

Arbeitsbericht NAB 20-08

**TBO Bülach-1-1:
Data Report
Dossier III
Lithostratigraphy**

February 2021

**National Cooperative
for the Disposal of
Radioactive Waste**

Hardstrasse 73
P.O. Box 280
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11

www.nagra.ch

Arbeitsbericht NAB 20-08

TBO Bülach-1-1: Data Report Dossier III Lithostratigraphy

February 2021

P. Jordan¹, H. Naef¹, P. Schürch¹, M. Schwarz¹,
T. Ibele¹, R. Felber¹ & M. Gysi²

¹Arbeitsgemeinschaft geosfer – Gruner Böhlinger

²Nagra

Keywords:

Bülach-1-1, Bülach-1-1B, BUL1-1, BUL1-1B, Nördlich Lägern,
TBO, deep drilling campaign, lithostratigraphy, lithostrati-
graphic profile, geological description, drill cores, cuttings

National Cooperative
for the Disposal of
Radioactive Waste

Hardstrasse 73
P.O. Box 280
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11

www.nagra.ch

Nagra Arbeitsberichte NAB ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

This NAB aims at reporting drilling results at an early stage. Additional borehole-specific data will be published elsewhere.

In the event of inconsistencies between dossiers of this NAB, the dossier addressing the specific topic takes priority. In the event of discrepancies between Nagra reports, the chronologically later report is generally considered to be correct. Data sets and interpretations laid out in this NAB may be revised in subsequent reports. The reasoning leading to these revisions will be detailed there.

This Dossier was prepared by:

P. Jordan (core description, profile compilation, writing and QC)

M. Schwarz (cuttings and core description and QC)

R. Felber (cuttings and core description)

T. Ibele (cuttings and core description)

P. Schürch (writing, QC)

H. Naef (QC)

S. Wohlwend (QC)

H.R. Bläsi (QC)

G. Deplazes (QC)

M. Gysi (project management, conceptualization and QC)

Editorial work: Geomecon, L. McKinley and M. Unger

The Dossier has greatly benefitted from technical discussions with, and reviews by, external and internal experts. Their input and work are very much appreciated!

"Copyright © 2021 by Nagra, Wettingen (Switzerland) / All rights reserved.

All parts of this work are protected by copyright. Any utilisation outwith the remit of the copyright law is unlawful and liable to prosecution. This applies in particular to translations, storage and processing in electronic systems and programs, microfilms, reproductions, etc."

Table of Contents

Table of Contents	I
List of Tables.....	III
List of Figures	III
List of Appendices	IV
1 Introduction	1
1.1 Context.....	1
1.2 Location and specifications of the borehole	2
1.3 Documentation structure for the BUL1-1 borehole	5
1.4 Scope and objectives of this dossier	6
1.5 Petrophysical logs available	7
1.6 Work undertaken	7
1.6.1 General workflow	7
1.6.2 Description and representation of the cuttings samples (0 – 534.95 m).....	8
1.6.3 Description and representation of cores (534.95 – 1'040.26 m: BUL1-1; 995.85 – 1'370.19 m: BUL1-1B).....	9
2 Inventory and quality of cores and cuttings samples	13
3 Stratigraphy and lithology of drilled formations and members.....	15
3.1 Unconsolidated rocks (Quaternary), 0 – 36 m (about 36 m)	15
3.2 Lower Freshwater Molasse Group, 36 – 502 m (about 466 m).....	15
3.3 Siderolithic Group, 502 – 504 m (about 2 m).....	17
3.4 Malm Group	17
3.4.1 «Felsenkalke» / «Massenkalk», 504 – 653.57 m (about 150 m)	17
3.4.2 Schwarzbach Formation, 653.57 – 676.58 m (23.01 m).....	20
3.4.3 Villigen Formation, 676.58 – 751.11 m (74.53 m).....	21
3.4.4 Wildegg Formation, 751.11 – 805.28 m (54.17 m)	23
3.4.4.1 Effingen Member, 751.11 – 804.85 m (53.74 m).....	23
3.4.4.2 Birmenstorf Member and «Glaukonitsandmergel Bed» sensu Gygi (1977, 2000, 2012), 804.85 – 805.28 m (0.43 m).....	24
3.5 Dogger Group	25
3.5.1 Wutach Formation, 805.28 – 806.49 m (1.21 m)	25
3.5.2 Variansmergel Formation, 806.49 – 808.00 m (1.51 m)	26
3.5.3 «Parkinsoni-Württembergica-Schichten», 808.00 – 812.03 m (4.03 m)	26
3.5.4 «Herrenwis Unit», 812.03 – 853.94 m (41.91 m).....	27
3.5.5 «Humphriesioolith Formation», 853.94 – 855.53 m (1.59 m).....	29
3.5.6 Wedelsandstein Formation, 855.53 – 883.96 m (28.43 m).....	29
3.5.7 «Murchisonae-Oolith Formation», 883.96 – 891.70 m (7.74 m).....	30
3.5.8 Opalinus Clay, 891.70 – 995.85 m (104.15 m).....	31

3.6	Lias Group	34
3.6.1	Staffellegg Formation, 995.85 – 1'030.51 m (34.66 m).....	34
3.6.1.1	Gross Wolf Member, 995.85 – 1'000.70 m (4.85 m).....	34
3.6.1.2	Rietheim Member, 1'000.70 – 1'006.81 m (6.11 m).....	35
3.6.1.3	Breitenmatt and Rickenbach Members, 1'006.81 – 1'007.66 m (0.85 m).....	36
3.6.1.4	Grünschholz Member, 1'007.66 – 1'009.02 m (1.36 m)	36
3.6.1.5	Frick Member, 1'009.02 – 1'019.82 m (10.80 m)	37
3.6.1.6	Beggingen Member, 1'019.82 – 1'025.42 m (5.60 m)	37
3.6.1.7	Schambelen Member, 1'025.42 – 1'030.51 m (5.09 m)	39
3.7	Keuper Group	39
3.7.1	Klettgau Formation, 1'030.51 – 1'067.35 m (36.84 m).....	39
3.7.1.1	Gruhalde Member (upper part), 1'030.51 – 1'041.70 m (11.19 m).....	40
3.7.1.2	Seebi Member, 1'041.70 – 1'044.42 m (2.72 m).....	40
3.7.1.3	Gruhalde Member (lower part), 1'044.42 – 1'050.82 m (6.40 m).....	41
3.7.1.4	Gansingen Member, 1'050.82 – 1'052.03 m (1.21 m)	41
3.7.1.5	Ergolz Member, 1'052.03 – 1'067.36 m (15.33 m).....	42
3.7.2	Bänkerjoch Formation, 1'067.36 – 1'132.00 m (64.64 m)	43
3.8	Muschelkalk Group	45
3.8.1	Schinznach Formation, 1'132.00 – 1'204.73 m (72.73 m).....	45
3.8.1.1	Asp Member, 1'132.00 – 1'135.77 m (3.77 m).....	46
3.8.1.2	Stamberg Member, 1'135.77 – 1'174.24 m (38.47 m)	46
3.8.1.3	Liedertswil Member, 1'174.24 – 1'176.19 m (1.95 m)	48
3.8.1.4	Kienberg and Leutschenberg Members, 1'176.19 – 1'204.73 m (28.54 m).....	48
3.8.2	Zeglingen Formation, 1'204.73 – 1'267.94 m (64.34 m)	50
3.8.3	Kaiseraugst Formation, 1'267.94 – 1'306.17 m (38.23 m).....	52
3.9	Buntsandstein Group	55
3.9.1	Dinkelberg Formation, 1'306.17 – 1'319.63 m (13.46 m)	55
3.10	Permo-Carboniferous sediments.....	56
3.10.1	Weitenau Formation, 1'319.63 – 1'370.19 m (> 50.56 m).....	56
4	Comparison with the forecast profile.....	59
5	References	63

List of Tables

Tab. 1-1:	General information about the BUL1-1 borehole.....	2
Tab. 1-2:	List of dossiers included in NAB 20-08	5

List of Figures

Fig. 1-1:	Tectonic overview map with the three siting regions under investigation	1
Fig. 1-2:	Overview map of the investigation area in the Nördlich Lägern siting region with the location of the BUL1-1 borehole and the existing Weiach-1 borehole.....	3
Fig. 1-3:	Lithostratigraphic profile and casing scheme for the BUL1-1 borehole	4
Fig. 1-4:	Füchtbauer scheme as applied for lithology names in geological profiles and continuous text in the report	11
Fig. 1-5:	Folk classification as applied to the description of carbonate rocks in Folk (1959, 1962), Flügel (1982), Lokier & Al Junaibi (2016).....	12
Fig. 2-1:	Comparison of cuttings and core quality in BUL1-1 and BUL1-1B	14
Fig. 4-1:	Comparison of the forecast with the actual findings of BUL1-1 and BUL1-1B	61

List of Appendices

- App. A: Lithostratigraphy profile Bülach-1-1 and Bülach-1-1B, 1:2'500, 0.00 m to 1'370.19 m MD core depth
- App. B: Lithostratigraphy profile Bülach-1-1 and Bülach-1-1B, 1:1'000, 0.00 m to 1'370.19 m MD core depth
- App. C-1: Lithostratigraphy profile Bülach-1-1 and Bülach-1-1B, 1:100, 0.00 m to 290.00 m MD core depth
- App. C-2: Lithostratigraphy profile Bülach-1-1 and Bülach-1-1B, 1:100, 280.00 m to 570.00 m MD core depth
- App. C-3: Lithostratigraphy profile Bülach-1-1 and Bülach-1-1B, 1:100, 560.00 m to 850.00 m MD core depth
- App. C-4: Lithostratigraphy profile Bülach-1-1 and Bülach-1-1B, 1:100, 840.00 m to 1'130.00 m MD core depth
- App. C-5: Lithostratigraphy profile Bülach-1-1 and Bülach-1-1B, 1:100, 1'120.00 m to 1'370.19 m MD core depth
- App. D: Lithostratigraphy patterns, colours, weathering index and symbols for lithostratigraphy

Note: In the digital version of this report the appendices can be found under the paper clip symbol.

1 Introduction

1.1 Context

To provide input for site selection and the safety case for deep geological repositories for radioactive waste, Nagra has drilled a series of deep boreholes in Northern Switzerland. The aim of the drilling campaign is to characterise the deep underground of the three remaining siting regions located at the edge of the Northern Alpine Molasse Basin (Fig. 1-1).

In this report, we present the results from the Bülach-1-1 borehole.

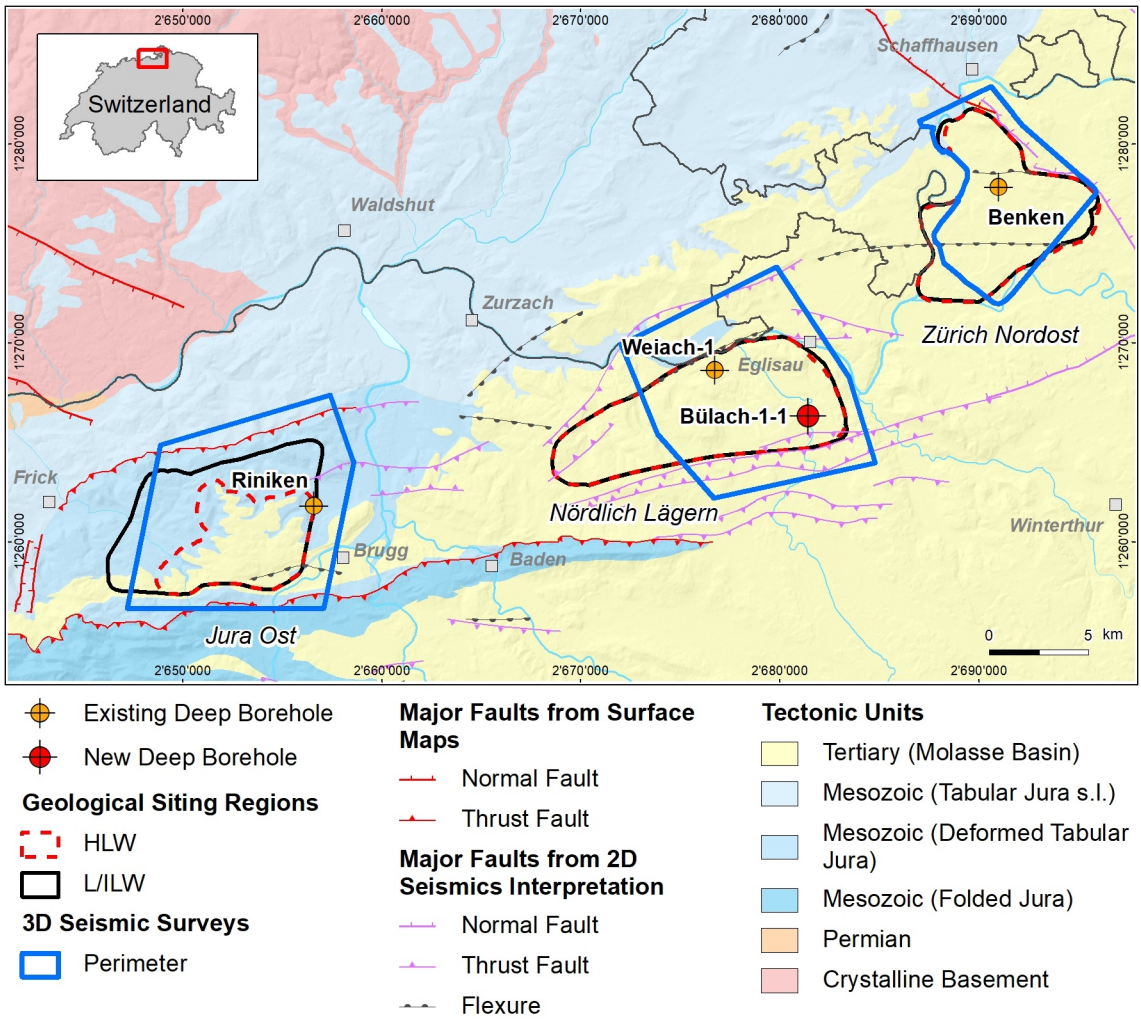


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Bülach-1-1 (BUL1-1) exploratory borehole is the first deep borehole drilled within the framework of the TBO project. BUL1-1 is a vertical borehole. The drill site is located in the south-eastern part of the Nördlich Lägern siting region (Fig. 1-2). The borehole specifications are provided in Tab. 1-1. The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. Due to instabilities, the borehole was plugged back from 1'043.00 m to 918.70 m (*cf.* Dossier I). Resuming coring operations, a sidetrack was initiated with a kickoff point at 995.85 m. This sidetrack was labelled Bülach-1-1B (BUL1-1B). BUL1-1B reached the final depth of 1'370.19 m (measured depth MD core depth)¹. For easier communication and labelling, the name BUL1-1 is generally used for the complete vertical borehole unless stated otherwise. Fig. 1-3 shows the combined lithostratigraphic profile of BUL1-1.

