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Litho- and biostratigraphy of the Opalinus Clay and bounding formations in the Mont Terri rock laboratory (Switzerland)

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Abstract A 250 m-deep inclined well, the Mont Terri BDB-1, was drilled through the Jurassic Opalinus Clay and its bounding formations at the Mont Terri rock laboratory (NW Switzerland). For the first time, a continuous section from (oldest to youngest) the topmost members of the Staffelegg Formation to the basal layers of the Hauptrogenstein Formation is now available in the Mont Terri area. We extensively studied the drillcore for lithostratigraphy and biostratigraphy, drawing upon three sections from the Mont Terri area. The macropaleontological, micropaleontological, and palynostratigraphical data are complementary, not only spatially but they also cover almost all biozones from the Late Toarcian to the Early Bajocian. We ran a suite of geophysical logs to determine formational and intraformational boundaries based on clay content in the BDB-1 well. In the framework of an interdisciplinary study, analysis of the above-mentioned formations permitted us to process and derive new and substantial data for the Mont Terri area in a straightforward way. Some parts of the lithologic inventory, stratigraphic architecture, thickness variations, and biostratigraphic classification of the studied formations deviate considerably from occurrences in northern Switzerland that crop out further to the east. For instance, with the exception of the Sissach Member, no further lithostratigraphic subdivision in members is proposed for the Passwang Formation. Also noteworthy is that the ca. 130 m-thick Opalinus Clay in the BDB-1 core is 20 m thinner than that equivalent section found in the Mont Terri tunnel. The lowermost 38 m of the Opalinus Clay can be attributed chronostratigraphically solely to the Aalensis Zone (Late Toarcian). Deposition of the Opalinus Clay began at the same time farther east in northern Switzerland (Aalensis Subzone, Aalensis Zone), but in the Mont Terri area the sedimentation rate was two or three orders of magnitude higher.

Editorial handling: P. Bossart and A. G. Milnes.

Keywords Early–Middle Jurassic · Geophysical logging · Clay content · Ammonites · Microfossils · Palynomorphs

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1 Introduction

1.1 Outline and aim of this study

The Opalinus Clay in Switzerland has been studied in detail as a potential host rock for the deep geological disposal of high-level radioactive waste (for overviews see Bossart et al. 2008; Bossart et al. 2017). Since 1996, numerous experiments have been conducted on the Opalinus Clay in the Mont Terri rock laboratory (Canton of Jura (NW Switzerland)] as part of the international research programme of the Mont Terri Consortium (Fig. 1). In 1989, the security gallery of the Mont Terri A16 highway tunnel was built and revealed that the Opalinus Clay has a total horizontal length of almost 250 m yielding a thickness of ca. 150 m at rock lab level (e.g. Bläsi et al. 1991, 1996; Bossart and Thury 2008) at this location. The rock lab offers unique access to the Opalinus Clay 300 m below the surface. Over the last 20 years, the Mont Terri rock laboratory has evolved into a system of galleries and niches exceeding 600 m in total length, with numerous experiment sites and more than 1000 boreholes. After initial lithostratigraphic studies were carried out in the galleries of the rock laboratory (e.g. Bläsi et al. 1996), there followed a long period focusing mainly on structural studies, summarized in Nussbaum et al. (2011). In 2010, the 217 m-deep BDS-5 borehole was drilled from the surface into the northern limb of the Mont Terri anticline (Jaeggi et al. 2012). In 2013, Reisdorf et al. 2014 initiated a biostratigraphic study of the Opalinus Clay under the framework of the SO (Sedimentology of Opalinus Clay) experiment, which was based on existing boreholes and outcrops within the Mont Terri rock laboratory. Ammonites found in the basal part of the Opalinus Clay supported dating this formation to the Aalensis Subzone (Aalensis Zone). Thus, sedimentation of the Opalinus Clay at Mont Terri had already begun during the Late Toarcian.

From December 2013 to January 2014, the 247.5 m-deep inclined borehole BDB-1 (Swiss coord. 2 579 515/1 247 412; Yu et al. 2017) was drilled with a downward inclination of 45° in order to achieve an orientation perpendicular to the bedding in the target interval, the Opalinus Clay. The borehole started in the lower part of the Hauptrogenstein (Bajocian) with beds dipping 65° towards the SSE, then penetrated the entire Passwang Formation and the Opalinus Clay with beds dipping around 45°, and ended in the upper (Toarcian) part of the Staffelegg Formation [Figs. 1, 2 (s. fold-out plate at the end of the issue or the electronic supplementary material under DOI 10.1007/s00015-016-0250-3); Table 1]. The borehole was drilled within the framework of the DB (Deep borehole) experiment, which aims to (1) study the hydraulic head profile through the Opalinus Clay and its adjacent bounding formations, (2) assess continuous profiles of petrophysical and geochemical parameters on core material and in the borehole itself, and (3) constrain stratigraphy, variability of facies distribution and structure of the Opalinus Clay in an undisturbed continuous section.

1.2 Borehole BDB-1

The present study focuses on the third aim, the stratigraphy of borehole BDB-1. The borehole was drilled in two separate phases. In December 2013, the upper part ranging from 0 to 97.3 m measured depth was drilled with water, beginning in the lower part of the Hauptrogenstein and reaching up to ca. 9 m above the base of the Passwang Formation. After geophysical logging of the first part by Terratec geophysical services (Fischer 2014), the drill team cemented in a steel casing. Using air as a flushing medium, drilling was continued through the entire Opalinus Clay and into the uppermost 10 m of the Staffelegg Formation in January 2014. Drilling was then stopped at a water-bearing fracture within the Rietheim Member at a final measured depth of 247.5 m. The borehole yielded continuous core material of excellent quality. The core diameter was 101 mm in the upper section and 85 mm in the lower section. The present study includes the lithostratigraphic description and biostratigraphic subdivision based on ammonites, palynomorphs, ostracodes, and foraminifers (Chapters 3–6), as well as the interpretation of selected geophysical logs (see Suppl. Chapter 4).

1.3 Geological framework

At Mont Terri and directly adjacent areas, the Opalinus Clay is rarely exposed at the surface. One of the first lithological descriptions of the Opalinus Clay was given by Schmidt et al. (1924) from a borehole near Buix, located about 20 km to the NW of Mont Terri, where they encountered a total thickness of 157.5 m. Within the security gallery of the Mont Terri highway tunnel, the thickness of the Opalinus Clay was measured at 150 m (Schaeren and Norbert 1989; Bläsi et al. 1991, 1996). Bläsi et al. (1991) provided a detailed lithostratigraphic description of the Opalinus Clay located in a reconnaissance gallery at Mont Terri.

The entire Mont Terri rock laboratory is situated within the Opalinus Clay. This Formation can be subdivided into five units comprising three lithofacies types (Figs. 1, 2). From bottom to top, these are (1) a shaly facies consisting of mica-bearing calcareous claystones with lenses or with mm-thick layers of quartz in the silt fraction, (2) a sharp transition to a thin carbonate-rich sandy facies, characterized by quartz-bearing calcareous biodetritic layers of up to 10 cm thickness, (3) a sandy facies with calcareous
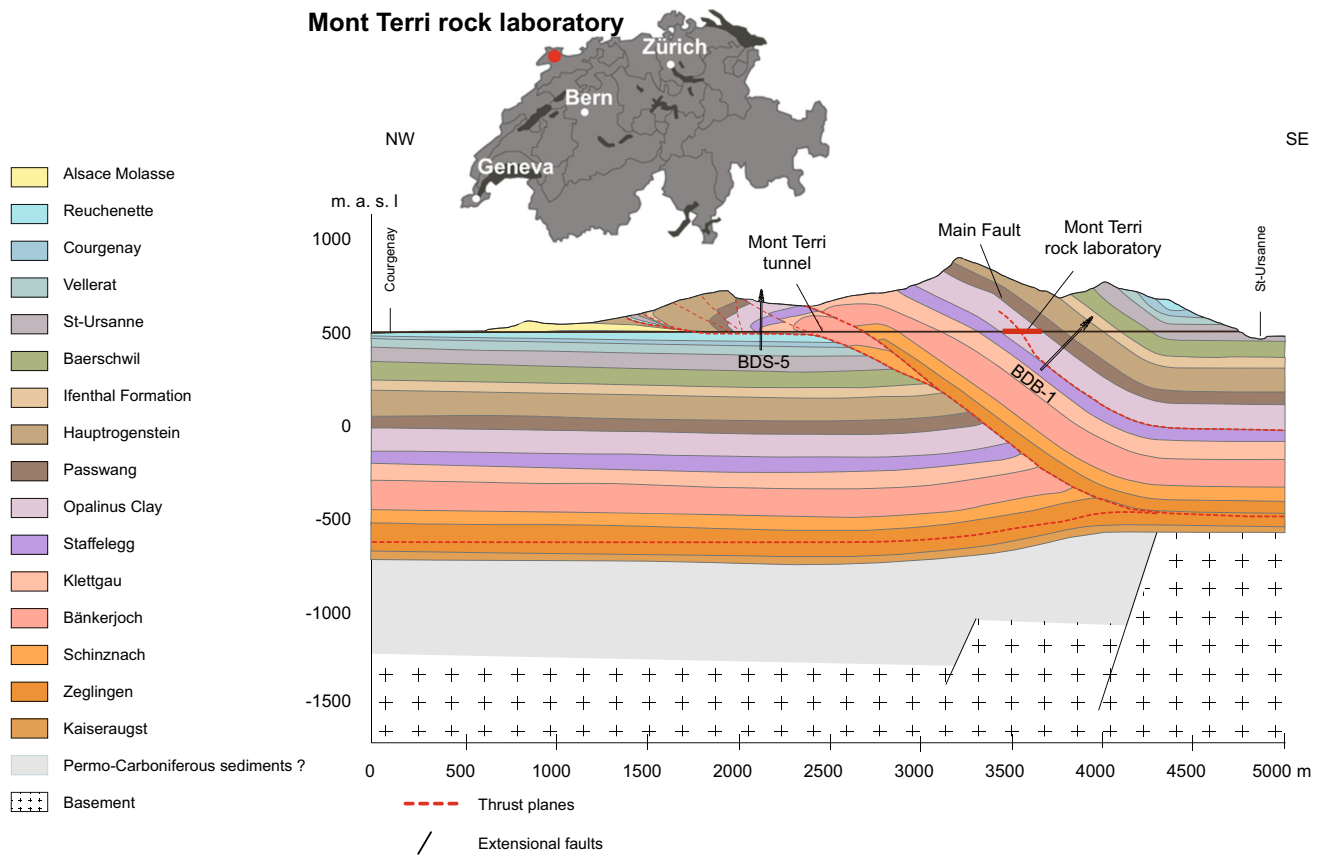
Fig. 1 Location of the Mont Terri rock laboratory within the Mont Terri anticline and geological situation of BDB-1 borehole (adapted from Caër et al. 2015). For comparison, the location of borehole BDS-5 is also displayed

