Z. Dt. Ges. Geowiss. (German J. Geosci.), **165 (2)**, p. 179–208, 12 figs.
Published online August 2013 **Article**

Sequence stratigraphy of the lower Upper Cretaceous Elbtal Group (Cenomanian–Turonian of Saxony, Germany)

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Janetschke, N. & Wilmsen, M. (2014): Sequence stratigraphy of the lower Upper Cretaceous Elbtal Group (Cenomanian–Turonian of Saxony, Germany). [Sequenzstratigrafie der unteren Oberkreide der Elbtal-Gruppe (Cenoman–Turon von Sachsen, Deutschland).] – Z. Dt. Ges. Geowiss., 165: 179–208, Stuttgart.

Abstract: A detailed sequence stratigraphic study of the Cenomanian–Turonian strata of the Elbtal Group focussing on new core and outcrop data provided important clues for the understanding of early Late Cretaceous sea-level changes in the Saxonian Cretaceous Basin. Depositional sequence-bounding unconformities have been dated using high-resolution macrofossil biostratigraphy, relying on newly obtained and previously published data, and correlated between individual sections. In the Middle Cenomanian–Late Turonian, seven sequence boundaries (SB Ce 4 and 5, SB Tu 1–5) have been identified that define seven 3rd-order depositional sequences (DS Ce 4 and 5, DS Ce–Tu 1, DS Tu 2–5). Sequences DS Ce 4 and DS Ce 5 are capped by unconformities SB Ce 4 and SB Ce 5 (latest Middle and mid-Late Cenomanian in age). Their deposition was strongly influenced by pre-transgression palaeo-topography; they can be completely missing on basement highs. DS Ce–Tu 1 (mid-Upper Cenomanian–Early Turonian) started with the major *plenus* Transgression and onlap continued with a second pulse into the earliest Turonian, finally levelling the pre-existing topography and giving rise to more uniform sedimentation patterns of a graded shelf system during the Turonian. The next sequence boundary is SB Tu 1, a conspicuous unconformity within the Lower–Middle Turonian boundary interval. DS Tu 2 has an early Middle Turonian age. The up-section following sequence DS Tu 3 is of late Middle–earliest Late Turonian age and was characterised by a significant rise in sea-level terminated by a forced regression in the earliest Late Turonian (SB Tu 3, abrupt basinward shift into coarse-grained sandstone facies). Renewed sea-level rise during the early to mid-Late Turonian within DS Tu 4 is documented by a fining trend. A rapid coarsening in grain size in response to strong forced regression resulted in the formation of SB Tu 4 (mid-Late Turonian) and basinward progradation of thick-bedded sandstones in the lower part of DS Tu 5, followed by a major mid-Upper Turonian transgression culminating in a maximum flooding interval equating the *Hyphantoceras* Event. Highstand shallowing ended at the late Late Turonian unconformity SB Tu 5. The sequence stratigraphic subdivision of the Elbtal Group compares well to the results of earlier studies and can be translated into the genetic sequence stratigraphy developed for the Bohemian Cretaceous Basin.

Kurzfassung: Detaillierte sequenzstratigrafische Untersuchungen der cenomanen–turonen Abfolgen der Elbtal-Gruppe, die sich auf neue Daten, sowohl aus Bohrkern-, als auch aus Aufschlussaufnahmen stützen, lieferten wichtige Hinweise zum weiteren Verständnis der Meeresspiegelschwankungen im Sächsischen Kreidebecken während der frühen Oberkreidezeit. Die exakte zeitliche Einordnung und die Korrelation der die einzelnen Ablagerungssequenzen gegeneinander abgrenzenden Diskordanzen zwischen den verschiedenen bearbeiteten Profilen erfolgten anhand einer hochauflösenden Makrofossilbiostratigrafie und basieren auf neuen sowie bereits veröffentlichten Daten. Vom Mittelcenoman–Oberturon konnten sieben Sequenzgrenzen (SB Ce 4 und 5, SB Tu 1–5) ausgeschieden werden, die entsprechend sieben Ablagerungssequenzen (DS Ce 4 und 5, DS Ce–Tu 1, DS Tu 2–5) – resultierend aus Meeresspiegelschwankungen dritter Ordnung – definieren. Die Sequenzen DS Ce 4 und DS Ce 5 werden dabei von den Diskordanzen SB Ce 4 und SB Ce 5 (spätes Mittel- und mittleres Obercenoman) begrenzt. Da ihre Ablagerung und Ausbildung in engem Zusammenhang mit der prätransgressiven Paläotopografie stehen, können diese Sequenzen auf ehemaligen Hochflächen komplett fehlen. DS Ce–Tu 1 (mittleres Obercenoman–Unterturon) beginnt mit der bedeutenden *plenus*-Transgression, wobei sich das Onlap mit einem zweiten Puls im frühesten Turonian fortsetzt und damit endgültig jegliche vorher bestehende Topografie nivellierte. Aus dieser Situation ergaben sich einheitlichere Sedimentationsmuster eines gradierten Schelfsystems während des Turons. Die nächstfolgende Sequenzgrenze (SB Tu 1) stellt eine signifikante Diskordanz im Bereich der Unter-/Mittelturon-Wende dar. DS Tu 2 zeigt ein frühmittelturones Alter. Die Ablagerungssequenz DS Tu 3 (spätes Mittel- bis unterstes Oberturon) wird durch einen markanten Meeresspiegelanstieg charakterisiert, der wiederum mit einem bedeutenden Regressionsereignis im frühesten Oberturon endet (SB Tu 3, beckenwärts abrupter Wechsel hin zu einer groben Sandsteinfazies). Ein erneuter Meeresspiegelanstieg vom frühen bis ins mittlere Oberturon drückt sich in DS Tu 4 durch einen Trend zur Sedimentverfeinerung aus. Ein plötzlicher Korngrößenanstieg – verursacht durch eine starke Regression – führte zum Einen zur Ausbildung der Sequenzgrenze

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 www.schweizerbart.de
DOI: 10.1127/1860-1804/2013/0036 1860-1804/0036 $ 12.60

SB Tu 4 (mittleres Oberturon), zum Anderen zur beckenwärts gerichteten Progradation dickbankiger Sandsteinkörper im liegenden Abschnitt von DS Tu 5. Die anschließende beachtliche Transgression während des mittleren Oberturons gipfelt in einem Intervall maximaler Überflutung, das mit dem *Hyphantoceras*-Event korrespondiert. Der nachfolgende Hochstand und die sukzessive Verflachung enden mit SB Tu 5 im späten Oberturon. Die neue Sequenzgliederung der Elbtal-Gruppe korreliert gut mit den Ergebnissen früherer Arbeiten und lässt sich auch auf die genetische Sequenzstratigrafie des Böhmischen Kreidebeckens übertragen.

Keywords: Cenomanian, Turonian, Saxony, Elbtal Group, sequence stratigraphy, correlation

Schlüsselwörter: Cenoman, Turon, Sachsen, Elbtal-Gruppe, Sequenzstratigrafie, Korrelation

1. Introduction

In Saxony (Germany), a southeast–northwest-oriented outcrop belt of lower Upper Cretaceous (Cenomanian–Coniacian) sedimentary rocks, more or less paralleling the course of the Elbe River, occurs between the Czech border, Pirna and the Dresden–Meißen area (Fig. 1). The facies of these Cretaceous strata is dominated by partly fluvial, but mostly marine siliciclastics as well as marls and marly–silty limestones (so-called "Pläner"), lithostratigraphically combined in the Elbtal Group (Voigt & Tröger in Niebuhr et al. 2007). The Saxonian Cretaceous forms an important link between the temperate Boreal shelf of northern and northwestern Europe and, via the Bohemian Cretaceous Basin, the Tethyan warm-water areas to the south.

The palaeontology, litho- and biostratigraphy as well as the sedimentology of the Elbtal Group are well studied (e.g. Geinitz 1871–1875, 1872–1875, Prescher 1954, 1981, Seifert 1955, Tröger 1956, 1967, 1969, 2003, Voigt 1994, 1998, 1999, 2011 among many others) and also sea-level development has been reconstructed (Voigt 1994, Voigt et al. 1994, Tröger & Voigt 1995, Voigt & Tröger 1996, S. Voigt et al. 2006). However, a synoptic study with a continuous, stratigraphically reinterpreted record from the important key region of the "Faziesübergangszone" (facies transition zone) around Pirna, located between the sandy nearshore zone of the Elbsandsteingebirge and the marly offshore facies of the Dresden-Meißen area (Fig. 1), was still lacking. Based on the detailed study of a newly available, stratigraphically complete Cenomanian–Upper Turonian core section from this Faziesübergangszone, the logging of numerous outcrops, and the lateral tracking of the sequence-bounding unconformities, a reconstruction of the Cenomanian–Turonian sequence stratigraphy of the Elbtal Group and a sequential correlation to other regional charts are attempted.

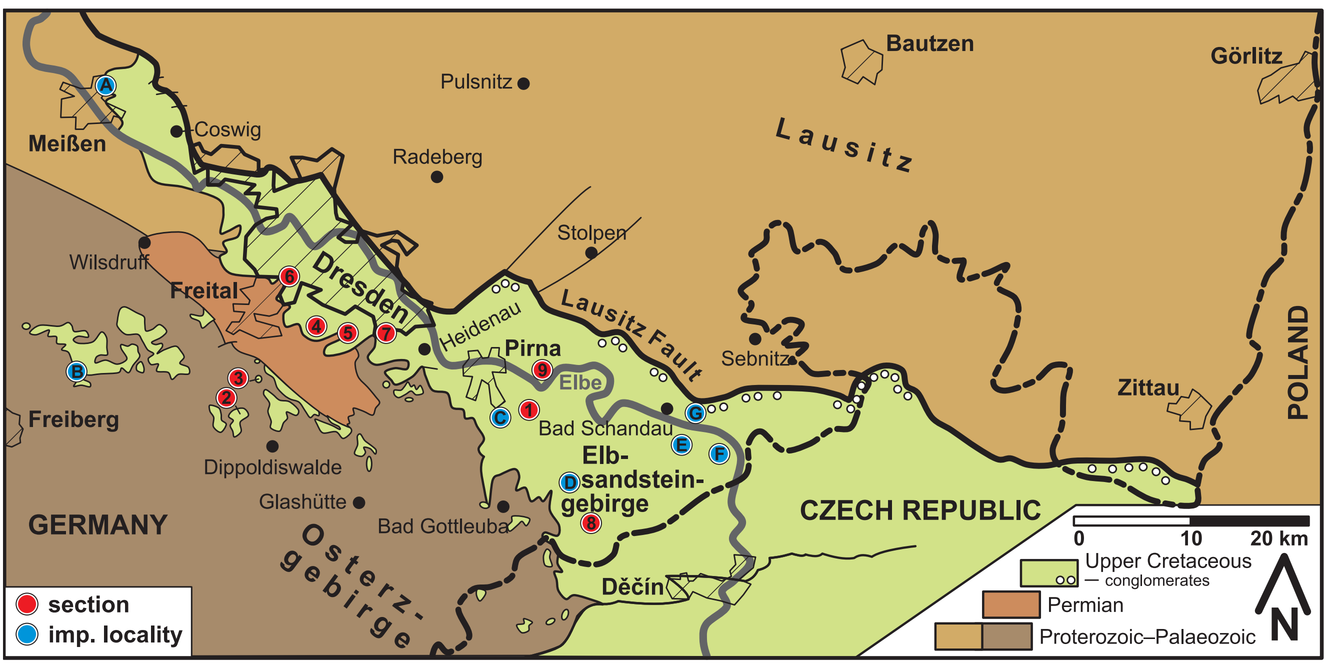


Fig. 1: Simplified geological map of Saxony, showing the distribution of the Elbtal Group (green). Sections (red) and important localities (blue) are marked by circles. (1) = Krietzschwitz borehole; (2) = Sandberg section, Paulsdorfer Heide; (3) = Götzenbüschchen section, Oelsa; (4) = Bannewitz, Horkenberg and Goldene Höhe sections; (5) = Gebergrund section, Goppeln; (6) = Heidenschanze/Gittersee sections and Hoher Stein locality, Dresden; (7) = Lockwitz section, Dresden; (8) = Felsengasse section near Ottomühle, Bielatal; (9) = Dorf Wehlen section, Zeichener Brüche; (A) = Meißen-Zscheila (transgression of DS Ce 3); (B) = Niederschöna (type locality of the Niederschöna Formation); (C) = Lohmgrund quarry; (D) = Raum, former brick pit; (E) = Reinhardtsdorf quarry; (F) = Kaiserkrone; (G) = Latengrund and Schrammsteine.

2. Geological setting

The Elbtal Group was deposited in a relatively narrow strait between the Westsudetic Island in the northeast and the Erzgebirge as the central part of the Mid-European Island in the southwest (Fig. 2). The sediments demonstrate strong relationships in terms of (bio-) facies to contemporaneous strata from the Bohemian Cretaceous Basin in the southeast. However, the special palaeogeographic position results in certain independence of the depositional area of the Elbtal Group, forming a subbasin called Saxonian Cretaceous Basin herein, whose active northeastern margin is represented by the Lausitz Fault (Fig. 1). The thickness and facies changes of Cretaceous strata within the thrust basin show that from the Late Cenomanian and with increasing intensity from the Middle Turonian onward, deposition was influenced by synsedimentary activity of the Lausitz Fault (Voigt 1994, 2009). This fault is part of a group of northwest–southeast-trending Late Cretaceous structural elements in Central Europe (e.g. T. Voigt et al. 2006, Voigt 2009, Niebuhr et al. 2011) that have been affected by compression since the Turonian, forced by changes in plate motion of Africa and Iberia with respect to Europe (Kley & Voigt 2008). Despite tectonics being a formative factor in basin evolution, a number of Cenomanian and Turonian depositional sequences and their bounding unconformities can be recognised in the successions of the Saxonian Cretaceous Basin. These can now be correlated with high preci-

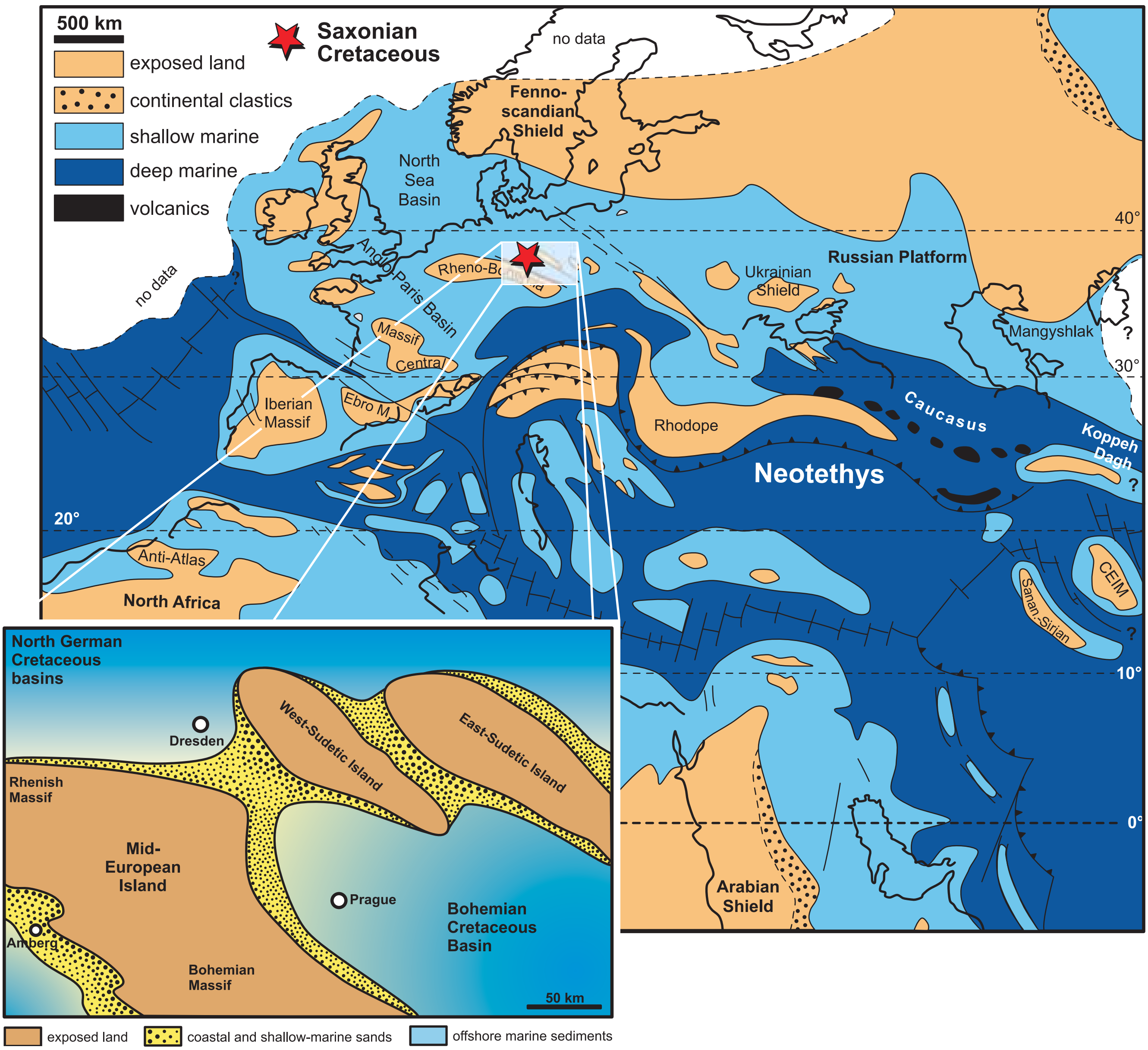


Fig. 2: Late Cenomanian–Early Turonian palaeogeography (modified after Philip & Floquet 2000) and detail of the Saxonian and Bohemian Cretaceous basins (modified after Voigt 1994). The study area is marked by a red asterisk.