Tab. 1-1: General information about the BUL1-1 borehole

Location	Bülach (Canton Zurich / ZH), Switzerland
Siting region	Nördlich Lägern
Coordinates	2'681'446.028 / 1'266'298.472
Elevation	389.62 m asl (top of rig cellar)
Borehole depth	1'370.19 m MD core depth
Drilling period	15 April 2019 – 27 November 2019 (spud – rig release)
Drilling company	Daldrup & Söhne AG
Drilling rig	Wirth B 152t
Drilling fluid	Water-based mud with varying amounts of Pure-Bore®, Pure-Bore® ULV, soda ash, sodium bicarbonate, xanthan gum

¹ *Measured depth (MD)* below top rig cellar along borehole trajectory. In all dossiers, depth refers to MD unless stated otherwise.

MD core depth refers to the depth marked on the cores. Note that petrophysical logs have not been shifted to core depth, hence MD log depth differs from MD core depth. The depth shift between core depth and log depth is documented in Dossier V, Appendix E-1.

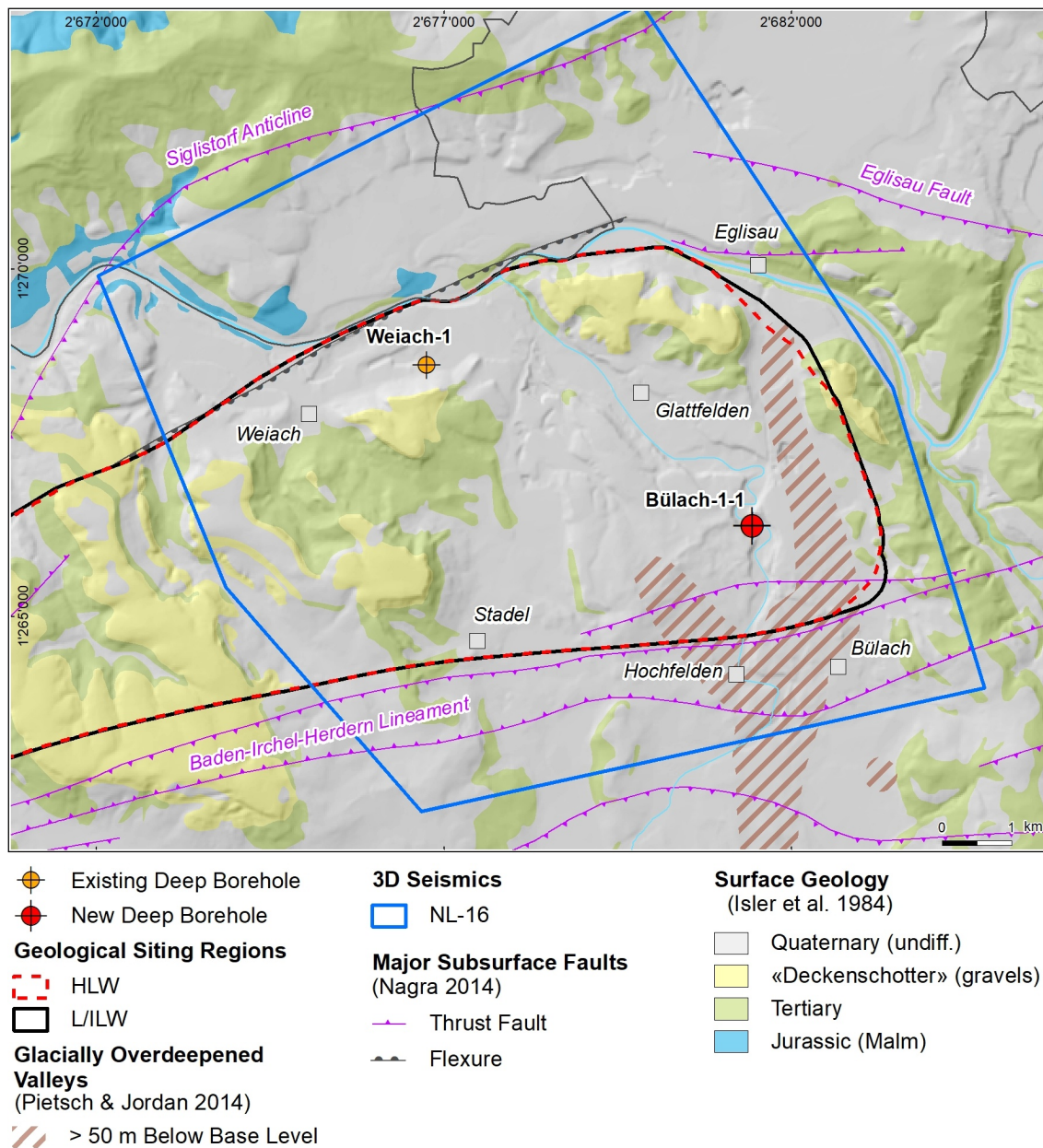


Fig. 1-2: Overview map of the investigation area in the Nördlich Lägern siting region with the location of the BUL1-1 borehole and the existing Weiach-1 borehole

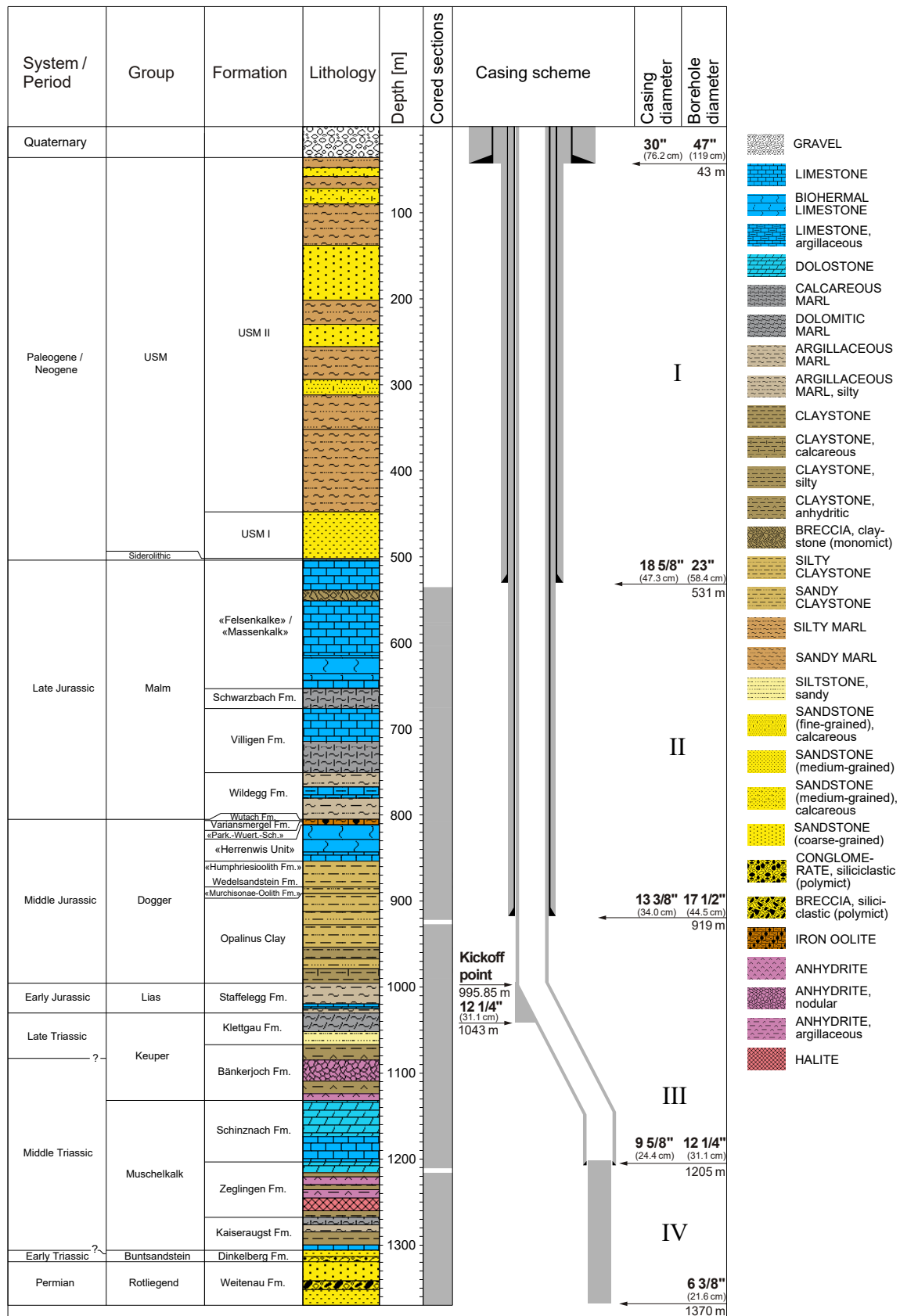


Fig. 1-3: Lithostratigraphic profile and casing scheme for the BUL1-1 borehole

1.3 Documentation structure for the BUL1-1 borehole

NAB 20-08 documents the majority of the investigations carried out in the BUL1-1 borehole, including laboratory investigations on core material. The NAB comprises a series of stand-alone dossiers addressing individual topics and a final dossier with a summary composite plot (Tab. 1-2).

This borehole documentation aims at early publication of the data collected in the BUL1-1 borehole. It includes the majority of the data available approximately one year after completion of the borehole. Some analyses are still ongoing (e.g. diffusion experiments, analysis of veins, hydrochemical interpretation of water samples) and will be published in separate reports.

The current borehole report will provide an important basis for the integration of datasets from different boreholes. The integration and interpretation of the results in the wider geological context will be documented later in separate geoscientific reports.

Tab. 1-2: List of dossiers included in NAB 20-08

Black marks the dossier at hand.

Dossier	Title	Authors
I	TBO Bülach-1-1: Drilling	M. Ammen & P.-J. Palten
II	TBO Bülach-1-1: Core Photography	D. Kaehr & M. Gysi
III	TBO Bülach-1-1: Lithostratigraphy	P. Jordan, H. Naef, P. Schürch, M. Schwarz, T. Ibele, R. Felber & M. Gysi
IV	TBO Bülach-1-1: Microfacies, Bio- and Chemostratigraphic Analysis	S. Wohlwend, H.R. Bläsi, S. Feist-Burkhardt, B. Hostettler, U. Menkveld-Gfeller, V. Dietze & G. Deplazes
V	TBO Bülach-1-1: Structural Geology	A. Ebert, L. Gregorczyk, E. Hägerstedt & M. Gysi
VI	TBO Bülach-1-1: Wireline Logging and Microhydraulic Fracturing	R. Garrard, J. Gonus, J. Desroches & E. Bailey
VII	TBO Bülach-1-1: Hydraulic Packer Testing	R. Schwarz, L. Schlickenrieder & T. Vogt
VIII	TBO Bülach-1-1: Rock Properties, Porewater Characterisation and Natural Tracer Profiles	M. Mazurek, L. Aschwanden, L. Camesi, T. Gimmi, A. Jenni, M. Kiczka, U. Mäder, D. Rufer, H.N. Waber, P. Wanner, P. Wersin & D. Traber
IX	TBO Bülach-1-1: Rock-mechanical and Geomechanical Laboratory Testing	E. Crisci, L. Laloui & S. Giger
X	TBO Bülach-1-1: Petrophysical Log Analysis	S. Marnat & J.K. Becker
	TBO Bülach-1-1: Summary Plot	Nagra

1.4 Scope and objectives of this dossier

The dossier at hand (Dossier III) documents the work of the lithostratigraphy experts. The objectives of the report are:

- complete, detailed and consistent documentation of the cuttings samples and cores according to the guidelines set out in Naef et al. (2019) and modifications and additions to the procedures (Section 1.6.3)
- stratigraphic classification of drilled strata according to the principles defined in Jordan & Deplazes (2019); if delimitations deviate from these principles, further descriptions are given
- first verification and crosschecking of (macroscopic) findings with additional data from laboratory analyses (XRD mineralogy; *cf.* Dossier VIII), thin sections (*cf.* Dossier IV), biostratigraphy (*cf.* Dossier IV) and borehole geophysics (*cf.* Dossier VI) made available up to data cut-off
- detailed description of lithology and lithostratigraphic units down to member and bed level (if applicable), with the focus on special features and deviations from current knowledge and understanding (Jordan & Deplazes 2019)
- visualisation of lithostratigraphic data as profiles:
 - 1:2'500: Appendix A
 - 1:1'000: Appendix B
 - 1:100: Appendices C-1 to C-5

As the cores of the sidetrack BUL1-1B were not sampled in the Lias and having a full suite of petrophysical logs available for this sidetrack, it was decided to use the lithostratigraphic core description of the entire BUL1-1B section as the base for the combined lithostratigraphic profile. The core descriptions from 995 m to 1'043.00 m of BUL1-1 are therefore neither documented in this report nor included in the lithostratigraphic profiles (schematic correlation can be found in Dossier IV).

The level of detail in this dossier is limited by the data availability at data-freeze two months after the end of drilling operations. Some obvious, well preserved fossils were identified by the lithostratigraphy experts, but this record is neither complete nor exhaustive. A detailed biostratigraphic documentation, as well as thin section (microfacies) can be found in Dossier IV.

1.5 Petrophysical logs available

The petrophysical logs listed below were available at the data-freeze and considered as a supplementary source of information for this report (for more details, see Dossier VI).