silty claystones, which is then overlain by (4) a dark grey mica-bearing and slightly silty claystone attributed to the shaly facies. Finally, (5) the uppermost unit of the Opalinus Clay consists again of a sandy facies, a light grey silty claystone with laminated silt lenses, and lenses of bioclastic material.

Schaeren and Norbert (1989) and Bläsi et al. (1991) defined the base of the Opalinus Clay as a lithological transition of argillaceous sediments to more calcareous sediments. The latter have been identified as the "Jurensis-Mergel" (=Gross Wolf Member of the Staffelegg Formation, after Reisdorf et al. 2011a; see Table 1). The upper boundary of the Opalinus Clay is defined in the Mont Terri area by a distinct hardground of chamositic crusts and Fe-oolithes (this study). Bläsi et al. (1991) described this horizon with chamositic crusts, but set the top of Opalinus Clay in the Mont Terri rock laboratory ca. 7 m further upsection. A prominent tectonic overprint of the Opalinus Clay is confirmed by numerous studies on structural data conducted during the evolution of the rock laboratory (e.g. Nussbaum et al. 2011). The Mont Terri rock laboratory is located in the southern limb of the Mont Terri anticline (see Bossart et al. 2017: Fig. 1); the overburden varies between 230 m and 320 m and the stratal dip has an angle

between 30° and 50° towards the SSE in the northern and southern parts, respectively. The Mont Terri anticline developed in during 12–3 Ma at the junction between the frontal part of the Jura thrust-and-fold belt and the Rhine-Bresse transfer zone (Nussbaum et al. 2011). The geometry is a fault-bend fold that developed above a frontal ramp featuring an overturned forelimb with a detachment in the Triassic evaporites. The maximal overburden is estimated to be 1350 m, resulting in a maximum temperature of 85 °C during Cretaceous burial (Mazurek et al. 2006). At Mont Terri, three different fault systems are identified that correlate with regional-scale tectonic structures: (1) N- to NNE-striking normal faults of the Rhine-Bresse graben system that were reactivated in sinistral strike-slip mode during the Late Miocene Jura thrusting phase, (2) SSE-dipping faults parallel to bedding that were initiated during the late stage of reverse faulting, and (3) anticline folding by flexural slip and SW-dipping sub-horizontal faults that resulted from lateral extension during the thrusting of the Mont Terri anticline above the frontal ramp. The largest tectonic feature of the rock lab is the so-called Main Fault, a thrust fault, which at rock lab level dips on average about 15° steeper than the bedding planes but exhibits a similar strike direction (Nussbaum et al. 2011).
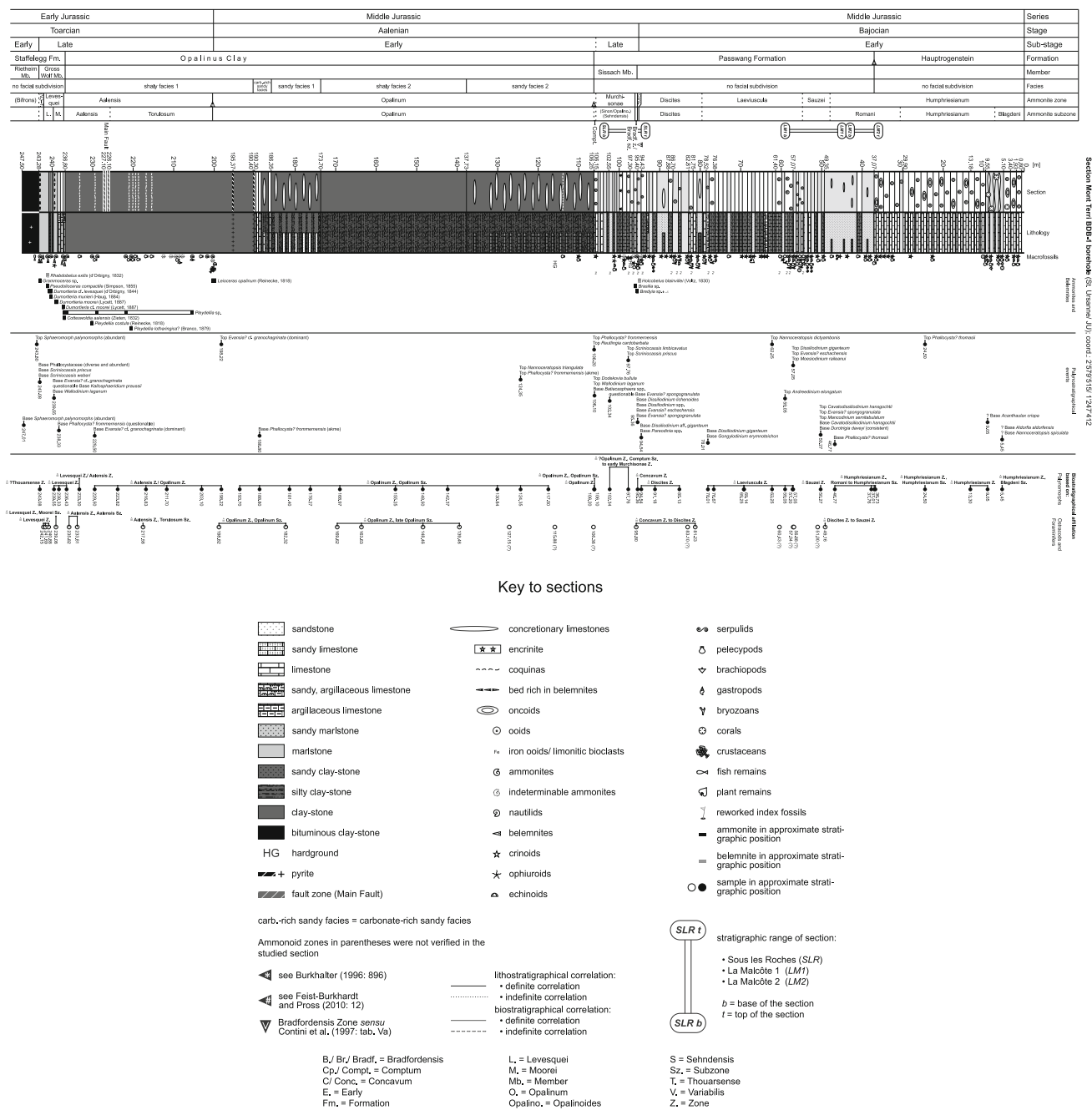
Fig. 2 Detailed section of the Early and Middle Jurassic strata of the Mont Terri BDB-1 core. Plotted next to the section are the position of macrofossil finds, selected palynological events in the section used for palynostratigraphical age dating, and the biostratigraphic interpretation and age assignment of samples to ammonite zones/subzones based on palynomorphs, and ostracods and foraminifers respectively. A high-resolution version of this figure is published as Electronic Supplementary Material with the online version of this paper. In the printed version, Fig. 2 is included as an A3-size foldout

2 Materials and methods

We processed the paleontological inventory with the goal of undertaking a detailed biostratigraphic subdivision of the studied formations. The latter was compiled on the basis of ammonites, ostracodes, foraminifera, and palynomorphs. Micropaleontological dating was based on 24 outwash samples and 47 samples extracted from the drill-core BDB-1 and processed for quantitative palynological analysis. The methodology used for the micropaleontological and quantitative palynological analysis is described in Reisdorf et al. (2016) and Feist-Burkhardt (2014). We present the geophysical logs and clay content estimates in Chapter 4 of the Supplement.