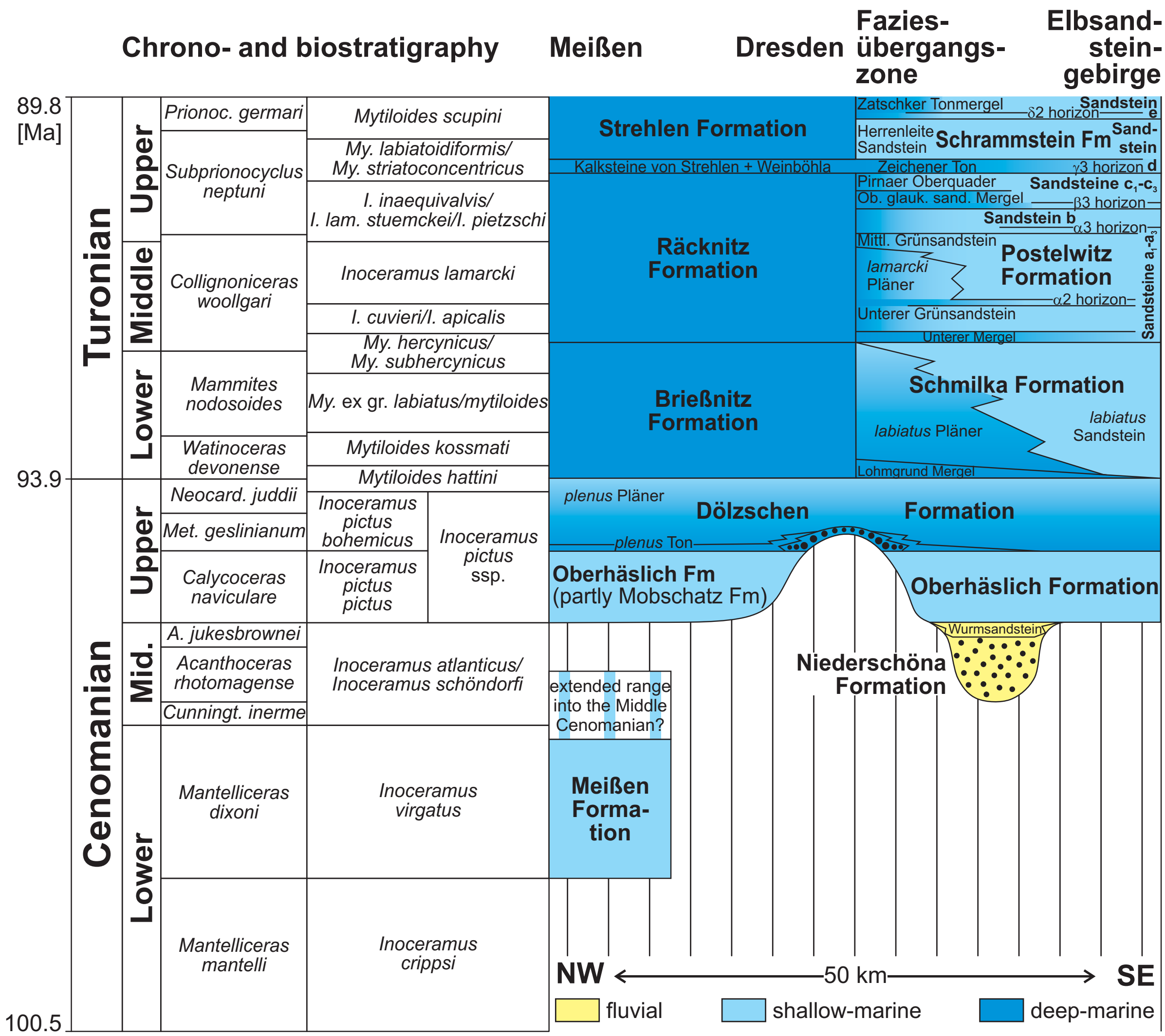


Fig. 3: Litho-, chrono- und biostratigraphic framework of the Elbtal Group. Ammonite standard zones after Kennedy (1984, 1986), Wright et al. in Wright & Kennedy (1984) and Hancock (1991), inoceramid zones after Tröger (1989), partly modified. Sandstone and boundary horizon terminology in the Elbsandsteingebirge after Lamprecht (1928, 1934), litho-units of the Faziesübergangszone after Seifert (1955). Absolute ages according to Ogg & Hinnov (2012).

sion to obviously coeval in other Cretaceous basins, implying a predominantly eustatic control on deposition.

A first marine transgression, advancing from the north, occurred in the late Early Cenomanian. It reached the area of Meißen (Meißen Formation; lithostratigraphy after Tröger & Voigt in Niebuhr et al. 2007), where conglomeratic bioclastic limestones indicate high-energy nearshore conditions (Fig. 3). The Meißen Formation may also range into the Middle Cenomanian and a continuing Mid-Cenomanian base-level rise with concomitant back-filling of river valleys is indicated by the fluvial Niederschöna Formation (Voigt 1998). A major intermittent transgression occurred during the Late Cenomanian, submerging a pronounced relief of valleys and highs related to the different erosional resistance of basement rocks. Clastic sediments were predominantly sourced from the southwest (Erzgebirge) and the northeast (Westsudetic Island). The Late Cenomanian transgression took place in two main pulses. In the *Calycoceras naviculare* Zone (early Late Cenomanian), the shallow-marine and fossiliferous sands and clayey silts of the Oberhäslich and Mobschatz formations have been deposited, usually missing on swells. The second pulse occurred in the mid-Late Cenomanian *Metoicoceras geslinianum* Zone (*plenus* Transgression of authors), resulting in the final drowning of remaining islands and the onlap of the Dölzschen Formation (with basal "*plenus* Ton", followed by silty spiculitic marlstones of the "*plenus* Pläner") onto formerly emergent basement areas, not only in Saxony (e.g. Schander 1923, Tröger 1956, Voigt et al. 1994, S. Voigt et al. 2006, Wilmsen et al. 2011), but also in many parts of the Bohemian Cretaceous Basin (e.g. Žítt et al. 1998, 2006, 2010). In the Danubian Cretaceous (northeastern Bavaria), on the opposing flank of the Bohemian Massif, contemporaneous onlap architectures have been documented, too (Niebuhr et al. 2009, Wilmsen et al. 2010a, Richardt et al. 2013).

Following the Late Cenomanian levelling of the pre-transgression topography, more homogeneous sedimentation patterns of a graded shelf became established during the Turonian (Figs. 2, 3); the area of the Elbsandsteingebirge was formed by sandy nearshore facies, while in the Dresden–Meißen area, offshore marls and Pläner prevailed, with a transitional zone of intercalated Pläner and sandstone deposition (Faziesübergangszone). During the Early Turonian, the still relatively narrow seaway between the Westsudetic Island and the Erzgebirge was characterised by cross-bedded sands (Schmilka Formation; see Voigt 1994, 1999), grading with an intermediate transitional facies of bioturbated, silty–clayey fine-grained sandstones and silty Pläner into fine-grained basinal deposits, dominating the Dresden area (calcareous, silty marls of the Brießnitz Formation; Fig. 3). The Middle Turonian transgression shifted the coastline far westward onto the Bohemian Massif and consequently, the bulk of the Middle and Upper Turonian clastic material of the Saxonian Cretaceous Basin (Postelwitz and Schrammstein formations) has been derived from the uplifted Westsudetic Island with a depocentre immediately southwest of the Lausitz Fault (Voigt 1994, 2009). The coarse units grade into fine-grained, calcareous basinal deposits (Pläner sediments of the Räcknitz and Strehlen formations) in the Dresden–Meißen area (Fig. 3). In the Faziesübergangszone and in the Elbsandsteingebirge, a large number of subordinate lithological names have formerly been introduced that are partly still in use (sandstone and boundary horizon terminology in the Elbsandsteingebirge after Lamprecht 1928, 1934; Faziesübergangszone after Seifert 1955). Albeit mostly neither being formal members nor beds of the modern formations, important ones of those names are indicated in Fig. 3 and along the sections in order to facilitate a comparison with previous literature or geological maps.

The biostratigraphy of the Elbtal Group is mainly based on macrofossils, most notably inoceramid bivalves (e.g. Tröger 1967, 1969) and ammonites (e.g. Petrascheck 1902, Tröger 1968, Wilmsen & Nagm 2013a). Biostratigraphic accounts have also been given for individual formations (e.g. Tröger & Wolf 1960, Tröger 1987: Strehlen Formation; Tröger 1988: Brießnitz Formation; Prescher & Tröger 1989: Meißen Formation). Thus, the succession of the Elbtal Group can be calibrated with high precision to the standard biozonations (ammonite standard zones after Kennedy 1984, 1986, Wright et al. in Wright & Kennedy 1984 and Hancock 1991; inoceramid zones after Tröger 1989, modified; see Fig. 3). The high-resolution macrofossil biostratigraphy also forms the basic tool for the dating and the correlation of the sequence boundaries recognised in this study. A further dating and correlation instrument applied to the Saxonian Cretaceous is bioevent stratigraphy (e.g. Tröger & Voigt 1995). The formation of bioevents is deeply interwoven with sea-level changes, and thus bioevent stratigraphy is also an important tool for sequence stratigraphic interpretations (Wilmsen 2012).

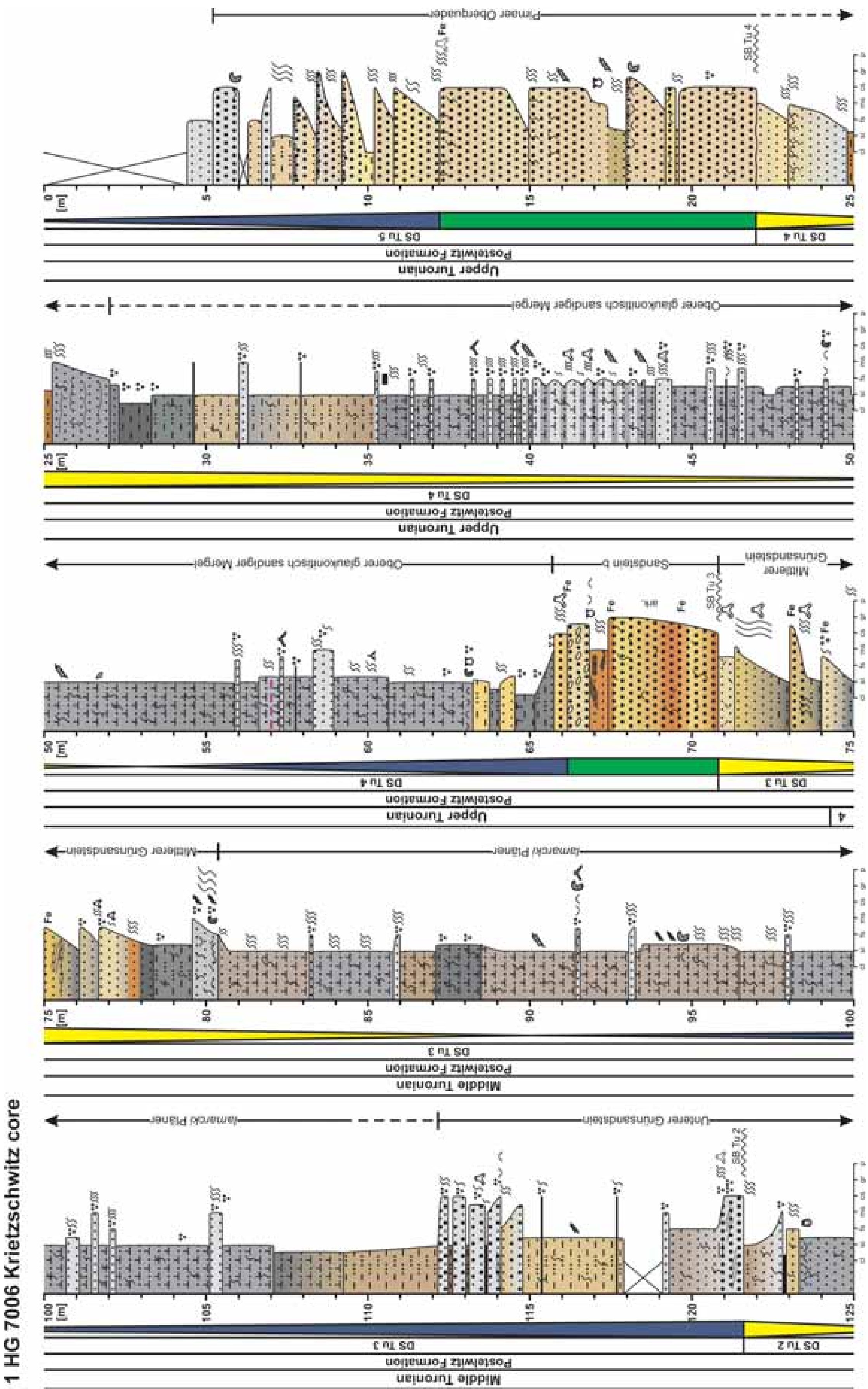
3. Approach and methods

All sections (core and outcrops) have been logged in great detail (cm-scale). The Krietzschwitz core has been measured in the core workshop of the Wismut GmbH Königstein at Leupoldishain. In the meantime, the core is stored in the collection of the Senckenberg Naturhistorische Sammlungen Dresden (SNSD). Rocks have been classified using a hand lense according to grain size and fabric. Observations on sedimentary structures, macro- and trace fossils were keyed to the stratigraphic logs, which have been drawn in the field and were digitised later. In addition to field classification, important facies types have been sampled for thin-section analysis using a Leica M125 stereo microscope. All observations have been integrated to obtain a high-resolution bio- and lithostratigraphic subdivision.

For the sequence stratigraphic analysis, we focussed on the identification of major, i.e. sequence-bounding unconformities. These surfaces evidence significant non-depositional or erosional periods (stratigraphic gaps), or are characterised by rapid basinward shifts of facies. They have been dated and tracked laterally between the different sections. Our sequence boundaries (SB) define 3rd-order depositional sequences (DS, in the sense of Haq et al. 1987 and Posamentier et al. 1988), and we tried to separate them from subordinate (i.e. 4th- and higher order) surfaces by means of their characters (e.g. duration of gap, magnitude of erosion, shift of facies). Depositional sequences usually consist of retro- and progradational facies units, i.e. transgressive and highstand systems tracts (TST, HST). Sequence boundaries and transgressive surfaces fuse in these cases. Maximum flooding intervals correspond to most distal facies development in a depositional sequence, usually characterised by fine-grained, argillaceous–marly sediments in the sandy nearshore facies zone. However, with increasing distance from the shore, these stratigraphic intervals are increasingly difficult to identify, and we thus refrain from using the genetic sequence stratigraphic approach (cf. Galloway 1989). Falling stage (FSST) and lowstand deposits (LST) only have been recognised in the Upper Turonian (sharp-based, prograding, thick-bedded sandstone units), and there, the sequence boundaries are consequently placed between HST and FSST/LST (see Coe 2003 for internal sequence architecture and terminology). We have to stress that due to the limited number of sections, 2D- and 3D-reconstructions of sequence stratigraphic architectures are difficult to obtain. On the other hand, the typical sequence geometry of a siliciclastic system is not developed in the Saxonian Cretaceous due to the basin configuration with a depocentre close to the northeastern active basin margin (Voigt 1994).

Naming of sequence boundaries is accomplished according to their time-equivalent counterparts in other Cretaceous basins of Europe (e.g. Hardenbol & Robaszynski 1998, Hardenbol et al. 1998, Robaszynski et al. 1998, Wilmsen

Fig. 4: Stratigraphic log of the Krietzschwitz core section with sequence stratigraphic interpretation and lithological terminology after Seifert (1955). Numbering refers to locality map (Fig. 1). For key of symbols see Fig. 7.