- total natural gamma ray borehole corrected (GR)
- spectral gamma ray: hostile natural gamma ray standard gamma ray (HSGR) and hostile natural gamma ray computed gamma ray (HCGR)
- caliper / radius (RD1 to RD6)
- near / array corrected limestone porosity (APLC)
- high resolution formation density (RHO8)
- high resolution formation photoelectric factor (PEF8)
- array laterolog apparent resistivity from computed focusing mode 0 to 5 (RLA1 to RLA5)
- formation micro imager (FMI)

1.6 Work undertaken

1.6.1 General workflow

Four lithostratigraphy experts worked in turns on the cuttings samples and cores following the procedures detailed in Naef et al. (2019). All findings were originally documented in DIN A3 field logs (manuscript), including a detailed drawing of the lithological column. Following this initial description of the samples, the field logs were checked internally by a second expert and compared to logs of the nearby Weiach borehole (Matter et al. 1988). This workflow ensured that important features were identified if present and that the stratigraphic classification was consistent with Jordan & Deplazes (2019). Internal complementary notes were made with red ink on the field logs. The Nagra quality control team (QC team) closely monitored this process and progress was discussed monthly with all parties involved, including Nagra project managers. This enabled rapid implementation of improvements to the workflow. The QC team used green ink to make further complementary notes on the field logs. After approval of the field logs by the QC team, the 1:100 profile was drawn using the software TerraStation (TERRASCIENCES Inc.). To corroborate the lithological identification and representation in the 1:100 profile, the lithostratigraphy experts received regular updates of the petrophysical logs and lab analyses.

The lithostratigraphic classification in this report is based on system / period, group, formation and member boundaries at the data-freeze on 31.01.2020.

All depths in this report refer to metres measured depth (MD) core depth.

1.6.2 Description and representation of the cuttings samples (0 – 534.95 m)

The cuttings samples were taken from the shaker with a sampling interval of 2 metres. They were then washed, sieved and roughly described at the drill site by the mud logger for the purpose of operational decisions. The washed and dried cuttings samples were packed in transparent plastic boxes, labelled, and delivered to Nagra's core storage facility in Würenlingen. The different lithologies of a single sample were identified using a microscope, hydrochloric acid and colour and grain size charts. An important additional source of information was the operational geology plot produced by the mud logging company containing data on the rate of penetration (ROP), rotations per minute (RPM), a quick-look lithological composition of the cuttings of the shale shakers and gas chromatography (for more details on drilling operation, see Dossier I).

Besides the general limitations associated with the interpretation of cuttings, the following points have been specified for this borehole:

1. Fine-grained fractions lost during sample preparation: it was unclear which weight fraction was lost during sampling and sample preparation (washing and sieving) at the drill site. Molasse lithologies are often insufficiently lithified and the lost fraction is therefore more likely part of fine-grained clastic lithologies such as silt-, claystones or marls. Therefore, the descriptions given in the field logs refer solely to the material in the washed samples and do not consider potentially lost lithologies. Thus, the lithologies presented for the Molasse cuttings sections are systematically overestimated with respect to coarser-grained lithologies such as sandstones.
2. It was agreed to quantify all distinguishable lithologies with a proportion of 10 % or more of the total sample volume, and to specify the three dominant lithologies in detail. This is also applicable for the description of mixed lithologies and small-scale interbedding of different lithologies.
3. Whilst Molasse rock sequences in outcrops or cores often show a small-scale interbedding of different lithologies, destructive drilling evens out this complexity over the 2 m sample interval. The pattern of the dominant lithology was used for the graphical display in the 1:100 TerraStation profile. Minor lithologies are mentioned in the lithological description only.
4. The total natural gamma ray log for Section I (44 – 536 m) yielded inconclusive results and could not be used for the lithological identification and quantification of claystone- and marl-rich sections. Instead, ROP recordings were used as a proxy for clay-rich lithologies. However, this technical log depends on more parameters than lithology and is therefore an inferior and uncertain source of information.
5. A detailed description of grain size, sorting, grain shape, colour, cement and accessory minerals was provided for sandstones.

While each individual sample had to be described in detail for the field logs, samples with the same primary lithology were combined into larger sections for the 1:100 TerraStation profile and described in summary form. All lithological boundaries of the TerraStation profile correspond to sample boundaries along the 2-m intervals.

1.6.3 Description and representation of cores (534.95 – 1'040.26 m: BUL1-1; 995.85 – 1'370.19 m: BUL1-1B)

Core recovery and a first geological description were completed on-site by the mud loggers; this included reassembling, orientation, labelling and packing the core into 1 m long core boxes. The core boxes were periodically moved to the core storage facility in Würenlingen for further investigation.

The lithology manual (Naef et al. 2019) proved to be a good basis for core description. The following modifications and additions to the procedures described in the lithology manual were defined for this borehole:

Depths of features or beds were always measured on the non-red line (i.e. the line with depths marks, usually a yellow line).

Resolution of field logs and profiles: all findings of the experts were documented in the manuscript field logs at a scale of 1:50 covering 10 m of core per DIN A3 page. At this scale, a detailed profile sketch and description is feasible using patterns, symbols, and plain text as indicated in Naef et al. (2019). The general objective of the field notes was to ensure a comprehensive documentation of all relevant features visible in the core. The subsequent representation of the field logs in the TerraStation profile at a scale of 1:100 required substantial graphical generalisations and, to some extent, also summaries of lithological descriptions. Beds of 20 cm thickness measure 2 mm in thickness at a scale of 1:100 and still clearly show the lithological colour code from Naef et al. (2019). An individual lithological description is however not feasible. They were described together with adjacent lithological units instead. For thinner beds (< 20 cm), the patterns are increasingly difficult to identify and eventually collapse into black lines, interrupting the lithological pattern above and below (e.g. 853.94 m, «Humphriesioolith Formation»; 1'007.66 m, Grünschholz Member). Nevertheless, within the weathering plot, this may still be a desired visual effect for depicting argillaceous interlayers within more competent rock (e.g. limestone) or thin limestone beds in successions of marl, clay- or siltstones. Therefore, the following rules were defined:

- limestone beds within the Opalinus Clay are always recorded and represented in the profile with actual depths – irrespective of their thickness
- hardgrounds and iron-oolites within the Opalinus Clay are always recorded with actual depths, irrespective of thickness; thin iron-oolite layers may be represented with the corresponding symbol instead of a lithological pattern
- breccia patterns must be used for beds with a thickness of more than 50 cm, otherwise the corresponding breccia symbols must be used
- an artificial enlargement of thin but prominent or important beds (e.g. hardgrounds) for illustration purposes is not allowed
- every depth measured in the recorded data should be reproducible from the core, core photographs or FMI; depths are given with two significant digits

The description of lithologies rich in clay minerals adheres to the principles outlined in Mazurek & Aschwanden (2020). For the sake of brevity, terms such as "clay-rich" or "clay-poor" are used in the following. These terms are used in a mineralogical sense. The correct (but longer) term would be "rich / poor in clay minerals".

Additional rules for lithology names: lithology names were assigned according to the scheme modified after Füchtbauer (1988). The lithological terms differ slightly for use in profiles compared to continuous text in the report (see Fig. 1-4).

While the implementation of the detailed Füchtbauer scheme as defined for the TBO project in Naef et al. (2019) results in more than 60 lithologies and corresponding patterns (see Naef et al. 2019), the macroscopic assessment focuses on the main lithotypes 1 to 10. Often a more detailed classification is not feasible without further mineralogical / petrographic analyses. However, experts were requested to differentiate the lithologies as far as possible, especially in the lithological column of the graphical field log, and then generalise them in the TerraStation profile. Finally, considering all macroscopically distinguishable rock types expected in the stratigraphy of Northern Switzerland, Nagra provided a comprehensive legend of 197 lithology patterns (Appendix D).

For the description of limestones, the Folk and Dunham classifications were also applied in the best possible manner (see also Naef et al. 2019). However, neither classification is fully suited for a macroscopic classification, because they rely heavily on the distinction of very small components and their abundance in the rock (microfacies). The usage of the Folk classification was further substantiated in order to avoid ambiguous terminology. All Folk classifications in this text and in the profile follow Fig. 1-5.

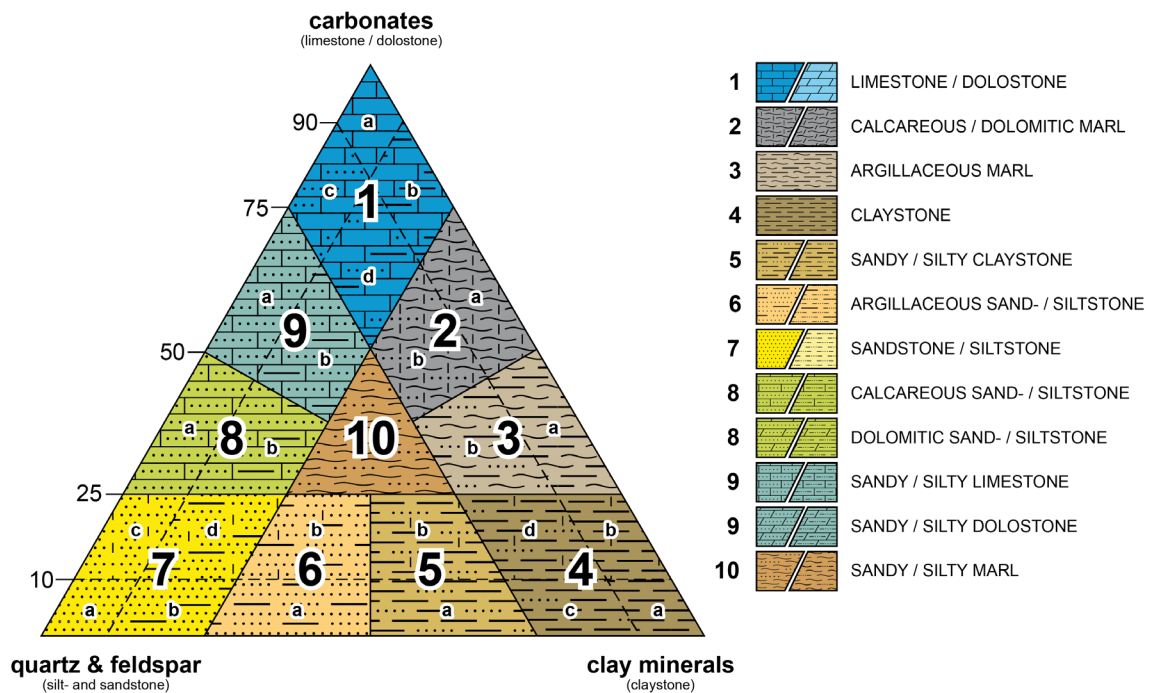
For diagenetically altered limestones, composed of small calcite crystal, possibly dolomitised and then dedolomitised, the term "limestone (saccharoidal)" was used exclusively. The term saccharoidal was used instead of, or in addition to, the Folk classification.

The description of **breccias and conglomerates** requires details on the matrix and components. The breccia / conglomerate pattern distinguishes between monomict and polymict rocks, while the colour represents the mineralogy of the dominant clast fraction. Since this choice could conflict with evidence from petrophysical logs regarding the matrix mineralogy, such discrepancies are discussed in the lithological description.

The use of the **bituminous shale** pattern was restricted to well-known organic-rich formations such as parts of the Asp Member, Rietheim Member and Schambelen Member. In all other cases the corresponding symbol "bituminous" was used.

Lithological patterns were chosen according to the primary lithotype of a core section. In the field log, all patterns had to be labelled according to the Füchtbauer scheme (Fig. 1-4) as well as drawn as patterns based on the graphical representation according to Naef et al. (2019). No patterns were used for small-scale interbedding.

XRD mineralogy results come from core samples of 25 cm length. The XRD mineralogy is therefore representative of an average rock composition of the sample which might or might not be comparable to a certain rock type in the vicinity of the sample; careful judgment was necessary.



profile nomenclature

- 1a Limestone / Dolostone
- 1b Limestone / Dolostone, argillaceous
- 1c Limestone / Dolostone, sandy / silty
- 1d Limestone / Dolostone, sandy / silty, argillaceous
- 2a Calcareous / Dolomitic Marl
- 2b Calcareous / Dolomitic Marl, sandy / silty
- 3a Argillaceous Marl
- 3b Argillaceous Marl, sandy / silty
- 4a Claystone
- 4b Claystone, calcareous / dolomitic
- 4c Claystone, sandy / silty
- 4d Claystone, sandy / silty, calcareous / dolomitic
- 5a Sandy / Silty Claystone
- 5b Sandy / Silty Claystone, calcareous / dolomitic
- 6a Argillaceous Sand- / Siltstone
- 6b Argillaceous Sand- / Siltstone, calcareous / dolomitic
- 7a Sand- / Siltstone
- 7b Sand- / Siltstone, argillaceous
- 7c Sand- / Siltstone, calcareous / dolomitic
- 7d Sand- / Siltstone, calcareous / dolomitic, argillaceous
- 8a Calcareous / Dolomitic Sand- / Siltstone
- 8b Calcareous / Dolomitic Sand- / Siltstone, argillaceous
- 9a Sandy / Silty Limestone / Dolostone
- 9b Sandy / Silty Limestone / Dolostone, argillaceous
- 10 Sandy / Silty Marl

report nomenclature

- 1a limestone / dolostone
- 1b limestone / dolostone (argillaceous)
- 1c limestone / dolostone (sandy / silty)
- 1d limestone / dolostone (sandy / silty, argillaceous)
- 2a calcareous / dolomitic marl
- 2b calcareous / dolomitic marl (sandy / silty)
- 3a argillaceous marl
- 3b argillaceous marl (sandy / silty)
- 4a claystone
- 4b claystone (calcareous / dolomitic)
- 4c claystone (sandy / silty)
- 4d claystone (sandy / silty, calcareous / dolomitic)
- 5a sandy / silty claystone
- 5b sandy / silty claystone (calcareous / dolomitic)
- 6a argillaceous sand- / siltstone
- 6b argillaceous sand- / siltstone (calcareous/dolomitic)
- 7a sand- / siltstone
- 7b sand- / siltstone (argillaceous)
- 7c sand- / siltstone (calcareous / dolomitic)
- 7d sand- / siltstone (calcareous / dolomitic, argillaceous)
- 8a calcareous / dolomitic sand- / siltstone
- 8b calcareous / dolomitic sand- / siltstone (argillaceous)
- 9a sandy / silty limestone / dolostone
- 9b sandy / silty limestone / dolostone (argillaceous)
- 10 sandy / silty marl