Three partial sections of the Passwang Formation and the basal Hauptrogenstein located in the vicinity of the BDB-1 drilling site were logged [see Supplementary Chapters 1 to 3: Sous les Roches, La Malcôte 1, and La Malcôte 2 (see Bossart et al. 2017: Fig. 2)]. Correlating these partial sections with the BDB-1 log allowed us to cross-check the bio- and lithostratigraphy with the drillcore (Suppl. Figures 1 to 2). The macrofossils obtained from the BDB-1 drillcore and the outcrop samples have been deposited at the Naturhistorisches Museum der Burgergemeinde Bern.

3 Lithostratigraphy of the Mont Terri BDB-1 core

3.1 Staffelegg Formation (247.50–236.80 m)

The stratigraphically lowermost part of the core (247.50–243.28 m) comprises thinly bedded, brownish-black, bituminous, silty mudstones of the Rietheim Member (Fig. 2; Table 1). Above this follows the Gross Wolf Member (243.28–236.80 m) containing grey clayey marls and light grey marls, argillaceous limestones with filamentous bivalves and occasional layers rich in belemnites. These layers feature cone-in-cone calcite. The top of the Staffelegg Formation is defined by the last argillaceous limestone bed.

3.2 Opalinus clay (236.80–106.25 m)

From bottom to top, we classify the 130.55 m thick Opalinus Clay in the BDB-1 core into five subunits of specific facies:

1. Shaly facies 1 (236.80–190.40 m): dark grey calcareous, silty-sandy claystones containing mica and pyrite. It features numerous white, mm thin to max. 3 cm thick calcite lenses, consisting of cone-in-cone calcite.
2. Carbonate rich sandy facies (190.40–186.35 m): dark grey, calcareous, silty-sandy claystone layers alternating with light-grey calcareous lenses and dm-size layers. These latter consist of silt- to fine-sand-size grains and biogenic components derived mainly from bivalves and echinoderms up to 2 cm in size.
3. Sandy facies 1 (186.35–173.70 m): calcareous, silty-sandy claystones interspersed with numerous light-grey, thinly bedded sandstone lenses. The latter features small ripple and bioturbation structures with a lens-like shape due to compaction.
4. Shaly facies 2 (173.70–137.73 m): dark grey, mostly mica and pyrite containing calcareous silty-sandy claystones.
5. Sandy facies 2 (137.73–106.25 m): calcareous, silty-sandy claystones with numerous light-grey, laminated sandstone lenses. The latter feature small ripples,

occasionaly lens-like due to compactional overprinting. Additionally, several bioclast-rich lenses and layers occur in this facies.

3.3 Passwang formation (106.25–37.07 m)

In the Mont Terri area, the base of the Passwang Formation begins with the first bed containing chamositic iron ooids and lithoclasts. In the borehole we measured upwards nearly 70 m of silty to fine-sandy marls, quartz sand and limestones with biodetritus in the sand fraction, ferruginous limestones, and iron oolithic marls and limestones. This section between 106.25 and 76.38 m is very heterogeneous: grey, silty to fine sandy marls, with thin sandstone lenses, of which one part is rich in quartz sand, the other rich in calcareous biodetritus. Within this marl series, rust-red limonitic and sandy limestone beds are repeatedly interspersed. They contain limonitic bioclasts and occasional iron ooids. This lower stratigraphic sequence of the Passwang Formation can be attributed to the Sissach Member (106.25–95.40 m; cf. Burkhalter 1996: 900). In the drillcore, the topmost beds of the Sissach Member (97.90–95.40 m) are represented by iron oolithic limestones with lithoclasts. The beds overlying the Sissach Member can be clearly distinguished from the members of the Passwang Formation sensu Diebold et al. (2006) and Jordan et al. (2008) and, as defined in the area of geographical extension (Burkhalter 1996: 908-916), by their lithology and stratigraphic architecture. A subcategorization of these sediments into members of the Passwang Formation sensu Jordan et al. (2008) is therefore not possible (Fig. 2; Table 1).

The section 76.38–61.40 m comprises alternating beds of light-grey, partially laminated and crossbedded sandy limestones alternating with thin marl layers. In several of the sandy limestones, quartz-sand-rich laminae alternate with bioclast-rich laminae. The core section 61.40–57.07 m is dominated by coarse, sparitic and biodetrital sandy limestone beds featuring rust-red bioclasts (bryozoans, bivalves, and echinoderms) as well as limonitic intraclasts. The sandy limestone beds alternate with biodetritus-rich marls.

The uppermost part of the Passwang Formation (57.07–37.07 m) begins with slab-shaped, fine-sandy, biodetrital limestones alternating with fine-sandy marls. Above, silty to fine-sandy marls with mm-thin sandstone lenses follow. Both the limestones and marls are occasionally rich in ferruginous dolomite.

3.4 Hauptrogenstein (37.07–0 m)

The base of the Hauptrogenstein is the first oolithic limestone. The entire section of the core measured between

Table 1 Names of the Mesozoic rocks in the Mont Terri area and the subunits previously in use, the units of the BDB-1 borehole are highlighted in grey

Formation	Member	Old names
Reuchenette		*Kimméridgien, Ptérocérien*
	Vabenau	*Calcaires à Ptérocères inférieurs*
Courgenay		*Séquanien, Humeralis-Kalk*
	Porrentruy	*Séquanien supérieur*
	La May	*Calcaires à Térébratules*
Vellerat		*Séquanien, Couches d'Angolat*
	Bure	*Humeralis-Mergel*
	Hauptmumienbank	*Oolithe nuciforme, Oolithe pralinée, Oolithe grossière*
	Röschenz	*Séquanien inférieur, Natica-Mergel*
	Vorbourg	*Séquanien inférieur, Plattige Kalke, Couches du Vorbourg*
St-Ursanne		*Rauracien*
	Buix	*Calcaires crayeux ou corallien*
	Chestel	*ex Membre de Delémont, Oolithe corallienne, Pisolite de la Caquerelle*
Bärschwil		
	Liesberg	*Liesberg Schichten, Couches de Liesberg*
	Sornetan	*Terrain à Chailles*
	Renggeri	*Renggeriton, Marnes oxfordiennes*
Ifenthal		*Calcaire roux sableux-Callovien*
	Herznach	*Anceps-Athleta-Schichten*
	Bollement	*Dalle nacrée*
	Ängistein	*equivalent Dalle nacrée*
	Saulcy	*Callovien-Ton, Marnes calloviennes*
	Châtillon	*Makrocephalen-Kalke*
	St-Brais	*Calcaire roux sableux*
Hauptrogenstein		
	Pierre Blanche	
	Movelier	*Movelier Schichten*
	Oberer Hauptrogenstein	*Grande Oolithe, Oolithe supérieure*
	(Obere) Acuminata-Mergel	*Homomya-Mergel, Marnes à Ostrea acuminata*
	Unterer Hauptrogenstein	*Oolithe subcompacte, Oolithe inférieure*
Passwang		*Unterer Dogger/Blaukalk*
	undiff.	
	Sissach	*Murchisonae-Schichten*
Opalinus Clay		*Lias, Marnes aalenienes, Lias supérieur*
Staffelegg		*Lias, unterer und mittlerer Lias*
	Gross Wolf	*Jurensis-Mergel/ -Schichten*
	Rietheim	*Posidonienschiefer, Schistes cartons, Schistes à Posidonies*
	?Rickenbach	*Mittlerer Lias?*
	Breitenmatt	*Mittlerer Lias?*
	Mont Terri	*Obliqua-Schichten? und Mittlerer Lias?*
	Beggingen	*Gryphitenkalk*
Klettgau		*Rhät und (oberer) Mittlerer Keuper*
	Belchen	*Rhätsandstein, Rhétien*
	Gruhalde	*Oberster Keuper, Marnes bigarrées supérieures*
	Gansingen	*Hauptsteinmergel, Gansinger Dolomit*
	Ergolz	*Untere Bunte Mergel und Schilfsandsteinstufe, grès à roseaux*
Bänkerjoch		*unterer Mittlerer Keuper, Gipskeuper, Marnes à anhydrite*
Schinznach		*Oberer Muschelkalk und Unterer Keuper (Lettenkohle)*
	Asp	*Unterer Keuper, Lettenkohle*
	Stamberg	*Trigonodusdolomit*
	Liedertswil	*Plattenkalk*
	Kienberg	*Oberer Trochitenkalk*
	Leutschenberg	*Unterer Trochitenkalk*
Zeglingen		*Mittlerer Muschelkalk; Anhydrit-Formation, Anhydrit-Gruppe*
	"Dolomitzone" (der Anhydritgruppe)	*Anhydritdolomit*

37.07 and 0 m belongs to the lower part of the Hauptrogenstein (="Lower Oolitic Series"; Gonzalez and Wetzel 1996). The lowermost layers (37.07–29.90 m) consist of grey, oolithic, oncolithic and bioclastic micrites. Upsection (29.90–13.18 m), there are well-defined, coarse-grained, beige and light grey calcarenites, in which oncosparites clearly dominate. In the interval above (13.18–5.10 m), coral-containing, bioclast-rich marls follow, then oncomicritic and oncosparitic limestones reappear.

