Depositional setting and limiting factors of early Late Cretaceous glaucony formation: implications from Cenomanian glauconitic strata (Elbtal Group, Germany)

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Abstract
Cenomanian strata of the Elbtal Group (Saxony, eastern Germany) reflect a major global sea-level rise and contain, in certain intervals, a green authigenic clay mineral in abundance. Based on the integrated study of five new core sections, the environmental background and spatio-temporal patterns of these glauconitic strata are reconstructed and some general preconditions allegedly needed for glaucony formation are critically questioned. XRD analyses of green grains extracted from selected samples confirm their glauconitic mineralogy. Based on field observations as well as on the careful evaluation of litho- and microfacies, 12 glauconitic facies types (GFTs), broadly reflecting a proximal–distal gradient, have been identified, containing granular and matrix glaucony of exclusively intrasequential origin. When observed in stratigraphic succession, GFT-1 to GFT-12 commonly occur superimposed in transgressive cycles starting with the glauconitic basal conglomerates, followed up-section by glauconitic sandstones, sandy glauconitites, fine-grained, bioturbated, argillaceous and/or marly glauconitic sandstones; glauconitic argillaceous marls, glauconitic marlstones, and glauconitic calcareous nodules continue the retrogradational fining-upward trend. The vertical facies succession with upwards decreasing glaucony content demonstrates that the center of production and deposition of glaucony in the Cenomanian of Saxony was the nearshore zone. This time-transgressive glaucony depocenter tracks the regional onlap patterns of the Elbtal Group, shifting southeastwards during the Cenomanian 2nd-order sea-level rise. The substantial development of glaucony in the thick (60 m) uppermost Cenomanian Pennrich Formation, reflecting a tidal, shallow-marine, nearshore siliciclastic depositional system and temporally corresponding to only ~400 kyr, shows that glaucony formation occurred under wet, warm-temperate conditions, high accumulation rates and on rather short-term time scales. Our new integrated data thus indicate that environmental factors such as great water depth, cool temperatures, long time scales, and sediment starvation had no impact on early Late Cretaceous glaucony formation in Saxony, suggesting that the determining factors of ancient glaucony may be fundamentally different from recent conditions and revealing certain limitations of the uniformitarian approach.

Keywords Lower Upper Cretaceous · Transgression · Glaucony · Stratigraphy · Depositional environments

Introduction
The sedimentary strata of the Cenomanian Stage record one of the largest sea-level rises of the Mesozoic Era (e.g., Hancock and Kauffman 1979; Haq et al. 1987; Hancock 1989; Robaszynski et al. 1998; Wilmsen 2003; Kuhnt et al. 2009; Haq 2014). Consequently, lower Upper Cretaceous strata often onlap former non-depositional areas, sealing inherited palaeo-topographies and commonly recording a significant up-section deepening of the depositional environment (Wilmsen et al. 2005). In many cases, the sedimentary rocks deposited during this transgressive megacycle contain an authigenic green mineral (presumed glauconite) in...
abundance, leading to the formation of in part very thick greensand successions (e.g., in the Münsterland Cretaceous Basin of northern Germany; Bärtling 1920; Seibertz 1977; Wildberg 1980; Hiss 1982; Berensmeier et al. 2018a, b). Also in the Saxonian Cretaceous Basin of eastern Germany, transgressive glauconitic strata received early attention (Geinitz 1850) and also have been regionally mapped at the base of the Cretaceous successions in the Meißen–Dres-

Geological setting

The Lower Cenomanian to Middle Coniacian Elbtal Group, formally defined by Voigt and Tröger in Niebuhr et al. (2007) and recently revised by Niebuhr et al. (2020), comprises marine sandstones and conglomerates, calc-arenites, calcaceous siltstones, and silty marlstones (regionally called Pläner), marls and marly limestones as well as continental deposits that occur locally at the base (fluvial gravels, sand- and siltstones and coals of the Lower–Middle Cenomanian Niederschöna Formation). The strata of the Elbtal Group were deposited in a fairly narrow strait between the small West-Sudetic Island in the northeast and the large Mid-European Island in the southwest, widening to the southeast into the much larger Bohemian Cretaceous Basin. To the northwest, the strait opened into the Elbe Zone; the studied sections are indicated by blue asterisks (1: Meißen-Oberau area; 2: temporary exposure at motorway A4; 3: core section Nossener Brücke; 4: cores HG 6512 and 6513; 5: core Nasser Grund. b Palaeogeographic setting of the Saxonian Cretaceous Basin (SCB). c Chrono-, bio- and lithostratigraphry of the Elbtal Group, supplemented and modified after Wilm-

Material and methods

Stratigraphic sections have been logged and sampled in great detail bed-by-bed, applying standard sedimentary and palaeontological field methods (e.g., Goldring 1999; Stow...
were scanned from 5° to 90° 2 of the Federal State of Saxony (LfULG), Freiberg. Nasser Grund in the core archive of the Geological Survey Brücke is in a repository of the city of Dresden and the core Nossener HG 6512 and 6513 are likewise stored at the SNSD while Sammlungen Dresden (SNSD), repository SaK. The cores diffraction peaks were studied to identify the mineral 'glauconite'.

Detector based in the Mineralogy Section of the Museum of the Upper Cretaceous in the Oberau area. The basement rocks at Gröbern consist of an Augengneiss belonging to the large intrusive body of the Carboniferous Meißen Massif. They are overlain in core B14 along a fissured erosion surface by the ca. 0.8-m-thick Oberau Conglomerate consisting of moderately rounded to sub-angular gneiss pebbles and cobbles within a marly-glauconitic matrix (Figs. 2a, 3a). This basal conglomerate of the Mobschatz Formation is followed by 1.6 m of feldspatic, partly cross-bedded, medium- to coarse-grained glauconitic sandstones to sandy glauconitites, overlain by weakly glauconitic argillaceous marls. A sample from

Results

Five new sections were studied and are described following a NW–SE transect (chapter Measured sections). They are located in the Oberau area northeast of Meißen, in the city of Dresden, on the northeastern margin of the Erzgebirge and in the Saxonian Switzerland (Fig. 1a). Glaucophane strata have been subdivided into facies types (chapter Glaucophane facies types, GFTs) and picked green grains from selected samples have been analyzed for their mineralogy using X-ray diffraction (chapter XRD analyses).