Fig. 1-4: Füchtbauer scheme as applied for lithology names in geological profiles and continuous text in the report

Pers. comm. S. Wohlgend modified after Naef et al. (2019)

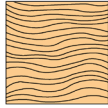
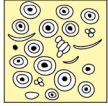
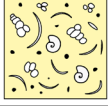
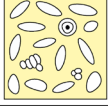
Classification of Carbonate Rocks after Folk (1959, 1962) slightly modified after Flügel (1982) and Lokier & Junaibi (2016)									
		> 10% Allochems (grains): Allochemical Rocks				< 10% Allochems		In situ organic growth structures	
		Sparry Allochemical rocks		Microcrystalline Allochemical rocks		Microcrystalline rocks			
		Sparite (cement) > micrite (matrix)		Micrite (matrix) > sparite (cement)		1-10% grains	<1% grains		
Volumetric Allochem Compositions	> 25% Intracrasts			Intrasparite (median grains < 2mm) Intrasparrudite (median grains > 2mm)		Intramicrorite (median grains < 2mm) Intramicrorudite (median grains > 2mm)		Intraclast-bearing micrite (Intraclasts dominate)	 Micrite (< 1% grains)  Biolithite (Undisturbed bioherm rocks such as algal, coral, sponge biolithite, ...)
		> 25% Ooids		Oosparite (median grains < 2mm) Oosparrudite (median grains > 2mm)		Oomicrite (median grains < 2mm) Oomicrudite (median grains > 2mm)		Ooid-bearing micrite (Ooids dominate)	
	Volume ratio of Fossils to Pellets		> 3:1	Biosparite (median grains < 2mm) Biosparrudite (median grains > 2mm)		Biomicrite (median grains < 2mm) Biomicrudite (median grains > 2mm)		Bioclastic micrite (Bioclasts dominate)	
			3:1 – 1:3	Biopelsparite		Biopelmicrorite		Peloidal micrite (Peloids dominate)	
			< 1:3	Pelsparite		Pelmicrorite			
	Volume ratio of Fossils : Oncoids		1:2	Oncosparite (median grains < 2mm) Oncosparrudite (median grains > 2mm)		Oncomicrorite (median grains < 2mm) Oncomicrorudite (median grains > 2mm)		Ooncoid-bearing micrite (Oncoids dominate)	

Fig. 1-5: Folk classification as applied to the description of carbonate rocks in Folk (1959, 1962), Flügel (1982), Lokier & Al Junaibi (2016)

Pers. comm. Wohlwend & Bläsi

Symbols apply either to a whole bed, or to a specific feature at a specified depth. For certain individual features the exact depth had to be recorded in the field log and was subsequently used in the profile at a scale of 1:100. Four columns in the TerraStation profile display symbols: the first column contains "symbols at depth" (single features) and the last three columns contain symbols representative of the whole bed or section as specified in the lithology column. The symbol for **stylolites** was not used in the TerraStation profile, even if stylolites were diagnostic for a core section, but had to be mentioned in the text instead, because stylolites are tectonic features. All symbols used are listed in Appendix D.

2 Inventory and quality of cores and cuttings samples

The cuttings quality in respect of the lithostratigraphic investigations was overall good (Fig. 2-1). Problems regarding the representativeness of the sample material are discussed in Section 1.6.2 and are related to inherent limitations of destructive drilling, sampling, and to the rock properties within the Molasse section.

The core quality in respect of the lithostratigraphic investigations was assessed using core photographs and the following qualitative criteria:

1. good core quality = cracks / fractures rarely visible (max. 3 per metre of core), little to no core discing, consistent core diameter
2. medium core quality = few cracks / fractures present (> 3 per metre of core), moderate core discing, mostly consistent core diameter with only slight variations on broken disks
3. poor core quality = many cracks / fractures throughout the core, intense core discing, discs have a highly variable core diameter

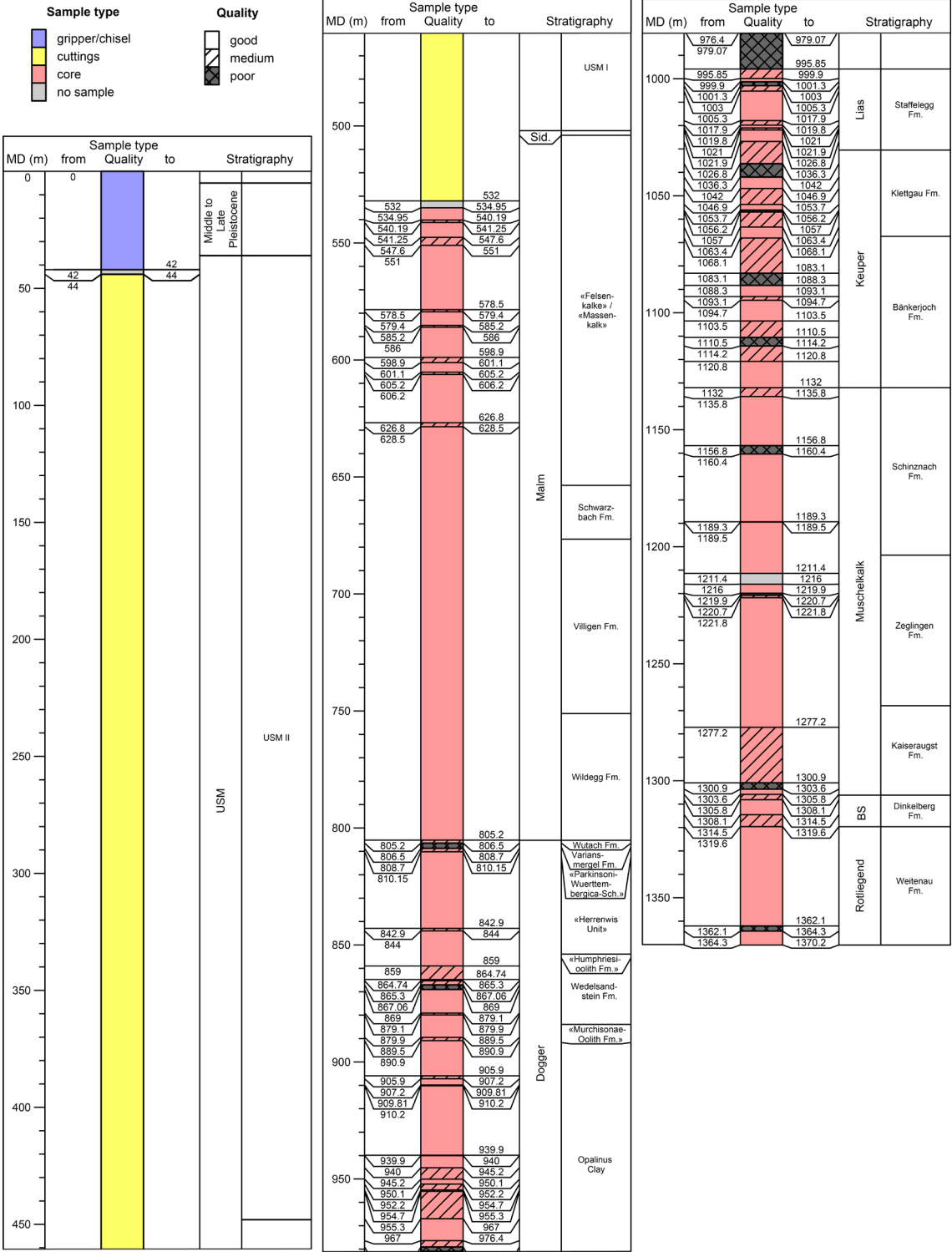


Fig. 2-1: Comparison of cuttings and core quality in BUL1-1 and BUL1-1B

Core quality is assessed based on cracks / fractures present, core discing, core shape and core diameter

3 Stratigraphy and lithology of drilled formations and members

3.1 Unconsolidated rocks (Quaternary), 0 – 36 m (about 36 m)

Unconsolidated rocks were only encountered in the conductor pipe excavation.

Lithostratigraphic subdivision

Down to a depth of about 5 m, bricks, tiles, glass, steel barrels as well as contamination by grease or oil document an old landfill.

The section from about 5 to 34 m includes gravel of Alpine origin.

The section between from 34 to 36 m contains striated clasts and is interpreted as a probable moraine.

Lithology

The uppermost 5 m consist of gravel, polymict (quartz, carbonates of Alpine origin), and is dark yellowish to dark greyish brown, subangular to well rounded, poorly sorted, argillaceous, silty, slightly sandy, with sporadic blocks and anthropogenic components such as bricks, tiles, glass, polystyrene, plastic, steel barrels, grease or oil.

The section from 5 to 34 m is made up of gravel, polymict (quartz, carbonates of Alpine origin), light grey to pale yellow, sub-rounded to well rounded, poorly sorted, argillaceous, silty, slightly to very sandy, with sporadic blocks.

The lowermost section from 34 to 36 m consists of gravel, polymict (quartz, carbonates of Alpine origin), light grey to pale yellow, sub-rounded to well rounded, poorly sorted, slightly to moderately argillaceous, silty, slightly sandy, slightly pebbly, with some blocks. Some cobbles and blocks show features that may be interpreted as glacial striation.

3.2 Lower Freshwater Molasse Group, 36 – 502 m (about 466 m)

Lithostratigraphic subdivision

The Molasse-type sediments are identified as Lower Freshwater Molasse Group for two main reasons: first, the mapped base of the Upper Marine Molasse in the surroundings is always higher than the kelly bushing of the BUL1-1 borehole. Second, no indication of marine fossils or minerals, e.g. glauconite, was found. Furthermore, at 466 m two gyrogonites of *Stephanochara gr. praeberdotensis* (green algae of the Characea family) were found (and identified by P.-O. Mojon), indicating Late Chattian (MP28b) to Early Aquitanian (MN1-2). This finding is a clear confirmation of the lithostratigraphic classification.

Based on the dominance of marly over sandy lithologies, the upper part of the section from about 36 to 138 m can be correlated with the «Oberaquitane Mergelzone», sensu stricto, which represents the upper part of the USM II also referred to as «Obere Bunte (or: Granitische) Molasse» or «Oberaquitane Mergelzone», sensu lato, an informal unit representing the upper part of the Lower Freshwater Molasse in the area.

The following sediments down to a depth of about 448 m may represent the main body of the «Obere Bunte (Granitische) Molasse» showing the typical "granitic composition". They consist of a succession of fine- to medium-grained terrestrial sediments (marls, silt- and sandstones) of variable thickness. Very diagnostic are chips of porous, calcite-cemented, coarse-grained sandstone consisting of quartz grains of different colour, including colourless transparent grains, plus apparent dark mineral grains as well as mica glitter, which are interpreted as weathering products of granitic rock bodies («Granitischer Sandstein», see below).

The lowest part from about 448 to 502 m may represent the marl-dominated lower part of the Lower Freshwater Molasse, the USM I, or «Untere Bunte (Granitische) Molasse». This is contradicted by P.-O. Mojon who intuitively assigned the two gyrogonites to the younger, Aquitanian part of the span of existence of *Stephanochara* gr. *Praeberdotensis*, based on similar findings in western Switzerland.

Lithology

In the whole section from 36 to 502 m five different lithologies of variable abundance were identified:

- sandstone (medium- to coarse-grained), rather poorly cemented by calcite, generally porous. In most cases, the colour is light beige to light grey or even whitish. It consists predominantly of quartz and feldspar of various colours and variable transparency. Additionally, black to dark grey and red minerals may be addressed as hornblende, garnet etc. Fine-grained feldspar is always present. In many samples there are almost no rock chips of this lithology because it was completely milled to loose sand. This rock type is known as «Granitischer Sandstein» because its grain composition roughly corresponds to the mineralogy of granite. It is very common in the USM II but may also be found in older USM I sediments. Lithostratigraphy is commonly based on heavy minerals which were not analysed. The «Granitischer Sandstein» is genetically associated with river courses which are now represented as channels in the Molasse architecture
- sandstone (fine-grained), silty, in most cases well cemented by calcite, consisting mainly of quartz but also feldspar and other minerals. Fine-grained mica is always present. The colour of the fine-grained sandstone may vary from grey to beige to reddish grey
- claystone (silty, calcareous) to argillaceous marl occurring in colours from greenish to yellowish and reddish grey as well as light to dark grey
- splintery limestone (micrite), beige to whitish
- crumbly limestone (micrite), in most cases whitish

The latter four lithologies represent various facies outside the channels: the floodplain sediments, soil formation atop them and sedimentation in oxbow lakes. Because neither image logs nor reliable petrophysical logs are available, and due to lag time variability of cuttings in the borehole, nothing can be said about sedimentary structures or Molasse architecture in detail.

3.3 Siderolithic Group, 502 – 504 m (about 2 m)

The Siderolithic Group was first encountered in the destructively drilled part of the BUL1-1 section. The main argument for the Siderolithic Group is the presence of iron-pisoids («Bohnerz»). Further characteristic components are isolated, large transparent quartz grains without sticking calcite cement, which is characteristic for "Glassand", another common lithology in the Siderolithic Group.

The first few iron-pisoids and transparent quartz grains were already found in the sample from 500 to 502 m. They are abundant (> 50 % of cuttings yield) in the following sample from 502 to 504 m and still noticeable in the following two samples down to 508 m (30 % and 20 %, respectively). However, Jurassic marine limestone is also found in the latter two samples. Since cuttings material is mixed along the way back to surface, the depth allocation of sampled material is not trivial. It is postulated that the few pisolites of the 500 to 502 m sample either "overtook" other cuttings or that the Lower Freshwater Molasse / Siderolithic Group boundary is close to 502 m. However, the lower boundary must be below 504 m as no marine limestone is found in the sample from 502 to 504 m. As the description of the cuttings section is done in 2 m steps, the depth of 504 m was chosen to allocate the lower boundary. The evidence from cuttings is too vague to decide whether this upper occurrence of Siderolithic Group sediments is stratiform or a karst fill reaching down a few metres into the Jurassic limestone.