4 Macrofossils and biostratigraphy of the Mont Terri BDB-1 core

The timeframe of the lithological succession in the core ranges from the Late Toarcian (Early Jurassic) to the Early Bajocian (Middle Jurassic) and can be fixed with certainty by means of ammonite biostratigraphy. Furthermore, we list fossils (bivalves, corals) that are characteristic of specific stratigraphic levels and provide clues to the stratigraphic correlation (see also Suppl. Chapter 3). The complete documentation for the macrofossils at the studied localities can be found in Reisdorf et al. (2016).

The BDB-1 core provides no evidence of the Variabilis Zone, nor did our assessment of microfauna or palynomorphs provide any such evidence. A fragment of a *Grammoceras* sp. recovered from the core at depth 243.23–243.28 m represents the oldest datable finding (Fig. 2). Its stratigraphic position within the Gross Wolf Member permits a tentative dating of the sediments to the Thouarsense Zone (Late Toarcian). As expected, the presence of *Cotteswoldia aalensis* (ZIETEN, 1832) a few cm below the topmost bed of the Gross Wolf Member indicates Aalensis Subzone age (Aalenis Zone, Late Toarcian; cf. Reisdorf et al. 2011a).

Numerous *Pleydellia* sp. specimens and a specimen of *Pleydellia lotharingica*? (BRANCO, 1879) were found in the basal strata of the Opalinus Clay. This fauna of late Toarcian age in sediments with typical (shaly) facies of the Opalinus Clay confirm the result of our initial study undertaken at the Mont Terri rock laboratory according to which the lithostratigraphic boundary between the Staffelegg Formation and the Opalinus Clay deviates by many m from the biostratigraphic boundary between the Toarcian (Early Jurassic) and the Aalenian (Middle Jurassic) (Reisdorf et al. 2014). The *Pleydellia lotharingica*? (BRANCO, 1879) specimen provides evidence to substantiate the Torulosum Subzone dating (Late Aalensis Zone) (cf. Ohmert and Rolf 1994, Feist-Burkhardt and Pross 2010). In the BDB-1 core, the Early–Middle Jurassic boundary is determined by the first occurrence of *Leioceras opalinum* (REINECKE, 1818) within the shaly facies of the Opalinus Clay at 200.37 m.

The next ammonite findings do not appear again until the Sissach Member (Passwang Formation). The first biostratigraphically useful finds permit an allocation to the genus *Brasilia*. Four specimens date the level at 95.95 m to the Bradfordensis Zone (Late Aalenian; cf. Burkhalter 1996: 900). Moreover, the finding of a *Bredyia* sp. at 95.50–95.55 m is noteworthy; this specimen was found at the top of an approx. 50 cm-thick, iron ooid-bearing layer sequence embedded in a lithoclast. Numerous specimens of *Bredyia* sp. preserved in this way were also found in the Sous les Roches section in similar sediments of Bradfordensis Zone age (see Supplement Chapter 2.1). The sedimentological context of these findings indicates reworking processes within a condensed layer sequence during the Bradfordensis Zone (cf. Dietze et al. 2014).

5 Invertebrate microfossils and biostratigraphy

5.1 Results

The complete documentation for the microfossils of the BDB-1 core can be found in Reisdorf et al. (2016).

5.1.1 Gross Wolf Member (Staffelegg Formation)

The four samples taken from the Gross Wolf Member of the BDB-1 core contain several ostracode species that are characteristic for the Late Toarcian: *Cytherella apostolescui* AINSWORTH, 1986; *Cardobairdia toarcensis* AINSWORTH, 1986; *Cytheropteron groissi* KNITTER, 1984; *Supratoarcina supratoarcensis* KNITTER and RIEGRAF, 1984; *Kinkelinella costata* KNITTER, 1983 and *Ektyphocythere furcata* (WIENHOLZ, 1967). The last one is an index species for the Latest Dispansum Subzone (Insigne Zone) up to the Earliest Aalensis Subzone (Aalensis Zone) in southern Germany. In sample 4 (239.08 m) *Praeschuleridea ventriosa* (PLUMHOFF, 1963), the most important index species for the Late Toarcian and Aalenian, has its first appearance (Table 2). Some typical Late Toarcian foraminifera have a maximal abundance in these four samples as well: *Thurammina jurensis* (FRANKE, 1936), *Lenticulina helios* (TERQUEM, 1870) and *Palmula jurensis* (FRANKE, 1936) (Table 3).

5.1.2 Opalinus Clay

At the base of the Opalinus Clay (sample 5 at 235.82 m), there is evidence of a faunal change. *Aphelocythere kuhni* TRIEBEL and KLINGLER, 1959 occurs here for the first time (Table 2). This ostracode species is the only reliable marker for the Toarcian–Aalenian transition range (but not for the exact Toarcian–Aalenian boundary).

Table 2 Stratigraphical occurrence and frequency of ostracoda in the BDB-1 section, light grey = seldom (1–3 specimens/3 trays), medium grey = not seldom (4–10), black = abundant (>10)

Formation	Staffelegg				Opalinus Clay												Passwang							
Member	Gross Wolf																Sissach							
Ammonite Zone	Levesquei				Aalensis			Opalinum						?	?	?	Concavum to Discites			?	?	?	?	Discites to Sauzei
Ammonite Subzone				Moorei	Aalensis		Torulosum	Opalinum																
Drill core depth [m]	242.15	241.69	240.88	239.08	235.82	233.81	217.58	198.82	182.32	169.62	163.63	148.46	139.46	127.15	115.88	106.36	95.80	83.10	81.23	60.43	57.04	56.88	51.00	49.16
Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Ostracodes

- *Cytherella apostolescui* AINSWORTH, 1986
- *Cytherella callosa ampla* BRAUN in DILGER, 1963
- *Cytherelloidea cadomensis* BIZON, 1960
- *Bairdia hilda* JONES, 1884
- *Bairdiacypris* sp.
- *Cardobairdia toarcensis* AINSWORTH, 1986
- *Bythocypris dorisae* KNITTER, 1984
- *Cytheropteron groissi* KNITTER, 1984
- *Cytheropteron supraliassicum* (HERRIG, 1981)
- *Cytheropterina alafastigata* (FISCHER, 1962)
- *Cytheropterina cribra* (FISCHER, 1962)
- *Bythoceratina scrobiculata* (TRIEBEL and BARTENSTEIN, 1938)
- *Monoceratina ungulina* TRIEBEL and BARTENSTEIN, 1938
- *Otocythere callosa* TRIEBEL and KLINGLER, 1959
- *Pleurocythere? kirtonensis* BATE, 1963
- *Kirtonella plicata* BATE, 1963
- *Eucytherura angulocostata* KNITTER, 1983
- *Eucytherura liasssica* BATE and COLEMAN, 1975
- *Eucytherura?* sp. 1
- *Rutlandella transversiplicata* BATE and COLEMAN, 1975
- *Procytherura* sp. 1
- *Procytherura* sp. 2
- *Aaleniella reticulata* KNITTER, 1983
- *Aaleniella* sp. 1
- *Aaleniella?* sp.
- *Supratoarcina supratoarcensis* KNITTER and RIEGRAF, 1984
- *Kinkelinella costata* KNITTER, 1983
- *Kinkelinella fischeri* MALZ, 1966
- *Kinkelinella sermoisensis* (APOSTOLESCU, 1959)
- *Kinkelinella* sp. A OHMERT, 1988
- *Ektyphocythere furcata* (WIENHOLZ, 1967)
- *Praeschuleridea gallemannica* MALZ, 1966
- *Praeschuleridea punctulata* (PLUMHOFF, 1963)
- *Praeschuleridea ventriosa* (PLUMHOFF, 1963)
- *Praeschuleridea? pinguis* (PLUMHOFF, 1963)
- *Praeschuleridea decorata* BATE, 1968
- *Praeschuleridea subtrigona* (JONES and SHERBORN, 1888)
- *Acrocythere pumila* PLUMHOFF, 1963
- *Aphelocythere asymmetrica* FRANZ et al., 2009
- *Aphelocythere kuhni* TRIEBEL and KLINGLER, 1959
- *Aphelocythere hamata* PLUMHOFF, 1963
- *Aphelocythere pygmaea* PLUMHOFF, 1963
- *Aphelocythere* sp. 1 PLUMHOFF, 1963
- *Camptocythere gracilis* PLUMHOFF, 1963
- *Camptocythere modesta* TRIEBEL, 1950
- *Fuhrbergiella sauzei* BRAND and MALZ, 1962
- *Paracypris* sp.

