Biostratigraphy and sequence stratigraphy of the Toarcian Ludwigskanal section (Franconian Alb, Southern Germany)

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Abstract

Extensive construction work at the canal cutting of the Ludwigskanal near Dörlbach, Franconian Alb, provided the opportunity to re-investigate a scientific-historical and biostratigraphically important reference section of the South-German Toarcian. The 16 m thick section, described bed by bed with respect to lithology and macrofossils, starts within the Upper Pliensbachian Amaltheenton Formation, covers the Toarcian Posidonienschiefer and Jurensismergel Formation, and ends in basal parts of the Opalinuston Formation. Carbonate contents are high in the Posidonienschiefer and successively decline within the Jurensismergel to basal parts of the Opalinuston. The high carbonate contents in the Posidonienschiefer are associated with comparatively low organic carbon contents. However, organic carbon contents normalized to the silicate fraction are similarly high if compared to other regions in Germany. Only the persistence of high organic carbon levels into middle parts of the Upper Toarcian differs from those of most regions in central Europe.

Ammonite biostratigraphy indicates a thickness of >9 m for the Upper Pliensbachian, 1.15–1.20 m for the Lower Toarcian, 5.04 m for the Upper Toarcian, and >0.5 m for the Lower Aalenian. Despite the low sediment thickness, all Toarcian ammonite zones and almost all subzones are present, except for major parts of the Tenuicostatum Zone and the Fallaciosum Subzone.

On the basis of discontinuities, condensed beds, and correlations with neighbouring sections in Southern Germany, a sequence stratigraphic interpretation is proposed for the Toarcian of this region: (i) The Posidonienschiefer Formation corresponds to one 3rd order T-R sequence, from the top of the Hawskerense Subzone to a fucoid bed at the top of the Variabilis Subzone, with a maximum flooding surface at the top of the Falciferum Zone. (ii) The Jurensismergel Formation exhibits two 3rd order T-R sequences: The first ranges from the basis of the Illustris Subzone (i.e., the Intra-Variabilis-Discontinuity) to the top of the Thouarsense Zone, with a maximum flooding surface within the Thouarsense Zone. The “belemnite battlefield” reflects a transgressive “ravinement surface” within the first Jurensismergel Sequence, not a maximum regression surface at its basis. The second sequence extents from the erosive basis of the Dispansum Zone to the top of the Aalensis Subzone, with a maximum flooding surface at the Pseudoradiosa-Aalensis Zone boundary. Finally, the Opalinuston starts with a new sequence at the basis of the Torulosum Subzone. Transgressive system tracts of these 3rd order T-R sequences are commonly phosphoritic, while some regressive system tracts show pyrite preservation of ammonites. The maximum regression surfaces at the basis of the Toarcian and within the Variabilis Zone reflect a significant submarine erosion and relief formation by seawater currents, while this effect is less pronounced at the basis of the Dispansum Zone and basis of the Torulosum Subzone (i.e., the boundary Jurensismergel-Opalinuston Formation).

Kurzfassung

Umfangreiche Bauarbeiten am Kanaleinschnitt des Ludwigskanals bei Dörlbach auf der Fränkischen Alb boten die Gelegenheit ein wissenschaftlich-historisch und biostratigraphisch wichtiges Referenzprofil des süddeutschen Toarciums neu zu untersuchen. Das 16 m mächtige Profil, dessen Lithologie und Makrofossilien Schicht für Schicht beschrieben werden, beginnt innerhalb der Amaltheenton-Formation des Oberpliensbachiums, umfasst die Posidonienschiefer- und Jurensismergel-Formationen des Toarciums und endet mit basalen Teilen der Opalinuston-Formation. Die Karbonatgehalte sind im Posidonienschiefer hoch und nehmen innerhalb des Jure-
sissiomergel successively to basa Teile of Opalinuston-Formation ab. The hohen Karbonatgehalte im Posidonienschiefer sind mit vergleichsweise niedrigen organischen Kohlenstoffgehalten verbunden. Die auf die Silicafraction normierten organischen Kohlenstoffgehalte sind jedoch im Vergleich zu anderen Regionen in Deutschland ähnlich hoch. Lediglich die anhaltend hohen organischen Kohlenstoffgehalte bis in den mittleren Teil des Obertoraciums unterscheiden sich von denen der meisten Regionen Mitteleuropas.

Biostratigraphisch verwertbare Ammoniten-Funde belegen eine Mächtigkeit von >9 m für das Obere Pliensbachium, 1.15–1.20 m für das Untere Toarcium, 5.04 m für das Obere Toarcium, und >0.5 m für das Untere Aalenium. Trotz der geringen Sedimentmächtigkeiten sind alle Ammoniten-Zonen und nahezu alle Subzonen nachweisbar, mit Ausnahme großer Teile der Tenuicostatum-Zone und der Fallaciosum-Subzone.

A Auf Grundlage von Diskontinuitäten, kondensierten Horizonten und Korrelationen mit Nachbarprofilen in Süddeutschland wird eine sequenzstratigraphische Interpretation für das Toarcium dieser Region entwickelt: (i) Die Posidonienschiefer-Formation entspricht einer Sequenz dritter Ordnung, vom Top der Hawskerense-Subzone bis zu einem Fucoidenhorizont am Top der Variabilis-Subzone, mit einer maximalen Überflutung am Top der Falciferum-Zone. (ii) Die Jurensismergel-Formation weiß zwei Sequenzen dritter Ordnung auf: Die erste reicht von der Basis der Illustris-Subzone (d.h. der Intra-Variabilis-Diskontinuität) bis zum Top der Thouarsense-Zone. Das „Bekanntschalcenfeld“ spiegelt einen transgressiven „Ausschüttungshorizont“ innerhalb der ersten Jurensismergel-Sequenz wider, keinen Meeresspiegelstabilisierung auf ihrer Basis. Die zweite Sequenz reicht von der erosiven Basis der Dispansum-Zone bis zum Top der Aalenische-Subzone, mit einer maximalen Überflutung an der Grenze Pseudoradiosa-Aaensis Zone. Die Opalinuston-Formation beginnt schließlich mit einer neuen Sequenz an der Basis der Torulosum-Subzone. Transgressive Phasen dieser Sequenzen dritter Ordnung sind häufig phosphoritisch ausgebildet, während regressive Phasen eine Pyritmächtigkeit von Ammoniten aufzeigen. Die Meeresspiegelstabilisierung nahe der Basis des Toraciums und innerhalb der Variabilis-Zone sind mit einer deutlichen submarinen Erosion und Reliefbildung durchgrundberührende Meeresströmungen verbunden. Dieser Effekt ist an der Basis der Dispansum-Zone und Torulosum-Subzone (d.h. der Formationsgrenze Jurensismergel-Opalinuston) weniger stark ausgeprägt.

Keywords
Ammonoidea, Jurensismergel, Lower Jurassic, Posidonienschiefer, sealevel changes, Southern Germany, stratigraphy

Schlüsselwörter
Ammonoidea, Jurensismergel, Unterer Jura, Posidonienschiefer, Meeresspiegel-Schwankungen, Südostdeutschland, Stratigraphie

Introduction

The Franconian Alb is a classical region of Jurassic geosciences in Europe, and specifically the area of Altdorf SE of Nürnberg has been of great importance in the early times of palaeontology (von Freyberg 1958a, b, c, 1972; Schmidt-Kaler 1974; Mayr 1995; Kursawe 1995, 1996; Mäuser 2001). Indeed, the construction of the Ludwigs-kanal cutting at Dörlich south of Altdorf (Fig. 1) lead 1840–1841 to the first large-scale temporary exposure of the Schwarzjura-Group in Southern Germany and corresponding fossil discoveries such as one of the worldwide first finding of a large, 1.6 m long, Temnodontosaurus skull (von Freyberg 1972). Furthermore, the Ludwigskanal outcrop delivered many invertebrate type fossils, among them a number of ammonoids, described in the monographs of Quenstedt (1845–1849, 1851–1852, 1856–1858, 1865– 1866, 1872–1875, 1876, 1881–1884, 1882–1885a, b).

However, the only contemporary description of the exposed strata was given by Beyschlag (1841), and it took over eight decades until more details on the section were provided by Reuter (1927), Kolb (1964) and Urichs (1971), all of them focussing on the Posidonienschiefer Formation. Despite these previous descriptions, and despite that the sediment succession of the Schwarzjura Group in this region is generally well known (Reuter 1927; Meyer and Schmidt-Kaler 1996; Bloos et al. 2005), a number of crucial stratigraphic details are subject to controversial views and remained unclear to date. Above all, this applies to the extent and position of discontinuities and condensed beds. Consequently, no sequence stratigraphic interpretation of the Toarcian has been suggested for this region, except for the Posidonienschiefer (Röhl and Schmid-Röhl 2005).

Slope failure at the Ludwigs-kanal cutting near Dörlich and following extensive construction activities re-exposed the section in 2010–2012, allowing a re-investigation of the complete succession from the middle part of the Amaltheen-ton, through the Posidonienschiefer and Jurensismergel, to the basis of the Opalinuston Formation (Fig. 2A, B). An overview and preliminary description of the new exposure was already given in Arp et al. (2014). Gastropods of the Amaltheen-ton were described by Gründel and Nützel (2015).

The aim of the present study is to provide a detailed description of the lithologic succession and its macrofossils.
The high-resolution biostratigraphy and sequence stratigraphy may form a basis for further investigations on seawater temperatures ($\delta^{18}O$ of low-Mg calcite skeletons), seawater currents, sea-level changes, and causes for the persistence of the Toarcian Oceanic Anoxic Event (T-OAE; Jenkyns 1988) in the eastern part of the NW European Epicontinental Seaway. The present study focusses on the description and stratigraphic interpretation of this section.

Location and geological overview

The Ludwigskanal cutting is located in Southern Germany, Bavaria, approximately 20 km ESE of Nürnberg (Fig. 1) in the western foreland of the middle Franconian Alb. The village Dörlbach lies 1 km W of the cutting, while Altdorf/Mfr. is located 3 km N of it. The coordinates of the section, located on the topographic map 1:25000, sheet 6634 Altdorf b. Nürnberg, are 49°21.238938N, 11°21.534298E. The region is part of the South German Scarplands (Petterek and Schröder 2010 and references therein), and the escarpment of the Franconian Alb, i.e., the edge of the Upper Jurassic limestone plateau, is located approximately 5 km E of the investigated section (Schmidt-Kaler 1974).

Geologically, the deep subsurface of the region is formed by high-grade metamorphics and plutonites of the Variscan basement (Moldanubian gneiss and granite). These basement rocks are overlain by a Mesozoic cover sequence starting with Triassic fluvial coarse siliciclastics of the Buntsandstein (63 m), Muschelkalk (45 m) and Keuper Group (270 m) (drilling Eschertshofen: Salger and Schmid 1982). After a stratigraphic gap comprising the Rhaetian, the Lower Jurassic Schwarzjura Group (47–69 m) starts with fluvial arkoses of the Bayreuth Formation, followed by marine near-shore sandstones of the Gryphaeensandstein Formation, condensed dolomitic limestones of the Numismalismergel Formation, monotonous claystones of the Amaltheenton Formation, condensed bituminous limestones and shales of the Posidonienschiefer Formation, and finally fossiliferous marls of the Jurensismergel Formation (Schmidt-Kaler 1974; Salger and Schmid 1982; Fig. 3). The Middle Jurassic Braunjura Group (125 m) is composed of marine, monotonous claystones (Opalinuston Formation), condensed bituminous limestones and shales of the Posidonienschiefer Formation, and finally fossiliferous marls of the Jurensismergel Formation (Schmidt-Kaler 1974; Salger and Schmid 1982; Fig. 3). The Middle Jurassic Braunjura Group (125 m) is composed of marine, monotonous claystones (Opalinuston Formation), iron-ore-bearing sandstones (Eisensandstein Formation) and a condensed, highly fossiliferous succession of iron-oolites and glauconitic siltstones (Sengenthal Formation). Up to 70 m of the Upper Jurassic Weißjura Group are preserved.
in the Altdorf region, with bedded marine limestones and sponge-microbialite mounds, some of them dolomitized (Schmidt-Kaler 1974). Subaerial exposure, erosion and karstification during Cretaceous and Tertiary times led to the present-day landscape (Wagner 1960; Hofbauer 2001; Peterek and Schröder 2010).