Measured sections

Gröbern composite section

The Cenomanian–Lower Turonian succession of the Oberau area is a composite section based on the newly logged core B14 (lowermost part) and the core Gröbern 2/91 (upper part). Both cores were drilled in the Gröbern area in 1991 for subsurface investigation of a planned landfill site. The lowermost part of the core 2/91 including the contact of the Cretaceous strata to the basement is not anymore available and was replaced in the paper of Wilmsen et al. (2019) by an only moderately exposed railway slope cut section ca. one km to the southwest. However, the B14 core was drilled directly adjacent to core 2/91 and was recently re-discovered in the core archive of the TU Bergakademie Freiberg, forming a much better, fully exposed, indigenous foundation of the Upper Cretaceous in the Oberau area.

The basement rocks at Gröbern consist of an Augengneiss belonging to the large intrusive body of the Carboniferous Meißen Massif. They are overlain in core B14 along a fissured erosion surface by the ca. 0.8-m-thick Oberau Conglomerate consisting of moderately rounded to sub-angular gneiss pebbles and cobbles within a marly-glauconitic matrix (Figs. 2a, 3a). This basal conglomerate of the Mobschatz Formation is followed by 1.6 m of feldspatic, partly cross-bedded, medium- to coarse-grained glauconitic sandstones to sandy glauconitites, overlain by weakly glauconitic argillaceous marls. A sample from
Careous strata for about 12 m (Fig. 3a); calcareous nanofossils of the biozones UC2c to UC3a (upper – this level contained C. sculpus and G. theta, i.e., calcareous nanofossils of the biozones UC2c to UC3a (upper – most Lower to lower Middle Cenomanian) sensu Burnett (1998). Up-section, the succession of core 2/91 continues with bioturbated, fine-grained silty, glaucony-bearing calcareous strata for about 12 m (Fig. 3a); calcareous nanofossils and stable carbon isotopes date this part as Middle Cenomanian (Wilmsen et al. 2019). Above an abrupt facies change at 14.6 m, argillaceous marls form the upper Mobschatz Formation (lower Upper Cenomanian). At a shell bed at 20.6 m, the mid- to uppermost Cenomanian Dölzschen Formation starts, ranging up to the base of the argillaceous Lohmgund Horizon at 39.6 m that is forming the base of the overlying Brießnitz Formation and contains the Cenomanian–Turonian boundary (Wilmsen et al. 2019). The Dölzschen Formation consists of a monotonous intercalation of argillaceous marls and calcareous marlstones with rare macrofossils, occasionally containing a little glaucony. Above the Lohmgund Horizon, carbonate contents start to rise and the Lower Turonian Brießnitz Formations comprises calcareous bioturbated marlstones (Fig. 3a).

Core section Nossener Brücke

The basement rocks of the Nossener Brücke section consist of a Carboniferous monzonite belonging to Meißen Massif (Fig. 3b). They are overlain by the ca. 8-m-thick lower Upper Cenomanian Mobschatz Formation. At the base of the Mobschatz Formation, a ca. 0.2-m-thick conglomerate bed consisting of angular to sub-rounded pebbles of weathered basement occurs, showing a marly-glaucolithic matrix (Fig. 3b). The basal conglomerate gradationally passes into a glaucony-rich, ca. 1.2-m-thick interval of bioturbated sandstones containing numerous large Macaronichnus burrows and intercalated parallel-laminated, sharp-based glauconitic sandstones. An argillaceous marl bed at 72.7 m marks the transition from glauconitic sandstones and glauconitic marlstones to strongly-bioturbated, non-glaucolithic marls and Pläner forming the middle and upper part of the Mobschatz Formation. A coprolite bed at 71.3 m occurs within this interval. At 69.5 m, a ca. 2-m-thick argillaceous marl unit forms the basal plenus Horizon of the upper Upper Cenomanian Dölzschen Formation, followed by strongly bioturbated argillaceous marlstones characterized by abundant, in part weakly glauconitic calcareous nodules in the lower part (up to ca. 60 m). Argillaceous layers occur at different levels (62 m, 60 m and 53.9 m), the deepest associated with rare glaucony. Sample NB-NF3 at 67 m contains a rather poor calcareous nanofossil assemblage with ca. 10 species including A. albianus; it is thus not younger than UC5a sensu Burnett (1998), i.e. upper Metoicoceras geslinianum ammonite Zone (mid-Late Cenomanian). Up-section, the Dölzschen Formation passes conformably into the lowermost Turonian Lohmgund Horizon at 49 m.

A few kilometers to the northwest of the Nossener Brücke core section, the glauconitic strata at the base of the Dölzschen Formation have been exposed in 2004–05 during construction at the motorway A4 exit Dresden-Altstadt. The observed lithofacies includes hummocky-cross-bedded, graded glauconitic sandstones and bioturbated glauconitic sandstones, similar to what has been logged between 76.10 and 74.80 m at Nossener Brücke.

Cores HG 6512 and 6513

The substrate at core sections HG 6512 and 6513 (Fig. 3c, d) consist of Permian rocks of the Döhlen Basin. These volcanioclastic rocks comprise kaolinitic clays, arkosic altered tuffs with beige-red mottling, brick-red sandstones, and grey breccia layers. The pre-Cretaceous substrate is overlain by lower Upper Cenomanian Oberhäslich Formation in both the sections that are only ca. 500 m apart. The ca. 5.5 m thick Oberhäslich Formation in core HG 6512 predominantly consists of weakly bioturbated sandstones (Fig. 3c). The sandstones are glauconitic at the base with abundant large Macaronichnus burrows followed by a coarse-grained sandstone that fines upwards into a ca. 0.2-m thick fine-grained siltstone bed at 255 m. The upper part of the formation shows a coarsening-upward trend and contains white mica. In section HG 6513, the ca. 6.2 m thick Oberhäslich Formation exhibits similar lithological characteristics with Macaronichnus-bioturbated glauconitic sandstones at the base followed by grey, medium-grained sandstones above. A fine-grained siltstone bed at 5 m can be used to correlate both sections. The top surface of the Oberhäslich Formation is sharp and bioturbated, and unconformably over lain by ca. 2-m-thick fine argillaceous siltstones of the plenus Horizon at the bases of the upper Upper Cenomanian Pennrich Formation (Fig. 3c, d). The Pennrich Formation, of which only the lower 4 m are preserved in the HG 6513 core, essentially comprises ca. 6.3 m of medium-grained, weakly bioturbated, non-glaucolithic sandstones rich in Ophiomorpha burrows that also contain a few macrofossils such as oysters and serpulids as well as fine plant debris. The top of the lower sandstone unit is marked by bioclasts and ferruginous staining. Above a siltstone bed, ca. 3.6 m of wavy laminated, slightly bioturbated siliceous sandstones form the upper part of the Pennrich Formation. A dark mudstone bed starting at 269.8 m belongs to the overlying Lohmgund Horizon of the Lower Turonian Schmilka...
Formation (Fig. 3c). Loamy to sandy Quaternary deposits containing Cretaceous pebbles and cobbles conclude the succession in the HG 6512 core section.