Table 3 Stratigraphical occurrence and frequency of foraminifera in the BDB-1 section, light grey = seldom (1–3 specimens/3 trays), medium grey = not seldom (4–10), black = abundant (>10)

	Staffelegg				Opalinus Clay												Passwang							
Formation																								
Member	Gross Wolf																Sissach							
Ammonite Zone	Levesquei				Aalensis			Opalinum						?	?	?	Concavum to Discites			?	?	?	?	Discites to Sauzei
Ammonite Subzone				Moorei	Aalensis		Torulosum	Opalinum																
Drill core depth [m]	242.15	241.69	240.88	239.08	235.82	233.81	217.58	198.82	182.32	169.62	163.63	148.46	139.46	127.15	115.88	106.36	95.80	83.10	81.23	60.43	57.04	56.88	51.00	49.16
Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Foraminifers

- *Reophax metensis* FRANKE, 1936
- *Thurammina jurensis* (FRANKE, 1936)
- *Ammobaculites coprolithiformis* (SCHWAGER, 1867)
- *Ammobaculites fontinensis* (TERQUEM, 1870)
- *Lingulina spatulata* TERQUEM, 1870
- *Frondicularia oolithica* TERQUEM, 1870
- *Pseudonodosaria vulgata* (BORNEMANN, 1854)
- *Nodosaria fontinensis* TERQUEM, 1870
- *Nodosaria sexcostata* TERQUEM, 1858
- *Nodosaria striatojurensis* KLÄHN, 1923
- *Marginulina oolithica* (TERQUEM, 1870)
- *Lenticulina dictyodes* (DEECKE, 1884)
- *Lenticulina dorbignyi* (ROEMER, 1839)
- *Lenticulina helios* (TERQUEM, 1870)
- *Lenticulina muensteri* (ROEMER, 1839)
- *Lenticulina prima* (D'ORBIGNY, 1850)
- *Lenticulina varians* (BORNEMANN, 1854)
- *Subhercynella paucinodula* BARTENSTEIN and LUPPOLD, 2005
- *Astacolus suprajurassicus* (SCHWAGER, 1865)
- *Planularia cordiformis* (TERQUEM, 1863)
- *Palmula deslongchampsi* (TERQUEM, 1863)
- *Palmula jurensis* (FRANKE, 1936)
- *Citharina infraopalina* BRAND, 1962
- *Reinholdella dreheri* (BARTENSTEIN, 1937)
- *Reinholdella traubensis* OHM, 1967
- *Spirillina oolithica* (SCHWAGER, 1867)
- *Spirillina polygyrata* GÜMBEL, 1862

The microfauna in sample 7 (217.58 m) is dominated by two foraminiferal species: *Reinholdella dreheri* (BARTENSTEIN, 1937) and *Reinholdella traubensis* OHM, 1967. *Aphelocythere kuhni* TRIEBEL and KLINGLER, 1959 has its last occurrence in sample 10 (169.62 m). *Aphelocythere pygmaea* PLUMHOFF, 1963, *Aphelocythere hamata* PLUMHOFF, 1963 (both in samples 10–13), and *Acrocythere pumila* PLUMHOFF, 1963 (in sample 13 only) were introduced by PLUMHOFF (1963) as index species of the Sinon to Staufensis Subzones (Murchisonae

Zone). In sample 13 (139.46 m), *Cytherelloidea cadomensis* BIZON, 1960; *Cytheropterina cribra* (FISCHER, 1962), and *Aaleniella reticulata* KNITTER, 1983, all remnant Toarcian species, have their last occurrence. Thus, a faunal break is evident at the top of this sequence, with several new species arising in higher stratigraphic levels (Tables 2, 3). Only a few species like *Kinkelinella sermoisensis* (APOSTOLESCU, 1959) and *Praeschuleridea punctulata* (PLUMHOFF, 1963) cross this chronostratigraphic boundary.

5.1.3 Passwang Formation

Samples 17 (95.80 m) and 19 (81.23 m) contain an almost identical and rich microfauna. The foraminiferal species *Lenticulina dictyodes* (DEECKE, 1884) makes its first appearance in sample 19. Its biostratigraphical range is from the Discites to the Humphriesianum Zone. Several ostracode index species appear for the first time in core samples from this range: *Cytherella callosa ampla* BRAUN in DILGER, 1963 and *Praeschuleridea decorata* BATE, 1968 (in sample 17 only), *Praeschuleridea? pinguis* (PLUMHOFF, 1963); *Camptocythere gracilis* PLUMHOFF, 1963; *Camptocythere modesta* PLUMHOFF, 1963; *Kinkelinella* sp. A OHMERT, 1988 (all in samples 17 and 19); *Praeschuleridea subtrigona* (JONES and SHERBORN, 1888) and *Aphelocythere asymmetrica* FRANZ et al., 2009 (both in sample 19). The biostratigraphical range of these ostracode species, as stated in the literature, seems somewhat controversial (for more details see Reisdorf et al. 2016). Summarising our findings, we deem a dating between the Murchisonae- and Discites Zone to be most appropriate. Sample 24 (49.16 m) yielded a rather rich and diverse fauna and several ostracode species appear for the first time in the BDB-1 core samples: *Bairdia hilda* JONES, 1884; *Bairdiacypris* sp.; *Pleurocythere? kirtonensis* BATE, 1963; *Kirtonella plicata* BATE, 1963; *Eucytherura?* sp. 1; *Procytherura* sp. 1; *Procytherura* sp. 2; *Aaleniella?* sp.; *Aphelocythere* sp. 1 PLUMHOFF, 1963, as well as *Fuhrbergiella sauzei* BRAND and MALZ, 1962. In England *Bairdia hilda* JONES, 1884; *Kirtonella plicata* BATE, 1963 and *Pleurocythere? kirtonensis* BATE, 1963 are reported from the Discites Zone (Bate 1963), the latter also from the Discites- to Laeviuscula Zone in southwestern Germany (Ohmert 1988). *Fuhrbergiella sauzei* BRAND and MALZ, 1962 appears first in the Early Bajocian and is most abundant in the Sauzei Zone. Of the foraminifera, *Ammobaculites coprolithiformis* (SCHWAGER, 1867) is a characteristic component of the fauna.

5.2 Interpretation

Based on the range charts of certain ostracode species, we can make a biostratigraphical subdivision of the BDB-1 drillcore (Table 2; Fig. 2). There is a basal unit of "Toarcian character" (in quotes because of its onset in the Late Toarcian with no relevant change at the Toarcian–Aalenian boundary) ranging from 242.15 to 198.82 m. After a faunal depletion in the lower sandy facies of the Opalinus Clay (184–171 m), a second biostratigraphic interval from 169.62 to 139.46 m is characterized by the continuing occurence of Toarcian taxa, with some newly appearing index species of the Sinon to Staufensis Subzone (Murchisonae Zone) as known from NW Germany (where the Comptum Subzone of the Opalinus Zone is missing;

Plumhoff 1963). Separated by a further faunal hiatus in the upper sandy facies of the Opalinus Clay (127.15–106.36 m), the stratigraphic interval from 95.80 to 81.23 m exhibits a significant faunal change with index species for the Concavum to Discites zones. Up to 51.00 m the microfauna again diminishes, but the sample from 49.16 m contains further new ostracode taxa typical for the Discites to Sauzei zones. The extension and the limits of these biostratigraphical intervals of the BDB-1 core are somewhat uncertain because of the restricted number and distribution of the collected samples.

We can achieve a finer subdivision of the "Toarcian character" in the basal interval. The interval from 242.15 to 240.88 m with *Ektyphocythere furcata* (WIENHOLZ, 1967) and the absence of *Praeschuleridea ventriosa* (PLUMHOFF, 1963) could represent the Levesquei to Early Moorei subzones (Levesquei Zone). According to Knitter (1983), *Praeschuleridea gallemannica* MALZ, 1966 disappears in the Earliest Aalensis Subzone (Aalensis Zone); its last occurrence in the BDB-1 core is in sample 6 (233.81 m). With *Aphelocythere kuhni* TRIEBEL and KLINGLER, 1959 at 235.82 m, the Toarcian–Aalenian boundary should be expected somewhat higher (but not lower) in the section. Based on foraminifera in the Wittnau section (SW Germany), Ohmert (1996) established a Traubensis Zone crossing the Toarcian–Aalenian boundary, and a Dreheri Zone covering the Torulosum- and Opalinum Subzones (Late Aalensis to Early Opalinum zones). In the BDB-1 section *Reinholdella traubensis* OHM, 1967 is found at 217.58 m (Table 3). The exact position of the Toarcian–Aalenian boundary cannot be determined by means of microfossils, but a transition range is suspected between 230 and 199 m.

6 Palynomorphs and palynostratigraphy

Whereas biostratigraphic resolution of pollen and spores is limited in Jurassic assemblages, it is possible to perform high-resolution biostratigraphy based on dinoflagellate cyst occurrences. Indeed, dinoflagellate families show numerous first appearances (FAD = first appearance date) during the Early Jurassic followed by a diversification within families. In the past few years, dinoflagellate cyst assemblages have been identified from outcrops and boreholes in southern Germany and northern Switzerland (see Feist-Burkhardt and Wille 1992; Feist-Burkhardt and Pross 2010). These works form the basis for a Composite Standard developed by Feist-Burkhardt (unpublished) for the Early to Middle Jurassic that serves as a reference for validating the new biostratigraphic scheme of the Mont Terri area, adapted primarily on ammonite zonation.