Few iron-pisoids were also found in the cuttings samples from 508 to 518 m and from 526 to 532 m. It cannot be decided whether they represent caving material from the overlying rocks or individual Eocene karst fills.

3.4 Malm Group

3.4.1 «Felsenkalke» / «Massenkalk», 504 – 653.57 m (about 150 m)

According to the informal stratigraphic scheme for the current deep drilling campaign (Jordan & Deplazes 2019), the Jurassic carbonate rocks above the Schwarzbach Formation are to be attributed to the «Massenkalk» or to the «Felsenkalke», two informal units in ranks of formations. The latter summarise a succession of lithostratigraphic units which were formally established as formations in adjacent areas in Germany and used to some extent when recording earlier drilling campaigns performed or accompanied by Nagra (e.g. Benken, Nagra 2001). The «Massenkalk» (Massenkalk Formation in Germany, see Geyer & Gwinner 1986) encompasses sponge bioherm facies including closely related, poorly or non-bedded sediments within and adjacent to the bioherms. The «Felsenkalke» represent the mostly well bedded and sponge-free facies between the bioherms. Thus, the two informal formations can also be understood as two facies units replacing each other laterally and vertically.

In the present core, the separation of the two formations is inconclusive. The transition is often unclear, repetitive and gradual. In addition, a profound Eocene karstification makes an assignment and delimitation difficult up to a depth of 551.55 m. Consequently, the succession above the Schwarzbach Formation is described as one informal unit «Felsenkalke» / «Massenkalk».

The upper boundary is set at 504 m. The transition between Paleogene and Late Jurassic sediments was drilled destructively. Due to proven significant detritus from younger strata and mixing of cuttings during transport to the surface, the delimitation is rather ambiguous. The upper boundary (504 m) of the 2 m sample containing the first micritic limestone cuttings is set as the upper boundary of the «Felsenkalke» / «Massenkalk».

The lower boundary is set at 653.57 m. It is set at the top of the first calcareous marl bed of the underlying Schwarzbach Formation more than a few centimetres in thickness.

Lithostratigraphic subdivision

As outlined above, a well-defined lithostratigraphic subdivision is not yet possible. The following subdivision is therefore based on lithology:

504 – 532 m	Cuttings section, probably «Felsenkalke» facies (28 m), indication of Eocene karstification and residual fills (predominantly iron-pisoids) in the upper (from 504 to 518 m) and lower part (from 526 to 532 m)
532 – 534.95 m	No record, neither cuttings nor core
534.95 – 538.69 m	«Felsenkalke» facies, thick bedded (3.74 m)
538.69 – 551.55 m	Tectonised paleokarst (12.86 m)
551.55 – 556.50 m	«Felsenkalke» facies showing syndimentary deformation (3.74 m)
556.50 – 574.52 m	«Felsenkalke» facies, medium bedded (18.02 m)
574.52 – 576.43 m	«Felsenkalke» facies, well bedded, with a characteristic "dotted" look (1.91 m)
576.43 – 597.90 m	«Massenkalk» facies, limestone (saccharoidal) with chert nodules (21.47 m)
597.90 – 599.10 m	Predominantly breccia (tectonic, paleokarst or diagenetic?) (1.20 m).
599.10 – 614.82 m	«Massenkalk» facies, limestone (saccharoidal) with chert nodules (15.72 m)
614.82 – 634.38 m	«Massenkalk» facies, rich in sponges, partly biohermal, cavernous ("Lochfels") (19.56 m)
634.38 – 653.57 m	Intermediate facies, poorly to well bedded, with pellets and sponges (19.19 m)

Lithology

504 – 532 m	Predominantly cuttings of limestone (mudstone, micrite), beige; from 504 to 518 m and from 526 to 532 m with few pisoids and transparent, colourless quartz grains. The presence of Molasse-type cuttings is interpreted as caving material
534.95 – 538.69 m	Well bedded sequence formed by up to 1 m thick beds of limestone (mudstone, micrite; thin section BUL1-1-536.16 [all following thin sections <i>cf.</i> Dossier IV]), beige to dark beige, internally wavy bedded, layers of nodular limestone, light beige, with voids (up to 2 mm in diameter, former pellets?) and druses filled with calcite, and mostly thin but occasionally up to 8 cm thick layers of limestone (argillaceous) (mudstone, micrite)

538.69 – 551.55 m	Mostly brecciated host rock corresponding to the lithologies encountered above and below, i.e. predominantly limestone (mudstone, micrite), beige to dark beige, internally wavy bedded. Paleokarst evidence comprises claystone, mostly reddish brown, in aureoles also green, with sporadic quartz grains, relicts of stratiform freshwater limestone and nodular (vadose) limestone which could be interpreted as calc-sinter crusts (at 550.73 m) probably from rims, stalactites or stalagmites (some limestone clasts are fully encrusted; thin section BUL1-1-550.77). Tectonic evidence includes brecciation, slickensides and calcite veins
551.55 – 556.50 m	Thick bedded (> 1 m) limestone (mudstone, micrite), beige, internally laminated, separated by thin (< 1 cm), slightly darker interlayers of claystone. At several levels, slump structures and breccias, calcareous (monomict) probably of early diagenetic origin are found. Joints and voids are filled with white opaque calcite
556.50 – 574.52 m	Medium bedded (> 50 cm) limestone (mudstone, micrite), beige, internally laminated, separated by mostly very thin (< 0.5 cm), slightly darker interlayers of limestone (argillaceous). Thicker argillaceous marl layers are found from 564.63 to 565.75 m as well as from 573.40 to 573.55 m. Some of the limestone (argillaceous) layers comprise strongly flattened limestone nodules. Some of the limestone (argillaceous) layers are underlain by partly fossiliferous firmgrounds with abundant burrows. Macrofossils (bivalves, brachiopods, sponges) are present but not abundant. Burrows and bioturbation are found at several levels. Some irregular small cavities are filled with calcite crystals (druses)
574.52 m	Distinct surface accompanied by a significant change in rock colour persisting through the bed of calcareous marl into the uppermost part of the following limestone bed
574.52 – 576.43 m	At the top, from 574.52 to 575.04 m, bed of calcareous marl, brownish beige followed by limestone (mudstone, biomicrite to pseudosparite; thin section BUL1-1-575.05), first brownish beige then beige, with small white dots which probably result from dissolved or micritised fossils or pellets now replaced by opaque calcite
576.43 – 597.90 m	Thick bedded to massy limestone (saccharoidal), beige to grey beige with some chert nodules, dark brown with milky white rim (mostly disperse, but forming a distinct nodular layer at 587.95 m). At some levels, including the uppermost part, limestone (mudstone and wackestone, biomicrite), beige to grey. Macrofossils (bivalves, from 594.8 m also sponges) are generally micritised (dedolomite; thin section BUL1-1-594.92). Few thin-bedded claystone horizons, greenish grey. At some levels, e.g. from 596.75 to 597.00 m, porous ("Schaumkalk", Geyer et al. 2011) due to partial solution of small components (fossils, pellets?)
597.90 – 599.10 m	Strongly brecciated interval: components: limestone (saccharoidal), beige to beige brown, partly nodular including chert nodules; limestone (boundstone, biomicrite), grey beige to beige, fossiliferous (predominantly sponges; bioherms). Matrix and interlayers: claystone, greenish grey, gaps are filled with milky calcite. The presence of calc-sinter crusts points to a karstic origin and a later tectonic overprint. However, large sponge-biohermal components could indicate a mainly diagenetic origin of the section ("Lochfels", see below)

599.10 – 614.82 m	Thick bedded to massive limestone (saccharoidal), beige, with chert nodules, separated at great distance by thin to very thin marl horizons. The lowest part from 611.20 to 614.82 m is formed by an alternation of dense and porous limestone ("Schaumkalk", probably due to partial solution of small components such as fossils or pellets)
614.82 – 634.38 m	Biohermal limestone (boundstone, biopelmicrite to biopelsparite), beige grey, beige to slightly pink, and dark brown, partly nodular (cauliflower style), mainly formed by sponges, partly silicified or recrystallised to limestone (saccharoidal; thin section BUL1-1-626.22), with different bored surfaces and borings within the sponge bodies. Sporadic chert nodules. Two features found at 630.00 m and 631.00 m could be silicified steinkerns of (indefinable) ammonites Brecciation, present throughout most of the interval, is particularly prominent in sections from 620.30 to 620.77 m, 622.05 to 623.12 m, and from 627.30 to 627.85 m: reworked material is embedded in greenish-grey to reddish-brown marl interbedded layers and within the voids. Clay mineral analyses at 620.5 m and 628.7 m reveal a high kaolinite content which may indicate karstification. Many vugs and larger voids and lacunas are filled or lined by sparite in a first step. According to Geier et al. (2011) the so-called "Lochfels" facies in adjacent areas in Germany is similar. Within these intervals, gastropods and crinoids are also found besides sponges and thick-shelled bivalves The biohermal facies is interrupted from 619.40 to 620.30 m, 623.12 to 625.43 m and from 628.70 to 629.00 m by limestone (wackestone and packstone, biomicrite), beige, with sporadic macrofossils, mainly thick shelled bivalves, isolated sponges and crinoids, and sporadic chert nodules
634.38 – 653.57 m	Thick bedded limestone (wackestone and packstone, biopelmicrite [thin section BUL1-1-636.67]), beige grey to grey, at some levels brownish grey (limonitic), fossiliferous, abundant small sponges (recognisable as dark grey dots), fragments of larger sponges (some of them bored, some pyritised), bivalves including oysters, brachiopods, belemnites From 639.5 to 639.63 m and from 640.58 to 641.38 m, calcareous to argillaceous marl (to claystone) beds including pyrite and glauconite (thin section BUL1-1-641.26) are found. The lower glauconitic interval (from 640.58 to 641.38 m) could be the «Glauconitbank» or «Glauconitic marker bed» after Gygi (2000). Limestone (saccharoidal) is found in the lower part of the lowermost limestone bed (from 651.65 to 653.50 m)

3.4.2 **Schwarzbach Formation, 653.57 – 676.58 m (23.01 m)**

The Schwarzbach Formation represents a mostly calcareous to argillaceous marl interval within the predominantly calcareous formations of the Middle and Upper Malm Group. In the present section, it is delimited following the purely lithostratigraphic definition of Jordan & Deplazes (2019).

The upper boundary of the Schwarzbach Formation is set at 653.57 m at the top of the first thick (1.35 m) calcareous marl interval.

The lower boundary is set at 676.58 m at the base of the last thick (1.96 m) calcareous marl bed, underlain by several metres of limestone with very thin marl or claystone interlayers.

There is no formal subdivision of the Schwarzbach Formation. For practical reasons, the present core section can be divided into a more calcareous upper part and a more argillaceous part below 663.80 m.

Lithology

653.57 – 663.80 m	The upper section starts with a thick bed (1.42 m) of fossiliferous calcareous marl, glauconitic, with small lithoclasts and oncoids (thin section BUL1-1-653.67), which is followed by an alternation of limestone, limestone (argillaceous), and calcareous to argillaceous marl. The thickness of the beds varies from a few decimetres to more than 1 m. Within the limestone (wackestone and packstone, biopelmicrite) macrofossils are relatively rare in the upper part and become more abundant in the lower part (echinoderms including crinoids, bivalves, brachiopods, belemnites and sponges). An ammonite fragment was found at 659.87 m. From 654.92 to 659.54 m, fucoids are abundant on bedding planes. Chert nodules are found but not very abundant
663.80 – 676.58 m	Calcareous marl, medium grey, generally fossiliferous, dominates in this lower section. Below a thick calcareous marl interval, an alternation (from 666.80 to 668.00 m) of calcareous marl as above, limestone (mudstone and wackestone, biomicrite), beige grey, partly very fossiliferous (thin section BUL1-1-676.10), and argillaceous marl, dark grey, is found. The fossil record is identical to the upper section. An ammonite was found at 676.16 m. Chert nodules are very rare

3.4.3 Villigen Formation, 676.58 – 751.11 m (74.53 m)

According to Gygi (e.g. 2000), the consistently mostly calcareous Villigen Formation is subdivided into four members in the western realm and three members in the eastern realm (Jordan & Deplazes, 2019). The latter is believed to represent deposition in a deeper marine environment characterised by the abundance of sponges. The Bülach area is part of a transitional domain delimited by the rivers Aare and Töss (Aare – Töss-Line; Jordan & Deplazes 2019). At present, a conclusive subdivision of the section found at Bülach-1-1 is not possible following one or another of the schemes. Also, some beds resemble known marker beds, but result in unexpectedly large thicknesses of the members when used for subdivision.

The upper boundary is set at 676.58 m at the base of the last thick (1.96 m) argillaceous to calcareous marl bed of the Schwarzbach Formation, i.e. at the top of a thick calcareous section with very thin marl or claystone beds. The limit is also marked by a significant change in rock colour from dark beige to light grey.

The lower boundary is set at 751.11 m at the top of the base of a sequence of three limestone beds which are underlain by a thicker (2.7 m) sequence of calcareous marl. The definition of the boundary is based on a distinct increase in the GR between the Villigen Formation and the

underlying Wildegg Formation. A densely bored hardground found here gives reason to set the boundary at the top instead of the base of this limestone layer. The succession of silty to sandy marls, siltstones and fine-grained sandstones is a typical feature in the upper part of the Effingen Member of the Wildegg Formation and starts below a sequence of calcareous marl at 755.00 m.

Lithostratigraphic subdivision

As outlined above a conclusive subdivision could not yet be established. The Villigen Formation is therefore described here in its entirety. In the following, a convenient subdivision is used for the lithological description.