1 HG 7006 Krietzschwitz core
Middle Turonian
Upper Turonian
Postelwitz Formation
DS Tu 2
DS Tu 3
DS Tu 4
DS Tu 5
SB Tu 2
SB Tu 3
SB Tu 4
Unterer Grünsandstein
lamarcki Pläner
Mittlerer Grünsandstein
Sandstein b
Oberer glaukonitisch sandiger Mergel
Pirnaer Oberquader
[m]

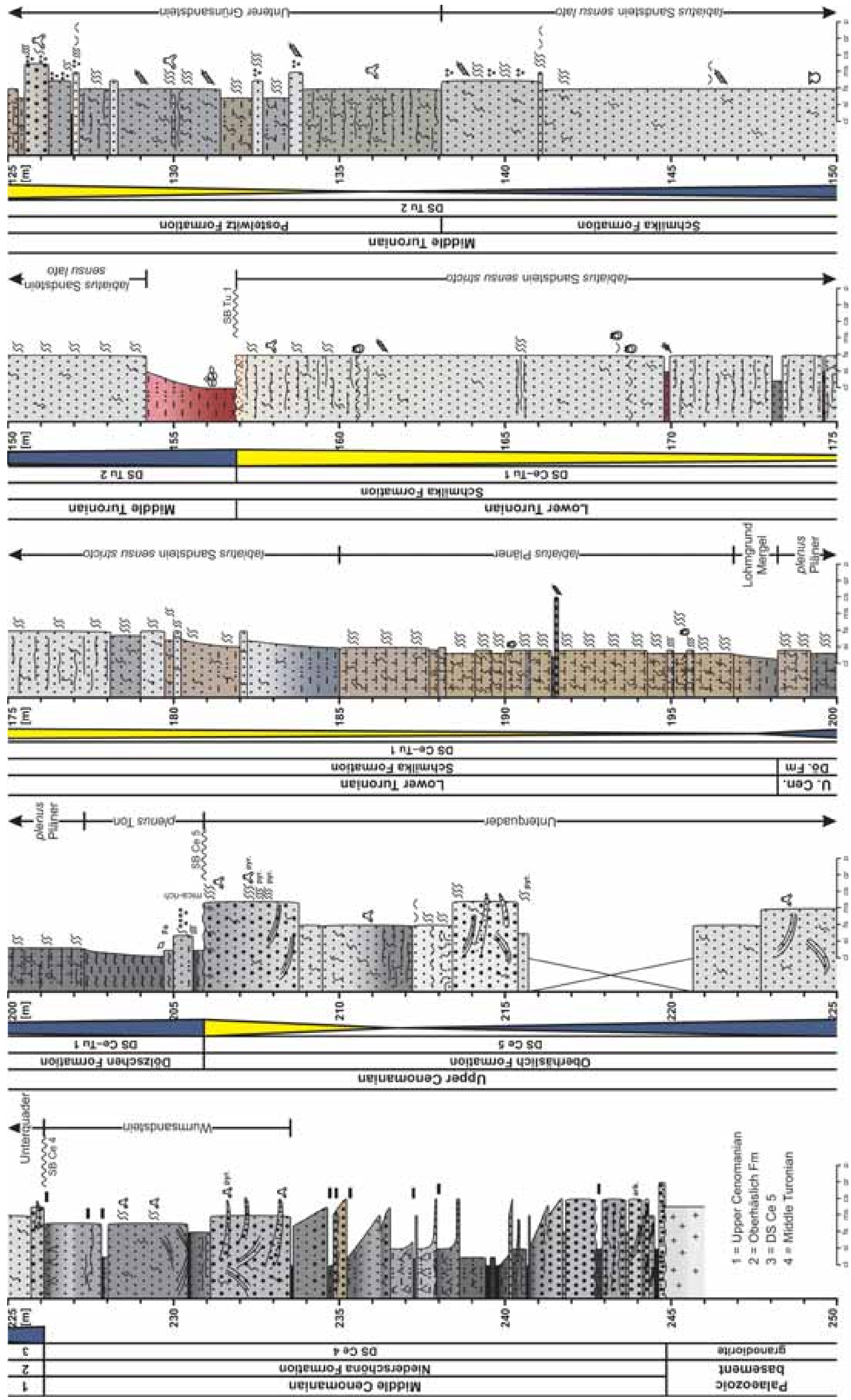

Unterer Grünsandstein
labiatus Sandstein sensu lato
DS Tu 2
Postelwitz Formation
Schmilka Formation
Middle Turonian
labiatus Sandstein sensu stricto
SB Tu 1
DS Ce–Tu 1
Lower Turonian
labiatus Pläner
Lohmgrund Mergel
plenus Pläner
Do. Fm
U. Cen.
plenus Ton
Unterquader
SB Ce 5
DS Ce 5
Dölzschen Formation
Oberhäslich Formation
Upper Cenomanian
Wurmsandstein
SB Ce 4
DS Ce 4
Niederschöna Formation
Middle Cenomanian
Palaeozoic basement granodiorite
1 = Upper Cenomanian
2 = Oberhäslich Fm
3 = DS Ce 5
4 = Middle Turonian

Fig. 4: cont.

2003, Niebuhr et al. 2011, Richardt & Wilmsen 2012): SB Ce(nomanian) 4 and 5, SB Tu(ronian) 1–5. Depositional sequences are named relating to their terminal unconformity: DS Ce 4 and 5, DS Ce–Tu 1, DS Tu 2–5. In the following descriptive part, we are already using these names when referring to the respective unconformities in order to avoid later confusion.

4. Sections

4.1 Krietzschwitz core (Figs. 4, 5)

The HG 7006 borehole has been drilled in 2001 at Krietzschwitz, Hohe Straße (topographic mapsheet TK 25: 5049 Pirna; UTM [WGS84] coordinates: 33U, 429096 E, 5641347 N) by the Wismut GmbH for hydrological monitoring of the former Königstein uranium mine. It is situated ca. 5 km southeast of Pirna in the Faziesübergangszone (facies transition zone) and reaches a final depth of 245.90 m.

The Krietzschwitz section nicely exposes the contact of the Palaeozoic basement, onlapped by 18.70 m of fluvial–estuarine sediments of the Niederschöna Formation (probably Middle Cenomanian). It starts with a 20-cm-thick conglomerate bed followed by light grey to grey, mainly coarse-grained, cross-bedded sandstones, representing deposits of a braided river system. Upward, grey to dark grey, rooted, fine sandy–silty units with intercalated black carbonaceous, clayey and lighter grey, gravelly layers predominate (Fig. 5A). The latter beds often show sharp bases and normal grading into carbonaceous fines, reflecting typical point bar cycles of a meandering stream (see Voigt 1998 for facies details of the Niederschöna Formation). The topmost 7.40 m of the formation display a slight coarsening trend. It is marked by grey, massive, bioturbated and cross-bedded, fine- to medium-grained sandstone packages. *Ophiomorpha* burrows document a marine influenced depositional environment. This interval represents the estuarine, so-called "Wurmsandstein" (Figs. 3, 4). Finally, the Niederschöna Formation is terminated by a prominent surface (sequence boundary SB Ce 4) with clear impact of pedogenic processes (rhizoliths; Fig. 5B), indicating an interruption of sedimentation.

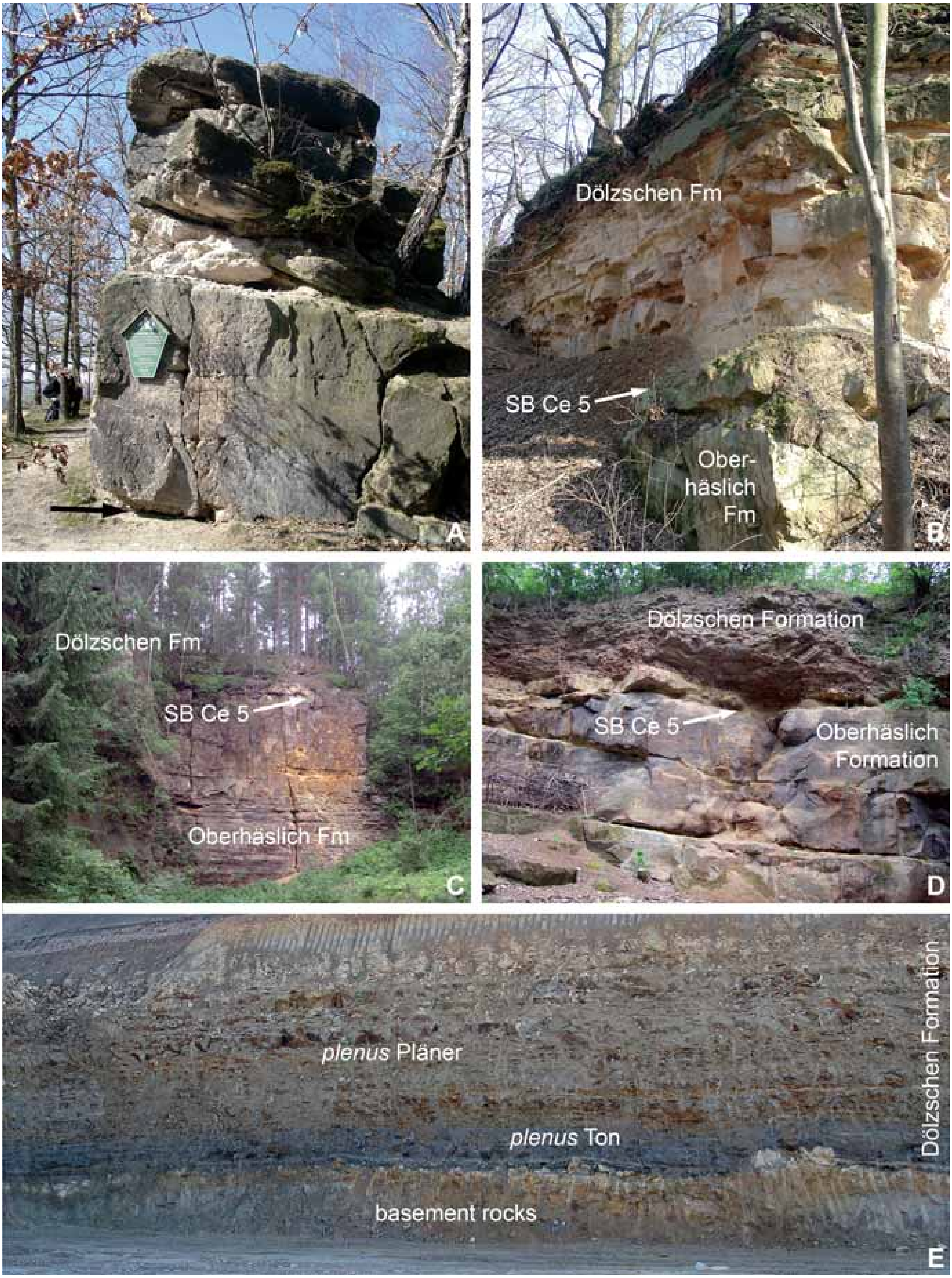
The overlying 20.20-m-thick Oberhäslich Formation (lower Upper Cenomanian, former "Unterquader") starts with a thin transgressive lag and consists of greyish to topward darker grey, thick-bedded to compact, bioturbated, cross-bedded, predominantly fine- to medium-grained quartz sandstones with some coarse-grained intercalations and oyster shell concentrations (*Rhynchostreon* sp.) around the 213-m-level. A terminal erosional and strongly bioturbated surface (SB Ce 5; Fig. 5C) is recognised at 205.90 m, followed by a very conspicuous lithological change to the Dölzschen Formation (uppermost Upper Cenomanian). This formation starts with two dark marl layers, embracing a bioturbated, glauconitic silt to fine-grained sandstone bed; all three beds are comparatively mica-rich. This interval represents the *plenus* Transgression (*plenus* Ton; Figs. 3, 4). The remaining 7.50 m of the Dölzschen Formation consist of an upward-coarsening package of silty Pläner (*plenus* Pläner).

The Dölzschen Formation is overlain by the 59.10-m-thick Schmilka Formation (Lower–lower Middle Turonian). This unit begins with a prominent, dark grey, argillaceous marl ("Lohmgrund Mergel"), changing gradually into grey-brown to brown, strongly bioturbated silty Pläner ("*labiatus* Pläner"; Fig. 3), continued by a coarsening-upward trend into light grey, moderately bioturbated, massive, fine-grained quartz sandstones. The lower part of this interval, up to a major unconformity at 156.90 m (SB Tu 1; Fig. 5D), contains abundant inoceramid shells and debris with concentrations at 160.60 m and 168.80 m, representing the "*labiatus* Sandstein" sensu stricto (see Voigt 1999 for details). The remarkable surface at 156.90 m shows a red mottling and rhizoliths. It is supposed to be a palaeosol formed in a terrestrial setting. According to the correlation with the Felsengasse section (see below), a position in the Lower–Middle Turonian boundary interval is inferred (Voigt 1994, 1999). The overlying 2.70-m-thick, fine-siliciclastic, partly nodular sediments are characterised by typical reddish, terrestrial colours and most likely accumulated in a non-marine depositional environment.

Up-section, the Schmilka Formation continues in similar lithology, but without *Mytiloides labiatus*, occasionally containing large wood fragments up to the 138.10-m-level (*labiatus* Sandstein sensu lato). The Postelwitz Formation (lower Middle–Upper Turonian) is developing gradually from the underlying strata. It has a thickness of 133.70 m and its base is placed at the level of change to greenish colour, the loss of compactness of beds and the onset of a broader lithological

Fig. 5: Photographic illustration of the Krietzschwitz core. (**A**) Rooted siltstone below carbonaceous–argillaceous silt at the top of a fining-upward cycle of the Niederschöna Formation at 236.50 m depth (Middle Cenomanian). (**B**) Bioturbated estuarine facies of the upper Niederschöna Formation (Wurmsandstein, HST of DS Ce 4) below unconformity SB Ce 4 (note 0.5-m-deep penetrating root traces) at the base of transgressive, light grey, medium- to coarse-grained quartzarenites of the lower Oberhäslich Formation (Middle–Upper Cenomanian boundary interval, 224.00–229.00 m depth). (**C**) Medium-grained sandstone of the upper Oberhäslich Formation (HST of DS Ce 5), sharply overlain at SB Ce 5 by glauconitic siltstones and argillaceous marls of the Dölzschen Formation (TST of DS Ce–Tu 1, Upper Cenomanian, 202.20–207.20 m depth). (**D**) Unconformity SB Tu 1 in the upper part of the Schmilka Formation: red–brown argillaceous siltstone with calcareous nodules, overlying fine-grained, bioturbated HST sandstones of DS Ce–Tu 1, capped by a feebly rooted surface (Lower–Middle Turonian boundary interval, 153.00–158.00 m depth). (**E**) Bioturbated sedimentary fabric of the middle Postelwitz Formation (*lamarcki* Pläner, upper Middle Turonian, 74.00–74.20 m depth). (**F**) Oyster shell-lined burrow filled with overlying brown, medium-grained sand and wood piece (tubular tempestite within the lower Postelwitz Formation, Unterer Grünsandstein, lower Middle Turonian, 127.20–127.40 m depth). (**G**) Coarse-grained sandstone of the upper Postelwitz Formation (Pirnaer Oberquader) with *Ophiomorpha* isp. (Upper Turonian, 11.80–12.00 m depth).


236,5
A
SB Ce 4
B
SB Ce 5
C
SB Tu 1
D
E
F
G


A
Dölzschen Fm
SB Ce 5
Ober-
häslich
Fm
B
Dölzschen Fm
SB Ce 5
Oberhäslich Fm
C
Dölzschen Formation
SB Ce 5
Oberhäslich
Formation
D
plenus Pläner
plenus Ton
basement rocks
Dölzschen Formation
E

variability ("Unterer Grünsandstein"; Fig. 3). Above, grain sizes and lithology fluctuate from silt-sized marly facies to coarse, sand- or sometimes gravel-sized units. Sometimes the sediments yield fossils (most common are bivalves, especially oysters and inoceramids) and small wood pieces. Bioturbation and glauconite are frequently observed, and a glauconitic interval between 138.10 m and 112.20 m represents the Unterer Grünsandstein, equating the "Unterer glaukonitführender Sandstein". It is overlain by the "*lamarcki* Pläner" (112.20–80.40 m), which coarsens upward into the "Mittlerer Grünsandstein" or "Mittlerer glaukonitführender Sandstein" (80.40–70.80 m). Above a sharp lithological boundary, a massive, arkosic, poorly sorted, coarse-grained sandstone to fine-grained gravelstone commences, ranging up to the 65.80-m-level and corresponding to "Sandstein b". The overlying sediments anew reflect a fining, followed by a coarsening- and thickening-upward trend, characterised by a marly–sandy, partly glauconitic Pläner unit (65.80–27.00 m; "Oberer glaukonitisch sandiger Mergel"), grading into a terminal sandstone package ("Pirnaer Oberquader", 27.00–5.20 m). This unit develops gradually from the underlying Pläner until a level at 22.00 m, where an abrupt increase in grain size to coarse-grained, thick-bedded and structurally immature sandstones occurs. Bioturbation and layers of *Rhynchostreon* sp. as well as scattered shells (*Neithea* sp.) indicate generally marine deposition. Nevertheless, strong terrestrial influence is implied by abundant large wood fragments between 18.00 m and 15.00 m, at the top of which violet mottling may reflect short-term emersion. In the upper part of the Pirnaer Oberquader, a thinning- and fining-upward trend is observed from 12.20 m onward.

For the Postelwitz Formation, some general observations can be stated: finer grained Pläner intervals are darker grey to grey and brownish coloured, while coarser, sandy packages have lighter colours such as light grey or ochre, yellowish or beige (Figs. 5E, G). Thicker sandstone layers may show relictic cross-stratification. However, bioturbation is generally strong and has obliterated most primary sedimentary structures; macrofossils (oysters, bivalves, wood pieces) are not rare. The sharp bases and occasional normal grading of fine- to medium-grained, often glauconitic and bioclastic sandstones suggest a deposition by storms. Frequently, coarse material has also been infilled into open burrow systems, forming tubular tempestites (38.30 m, 39.60 m, 57.40 m, around 80.00-m-level, 101.55 m, 104.20–104.70 m, 126.60 m, 127.30 m; Fig. 5F; for the concept of tubular tempestites see Tedesco & Wanless 1991). Voigt (2011) has pointed out the importance of storm-dominated sedimentation for the Postelwitz Formation.