6.1 Results

The studied samples yielded a well-preserved, rich, and diverse palynoflora. The palynomorph assemblages are composed mainly of dinoflagellate cysts (93 taxa in total). Pollen and spores (51 taxa) also occur, as well as minor components (24 taxa), among which are prasinophytes, acritarchs, fungal remains, foraminiferal test linings, and green algae. Feist-Burkhardt (2014 in Reisdorf et al. 2016) presents a range chart with quantitative stratigraphic distribution of palynomorphs together with proposed age assignments, as well as age and depth/age plots.

Fourteen stratigraphic intervals were identified based on their palynological content (mainly dinoflagellate cysts), ranging from the Early Toarcian to Early Bajocian. Table 4 summarises the palynostratigraphic subdivision and assigns each interval to the corresponding ammonite zone and occurrence within the lithostratigraphic unit.

6.2 Interpretation

At its lowermost level, the borehole reached the typical facies of the Rietheim Member of the Staffelegg Formation ("Posidonienschiefer"; see Table 1), containing almost exclusively amorphous organic matter and small sphaeromorph palynomorphs. This bituminous facies is considered to be of Early Toarcian age.

Uphole, the first rich palynoflora comprising abundant pollen, spores, and dinoflagellate cysts occurs at 243.08 m. This sample dates from the Late Toarcian, probably Thouarsense Zone (occurrence of diverse and abundant Phallocystaceae and Valvaeodiniaceae, in particular *Scriniocassis priscus* (GOCHT, 1979) BELOW, 1990. The uppermost part of the Staffelegg Formation (Gross Wolf Member) was deposited during the Levesquei Zone or Aalensis Zone.

The lowermost samples from the Opalinus Clay (at 236.43 m and 233.30 m) confirm that the deposition of this formation already began during the Late Toarcian (Levesquei to Aalensis Zones) in the Mont Terri area (Reisdorf et al. 2013, 2014).

Based on palynostratigraphy, the position of the Toarcian–Aalenian boundary interval (occurrence acme of *Evansia*? cf. *granochagrinata* BELOW, 1990 between 229.50 m and 198.22 m) is in good accordance with the results obtained from ammonite biostratigraphy (first

Table 4 Palynostratigraphic subdivision of the BDB-1 borehole into 14 intervals, with assignment to the corresponding ammonite zone and chronostratigraphy. The general lithostratigraphic scheme is given on the right side

Chronostratigraphy		Biostratigraphy		Palynostratigraphy		Remarks (resp. units in Feist-Burkhardt & Pross 2010)	Lithostratigraphy	
Stage	Substage	Zone	Subzone	Depth [m]	Nr.		Member	Formation
Bajocian	Middle	Humphriesianum	Blagdeni	5.45	14	FAD of *Aldorfia aldorfensis*		Hauptrogenstein
			undifferentiated	13.30 – 9.05	13	FAD of *Acanthaulax crispa* and *Meiourogonyaulax* spp.		
			Humphriesianum	46.77 – 24.50	12	rich in fungal remains and *Sentusidinium* spp.		
			Romani			rich in foraminiferal test linings, FAD of *Phallocysta thomasii*		Passwang
	Early	Sauzei		50.27	11	extremely abundant foraminiferal test linings, LAD of *Cavatodissiliodinium hansgochtii*		
		Laeviuscula		78.01 – 57.05	10	abundant and diverse *Dissiliodinium* spp.		
		Discites		94.54 – 85.13	9			
Aalenian	Late	Concavum		95.36	8	FAD of *Evansia*? *eschachensis*	Sissach	
		Murchisonae		102.34 – 97.76	7	strongly reduced diversity of Phallocystaceae		
	Early	Opalinum	Comptum	106.10	6	unit D		
			Opalinum	193.70 – 106.20	5	units B and C		
				229.50 – 198.22	4	acme of *Evansia*? cf. *granochagrinata* (unit A)		Opalinus Clay
Toarcian	Late	Aalensis		239.55 – 233.30	3	further diversification (Phallocystaceae and Valvaeodiniaceae)		
		Levesquei					Gross Wolf	
		Thouarsense		243.08	2	first rich palynoflora		Staffelegg
	Early	Variabilis						
		Bifrons		247.01 – 243.80	1	typical bituminous facies (AOM and sphaeromorphs)	Rietheim	
		Falciferum						

occurrence of *Leioceras opalinum* (REINECKE, 1818) at 200.50 m, see Chapter 4).

The overlying and major part of the Opalinus Clay was deposited during the Opalinum Subzone.

The base of the Passwang Formation dates from the Opalinum Subzone as well (samples at 106.20 and 106.10 m) whereas the top dates from the Humphriesianum Zone. Pollen and spores are relatively more abundant here than in the surrounding levels (especially the sporomorph taxon *Perinopollenites elatoides* COUPER, 1958). The Comptum Subzone, Concavum Zone, Discites Zone, Laevisucula Zone and Sauzei Zone are also documented palynostratigraphically.

The base of the Hauptrogenstein is dated palynostratigraphically as Romani Subzone to Humphriesianum Subzone (Humphriesianum Zone, based on the occurrence of the dinoflagellate cyst *Phallocysta thomasii* SMELROR, 1991). It is also characterized by its richness in fungal remains and *Sentusidinium* spp.

In conclusion, in combination with the revised ammonite and microfossil zonations, the present palynostratigraphic analysis provides a solid biostratigraphic framework for the Opalinus Clay and bounding formations in the Mont Terri area.

7 Discussion and concluding remarks

The BDB-1 drillcore provided a multitude of significant stratigraphic and geophysical data on the Mont Terri area. This data permits a straightforward subdivision of the sampled core into a lithostratigraphic resolution of individual formations (Fig. 2). Of particular significance is the fact that we have recorded a continuous section from the upper part of the Staffelegg Formation to the basal beds of the Hauptrogenstein in detail for the first time. It has proven useful to compare the BDB-1 core with the three studied sections close to the Mont Terri rock laboratory; nearly half of the encountered beds of the Passwang Formation, including the basal beds of the Hauptrogenstein, are covered stratigraphically by these partial sections (Fig. 2, Suppl. Figure 3 and Suppl. Figure 2). The outcrops that were referenced before the initiation of drilling had already served as suitable stratigraphic aids for orientation purposes during the drilling campaign, e.g. anticipation of the boundary between the Passwang Formation and the Hauptrogenstein.

A key result of the present study is that the lithological succession of the core, and also of the near-by outcrops, is at the formation level, clearly correlatable with the lithostratigraphical units that were defined in their type regions lying farther east.

This holds true for the Staffelegg Formation, of which only the upper part consisting of the Rietheim and Gross Wolf Members were encountered (cf. Reisdorf et al. 2011a). Aside from that, the basal strata of the Passwang Formation can be identified as the Sissach Member (cf. Burkhalter 1996). The "Lower Oolitic Series" is developed as an informal lithostratigraphic unit of the Hauptrogenstein in the study area (Gonzalez and Wetzel 1996).

On the other hand, the facial configuration and stratigraphic architecture of the Opalinus Clay and the Passwang Formation in the study area deviate to a greater or lesser degree from the occurrences that are situated farther east in northern Switzerland (Bläsi et al. 1996; Burkhalter 1996; Wetzel and Allia 2003; Jordan et al. 2008). As expected, the several m thick, relatively carbonate-rich sandy facies variations of the Opalinus Clay (Bläsi et al. 1991, 1996) typical of the Mont Terri region, are also traceable in the BDB-1 core. The subdivisions of the Opalinus Clay also correlate with the geophysical logs (Supplement Chapter 4). These geophysical logs observed in outcrops and boreholes in the Mont Terri rock laboratory are important to help better define transitional lithostratigraphic boundaries. Especially the intraformational transitions between sandy and shaly facies of the Opalinus Clay can be well constrained using geophysical criteria.

Of greater significance for the current stratigraphic nomenclature of northern Switzerland is the facial configuration of the beds of the Passwang Formation above the Sissach Member (see Supplement Chapter 1). No member of the Passwang Formation as defined in the extended area compares with the lithologies encountered in the Mont Terri area (cf. Burkhalter 1996: 908–916, Figs. 18 to 21; Jordan et al. 2008). We think that a definition of new lithostratigraphic units (members) to accommodate the local facial features would be desirable in this context, but this lies beyond the scope of the present work. However, comparing the BDB-1 core with the outcrops of Sous les Roches, La Malcôte 1 and La Malcôte 2, all close to the Mont Terri rock laboratory, suggests that distinct facies changes occur in the Mont Terri area over short distances thereby giving rise to more-or-less intense variations in the thickness of individual layers. For example, the marl following the Sissach Member, measured in the BDB-1 core, is 1.03 m thick whereas in the section Sous les Roches the marl is clearly more than 1.5 m thick. In the case of the sections described in this study, opportunities for correlation are limited to only a few stratigraphic levels (Fig. 2, Suppl. Figure 1 and Suppl. Figure 2).