Lithology

676.58 – 690.85 m	Generally thick bedded sequence of limestone (at the top) to limestone (argillaceous) (mudstone, biomicrite), beige grey at the top, alternatively dark grey brown and moderately grey in the lower part, with some thinner and few thicker beds of calcareous marl, with biotritus including crinoids but very few macrofossils including a belemnite, strongly bioturbated, in the lower part leading to a somewhat nodular look
690.85 – 694.82 m	Thin bedded alternation of limestone (argillaceous) (mudstone, biomicrite), calcareous and argillaceous marl, medium grey to dark grey and black, fossiliferous (mainly crinoids, biotritus, onchids). At the base (below 693.90 m) many fossils including belemnites, bivalves, brachiopods, echinoderms, sponges and serpulids are found together with bored lithoclasts originating from the underlying sediment (thin section BUL1-1-694.80). The interval ends with a prominent nodular and bored hardground (from 694.75 to 694.82 m)
694.82 – 701.08 m	Below the hardground, the rock colour changes to beige grey. The following section consists of limestone (packstone, biomicrite) and thin interlayers of calcareous (rarely argillaceous) marl at intervals of 20 to 80 cm, both fossiliferous, mainly biotritus, but also some macrofossils such as sponges and echinoderms (including crinoids)
701.08 – 714.80 m	This thick bedded (mostly > 1 m) sequence of limestone (wackestone and packstone, biomicrite), beige grey, is characterised by its abundance of fossils. At the top an encrinite is found, i.e. a limestone (arenitic) mainly consisting of crinoids but also including black rimmed sponges, bivalves, belemnites and ammonites. In the following beds, sponges are the dominant fossils, partly forming bioherms (thin section BUL1-1-703.37), followed by crinoids, bivalves and others. Fossiliferous calc-arenitic horizons are found at several levels. From 705.80 to 706.90 m and from 707.80 to 708.40 m, the succession is interrupted by two thicker layers of interbedded fossiliferous calcareous marl, dark grey, with intraclasts
714.80 – 726.00 m	Predominantly medium bedded (0.2 to 1.0 m) alternation of mostly limestone (argillaceous) (mudstone, micrite), beige grey, and calcareous marl, dark grey. Burrows and bioturbation are abundant, giving the rock a cloudy to lenticular and flasy look. Macrofossils are rare to absent

726.00 – 729.70 m	Interval of calcareous marl with a thin argillaceous marl interlayer
729.70 – 735.55 m	Alternation of similar lithologies as above, but with limestone (argillaceous) dominating
735.55 – 751.11 m	Succession of calcareous marl, dark grey with thin beds (mostly significantly less than 1 m) of limestone (argillaceous) (mudstone, pelmicrite; thin section BUL1-1-735.84), generally at distances of 1.5 m and more. The tops of these limestone beds usually show a firmground character with borings filled with bioturbated sediments of the above layer. Both lithologies are strongly affected by bioturbation. At some levels, two generations of burrows can be distinguished by various colours of infill. Macrofossils are rare

3.4.4 Wildegg Formation, 751.11 – 805.28 m (54.17 m)

The Wildegg Formation is made up of the dominant Effingen Member and the Birmenstorf Member. The Effingen Member consists of predominantly calcareous marl representing a relatively short period of deposition. In contrast, the Birmenstorf Member represents a relatively long period of deposition, but it is only a couple of metres thick in most cases (e.g. Gygi 2000). In Bülach-1-1, it is represented by an oncolitic horizon a few decimetres thick and is probably amalgamated with the underlying glauconitic and iron-oolitic sandy marl.

The *upper boundary* is set at 751.11 m at the top of the lowest of a sequence of three limestone beds which is underlain by a thicker succession of calcareous marl. The boundary is defined by a clear increase in the total natural gamma ray log between the Villigen Formation and the underlying Wildegg Formation.

The *lower boundary* of the Wildegg Formation is set at 805.28 m at the top of the first iron-oolite bed of the Wutach Formation.

3.4.4.1 Effingen Member, 751.11 – 804.85 m (53.74 m)

The Effingen Member is a predominantly calcareous marl section with limestone (argillaceous) beds and is characterised by its nearly omnipresent silt content.

The *upper boundary* of the Effingen Member (and the Wildegg Formation) is set at 751.11 m at the top of the lowest of a sequence of three limestone beds which are followed by a thicker sequence of calcareous marl. The boundary is defined by a clear increase in the total natural gamma ray log between the overlying Villigen Formation and the underlying Wildegg Formation. A densely bored hardground found here gives reason to set the boundary at the top of this limestone layer instead of the bottom.

The *lower boundary* is set at 804.85 m at the top of the uppermost glauconitic marl from the underlying unit. It coincides with the base of the lowermost, typically calcareous marl (silty) bed and the top of a characteristic bed consisting of iron-oolitic clasts encrusted by algae (oncolites).

Lithology

751.11 – 755.00 m	Thin bed of limestone (mudstone, micrite), light grey, with a hardground at the top, followed by calcareous marl, grey to dark grey, bioturbated, with lenticular silt interlayers and, again, a limestone (argillaceous) bed at the bottom
-------------------	---

755.00 – 767.46 m	Silty to fine sandy succession: starting with argillaceous marl to claystone, light to beige grey, including two thinner beds of marl and siltstone. From 757.85 m the succession becomes more marly and, from 763.00 m, the silt and clay mineral content decreases and calcite content increases
767.46 – 771.47 m	Limestone (argillaceous) (mudstone, at some levels wackestone, biomicrite), light grey. Macrofossils consist predominantly of crinoids; the highest number occurs from 770 to 771 m. This bed may be the Gerstenhübel Bed
771.47 – 778.88 m	Calcareous marl-dominated section, silty, grey to dark grey, laminated and bioturbated
778.88 – 780.80 m	Succession of bored surfaces on top of various thin fossiliferous, partly nodular, strongly bioturbated limestone beds (wackestone and packstone, biomicrite and biosparite; thin section BUL1-1-779.21), dark grey brown to dark grey, separated by limestone (argillaceous) interlayers. Fossils are abundant and comprise sponges, bivalves, belemnites, ammonites and echinoderms
780.80 – 797.34 m	Succession starting with calcareous marl (silty to fine sandy, bioclastic), continuing into argillaceous marl (silty) with thin (up to 0.8 m) interbeds of calcareous marl, dark grey to dark grey brown, strongly bioturbated, fossil detritus is very abundant in the upper part. Macrofossils (ammonites, bivalves) were only recognised at the marl-rich level from 787.35 to 789.40 m
797.34 – 801.55 m	Alternation of argillaceous marl, dark grey brown, and increasingly thicker beds (0.2 to 1.5 m) of limestone (argillaceous) (mudstone, biomicrite), dark grey, strongly bioturbated, apparently no macrofossils
801.55 – 804.85 m	Fossiliferous calcareous marl, light to dark grey, glauconitic, with a hardground at 802.60 m at the top of a thin, very fossiliferous limestone bed (wackestone, biomicrite; thin section BUL1-1-802.68). The fossil record includes ammonites (801.65 m, 802.61 m, 802.85 m & 803.77 m: most of the following ammonites <i>cf.</i> Dossier IV), belemnites, gastropods, bivalves, sponges and echinoderms, including crinoids. Reworked lithoclasts are found at the top of the hardground at 802.60 m

3.4.4.2 Birmenstorf Member and «Glaukonitsandmergel Bed» sensu Gygi (1977, 2000, 2012), 804.85 – 805.28 m (0.43 m)

As postulated by Gygi (1977, 2000, 2012) for north-eastern Switzerland, the "classical" Birmenstorf Member is replaced by a thin sequence of oncolitic sediments, including an «unnamed glauconitic marl», «Mumienkalk Bed», and «Mumienmergel Bed» (*cf.* Gygi 2000, Jordan & Deplazes 2019). At BUL-1-1 the «Mumienkalk Bed» can clearly be identified. The underlying glauconitic and iron-oolitic sandy marl may represent the «Glaukonitsandmergel Bed» sensu Gygi (1977, 2000, 2012).

The upper boundary is set at 804.85 m at the top of a characteristic bed consisting of iron-oolitic clasts encrusted by algae (oncolites).

The lower boundary is set at 805.28 m at the top of a persistent iron-oolite bed of the uppermost Wutach Formation.

Lithology

804.85 – 805.00 m	The top few centimetres are characterised by oolitic, subangular to well-rounded lithoclasts (up to 1.5 cm in diameter), some of them heavily encrusted with algae, within a glauconitic marly matrix with single iron-ooloids, probably reworked
805.00 – 805.15 m	Nodular limestone bed (mudstone, intramicrite), beige grey, glauconitic and limonitised, small iron-oolid lithoclasts (thin section BUL1-1-805.13), with thin interlayers of glauconitic marl in the upper part
805.15 – 805.28 m	Grading to smaller limestone nodules with a more prominent glauconitic, sandy matrix and ending in a glauconitic marl horizon with limestone nodules and some iron-ooloids

3.5 Dogger Group

3.5.1 Wutach Formation, 805.28 – 806.49 m (1.21 m)

The Wutach Formation is an iron-oolite dominated succession, not very thick at other localities, and was found in a strongly reduced form in BUL-1-1.

The upper boundary is set at 805.28 m at the top of the topmost continuous iron-oolite bed which is overlain by glauconitic marl.

The lower boundary is set at 806.49 m (on the yellow marker line on the core), at an erosional surface at the base of the lowermost continuous iron-oolite bed. The surface is very irregular and reaches down to about 806.60 m in other parts of the core.

Lithology

805.28 – 806.49 m	The Wutach Formation comprises a succession of thin (few centimetres) and irregular beds of iron-oolite (calcareous). The rock colour changes from ochre brown to ochre dotted dark beige grey and light grey. The succession is quite rich in macrofossils, including ammonites (at 805.80, 806.33 and 806.21 m), belemnites, bivalves (oysters and others), gastropods and possibly brachiopods. Some of the fossils are bored and encrusted with microbial mats. Sedimentary infill of fossils with a different content of iron-ooloids than the host rock indicates reworking
-------------------	---

There are several hardgrounds and erosional surfaces. Most of them coincide with a change in iron-oolid content. Based on the available facts these irregularly bedded layers cannot conclusively be assigned to the common beds of the German stratigraphic scheme («Orbisoolith», «Macrocephalenoolith», «Ancepsoolith») or to other concepts applied in the adjacent outcrop area (e.g. to the various «Erzlager» of Dietl 2010)

3.5.2 Variansmergel Formation, 806.49 – 808.00 m (1.51 m)

The Variansmergel Formation is usually quite thick and characterised by its unique facies with an abundance of fossils, especially brachiopods, and uneven alternating beds of silty marl and limestone. In BUL1-1, only the interval from 807.00 to 808.00 m shows affinities with this typical facies. Together with the overlying argillaceous marl free of iron-oolids, they are addressed here as the Variansmergel Formation and are strongly reduced in thickness.

The upper boundary is set at 806.49 m at an erosional surface at the base of the lowermost continuous iron-oolite bed of the Wutach Formation. The erosional surface is very irregular and reaches down to about 806.60 m in other parts of the core. Disperse iron-oolids are also found below this irregular erosional surface (down to about 806.75 m).

The lower boundary is set at 808.00 m with an abrupt decrease in shell fragment content which correlates with a decrease in carbonate content.

Lithology

806.49 – 808.00 m	Down to about 807.00 m, there is an upper part in which macrofossils are rare and the rock must be addressed as argillaceous marl (silty), dark grey, with thin (cm) and undulate bedding. It is followed by an around 1 m thick claystone (calcareous, silty) bed, medium grey, with abundant single shells of brachiopods and bivalves. The distribution varies from disperse to thin coquina horizons. There are very few intact shells with beige filling
-------------------	---

3.5.3 «Parkinsoni-Württembergica-Schichten», 808.00 – 812.03 m (4.03 m)

The informal «Parkinsoni-Württembergica-Schichten» represent a mostly monotonous, usually thick succession of argillaceous marl with few thin, mostly iron-oolitic interbeds. Traditionally, the informal «Parkinsoni-Württembergica-Schichten» are subdivided by an iron-oolite bed, the informal «Parkinsoni-Oolith», into «Württembergica-Schichten» (upper part) and «Parkinsoni-Schichten» (lower part). The iron-oolite bed from 811.45 to 812.03 m may be correlated with the «Parkinsoni-Oolith». If this is the case, the main part of the present section corresponds only to the informal «Württembergica-Schichten».

The upper boundary is set at 808.00 m, with an abrupt decrease in the content of shell fragments which correlates with a decreased carbonate content and a change from calcareous to argillaceous marl.

The lower boundary is set at 812.03 m at the base of an iron-oolite which overlies biohermal coralligenous sediments. The boundary is formed by a strongly bored erosional surface (hard-ground) which is overlain by a fossiliferous bed a few centimetres thick, including bivalves, belemnites and an ammonite, many of them with borings.

Lithology

808.00 – 810.53 m	Argillaceous marl (silty at the top to sandy at the bottom), medium grey, with thin (cm) and undulating bedding. Significantly less fossiliferous than the overlying Variansmergel Formation. Fossil record includes ammonites, aptychs and bivalves but only few brachiopods
-------------------	---

	From 810.00 to 810.53 m, argillaceous marl (sandy), dark grey with brown dots, with fossil detritus (crinoids, brachiopods) and few dispersed iron-oids at the base
810.53 – 811.45 m	Calcareous marl to limestone (argillaceous), dark grey to dark greyish brown, with limonite and iron-oids, dispersed macrofossils (crinoids, brachiopods, bivalves) rarely in coquina and an ammonite at 810.58 m
811.45 – 812.03 m	Below a bored surface, limestone (iron-oolitic) to iron-oolite (calcareous), medium to dark grey with brownish dots to ochre, fossiliferous (ammonites, belemnites, bivalves, brachiopods), including a few centimetres thick, very fossiliferous bed at the base with an ammonite at 812.03 m

3.5.4 «Herrenwis Unit», 812.03 – 853.94 m (41.91 m)

From 812.03 to 853.94 m, a sedimentary succession consisting mainly of coral bioherms, reef detritus and crinoidal limestone was encountered. «Herrenwis Unit» was chosen as informal working name. The term "unit" expresses that the lithostratigraphic rank, whether an independent formation or a member or different members of an existing formal formation, could not yet be set.