**Material and methods**

Fieldwork and sampling was carried out on 16 days between September 2010 and August 2014. Lithological descriptions are based on field observation and binocular observations on hand specimens, supplemented by 21 thin sections between 5 × 7.5 cm and 7.5 × 10 cm in size, and about 80 µm thick.

Total carbon (C\text{tot}), nitrogen (N\text{tot}), and sulfur (S\text{tot}) of bulk rock samples were analysed with a Euro EA 3000 Elemental Analyser (HEKAtech, Wegberg, Germany) applying 2,5-bis(5-tertbenzoxazol-2-yl)thiophene (BBOT) and atropine sulfate monohydrate (IVA Analysetechnik, Meerbusch, Germany) as reference material. Organic and carbonate carbon (C\text{org}, C\text{carb}) contents were determined by a LECO RC612 (Leco, St. Joseph, MI, USA) multi-phase carbon and water analyser. For calibration, Leco synthetic carbon (1 and 4.98 carbon %) and Leco calcium carbonate (12 carbon %) standards were used. All analyses were performed as duplicates. Analytical accuracy of all analyses was bet-

**Figure 2.** Field images of the Ludwigskanal section and ammonites. **A.** Western section of the canal cutting, showing basal parts of the exposure, from the "Delta-Fossil Bed" to the basis of the Posidonienschiefer Formation. **B.** Eastern section of the canal cutting, showing the Amaltheenton, Posidonienschiefer, Jurensismergel, and basal parts of the Opalinuston Formation. **C.** Harpoceras falciferum (Sowerby), "Falciferum Shale", bed 10, field image (specimen not recovered). **D.** Polished section of rock sample, from "Fucoid Bed" (bed 17), basal marl of Jurensismergel (bed 18) and "Belemnite Battlefield" (bed 19) to the "Main Phosphorite Bed" (bed 20).
Figure 3. Overview of the Lower Jurassic Schwarzjura Group, Drilling Dörnbach D2 (top ground surface 436 m a.s.l., 49°21.679543N, 11°21.797843E; topographic map sheet 6634 Altdorf b. Nürnberg; unpublished drilling report), ca. 750 m N of the Ludwigskanal/Dörnbach section. For legend see Fig. 7.
ter than 3%. The carbonate-free fraction was calculated from the total weight minus the CaCO₃ and C_eq content.

Biostratigraphy is based on approximately 425 determinable ammonites that were recovered in situ. Few additional ammonites recovered by private fossil collectors were taken into account. Ammonite determinations follow the systematic descriptions in Howarth (1958, 1978, 1992), Gabilly (1976a, b), Schulbert (2001a), Rulleau (2007), Hoffmann (2010, 2015), Arp (2010), and Di Cenzo and Weis (2020).

Repository: The material is stored in the Museum and Collection of the Geoscience Centre, University of Göttingen, under the numbers GZG.INV.45641–GZG.INV.45644 and GZG.INV.70496–GZG.INV.70650.

Data Availability Statement: All data used in this publication are stored on the Göttingen Research Online Data repository (https://doi.org/10.25625/8PLFNS).

Figure captions: unless otherwise noted, all specimens are coated by ammonium chloride prior to photography. Abbreviations: diameter (d), diameter of penultimate half whorl (di), umbilical width (u), whorl height (wh), whorl breadth (wb), primary ribs per half whorl (rb/2).

Results

Description of the section

Informal bed names are given in quotation marks. From bottom to top:

Amaltheenton Formation:

Bed 1: >100 cm bluish-grey, well bedded claystone;
Bed 2: 0–15 cm "Septaria Bed": grey marlstone concretions with mm-thick, calcite-cemented shrinkage cracks;
Bed 3: 25 cm bluish-grey, well bedded claystone with scattered cm-sized septarian concretions; ammonoids: at the top one juvenile *Pleuroceras solare* (Phillips);
Bed 4: 10 cm "Delta-Fossil Bed": bluish-grey, fissile, calcareous claystone to argillaceous marl with abundant ammonoids, belemnites, echinoderm remains and bivalves; lower part of the bed with reworked bluish-grey marlstone concretions with borings and serpulid tubes; ammonoids: *Pleuroceras spinatum* (Brugièrè); *Amaltheus* sp. (juvenile), *Pleuroceras solare* (Phillips) (within reworked concretions; Fig. 10: 1), *Pleuroceras solare var. solitarius* (Simpson) (within reworked concretions; Fig. 10: 2), *Amaptoroceras ferrugineum* (Simpson) (within reworked concretions; Fig. 10: 2); other fossils: *Passaloteuthis* sp., *Pseudopecten velatus* (Goldfuss), *Pseudomytiloides* sp., *Nicaniella pumila* (Sowerby), *Harpax spinosus* (Sowerby), *Mactromya* sp., *Ryderia doris* (d’Orbigny), *Pseudolimnea* sp., *Palaeonello elliptica* (Goldfuss), *Oxytoma inaequivalvis* (Sowerby), *Terquemia arieti* (Quenstedt), *Palmoxytoma cygnipes* (Young & Bird), *Pleurotomaria amalthei* Quenstedt, *Laeviconus subimbricatus* (Koch & Dunker), *Levipleura blainvillei* (von Münster), rhynchonellid brachiopods, *Amaltheocrinus* sp., echinid spines, drift wood; bluish-grey, slightly meous, fissile claystone with scattered small bivalves; 15 and 75 cm below top layers of flat-lenticular, grey siderite nodules; ammonoids: *Pleuroceras spinatum* (Brugièrè) (0.8 m, 1.5 m, 2.0 m, 3.0 m, 5.5 m, 7.25 m and 7.5 m below top; Fig. 10: 3, 4); other fossils: *Palaeonello* sp.;
Bed 6: 0–1 cm reworked flat concretions composed of bluish-grey pyrite-rich argillaceous limestone, with corroded surfaces;

Posidonienschiefer Formation:

Bed 5: 800 cm

Bed 7: 5–15 cm "Laibstein I": dark grey, laminated calcareous marl with coarse shell debris and one 15 cm-sized limestone concretion composed of laminated bituminous pellet packstone, with intercalated layers of coarse shell debris and fish scales; basis with reworked flat concretions from the Amaltheenton; ammonoids: *Tiltoniceras antiquum* (Wright) (1–2 cm above basis; and one juvenile specimen in middle part; Fig. 10: 5, 6), middle and upper part with *Cleviceras exaratum* (Young & Bird) (Fig. 10: 10), *Hildaites murleyi* (Moxon) (Fig. 10: 8, 9), and *Lytoceras ceratophagum* (Quenstedt) (Fig. 10: 7); other fossils: *Pseudomytiloides dubius* (Sowerby), *Nicaniella* sp., scattered Coelodiscus minutus (Schühber in Zieten);
Bed 8: 15 cm "Laibstein II": dark grey, laminated bituminous limestone concretions (pellet packstone) up to 50 cm width, with abundant mm-sized holoplanktonic gastropods; ammonoids: *Cleviceras elegans* (Sowerby) (Fig. 11: 6), rare *Cleviceras cf. exaratum* (Young & Bird), *Phylloceras heterophyllum* (Sowerby) (Fig. 11: 5), *Harpoceras serpentinum*
(Schlotheim) (Fig. 11: 1), "Peronoceras" desplacei (d’Orbigny) (Fig. 11: 4), Noticoeloceras crossoideos (Simpson), Dactylioceras semiannulatum Howarth (Fig. 11: 7), Dactylioceras anguinum (Reinecke) (Fig. 11: 3); other fossils: Meleagrinella cf. substrata (von Münster), Pseudomytiloides dubius (Sowerby), Goniomyra rhombifera (Goldfuss), Camptonectes sublatus (von Münster in Goldfuss), Pleuromya sp., abundant Coelodiscus minutus (Schübler in Zieten);

Bed 9: 5–6 cm
"Fish Scale Bed": dark grey, bituminous argillaceous fissile limestone composed of mollusc shell fragments and fish scales, with abundant belemnites; ammonoids: Dactylioceras sp. (upper bedding plane), Clevericera cf. elegans. (lower bedding plane); other fossils: Meleagrinella cf. substrata (von Münster), Pseudomytiloides dubius (Sowerby), belemnites, ichthyosaurus vertebrae;

Bed 10: 10 cm
"Falciferum Shale": dark grey, laminated, bituminous marl; lower part with one dark grey, 8 × 12-cm-sized, poorly laminated bituminous limestone concretion (pellet packstone) with mollusk shell debris, few phosphatic vertebrate microfragments and abundant small Dactylioceras shells (spar filled); ammonoids: Harpoceras falciiferum (Sowerby) (middle part; Fig. 2C), Phylloceras heterophyllum (Sowerby); other fossils: Pseudomytiloides dubius (Sowerby) abundant on bedding planes, drift wood;

Bed 11: 3–4 cm
grey, bituminous argillaceous fissile limestone with abundant fish scale and shell debris; fossils: few large (2-cm-sized) Meleagrinella cf. substrata (von Münster);

Bed 12: 25 cm
"Dactylioceras Bed": grey, bituminous limestone consisting of densely packed Meleagrinella shells and shell fragments, faecal pellets, and scarce phosphatic vertebrate microfragments; abundant sparite and micrite filled casts of Dactylioceras; relictic cross-stratification in the lower part of the bed; ammonoids: Dactylioceras athleticum (Simpson) (abundant throughout the bed; Fig. 12: 3), Dactylioceras cf. commune (Sowerby) (lower bedding plane; Fig. 12: 1), Hildoceras cf. lusitanicum Meister (lower bedding plane; Fig. 12:

Bed 13: 1–2 cm
grey, bituminous argillaceous limestone consisting of densely packed Meleagrinella shells and scattered phosphatic vertebrate microfragments; fossils: Meleagrinella substrata (von Münster);

Bed 14: 10–12 cm
"Monotis Bed": bituminous limestone (lumachelle) consisting of densely packed Meleagrinella shells, faecal pellets, and scarce phosphatic vertebrate microfragments; ammonoids: Dactylioceras cf. athleticum (Simpson); other fossils: Meleagrinella substrata (von Münster), Pseudomytiloides dubius (Sowerby);

Bed 15: 40 cm
"Bifrons Shale": dark-grey, bituminous marl, laminated; with scattered shell debris in layers, scattered phosphatic fish scale and bone microfragments, abundant belemnites 26 cm and 38 cm below top; ammonoids: Hildoceras semipolitum Buckman (2 cm, 17 cm, 18 cm, and 22 cm below top; Fig. 12: 4, 5), Pseudolioceras cf. lythense (Young & Bird) (20 cm below top), Phylloceras heterophyllum (Sowerby) (28 cm below top); other fossils: Pseudomytiloides dubius (Sowerby), Bositra buchi var. elongata (Goldfuss), rare Orbiculoidea papyracea (von Münster), Lenticulina sp., rare echinoderm fragments, belemnites;

