the *Mytiloides scupini* inoceramid Zone by Wiese and Kröger (1998) in the Salzgitter area (northern Germany). Richardt and Wilmsen (2012) recognized this sequence boundary in the Erwitte Formation of the southern Münsterland. In England, it matches a condensed hardground sequence immediately above the Hitch Wood Event (Jarvis *et al*. 2006) and a high-Upper Turonian sequence boundary of Gale (1996).

The change from non-marine and shallow-marine deposits to fine-grained marly–clayey sedimentation can be followed all across the study area of the Danubian Cretaceous Group of Bavaria (Niebuhr *et al.* 2009; Niebuhr 2011; Schneider *et al.* 2011) and may be connected with increased flexural subsidence of the marginal troughs in front of the future frontal thrusts bounding the Bohemian Massif to the southwest (Franconian Lineament and Pfahl Fault; see Text-figs 1, 10 and Niebuhr *et al.* 2011). According to Kley and Voigt (2008), the onset of tectonic inversion in Central Europe is related to a change in relative motion between the European and African plates (NE-directed convergence) starting at ca. 90 Ma, i.e., within the Late Turonian. In northern Germany, uplift of inversion structures and subsidence of marginal troughs also started at that date, associated with large-scale redeposition and a widespread shift to marly–clayey facies (e.g., Voigt 1962; Voigt *et al*. 2006b).

CONCLUSIONS

The Upper Turonian Großberg Formation of the Regensburg area (Danubian Cretaceous Group, Bavaria, southern Germany) has been investigated using an integrated approach. Several sections and outcrops have been logged in detail bed-by-bed and sampled for macrofossil palaeontology, microfacies and stable isotope geochemistry. This resulted in a detailed multi-stratigraphic calibration of the formation as well as the reconstruction of its depositional environment and palaeogeographic significance.



Text-fig. 11. Sequence stratigraphic correlation of the Großberg Formation of the Regensburg area with the fluvial Seugast Member of the Roding Formation in the Bodenwöhrer Senke (see Text-fig. 1A for localities). Log colours correspond to the natural colouration of strata. Key of symbols also applies for other figures. See text for further explanations

The Großberg Formation has a mean thickness of 20–25 m and consists of sandy bioclastic calcarenites and calcareous sandstones which are rich in macrofossils [bryozoans, serpulids, bivalves (oysters, rudists, inoceramids), echinoids, corals, brachiopods]. Especially the coarse-grained basal units show large-scale planar cross-bedding and most of the biogenic components are more-or-less fragmented and abraded bioclasts. By means of microfacies analysis, eight typical facies types have been recognized that characterize a mixed siliciclastic–carbonate ramp setting: the inner ramp sub-environment was characterized by high-energy sandwave deposits (sandy bioclastic rud- and grainstones, bioclastic sandstones) with sheltered inter-shoal areas. The migration of the sandwaves was ESE–SE-directed, paralleling the coastline of the Bohemian Massif in the northeast. In mid-ramp settings, bioturbated glauconitic calcareous sand- and siltstones as well as bioturbated bioclastic wacke- and packstones predominated. The carbonate facies of the Großberg Formation can be categorized as a temperate bryomol grain association albeit palaeogeographic considerations, a few biofacies indicators (some rudists and corals, widespread micritization) and oxygen stable isotope palaeo-thermometry also indicate warm-water influences. It is suggested that a surplus of land-derived nutrients resulted in eutrophic conditions and favoured the heterozoan communities of the Großberg Ramp.

Carbon stable isotope geochemistry cannot significantly contribute to the stratigraphic calibration of the Großberg Formation. The trendless course of the bulk-rock $\delta^{13}C$ values and their conspicuous negative offset at the formational boundaries are explained by the decoupling of shallow neritic from open marine seawater, resulting in different physico-chemical properties of water masses (shallow-water aquafacies with depleted $\delta^{13}C_{DIC}$ values). Furthermore, pore waters with strongly depleted $\delta^{13}C_{DIC}$ values due to respiration of organic matter may have generated low $\delta^{13}C$ values of syndepositional and early diagenetic carbonate phases inevitably present in bulk-rock samples from the Großberg Formation. In support of this, diagenetically stable shell calcite of a few oyster samples from the Großberg Formation are strongly enriched in $\delta^{13}C$ (up to 3.8 ‰ vs. V-PDB). These very high values also support a correlation of the Großberg Formation with the mid-Late Turonian positive Hitch Wood isotope event (*Hyphantoceras* Event of northern Germany).

Biostratigraphically, the Großberg Formation can be dated as mid-Late Turonian, ranging from the *Mytiloides striatoconcentricus* Zone into the lower *My. scupini* Zone. Both its base and top are characterized by unconformities. The lower one, sequence boundary SB Tu 4, is a major regional erosion surface corresponding to erosional truncation of the underlying Kagerhöh Formation in the Regensburg area and the fluvial incision at the base of the Seugast Member of the Roding Formation in the north and northeast (Bodenwöhrer Senke). It is suggested that this unconformity corresponds to a major sea-level drop recognized in many other Cretaceous basins below the Hitch Wood or *Hyphantoceras* Event. The transgression and highstand of the Großberg Formation is concomitant to the deposition of the fluvial Seugast Member and the onlap of the marginal-marine "Veldensteiner Sandstein" onto the Fränkische Alb. The unconformity at the top of the Großberg Formation (late Late Turonian SB Tu 5) is indicated by a ferruginous firm-/hardground, an underlying zone of strongly depleted $\delta^{13}C$ values, and the abrupt superposition of deeper marine marls of the lower Hellkofen Formation (uppermost Turonian–Lower Coniacian). It is possible that this widespread deepening pulse, that can be traced all across the Danubian Cretaceous (and beyond), was connected with inversion tectonics (increased flexural subsidence of the marginal troughs in front of the future frontal thrusts bounding the Bohemian Massif).

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