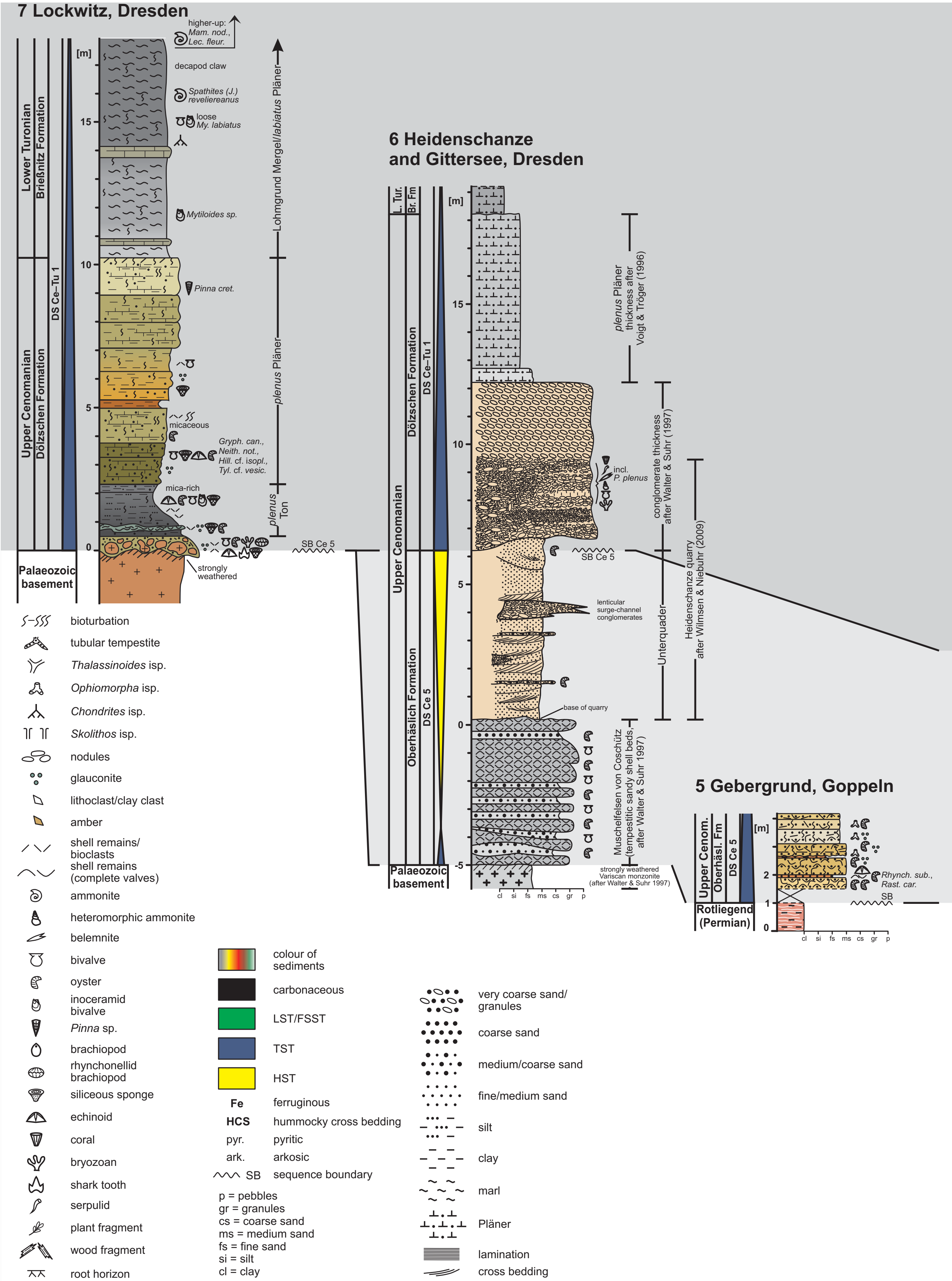
Three Postelwitz formational unconformities are reported that occur at the base of decametre-scale deepening–shallowing cycles and are marked by abrupt shifts in grain size. A first one (SB Tu 2) lies at the 121.60-m-level, in the Middle Turonian, within the Unterer Grünsandstein. Up-section, a second unconformity (SB Tu 3) is implicated by the sudden grain-size increase at the base of Sandstein b (70.80 m). According to biostratigraphic evidence (occurrence of large *Inoceramus lamarcki stuemkei* in the topmost part of underlying "Sandstein a_3") from the Reinhardtsdorf quarry (for locality see Fig. 1), this sequence boundary already has an early Late Turonian age (Wilmsen & Niebuhr 2009). In the lower part of the Pirnaer Oberquader, the base of a thick, coarse sandstone bed marks the last unconformity (SB Tu 4 at 22.00 m) recognised within this section. As the Pirnaer Oberquader is overlain by the "Zeichener Ton" (Dorf Wehlen section, see below), which corresponds to the *Hyphantoceras* Event (Seifert 1955, Tröger 1968, 1987, Voigt 1994), a mid-Late Turonian age for SB Tu 4 is biostratigraphically confirmed.

4.2 Miscellaneous sections

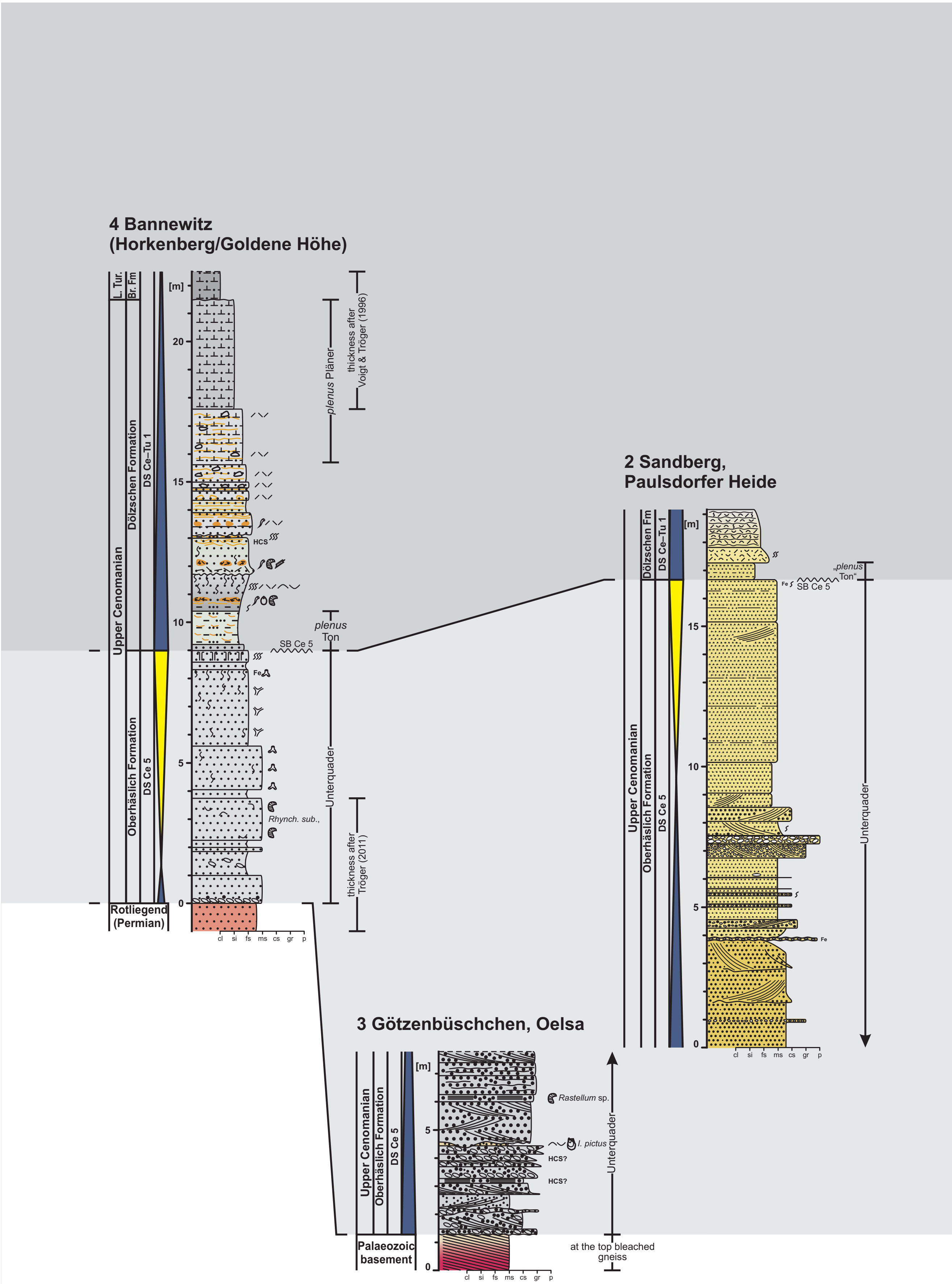
A number of stratigraphically more restricted sections has been logged in the area south of Dresden and in the Elbsandsteingebirge. They are briefly described from south to north and west to east, essentially in chronostratigraphic order, and illustrated in Figs. 7, 8, 10. Each chapter starts with a short introduction (locality, previous work), followed by a lithological description and ends with a résumé summarising the most important findings.

Fig. 6: Photographic illustration of different Cenomanian sections. (**A**) Götzenbüschchen section near Oelsa: cross-stratified, pebbly sandstone of the lower Oberhäslich Formation (lower Upper Cenomanian), transgressively overlying basement rocks (contact arrowed, TST of DS Ce 5). (**B**) Bannewitz, Goldene Höhe section: upper Oberhäslich Formation (lower Upper Cenomanian, HST of DS Ce 5), overlain along an erosional unconformity (SB Ce 5) by the Dölzschen Formation (middle–upper Upper Cenomanian, TST of DS Ce–Tu 1); the fine-grained, recessive lowermost part of the Dölzschen Formation corresponds to the *plenus* Ton. (**C**) Sandberg section: well-bedded sandstones of the Oberhäslich Formation (lower Upper Cenomanian, DS Ce 5), capped by the lower part of the fine sandy Dölzschen Formation (middle–upper Upper Cenomanian, TST of DS Ce–Tu 1); SB Ce 5 is indicated by an arrow. (**D**) Heidenschanze section: medium-grained, channelised sandstones of the upper Oberhäslich Formation (lower Upper Cenomanian, late HST of DS Ce 5) are truncated along SB Ce 5 by the basal conglomerate of the middle–upper Upper Cenomanian Dölzschen Formation, containing the *plenus* Event (cf. Voigt et al. 1994, TST of DS Ce–Tu 1). (**E**) Lockwitz section (exposure situation from 2006): crystalline basement rocks are overlain along a highly irregular onlap surface by the Dölzschen Formation (middle–upper Upper Cenomanian), showing a basal conglomerate, the *plenus* Ton and the *plenus* Pläner (TST of DS Ce–Tu 1).

Fig. 7: Correlation chart of different Cenomanian sections with sequence stratigraphic interpretation. Numbering refers to locality map (Fig. 1). Key of symbols also applies for other figures.



7 Lockwitz, Dresden
higher-up: Mam. nod., Lec. fleur.
decapod claw
Spathites (J.) reveliereanus
loose My. labiatus
Mytiloides sp.
Pinna cret.
micaceous
Gryph. can., Neith. not., Hill. cf. isopl., Tyl. cf. vesic.
mica-rich
strongly weathered
Lower Turonian
Brießnitz Formation
Upper Cenomanian
Dölzschen Formation
DS Ce–Tu 1
Palaeozoic basement
Lohmgrund Mergel/labiatus Pläner
plenus Pläner
plenus Ton
SB Ce 5
6 Heidenschanze and Gittersee, Dresden
L. Tur.
Br. Fm
Dölzschen Formation
DS Ce–Tu 1
Upper Cenomanian
Oberhäslich Formation
DS Ce 5
Palaeozoic basement
incl. P. plenus
lenticular surge-channel conglomerates
base of quarry
strongly weathered Variscan monzonite (after Walter & Suhr 1997)
plenus Pläner thickness after Voigt & Tröger (1996)
conglomerate thickness after Walter & Suhr (1997)
Unterquader
Heidenschanze quarry after Wilmsen & Niebuhr (2009)
Muschelfelsen von Coschütz (tempestitic sandy shell beds, after Walter & Suhr 1997)
5 Gebergrund, Goppeln
Upper Cenom.
Oberhäsl. Fm
DS Ce 5
Rotliegend (Permian)
Rhynch. sub., Rast. car.
SB
[m]
cl si fs ms cs gr p
bioturbation
tubular tempestite
Thalassinoides isp.
Ophiomorpha isp.
Chondrites isp.
Skolithos isp.
nodules
glauconite
lithoclast/clay clast
amber
shell remains/ bioclasts
shell remains (complete valves)
ammonite
heteromorphic ammonite
belemnite
bivalve
oyster
inoceramid bivalve
Pinna sp.
brachiopod
rhynchonellid brachiopod
siliceous sponge
echinoid
coral
bryozoan
shark tooth
serpulid
plant fragment
wood fragment
root horizon
colour of sediments
carbonaceous
LST/FSST
TST
HST
Fe ferruginous
HCS hummocky cross bedding
pyr. pyritic
ark. arkosic
SB sequence boundary
p = pebbles
gr = granules
cs = coarse sand
ms = medium sand
fs = fine sand
si = silt
cl = clay
very coarse sand/ granules
coarse sand
medium/coarse sand
fine/medium sand
silt
clay
marl
Pläner
lamination
cross bedding


4 Bannewitz
(Horkenberg/Goldene Höhe)
L. Tur.
Br. Fm
Upper Cenomanian
Dölzschen Formation
DS Ce–Tu 1
Oberhäslich Formation
DS Ce 5
Rotliegend
(Permian)
[m]
plenus Pläner
thickness after
Voigt & Tröger (1996)
HCS
plenus
Ton
SB Ce 5
Fe
Rhynch. sub.,
Unterquader
thickness after
Tröger (2011)
cl si fs ms cs gr p
2 Sandberg,
Paulsdorfer Heide
Dölzschen Fm
„plenus
Ton"
SB Ce 5
3 Götzenbüschchen, Oelsa
Palaeozoic
basement
Rastellum sp.
I. pictus
HCS?
at the top bleached
gneiss

4.2.1 Sandberg, Paulsdorfer Heide (Figs. 6C, 7)

The Sandberg section (TK 25: 5047 Freital; 33U, 402972 E, 5642031 N) is a disused quarry, located in the Paulsdorfer Heide, ca. 2 km northwest of Paulsdorf and 4.5 km northwest of Dippoldiswalde. Häntzschel (1933) and Voigt (1994) already briefly described this section. However, in contrast to our subsequent description, Voigt (1994) considered the complete succession being part of the Oberhäslich Formation.

Total thickness of the logged succession is 19.15 m. The lower part (up to 16.65 m) is represented by the macrofossil-poor Oberhäslich Formation (lower Upper Cenomanian). In its lower portion, the Oberhäslich Formation shows light grey to beige and light brownish, compact, cross-bedded, middle- to coarse-grained sandstones up to the 3.80-m-level. Intercalations and occasional, dm-scale foresets of coarse-grained sand and fine-grained gravel are observed. The uppermost 80 cm of this unit are comparatively mica-rich and terminated by an undulating surface.

The overlying interval (3.80–8.55 m) is characterised by alternations of medium- to coarse-grained sandy units with intercalated thin, coarse sandy and gravelly layers. The coarser beds commonly display sharp bases and sporadic cross-bedding. Components of pebble-size (1–5 cm) mainly consist of milky quartzes (primarily well-rounded to rounded, around the 7.00-m-level also angular ones appear), at distinct beds, dark grey to black slate components are additionally recognised. Generally, the units of this interval are light grey to beige coloured and partly weakly bioturbated.

Up-section (8.55–16.65 m), massive, monotonous, fine- to medium-grained quartz sandstones are developed with a typical thickening-upward trend. Colouration continues as below; cross-stratification is observed from two levels. Furthermore, the uppermost package of this unit shows sparse bioturbation and iron-staining at the top.

This stratum is unconformably overlain by the following 2.50-m-thick Dölzschen Formation (upper Upper Cenomanian) along a sharp surface and a clear change in lithology (SB Ce 5; Figs. 6C, 7). The Dölzschen Formation starts with a 60-cm-thick, silty–fine sandy, partly covered layer. It is continued by bioturbated, predominantly fine-grained sandy beds, illustrating a general fining-upward. Colours of these fine sediments are similar to the underlying, but shift into grey for the topmost 65 cm. Fossils such as pectinid bivalves, small oysters and a *Pinna* sp. as well as shell debris occur between 17.25 m and 19.15 m.

The above stated observations suggest a nearshore setting for the sedimentation of the Oberhäslich Formation at the Sandberg section, followed by a deepening after SB Ce 5 (Dölzschen Formation).

4.2.2 Götzenbüschchen, Oelsa (Figs. 6A, 7)

Situated ca. 1 km west to northwest of Oelsa and 2 km south-southeast of Rabenau, the Götzenbüschchen (TK 25: 5047 Freital; 33U, 405553 E, 5644995 N) is a sparsely wooded hill, forming a widely visible landmark. Due to its geological importance, it is designated as a natural heritage site. The Götzenbüschchen section has already been treated by Häntzschel (1933) and Voigt (1994).

At this locality, a section of 7.80 m thickness has been measured. The succession starts with a 1.30-m-thick Palaeozoic gneiss. This metamorphic basement unit is of red colour and at its top a ca. 30-cm-thick, reddish, light grey to beige-white bleaching zone is developed. The gneiss is overlain by 6.10 m of the Oberhäslich Formation (lower Upper Cenomanian), predominantly consisting of grey, coarse-grained quartz sand- and gravelstones. The Oberhäslich Formation begins with a 20-cm-thick, gravelly, conglomeratic horizon full of well-rounded, mainly milky varieties of quartz granules and pebbles. Up-section, a 2-m-thick upward-coarsening intercalation of quartz-dominated, well-bedded and usually normal graded coarse-grained sandy to gravelly siliciclastic sediments with low-angle cross-bedding and hummocky cross-stratification (HCS) is observed. Pebbles (brown-coloured or milky quartz) reach a size of up to 7 cm in diameter. At 4.50 m, a noticeable medium-grained, soft, sandy layer is intercalated, bearing abundant *Inoceramus pictus*. Due to the strong erosion, it is only partially preserved in lenticular forms at the base of the overlying strata. The following 3.30 m of the Oberhäslich Formation are re-presented by coarse, compact, gravelly sand- to fine gravelstones with occasional oyster remains (*Rastellum* sp.), showing northeastward-dipping planar cross-stratification.