A further essential finding from the BDB-1 borehole is the significant deviation of the total thickness of the Opalinus Clay from the most recent thickness calculations: the BDB-1 core thickness measured at ca. 130 m is 20 m thinner than that calculated for the Mont Terri rock laboratory (cf. e.g. Reisdorf et al. 2014). The Mont Terri mountain is built of a

structurally complicated anticlinal feature and numerous, mostly layer-parallel, faults are interspersed throughout the rock laboratory section as well as in the borehole. Thus for the time being, we cannot determine whether (1) one of the two thickness values represents a true thickness; (2) the lesser thickness in the drillcore was produced by shearing and/or squeezing; or (3) a doubling of the thickness of certain strata is present in the rock laboratory section and thus is responsible for a total thickness of 150 m.

The stratigraphic architecture and facies configuration of the Opalinus Clay (including two thin, horizon-stable pyrite horizons; see Reisdorf et al. 2014), typically developed in both sections for the Mont Terri area, does not permit us to decide on one thickness value or the other. Additionally, neither in the rock laboratory section nor in the drillcore are tectonically based doublings of strata, or gaps in strata, evident (see below). In the end, the stratigraphic position of the Main Fault in the drillcore, which deviates from that in the rock laboratory section, does not—according to the present state of understanding—contribute to solving the problem.

The independently derived macro- and micropaleontological findings from the studied core material are in themselves consistent in a noteworthy manner. The individual methods (ammonite, ostracode, foraminiferal biostratigraphy, and palynostratigraphy) supplement one another, not only spatially, but they also provide evidence for nearly all relevant biozones in a time period that extends from the Bifrons Zone (Early Toarcian) to the Humphriesianum Zone (Early Bajocian) (Fig. 2). The obtained biostratigraphic data thereby permit the following statements and conclusions:

1. the ammonite findings of Toarcian age in sediments with typical facies of the Opalinus Clay (shaly facies) confirm the conclusion of our first study (Reisdorf et al. 2014), according to which the lithostratigraphic boundary between the Staffelegg Formation and the Opalinus Clay deviates by several m from the chronostratigraphic boundary between the Toarcian (Early Jurassic) and the Aalenian (Middle Jurassic);

2. in terms of micropaleontology, the Torulosum Subzone (Late Aalensis Zone) was substantiated in the drillcore for the first time in the study area. In particular we emphasize that when applying the currently valid European Standard ammonite biostratigraphy, the Torulosum Subzone should be allocated to the Aalensis Zone, and thereby to the Latest Toarcian (Early Jurassic) (Feist-Burkhardt and Pross 2010; Reisdorf et al. 2014). The stratigraphic position of the extracted rock sample of Torulosum Subzone age and the first appearance of *Leioceras opalinum* (REINECKE, 1818) in BDB-1 core material suggests a

minimum thickness of 17 m, respectively a maximum thickness of ca. 25 m for sediments of a Torulosum Subzone age. These thickness relations correspond to the orders of magnitude that occur in Wittnau (south of Freiburg i. Br., Germany), featuring nearly 23 m of strata of the same age and configured similarly in terms of facies (cf. Geologisches Landesamt Baden-Württemberg 1996; note the stratigraphic correlation in Reisdorf et al. 2014: Figs. 5-1 and 5-2).

3. The chronostratigraphic boundary between the Toarcian (Early Jurassic) and the Aalenian (Middle Jurassic) lies in the shaly facies 1 of the Opalinus Clay. Approx. 38 m-thick strata in the typical Opalinus Clay facies (shaly facies 1) are chronostratigraphically attributable to the Late Toarcian (Aalensis Zone inclusive of the Torulosum Subzone). We would like to emphasise this result as derived from the present study, since occurrences in sediments of the same age in typical Opalinus Clay facies situated farther to the east are at most only a few cm thick (Etter 1990; Reisdorf 2001; Reisdorf et al. 2011b). Moreover, farther to the east, the Aalensis Zone is most notably represented by sediments up to a few m thick and these can be attributed to the upper strata of the Gross Wolf Member (Staffelegg Formation) (Etter 1990, Nagra 1992; Reisdorf et al. 2011a, b).

4. The oldest sediments of the Opalinus Clay in the Mont Terri area were deposited during the Aalensis Subzone (Aalensis Zone, Late Toarcian). This also applies to many of the Opalinus Clay occurrences to the east of northern Switzerland and neighboring areas in southern Germany (Etter 1990; Reisdorf et al. 2011a, b, 2014: 17). Only a few deviating findings from northern Switzerland have been documented: Bläsi (1987: 417) and Etter (1990: Fig. 8) reported *Leioceras opalinum* from the uppermost part of the "Jurensis-Mergel" (=Gross Wolf Member) of the Riniken borehole, the Weiach borehole, and in the Siblingen section.

5. Sedimentation of the Opalinus Clay initiated in northern Switzerland and SW Germany mostly during the same time period (Aalensis Subzone, Aalensis Zone, Late Toarcian), but in the Mont Terri area with a considerably higher sedimentation rate.

6. Biostratigraphic data derived from outcrops by means of ammonites are better suited to chronostratigraphically comprehend the entire index-fossil-poor strata of the Passwang Formation in the BDB-1 core. Overall, these data suggest that sedimentation of the Sissach Member starts at the Opalinum to Comptum Subzone (Opalinum Zone) boundary and continues up to the Concavum Zone. The latest dating confirms the chronostratigraphic coverage as compared to the area of extension of the Sissach Member (cf. Burkhalter

1996: 900; note: the Bradfordensis Subzone has, in the meantime, been added to the independent Bradfordensis Zone, see e.g. Chandler and Callomon 2009; Contini et al. 1997).

7. According to our findings from the BDB-1 core and the La Malcôte 2 section in the Mont Terri area, deposition of the "Lower Oolitic Series" of the Hauptrogenstein began as early as within the Humphriesianum Subzone (Humphriesianum Zone) (for the stratigraphic subdivision of the Hauptrogenstein see Gonzalez and Wetzel 1996, Jordan et al. 2008), in contrast to the occurrences of the formation situated farther to the east. Sediments of the same age are represented farther east in the lithology of the Brüggli Member and the Rothenfluh Member (both belonging to the Passwang Formation; see Diebold et al. 2006). Accretion of ooids in the "Lower Oolitic Series" took place later (Niortense Zone) in the easterly occurrences. This confirms the west to east progradation of this carbonate platform (cf. Gonzalez and Wetzel 1996).

8. In most cases, the chronological precision of the resolution for the sections we studied and the drillcore material of BDB-1 are in the scope of a biozone. Consequently, these data do not permit substantiating possible stratigraphic gaps below this resolution. In any case, lithoclasts, in which ammonites of the genus *Bredyia* are embedded, definitively demonstrate reworking processes in sediments of Late Aalenian age during the Bradfordensis Zone.

References

Bate, R. H. (1963). Middle Jurassic Ostracoda from North Lincolnshire. *Bulletin of the British Museum (Natural History) Geology, 8,* 176–219.

Bläsi, H.-R. (1987). Lithostratigraphie und Korrelation der Dogger Sedimente in den Bohrungen Weiach, Riniken und Schafisheim. *Eclogae Geologicae Helvetiae, 80,* 415–430.

Bläsi, H.-R., Moeri, A., & Bossart, P. (1996). *Results of the Phase 1 drilling campaign.* Mont Terri technical report, TR 96-01, 54 pp. Federal Office of Topography (swisstopo), Wabern, Switzerland. www.mont-terri.ch.

Bläsi, H.-R., Peters, T. J., & Mazurek, M. (1991). Der Opalinus Clay des Mont Terri (Kanton Jura): Lithologie, Mineralogie und physiko-chemische Gesteinsparameter. *Nagra interner Bericht,* 90–60, Nagra, Wettingen, Switzerland. www.nagra.ch.

Bossart, P., Bernier, F., Birkholzer, J., Bruggeman, C., Connolly, P., Dewonck, S., Fukaya, M., Herfort, M., Jensen, M., Matray, J-M., Mayor, J. C., Moeri, A., Oyama, T., Schuster, K., Shigeta, N., Vietor, T., & Wieczorek, K. (2017). Mont Terri rock laboratory, 20 years of research: introduction, site characteristics and overview of experiments. *Swiss Journal of Geosciences, 110.* doi:10.1007/s00015-016-0236-1 (this issue).

Bossart, P., & Thury, M. (2008). *Mont Terri Rock Laboratory. Project, programme 1996 to 2007 and results.* Reports of the Swiss Geological Survey, No. 3, Federal Office of Topography (swisstopo), Wabern, Switzerland. www.mont-terri.ch.

Burkhalter, R. M. (1996). Die Passwang-Alloformation (unteres Aalénien bis unteres Bajocien) im zentralen und nördlichen Jura. *Eclogae Geologicae Helvetiae, 89,* 875–934.

Caër, T., Maillot, B., Souloumiac, P., Leturmy, P., Frizon De Lamotte, D., & Nussbaum, C. (2015). Mechanical validation of balanced cross-sections: The case of the Mont Terri anticline at the Jura front (NW Switzerland). *Journal of Structural Geology, 75,* 32–48.