Bed 16: 70 cm
"Variabilis Shale": dark-grey, laminated to well bedded; bituminous marl (lower 60 cm) to calcareous marl (top 10 cm) with scattered shell debris, rare phosphatic fish scale and bone microfragments; ammonoids compressed or as pyrite casts preserved, scattered pyrite nodules up to 3 cm in size; light-grey Chondrites horizons 5–6 cm and 18–19 cm below top; ammonoids: Denckmannia cf. rude (Simpson) (1 cm below top), Haugia jugosa (Sowerby) (3 cm below top; Fig. 12: 9), Haugia sp. (7 cm and 70 cm below top), Haugia variabilis (d’Orbigny) (13 cm below top; Fig. 12: 8), Pseudolioceras compactile (Simpson) (13 cm, 19 cm, 21 cm, 24 cm, 25 cm, 37 cm, and 65 cm below top; Fig. 12: 10, 11), Pseudolioceras sp. (23 cm and 25 cm below top), Catacoceloceras raquinianum (d’Orbigny) (3 cm, 7 cm, 13 cm, 15 cm, 19 cm, 22 cm, 37 cm, 38 cm, and 53 cm below top; Fig.
Bed 19: 6 cm "Belemnite Battlefield": grey, bituminous calcareous marl with abundant bivalve shell debris (Propeamussium), belemnite accumulation, and reworked phosphorite nodules; at the basis reworked plate-like, bored white-grey phosphorite nodules up to 2.5 × 5 × 10 cm in size; thin burrows; ammonoids: Lytoceras cf. cornucopia (Young & Bird), Pseudogrammoceras sp., lower bedding plane with Catacoeloceras raquinianum (d’Orbigny) (Fig. 13: 6); other fossils: Dactyloteuthis irregularis (Schlotheim); ammonoids: Pseudo-grammoceras dispansum (Lycett) (12–20 cm and 20–25 cm below top; Fig. 14: 5, 8), Pseudolioceras cf. boulbiense (Young & Bird) (12–20 cm below top; Fig. 14: 3), Alcocolytoceras rugiferum (Pompeckj) (12–20 cm, 20–25 cm, and 29 cm below top; Fig. 14: 2, 4), Hammatoceras insign (Schübler in Zieten) (15 cm below top; Fig. 15: 10, 13: 2, 3), Catacoeloceras sp. (68 cm below top), Murodactylites mucronatus (d’Orbigny) (43 cm below top; Fig. 12: 7, 8), Lytoceras sp. (5 cm below top), Lytoceras cf. cornucopia (Young & Bird) (13 cm below top), Lytoceras sublineatum (Oppel) (26 cm and 38 cm below top; Fig. 13: 1), Hildoceras cf. semipolitum Buckman (70 cm below top); other fossils: Salpingoteuthis sp. (15 cm below top), further belemnites, Bositra buchi var. elongata (Goldfuss), Pseudomytiloides dubius (Sowerby), Propeamussium pumilum (Lamarck), Grammatodon sp., Lenticulina sp. (rare);

Bed 20: 6–7 cm "Main Phosphorite Bed": grey, marl to calcareous marl, poorly bedded, with abundant bivalve shell debris (Propeamussium) with white-grey phosphorite nodules up to 1 × 3 × 6 cm and abundant belemnites; Chondrites burrows; ammonoids: Lytoceras cornucopia (Young & Bird) (Fig. 13: 8), Pseudogrammoceras sp., Denckmannia rude (Simpson) (Fig. 13: 9), Oesperocioeras bicaninatum (Zieten) (Fig. 13: 7); other fossils: Dactyloteuthis irregularis (Schlotheim), Chlamys textoria (Schlotheim), Camptonectes cf. subulatus (Münster);

Bed 21: 14–15 cm "Toarcensis Shale": dark grey, well bedded, bituminous marl transected by numerous small branching burrows (Chondrites); abundant compressed ammonoids (solely Grammoceras) and bivalves (solely Pseudomytiloides); ammonoids: Grammoceras thouarsense (d’Orbigny) (Fig. 14: 1) throughout the bed; other fossils: Pseudomytiloides dubius (Sowerby), few belemnites;

Bed 22: 5 cm "Belemnite accumulation": grey, poorly stratified argillaceous marl full of belemnites (Dactyloteuthis); nubeculariid foraminifera on shell fragments and belemnites; one compressed Lytoceras shell fragment with stromatolitic crust at the top inside of the body chamber; one phosphorite nodule with microbialite-like corroded upper surface; locally small lenticular phosphorite nodules; basis with flat corroded phosphorites (11 × 7 × 1 cm in size) and double-sided-corroded belemnite rostra; ammonoids: Alloclytoceras cf. rugiferum (Pompeckj); other fossils: Liostrea erina (d’Orbigny) attached to belemnite rostra, Chladocrinus sp.;

Bed 23: 30 cm "Levesquei-Dispansum-Marl": grey, poorly bedded marl rich in nubeculariid foraminifera, shell debris, and with small phosphorite nodules; abundant mid-sized and large compressed ammonites (top 12 cm and at 20–25 cm below top); deformed phosphorite casts of smaller ammonoids, rare pyrite casts;

Jurensismergel Formation:

Bed 18: 5 cm grey, well bedded calcareous marl; ammonoids: Pseudogrammoceras subregale (Pinna) (Fig. 13: 4), Haugia cf. philippi (Simpson) (Fig. 13: 5); abundant Catacoeloceras raquinianum (d’Orbigny); Haugia cf. variabilis (d’Orbigny), Phylloceras heterophyl- lum (Sowerby), Lytoceras cf. cornucopia (Young & Bird); other fossils: Pseudomytiloides dubius (Sowerby), Camptonectes subulatus (Münster);
Bed 24: 95 cm

Bed 25: 2 cm

Bed 26: 50 cm

Bed 27: 5–10 cm

Bed 28: 80–85 cm

12), Hammatoceras sp. (20–25 cm below top), Dumortieria insiginisimilis (Brauns) (11 cm below top; Fig. 14: 6, 7), Dumortieria levaesquei (d’Orbigny) (6 cm and 9 cm below top; Fig. 14: 11, 13), Dumortieria radians (Reinecke) (6 cm below top), Dumortieria pseudoradiosa (Brancion) (4 cm below top; Fig. 14: 14), Dumortieria radiosa (Seebach) (4 cm below top), Dumortieria striatulocostata (Quenstedt) (4 cm below top), Dumortieria sp. (pyrite cast at 8 cm below top); other fossils: Chlamys textoria (Schlotheim), Camptonectes subulatus (Münster in Goldfuss), Entolium sp., Eopecten velatus (Goldfuss), Plagiostoma giganteum Sowerby, Pseudolimea sp., Pseudomytiloides sp., Nicaniella voltzi (Hoeninghaus in Roemer), Liostra erina (d’Orbigny), belemnites; grey, well bedded argillaceous marl to marl with abundant shell microdebris; lower 60 cm rich in nubeculariid foraminifera; lower 45 cm with small marcasite nodules; 40–45 cm below top accumulation of phosphorite nodules and ammonites, 70 cm below top accumulation of compressed ammonites; ammonoids: Paradumortieria cf. tectiforme Elmi & Caloo-Fortier (20 cm, 25 cm, 40–45 cm, and 50 cm below top; Fig. 15: 5), Dumortieria cf. kochi Benecke (40 cm below top; Fig. 15: 11), Dumortieria moorei (Lycett) (7 cm, 40 cm, and 54 cm below top; Fig. 15: 10), Dumortieria cf. moorei (Lycett) (5 cm and 40 cm below top), Dumortieria pseudoradiosa (Brancion) (40–45 cm and 70 cm below top), Dumortieria cf. pseudoradiosa (Brancion) (65 cm and 94 cm below top), Dumortieria radiosa (Seebach) (40–45 cm, 73 cm, and 75 cm below top; Fig. 14: 9), Dumortieria cf. radiosa (Seebach) (40–45 cm, 70 cm, and 75 cm below top); other fossils: Chlamys textoria (Schlotheim), Pseudomytiloides sp., belemnites; grey, poorly bedded, argillaceous marl with shell microdebris and abundant ammonites (pyrite casts and marcasite-veneered imprints), abundant belemnites, and small phosphorite nodules; ammonoids: Cotteswoldia aalensis (Zieten) (5 cm, 22 cm, 25 cm, 30 cm, and 35 cm below top), Cotteswoldia distans (Buckman) (35 cm below top), Cotteswoldia macra (Dumortier) (40 cm below top), Dumortieria cf. moorei (Lycett) (40 cm below top), Dumortieria costula (Reinecke) (30 cm below top; Fig. 15: 8), Dumortieria externicostata (Brancion) (30 cm below top; Fig. 15: 7), Pleurolytoceras wrighti (Buckman) (25 cm below top), Pleurolytoceras hircinum (Schlotheim) (35 cm below top), other fossils: Bositra suessi Oppel, belemnites; grey (unweathered) to yellowish-brown (weathered), well bedded, calcareous claystone with scattered small branching burrows (Chondrites), minor shell microdebris, very few nubeculariid foraminifera, and very few echinoderm bioclasts; abundant small pyrite casts of ammonites, especially near the basis of the bed; ammonoids: Pleydellia subcompta (Brancion), Pleydellia cf. subcompta (Brancion) (transitional form to C. macra), Pleurolytoceras wrighti (Buckman); other fossils: rhynchonellid brachiopode, belemnites; grey, well bedded, argillaceous marl rich in shell microdebris of Bositra suessi, with scattered small branching burrows (Chondrites), scarce nubeculariid foraminifera, small pyrite nodules and pyrite ammonite casts; Bositra suessi pavement 32 cm below top; Pleydellia subcompta (Brancion) (35 cm below top; Fig. 15: 12), Cotteswoldia aalensis (Zieten) (5 cm, 22 cm, 25 cm, 30 cm, and 35 cm below top), Cotteswoldia distans (Buckman) (35 cm below top), Cotteswoldia macra (Dumortier) (40 cm below top), Dumortieria cf. moorei (Lycett) (40 cm below top), Dumortieria costula (Reinecke) (30 cm below top; Fig. 15: 8), Dumortieria externicostata (Brancion) (30 cm below top; Fig. 15: 7), Pleurolytoceras wrighti (Buckman) (25 cm below top), Pleurolytoceras hircinum (Schlotheim) (35 cm below top), other fossils: Bositra suessi Oppel, belemnites; grey, well bedded, calcareous claystone in shell microdebris of Bositra suessi and nubeculariid foraminifera; with scattered small pyrite nodules and pyrite ammonite casts; at the top accumulation of small pyritic ammonites (embedded in various orientation); Bositra suessi pavement 50 cm below top; ammonoids: Pleydellia subcompta (Brancion) (1 cm below top), Pleydellia costulata (Zieten) (1 cm below top; Fig. 15: 13), Cotteswoldia aalensis (Zieten) (1 cm below top), Pseudolioceras bey-
Bed 30: 30 cm

grey, well bedded, marl to calcareous claystone rich in shell microdebris of *Bositra suessii* (Oppel) and nubeculariid foraminifera;

**Opalinuston Formation:**

Bed 31: 2 cm

grey (unweathered) to brownish-grey (weathered), poorly bedded calcareous claystone with abundant, partially aligned belemnites of the *Hastites* group;

Bed 32: 80 cm

grey, well bedded, calcareous claystone rich in shell microdebris of *Bositra suessii* (Oppel); at 50 cm below top rich in nubeculariid foraminifera;

Bed 33: 2–3 cm

grey (unweathered) to brownish-grey (weathered), poorly bedded calcareous claystone with few small phosphorite nodules, abundant belemnites and compressed ammonoids; one shell fragment of *Lytoceras* with a stromatolitic crust at the top inside of the body chamber; ammonoids: *Cotteswoldia lotharingica* (Branco) (Fig. 15: 15), *Pleydellia buckmani* Maubeuge (Fig. 15: 16), *Pleydellia cf. falcifer* Maubeuge (Fig. 15: 17), *Pleurotyloceras torulosum* (Schübler in Zieten) (Fig. 15: 14); other fossils: *Acrocoelites* sp., *Hastites subclavatus* (Voltz), *Thecocysthus macrurus* (Goldfuss), *Palaeonucula hammeri* (De france), *Nicaniella voltzii* (Hoenig haus in Roemer), *Chlamys textoria* (Schlotheim), *Pseudomytiloides* sp., *Sphenodus* sp. (tooth 4 mm);

Bed 34: >50 cm

grey (unweathered) to brownish-grey (weathered), well bedded clay;

**Carbonate and organic carbon contents**

The Amaltheenton Formation is characterized by low CaCO$_3$ contents (2.5–3.3 wt%) as well as low C$_{org}$ contents (0.8–1.0 wt%) (Table 1, Fig. 4).