Facies patterns and sedimentary fabrics (e.g. grain-size, cross-bedding) implicate a high-energy, nearshore depositional environment above the fair-weather wave-base. Graded beds, HCS and the accumulation of isolated inoceramid valves, predominantly in convex-up position (Voigt 1994), indicate the importance of storm events (e.g. Aigner 1985, Myrow & Southard 1996).

4.2.3 Bannewitz (Goldene Höhe and Horkenberg) (Figs. 6B, 7)

The Bannewitz section is a composite section, measured at the disused Horkenberg quarry (TK 25: 5048 Kreischa; 33U, 408738 E, 5649750 N) and the former quarry area at the Goldene Höhe (TK 25: 5048 Kreischa; 33U, 410020 E, 5648815 N), in combination with data from Häntzschel (1933), Uhlig (1941), Tröger (1964), Voigt (1994) and Tröger (2011: fig. 4.4-8.). The Horkenberg and the Goldene Höhe are located near Bannewitz, south of Dresden. The former is situated at Neucunnersdorf, ca. 1.5 km west of Bannewitz; the latter lies ca. 1 km south of Bannewitz.

At the disused Horkenberg quarry, the 9-m-thick Oberhäslich Formation (lower Upper Cenomanian) unconformably overlies Rotliegend (Permian) strata, but the contact is not exposed nowadays. The estimated thickness of the Oberhäslich Formation is based on Tröger (2011). It consists of thick-bedded to massive, light grey, fine-grained quartz sandstones with dispersed *Rhynchostreon suborbiculatum*. Bioturbation is also very common; *Thalassinoides* burrows predominate, but *Ophiomorpha* isp. and at the top of the unit *Skolithos* isp. occur as well. Intercalations of some thinner, finer grained layers and of pebbly horizons (especially at the base) have been observed.

A conspicuous change in lithology at the 10.00-m-level (SB Ce 5) designates the formational boundary to the overlying Dölzschen deposits (upper Upper Cenomanian). The Dölzschen Formation (10.00–22.50 m) starts with the 1.40-m-thick, grey to greenish, orange to brownish mottled, clayey–fine sandy to clayey–silty *plenus* Ton. Up-section, it is followed by an interval (11.40–14.00 m) of grey to topward greenish, fine-grained sandstone, centrally subdivided into two packages by a minor erosion surface. Both of which yield distinct levels with lenticular nests of orange-brown coloured, uncemented sand and shell detritus (e.g. serpulids, oysters, brachiopods) or wood remains. The *Metoicoceras geslinianum* zonal index belemnite *Praeactinocamax plenus* has been found in this interval (Uhlig 1941). The lower bed additionally is strongly bioturbated in its uppermost 60 cm, while the upper one shows HCS at the top. From 14.00–16.60 m, an alternation of light grey to greenish, orange-brown, thin-bedded, silty–fine sandy Pläner is developed. More competent beds bear smaller, fossiliferous lenses (diameters of ca. 10 cm), while softer layers often are flaser-bedded. Generally, a thinning- and fining-upward trend is recognised. The topmost part (16.60–22.50 m) of the Dölzschen Formation is represented by 5.90 m of light grey, flaser-bedded, fine-clastic Pläner sediments. The last 8.50 m constitute the *plenus* Pläner (Uhlig 1941, Voigt 1994). From 22.50 m upward, the silty marls of the Lower Turonian Brießnitz Formation follow above a sharp boundary (Uhlig 1941, Voigt 1994).

The facies development of the composite Bannewitz section reflects an early Late Cenomanian transgressional event and flooding of the Palaeozoic basement. After a short regression (SB Ce 5), a successive deepening during the late Late Cenomanian and earliest Turonian into a hemipelagic setting is indicated by the onlap of the Dölzschen (see also Föhlisch 1998) and lower Brießnitz formations.

4.2.4 Gebergrund, Goppeln (Fig. 7)

The Gebergrund (TK 25: 5048 Kreischa; 33U, 412915 E, 5648732 N), located ca. 500 m south of Goppeln, is a small valley, exposing Permian sediments, overlain by the lower Oberhäslich Formation. In total, 4.15 m have been logged. At the base of the succession, a red, whitish mottled clay of 1 m thickness of Rotliegend (Permian) age has been exposed by trenching. Above a gap of ca. 50 cm, this bed is followed by lower Upper Cenomanian deposits of the Oberhäslich Formation (2.65 m thick), composed of yellow, brownish to greyish, fine- to medium-grained sandstones. They are extremely fossiliferous; especially the beds between 1.50 m and 3.10 m yield numerous oyster shells (*Rhynchostreon suborbiculatum*, *Rastellum carinatum*). At 2.05 m, an irregular echinoid has been observed. Bioturbation, primarily by *Ophiomorpha* burrows, is common. Additionally, from 2.40 m toward the top sparse glauconite is reported.

The Gebergrund section documents the early Late Cenomanian transgression onto Rotliegend strata of the Döhlener Becken. The shell-rich facies at the base of the Oberhäslich Formation shows the significance of current-induced bivalve accumulations (shelly tempestites) during early transgression and can be compared to the "Muschelfelsen von Coschütz" at the base of the Heidenschanze section (see below).

4.2.5 Heidenschanze and Gittersee, Dresden (Figs. 6D, 7)

The Heidenschanze and Gittersee composite section combines data from different authors (Voigt et al. 1994, Voigt & Tröger 1996, Walter & Suhr 1997, S. Voigt et al. 2006, Wilmsen & Niebuhr 2009) with own observations. It consists of the Heidenschanze outcrop, a former quarry section (TK 25: 4948 Dresden; 33U, 408188 E, 5652925 N) and two nearby drilled boreholes. One of these, borehole 2-26/95, has been drilled directly through the succession exposed in the quarry during construction of the motorway A17 in 1995 (final depth 28.00 m, kept in the core storage of the Sächsisches LfULG in Freiberg; Walter & Suhr 1997) and delivers data for the lowermost part of the section. The other one, the Gittersee borehole (Voigt & Tröger 1996; Fig. 7), gives information about the top portion. The Heidenschanze and Gittersee are situated at the southwestern margin of Dresden, ca. 4.5 km southwest from its centre and ca. 3.5 km east-northeast of Freital.

The composite section starts above the Variscan monzonite of the Plauenscher Grund with ca. 5.20 m of a thickening- and coarsening-upward interval of shell-rich, fine- to medium-grained, tempestitic sandstone layers (Walter & Suhr 1997). This alternation represents the initial onlap of Cretaceous strata and forms the lower part of the Oberhäslich Formation (lower Upper Cenomanian). Isolated blocks of corresponding lithology appear in the surrounding area of the Heidenschanze quarry and have been described by Geinitz (1871–1875) as the so-called Muschelfelsen von Coschütz. These beds are rich in the glycymerid bivalve *Pectunculus obsoletus* and oysters (*Rhynchostreon suborbiculatum*, *Rastellum carinatum*). In the Heidenschanze quarry (Wilmsen & Niebuhr 2009), the Oberhäslich Formation continues with an interval (0.00–6.00 m) of thick-bedded, medium- to coarse-grained quartz sandstones. Beds are interrupted by thin (ca. 20 cm thick) fine gravelly horizons and show a high lateral variability in thickness. Several lenticular surge-channel conglomerates (components of rounded boulders with diameters of up to 50 cm, primarily of weathered monzonite) occur in the upper part (see Voigt et al. 1994 for further details). Trough cross-bedding is observed as well. Fossils are rare within this interval, only few oyster remains have been found.

Above, the Dölzschen Formation follows with an up to 6.00-m-thick conglomerate unit (Walter & Suhr 1997) with a sharp erosional base (SB Ce 5), incising deeply into the underlying strata (Figs. 6D, 7). Components of the conglomerate are predominantly well-rounded monzonite pebbles, cobbles and boulders of highly varying grain size (ranging from cm–dm-scale). The matrix consists of very fossiliferous (bivalves, especially oysters and rudists, gastropods, serpulids, and in the upper part the belemnite *Praeactinocamax plenus*), sandy-bioclastic grain- to rudstones (Voigt et al. 1994 and own thin-section studies). It is overlain by partly silicified (siliceous sponge-bearing), calcareous siltstones (Voigt & Tröger 1996; *plenus* Pläner of the upper Dölzschen Formation) of ca. 6.00 m thickness, displaying an obvious fining-upward trend. Altogether, the Dölzschen Formation is ca. 12.00 m thick. Above a sharp contact, the silty marls of the Brießnitz Formation (Lower Turonian) follow.

Sedimentary facies and fabrics implicate that after initial transgression with the deposition of shelly tempestites (Walter & Suhr 1997), a high-energy, nearshore surf-zone environment in the vicinity of cliffs and swells was established ("Klippen-/Schwellenfazies"; see Tröger 1956, Voigt et al. 1994). After a major unconformity, marked by the basal conglomerate of the Dölzschen Formation, the mid-Late Cenomanian *plenus* Transgression resulted in the deposition of a condensed, sponge-rich siltstone unit (T. Voigt et al. 1994, 2006). A further deepening trend into the Early Turonian is represented by the fine-grained marls of the Brießnitz Formation.

4.2.6 Lockwitz, Dresden (Figs. 6E, 7)

Lockwitz is an urban district of Dresden, located at its southern margin. The logged section (TK 25: 5048 Kreischa; 33U, 416120 E, 5648033 N) is situated ca. 9.5 km southeast of the centre of Dresden and ca. 10 km northwest of Pirna. It has been measured in a former brick pit, nowadays used for waste dumping. The brief description and illustration given in this study follow Wilmsen et al. (2011) – for more details see there.

In total, the Lockwitz section reaches a thickness of ca. 20.00 m, exposing the transgression of Cretaceous sediments onto the underlying crystalline basement (syenite or monzonite) of Palaeozoic age. Deposition of Cretaceous strata starts above a conspicuous erosional surface (SB Ce 5 at 0.00 m) with an unconformably overlying 50-cm-thick, fossil-rich and glauconite-bearing syenite/monzonite pebble–boulder basal conglomerate of the lower Dölzschen Formation (Upper Cenomanian; Fig. 6E). Up-section, the conglomerate is followed by a glauconitic sponge-bed and a fossiliferous (e.g. echinoids, oysters, bivalves, sponges), bioturbated, black, clayey–silty interval (0.50–2.30 m, *plenus* Ton). Topward, the Dölzschen Formation indicates a coarsening and thickening trend, represented by a silty–fine sandy, micaceous, green to brownish, bioturbated Pläner unit (2.30–10.00 m, "*plenus* Pläner"), yielding scattered fossils and occasional glauconite. The Dölzschen Formation is terminated at the sharp top of the *plenus* Pläner, characterised by strong bioturbation.

The bioturbated, light to dark grey marls of the Brießnitz Formation (Lower Turonian) follow unconformably atop the Dölzschen Formation. Lower Turonian fossils are not rare within this interval, mainly bivalves and ammonites are reported (Heidrich 1983, Tröger 1988, Wilmsen et al. 2011).

The Lockwitz section exemplarily displays the mid-Late Cenomanian sea-level rise (*plenus* Transgression of authors) and the accompanying facies levelling, demonstrated by the onlap of marine strata onto formerly emergent basement units. Rapid deepening continued after a brief halt into the Early Turonian, as indicated by the hemipelagic marls of the lower Brießnitz Formation.

4.2.7 Felsengasse near Ottomühle, Bielatal (Figs. 8, 9B, C)

The "Felsengasse" is a well-known rock passage in the Bielatal, situated in the southernmost western Elbsandsteingebirge, very close to the Czech border. It is located ca. 750 m north-northwest of the Ottomühle and ca. 8.5 km south-southwest of Königstein. The Felsengasse section (TK 25: 5150 Rosenthal-Bielatal; 33U, 432707 E, 5632735 N) was logged from below the passage sensu stricto, via the Felsengasse itself (Fig. 9C), up to the viewpoint of the "Kaiser-Wilhelm-Feste" (Fig. 9B), comprising a total thickness of 16.20 m and representing the upper Schmilka Formation.

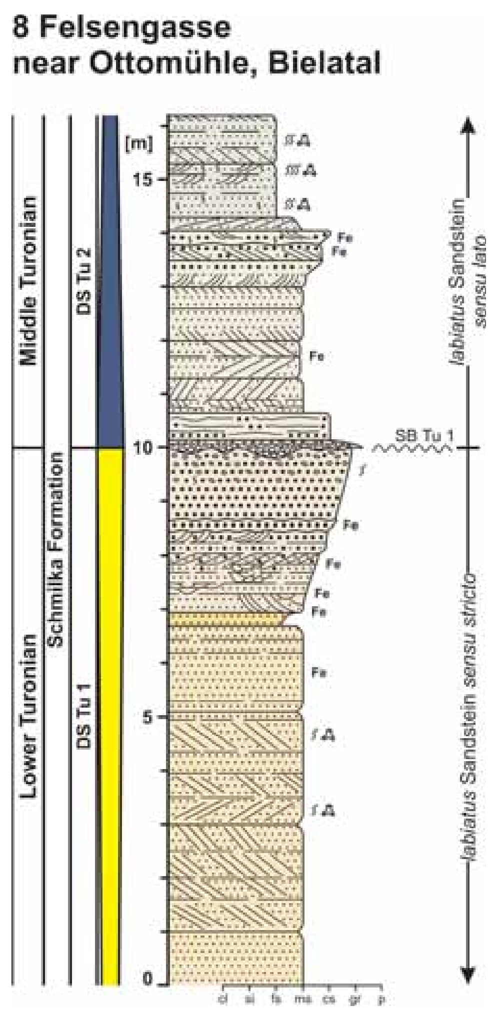
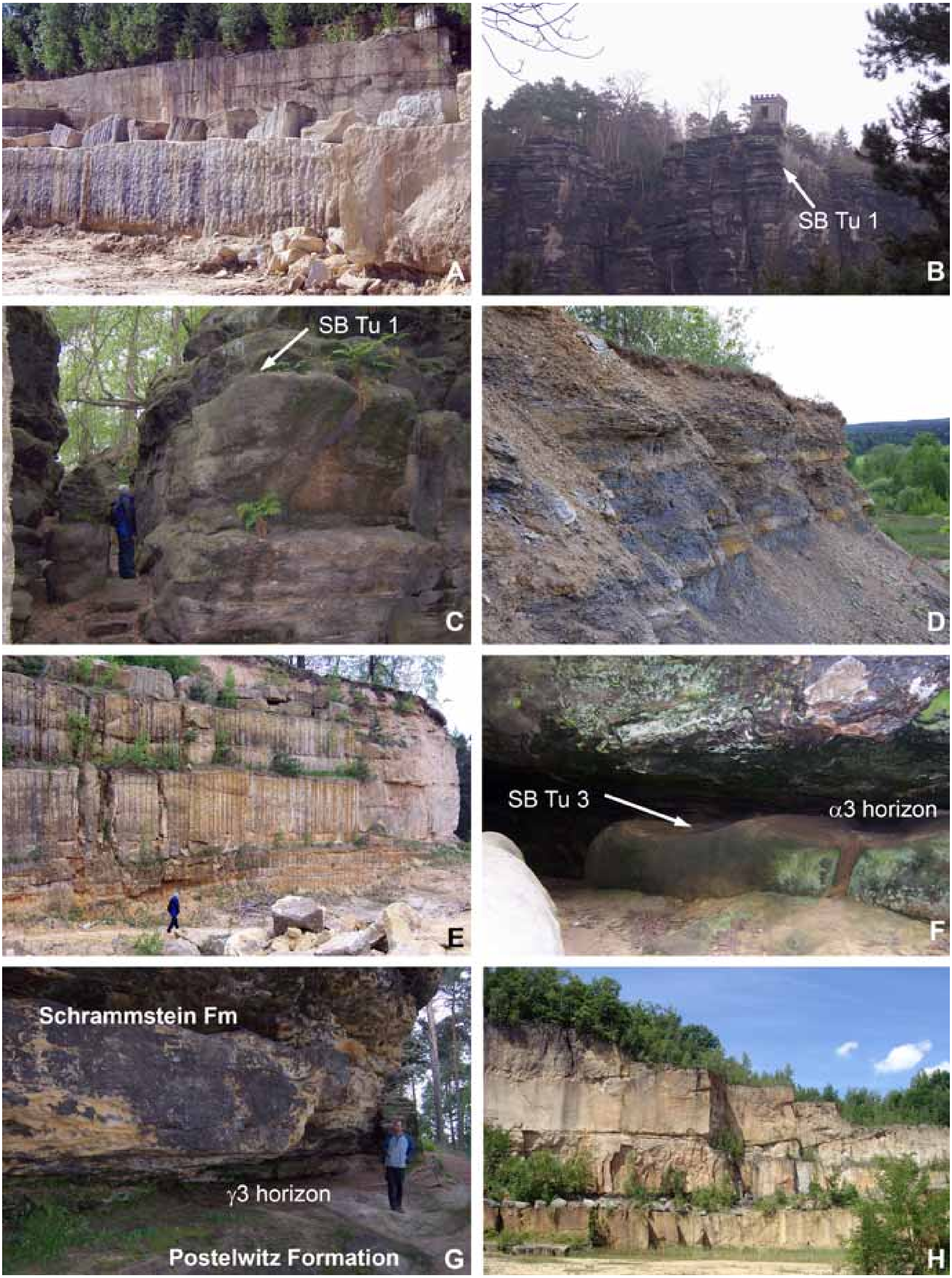


Fig. 8: Stratigraphic log of the Felsengasse section with sequence stratigraphic interpretation. Numbering refers to locality map (Fig. 1). For key of symbols see Fig. 7.