Chandler, R., & Callomon, J. (2009). The Inferior Oolite at Coombe Quarry, near Mapperton, Dorset, and a new Middle Jurassic ammonite faunal horizon, Aa-3b, *Leioceras comptocostosum* n. biosp. In the Scissum Zone of the Lower Aalenian. *Proceedings of the Dorset Natural History and Archaeological Society, 130,* 99–132.

Contini, D., Elmi, S., Mouterde, R., & Rioult, M. (1997). 5 Aalénien. In E. Cariou & P. Hantzpergue (Eds.), *Biostratigraphie du Jurassique Quest-Européen et Méditerranéen. Zonations parallèles et distribution des invertébrés et microfossiles* (pp. 37–40). Pau Cedex: Elf Exploration Production.

Diebold, P., Bitterli-Brunner, P., & Naef, H. (2006). Blatt 1069/1049 Frick-Laufenburg. *Geologischer Atlas der Schweiz 1:25000 Erläut., 110,* 1–136.

Dietze, V., Rieber, H., Auer, W., Franz, M., Schweigert, G., Chandler, R. B., et al. (2014). Aalenian (Middle Jurassic) ammonites and stratigraphy of the Geisingen clay pit (SW Germany). *Palaeodiversity, 7,* 61–127.

Etter, W. (1990). *Paläontologische Untersuchungen im Unteren Opalinuston der Nordschweiz.* Ph.D. dissertation, University of Zürich, Zürich, Switzerland.

Feist-Burkhardt, S. (2014). *SO-A experiment: Palynological analyses of samples from the BDB-1 borehole.* Mont Terri technical note, TN 2014-61, 11 pp. Federal Office of Topography (swisstopo), Wabern, Switzerland. www.mont-terri.ch.

Feist-Burkhardt, S., & Pross, J. (2010). Dinoflagellate cyst biostratigraphy of the Opalinuston Formation (Middle Jurassic) in the Aalenian type area in southwest Germany and north Switzerland. *Lethaia, 43,* 10–31.

Feist-Burkhardt, S., & Wille, W. (1992). Jurassic palynology in southwest Germany - state of the art. *Cahiers de Micropaléontologie, 7,* 141–164.

Fischer, D. (2014). *Borehole Logging Mont Terri Test Site, in the borehole BDB-1.* Mont Terri Technical Note, TN2014-29, 23 pp. Federal Office of Topography (swisstopo), Wabern, Switzerland. www.mont-terri.ch.

Geologisches Landesamt Baden-Württemberg (1996, ed.): Die Grenzziehung Unter-/Mitteljura (Toarcium/Aalenium) bei Wittnau und Fuentelsaz. - Beispiele interdisziplinärer

geowissenschaftlicher Zusammenarbeit. *Informationen Geologisches Landesamt Baden-Württemberg*, 8, 52 pp. Freiburg i. Br.

Gonzalez, R., & Wetzel, A. (1996). Stratigraphy and paleogeography of the Hauptrogenstein and Klingnau Formations (middle Bajocian to late Bathonian), northern Switzerland. *Eclogae Geologicae Helvetiae, 89,* 695–720.

Jaeggi, D., Müller, P., & Nussbaum, C. (2012). *DS (determination of stress) Experiment: Report about the drilling activities and the geology/hydrogeology encountered at borehole BDS-5*. Mont Terri Technical Report, TR 12-05, 42 pp. Federal Office of Topography (swisstopo), Wabern, Switzerland. www.mont-terri.ch.

Jordan, P., Wetzel, A., & Reisdorf, A. G. (2008). Jurassic. Swiss Jura Mountains. In T. McCann (Ed.), *The Geology of Central Europe. Volume 2: Mesozoic and Cenozoic* (Vol. 2, pp. 880–889). London: Geological Society.

Knitter, H. (1983). Biostratigraphische Untersuchungen mit Ostracoden im Toarcien Süddeutschlands. *Facies, 8,* 213–262.

Mazurek, M., Hurford, A. J., & Leu, W. (2006). Unravelling the multi-stage burial history of the Swiss Molasse Basin: integration of apatite fission track, vitrinite reflectance and biomarker isomerization analysis. *Basin Research, 18,* 27–50.

Nagra. (1992). Sondierbohrung Schafisheim Untersuchungsbericht (Gemeinde Schafisheim, Kanton Aargau, Schweiz), Nagra Technischer Bericht, NTB 88-11. In Swiss Geotechnical Commission (Ed.), *Beiträge zur Geologie der Schweiz, Geotechnische Serie, Lieferung 84* (pp. 1–183). www.swisstopo.ch.

Nussbaum, C., Bossart, P., Amann, F., & Aubourg, C. (2011). Analysis of tectonic structures and excavation induced fractures in the Opalinus Clay, Mont Terri underground rock laboratory (Switzerland). *Swiss Journal of Geosciences, 104,* 187–210.

Ohmert, W. (1988). The Ovalis Zone (Lower Bajocian) in the Type Area, Southwestern Germany. In *2nd international symposium on Jurassic stratigraphy* (pp. 255–268). Lisboa.

Ohmert, W. (1996). Mikrofossilien. In: Geologisches Landesamt Baden-Württemberg (Ed.), *Die Grenzziehung Unter-/Mitteljura (Toarcium/Aalenium) bei Wittnau und Fuentelsaz – Beispiele interdisziplinärer geowissenschaftlicher Zusammenarbeit* (pp. 36–42). Freiburg i.Br.: Informationen Geologisches Landesamt Baden-Württemberg, 8.

Ohmert, W., & Rolf, C. (1994). The Aalenian boundary at Wittnau (Oberrhein area, south-west Germany). *Miscellanea del Servizio Geologico Nazionale, 5,* 33–62.

Plumhoff, F. (1963). Die Ostracoden des Oberaalenium und tiefen Unterbajocium (Jura) des Gifhorner Troges, Nordwestdeutschland. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft, 503,* 1–100.

Reisdorf, A. (2001). Neue Lias-Profile entlang der Transitgasleitung der TRG 3: Wirbligen (BL) und Titterten (BL). *Archäologie und Museum, Berichte aus Archäologie und Kantonsmuseum Baselland, 43,* 43–48.

Reisdorf, A. G., Maisch, M. W., & Wetzel, A. (2011a). First record of the leptonectid ichthyosaur Eurhinosaurus longirostris from the Early Jurassic of Switzerland and its stratigraphic framework. *Swiss Journal of Geosciences, 104,* 211–224.

Reisdorf, A. G., Wetzel, A., Schlatter, R., & Jordan, P. (2011b). The Staffelegg formation: a new stratigraphic scheme for the Early Jurassic of northern Switzerland. *Swiss Journal of Geosciences, 104,* 97–146.

Reisdorf, A. G., Hostettler, B., Waltschew, A., Jaeggi, D., & Menkveld-Gfeller, U. (2013). Chrono- and Biostratigraphy of the Opalinus Clay of the Mont Terri Rock Laboratory, Canton Jura, Switzerland. *Abstract Volume, 11th Swiss Geosciences Meeting*, Lausanne, p. 161.

Reisdorf, A. G., Hostettler, B., Waltschew, A., Jaeggi, D., & Menkveld-Gfeller, U. (2014). *SO (Sedimentology of the Opalinus Clay), Biostratigraphy of the Basal Part of the Opalinus-Ton at the Mont Terri rock laboratory, Switzerland*. Mont Terri technical report, TR 14-07. Federal Office of Topography (swisstopo), Wabern, Switzerland. www.mont-terri.ch.

Reisdorf, A. G., Hostettler, B., Jaeggi, D., Deplazes, G., Bläsi, H.-R., Morard, A., et al. (2016). *SO (Sedimentology of the Opalinus Clay) Experiment: Litho- and biostratigraphy of the 250 m deep Mont Terri BDB-1 borehole through the Opalinus Clay and bounding formations, St. Ursanne, Switzerland*. Mont Terri technical report, TR 16-02, Federal Office of Topography (swisstopo), Wabern, Switzerland. www.mont-terri.ch.

Schaeren, G., & Norbert, J. (1989). Tunnels du Mont Terri et du Mont Russelin—La traversée des « roches à risques » : marnes et marnes à anhydrite. In Juradurchquerungen - aktuelle Tunnelprojekte im Jura. *Mitteilungen der Schweizerischen Gesellschaft für Boden- und Felsmechanik, 119,* 19–24.

Schmidt, C., Braun, L., Paltzer, G., Mühlberg, M., Christ, P., & Jacob, F. (1924). Die Bohrungen von Buix bei Pruntrut, und Allschwil bei Basel. *Beiträge zur Geologie der Schweiz, Geotechnische Serie, 10,* 74 pp. Zurich: Aschmann & Scheller.

Wetzel, A., & Allia, V. (2003). Der Opalinuston in der Nordschweiz: Lithologie und Ablagerungsgeschichte. *Eclogae Geologicae Helvetiae, 96,* 451–469.

Yu, C., Matray, J-M., Gonçalvès, J., Jaeggi, D., Gräsle, W., Wieczorek, K., et al. (2017). Comparative study of methods to estimate hydraulic parameters in the hydraulically undisturbed Opalinus Clay, Mont Terri rock laboratory (Switzerland). *Swiss Journal of Geosciences, 110*. doi:10.1007/s00015-016-0257-9 (this issue).