The Posidonienschiefer Formation, however, shows a sudden and strong increase in CaCO$_3$ to 94 wt% at its basis, followed by consistently high values (73–98 wt%) in the lower part of the formation (i.e. limestone and argillaceous limestone), with only the Falciferum Shale showing a lower value (45 wt%). Higher parts of Posidonienschiefer exhibit marl equivalent values around 50–65 wt% CaCO$_3$, with only two intercalations of reduced CaCO$_3$ content (35 wt%) in the upper third (Table 1, Fig. 4). C$_{org}$ contents of the Posidonienschiefer vary between 0.3 and 2.0 wt% in limestone beds, and higher values up to 5.3 wt% in less CaCO$_3$-rich lithologies. The highest value (7.5 wt%) was measured in the Falciferum Shale. However, C$_{org}$ contents calculated for the carbonate-free rock fraction demonstrate a different trend: Very high contents characterize Laibstein I and II near basis of formation (i.e., bed 7 and 8, with up to 17.6 wt%), while fish scale debris bed 9 shows a slightly lower value (7.4 wt%). It follows a further maximum in the interval Falciferum Shale to Monotis Bed (up to 14.1 wt%). Higher parts of the formation finally show fluctuating C$_{org}$ contents (4.4–14.0 wt%), with two minima in top parts (1.5 and 1.8 wt%) (Table 1, Fig. 4).

CaCO$_3$ contents at the basis of the Jurensismergel Formation correspond to calcareous marl (65–71 wt%) and marl (44–53 wt%), then decrease to marls (37–62 wt%) and argillaceous marls (17–34 wt%). Near the top of the formation, one last bed of calcareous marl (66 wt%) is found. Increased C$_{org}$ values (3.0 and 4.3 wt%) were found near basis (bed 18, "Belemnite Battlefield", "Toarcensis Shale"), followed by low values of 1–2 wt% in middle and upper parts of the formation. Only two horizons, basis of bed 24 and bed 25, show slightly increased C$_{org}$ contents (2.5 and 2.8 wt%). Finally, the Opalinuston Formation revealed CaCO$_3$ contents only slightly lower than top parts of the Jurensismergel, and C$_{org}$ as low as in the Amaltheenton (Table 1, Fig. 4).

**Discussion**

**Lithostratigraphy**

The assignment of beds to specific formations of the Schwarzjura Group follows the definitions given in Bloos et al. (2005), Mönnig et al. (2015), and Nitsch et al. (2015), with only minor modifications.

1. The lower part of section, i.e. beds 1–6, represent the top 9 m of the Amaltheenton Formation (Figs 2A, 5), which shows a total thickness of 36 m at this location (Fig. 3). The formation is characterized by monotonous bluish-grey claystones with disseminated pyrite, low CaCO$_3$, and low C$_{org}$ contents.

2. The Posidonienschiefer Formation (Figs 2B, 4), with a total thickness of 1.85–1.90 m, is characterized by bituminous marls and limestones rich in fossils. The basis is drawn with the first bituminous and calcareous bed, i.e. "Laibstein I". The erosive discontinuity...
Table 1. Carbon (C_{tot}, C_{org}, C_{calc}) total sulphur (S_{tot}), and total nitrogen (N_{tot}) contents of sedimentary rocks of the Ludwigskanal section.

| Sample number | Formation         | Bed number | Section from–to [cm] | Lithology               | Remarks                                      | C_{org} mean [wt %] | C_{calc} mean [wt %] | CaCO_{3} calculated [wt %] | C_{tot} carbonate-free [wt %] | N_{tot} mean [wt %] | S_{tot} mean [wt %] | C_{calc} carbonate-free [wt %] |
|---------------|-------------------|------------|----------------------|-------------------------|-----------------------------------------------|--------------------|---------------------|-------------------------|-------------------------------|-------------------|-------------------|-----------------------------|
| Lud 72        | Opalinuston       | 34         | 639                  | calcareous clay–stone   |                                               | 3.23               | 0.33                | 2.90                    | 24.2                          | 0.44              | 0.035             | 0.013                       |
| Lud 14        | Opalinuston       | 27         | 405 to 410           | calcareous clay–stone   | Yellow Bed                                   | 3.62               | 1.07                | 2.55                    | 21.2                          | 1.4               | 0.07              | 0.05                        |
| Lud 15        | Jurensismergel    | 26         | 395 to 400           | calcareous clay–stone   |                                               | 3.31               | 0.85                | 2.46                    | 20.5                          | 1.1               | 0.05              | 0.05                        |
| Lud 16        | Jurensismergel    | 26         | 385 to 390           | calcareous clay–stone   |                                               | 4.14               | 1.17                | 2.97                    | 24.7                          | 1.6               | 0.06              | 0.05                        |
| Lud 17        | Jurensismergel    | 26         | 375 to 380           | argillaceous marl       | matrix of “Mactra Bed”                        | 4.57               | 1.29                | 3.28                    | 27.3                          | 1.8               | 0.07              | 0.12                        |
| Lud 18        | Jurensismergel    | 26         | 365 to 370           | argillaceous marl       |                                               | 4.34               | 0.92                | 3.42                    | 28.5                          | 1.3               | 0.05              | 0.05                        |
| Lud 19        | Jurensismergel    | 25         | 355 to 360           | bituminous marl         | matrix of “Mactra Bed”                        | 10.26              | 2.83                | 7.43                    | 61.9                          | 7.4               | 0.09              | 0.61                        |
| Lud 20        | Jurensismergel    | 24         | 345 to 350           | argillaceous marl       |                                               | 4.82               | 1.01                | 3.81                    | 31.7                          | 1.5               | 0.06              | 0.16                        |
| Lud 21        | Jurensismergel    | 24         | 335 to 340           | argillaceous marl       |                                               | 5.02               | 1.36                | 3.66                    | 20.5                          | 2.0               | 0.07              | 0.20                        |
| Lud 22        | Jurensismergel    | 24         | 325 to 330           | argillaceous marl       |                                               | 5.09               | 1.09                | 4.00                    | 33.3                          | 1.6               | 0.07              | 0.94                        |
| Lud 23        | Jurensismergel    | 24         | 315 to 320           | calcareous clay–stone   | rich in nubeculariid foraminifera             | 3.60               | 1.03                | 2.57                    | 21.4                          | 1.3               | 0.07              | 0.52                        |
| Lud 24        | Jurensismergel    | 24         | 305 to 310           | calcareous clay–stone   | rich in nubeculariid foraminifera             | 3.53               | 1.04                | 2.49                    | 20.7                          | 1.3               | 0.07              | 0.60                        |
| Lud 25        | Jurensismergel    | 24         | 295 to 300           | argillaceous marl       | rich in nubeculariid foraminifera             | 4.75               | 0.94                | 3.81                    | 31.7                          | 1.4               | 0.06              | 0.51                        |
| Lud 26        | Jurensismergel    | 24         | 285 to 290           | marl                    | rich in nubeculariid foraminifera             | 6.22               | 0.90                | 5.32                    | 44.3                          | 1.6               | 0.05              | 0.66                        |
| Lud 27        | Jurensismergel    | 24         | 275 to 280           | argillaceous marl       | rich in nubeculariid foraminifera             | 5.89               | 1.78                | 4.11                    | 34.2                          | 2.7               | 0.08              | 1.45                        |
| Lud 28        | Jurensismergel    | 24         | 265 to 270           | poorly bituminous, argillaceous marl           | rich in nubeculariid foraminifera             | 5.83               | 2.54                | 3.29                    | 27.4                          | 3.5               | 0.08              | 1.53                        |
| Lud 29        | Jurensismergel    | 23         | 255 to 260           | marl                    | rich in nubeculariid foraminifera             | 5.41               | 1.09                | 4.32                    | 36.0                          | 1.7               | 0.05              | 0.18                        |
| Lud 30        | Jurensismergel    | 23         | 245 to 250           | marl                    |                                               | 5.65               | 1.06                | 4.59                    | 38.2                          | 1.7               | 0.04              | 0.23                        |
| Sample number | Formation | Bed number | Section from-to [cm] | Lithology |
|---------------|-----------|------------|----------------------|-----------|
| Lud 31 | Jurensismergel | 23 | 235 to 240 | marl |
| Lud 32 | Jurensismergel | 23 | 225 to 230 | argilloseous marl |
| Lud 33 | Jurensismergel | 22 | 220 to 225 | argilloseous marl |
| Lud 34 | Jurensismergel | 21 | 205 to 220 | bituminous marl |
| Lud 35 | Jurensismergel | 20 | 198 to 205 | marl |
| Lud 36 | Jurensismergel | 19 | 195 to 198 | poorly bituminous, calcarceous marl |
| Lud 37 | Jurensismergel | 19 | 192 to 195 | bituminous marl |
| Lud 38 | Jurensismergel | 18 | 187 to 192 | poorly bituminous, calcarceous marl |
| Lud 39 | Posidonischen-schiefer | 17 | 185 to 187 | poorly bituminous marl |
| Lud 40 | Posidonischen-schiefer | 16 | 180 | bituminous, calcareous marl |
| Lud 41 | Posidonischen-schiefer | 16 | 179 | bituminous, calcareous marl |
| Lud 42 | Posidonischen-schiefer | 16 | 175 | bituminous, calcareous marl |
| Lud 43 | Posidonischen-schiefer | 16 | 165 | poorly bituminous, argilloseous marl |
| Lud 44 | Posidonischen-schiefer | 16 | 155 | bituminous marl |
| Lud 45 | Posidonischen-schiefer | 16 | 145 | bituminous marl |
| Lud 46 | Posidonischen-schiefer | 16 | 135 | bituminous marl |
| Lud 47 | Posidonischen-schiefer | 16 | 125 | bituminous marl |
| Lud 48 | Posidonischen-schiefer | 15 | 115 | bituminous marl |
| Lud 49 | Posidonischen-schiefer | 15 | 105 | bituminous marl |
| Lud 50 | Posidonischen-schiefer | 15 | 95 | bituminous marl |
| Lud 51 | Posidonischen-schiefer | 15 | 85 | bituminous marl |
| Lud 52 | Posidonischen-schiefer | 15 | 76 | bituminous marl |
| Lud 53 | Posidonischen-schiefer | 14 | 66 to 75 | poorly bituminous limestone |
| Lud 54 | Posidonischen-schiefer | 13 | 65 to 66 | poorly bituminous, argilloseous limestone |
| Lud 55 | Posidonischen-schiefer | 12 | 40 to 65 | poorly bituminous limestone |
| Lud 56 | Posidonischen-schiefer | 11 | 37 to 40 | poorly bituminous, argilloseous limestone |
| Lud 57 | Posidonischen-schiefer | 10 | 27 to 37 | bituminous marl |
| Lud 58 | Posidonischen-schiefer | 9 | 22 to 27 | poorly bituminous, argilloseous limestone |
| Lud 59 | Posidonischen-schiefer | 8 | 17 to 22 | poorly bituminous, argilloseous limestone |
| Lud 60 | Posidonischen-schiefer | 8 | 12 to 17 | poorly bituminous limestone |
| Lud 61 | Posidonischen-schiefer | 8 | 7 to 12 | poorly bituminous, argilloseous limestone |
| Lud 62 | Posidonischen-schiefer | 7 | 0 to 7 | poorly bituminous, calcarceous marl |
| Lud 63 | Posidonischen-schiefer | 7 | 5 to 7 | poorly bituminous, argilloseous limestone |
| Lud 64 | Posidonischen-schiefer | 7 | 2 to 5 | poorly bituminous limestone |
| Lud 65 | Posidonischen-schiefer | 7 | 0 to 2 | poorly bituminous, argilloseous limestone |
Figure 4. Lithology and lithostratigraphy of the Ludwigskanal section (top Amaltheenton to basis Opalinuston Formation) with CaCO$_3$ and organic carbon contents. For legend see Fig. 7.
Figure 5. Litho- and biostratigraphy of the upper Amaltheenton Formation, Upper Pliensbachian, exposed at the Ludwigskanal. For legend see Fig. 7.
at its basis is indicated by reworked concretions of the Amaltheenton. Accordingly, the basal alternation of marls, bituminous marls and Chondrites-rich beds, as seen in the Swabian Posidonienschiefer (Urlichs 1977a; Riegraf et al. 1984; Riegraf 1985a; Bloos et al. 2005), is absent in this region. While the total rock C\textsubscript{org} contents are clearly lower than in the Swabian sections (mean C\textsubscript{org} = 2.45 wt% at Ludwigskanal versus 6.77 wt% at Dotternhausen, for top Semicelatum to Bifrons Zones), C\textsubscript{org} contents of the carbonate-free fraction are almost identical (mean C\textsubscript{org} carbonate-free = 11.18 wt% at Ludwigskanal versus 12.22 wt% at Dotternhausen; Frimmel et al. 2004). Therefore, the comparatively low C\textsubscript{org} values at Ludwigskanal section reflect a "di-lution effect" by increased carbonate contents.