A
SB Tu 1
B
SB Tu 1
C
D
E
SB Tu 3
α3 horizon
F
Schrammstein Fm
γ3 horizon
Postelwitz Formation
G
H

The lowermost part of the measured section (0.00–6.70 m) consists of light grey to beige, compact, medium-grained sandstones. Planar cross-stratification characterises this interval of the Schmilka Formation (upper Lower Turonian) while bioturbation (*Ophiomorpha* isp.) occurs quite sparsely. Above a 25-cm-thick, fine- to medium-grained sandy layer, the following strata display a clear coarsening-upward trend, culminating in gravelly deposits at the 10.00-m-level. Granule- to pebble-sized components are quartzes, primarily of white (milky), but subordinated also of red colour. Grain-size sorting is poor, especially at distinctly coarser levels. An undulating surface is developed at 8.65 m, internally subdividing the gradually coarsening package into two units, a lower trough cross-bedded and an upper more massive, gravelly interval with indistinct bioturbation. The succession continues with a conspicuous, erosionally incised, conglomeratic bed of 15–20 cm thickness. The base of this layer forms a sharp and strongly undulating erosion surface (SB Tu 1) with the coarsest components (granules and pebbles) observed in shallow scours. Upward, the light grey deposits of the uppermost Schmilka Formation demonstrate a general thinning and fining trend, arranged in two cycles (10.00–14.05 m and 14.05–16.20 m). Medium- to fine-grained quartz sandstones with low-angle and trough cross-stratification as well as occasional *Ophiomorpha* burrows predominate.

The sedimentological observations imply that the deposits of the Felsengasse section represent a typical costal setting, strongly influenced by currents (see also Voigt 1994, 1999). The succession shows a striking shallowing and a following deepening trend, separated by an erosion surface (SB Tu 1). According to inoceramid finds, the deepening interval of the uppermost Schmilka Formation already dates into the earliest Middle Turonian (Voigt 1999).

4.2.8 Dorf Wehlen, Zeichener Brüche (Figs. 9H, 10)

The Dorf Wehlen section is situated ca. 1.5 km south to south-southeast of Dorf Wehlen and 5 km east of Pirna. It has been composed from measurements at two different localities that constitute a standard section of the Wehlen–Zeichen area. The succession reaches 31.10 m in total and continues the Krietzschwitz core up-section.

The lower interval (0.00–4.70 m, logged at TK 25: 5050 Bad Schandau; 33U, 430876 E, 5644911 N consists of two compact, grey-brown packages of medium- to coarse-grained sandstones, divided by a 10-cm-thick, yellowish brown, silty–fine sandy seam. The two beds show a high compositional, but low textural maturity and are strongly bioturbated – mainly by *Thalassinoides* burrows – especially at their tops. The upper package bears also large wood fragments in the upper 70 cm, aligned parallel to stratification. These strata represent the Pirnaer Oberquader of the upper Postelwitz Formation (Upper Turonian). Even if the direct contact with the overlying clayey unit is not exposed, field observations (geomorphology, hydrological implications) indicate an abrupt change in lithology, supported by a formerly existing trench (K.-A. Tröger, pers. comm. 05/2012). This layer, the so-called "Zeichener Ton", shows a thickness of ca. 3.00 m and initiates the Schrammstein Formation (Upper Turonian). The Zeichener Ton is a prominent mid-Upper Turonian marker bed, which yields the heteromorph ammonite *Hyphantoceras reussianum* (Seifert 1955, Tröger 1968) and correlates to the "Burglehntonbank" of the Pirna area as well as to the "Kalk von Strehlen" and the "Kalk von Weinböhla" of the Dresden–Meißen area (Seifert 1955, Tröger 1987, Voigt 1994, Tröger & Wejda 1997; see Fig. 3). Its fine-grained fabric and open-marine fauna mark an important mid-Upper Turonian flooding event.

Up-section, the lower Schrammstein Formation (26.40 m of total thickness in this section) commences with an at least 7.00-m-thick interval, composed of two massive, fine- to medium-grained, yellow to greyish sandstone beds. Generally, quartz grains show a better rounding than in the upper Postelwitz Formation, but sorting is still poor. The top part of this unit bears drift wood up to dm-length. It is terminated by an undulating, bioturbated and iron-stained surface. Thickness of the upper bed changes laterally from ca. 6.50–4.00 m (decreasing southward).

Logging is continued in the disused Dorf Wehlen quarry (TK 25: 5050 Bad Schandau; 33U, 430448 E, 5644609 N), situated within a formerly very active quarry region

Fig. 9: Photographic illustration of different Turonian sections and localities. (**A**) Active quarry of the Sächsische Sandsteinwerke GmbH in the Lohmgrund, south of Pirna, showing thick-bedded, fine-grained, bioturbated sandstones of the Schmilka Formation (*labiatus* Sandstein, Lower Turonian, HST of DS Ce–Tu 1). (**B**) Upper part of the Schmilka Formation (upper Lower–lower Middle Turonian) in the Bielatal near the Ottomühle; the Felsengasse section (see Fig. 9C) is located behind the Kaiser-Wilhelm-Feste and the level of SB Tu 1 is indicated with an arrow. (**C**) Felsengasse section near the Kaiser-Wilhelm-Feste (see Fig. 9B): a coarsening-upward package of coarse-grained, increasingly pebbly sandstones (latest HST of DS Ce–Tu 1) is capped at an erosion surface (SB Tu 1, Lower–Middle Turonian boundary interval). (**D**) Disused pit of the former brickworks at Raum, showing light bands (Pläner), characterised by higher carbonate content, alternating with sandy–silty, dark coloured marls (*lamarcki* Pläner of the Middle Postelwitz Formation, Middle Turonian, mfz of DS Tu 3). (**E**) Progradationally stacked, thick-bedded, medium- to coarse-grained sandstones of the Postelwitz Formation in the Reinhardtsdorf quarry characterise the late part of the HST of DS Tu 3 (lowermost Upper Turonian, upper part of Sandstein a_3). (**F**) Lattengrund near Bad Schandau: the α3 horizon between Sandstein a_3 and Sandstein b of the Postelwitz Formation represents SB Tu 3 (lowermost Upper Turonian) in the Elbsandsteingebirge; the coarse-grained, pebbly Sandstein b equates to the FSST and LST of DS Tu 4. (**G**) Kaiserkrone near Reinhardtsdorf: the γ3 horizon is a fine-grained intercalation into coarse-grained siliciclastics and separates the Postelwitz and the Schrammstein formations; it is inferred to correlate with the mid-Upper Turonian Zeichener Ton and thus represents the mfz of DS Tu 5. (**H**) Lower part of the Schrammstein Formation (Herrenleite Sandstein) in the disused Dorf Wehlen quarry section (HST of DS Tu 5); the Zeichener Ton (mfz of DS Tu 5) crops out a few metres below the base of the quarry.

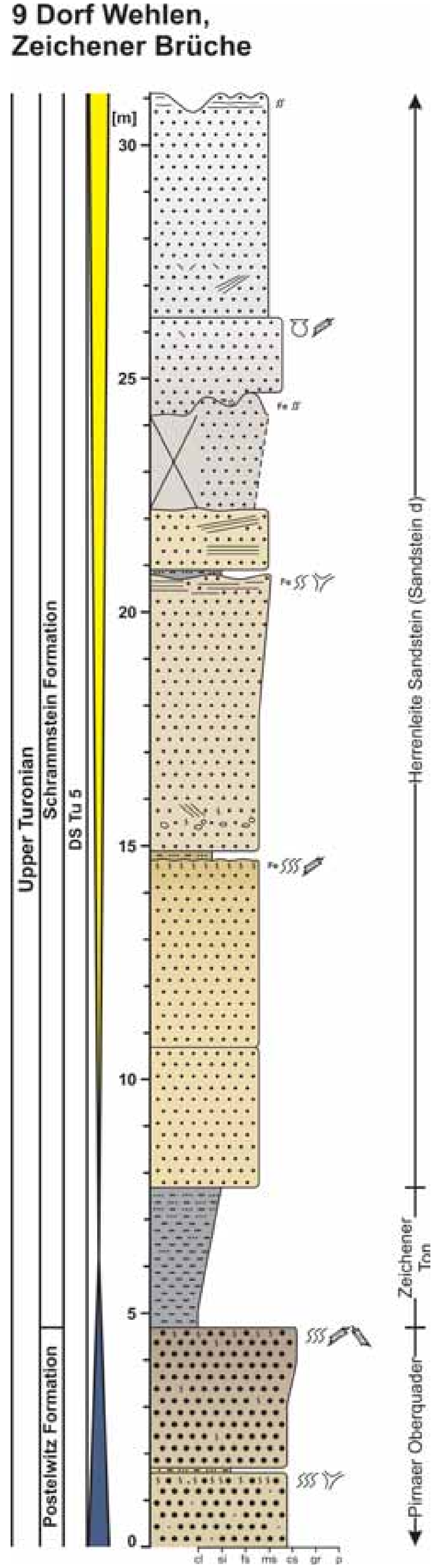


Fig. 10: Stratigraphic log of the Dorf Wehlen section with sequence stratigraphic interpretation. Numbering refers to locality map (Fig. 1). For key of symbols see Fig. 7.

("Zeichener Brüche"). A thin (20-cm-thick), obvious, clayey–silty, partly fine sandy horizon follows. It is overlain by a further massive, light grey to ochre, mature quartz sandstone, grading upward into a platy, medium-grained sandy unit. In its lower part, bioturbation, relictic cross-stratification, black components (heavy minerals or lithic fragments) and lenticular, whitish to light grey, kaolinitic zones are observed. The top is formed by an erosional surface, strongly bioturbated by *Thalassinoides* isp. Above another thin (10 cm) silty layer, a package of yellow to ochre, greyish, medium-grained sandstone with cross-bedding and a variable thickness of 1.30–1.70 m occurs. Extreme variations of bed thicknesses persist in the uppermost 8.90 m of the measured section. Grain-size development indicates a coarsening-upward trend to medium- and coarse-grained, light grey to brown and light grey to whitish sandstones.

The lateral thickness variations mark huge foresets toward the south. Megaripples of 50-cm-dimensions and persistent cross-bedding confirm a highly energetic, coastal depositional environment and support the assumption of a general shallowing trend, documented by the Schrammstein Formation above the Zeichener Ton.

5. Sequence stratigraphy

In the Cenomanian–Turonian of the Elbtal Group, seven significant sedimentary unconformities have been identified and biostratigraphically dated. These sequence boundaries (SB) define seven 3rd-order depositional sequences that are described and discussed in stratigraphic order below. This chapter largely follows the 2D-correlation diagram of Cenomanian sections (Fig. 7) and the standard section of the Elbtal Group in the Faziesübergangszone as displayed in Fig. 11.

Marine ingression into the Elbtal area and flooding during the Cretaceous already started in late Early Cenomanian times with DS Ce 3. Relictic sediments of this sequence occur around Meißen (Tröger & Voigt in Niebuhr et al. 2007), north of Dresden, but the current exposure situation does not permit a detailed study. The Meißen Formation (Prescher & Tröger 1989, Tröger & Voigt in Niebuhr et al. 2007) consists of characteristic red to red-brownish, bioclastic transgression conglomerates, overlain by fossil-poor, fine- to medium-grained, glauconitic sandstones, the latter questionably attributed to the Upper Cenomanian Mobschatz Formation (cf. Tröger & Voigt in Niebuhr et al. 2007, Tröger et al. in Niebuhr et al. 2007). Commonly, the Meißen Formation is regarded as only late Early Cenomanian in age (*Mantelliceras dixoni* Zone; see Fig. 3; Prescher & Tröger 1989, Tröger & Voigt in Niebuhr et al. 2007). However, hard biostratigraphic evidence is lacking as the quoted ammonoids and inoceramids can all range into the Middle Cenomanian.

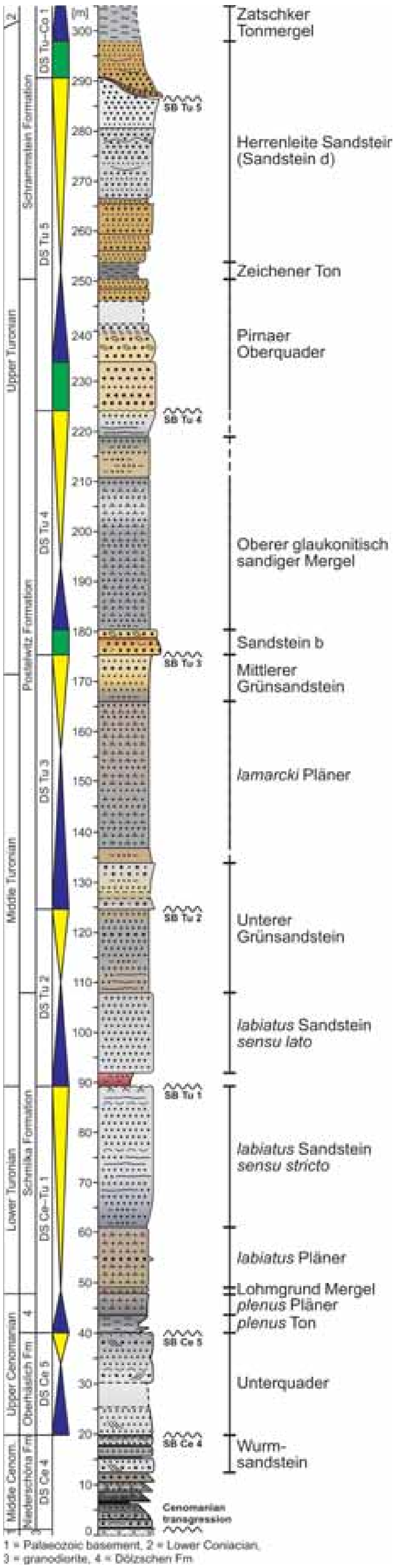


Fig. 11: Standard section of the Elbtal Group in the Faziesübergangszone (facies transition zone) with sequence stratigraphic interpretation and lithological terminology after Seifert (1955). For key of symbols see Fig. 7.

Evidence for a potentially also Middle Cenomanian age is given by a wrongly identified turrilitid heteromorph ammonite ("*Turrilites* cf. *scheuchzerianus*" of Köhler 2001). This specimen is either a *Turrilites wiestii* or a *Turrilites costatus*; the former characterising the Lower–Middle Cenomanian boundary interval, the latter being the index fossil of the *T. costatus* Subzone of the *Acanthoceras rhotomagense* ammonite Zone (lower Middle Cenomanian age; e.g. Wilmsen et al. 2007). We therefore suggest that Mid-Cenomanian time is also represented in the strongly condensed, rocky nearshore facies of Meißen. The onlap of the fluvial Middle Cenomanian Niederschöna Formation (which is clearly related to a Middle Cenomanian base-level rise, see below) calls for the contemporaneous deposition of marine Middle Cenomanian strata (which could be the fossil-poor, fine- to medium-grained, glauconitic sandstones overlying the Meißen Formation) as well.

5.1 Depositional sequence Cenomanian 4 (DS Ce 4)

The age of DS Ce 4, comprising the predominantly fluvial Niederschöna Formation, is palynologically dated as Mid-Cenomanian (Krutzsch 1963), further constrained by the stratigraphic superposition of the fully marine lower Upper Cenomanian Oberhäslich Formation. It is inferred to correlate with the *Acanthoceras rhotomagense* and *A. jukesbrownei* as well as the *Inoceramus atlanticus/schöndorfi* biozones (Fig. 3). Two bounding unconformities are recognised. The basal one marks the beginning of Cretaceous sedimentation and corresponds to a major onlap surface. DS Ce 4 initiates with conglomerates, overlying Palaeozoic basement (Krietzschwitz core; Figs. 4, 11). The unconformity (SB Ce 4) terminating the sequence is described below (see DS Ce 5).

DS Ce 4 superbly illustrates the gradual evolution of a fluvial system in response to a cycle of base-level rise and fall, evidenced by the Niederschöna Formation (Voigt 1998). Starting with coarse-grained braided river deposits (lower Niederschöna Formation), it develops, via alternations of coarse- to fine-grained, normally graded siliciclastics indicating a meandering river system (middle part of the Niederschöna Formation), into typical estuarine sediments (Wurmsandstein of the upper Niederschöna Formation). The sequence shows an overall retrogradational facies development. Thus, it seems to lack any highstand deposits, the time of which may be represented in the terminal unconformity (rooted palaeosol, SB Ce 4).

Due to its fluvial character, the deposition of DS Ce 4 strongly depends on the palaeo-topographic situation (restriction to river valleys) and explains its striking variations in thickness (Voigt 1998). However, because of its conspicuous terminal unconformity, the Niederschöna Formation is regarded as the product of a complete depositional cycle and not just as a part of the TST of DS Ce 5 (cf. Voigt 1998, Tröger & Voigt in Niebuhr et al. 2007).