**Core Nasser Grund**

The core GWMS1 1/18 Nasser Grund has been drilled in 2018 east of Bad Schandau in the Saxonian Switzerland (Figs. 1a, 4). It reached a final depth of 330 m and was drilled to serve as a groundwater gauge. At 328.20 m depth it reached the basement consisting of the Proterozoic Lusatian granodiorite. Only the lower part of the Cretaceous succession up to a depth of 205 m is treated herein, specifically the Pennrich Formation between 291 and 228 m.

The lowermost part of the Cretaceous succession between 328.20 and 318.20 m is formed by coarse-grained breccia, conglomerates, and coarse-grained sandstones of the Niederschöna Formation (Fig. 4). Components are mainly quartz clasts and the matrix is argillaceous-carbonaceous. Thin coal seams and lenses, as well as coal fragments, are common. *Ophiomorpha* burrows have been observed at several levels. This marine-influenced upper part of the Niederschöna Formation is informally called “Wurmsandstein” and assigned to the Middle Cenomanian (Janetschke and Wilmsen 2014).

At 318.20 m, a sharp lithofacies change to yellow-beige quartz sandstones of the Oberhäslich Formation occurs (Fig. 4). In its lower part up to 305 m, fine-grained quartz conglomerates intercalate with coarse-grained, cross-bedded sandstones while the upper part consists of medium-grained, rather homogeneous quartz arenites with occasional bioturbation. Between 302 and 300 m, the sandstones are fine- to medium-grained, slightly argillaceous, and show more bioturbation. A coarsening trend with reappearance of cross-bedding characterized the uppermost 2–3 m of the formation. The Oberhäslich Formation encompasses the lower Upper Cenomanian (Tröger and Voigt in Niebuhr et al. 2007; Wilmsen 2017).

At 291.20 m, the Oberhäslich Formation is unconformably overlain by the basal conglomerate of the upper Upper Cenomanian Pennrich Formation. The basal bed consists of varicolored, well-rounded quartz pebbles in a greenish sandy-argillaceous matrix containing matrix glaucony (Figs. 2b, 4); exotic clasts comprise dolomitized limestone and speleothem fragments. The lower Pennrich Formation consists of an intercalation of bioturbated fine- and coarse-grained sandstones, the latter often pebbly. Both lithofacies may contain grainy and/or matrix glaucony and are stacked with a fining-upward trend. From a depth of 283 m, fine-grained, bioturbated glauconitic sandstones prevail, showing only thin sharp-based coarser interbeds (Fig. 4). At ca. 272.5 m, the fine-grained interval is followed by coarse-grained, oyster shell-bearing brownish sandstones with cross-bedding and parallel lamination, placing the top of a coarsening-upward trend at 270.30 m (top of cycle P1; Figs. 2c, 4). Above the sharp top surface, cycle P2 starts with bioturbated, fine-grained sandy-argillaceous strata which are weakly glauconitic only in the lowermost part up to 267 m.

**Glaucnconitic facies types (GFTs)**

The facies analysis of the glauconitic facies within the lower Elbtal Group is based on evaluation of litho- and microfacies, supplemented by field observations of features such as bedding, sedimentary structures as well as trace and body fossil contents. On the basis of these integrated data, the glauconitic strata have been grouped into 12 facies types (GFTs), briefly described in Table 1 and...
| Facies type | Name | Short description | Thin-sections (example) | Interpretation, remarks |
|-------------|------|------------------|-------------------------|-------------------------|
| GFT-1       | Glauconitic basal conglomerate | Consist of commonly clast-supported conglomerates with granule- to cobble-sized, poorly sorted and rounded lithoclasts in a sandy-glauconitic to marly-glauconitic matrix; clasts are either the local basement rocks (e.g., monzonites, syenites, gneiss) or quartz clasts. There are two subtypes: GFT1a: basal conglomerate with marly-glauconitic matrix in which lobate, cracked, zoned and rounded glaucony grains occur; a few mica flakes or feldspar grains are glauconitized, too (e.g., Oberau Conglomerate, Figs. 2a, 6a, b) | GFT-1a: Oberau O-0, O-1, NB-1 GFT-1b: NG-OP1, NG-P1 | Transgressive high-energy nearshore setting, rocky coast (GFT-1a) or transgressed lowland with lag concentration of coarse components (GFT-1b); matrix infiltrated conglomeratic pore spaces during quite phases and/or progressive deepening |
| GFT-2       | Pebby glauconitic sandstone  | Medium-grained, poorly-sorted, dark-green glauconitic sandstone; glaucony is present as matrix; small sub-rounded to angular lithoclasts (predominantly quartz) occur scattered in sandy-glauconitic matrix (Fig. 6e) | NG-P2 | Nearshore sands of high- to moderate-energy settings |
| GFT-3       | Glauconitic sandstone  | Medium to coarse grained, dark-green glaucony grains (10–30%) occur in a poorly-sorted, sandy matrix; scattered small bioclasts may occur; inhomogeneous fabric due to bioturbation (Fig. 6f) | NB-2 | Nearshore sands of high- to moderate-energy settings |
| GFT-4       | Bioclastic glauconitic sandstone  | Fine to medium-grained, poorly to moderately sorted, grass- to light-green bioclastic glauconitic sandstone; glaucony mainly occurs as grains, rarely as matrix; quartz grains with poor textural maturity predominating; bioclasts (commonly oysters) occur scattered or concentrated in loosely to densely packed shell beds within the sandy-glauconitic matrix; a few brown grains (phosphate or oxidized glaucony) may occur (Figs. 2g, 6g, h) | NG-P8 | Bioclastic nearshore sands of moderate energy; shell beds result from episodic high-energy events (storms) |
| GFT-5       | Glauconitite  | Medium-grained, well-sorted, grass-green glauconinites with a predominance of grainy glaucony (≥ 50%), commonly well-sorted. In some cases, iron oxides occur in form of goethite (confirmed by XRD) as cortices around some grains; quartz and grainy glaucony embedded in fine-grained sandy (GFT-5a) or marly matrix (GFT-5b); minor glauconitization of mica flakes; bioclasts maybe present (Figs. 2h, 7a, b) | GFT-5a: NG-P7, NG-7, NG-P11 GFT-5b: M-Z-1 | Nearshore glaucony sands of high- (GFT-5a) to moderate-energy (GFT-5b) settings |
| Facies type          | Name                          | Short description                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Thin-sections (example)                                                                 | Interpretation, remarks                                                                 |
|---------------------|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------|----------------------------------------------------------------------------------------|
| GFT-6               | Bioturbated glauconitic sandstone | Fine- to medium-grained, well- to moderately sorted, variably bioturbated glauconitic sandstone with two subtypes: GFT-6a: dark green glaucony grains predominate within a fine-grained sandy-marl matrix; glaucony grains concentrated along parallel laminae and the linings of Macaronichnus burrows (Fig. 7c); bioturbation moderate (Fig. 5b) to strong (Fig. 5c) GFT-6b: grass-green grainy glaucony within sandy matrix; glaucony grains zoned/rimmed; relict cross- or parallel-lamination or low-angle bedding, weak bioturbation (Fig. 7d) | GFT-6a: NB-3 GFT-6b: NG-P9, NG-P12, Mo-2 | Rapidly deposited nearshore glauconitic sands, variably affected by post-depositional bioturbation |
| GFT-7               | Sandstone with glaucony       | Fine- to medium-grained, well-sorted, yellow to pale green sandstones with low glaucony content (<10%) and rare shell fragments; iron oxide-mottling common; often structureless to massive; component spectrum quartz-dominated with rare, often zoned light-green (i.e., poorly evolved) glaucony grains; glauconitic matrix also present; bioturbated fabric, scarce Ophiomorpha and Macaronichnus burrows present (Fig. 7e) | HG-6512-Sample 1 and HG-6513-Sample A and B | Nearshore sands with rare glaucony, homogenized by post-depositional bioturbation               |
| GFT-8               | Glauciotic tempestite         | Normally graded, parallel-laminated to hummocky-cross-stratified, coarse- to fine-grained glauconitic sandstones with quartz granules and shell fragments commonly concentrated at the base of the beds (thickness between 5–20 cm); glaucony almost exclusively grainy, often concentrated along laminae; glaucony content very variable up to non-glauconitic varieties (Fig. 5a) | Mo-1 | Storm event deposition, offshore transport of nearshore material by sediment-loaden backflow |
| GFT-9               | Fine-grained bioturbated glauconitic sandstones | Fine-grained, well-sorted sandstones with both small glaucony grains and matrix glaucony and some bioclasts (oyster debris); matrix argillaceous; homogeneous fabric due to strong bioturbation (e.g., Ophiomorpha isp., Macaronichmus isp.); intercalated tabular and tubular tempestites may occur (Fig. 7f) | NG-P3 (upper part), NG-4 | Fine-grained sandy-argillaceous sediments deposited in sheltered setting under moderate to low energy (below fair-weather wave base) |
| GFT-10              | Glaucotic argillaceous marls  | Silty to sandy argillaceous marls with dispersed glaucony pellets; mud-supported fabric, inhomogeneous due to bioturbation; scattered bioclasts/shells may occur; soft-weathering (differing from GFT-11 mainly in lower carbonate content) | Field observations | Low-energy deposit accumulating below average storm wave base, moderate terrigenous input |
illustrated in Figs. 5, 6, 7. Thin-section photomicrographs are shown according to their original stratigraphic orientation, i.e., up-section corresponds to the page top. The GFTs have been arranged according to their grain size from coarse (GFT-1) to fine (GFT-12). Their order thus broadly corresponds to the stratigraphic occurrence in a typical transgressive fining-upward cycle in which, of course, commonly not all GFTs are developed from base to top. The following GFTs have been identified:

**GFT-1**: Glaucolithic basal conglomerate with either marly-glaucolithic (GFT-1a) or sandy glauconitic matrix (GFT-1b) (Figs. 2a, b, 6a–d).

**GFT-2**: Pebbley glauconitic sandstone merges medium-grained glauconitic sandstones with scattered granule- to pebble-sized lithoclasts (commonly quartz; Fig. 6e).

**GFT-3**: Glaucolithic sandstone, consisting of medium- to coarse-grained sandstones (Fig. 6f).

**GFT-4**: Bioclastic glauconitic sandstone contains scattered bioclasts and disarticulated valves, commonly of oysters (Figs. 2g, 6g, h).

**GFT-5**: Glaucolithicites consist of well-sorted, commonly medium-grained glaucony (> 50%) and quartz grains within a finer sandy (GFT-5a) and marly matrix (GFT-5b) (Figs. 2h, 7a, b).

**GFT-6**: Bioturbated glauconitic sandstone are fine- to medium-grained and may contain relict sedimentary structures (Figs. 5c, 7c, d).

**GFT-7**: Sandstone with glaucony combines commonly structureless sandstones with a low glaucony content (< 10%) (Fig. 7e).

**GFT-8**: Glaucolithic tempestites, comprising sharp-based, normally graded glauconitic sandstones with parallel lamination and/or hummocky cross-stratification (HCS) (Fig. 5a).

**GFT-9**: Fine-grained bioturbated glauconitic sandstones comprise well-sorted, strongly bioturbated sediments with matrix glaucony and small glauconitic grains (Fig. 7f).

**GFT-10**: Glaucolithic Pläner are soft sediments with scattered glaucony grains.

**GFT-11**: Glaucolithic Pläner are bioturbated silt- and fine-sand-containing marlstones with dispersed glaucony grains (Fig. 7g).

**GFT-12**: Calcareous nodules with glaucony Few glaucony grains (1–2%) dispersed within a calcareous-marly matrix characterize the calcareous nodules in the Dölzschen Formation; microbioclasts, calcispheres, calcified sponge spicules and planktic foraminifera are important components in descending importance (Fig. 7h).

**XRD analyses**

X-ray diffractograms (XRD) of separated green grains in air-dried mode of scanning distinguish the clay-minerals and their association (Fig. 8). Green grains have been separated from the Mobschatz Formation of the Oberau-Gröbern area (sample O-1, lower Middle Cenomanian) and the Nossener
Brücke core (samples NB-1 and -3, lower Upper Cenomanian) as well as the from the Pennrich Formation at core Nasser Grund (sample NG-7, upper Upper Cenomanian). Sample O-1 reveals the basal reflection at 10.09 Å (001) as well as reflections at 4.53 Å (020), 3.65 Å (112), 3.33 Å (003), 3.06 Å (112), 2.58 Å (004), 1.99 Å (005) and 1.51 Å (006) (Thompson and Hower 1975; Odin and Matter 1981; Amorosi et al. 2007) with sub-ordinate peaks at 2.80 Å, 2.70 Å and 1.84 Å (Fig. 8a). The peaks are intense, sharp, symmetrical and narrow-based. Similarly, the XRD diagrams of samples NB-1 and NB-3 exhibit the basal (001) reflection at 10.16 Å, a (003) reflection at 3.33 Å, a (004) reflection at 2.57 Å and a (005) reflection at 1.99 Å. Other prominent peaks include the reflections (020) at 4.53 Å and (006) at 1.51 Å (Odin and Matter 1981; Amorosi et al. 2007; Fig. 8b). Sample NB-3 further exhibits the shoulder reflections 112 and 112 at 3.66 Å and 3.08 Å, respectively (Fig. 8c). The peaks are narrow-based, sharp, symmetrical and intense. Subsidiary peaks occur at 7.14 Å and at 4.99 Å in sample NB-1, indicating kaolinite and illite, respectively (Fig. 8b), the latter peak also occurring at 4.98 Å in sample NB-3 (Fig. 8c). Finally, also sample NG-7 (Pennrich Formation) reveals the peaks at 10.15 Å (001), followed by (020) at 4.53 Å, (112) at 3.66 Å, (003) at 3.33 Å, (004) at...
Glauconitic grains.