3. The Jurensismergel Formation (Figs 2B, 4), with a total thickness of 3.50 m, is formed by highly fossiliferous marls with phosphate (lower part) or pyrite nodules (higher part). Major parts of the formation show abundant nubeculariid foraminifera as a significant component of the sediment. Increased C\textsubscript{org} contents were only detected near the basis ("Belemnite Battlefield", "Toarcensis Shale") and in bed 25, a condensed bed in the middle of the formation. Carbonate contents are generally lower (predominantly argillaceous marls; Table 1), if compared to sections of the Swabian alb (e.g. Göppingen-Ursenwang and Asselfingen: marls and argillaceous limestone beds: Bruder 1968, his tab 4.).

The lower boundary of the Jurensismergel has previously been drawn at the top of the "Belemnite Battlefield": Urlichs (1971: p. 70f) argued that earlier publications (von Gümbel 1891: p. 359; Reuter 1927: p. 56) assigned this belemnite accumulation to the Posidonienschiefer, and that its components are reworked from the Posidonienschiefer below. However, the phosphate nodules with borings (Fig. 2D) are not derived from bituminous shales below, and correlations with sections in the Swabian Alb (Figs 7, 9) indicate an erosive discontinuity at the basis of the marl bed 18 below the "Belemnite Battlefield" (see discussion of sequence stratigraphy below). Therefore, the "Fucoid Bed" (bed 17) forms, in our view, the top of the Posidonienschiefer Formation, and the poorly bituminous marls of bed 18 form the basis of a new stratigraphic sequence, i.e., the basis of the Jurensismergel Formation.

4. The basis of the comparatively thick Opalinuston Formation (Figs 2B, 4) should be drawn with the lithological change from marl (Jurensismergel) to claystone (Opalinuston). While this change appears gradual in the northern Franconian Alb (e.g. Mistelgau; Schubert 2001a, b), the Ludwigskanal section still shows a clear calcareous marl bed 308–318 cm above the basis of the Jurensismergel. A calcareous marl bed has also been found in a similar position in the neighbouring section Pölling and likewise assigned to the Jurensismergel (Arp 2010). Therefore, the change from marl to claystone occurs above this bed, and the belemnite accumulation of bed 31, marking a 3\textsuperscript{rd} order sequence boundary (see sequence stratigraphic discussion below) could be taken as the lithostratigraphic lower boundary of the Opalinuston Formation. This suggested boundary definition coincides with change from pyritic to phosphoritic or compressed preservation of ammonoids in this region.

**Biostratigraphy**

The biostratigraphic subdivision of the investigated section follows the standard scheme by Dean et al. (1961), with revisions for the Lower Toarcian by Howarth (1973) and Riegraf et al. (1984: p. 19), and for the Upper Toarcian by Knitter and Ohmert (1983), Ohmert et al. (1996), Elmi et al. (1997), Cresta et al. (2001), and Schulbert (2001a) (Fig. 8). As a principal, the lower boundaries of subzones are drawn in the present paper by the first appearance datum (FAD) of the corresponding index species, with the exception of the Hawkskerense Subzone (last appearance datum of Pleuroceras solare: Dean et al. 1961). The distribution of each of the ammonite genera and species along the investigated section is given in Figs 5 and 6.

(i) Upper Pliensbachian (>9 m)

The first Pleuroceras solare of the investigated section has been found 5 cm below the "Delta-Fossil Bed" (bed 4), indicating the Apyrenum Subzone of the Spinatum Zone. Abundant specimens of this species were found enclosed within reworked concretions of the "Delta-Fossil Bed" (bed 4), together with rare Amauroceras ferrugineum (Fig. 10: 1, 2). Few of the Pleuroceras solare specimens already show minor tubercles, corresponding to var. solitarium (Fig. 10: 2).

The marl matrix of the "Delta-Fossil Bed" (bed 4) enclosing the reworked concretions already yielded compressed Pleuroceras spinatum with clear tubercles, while P solare is absent. This suggests that the conglomeratic bed represents the base of the Hawkskerense Subzone (sensu Dean et al. 1961: "lower boundary [...] drawn immediately above the highest Pleuroceras solare"; equivalent to "Upper Spinatum Zone" sensu Hoffmann et al. 2007). Besides, a juvenile Amaltheus sp. (possibly a Pseudoamaltheus) was recovered.

The following top 8 m claystones of the Amaltheenton (bed 5) contain sideritic concretions with typical morphotypes of Pleuroceras spinatum (strong ribs with clear tubercles, whor section square; Fig. 10: 3, 4). However, neither Pleuroceras hawskerense nor Pleuroceras buckmani, characteristic for the top parts of the Hawkskerense Subzone (see e.g. Jordan 1960), were found at the Ludwigskanal/Dörlichbach, although they are known from the very top of the Amaltheenton in this region (Zeiss and Schirmer 1965; Arp 1989).
Figure 6. Litho- and biostratigraphy of the Posidonienschiefer, Jurensismergel, and basal Opalinuston Formation, Toarcian, exposed at the Ludwigskanal near Dörflbach. For legend see Fig. 7.
Figure 7. Correlation of the investigated section Ludwigskanal/Dörnbach with sections from the northern Franconian Alb (Mistelgau: Krumbeck 1932c; Schulbert 2001a, b; Arp and Gropengießer 2015; Basis Mactra Subzone drawn with the “Dumortieria bed I”; Basis Aalenius Subzone defined by FAD of $P. subcompta$) and Swabian Alb (Rainau-Weiler: Etzold et al. 1989; Gross-Eislingen: Wiedemann 1966; Holzmaden: Hauff 1921; Riegraf 1985a; Urlichs 1977a), with suggested T-R cycles.
(ii) Lower Toarcian (1.15–1.20 m)

Posidonienschiefer Formation starts with a clear discontinuity and Amaltheenent-derived intraclasts within the shell-debris-rich "Laibstein I" (bed 7). These laminated limestone concretions revealed a layer with several *Tritonoceras antiquum* 2–3 cm above their basis (Fig. 10: 5, 6), representing the latest interval of the Semicelatum Subzone (Antiquum Horizon; Page 2003, 2004). This finding confirms previous rare reports on *Tritonoceras antiquum* (syn.: *T. Schroederi*; Krumbeck 1932a; Kolb 1964; *T. antiquum*; Kraus 1983: his fig. on p. 415), which – together with "Lytoceras siemensii" (most of them belong to *L. ceratophagum*; see Riegraf 1985b) – have initially lead to the assumption that the Laibstein concretions are representing the Tenuicostatum Zone (e.g., Urlichs 1971). However, no dactylioceratid ammonoids of the *tenuicostatum* group have been reported from the working area. Likewise in middle and upper parts of the "Laibstein I"-bed abundant *Cleviceras exaratum* (Fig. 10: 10), *Lytoceras ceratophagum* (Fig. 10: 7), and *Hildaites murleyi* (Fig. 10: 8, 9) clearly indicate the Exaratum Subzone of the Falciferum Zone. Rare reports of *Eleganticeras* (Weißmüller 2017: his fig. 187) suggest that the Elegantulum Zone might be present, too, condensed within the "Laibstein I" (bed 7). Nonetheless, the Laibstein I bed largely represents the Exaratum Subzone, as previously shown by Riegraf (1985b) and Arp (1989).

The following "Laibstein II" (bed 8), with the abundant holoplanktic gastropod *Coelodiscus minutus*, comprises an ammonoid assemblage typical of the Elegans Subzone: *Cleviceras exaratum* (Fig. 11: 6), *Harpoceras serpentinum* (Fig. 11: 1), and a number of dactylioceratids (*Dactylioceras anguinum*, *D. semiannulatum*, *Notodicoeloceras crossoide*, "*Peronoceras* desplacei; Fig. 11: 2–4, 7). *Phylloceras heterophyllum* (Fig. 11: 5), which is absent in "Laibstein I", has also been found in this limestone concretion bed (Kolb 1964; Arp 1989; Weissmüller 2017).

Higher parts of the Falciferum Zone are less well documented at the Ludwigskanal section as well as in the whole region. One compressed specimen of *Harpoceras falciferum* (Fig. 2C) has been found within the "Falciferum Shale" (bed 10), indicating that these bituminous marls below the "Fish Scale Bed" (bed 9) belong to the Falciferum Subzone.

The lower bedding plane of "Dactylioceras Bed" (bed 12) and the fish-scale-rich argillaceous limestone layer at its base (bed 11) exhibit poorly preserved specimen of *Dactylioceras commune* (Fig. 12: 1), marking the basis of the Bifrons Zone. The lowermost part of "Dactylioceras Bed" (bed 12) also revealed a poorly preserved *Hildoceras cf. lusitanicum* (Fig. 12: 2), consistent with basis of the Bifrons Zone. In addition, *Frechiella subcarinata* has been reported for this bed 5.5 km ESE of the Ludwigskanal section (Krumbeck 1932a; Weiß and Freitag 1991). No indication of the Ovatum Horizon (Howarth 1992; Page 2003) was found. Within the "Dactylioceras" to "Monotis Bed", however, Dactylioceras *athleticum* (Fig. 12: 3) is most abundant. Therefore, the complete event bed (Arp and Gropengießer 2016) as well as the fish-scale-rich layer below, belongs to the Commune Subzone.

Between 18 and 38 cm above the basis of the "Bifrons Shale" (bed 15), the occurrence of compressed *Hildoceras semipolitum* (Fig. 12: 4, 5) defines the Semipolitum Horizon at the top of the Bifrons Zone, as known from France and the Mediterranean (Guex 1975; Gabilly 1976a; Elmi et al. 1994, 1997). *Hildoceras semipolitum* has also been recovered from the condensed Variabilis Zone immediately below the “Belemnite Battlefield” of Miestelgau, together with *Haugia jugosa* and *Denckmannia tumefacta* (Simon sen 2013). Associated ammonoids are *Pseudolioceras* cf. *lytens* and *Phylloceras* *heterophyllum*. Neither *Hildoceras bifrons*, *Catacoeloceras crassum* nor representatives of the genus *Peronoceras* were found in this bed at Dörlbach. However, a poorly preserved *H. bifrons* 5 cm above the Monotis Bed in the neighbouring section Alt dorf-Hirschbühler Bach and findings noted in Kolb (1964: p. 131) and Urlichs (1971: p. 70) suggest that the Fublatum Subzone (see Dean et al. 1961: p. 482) is present.