Based on a 2D seismic analysis in this area, a so-called «Schwellenzone», a sedimentary body forming a positive relief on top of the underlying sediments (ca. above Opalinus Clay), was identified by Meier & Deplazes (2014). The lithological composition of this sedimentary body was unknown because it had not been drilled through before and could not be correlated to outcrops. It was postulated that it could indicate a sand bar composed of limestones, sandstone and/or iron-oolites. This hypothesis was also used in the prospective sections. However, alternative explanations such as biogeological structures were also mentioned by Meier & Deplazes (2014). This «Schwellenzone» was drilled in BUL-1-1 and, for the first time, the «Herrenwis Unit» including bioherms, reef detritus and crinoidal limestone could be described.

The upper boundary is set at 812.03 m at a strongly bored erosional surface at the top of the coralligenous limestone which is overlain by a fossiliferous bed. The bed includes bivalves and belemnites, many with borings, with iron-oids.

The lower boundary is set at 853.94 m at the top of the uppermost iron-oolitic and limonitic beds of the «Humphriesoolith Formation».

Lithology

812.03 – 822.20 m	Upper coral bioherm: limestone (boundstone, biomicrite to biosparite), beige grey to pale green (matrix) and dark beige to pale pink to yellow (corals). Rock and shell detritus are found between the bored in situ coral stocks, originating from corals, bivalves, crinoids, brachiopods etc. Calcite-rimmed druses and pores are abundant
822.20 – 825.50 m	Upper reef detritus section which can be separated into an upper (822.20 to 831.40 m) calcareous marl, medium to dark grey, with few coral fragments and other biodebris, an alternation of limestone and cal-

	careous to argillaceous marl. The limestone includes biohermal boundstone (biomicrite to biosparite) and wackestone (biomicrite) which is mainly abundant in fossil detritus, predominantly from corals, but also spikes of regular echinoids, other echinoderms, bivalves, etc. Rock colour is variegated, including various shades of grey, pale green, pale pink and yellow. Calcite-rimmed druses and pores are abundant. A surface with borings is found at the base
825.50 – 830.30 m	Intermediate coral bioherm with intercalations of reef detritus: limestone (wackestone and boundstone, biomicrite to biosparite), beige grey to pale green, the bored in situ coral stock is pale pink to yellow, fossiliferous (mainly detritus, echinoids, bivalves) and calcareous marl interlayers, dark brown, fossiliferous
830.30 – 832.45 m	Intermediate reef detritus section: a calcareous marl interval with few coral fragments at 831.40 m turns into an irregular alternation of argillaceous marl matrix, beige grey to pale green, with limestone components including fossil detritus, fossils (e.g. spikes of regular echinoids, other echinoderms, bivalves) up to coral stocks, many with borings of which some are possibly in situ. The limestone colour varies between dark beige, pale pink and yellow. Calcite-rimmed druses, pores and cavities, some resembling karst dissolution features
832.45 – 840.35 m	Lower coral bioherm: prevailing in situ coral stocks, many of them bored. Limestone (boundstone, biomicrite to biosparite), pale pink to yellow. The in situ coral stocks are separated by often irregular layers of limestone (wackestone and packstone, biopelmicrite), beige, and argillaceous marl to claystone, dark grey to dark green. This matrix is very fossiliferous and includes coral fragments, echinoid spikes, other echinoderms and bivalves. Calcite-rimmed druses and pores continue to be abundant
840.35 – 844.75 m	Lower reef detritus section and basal bioherm: the upper part (to 843.40 m) is an irregular alternation of detritic limestone (wackestone, biomicrite to biosparite), coralligenous limestone (boundstone, biosparite) and argillaceous marl, dark grey. In the lower part in situ tree-like coral stocks are found besides coral and other fossil detritus. The base (below 844.50 m) is formed by limestone (arenitic, silty), beige-grey, with lithoclasts, representing a breccia-like reworked layer
844.75 – 850.21 m	Upper encrinite ("Echinodermenspatkalk"): the limestone (silty) (grainstone, biosparite), light brown to beige grey, is mainly composed of crinoid fragments (up to 5 mm, "micro-breccia"). Echinoids (abundant in the uppermost bed), belemnites, bivalves (including oysters) and coral fragments are also found. The limestone beds are separated by thin bioclastic marl layers
850.21 – 853.94 m	Lower encrinite ("Echinodermenspatkalk"): the top (from 850.21 to 850.55 m) is formed by sandy marl with abundant serpulides (thin section BUL1-1-850.27) and crinoids followed by bioclastic limestone (packstone, biosparite), beige grey to light brown. Crinoids are smaller and less dominant than in the upper encrinite. Besides small detritus, larger bivalves, few ammonites and some corals are also found

3.5.5 «Humphriesioolith Formation», 853.94 – 855.53 m (1.59 m)

An unexpectedly thin succession of predominantly limonitic to iron-oolitic beds was identified as the «Humphriesioolith Formation».

The upper boundary is set at 853.94 m at the top of the uppermost iron-oolitic and mainly limonitic marl bed of 6 cm thickness, which is overlain by a limestone bed free of iron-oolids and limonite.

The lower boundary is set at 855.53 m at the base of a reworked bed (from 855.49 to 855.53 m). It separates the grey calcareous marl (silty) of the Wedelsandstein Formation from an overlying bed with encrusted iron-oolitic to reworked limonitic intraclasts.

Lithology

853.94 – 854.00 m	Calcareous marl, dark grey, sporadic iron-oolids
854.00 – 854.80 m	Two beds of bioclastic limestone (packstone, biosparite), beige grey to light brown, increasingly limonitic, with few iron-oolids in the lower part, separated by a thin bed of calcareous marl, dark grey
854.80 – 854.99 m	Iron-oolite, beige grey to light brown with echinoderms and bivalves.
854.99 – 855.49 m	Argillaceous marl (silty), medium to dark grey, micaceous, with few iron-oolids, echinoderms and brachiopods
855.49 – 855.53 m	Calcareous marl, light brown, limonitic to iron-oolitic, with reworked lithoclasts, oysters and fossil detritus

3.5.6 Wedelsandstein Formation, 855.53 – 883.96 m (28.43 m)

The Wedelsandstein Formation comprises a mostly monotonous succession of predominantly silty claystone to limestone. It can be subdivided into two shallowing upward cycles: an upper, more argillaceous cycle (from 855.53 to 869.70 m) can be distinguished from a lower one with siltstone and silty marl (from 871.50 to 883.30 m). They are separated by a more calcareous section with an erosional surface from 869.70 to 870.76 m. At the base, from 883.30 to 883.96 m, a limonitic bed overlies an iron-oolitic limestone bed which is believed to correspond to the «Sowerbyi-Oolith».

The upper boundary is set at 855.53 m at the base of a reworked bed. It separates the grey calcareous marl (silty) from the basal bed of the «Humphriesioolith Formation» and is characterised by reworked and encrusted iron-oolitic to limonitic intraclasts.

The lower boundary is set at 883.96 m at the base of a limestone. This iron-oolitic bed (from 883.85 to 883.96 m) is believed to correspond to the «Sowerbyi-Oolith».

Lithology

855.53 – 869.70 m	Monotonous succession of silty claystone (thin section BUL1-1-860.36), dark grey, micaceous. Pyrite, framboidal to rose-shaped, is abundant. At some levels, small limonitic nodules occur. Macrofossils are rare. In the upper part, some thin coquinas are found
869.70 – 871.50 m	Hardground (from 869.70 to 869.76 m) on top of a sandy limestone (grainstone, biosparite) (thin section BUL1-1-870.35), medium to dark grey, with pyrite, which changes with depth into a calcareous marl. Crinoids and echinoderm detritus are the dominant biogenic component
871.50 – 883.96 m	From the top downwards, biogenic carbonate components become successively less important and the carbonate content is reduced. In its upper part the section consists of silty marl (sandy), medium to dark grey, (top), micaceous; in its lower part it is silty to sandy claystone, medium to dark grey, micaceous. The sediment is mostly thin bedded. Small ripples are found in some places and sedimentary structures are wavy due to bioturbation in other places. In the middle part limestone nodules and silt lenses are found at several levels. At 882.71 m an ammonite was found From 883.30 to 883.96 m, a bed of bioclastic limestone (limonitic, silty, partly argillaceous) (packstone, biosparite), with bivalves and shell detritus (thin section BUL1-1-883.33) is underlain by a thin limestone (iron-oolitic)

3.5.7 «Murchisonae-Oolith Formation», 883.96 – 891.70 m (7.74 m)

The «Murchisonae-Oolith Formation» is represented by two fossiliferous, predominantly iron-oolitic sections at the top (from 883.96 to 885.02 m) and at the base (from 891.25 to 891.70 m) which are separated by silty claystone with few to no macrofossils. Crinoids and thus sparitic limestone which make up an important portion of the corresponding (much thinner) section at Weiach (Matter et al. 1988) are virtually absent.

The upper boundary is set at 883.96 m at the base of a limestone (iron-oolitic) (from 883.85 to 883.96 m), which is believed to correspond to the «Sowerbyi-Oolith».

The lower boundary is set at 891.70 m at the erosional and bored base of a fossiliferous, limonitic, iron-oolitic hardground (from 891.60 to 891.70 m).

Setting the boundary between the «Murchisonae-Oolith Formation» and the Opalinus Clay at this level is supported by a resistivity log as well as by bio- and chemostratigraphic evidence (*cf.* Dossier IV).

Lithology

883.96 – 888.65 m	At the top, from 883.96 to 884.10 m, thin calcareous marl, medium grey, underlain, from 884.10 to 884.63 m, by a limestone (iron-oolitic) (packstone, biomicrite), medium grey to ochre, micaceous, with bivalves and biodetritus (thin section BUL1-1-884.38), possibly the «Concava-Bank», which is underlain by a second limestone (iron-oolitic), light to medium grey, micaceous, with fossil detritus from 884.63 m onwards
-------------------	---

	From 885.02 to 888.65 m, succession of sandy marl and silty claystone, medium to dark grey, micaceous, fossiliferous, laminated, with small ripples at some levels
888.65 – 891.70 m	Succession of sandy marl and silty claystone (sandy at the very bottom), moderately grey, micaceous, with pyrite (partly framboidal), mostly laminated, small ripples at some levels, virtually no macrofossils. Below a hardground at 891.25, first silty to sandy marl (bioarenitic, iron-oolitic), grey to dark grey, micaceous, and another hardground from 891.55 m onwards (limestone [iron-oolitic] [packstone, biosparite]; thin section BUL1-1-891.55), including reworked, increasingly larger, partly iron-oolitic lithoclasts, encrusted by limonite and fossiliferous in the lower part. Fossils include ammonites (891.63 m), belemnites, gastropods, bivalves and brachiopods, some of them are phosphoritized

3.5.8 Opalinus Clay, 891.70 – 995.85 m (104.15 m)

The Opalinus Clay is generally regarded as a monotonous succession of dark grey silty claystone with silty to sandy lenses. It is interbedded very sparsely by thin layers of sandstone and limestone (Wetzel & Allia 2003). Fossils are usually rare besides a few limestone beds and enriched intervals mainly in the lowermost section.

The upper boundary is set at 891.70 m at the erosional and bored base of a fossiliferous, limonitic, iron-oolitic hardground (from 891.60 to 891.70 m). Setting the boundary at this level between the «Murchisonae-Oolith Formation» and the Opalinus Clay is also supported by a resistivity log and bio- and chemostratigraphic evidence (*cf.* Dossier IV).

The lower boundary is set at 995.85 m in the BUL1-1B core at the top of a thin calcareous marl horizon (from 995.85 to 995.99 m). This horizon is followed by argillaceous marl and claystone containing ammonites of the genus *Pleydellia*. At the same depth, a significant drop of the total natural gamma ray log marks a change from predominantly argillaceous to marly lithologies.

Lithostratigraphic subdivision

Although there is no formal subdivision of the Opalinus Clay, there are several informal attempts (*cf.* Jordan & Deplazes 2019). A recent proposition by Mazurek & Aschwanden (2020) includes four units. They presumably apply to the present section as follows:

891.70 – 912.55 m	«Sub-unit with silty calcareous beds» (20.85 m)
912.55 – 927.77 m	«Upper silty sub-unit» (15.22 m)
927.77 – 978.80 m	«Mixed clay-silt-carbonate sub-unit» (51.03 m)
978.80 – 995.85 m	«Clay-rich sub-unit» (17.05 m)

Lithology

«Sub-unit with silty calcareous beds», 891.70 – 912.55 m (20.85 m)

The «Sub-unit with silty calcareous beds» is defined by the presence of discrete heterogeneities, in particular silty calcareous beds and nodules which are also well expressed as excursions in petrophysical logs (Mazurek & Aschwanden 2020).

891.70 – 904.18 m Argillaceous siltstone (calcareous), in the upper part to silty to fine sandy claystone (calcareous) in the lower part. Both medium to dark grey, micaceous, with pyrite. This interval is characterised by a slight increase in carbonate content, culminating from 898.05 to 898.90 m. At 898.05 m, a horizon with a few up to 2 cm thick calcareous nodules with glauconite grains probably representing a firmground. Below, the carbonate content decreases again

904.18 – 912.55 m Three, up to several decimetre thick calcareous sections in the form of nodular horizons or hardgrounds are characteristic features of the lower interval which is 8.37 m thick. These features are embedded in a silty to slightly sandy claystone, micaceous, with pyrite as well as lenses and nodules of siltstone to fine sandstone (showing small ripples). The carbonate content is among the lowest of the whole Opalinus Clay

The upper calcareous section (from 904.18 to 904.48 m) consists of densely bored limestone lithoclasts in a sandy claystone (calcareous, biotrititic). A claystone layer separates this section into an upper (from 904.18 to 904.27 m) and a lower (from 904.42 to 904.48 m) hardground, rich in pyrite with intraclasts (thin section BUL1-1-904.47). At 905.05 m, a septarian nodule (5 to 7 cm thick) with calcite-filled shrinkage cracks can be found

The central calcareous section (from 907.90 to 908.60 m) consists of a succession of several hardgrounds, lithoclasts, calcareous marls and horizons of bioclastic limestone (argillaceous) (packstone, biomicrite), which are very fossiliferous (echinoderms, gastropods, belemnites and an ammonite at 908.22 m). The succession can be divided into an upper (from 907.90 to 908.45 m) and a lower (from 908.50 to 908.60 m) succession which are separated by a claystone layer. The two thin sections taken from hardgrounds (BUL1-1-908.33 and BUL1-1-908.54) show a very similar composition. Both include intraclasts containing former iron-ooids which are now replaced by calcite

The lower calcareous interval (from 912.45 to 912.55 m) consists of two biomicritic hardgrounds, strongly bioturbated and bored. The thin section BUL1-1-912.44 shows that the upper hardground consists of iron-stromatolitic nodules in an echinoderm-rich marly matrix

«Upper silty sub-unit», 912.55 – 927.77 m (15.22 m)

The «Upper silty sub-unit» is characterised by frequent lenses, typically a few centimetres wide and several millimetres thick, consisting of silty (mainly quartz) and calcite cement, and resulting in a flaser structure (Mazurek & Aschwanden 2020).