Presence of fluorapatite/carbonate-fluorapatite within these at 2.80 Å, 2.70 Å, and 1.84 Å in sample O-1 indicate the (cf. Odin and Fullagar 1988) while the subordinate peaks Banerjee et al. 2016; Fig. 8d). Subordinate peaks at 4.18 Å of the glaucony group (Fig. 8). The X-ray scanning of green grains from the lower Middle (sample O-1) and lower Upper Cenomanian Oberau Conglomerate, Oberau area, sample O-0; note lobate, cracked, zoned and round glaucony grains. e Basal conglomerate of GFT-1b, mid-Upper Cenomanian conglomerate at the base of the Pennrich Formation, core Nasser Grund at 291.10 m, sample NG-OP1; note well-rounded quartz pebbles. d Close-up of the sandy-glauconitic matrix of the basal conglomerate of GFT-1b, mid-Upper Cenomanian conglomerate at the base of the Pennrich Formation, core Nasser Grund at 291.10 m, sample NG-OP1. e Pebby glauconitic sandstones of GFT-2, mid-Upper Cenomanian, lower part of the Pennrich Formation, core Nasser Grund at 290.30 m, sample NG-P2. f Poorly sorted glauconitic sandstone of GFT-3, Mobschatz Formation, lower Upper Cenomanian, core Nossener Brücke at 75.6 m, sample NB-2. g Bioclastic glauconitic sandstones of GFT-4 showing numerous thick-shelled oyster shell fragments, upper Upper Cenomanian Pennrich Formation, core Nasser Grund at 238 m, sample NG-P8. h Close-up of GFT-4, bioclastic glauconitic sandstones, showing both, grass-green glaucony grains (gg) and matrix glaucony (mg); upper Upper Cenomanian Pennrich Formation, core Nasser Grund at 238 m, sample NG-P8

2.58 Å, (005) at 1.99 Å and (060) at 1.51 Å (Odom 1984; Banerjee et al. 2016; Fig. 8d). Subordinate peaks at 4.18 Å, 2.68 Å, and 2.45 Å indicate the presence of goethite. All the peaks are sharp, intense, and symmetrical with narrow bases (Fig. 8d). The characteristic peak at 10 Å in all studied samples belongs to the ‘glauconitic’ minerals group (cf. Odin and Fullagar 1988) while the sub-ordinate peaks at 2.80 Å, 2.70 Å, and 1.84 Å in sample O-1 indicate the presence of fluorapatite/carbonate-fluorapatite within these glauconitic grains.

Discussion

Clay mineralogy

The XRD analyses of green grains extracted from Cenomanian samples of the lower Elbtal Group in Saxony revealed that the constituting mineral is in any case a 10-Å-mineral of the glaucony group (Fig. 8). The X-ray scanning of green grains from the lower Middle (sample O-1) and lower Upper Cenomanian of the Mobschatz Formation (samples NB-1 and NB-3) clearly identifies the green mineral as a glauconitic mineral with minor illite (Thompson and Hower 1975; Odin and Matter 1981; Odom 1984; Amorosi et al. 2007; Banerjee et al. 2016). The X-ray diffractogram of sample O-1 indicates an association of the glauconitic mineral with fluoroapatite/carbonate-fluoroapatite. Petrographical studies relate the presence of the latter to the occurrence of small phosphatized vertebrate fragments (fish remains). The occurrence of kaolinite in sample NB-1 can be attributed to the chemical alteration of K-feldspars provided by the underlying basement rocks. The X-ray diffractogram of sample NG-7 (upper Upper Cenomanian Pennrich Formation) reveals the co-occurrence of the glauconitic mineral and goethite. Detailed thin-section petrography from that level corroborates the presence of goethite as iron oxide within the strata. The presence of goethite is possibly related to intra-formational sub-aerial exposure of the glauconitic sediments at cycle boundary P3 and the resultant oxidizing conditions, transforming glauconitic grains (partially) into iron hydroxides (see chapter on Spatio-temporal distribution of glauconitic strata below).

Glaucanitic facies types

Glaucanic facies types in the Cretaceous of Saxony have been defined and systematically analyzed as early as in 1850 by Hanns Bruno Geinitz. He differentiated glauconitic sandstones (“Grünsandstein”), glauconitic sands (“Grünsand”), glauconitic calcareous sandstones, glauconitic Pläner and calccareous glauconitic nodules, the latter commonly occurring in the plenus Pläner of the Dölzschen Formation. In its main features, his early lithofacies subdivision already back then reflected a proximal–distal gradient and broadly corresponds to the glauconitic facies types identified herein.

The glauconitic facies types (GFT) 1–12 (Table 1) recognized in this study contain granular and matrix glaucony. When the mineral occurs as a coating (film facies) or as pore-filling matrix, glaucony can always be supposed to be autochthonous (e.g. Odin and Matter 1981; Amorosi 1995, 1997) and is, with a few exceptions, a reliable indicator of marine conditions (Banerjee et al. 2016). Grainy glaucony, on the other hand, can be both, autochthonous and allochthonous, and grainy glauconitic facies must therefore be evaluated with care. However, the grainy glauconitic facies observed in the Mobschatz, Oberhäslich and Pennrich formations of Saxony by no means represents detrital (extrasequential) glaucony (Amorosi 1995, 1997), transported from an external source area into the basin, because no appropriate source rocks are present in the wider area and the transport capacity of glaucony is low. Thus, the glauconitic facies types in Saxony exclusively consist of authochthonous and parauthochthonous (intrasessional) glaucony sensu Amorosi (1997). For the grainy facies types, a parauthochthonous nature of the grains in the case of GFT-8 (graded glauconitic tempestites with HCS) can easily be derived from their arrangement in cross-laminae. The occurrence of shrinkage fractures at grain surface, on the other hand, such as in many green grains from the matrix of the glauconitic conglomerates (GFT-1), is a reliable indicator of an autochthonous origin of glauconite (McRae 1972; Odom, 1976; Fischer 1990). However, in detail, the differentiation of grainy glaucony...
into clear-cut authothonous and parauthothonous facies may be challenging and is not always unambiguous.