(iii) Upper Toarcian (5.04 m)

The first appearance of *Haugia* sp. at the basis of bed 16 ("Variabilis Shale"), i.e. one compressed fragment at 40 cm above the "Monotis Bed", indicated the lower boundary of the Variabilis Subzone, Upper Toarcian. Only a minor overlap of this genus with *Hildoceras* was observed at the Ludwigskanal/Dörlbach. Pyritized and compressed *Catacoeloceras raquinianum* (Fig. 13: 2, 3), *Pseudolioceras compactile* (Fig. 12: 10, 11), and *Lytoceras sublineatum* (Fig. 13: 1) are abundant in this zone, while compressed *Haugia variabilis* (Fig. 12: 8) concentrate in the top 15 cm. *Phylloceras heterophyllum*, *Mucroductylites mucronatus* (Fig. 12: 6, 7), and *Lytoceras* cf. *cornucopia* are present, too.

One compressed *Haugia jugosa* 3 cm below top (Fig. 12: 9) and one compressed *Denckmannia rude* 1 cm below top of bed 16 are consistent with the Jugosa Horizon (Elmi et al. 1997) at the top of the Variabilis Subzone. A finding of *Haugia ogerieni* from Berg by Krumbeck (1943), which is a coarse ribbed variety of *Haugia jugosa* according to Lacroix (2011), may further support this interpretation. The following "Fucoid Bed" (bed 17), containing *Haugia variabilis*, *Catacoeloceras raquinianum*, *Phylloceras heterophyllum*, and *Lytoceras* cf. *cornucopia* may also belong to this horizon.

A change in the ammonoid assemblage, however, is evident for bed 18, i.e., the 5 cm calcareous marl below the "Belemnite Battlefield": *Pseudogrammoceras subregale* (Pinna) (Fig. 13: 4) and *Haugia* cf. *philipisi* (Simpson) (Fig. 13: 5) point to the Illustri Subzone (Gabilly 1976a: p. 126), with *Catacoeloceras raquinianum* still abundant. Likewise, Krumbeck (1943: p. 298) reported a *Haugia* cf. *illustris* from shales just below the Belemnite Battlefield of the Teufelsgraben.
The “Belemnite Battlefield” (bed 19) is rather poor in ammonoids. Catacoeloceras raquinianum (d’Orbigny) has been recovered at the lower bedding plane (Fig. 13: 6), and deformed phosphoritic casts of Lytoceras cf. cornucopia occur within the bed. One fragmentary Pseudogrammoceras sp. is poorly preserved. This rather unspecific assemblage is, nonetheless, consistent with the view of Urichs (1971) that the Belemnite Battlefield still belongs to the (upper) Variabilis Zone, with no elements of the Thouarsense Zone. However, no direct evidence of the Vi- tiosia Subzone was found at Dörnbach.

The following “Main Phosphorite Bed” (bed 20) has been assigned by Krumbeck (1943: p. 305) to the Thouarsense Zone because of findings of Grammoceras thouarsense in the neighbouring section Hausheim. At the Ludvigskanal/Dörnbach, this bed yielded a number of Lytoceras cornucopia (Fig. 13: 8) specimens, one coarsely ribbed Pseudogrammoceras sp., one Osperleioceras bicornatum (Fig. 13: 7), and one phosphoritic cast of Denckmannia rude (Fig. 13: 9). While D. rude is restricted to the Variabilis Zone (Becaud et al. 2005; Lacroix 2011: p. 235), O. bicornatum ranges from the Semipolitum Horizon to the Bingmanni Horizon (Lacroix 2011: p. 113). The “Main Phosphorite Bed” (bed 20), therefore, represents a condensation horizon comprising the top of Variabilis and the basis of Thouarsense Zone.

Numerous, compressed Grammoceras cf. thouarsense (Fig. 14: 1) occur as a monospecific assemblage in the overlying “Toarcensis Shale” (bed 21), which consequently represents the Thouarsense Subzone. Neither lytoceratids nor any other ammonite genus was found in this bed. Indication of the Fallaciosum Subzone is absent at the Ludwigskanal/Dörnbach, but phosphoritic casts of Pseudogrammoceras gr. fallaciosum were mentioned by Krumbeck (1943: p. 305) from a belemnite-rich marl at the neighbouring section Hausheim (4.4 km SE of Dörnbach).

The “belemnite accumulation” of bed 22 yielded, except for Alolocytoceras cf. rugiferum, no determinable ammonoids. The range of A. rugiferum is not well constrained, but shows a maximum abundance in the Dispansum Zone in northern and southwestern Germany (Wunstorf 1904; Ernst 1923; Knitter and Riegraf 1984). Therefore, this bed is considered as erosive basis of the Dispansum Zone, and may contain reworked components of the Fallaciosum Subzone.

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First Phlyseogrammoceras dispansum (Fig. 14: 5, 8), however, have been found 5 cm above the “belemnite accumulation bed 22”, in bed 23. This ammonoid extends up to 18 cm above basis of bed 23 and is associated with abundant Alocytozerca rugiferum (Fig. 14: 2, 4) and rare Pseudolociceras cf. boulbienense (Fig. 14: 3). 10 and 15 cm above basis of bed 23, Hammatoceras insignis (Fig. 14: 10, 12) has been detected, clearly overlapping with the range of Phlyseogrammoceras dispansum in this section, so that the Dispansum Zone cannot be subdivided at the Ludvigskanal/Dörnbach.

At 11 cm below top of bed 23, first Dumortieria occur, specifically Dumortieria insignis (Fig. 14: 6, 7), cor-
(iv) Lower Aalenian (>0.5 m)

No *Leioceras opalinum* has been found in the Ludwigskanal/Dörlbach section. However, compressed *Leioceras opalinum* found in a drill core (highway viaduct Pilsach, unpublished observations) immediately above the equivalent of bed 33 suggests that the Toarcian-Aalenian boundary is located at the basis of bed 34.

### Sequence stratigraphy

Sequence stratigraphic interpretations require correlation and comparison of sections across the shelf with respect to discontinuities, facies trends, geometry and stacking patterns (e.g., Catuneanu et al. 2011). In the present paper, the definition of sequences as "transgressive-regressive cycles" (T-R cycles) follows Embry and Johannessen (1992), with "sequence boundaries" at maximum regression surfaces (mrs; for further discussion see Catuneanu et al. 2011 and Simmons 2012). However, it remains difficult to distinguish stratigraphic gaps at maximum regression surfaces (with reworked fauna in the following transgressive "ravinement surface"; Nummedal and Swift 1987) from condensation or non-deposition of maximum flooding surfaces (mfs) in sections distant from siliciclastic sediment influx.

This also applies to the South German Toarcian succession, because of low sedimentation rates and high distance to deltaic siliciclastic influx, no evident subaerial exposure surfaces, and (with respect to the Upper Toarcian) a limited number of sections with both, detailed sedimentological plus biostratigraphic observations. The following sequence stratigraphic interpretations, therefore, remain preliminary (Figs 7, 9).
A sequence stratigraphic framework, however, has been developed for the Toarcian of Northern Germany, based on a comprehensive analysis of drillings (sedimentology and gamma ray logs) covering the transition from marine to fluviodeltaic deposits of the NE-German Basin to fully marine deposits of the NW-German Basin (Zimmermann et al. 2015). Nonetheless, the biostratigraphic calibration of the drillings relies on a combination of microfossil records and comparatively rare ammonite records, with limited resolution at the subzone level. Furthermore, a sequence stratigraphic interpretation was given by Röhl and Schmid-Röhl (2005) for the Lower Toarcian in Southern Germany, specifically based on the biostratigraphically and sedimentologically well investigated sections Dotternhausen (Swabian Alb) and Schesslitz (Franconian Alb).

For the Upper Toarcian of Southern Germany, no such detailed analysis exists, but important information can be derived from proximal sections near Regensburg, where minor coarse siliciclastic influx during regressive phases intercalate between fine-grained open-marine sediments with ammonoids (Fig. 9). Furthermore, sequence stratigraphic interpretations based on well dated drillings and outcrops exist for the Toarcian of France (de Graciansky et al. 1998), including Quercy (Cubaynes et al. 1984; Lezin et al. 1997) and the type region of the Toarcian (Galbrun et al. 1994). Indeed, the most recent interpretation of the Toarcian eustatic sealevel curve by Haq (2018) is largely based on European sections from France, United Kingdom, Poland, and Switzerland, with additional data from sections in Argentina, Tibet, and the Arabian Platform (partially with tentative correlations).

The total duration of the Toarcian is about 8.5 Ma (Gradstein et al. 2012: from 182.7 to 174.1 Ma, i.e. 8.6 Ma; Bouilla et al. 2014: 8.3 Ma), while the duration of each of the ammonite zones is to date under discussion (Gradstein et al. 2012; Boulila et al. 2014; Rübsam and Al-Husseini 2020). In the following, vertical thickness and facies trends as well as discontinuities of the Ludwigskanal/Dörlbach section are discussed in comparison with neighbouring sections (Fig. 7) and areas to reveal T-R cycles for the top Pliensbachian to basis Aalenian succession in Southern Germany (Fig. 9).

(i) Amaltheenton Formation

Only two stratigraphic gaps in the otherwise monotonous claystones of the Amaltheenton are evident: The first gap is located within higher parts of the formation. Here, the "Delta-Fossil Bed" (Fig. 5) forms a distinct intraformational discontinuity at the basis of the Hawskerense Subzone. This discontinuity is also evident in neighbouring sections farther north (Buttenheim: Hoffmann et al. 2007) and south, where the section Sulzkirchen exhibits a clear erosional relief with compensation of the gap by sediment of the Hawskerense Subzone (Keupp and Arp 1990).
The second gap is developed at the top of the Amaltheen Formation, where reworked nodules indicate an erosion at the Ludwigskanal (Fig. 5). In neighbouring sections, these nodules are commonly accumulated to form the so-called "Bollernkalk" (Bandel and Knitter 1983; Böhm and Brachert 1993), which shows a non-bituminous bioclastic micrite matrix with minor phosphorite. This conglomeratic bed is probably still Upper Pliensbachian in age (Riegraf 1985a: his fig. 17) and coincides with the formation of an erosional relief including the "Altdorf Kalk" and a coast-parallel strip devoid of Amaltheentonen. This is in accordance with delta progradation and regression seen in parts of the Hawskerense Subzone (Fig. 9). This is in accordance with the Hawskerense Subzone, Amaltheentonen Formation. GZG.INV.70498: d = 54 mm, di = 37 mm, u = 23 mm, wh = 19 mm, wb = 18 mm, rb/2 = 11. 4. *Pleuroceras spinatum* (Brugièrê), 50 cm above basis of bed 5, Hawskerense Subzone, Amaltheentonen Formation. GZG.INV.70499: d = 76 mm, di = 58 mm, u = 36 mm, wh = 24 mm, wb = 24 mm, rb/2 = 14. 5. *Tiltoniceras antiquum* (Wright), 1–2 cm above basis of bed 7, Semicelatum Subzone, Posidonienschiefer Formation. Minor part (bright area) of the body chamber restored. GZG.INV.45641a: d = 48 mm, di = 33 mm, u = 12 mm, wh = 20 mm, wb = 12 mm, rb/2 = 22. 6. *Tiltoniceras antiquum* (Wright), 1–2 cm above basis of bed 7, Semicelatum Subzone, Posidonienschiefer Formation. GZG.INV.70501: d = 44 mm, di = 32 mm, u = 17 mm, wh = 15.5 mm, wb = 10 mm, rb/2 = 24; (leg. Arno Garbe). 10. *Cleviceras exaratum* (Young and Bird), middle part of bed 7, Exaratum Subzone, Posidonienschiefer Formation. GZG.INV.70501: d = 41 mm, di = 27 mm, u = 14 mm, wh = 16 mm, wb = 12 mm, rb/2 = 21; (leg. Arno Garbe). 9. *Hildaites murleyi* (Moxon), together with juvenile *Cleviceras exaratum* (Young and Bird), bed 7, Exaratum Subzone, Posidonienschiefer Formation. GZG.INV.70502: d = 44 mm, di = 32 mm, u = 17 mm, wh = 15.5 mm, wb = 10 mm, rb/2 = 24; (leg. Arno Garbe). 10. *Cleviceras exaratum* (Young and Bird), middle part of bed 7, Exaratum Subzone, Posidonienschiefer Formation. GZG.INV.70503: d = 39 mm, di = 27 mm, u = 10 mm, wb = 17 mm, wb = 8 mm, rb/2 = 24.
Figure 11. 1. *Harpoceras serpentinum* (Schlotheim), bed 8, Elegans Subzone, Posidonienschiefer Formation. GZG.INV.70504: d = 197 mm, di = 144 mm, u = 80 mm, wh = 70 mm, wb = 40 mm, rb/2 = n.a.; (leg. Matthias Weißmüller). 2. *Dactylioceras sp.* forma aegra *cunctum* (Martin 1858) Hölter 1956, bed 8, Elegans Subzone, Posidonienschiefer Formation. GZG.INV.70505a: d = 53 mm, di = 40.5 mm, u = 22 mm, wh = 13.5 mm, wb = 15 mm, rb/2 = 30. 3. *Dactylioceras anguinum* (Reinecke), bed 8, Elegans Subzone, Posidonienschiefer Formation. GZG.INV.70505b: d = 40 mm, di = 30 mm, u = 14.5 mm, wh = 11 mm, wb = (11 mm), rb/2 = 31. 4. *"Peronoceras" desplacesi* (d’Orbigny), bed 8, Elegans Subzone, Posidonienschiefer Formation. GZG.INV.70506: d = 68 mm, di = 53 mm, u = 38 mm (56%), wh = 16 mm (24%), wb = 16 mm, rb/2 = 41. 5. *Phylloceras heterophyllum* (Sowerby), bed 8, Elegans Subzone, Posidonienschiefer Formation. GZG.INV.70508: d = 86 mm, di = 53 mm, u = 15 mm, wh = 43 mm, wb = 19 mm, rb/2 = 49. 7. *Dactylioceras semiannullatum* Howarth, bed 8, Elegans Subzone, Posidonienschiefer Formation. GZG.INV.70509: d = 49 mm, di = 39 mm, u = 26 mm, wh = 12 mm, wb = 13 mm, rb/2 = 30.