5.2 Depositional sequence Cenomanian 5 (DS Ce 5)

DS Ce 5 is early Late Cenomanian in age, corresponding biostratigraphically to the *Calycoceras naviculare* ammonite Zone and *Inoceramus pictus pictus* inoceramid Zone, and lithostratigraphically to the Oberhäslich Formation and its finer grained equivalent, the Mobschatz Formation (see Fig. 3). It is defined by the unconformities SB Ce 4 (base) and SB Ce 5 (top, see DS Ce–Tu 1). SB Ce 4 coincides in many places (where the Niederschöna Formation is missing) to the base of the Cretaceous succession as the initial onlap matches the TST of DS Ce 5 (e.g. Fig. 6A). At the Krietzschwitz core, this unconformity is developed as a rooted palaeosol atop the estuarine Wurmsandstein (Figs. 5B, 11).

The lower TST of DS Ce 5 consists of coarse-grained siliciclastics (e.g. Götzenbüschchen) and/or shell-rich sandstones (e.g. Heidenschanze). Up-section, a general fining trend is evident, culminating in a fine-grained, partly strongly bioturbated interval within the upper Oberhäslich Formation (e.g. Sandberg, Krietzschwitz core). This level is regarded as the mfz of DS Ce 5. The overlying sediments show a clear coarsening- and thickening-upward development until the formational top, documenting the shallowing of the HST. Further support for this interpretation comes from ichnofabrics (*Skolithos* ichnofacies below SB Ce 5 at Bannewitz).

The thickness of DS Ce 5 is strongly variable on short distances due to considerable pre-transgression palaeo-topography (Voigt 1994, Tröger & Voigt 1995, Voigt & Tröger 1996, Tröger 2003). The sequence is missing on basement highs that were flooded not before the transgression of DS Ce–Tu 1 (e.g. Lockwitz, see below).

5.3 Depositional sequence Cenomanian–Turonian 1 (DS Ce–Tu 1)

This sequence consists of the upper Upper Cenomanian Dölzschen Formation and the Lower Turonian part of the Brießnitz (hemipelagic) or Schmilka (nearshore) formations. Thus, DS Ce–Tu 1 comprises the *Metoicoceras geslinianum*, the *Neocardioceras judii*, the *Watinoceras devonense* and the *Mammites nodosoides* ammonite zones (Wilmsen & Nagm 2013a; for corresponding inoceramid zones see Fig. 3). The sequence is bounded by the unconformities SB Ce 5 at its base and SB Tu 1 at its top (see DS Tu 2). SB Ce 5 is developed as a conspicuous erosional surface (e.g. Figs. 6E, 7), followed by a distinct transgressive interval (i.e. the *plenus* Transgression of mid- to late Late Cenomanian age), well documented in the Lockwitz, the Heidenschanze/Gittersee, the Bannewitz and the Sandberg sections (Figs. 6B–E) as well as in the Krietzschwitz core (Fig. 5C).

The transgression and onlap of DS Ce–Tu 1 finally levelled the pre-existing palaeo-topography and former highs, islands, cliffs or swells were flooded (Fig. 7; see also S. Voigt et al. 2006). The Lockwitz section, where the Dölzschen Formation unconformable overlies the basement (Fig. 6E) with a transgression conglomerate and a dark, clayey interval (*plenus* Ton), excellently illustrates the onlap of DS Ce–Tu 1. A further deepening trend during the TST is reflected by the *plenus* Pläner of the upper Dölzschen Formation (Figs. 4, 7, 11). At the top of the *plenus* Pläner, a weak coarsening- and thickening-upward trend is recognised, caused by a minor shallowing at the Cenomanian–Turonian boundary. This short interruption of the major transgressive trend is known from many sections around the Bohemian Massif (e.g. Uličný et al. 1993, 1997, Wilmsen et al. 2010a) and has been related to 4th-order orbital sea-level forcing (Richardt et al. 2013). Up-section, a renewed transgressive pulse (earliest Turonian transgression of Richardt et al. 2013) follows, forming the Lohmgrund Mergel (base of the Schmilka Formation) and marking the mfz of DS Ce–Tu 1. In the Krietzschwitz core, the overlying HST can be subdivided into two prograding cycles (parasequence sets); a first one including the Lohmgrund Mergel, the *labiatus* Pläner and the lower part of the *labiatus* Sandstein sensu stricto up to a reddish horizon, and a second one consisting of the upper *labiatus* Sandstein sensu stricto. These two prograding cycles within the Schmilka Formation have already been noted by Voigt (1999) and are also characteristic features of the contemporaneous HST deposits in the Danubian Cretaceous (Lower Turonian Winzerberg Formation; Richardt et al. 2013). The final portion of the shallowing trend of DS Ce–Tu 1 toward its terminal unconformity SB Tu 1 is well exposed at the Felsengasse section (Figs. 8, 9B, C). Another locality where the late HST of DS Ce–Tu 1 can nicely be observed, is the Lohmgrund quarry, ca. 4.5 km south-southeast of Pirna (Fig. 9A; TK 25: 5049 Pirna; 33U, 426201 E, 5640659 N; see Wilmsen & Niebuhr 2009 for detailed section). There, a continuous shallowing-upward trend composed of several stacked parasequences is documented, culminating in the terminal occurrence of *Skolithos* ichnofacies below SB Tu 1.

5.4 Depositional sequence Turonian 2 (DS Tu 2)

DS Tu 2 has an early Middle Turonian age, comprising the early *Collignoniceras woollgari* ammonite Zone and ranging from the mid-*Mytiloides hercynicus/My. subhercynicus* into the mid-*Inoceramus cuvieri/I. apicalis* inoceramid Zone (Fig. 3). Lithostratigraphically, this sequence embraces the uppermost Schmilka and lower Postelwitz formations (there are currently no exposures documenting the Middle–Upper Turonian sequences in the Pläner facies around Dresden and Meißen). Defining sequence boundaries are SB Tu 1 (base) and SB Tu 2 (top, see DS Tu 3). The basal sequence boundary is developed as a conspicuous unconformity surface in the Lower–Middle Turonian boundary interval of all logged sections. In the Krietzschwitz core (Figs. 4, 11), it is marked by a red mottled, rhizolithic palaeosol, followed above by reddish non-marine sediments (Fig. 5D). At the Felsengasse, SB Tu 1 forms a prominent, undulating erosion surface, overlain by a thin conglomeratic layer (Figs. 8, 9B, C). Furthermore, SB Tu 1 is also exposed in the Lohmgrund quarry (Fig. 9A; see Wilmsen & Niebuhr 2009).

DS Tu 2 starts with fine-clastic, bioturbated, rarely wood- and bivalve shell-bearing TST deposits in the Krietzschwitzsch core (uppermost part of the Schmilka Formation), reflecting a progressive deepening. In the Felsengasse section (upper Schmilka Formation), the TST commences with a thin conglomerate bed and continues up-section with a fining-upward trend, superbly documenting the rise of sea-level into the Mid-Turonian. The TST turns into a regressive HST (lower part of the Unterer Grünsandstein of the Postelwitz Formation, cf. Krietzschwitz core); the thickness of beds gradually reduces (decrease of accommodation space), the colour of sediments shifts to green (presence of glauconite) and a general coarsening trend completes the DS Tu 2.

5.5 Depositional sequence Turonian 3 (DS Tu 3)

Sequence DS Tu 3 is of late Middle–earliest Late Turonian age and relates to the middle part of the Postelwitz Formation. It corresponds to a biostratigraphic interval, ranging from the upper *Inoceramus cuvieri/I. apicalis* inoceramid Zone into the basal Upper Turonian *I. inaequivalvis/I. lamarcki stuemckei/I. pietzschi* inoceramid Zone (Fig. 3). Bounding unconformities are SB Tu 2 (base) and SB Tu 3 (top, see DS Tu 4). In the Krietzschwitz core, SB Tu 2 is placed at the base of a glauconite-bearing, cross-bedded, bioturbated, coarse-grained sandstone that rapidly fines upward (Figs. 4, 11).

A subsequent cycle of base-level rise (deepening) and fall (shallowing) is recognised. The glauconitic, siliciclastic-dominated succession above SB Tu 2 (upper part of the Unterer Grünsandstein in the Krietzschwitz section), already belongs to the TST, based on its retrogradational stacking pattern. Further deepening within the TST is documented by the change to Pläner sediments (*lamarcki* Pläner), culminating in a mfz around 90.00 m (Fig. 4). A section measured in the former brick pit at Raum (Fig. 9D; TK 25: 5150 Rosenthal-Bielatal; 33U, 431602 E, 5634859 N – for details and illustration see Wilmsen & Niebuhr 2009), ca. 3 km southeast of Langenhennersdorf and ca. 7 km south-southwest of Königstein, represents an equal stratigraphic position and shows the transition into the hemipelagic Räcknitz Formation. Up-section, a coarsening trend toward the top of the sequence characterises the HST. It nicely culminates in the coarsening-upward to the Mittlerer Grünsandstein in the Krietzschwitz core. The same stratigraphic interval (prograding late HST) is exposed in the Reinhardtsdorf quarry, in the sandy facies of the Elbsandsteingebirge, by means of a coarsening- and thickening-upward trend, sediment fabrics and biofacies development (Fig. 9E; see Wilmsen & Niebuhr 2009 for details and illustration). This section (TK 25: 5151 Reinhardtsdorf-Schöna; 33U, 441614 E, 5638503 N), located ca. 1.5 km west of Reinhardtsdorf and ca. 7 km east-southeast of Königstein, exposes Sandstein a_3 of the Postelwitz Formation below SB Tu 3 (see DS Tu 4), containing early Late Turonian index inoceramids in its uppermost part.

5.6 Depositional sequence Turonian 4 (DS Tu 4)

The sequence DS Tu 4 consists of the lower Upper Turonian sediments of the upper Postelwitz Formation (Krietzschwitz core: Sandstein b to the lower part of the Pirnaer Oberquader). In ammonite biostratigraphic terms, it includes the lower *Subprionocyclus neptuni* Zone (Fig. 3). It is defined by the sequence boundaries SB Tu 3 at its base and SB Tu 4 (see DS Tu 5) atop. In the Krietschwitz core, SB Tu 3 is marked by a sudden change in lithology from underlying thin-bedded, mainly fine-grained sandstones (Mittlerer Grünsandstein) to a compact, arkosic, gravelly, coarse-grained sandstone package (Fig. 11), corresponding to Sandstein b in the Elbsandsteingebirge. SB Tu 3 is thus inferred to correlate with the α3 horizon of Lamprecht (1928, 1934; Figs. 3, 9F).

Sandstein b overlies SB Tu 3 and represents an abrupt basinward shift in facies, nicely exemplifying the development of FSST and LST sediments in DS Tu 4; immaturity, cross-stratification and ichnofacies confirm a very shallow-marine and high-energy depositional setting that instantly replaced the quiet water setting documented by the underlying deposits (forced regression). Following sea-level rise and a return into the TST are confirmed by a rapid fining trend into Pläner facies sediments (Oberer glaukonitisch sandiger Mergel). Above, the mfz is indicated by a violet clay seam. The depositional cycle of DS Tu 4 concludes with the HST; coarsening-upward, increase of siliciclastic input and glauconite content in connection with storm-induced sedimentation (occurrence of tubular tempestites) prove renewed shallowing. The normal regression of the late HST of DS Tu 4 finally resulted in the deposition of the lower portion of the Pirnaer Oberquader.

It should be noted that during DS Tu 4 for the first time FSST and LST deposits have been recorded. This attributed to two factors: the Middle Turonian sea-level rise had shifted the depositional setting into deeper water zones, where also during falling and low sea-level stands accommodation space was available (in contrast to the situation at SB Ce 4–SB Tu 1; SB Tu 2 is transitional in this respect), and furthermore, increasing uplift along the Lausitz Fault and subsidence of the Elbtal Zone provided a large amount of clastic sediments derived from the Westsudetic Island and additional space for deposition.

5.7 Depositional sequence Turonian 5 (DS Tu 5)

DS Tu 5 ranges from the mid-Late Turonian mid-*Subprionocyclus neptuni* ammonite Zone, the *Mytiloides labiatoidiformis/My. striatoconcentricus* inoceramid Zone, respectively, up into the late Late Turonian (Fig. 3). The upper part of the sequence has not been studied in detail yet and biostratigraphic data are sparse. Lithologically, DS Tu 5 comprises the topmost portion of the Postelwitz Formation (Krietzschwitz core: upper part of the Pirnaer Oberquader equating "Sandstein c_3") and the lower part of the Schrammstein Formation (up to the top of "Sandstein d" equating the "Herrenleite Sandstein"; Fig. 11). The sequence is bounded below by SB Tu 4, developed in the Krietzschwitz core as a sharp, slightly undulating surface at the base of a massive, coarse-grained sandstone unit, resulting from a forced regression.

Replacement of compact packages of bioturbated, coarse-grained, immature sandstones by fine- to medium-grained sediments atop reflects an abrupt basinward shift of facies during the FSST and LST of DS Tu 5 (main part of the Pirnaer Oberquader). A relative richness of fossils (mainly thick-valved oysters and pectinids) and frequent wood remains document the vicinity to the source area and a shallow-water setting. The following change into the TST is marked by decrease of bed thickness and a fining-upward, characterising the upper portion of the Pirnaer Oberquader and culminating in the deposition of the Zeichener Ton (mfz of DS Tu 5). The base of this layer also marks the base of the Schrammstein Formation and correlates toward the Elbsandsteingebirge with the γ3 horizon (cf. Seifert 1955, Voigt 1994; Fig. 9G). In the Dorf Wehlen succession, the HST above the mfz is exposed, documenting a renewed shallowing (Fig. 10). Facies development shows a gradual upward-coarsening from fine- and medium- to medium- and coarse-grained sandstones (progradation). Megadimensional ripples occur in the top part of the measured section.

The terminating SB Tu 5 is provisionally placed in the upper part of the Herrenleite Sandstein in the Dorf Wehlen section (Fig. 11). Based on literature data (Seifert 1955, Voigt 1994), it should be of *Mytiloides scupini* zonal age. In the Elbsandsteingebirge, a corresponding unconformity should be located below the δ2 horizon – a fine-grained intercalation in the Schrammstein Formation that separates Sandstein d from "Sandstein e" (the latter corresponding to the "Sandstein von Rathewalde" of the Faziesübergangszone; Fig. 3). Similar to the γ3 horizon, the δ2 horizon forms the mfz of the above following depositional sequence (DS Tu–Co 1, not studied herein) and laterally correlates with the "Zatschker Tonmergel" of Seifert (1955) and equating marl units such as the "Brausnitzbach Mergel", which yield latest Turonian and basal Coniacian inoceramids.

6. Regional sequential comparisons

Sequence stratigraphy is an important tool for inter-basinal chronostratigraphic correlations and the first global Mesozoic sequence stratigraphic schemes ("Exxon chart") were published by Haq et al. (1987, 1988). These charts are outdated in the meantime and not considered anymore. Instead, the standard sequence stratigraphy of European basins (Hardenbol & Robaszynski 1998, Hardenbol et al. 1998) is used for comparison (Fig. 12), but primarily, a regional comparison of our data with earlier studies from Saxony and a correlation into the Bohemian Cretaceous Basin are attempted.

6.1 Saxonian Cretaceous

Sequence stratigraphic studies of (stratigraphic intervals or regional parts of) the Elbtal Group have been presented by Voigt (1994), Tröger & Voigt (1995), Voigt & Tröger (1996), Tröger (2003) and S. Voigt et al. (2006). These authors already recognised the most important aspects of the sequential subdivision of the succession. Especially the work of Voigt (1994) was very advanced, and it also stressed that due to the basin configuration in the Turonian (strongest subsidence and depocentre close to the northeastern active basin margin), the typical geometry of siliciclastic depositional sequences could not develop. A major problem is the fact that the biostratigraphic dating of the Middle and Late Turonian considerably changed since that time (see Fig. 12). In the following, we will briefly compare the early studies with our results.