When observed in a stratigraphic succession, GFT-1 to GFT-12 commonly occur superimposed in transgressive cycles starting with the glauconitic basal conglomerates (GFT-1). Up-section, medium- to coarse-grained, in part pebbly glauconitic sandstones and/or sandy glauconitites grading into (increasingly marly) bioturbated glauconitic sandstone (GFT-2–7) follow (e.g., lower part of the sections in Gröbern and Nossener Brücke; Fig. 3a, b). Graded glauconitic tempestites with hummocky cross-bedding are intercalated into the lower part of the transgressive cycles, too (GFT-8). Fine-grained, argillaceous, bioturbated glauconitic sandstones with matrix glaucony (GFT-9), argillaceous glauconitic marls and marlstones (GFT-10 and -11) continue the retrogradational fining-upward trend. Glauconitic calcareous nodules (GFT-12) are the distalmost glauconitic facies type observed in the lower Elbtal Group, characterizing the fine-grained offshore facies (calcisphere- and radiolaria-bearing wackestones with planktic foraminifers) of the Dölzschen Formation. When applying Walther’s law of facies, the vertical facies succession with the upwards decreasing glaucony content clearly indicates that the center of production and deposition of glaucony in the Cenomanian of Saxony was the nearshore zone (as already pointed out by Seifert 1955), nourishing disbelief in the doctrine of a deep-water origin of glaucony (cf. Odin and Matter 1981; Odin and Fullagar 1988; Föllmi 2016; Tang et al. 2017; see chapter on Prerequisites for glaucony formation below).

**Spatio-temporal distribution of glauconitic strata**

Green authigenic clays within sedimentary strata include a broad spectrum of minerals, i.e., iron smectite, glauconitic smectite, smectitic glauconite, berthierine, odinite (formerly phyllite v), a ferric chlorite (phyllite c), chamosite, ferric illite, or celadonite (Huggett 2005).
Fig. 9  (continued)
the sediment, green grains are commonly termed “glauconite”—mostly without analysing the exact chemical composition or mineralogy. Influential studies of “green marine clays” led to popular classification and formation theories mainly based on observations in recent environments (e.g., Odin and Matter 1981; Odin 1988). Allegedly, glauconitisation, i.e., the formation of 10-A glauconitic smectite and smectitic glauconite characterizing the glaucony facies, only occurs in fairly deep marine settings under cooler temperatures, low accumulation rates, and on long timescales (outer shelf to upper slope; Odin and Fullagar 1988) while shallow marine warm-water settings are characterized by the vertine facies with a different suite of rather rapidly forming green 7-A clay minerals such as odinite and ferric chlorite (Odin and Sen Gupta 1988; Odin 1990). However, the geological record of the vertine facies is scarce with only a few occurrences in pre-Quaternary strata (e.g., Harding et al. 2014) and several new findings show a mismatch between the recent mode of glaucony formation and ancient examples (e.g., Chafetz and Reid 2000; El Albani et al. 2005; Chafetz 2007; Banerjee et al. 2012, 2016; Huggett et al. 2017; Bansal et al. 2018, 2020).

This mismatch, which may be referred to as the “dilemma of nearshore glaucony”, is also corroborated by the occurrence of glaucony in the lower Elbtal Group. In most cases, the glaucony-rich strata occur at the bases of transgressive fining-upward cycles, already noted in earlier works (e.g., Seifert 1955; Tröger 1956), corresponding to the (lower) transgressive system tracts (TSTs) of depositional sequences, and they are almost always associated with shallow-water facies (Figs. 3, 9; see Janetschke and Wilmsen 2014; Janetschke et al. 2015; Wilmsen et al. 2019 for details on Cenomanian–Lower Turonian sequence stratigraphy of the Elbtal Group). The lower Middle Cenomanian Oberau Conglomerate of the lower Mobschatz Formation in the northwestern part of the study area is a high-energy deposit forming close to a retreating rocky coast (GFT-1). Even if the marly-glauconitic matrix infiltrated the pore space between the coarse basement components during lowered energy, e.g., during prolonged fair-weather conditions or during proceeding sea-level rise of depositional sequence DS Ce 4 (Fig. 9), a shallow-water nearshore formation of the glaucony grains is assured; their onshore transport is more than unlikely given the rarity/absence of glaucony in the offshore facies zone (see GFTs above) and appropriate onshore transport mechanisms (rather, an offshore transport of glaucony is indicated by the glauconitic tempestites of GFT-8). The same considerations apply for the lower Upper Cenomanian glauconitic conglomerate at the base of the Mobschatz Formation (depositional sequence DS Ce 5) in the Dresden area which is, in terms of lithofacies and general sequence stratigraphic position, almost identical to the older Oberau Conglomerate (Fig. 9). Furthermore, the up-section decrease in glaucony content above the basal conglomerates accompanied by decreasing grain size and increasing carbonate content suggest an increasing distance of the glauconitic zone (and depocenter) during deepening of the depositional environment (TST). When simply applying Walther’s law of facies to the transgressive successions of the Mobschatz Formation, a conglomeratic-glauconitic to sandy-glauconitic nearshore facies zone is distally followed by poorly to nonglauconitic marly-calcareous offshore facies (see also Berensmeier et al. 2018a, b for a similar setting in the Münsterland Cretaceous Basin). The intercalation of sharp-based, parallel-laminated or hummocky cross-stratified glauconitic sandstones in the lower part of the transgressive cycles, representing classic tempestites that absorbed their sediments during a storm event in the coastal zone and transported it basinward with a bottom current (e.g., Seilacher and Aigner 1991; Myrow and Southard 1996), gives further evidence for the nearshore origin of the green grains. Their up-section decrease during the transgressive systems tracts also demonstrates that maxima of authochthonous glaucony in depositional sequences cannot uncritically be used to identify maximum flooding surfaces (Amorosi 1995; Udgata 2007; Amorosi et al. 2012) because other factors than solely condensation, such as the geochemical environment and suitable substrates, similarly impact the glauconitization process.