Posidonienschiefer Formation unconformably overlies the Hawskerense Subzone, with a stratigraphic gap comprising the Paltum- to midst of Semicelatum Subzone (Riegraf 1985a, b).

All other ammonite subzones from top of the Semicelatum to the Crassum Subzone are present in the bituminous and laminated sediments of the Ludwigskanal/ Dörlbach area (Fig. 6), although minor sedimentary gaps below the ammonite subzone resolution may be developed. The laminated bituminous marls continue into the lower Variabilis Zone with non-bituminous intercalations, fucoid beds, and scattered re-occurrence of benthic fauna (*Grammatodon* sp.). The fish scale-rich beds in the Falciferum Zone and at the basis of the Bifrons Zone, however, may reflect considerable sedimentological condensation, while the Dactylioceras-Monotis bed itself is an exceptional event bed with an erosional basis, possibly formed by a tsunami (Arp and Gropengießer 2015).

Towards the basin margin (Regensburg area), bituminous shales of the Falciferum Zone are overlain by prograding sandstones containing *Dactylioceras commune* and *D. athleticum* (Pompeckj 1901; Putzer 1939; Krumbeck 1932b), followed by a discontinuity comprising the Fibulatum and Crassum Subzones (Fig. 9). Note that the "Crassum Bed" in this area does not contain *Catacoeloceras crassum*, but the younger species *Catacoeloceras raquinianum*, and is an equivalent of the "Belemnite Battlefield" (see below). In the Posidonienschiefer of Swabian Alb a number of fish scale-rich beds ("Schlacken") at top of Falciferum Zone (Riegraf et al. 1984; Riegraf 1985a) reflect a sedimentological condensation. Contrary to the Franconian Subzone, bituminous sedimentation in the Swabian Posidonienschiefer ends with the Fibulatum Subzone.

Consequently, the sequence stratigraphic interpretation is as follows (Fig. 9): The transgression in the lower half of the Posidonienschiefer is documented by the successive onlap of subzones from SW to NE (Riegraf et al. 1984: p. 26, fig. 7; Riegraf 1985a: p. 55, fig. 27), delayed onset of sedimentation on the Altdorf High and basin margin (Regensburg area), and delayed benthos elimination on the Altdorf High. Minor sediment condensation (fish scale rich beds) at the Falciferum-Commune Subzone transition (bed 11; Fig. 6) may correspond to a maximum flooding surface, probably equivalent to fish-scale-rich intercalations ("Schlacken"); Hauff 1921; Riegraf et al. 1984: p. 16 ff) in a similar lithostratigraphic position in the Swabian Posidonienschiefer (Fig. 7). Hence, higher Bifrons and Variabilis Subzone reflect regression with increasing siliciclastic influx, associated with pyrite preservation of ammonites (only Variabilis Subzone), and temporary re-oxygenation of the seafloor.

This interpretation is similar to the 3rd order T-R cycle previously proposed for the Swabian and Franconian Posidonienschiefer by Röhl and Schmid-Röhl (2005) (Fig. 9). The only addition to be made is, that the regressive system tract of the cycle extents into the lower Variabilis Zone. In N-Germany, this T-R cycle appears slightly shifted, with a maximum flooding surface already in top parts of the Tenuiostatum Zone (mfs Toa 1), followed by regression and maximum regression surface in top parts of the Bifrons Zone (mrs Toa 1) (Zimmermann et al. 2015). A possible explanation for this minor shift is the higher subsidence as well as higher sediment supply in North-German Basin at that time.

Considerable differences exist with respect to the proposed 3rd order sequences in France. De Graciansky et al. (1998) suggest four 3rd order sequences for the Lower Toarcian, and a fifth sequence for the Fibulatum to Thouarsense Subzone. None of these T-R cycles appear recognizable in Germany, and may refer to minor superimposed changes (4th order sequences) only seen in areas of high sedimentation rate. Strikingly, there is also a continuous sedimentation from the higher Bifrons throughout the complete Variabilis Zone, in contrast to the erosive Intra-Variabilis-Discontinuity in S-Germany (Fig. 9).

(iii) Jurenissmemergel

Similar to the previous formation, the thickness of the Jurenissmergel Formation is low (5 m). Ammonite zones and subzones are densely spaced and condensed at the phosphoritic and (slightly) bituminous basis of the formation (Fig. 6). Similar to the section Mistelgau (Schulbert 2001a, b), an increasing subzone thickness, decreasing carbonate content, and change from phosphoritic to pyritic ammonite preservation is observed towards the top of the formation (Fig. 7). A trend of increasing clay content is also recognizable from SW to NE, when compared to the increasingly
carbonate-rich sections in the Swabian Alb (Fig. 7). This points to a general progradation of deltas in N-Germany at that time, affecting the Franconian realm, with the Swabian area more proximal to the warm Tethyan Ocean.

The erosive basis of the Juresnismergel Formation, forming a sequence boundary, has early been recognized in the Swabian Alb, with an apparent transgression beginning with the Variabilis Zone (Stier 1922; Fischer 1964: p. 99; Bruder 1968: p. 150; Riegraf 1985a: his fig. 18; Etzold et al. 1989: p. 44 f). Indeed, a continuous sequence of ammonite subzones across the Posidonienschiefer-Juresnismergel boundary is only developed in the Wutach area SW of the Swabian Alb (Straub 1946: p. 56; Riegraf 1985a: p. 31). At the Ludwigskanal/Dörlbach, however, a continuous sedimentation across the Bifrons-Variabilis Zone boundary is evident, and a major stratigraphic gap appears developed at the “Belemnite Battlefield”, i.e. the top of the Variabilis Zone (Figs 6, 7). These contracting observations require a detailed look on the actual biostratigraphic evidence, i.e. ammonite records:

At the Ludwigskanal/Dörlbach, the Semipolitum Subzone is overlain by a Variabilis Subzone, characterized by abundant Catacoeloceras raquini, Pseudolioceras compactile, and Mucroductylites mucronatus (Fig. 6). The Illustrii Subzone follows after a thin, but evident fucoid bed, and grades in the “Belemnite Battlefield” containing reworked as well as autochthonous ammonite fossils of the higher Variabilis Zone (e.g., Urlichs 1971). On the other hand, the oldest ammonite assemblages of the channel-like occurrences of the Variabilis Zone in the Swabian Juresnismergel already comprise representatives of the Illustrii (Haugia illustris, Holzheim-Ursenwang: Stolz 1911 in Straub 1946: p. 27; Pseudogrammoceras doentense, Groß-Eislingen: Wiedemann 1966: p. 104) and Vitosia Subzones (Haugia vitiosa, Jebenhausen: Urlichs 1977a; Haugia cf. vitiosa, Weilheim: Knitter and Riegraf 1984: p. 75, their fig. 4). These ammonites co-occur with Haugia variabilis and Haugia navis, but – contrary to Ludwigskanal/Dörlbach – Catacoeloceras, Pseudolioceras and Collina are absent. The same applies to sections of the Freiburg area, with the Illustrii and Vitosia Subzone erosive on top of a partially eroded Posidonienschiefer (Ohmert 1976; Knitter and Ohmert 1983).

Therefore, we suggest that the erosive basis of the Juresnismergel Formation and sequence boundary lies within the Variabilis Zone, specifically at the basis of the Illustrii Subzone (Figs 7, 9). While no Intra-Variabilis-Zone mrs (maximum regression surface) is seen in N-German sections (Zimmermann et al. 2015), an equivalent mrs and sequence boundary at the basis of the Illustrii Subzone was identified in the Toarcian type area in western France (Galbrun et al. 1994: their fig. 5).

Consequently, the “Belemnite Battlefield” with its fossil accumulation and phosphate nodules rather represents a transgressive sediment, and indeed grades in basin margin sections into a cephalopod-rich sandstone bed (“Crassum Bed” with Dactylotheutis irregularis, Catacoeloceras raquinianum, Haugia sp., Mucroductylites mucronatus and Pseudolioceras compactile: Meyer and Bauberger 1998: p. 40–41, fig. 10; “nodule bed a” with Catacoeloceras raquinianum, Mucroductylites mucronatus, Hildoceras cf. bifrons: Krumbeck 1943: p. 332). At Dörlbach and other sections of the Franconian Alb (e.g. Miestelgau, Fig. 7), the “Belemnite Battlefield” is overlain by the “Main Phosphorite Bed” and the bituminous “Toarcensis Shale” (Krumbeck 1943), with a time-equivalent calcareous sandstone bed in basin margin sections (“Grammoceras limestone”: Putzer 1939; “nodule bed b” with Pseudogrammoceras aff. subquadratum; “nodule bed c” with G. thouarsense, P. cf. saemanni, P. fallaciosum: Krumbeck 1943: p. 332). These cephalopod-rich beds indicate flooding and highstand conditions at the basin margin.

In the Swabian Alb, submarine “swells” (i.e., remaining topographic highs after erosion within Variabilis Zone;
Stier 1922; Etzold et al. 1989), show aphytic microbialites in the Toarcian Zone (e.g., Aalen-Weidenfeld: Dietl and Etzold 1977; Keupp and Arp 1990; Ohmden: Arp and Heyng 2013), indicating highly reduced sedimentation (Keupp and Arp 1990). These condensed deposits may represent a maximum flooding, while the Fallaciosum Subzone shows a very discontinuous distribution of sediments, in the Swabian as well as in the Franconian Alb. High sealevel, however is still indicated by the sporadic occurrence of *P. fallaciosum* at the basin margin (*nodule bed c*, see above).