For the Cenomanian part, the interpretation of the sequence stratigraphy is very similar. The main transgressive onlap occurred in the early Late Cenomanian with the Oberhäslich Formation (DS Ce 5, *naviculare* Transgression of Voigt 1994 and Tröger & Voigt 1995) and in the late Late Cenomanian with the Dölzschen Formation (TST of DS Ce–Tu 1, *plenus* Transgression of authors; e.g. S. Voigt et al. 2006, Wilmsen et al. 2011). The interstratified mid-Late Cenomanian sequence boundary SB Ce 5 equates to the formational boundary. A minor difference is the placement of an additional sequence boundary at the top of the Dölzschen Formation in the Cenomanian–Turonian boundary interval by Voigt (1994), Tröger & Voigt (1995) and Voigt & Tröger (1996). This minor unconformity also has been recognised by Wilmsen et al. (2011), and it also occurs in the Danubian (Wilmsen et al. 2010a) and Bohemian Cretaceous basins (Uličný et al. 1993, 1997; see below). Nevertheless, Richardt et al. (2013) demonstrated that this surface reflects a subordinate unconformity of a high-frequency (4^{th}-order) sequence that is followed by the mfz of DS Ce–Tu 1 (lowermost Turonian Lohmgrund Mergel in Saxony). Up-section, progradation of the highstand is reflected within the Schmilka Formation (e.g. Voigt 1999), and a sequence boundary has been identified in the Lower–Middle Turonian boundary interval in the upper part of the formation (SB Tu 1 of this study). In the Felsengasse section (Fig. 8), a gravelly unit, centrally

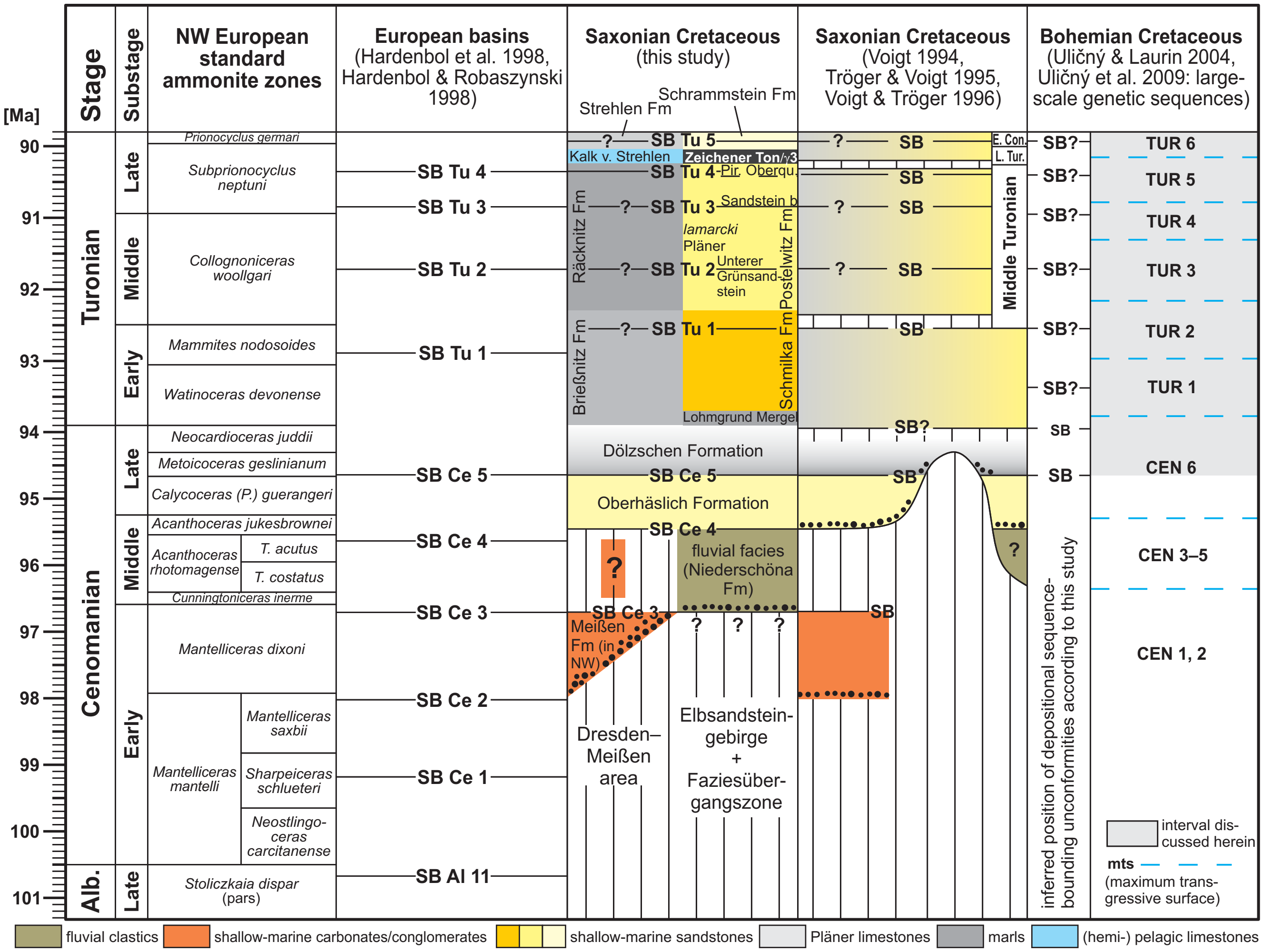


Fig. 12: Cenomanian–Turonian sequence stratigraphic correlation chart, comparing the results of this study with the sequential subdivision of the Elbtal Group of Voigt (1994) , Tröger & Voigt (1995) and Voigt & Tröger (1996), with the Bohemian Cretaceous (Uličný & Laurin 2004, Uličný et al. 2009) and with the so-called standard sequence chronostratiraphy of European basins (Hardenbol & Robaszynski 1998, Hardenbol et al. 1998). Absolute ages according to Ogg & Hinnov (2012). Question marks at Turonian sequence boundaries SB Tu 1–3 and 5 are related to the lack of exposures in the offshore facies of the Dresden–Meißen area. See text for further discussion.

containing an erosional unconformity, is of striking similarity to the contemporaneous "Hornsand unconformity" of the Danubian Cretaceous (Niebuhr et al. 2009, Richardt et al. 2013).

Voigt (1994) and Tröger & Voigt (1995) placed sequence boundaries within the Postelwitz Formation in the Unterer Grünsandstein, at the base of Sandstein b and at the base of the Pirnaer Oberquader (SB Tu 2–4 of this study; cf. Fig. 11). All these surfaces were dated as Middle Turonian. However, revised biostratigraphic dating and correlation to correlative unconformities in other Cretaceous basins (e.g. Niebuhr et al. 2011, Richardt & Wilmsen 2012) indicate that only SB Tu 2 is of Middle Turonian age. SB Tu 3 (base of Sandstein b) is already of earliest Late Turonian age (occurrence of *I. lamarcki stuemkei* in the upper part of the underlying Sandstein a_3; Wilmsen & Niebuhr 2009). This reduces the thickness of the Middle Turonian and expands the thickness of the Upper Turonian in the Elbtal Group, which was formerly very uneven (see Fig. 12). DS Tu 5 in Saxony had its maximum flooding with the mid-Upper Turonian *Hyphantoceras* Event within the Kalkstein von Strehlen/Weinböhla and the Zeichener Ton, which is correlated to the γ3 horizon of the Elbsandsteingebirge (see also Voigt 1994). The next unconformity of Voigt (1994) and Tröger & Voigt (1995) has already been placed in the Lower Coniacian. However, this surface occurs in the lower part of the Schrammstein Formation (within the upper part of the Herrenleite Sandstein) that is overlain by the Zatzschker Tonmergel, yielding uppermost Turonian–lowermost Coniacian inoceramids. Consequently, SB Tu 5 has a late Late Turonian age.

6.2 Bohemian Cretaceous

Sequence stratigraphic studies of the Cretaceous strata of the Bohemian Cretaceous Basin (BCB; see Čech et al. 1980 for lithostratigraphic terminology) have been presented by Uličný et al. (1993, 1997, 2009), Uličný & Špičáková (1996), Uličný (2001), Laurin & Uličný (2004) and Wiese et al. (2004). Sequential comparison of the Elbtal Group and the Bohemian Cretaceous has been hampered by problems in precise bio-/lithostratigraphic correlations (e.g. Prescher 1981) and different sequence stratigraphic approaches (sophisticated high-resolution genetic sequence stratigraphic interpretations by Laurin & Uličný 2004 and Uličný et al. 2009). Nevertheless, we attempt to sequentially calibrate the Upper Cenomanian–Upper Turonian successions in both basins (Fig. 12).

For the Upper Cenomanian part of the BCB, the depositional sequence approach can be applied. According to the work of Uličný et al. (1993, 1997) and Uličný & Špičáková (1996), there is a mid-Late Cenomanian sequence boundary at the base of the *M. geslinianum/N. juddii* zonal Pecinov Member of the Peruc-Korycany Formation, equating to SB Ce 5 of the Elbtal Group (base Dölzschen Formation). The above mentioned authors also recognised a sequence boundary in the Cenomanian–Turonian boundary interval at the base of the overlying Bílá Hora Formation, followed by an early Early Turonian maximum flooding. This succession of sequence stratigraphic surfaces is also reflected in the stratigraphy of the Elbtal Group, i.e. a minor unconformity occurs at the top of the Dölzschen Formation, followed by a maximum flooding in the lowermost Turonian Lohmgrund Mergel (e.g. Wilmsen et al. 2011). Furthermore, a minor unconformity and earliest Turonian maximum flooding have also been recorded from the Danubian Cretaceous (Wilmsen et al. 2010a, b, Richardt et al. 2013).

For the Turonian, the large-scale genetic sequences of Uličný et al. (2009) have been used for comparison (Fig. 12), provoking the problem that their sequences are bounded by maximum transgressive surfaces (mts). The lithofacies trends as displayed in the paper and biostratigraphic data are used to infer the potential stratigraphic position of their mts in Saxony and of our unconformities SB Tu 1–5 in the BCB, respectively. For the Lower Turonian, there is an additional sequence in the BCB, indicated by a late Early Turonian maximum flooding. According to Uličný et al. (2009), this genetic sequence TUR 1 correlates with the lower part of the Schmilka Formation in Saxony. We speculate that this sequence is related to the two Lower Turonian progradational cycles recognised in the Schmilka Formation (Voigt 1999) and in the Winzerberg Formation of the Danubian Cretaceous (Richardt et al. 2013). However, due to the magnitude of the capping unconformity SB Tu 1 and the overall short duration of the Early Turonian (ca. 800 ka), Richardt et al. (2013) regarded these cycles as 4^{th}-order high-frequency sequences.

For the Middle to mid-Upper Turonian, a corresponding number of unconformity- and mts-bounded sequences has been recorded from the Elbtal Group and the BCB (Uličný et al. 2009; Fig. 12). The lower Middle Turonian mts at the base of TUR 3 in the BCB is correlated with the maximum flooding of DS Tu 2 while the upper Middle Turonian mts at the base of TUR 4 is correlated with the maximum flooding of DS Tu 3 within the *lamarcki* Pläner. A small mismatch between both schemes in the Middle–Upper Turonian boundary interval may be related to a different biostratigraphic placing of the boundary: genetic sequence TUR 5 starts with a basal Upper Turonian maximum flooding, while the unconformity capping DS Tu 3 in Saxony (base of Sandstein b) is placed at a stratigraphically similar level. TUR 5 is bounded atop by a mts close to the *Hyphantoceras* Event, corresponding to the Kalk von Weinböhla/Strehlen, the Zeichener Ton and the γ_3 horizon in Saxony (see Fig. 12). The major mid-Upper Turonian (intra-*S. neptuni* zonal) SB Tu 4 (base of the Pirnaer Oberquader) can be correlated to the base of the Lower Coprolite Bed at the base of the Teplice Formation in the BCB (see Laurin & Uličný 2004, Wiese et al. 2004). This unconformity can also be recognised as an important sequence boundary in the Münsterland (base of the Soest Greensand Member of the Salder Formation; Richardt & Wilmsen 2012) and the Danubian Cretaceous basins (base of the Großberg Formation; Niebuhr et al. 2012). The sequence stratigraphy of the uppermost Turonian and Lower Coniacian are not discussed herein.

6.3 European standard sequence chronostratigraphy

After the careful construction of our local sequence stratigraphic framework and its regional correlation into the Bohemian Cretaceous Basin, the next step is the comparison to the so-called standard sequence chronostratigraphy for European basins (Hardenbol & Robaszynski 1998, Hardenbol et al. 1998). Even if the low biostratigraphic resolution of this chart imposes some problems, in general, there is a fairly good correlation to the sequence boundaries recognised in the Cenomanian–Turonian of Saxony – with a few exceptions. The two Cenomanian sequence boundaries SB Ce 4 and SB Ce 5 occur in identical positions, albeit SB Ce 4 has been placed slightly lower in the standard chart (Fig. 12). A further mismatch is shown by the Lower Turonian sequence boundary SB Tu 1, which has been situated by Hardenbol et al. (1998) within the Lower Turonian (lower part of *Mammites nodosoides* Zone). However, Gale (1996) in England, Wilmsen & Nagm (2013b) in Egypt as well as Niebuhr et al. (2011), Richardt & Wilmsen (2012) and Richardt et al. (2013) recognised this surface within the upper part of this biozone or the Lower–Middle Turonian boundary interval, respectively. As there is a minor mid-Lower Turonian cycle boundary, separating two high-frequency (i.e. 4^{th}-order) sequences (Richardt et al. 2013, Wilmsen & Nagm 2013b), we assume that this surface has been confused with a 3^{rd}-order boundary. Within the small uncertainties of biostratigraphic correlations (especially in the Middle–Upper Turonian boundary interval), unconformities SB Tu 2–4 all occur in quasi-identical positions in the standard chart. Only, SB Tu 5 has not been recognised by Hardenbol & Robaszynski (1998) and Hardenbol et al. (1998).

7. Conclusions

A detailed sequence stratigraphic study of the Cenomanian–Turonian strata of the Elbtal Group (Saxonian Cretaceous), focussing on new data from a continuous, recently available core section from the sea-level sensitive, so-called Faziesübergangszone around Pirna, mediating between the marly offshore facies of the Dresden–Meißen area and the sandy nearshore facies of the Elbsandsteingebirge, has been conducted. The recurrent stacking patterns of decametre-scale retrograding marly–calcareous Pläner intervals and progradational sandstone packages separated by unconformities, provided important clues for the unravelling of early Late Cretaceous sea-level changes in the basin. Additional data have been derived from the logging of numerous outcrops and the stratigraphic reinterpretation of published data. Depositional sequence-bounding unconformities have been laterally tracked between the sections and dated, using high-resolution macrofossil biostratigraphy, relying on newly obtained and previously published data. In the Middle Cenomanian–Late Turonian, seven sequence boundaries (SB Ce 4 and 5, SB Tu 1–5) have been identified that define seven depositional sequences (DS Ce 4 and 5, DS Ce–Tu 1, DS Tu 2–5).

DS Ce 4 is of mid-Cenomanian age and comprises the Niederschöna Formation. It records the gradual evolution of a fluvial system in response to base-level rise and fall, starting with coarse-grained braided river deposits, evolving into a meandering river system and culminating in typical estuarine sediments. The terminal unconformity (SB Ce 4) is a rooted palaeosol. The overlying DS Ce 5 of the Oberhäslich Formation comprises the lower Upper Cenomanian and consists of marine quartz- and shell-rich sandstones. Its thickness is strongly variable on short distances due to considerable pre-transgression palaeo-topography and DS Ce 5 as well as DS Ce 4 may completely be missing on basement highs. SB Ce 5 is a major mid-Late Cenomanian erosional unconformity that separates the Oberhäslich Formation from the overlying Dölzschen Formation. DS Ce–Tu 1 (mid Upper Cenomanian–Lower Turonian) starts with a distinct retrogradational interval (i.e. the *plenus* Transgression) and its TST continues with a second pulse into the earliest Turonian. DS Ce–Tu 1 finally levelled the pre-existing palaeo-topography and more uniform sedimentation patterns of a graded shelf became established during the Turonian (data from the Dresden–Meißen offshore zone are sparse for this interval). The following HST can be subdivided into two prograding parasequence sets, culminating in a subaerial unconformity (SB Tu 1, Lower–Middle Turonian boundary interval) in the upper Schmilka Formation. DS Tu 2 has an early Middle Turonian age, comprising the uppermost Schmilka and lower Postelwitz formations. Its terminal unconformity SB Tu 2 is placed within the Unterer Grünsandstein (informal member terminology after Seifert 1955). Sequence DS Tu 3 is of late Middle–earliest Late Turonian age and shows a complete cycle of base-level rise (deepening into the fine-grained, marly *lamarcki* Pläner) and late highstand shallowing (Mittlerer Grünsandstein or Sandstein a_3 of Lamprecht 1928, 1934). DS Tu 3 was terminated by a forced regression in the early Late Turonian (SB Tu 3), corresponding to the α3 horizon at the base of Sandstein b, which documents an abrupt basinward shift in facies. Renewed sea-level rise and a return into the TST of DS Tu 4 are documented by a rapid fining trend into Pläner sediments (Oberer glaukonitisch sandiger Mergel). The normal regression of the late HST resulted in the deposition of the lowermost portion of the Pirnaer Oberquader (uppermost Postelwitz Formation). A sudden change in grain size in response to forced regression marks the base of DS Tu 5, resulting in the formation of the mid-Late Turonian SB Tu 4. FSST and LST deposition of the Pirnaer Oberquader within DS Tu 5 was followed by a major mid-Upper Turonian transgression, culminating in a maximum flooding interval characterised by the Zeichener Ton (base of the Schrammstein Formation). It corresponds to the Kalk von Strehlen/Weinböhla in the offshore zone (Strehlen Formation) and the γ3 horizon in the nearshore Elbsandsteingebirge, matching the inter-regional marker of the *Hyphantoceras* Event. Highstand shallowing (Sandstein d of the Schrammstein Formation) ended in late Late Turonian unconformity (SB Tu 5) that has not been studied in detail.

Our sequence stratigraphic subdivision of the Elbtal Group compares well to the results of earlier studies in the region and can be translated into the genetic sequence stratigraphy developed for the Bohemian Cretaceous. A more or less identical number of sequences and key surfaces supports global sea-level changes as the main driver of early Late Cretaceous 3rd-oder sequence architecture, albeit inversion tectonics start to affect the eustatic signal from the Middle–Late Turonian onward.

8. Acknowledgements

We are indebted to T. Voigt (Jena) and D. Uličný (Prague) for constructive reviews. Further, we thank the Wismut GmbH, namely U. Zimmermann, R. Uebe (both Leupoldishain) and A. Hiller (Chemnitz), for the possibility to study the Krietzschwitz core and logistic support. We also express thanks to U. Jahr from the Sächsische Sandsteinwerke GmbH (Pirna) for giving access to their quarries. K.-A. Tröger (TU Bergakademie Freiberg) is sincerely thanked for fruitful discussion and valuable notes concerning stratigraphic questions. H. Fischer and S. Weinhold (both Dresden) helped us in drawing of some sections. B. Niebuhr, R. Winkler and M. Röthel are thanked very much for joint fieldwork. This paper is a contribution to project WI 1743/6-1 and /6-2, granted by the German Research Foundation (DFG).

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Manuscript received: 08.03.2013
Accepted for publication: 02.07.2013