In contrast to the (upper) Mobschatz Formation, the transgressive strata at the base of the lower Upper Cenomanian Oberhäslich Formation (depositional sequence DS Ce 5) are only faintly glauconitic (GFT-7), yielding light-green, poorly evolved glaucony grains, and the middle and upper parts are largely glaucony-free (Figs. 3c, d, 9; Geinitz 1850 already noted that at Rippien and Welschufe, close to the drilling sites of cores HG 6512 and 6513, the basal strata of the Oberhäslich Formation are weakly glauconitic). Obviously, the relatively clean quartz arenites of this formation reflect an environment unsuitable for widespread glaucony formation, either due to constant reworking and/or the absence of organic matter and argillaceous material. According to Harder (1980), the presence of labile organic matter and its microbial degradation is critical in creating favorable redox conditions at the interface between oxidizing and slightly reducing zones suitable for glaucony formation (Meunier and El Albani 2007). In such micro-milieus, rapid degradation of organic matter and accompanying, in part microbiologically catalyzed dissolution of K-feldspar, Fe-(oxy)hydroxides,
detrital clay minerals and carbonates provided the Si, Al, Ca, Mg, K and Fe ions that are required for the Fe(III)-smectite-to-glauconite reaction (Baldermann et al. 2017). It is worth noting that even in this relatively condensed position on the Eastern Ore Mountains, where depositional sequence DS Ce 5 attains a thickness of only six metres, the maximum flooding zone is completely devoid of glaucony (Figs. 3c, d, 9), again suggesting that sediment starvation had little or no impact on the glauconitization process.

Locally developed, commonly thin glauconitic strata at the base of the upper Upper Cenomanian Dölzschen Formation correspond in lithofacies and sequence stratigraphic position to the ones found at the bases of the depositional sequences formed by the lower and upper Mobschatz Formation (DS Ce 4 and 5; Fig. 10). Tröger (1956) described the stratigraphic occurrence of glaucony in this stratigraphic interval from the Plauenscher Grund in Dresden, a submerged basement uplift, in considerable detail: the glaucony content reached its maximum in the basal conglomerate of the Dölzschen Formation, tracing the course of the plenus Transgression with its up-section decrease into the overlying Plänner strata. Of much greater interest is, however, the new observation of the massive development of glaucony in the Pennrich Formation, the proximal sandy equivalent of the Dölzschen Formation, at core Nasser Grund. Both formations constitute the latest Cenomanian TST of depositional sequence DS Ce-Tu 1 which culminated in a global earliest Turonian maximum flooding zone regionally reflected by the fine-grained marker bed of the Lohmgrund Horizon (e.g., Janetschke and Wilmsen 2014; Wilmsen et al. 2019; Niebuhr et al. 2020), corresponding in stratigraphic position to maximum flooding surface K140 of Sharland et al. (2001) and the Cretaceous all-time peak in the curve of Haq (2014).

At core Nasser Grund, the Pennrich Formation rests unconformably with a glauconitic basal conglomerate (GFT-1b) on the Oberhäslich Formation. Up-section, the formation consists of four stacked retro- to progradational sub-cycles (P1–P4) that form a high-frequency sequence, comprising ca. 405 kyr, that has also been identified in the Danubian Cretaceous Basin on the opposite side of the Mid-European Island (Richardt et al. 2013). The four cycles thus most likely correspond to short-eccentricity cycles (ca. 100 kyr) that have been identified in the corresponding stratigraphic interval of other sections (M. geslinianum to N. juddii zones) by time series analyses of independent data sets (e.g., stable carbon isotopes: Voigt et al. 2008; Wendler et al. 2014). The four to five parasequences in each of the sub-cycles P1 to P4 (Fig. 4) are thus interpreted to reflect the precession signal (ca. 21 kyr) and their bundling into the sub-cycles P1–P4 the precession-eccentricity syndrome (PES, Fischer et al. 2004; see Gale et al. 1999 for Cenomanian examples), characteristic of low and mid latitudes, where obliquity is erratically identified (Berger and Loutre 1994; Kietzmann and Paulin 2019). Interestingly, only the lower and upper parts of the Pennrich Formation are strongly glauconitic while glaucony is rare in its middle part (Fig. 4), again reflecting the affiliation of glauconitic lithofacies to most proximal settings. The selective diagenetic alteration of
glaucony grains in the upper part of cycle P3 below its terminal surface suggests subaerial exposure and concomitant oxidation of the green grains into iron hydroxides, supporting sea-level changes as a driver of sub-cycle formation. In general, the Pennrich Formation at Nasser Grund reflects a very shallow-marine, nearshore siliciclastic depositional system with tidal influences (e.g., tidal bundles), strong bioturbation, abundant argillaceous material, and common wood remains, indicating the vicinity of a densely vegetated land (i.e., the Westsudetic Island; Fig. 1b). According to Heimhofer et al. (2018), mid-latitudinal terrestrial plant ecosystems supported a rich and diverse flora during the Late Cenomanian to Early Turonian thermal maximum, and Niebuhr (2019) documented coastal lowlands with moisture-adapted vegetation for the early Late Cenomanian in Saxony. Geochemical data from the nearby Bohemian Cretaceous Basin foster the assumption of warm-humid conditions during the Late Cenomanian and the upper part of the Peruc-Korycany Formation is in places strongly glauconitic (Al-Bassam et al. 2019). The thickness of the Pennrich Formation (60 m) approximately corresponds to the accommodation generated during the latest Cenomanian (up to 50 m of eustatic sea-level rise: Voigt et al. 2006; Wilmsen et al. 2010; Richardt et al. 2013, plus regional subsidence), suggesting that the available space was constantly filled with sediment and the site Nasser Grund was possibly located close to a locus of fluvial input (the lithofacies does not support major longshore transport). It should be noted that the Pennrich Formation temporarily corresponds to the latest Cenomanian segment of the oceanic anoxic event (OAE) 2 (Schlanger and Jenkyns 1976) and that there may be a genetic relationship between glauconitic episodes and oceanic anoxic events (cf. Föllmi 2016; Al-Bassam et al. 2019; Bansal et al. 2019). An important factor in this respect is an accelerated hydrological cycle due to an increase in temperature (cf. Larson and Erba 1999): Lithium isotope data require the riverine flux to increase approximately by two to four times during OAE 2 (Pogge von Strandmann et al. 2013). The warm and wet climatic conditions will promote chemical weathering and continental discharge to the ocean, considerably impacting marine biological, sedimentary and geochemical systems, preferentially in shallow-marine epeiric and peri-continental settings.