A clear and significant discontinuity is developed at the basis of the Dispansum Zone in the Franconian Alb. This erosive sequence boundary, commonly associated with a belemnite accumulation and aphytic microbialites (Dörflbach, Mistelgau: Fig. 7) is also recognizable in the Swabian Alb (Bad Boll: Wiedemann 1966: p. 91, Taf. 9; Bruder 1968: p. 15f.; middle part of bed 22 Rainau-Weiler, and KB4 Reutehau: Etzold et al. 1989). In N-Germany, the basis of the Dispansum Zone is a significant erosive surface (Heidorn 1928; Hoffmann 1968a: p. 465: “Zeta-Konglomerat”) and coincides with the mrs Toa 2 proposed by Zimmermann et al. (2015). Likewise, the Fallaciosum-Insigne Subzone boundary represents a mrs and sequence boundary in SW-France (Cubaynes et al. 1984: their fig. 18). The widespread erosion of the Fallaciosum Subzone in the Franconian Alb explains the scarcity of *Lytoceras jurensense* findings in this area, as this species is most common in this subzone.

Subsequently, condensation and phosphoritization characterize the transgressive sediments of the Dispansum Zone at the Ludwigskanal/Dörflbach and elsewhere in the Franconian Alb, while in the following Pseudoradiosa Subzone with several beds of compressed *Dumortieria* accumulations may reflect further deepening. A flooding at the basin margin area might be indicated by findings of Pompeckj (1901: p. 143), who noted the occurrence of *Phlyseogrammoceras cf. dispansum*, *Hammatoceras insigne* and *Dumortieria dumortieri* (syn.: *D. insignisimilis*) from the Regensburg area.

The condensed bed 25 (i.e., basis of Mactra Subzone; Fig. 7) at Dörflbach, with abundant ammonites, belemnites and phosphorite, may correspond to maximum flooding. The same horizon has also been described from Mistelgau (*Dumortieria* bed I: Schulbert 2001a) and Rainau-Weiler (Etzold et al. 1989: p. 49, their bed 16 with abundant phosphoritic *Dumortieria* and belemnites) (Fig. 6). By contrast, Galbrun et al. (1994: their fig. 5) infer a possible mrs and sequence boundary at the Pseudoradiosa/Aalensis Zone boundary from sections in western France.

Finally, the increasingly thick marls with pyritic ammonites of the Aalenius Subzone could reflect the regressive system tract of this 3rd order cycle, with increasing clay supply from N. Indeed, at the basin margin (Regensburg area) quartz-pebble and feldspar-containing calcareous sandstones document this regressive interval (Putzer 1939: p. 93, 107) (Fig. 9). Consistent with this interpretation, the sedimentary succession in Quercy/France appears regressive for the Macra to Aalensis Subzone, followed by a discontinuity and sequence boundary (Lezin et al. 1997).

(iv) Opalinuston

While basal parts of this formation, i.e., the Torulosum Subzone, still show a low thickness, discontinuities, phosphorite, and some carbonate, major parts are composed of a thick monotonous series of claystones. Discontinuities within the formation and lateral facies trends are poorly documented. However, the sections Grossenbuch (middle Franconian Alb) and Wittelshofen (southern Franconian Alb) described by Krumbeck (1943) demonstrate that the Aalenius-Torulosum Subzone boundary is associated with erosion, locally removing the complete Aalenius Subzone.

Therefore, the belemnite accumulation (bed 31) at the Aalenius-Torulosum Subzone boundary of the Ludwigskanal/Dörflbach section (Fig. 6), although unspectacular at first glance, can be interpreted as a mrs and sequence
**Conclusions**

- The 16 m thick Ludwigskanal/Dörlbach section exposed upper parts of the Schwarzjura Group, from top parts of the Amaltheenton (>9 m), through the Posidonienchiefer (1.8–1.9 m) and Juresismergel (3.5 m) to basal parts of the Opalinuston (>1.3 m). All formation boundaries are erosional discontinuities. Carbonate contents are low in the Amaltheenton, high in lower and middle parts of the Posidonienchiefer, followed by a successive decline to basal parts of the Opalinuston, with a last calcareous marl bed near the top of the Juresismergel. The Posidonienchiefer shows increased organic carbon contents, which are, nonetheless, significantly lower than in other N- and SW-German sections due to the “dilution effect” by high carbonate contents. However, normalized to the sediment silicate fraction, organic carbon contents show a clear first maximum in the Exaratum Subzone and high values in the Falciferum and Bifrons Zone, similar to SW-German reference sections. Highly fluctuating values characterize the Variabilis Zone and high values in the Falciferum and Bifrons Zone, while low organic carbon contents were found in the Dispansum and younger zones, with one single spike at the basis of the Aalenian Zone (Mactra Subzone).

- Despite of the low thickness of the formations and a number of sedimentological gaps and condensation, all ammonite zones and subzones from the top of the Pliensbachian to the top of the Toarcian are present, with the following exceptions: Paltatum and Clevelandicum (sedimentary gap), Vitiosa and Bingmannia (probably present, but no definite ammonite proof), and Fallaciosum Subzone (sedimentary gap). The erosive basis of the Torulosum Subzone may explain the lack of evidence for the Pseudolotharingicum (syn.: Lugdunensis) Horizon at the top of the Aalenian Subzone. The basis of the Aalenian is drawn in analogy to a neighbouring drill section that yielded *Leioceras opalinum*. Three subzones and horizons were detected for the first time in the investigated area: The Semipolitum Horizon, the Illustris Subzone, and the Dumortieri Horizon. The standard zone index ammonite *Harpoceras falciferum*, previously mentioned only by Urlichs (1971: p. 69), is figured for the first time for the Franconian Alb.
Figure 15. 1. Pleurolytoceras wrighti (Buckman), bed 27, Aalensis Subzone, Jurenismsmergel Formation. This species has previously been assigned to Pachytopics Buckman 1905, which is a junior subjective synonym of Pleurolytoceras Hyatt 1900 (Hoffmann 2010, 2015). GZG.INV.70540: d = 44 mm, di = 27 mm, u = 14 mm, wb = 19 mm, rb/2 = 19. 2. Pleurolytoceras hircinum (Schiolteim), bed 27, Aalensis Subzone, Jurenismsmergel Formation. GZG.INV.70541: d = 27 mm, di = 18 mm, u = 10 mm, wb = 10.5 mm, wb = 10 mm, constr/2 = 6. 3. Cottswoldia maclra (Dumortier), bed 25, Mactra Subzone, Jurenismsmergel Formation. GZG.INV.70542: d = 29 mm, di = 20 mm, u = 10 mm, wb = 11 mm, wb = 7 mm, rb/2 = 33. 4. Pseudolococeras beyrichi (Schloenbach), 1 cm below top of bed 28, Aalensis Subzone, Jurenismsmergel Formation. GZG.INV.45644: d = 34 mm, di = 21 mm, u = 6 mm, wb = 17.5 mm, wb = 10 mm, rb/2 = 15, (leg. Sebastian Demmel). 5. Paradurmiteria cf. tectiforme Elmi and Calco-Fortier, 45 cm below top of bed 24, Pseudoradiosa Subzone, Jurenismsmergel Formation. GZG.INV.70543: d = 32 mm, di = 23 mm, u = 13 mm, wb = 11 mm, wb = 7.5 mm, rb/2 = 20. 6. Cottswoldia aalensis (Zieten), bed 27, Aalensis Subzone, Jurenismsmergel Formation. GZG.INV.70544: d = 46 mm, di = 31 mm, u = 16 mm, wb = 18 mm, wb = 9.5 mm, rb/2 = 19. 7. Dumorteria extemicoasta (Branco), 30 cm below top of bed 26, Aalensis Subzone, Jurenismsmergel Formation. GZG.INV.70545: d = 21 mm, di = 14 mm, u = 7.5 mm, wb = 8 mm, rb/2 = 10. 8. Dumorteria costula (Reinecke), 30 cm below top of bed 26, Aalensis Subzone, Jurenismsmergel Formation. GZG.INV.70546: d = 36 mm, di = 26 mm, u = 12 mm, wb = 14 mm, wb = 9.5 mm, rb/2 = 11. 9. Pleydellia distans (Buckman), bed 27, Aalensis Subzone, Jurenismsmergel Formation. GZG.INV.70547: d = 22 mm, di = 15 mm, u = 8 mm, wb = 8 mm, wb = 6.5 mm, rb/2 = 11. 10. Dumorteria moorei (Lycett), 40 cm below top of bed 24, Pseudoradiosa Subzone, Jurenismsmergel Formation. GZG.INV.70548: d = 38 mm, di = 27 mm, u = 15 mm, wb = 13 mm, wb = (7 mm), rb/2 = 62. 11. Dumorteria cf. kochi Benecke, 40 cm below top of bed 24, Pseudoradiosa Subzone, Jurenismsmergel Formation. GZG.INV.70549: d = 37 mm, di = (27 mm), u = 14 mm, wb = 13 mm, wb = n.a., rb/2 = 17. 12. Pleydellia subcompta (Branco), 35 cm below top of bed 26, basis of Aalensis Subzone, Jurenismsmergel Formation. GZG.INV.70550: d = 44 mm, di = 29 mm, u = 16 mm, wb = 17 mm, wb = 9 mm, rb/2 = 30. 13. Pleydellia costulata (Zieten), 1 cm below top of bed 28, Aalensis Subzone, Jurenismsmergel Formation. GZG.INV.70551: d = 39 mm, di = 26 mm, u = 11.5 mm, wb = 16.5 mm, wb = 9 mm, rb/2 = 12. 14. Pleurolytoceras torulosum (Schübler in Zieten), bed 33, Torulosum Subzone, Opalinsuston Formation. This species has previously been assigned to Pachytopics Buckman 1905, which is a junior subjective synonym of Pleurolytoceras Hyatt 1900 (Hoffmann 2010, 2015). GZG.INV.70552a: d = 40 mm, di = (29 mm), u = 12 mm, wb = 16 mm, wb = n.a., cstr/2 = 20. 15. Cottswoldia lotharingica (Branco), bed 33, Torulosum Subzone, Opalinsuston Formation. GZG.INV.70553: d = 84 mm; di = 30 mm, u = 32 mm, wb = 28 mm, wb = n.a., rb/2 = (48). 16. Pleydellia buckmani Maubeuge, bed 33, Torulosum Subzone, Opalinsuston Formation. GZG.INV.70554; d = (55 mm), di = n.a., u = 18 mm, wb = 26 mm, wb = n.a., rb/2 = n.a. 17. Pleydellia cf. falcifer Maubeuge, bed 33, Torulosum Subzone, Opalinsuston Formation. GZG.INV.70552b: d = 40 mm, di = (27 mm), u = 12 mm, wb = 17 mm, wb = n.a., rb/2 = 20.

• The sequence stratigraphic standard Boreal 2nd order cycle (de Graciansky et al. 1998), with transgression during the Lower Toarcian, maximum flooding at the basis of the Bifrons Zone, and a regressive succession in the remaining Toarcian to Aalenian, is clearly developed in Southern Germany. Superimposed to that, three 3rd order T-R cycles are recognized at the Ludwigskanal/Dörlibach and adjacent sections, with a maximum regression near the basis of the Toarcian (i.e., within the lower Tenuicostatum Zon of Swabian Alb), within the Variabilis Zone (i.e., at the basis of the Illistris Subzone), at the basis of the Dispansum Zone, and less prominent at the basis of the Torulosum Zone. In turn, maximum flooding surfaces are developed at the basis of the Commune Subzone, basis of the Thouarsense Subzone, basis of Mactra Subzone, and basis of Opalum Zone. While transgressive sediments of the Franconian Toarcian commonly show phosphorites (similar to other epicontinental marine deposits: Loutit et al. 1988; Glenn et al. 1994: p. 767; Glenn and Garrison 2003: p. 524), regressive sediments frequently show pyrite preservation of fossils, especially ammonites. The extraordinary "Belemnite Battlefield" near the basis of the Jurenismsmergel is considered as transgressive sediment, consistent with the previous formation model by Urluchs (1971) of winnowing by a coast-parallel seawater current.

• The litho-, bio-, and sequence stratigraphic framework of the Ludwigskanal section may serve as a basis for further isotope and biogeochemical studies on the Toarcian Oceanic Anoxic Event, and its recovery phase, in this seawater current-affected part of the NW-European Epicontinental Seaway.

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