Prerequisites for glaucony formation—myths and facts

Glaucaly formation (i.e., the syndepositional precipitation of 10-Å glauconitic smectite and smectitic glauconite) allegedly depends on a number of environmental factors and occurs only in fairly deep marine settings (outer shelf to upper slope), under cool temperatures (10–15 °C), low accumulation rates and on long timescales (10^5 to 10^6 years for mature pellets; e.g., Odin and Matter 1981; Odin 1988; Odin and Fullagar 1988; Banerjee et al. 2016). We cannot comment much on the depositional temperatures in the Cenomanian of Saxony apart from the fact that the palaeo-latitudeal position of the Elbtal Group (ca. 40°N; e.g., Vejbæk et al. 2010) and the biofacies (see comprehensive synopses in Niebuhr and Wilmsen 2014, 2016 as well as Föhlisch 1998 and Wilmsen 2017 for the Pennrich and Oberhäslich formations, respectively) suggest rather warm-temperate conditions (supported by the data from contemporaneous glauconitic strata in the Bohemian Cretaceous Basin; Al-Bassam et al. 2019). Furthermore, as outlined above in detail, the center of Cenomanian intrasequential glaucony formation and deposition in Saxony were shallow-water nearshore settings rather than the deeper offshore zone. Overall, the time-transgressive glaucony depocenter tracks the regional onlap patterns of the Elbtal Group, shifting southeast-wards during the Cenomanian 2nd-order sea-level rise (Fig. 10).

Another perception challenged by the observations from the Elbtal Group is the assumption of the long-term mode of formation of glaucony (10^3 to 10^6 years for mature pellets; e.g., Odin and Matter 1981). The temporal constraints of the sedimentary units of the lower Elbtal Group (Fig. 10) suggest that rather limited intervals of geological time are represented by the glaucony-bearing strata. The Oberauf Conglomerate, for example, corresponds to the early Middle Cenomanian primus Event (Wilmsen et al. 2019) that forms an early transgressive marker bed in the lower A. rhoto- 
magense ammonite zone, representing not more than 20 kyr (Gale 1995; Wilmsen 2007, 2012; Wilmsen et al. 2007). Also the relatively thick glauconitic succession in the lower and upper Pennrich Formation at core section Nasser Grund shows that not much time was needed for the glauconitization as the temporal framework (Fig. 10) indicates that only 400 kyr were available for the deposition of the complete lithological unit. Accepting the four sub-cycles of the Pennrich Formation as an expression of the short eccentricity cycle (ca. 100 kyr), the temporal framework of glaucony formation can be narrowed down even more (e.g., the upper two glaucony-rich parasequences in cycle P3 will comprise less than 50 kyr). The glaucony development in the Pennrich Formation also wipes-out another myth on the prerequisites for glaucony formation, i.e., prevalent low accumulation rates. In the lower sub-cycle P1, where both matrix glaucony and small-grained glauconitic grains are common, the accumulation rate is ~ 200 m/kyr (21 m/100 kyr) which is a rather high value. Correspondingly, in the maximum flooding interval of the underlying depositional sequence DS Ce 5 for which lowered accumulation rates can be assumed at
least for the siliciclastic Oberhäslich Formation, no glauconitization can be observed at all.

In a nutshell, the new stratigraphic, sedimentological, and mineralogical data from Saxony suggest that other factors than water depth, cool temperatures, long time scales, and sediment starvation promoted early Late Cretaceous glaucony formation.

Conclusions

The Cenomanian sedimentary strata of the Elbtal Group (Saxony, eastern Germany) reflect a major global sea-level rise and contain, in certain stratigraphic intervals, a green authigenic mineral in abundance. Based on detailed logging and sampling of new sections associated by careful stratigraphic-sedimentological, petrographical and mineralogical analyses, the environmental background and spatio-temporal patterns of glauconitic strata in Saxony are reconstructed and some general preconditions allegedly needed for glaucony formation are critically questioned.

Five new core sections of the lower Elbtal Group in Saxony were studied, following a transect from Meißen in the northwest to Bad Schandau in the southeast. The Middle–Upper Cenomanian succession comprises the marly Mobschatz and Dölzschen formations, reflecting the offshore facies zone of the Saxonian Cretaceous Basin, while the Oberhäslich and Pennrich formations represent contemporaneous nearshore environments. The XRD analyses of green grains extracted from selected samples revealed that the constituting green mineral is in any case glaucony, i.e., 10-Å glauconitic mineral. Based on field observations as well as on the careful evaluation of litho- and microfacies, the Cenomanian glauconitic strata in Saxony have been grouped into 12 facies types, broadly reflecting a proximal–distal gradient. The glauconitic facies types (GFTs) contain granular and matrix glaucony that can be characterized as autochthonous to parautochthonous (i.e., intrasequential) in origin. When observed in a stratigraphic succession, GFT-1 to GFT-12 commonly occur superimposed in transgressive cycles starting with the glauconitic basal conglomerates (GFT-1). Up-section, glauconitic sandstones and/or sandy glauconitites grading into bioturbated, marly glauconitic sandstone (GFT-2–7) follow. Fine-grained, bioturbated, argillaceous glauconitic sandstones, glauconitic argillaceous marls and marlstones, and glauconitic calcareous nodules (GFT-9 and -12) continue the retrogradational fining-upward trend; graded glauconitic tempestites (GFT-8) predominantly occur in the lower part of the transgressive cycles. The vertical facies succession with the upwards decreasing glaucony content clearly indicates that the center of production and deposition of glaucony in the Cenomanian of Saxony was the nearshore zone, contrasting to the deeper marine offshore modus of recent glaucony formation and highlighting the “dilemma of ancient nearshore glaucony”. Overall, the time-transgressive glaucony depocenter tracks the regional onlap patterns of the Elbtal Group, shifting southeast-wards during the Cenomanian 2nd-order sea-level rise.

Furthermore, of great importance is the substantial development of glaucony in the uppermost Cenomanian Pennrich Formation, temporally corresponding to the Late Cenomanian interval of the oceanic anoxic event (OAE) 2. At the studied site, the formation reflects a shallow-marine, nearshore siliciclastic depositional system with tidal influences, abundant argillaceous material, and common wood remains, indicating the vicinity of a densely vegetated hinterland. The relatively large thickness (60 m) deposited in a relatively short period of time (ca. 400 kyr) signifies a constant filling of accommodation under wet, warm-temperate conditions. Temporal constraints based on sedimentary cycles reflecting the precession-eccentricity syndrome suggest that glaucony development occurred during the deposition of the Pennrich Formation despite high accumulation rates and on rather short-term time scales. Our new stratigraphic-sedimentological and mineralogical data thus indicate that environmental factors such as cool temperatures, great water depth, long time scales and sediment starvation had little or no impact on glaucony formation during the Cenomanian in Saxony, suggesting that the determining factors of early Late Cretaceous glaucony fundamentally differed from recent conditions and revealing certain limitations of the uniformitarian approach.

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