912.55 – 927.77 m Monotonous succession of silty to fine sandy claystone (calcareous / siderolithic) to silty to fine sandy marl, medium grey, with small lenses of siltstone to sandstone (fine-grained) showing ripples. The fine lamination is wavy due to bioturbation in some places. Macrofossils are virtually absent

«Mixed clay-silt-carbonate sub-unit», 927.77 – 978.80 m (51.03 m)

The «Mixed clay-silt-carbonate sub-unit», represents the section of the Opalinus Clay which is devoid of marked characteristics typical for the other sub-units (Mazurek & Aschwanden 2020).

927.77 – 954.00 m Heterogeneous section: the dominant lithology is silty claystone (calcareous / siderolithic) dark grey to medium grey, micaceous, with few pyrite nodules, and thin lenses and lenticular nodules of siltstone. The uppermost part (a few centimetres) contains thin limestone to siderite nodules and nodular beds, beige, in a claystone (calcareous) to argillaceous marl matrix, dark grey. Additionally, partly nodular limestone layers are found at several levels

From 943.00 to 954.00 m, similar lithology as above but with a significantly increased clay mineral content (dominant lithology: silty claystone). Macrofossils are rare

954.00 – 967.58 m Similar lithology to above, very fossiliferous with predominantly but not exclusively ammonites (e.g. at 959.07 and 959.52 m) (planktonic? bivalves)

967.58 – 978.80 m At the top, from 967.58 to 967.93 m, hardground with borings and limestone clasts. Below is a silty to sandy claystone (slightly calcareous / siderolithic), medium to dark grey, micaceous and partly pyritic, with thin siltstone to sandstone (fine-grained) lenses. The sediment is strongly bioturbated. Macrofossils are restricted to a few relatively thick-shelled individuals (e.g. at 969.10 and 971.67 m)

«Clay-rich sub-unit», 978.80 – 995.85 m (17.05 m)

The dark and homogeneous «Clay-rich sub-unit», as the name suggests, has a high clay-mineral content (mostly more than 60 %). At most localities, the «Clay-rich sub-unit» marks the base of the Opalinus Clay (Mazurek & Aschwanden 2020).

978.80 – 985.50 m Claystone (silty), to silty claystone (slightly calcareous / siderolithic), medium to dark grey, micaceous, with pyrite, laminated, very fossiliferous. Ammonites dominate an exclusively nektonic fossil record. Further, belemnites (at 984.83 m and 985.40 m) and fish remains (980.08 m) are also found. At 981.26 m and at 981.74 m, two sidero-calcareous nodule layers are found

985.50 – 995.85 m	Similar lithology to above, but strongly bioturbated. Macrofossils are mostly absent. In the lowermost part of the BUL1-1 core two ammonites were found at 995.78 m and 995.88 m. The lower boundary of the Opalinus Clay is set at 995.85 m at the top of a thin calcareous marl horizon in the BUL1-1B core. The lower boundary of the Opalinus Clay facies in the BUL1-1 core section was defined somewhat lower at 996.22 m, which can be explained by the irregular calcareous nodular facies of the underlying Gros Wolf Member of the Staffelegg Formation
-------------------	---

3.6 Lias Group

3.6.1 Staffelegg Formation, 995.85 – 1'030.51 m (34.66 m)

The Staffelegg Formation is a thin (i.e. highly condensed) and heterogeneous succession, dominated by marl and claystone, some bituminous, and including various thin limestone horizons, some of them iron-oolitic.

The Staffelegg Formation and upper Klettgau Formation were penetrated twice, in BUL1-1 and in BUL1-1B. The following observations were made when comparing the two cored intervals which were drilled parallel for about 45 m (from 995.85 to 1'040.26 m); see also Dossier IV for schematic correlation:

- the first section of BUL1-1 from 995 to 1'003.89 m shows an up-hole depth shift of 35 ± 5 cm using the sidetrack BUL1-1B as a reference
- from 1'003.89 to 1'006 m, the BUL1-1 core was lost due to technical problems. The top of the subsequent core retrieval was artificially set at 1'006 m
- the lower section of BUL1-1 from 1'006 to 1'040.26 m shows an up-hole depth shift of 10 ± 5 cm using the sidetrack BUL1-1B as a reference
- although less than a metre apart, the cores of BUL1-1 and BUL1-1B show a lateral heterogeneity, especially in the Gross Wolf Member and in the Gruhalde Member

The upper boundary is set at 995.85 m in the BUL1-1B core at the top of a thin calcareous marl horizon (from 995.85 to 995.99 m) which is followed by argillaceous marl and claystone containing ammonites of the genus *Pleydellia*. A significant drop of the total natural gamma ray log at the same depth marks a change from predominantly argillaceous to marly lithologies.

The lower boundary is set at an erosional surface at 1'030.51 m at the base of an argillaceous marl horizon containing ammonites, bivalves and crinoids. It is underlain by argillaceous / dolomitic marl to dolostone.

3.6.1.1 Gross Wolf Member, 995.85 – 1'000.70 m (4.85 m)

The Gross Wolf is usually composed of argillaceous marl (silty to sandy) to calcareous marl (silty to sandy). It is interbedded by nodular limestone layers up to a few decimetres in thickness. The member is characterised by a higher carbonate content and, consequently, brighter grey shades than the neighbouring units. Further characteristics are the specific abundance in well preserved belemnites, ammonites, and benthic fauna, as well as the nodular shape of the limestone interbeds with mottled surfaces due to intense bioturbation (Reisdorf et al. 2011)

The upper boundary in the BUL1-1B core is set in accordance with the upper boundary of the Staffelegg Formation at 995.85 m at the top of a thin calcareous marl horizon (from 995.85 to 995.99 m). It is followed by argillaceous marl and claystone containing ammonites of the genus *Pleydellia*.

The lower boundary is set arbitrarily at 1'000.70 m just below a horizon with very abundant belemnites and nodules of limestone (argillaceous) characteristic for the Gross Wolf Member.

Lithology

995.85 – 1'000.70 m At the top, from 995.85 to 995.99 m, calcareous marl horizon followed

From 995.99 to 996.84 m, by claystone to argillaceous marl (silty), dark grey with abundant ammonites and belemnites of Toarcian age

From 996.84 to 1'000.70 m, nodules of calcareous marl (to limestone [argillaceous]), light grey, in a marly matrix are present. The latter changes from argillaceous marl to calcareous marl (slightly silty) and back to argillaceous marl (slightly silty). The colour changes from dark grey to grey. Bioturbation is abundant in matrix and nodules. Well preserved burrows are clearly visible in the latter. Pyrite is often found in framboidal aggregates throughout the whole section. Macrofossils with prevailing ammonites (at 996.67, 996.84, 997.10, 997.36, 997.67, 998.16 and 999.05 m) and belemnites are quite abundant

3.6.1.2 Rietheim Member, 1'000.70 – 1'006.81 m (6.11 m)

The Rietheim Member (the former «Posidonia Shales») is known for its bitumen content and very fine layering (lamination) of the dominant claystone. In the present section, only the lower part fully corresponds to expectations. Accordingly, the transition to the overlying Gross Wolf Member is gradual and the demarcation is somewhat arbitrary.

The upper boundary is set arbitrarily at 1'000.70 m just below a horizon with very abundant belemnites and nodules of limestone (argillaceous) characteristic for the Gross Wolf Member.

The lower boundary is marked by a hardground at the top of the fossiliferous and bioturbated limestone of the Breitenmatt and Rickenbach Members at 1'006.81 m.

Lithology

1'000.70 – 1'004.42 m Argillaceous to silty marl, mostly medium grey, in thin layers also light grey, prevails. The interval is interrupted by a calcareous marl (silty) with abundant biotritus and pyrite from 1'000.90 to 1001.43 m. Most of the sediment is bioturbated and small phosphorous or sideritic limestone nodules are found at some levels

From 1'002.70 to 1'004.42 m, the sediment becomes increasingly bituminous and laminated. At 1'004.11 m fragments of an ammonites were found

1'004.42 – 1'006.81 m Calcareous marl bed from 1'004.42 to 1'004.62 m, followed by bituminous shale with vanishing silt content and a first limestone (argillaceous) (mudstone, micrite) bed from 1'005.43 to 1'005.50 m. The following significantly thicker limestone (argillaceous) (mudstone, micrite) bed from 1'005.86 to 1'006.08 m is separated by a dark grey claystone layer and can be correlated with the «Unterer Stein». It is underlain by laminated dark grey to black bituminous shale. Thin-shelled bivalves of *Bositra* genus ("Posidonia"), are quite abundant, dispersed and in coquinas. At 1'005.06 m, fragments of an ammonites were found. Crinoid or echinoid fragments at the very base of the member are noteworthy

3.6.1.3 Breitenmatt and Rickenbach Members, 1'006.81 – 1'007.66 m (0.85 m)

The Breitenmatt and Rickenbach Members correspond to what was known as "Mittellias", a strongly condensed section throughout Northern Switzerland.

The upper boundary is set at 1'006.81 m and marked by a hardground at the top of the fossiliferous and bioturbated limestone underlying the bituminous shale of the basal Rietheim Member.

The lower boundary is set at 1'007.66 m at the top of a limestone (argillaceous) with abundant *Gryphaea obliqua*.

Lithology

1'006.81 – 1'007.42 m At the top, from 1'006.81 to 1'007.20 m, limestone (argillaceous, slightly silty) (packstone, biomicrite), glauconitic, medium to dark grey, moderately fossiliferous

From 1'007.20 to 1'007.42 m, very fossiliferous interval with limestone (argillaceous) (grainstone, biosparite), glauconitic, with abundant belemnites

1'007.42 – 1'007.66 m Succession of bored and phosphoritised hardgrounds giving the limestone (glauconitic) (packstone, biomicrite), medium grey, a nodular look. Fossils, mainly belemnites, are still present but less abundant than above

Rather large belemnites dominate the fossil record which also contains many unidentified fossil fragments. Remains of ammonites were not recognised. The identification as Breitenmatt and Rickenbach Members is based on lithostratigraphic evidence, including the abundance of belemnites ("Belemniten-Schlachtfeld").

3.6.1.4 Grünschholz Member, 1'007.66 – 1'009.02 m (1.36 m)

The Grünschholz Member is a highly condensed, phosphorous succession. Due to the presence of *Gryphaea obliqua* (and its nodular look) it can be clearly distinguished from the also condensed overlying beds.

The upper boundary is set at 1'007.66 m at the top of a limestone (argillaceous) with abundant *Gryphaea obliqua*.

The lower boundary is set at 1'009.02 m and located at the base of the lowest calcareous marl bed with glauconite and phosphorite. It overlies a silty claystone with a bored erosional surface at the top of the Frick Member.

Lithology

1'007.66 – 1'009.02 m Alternation of nodular limestone (packstone, biomicrite), dark to beige grey, glauconitic, partly phosphoritised, with lithoclasts (thin sections BUL1-1-1007.70 and BUL1-1-1008.20), and calcareous marl, light to medium and dark grey, both fossiliferous (including *Gryphaea obliqua*). At the base, phosphoritised intraclasts are found alongside belemnites, other bivalves and, in the lower part, crinoids

3.6.1.5 Frick Member, 1'009.02 – 1'019.82 m (10.80 m)

The Frick Member shows some affinities to the lowest part of Opalinus Clay. However, ammonites (and other macrofossils) are virtually absent in the Frick Member although common in the Opalinus Clay.

The upper boundary is set at 1'009.02 m at an erosional surface at the top of the uppermost silty claystone. It is overlain by calcareous marl with glauconite and phosphorite and intruded due to boring.

The lower boundary is set along a bored and encrusted hardground at the top of a phosphoritised limestone at 1'019.82 m.

Lithology

1'009.02 – 1'019.82 m Succession of argillaceous siltstone, silty claystone and silty claystone to claystone (silty), dark to medium grey, with small-sized detritic mica and diagenetic pyrite, abundant in the lower part. Core and the total natural gamma ray evidence suggests that the minimum claystone content (i.e. maximum silt content) is found at the very top at 1'009.7 m

3.6.1.6 Beggingen Member, 1'019.82 – 1'025.42 m (5.60 m)

The limestone with abundant ammonites and gryphid oysters, typical for the upper part of the Beggingen Member at other locations, is reduced to some few beds. The same applies for the iron-oolitic beds of the lower part.

The upper boundary is set at 1'019.82 m on top of a bored and encrusted hardground which is at the top of a phosphoritised limestone bed and overlain by silty claystone.

The lower boundary is set at 1'025.42 m at the base of a marl (iron-oolitic), which lies below an erosional surface and above a limestone (argillaceous) with distinctly less, i.e. very sporadic, iron-oxides.

Lithology

- 1'019.82 – 1'021.20 m Very fossiliferous limestones (wackestone and packstone, biomicrite, locally grainstone, biosparite), medium light grey to beige, glauconitic. At the top a strongly bored hardground is draped with microbial mats and characterised by strong pyritisation, partly phosphorous. At the base another thin hardground (limestone [packstone, biosparite], glauconitic, with lithoclasts; thin section BUL1-1-2021.30, number refers to depth in parallel BUL-1-1 core section) is found
- 1'021.20 – 1'021.96 m Micaceous claystone (to marl) interval which is interrupted by a thin glauconitic, lithoclastic layer (1'021.48 m). At the base iron-oolitic lithoclasts are found overlying a hardground. The clasts are probably reworked from the underlying strata
- 1'021.96 – 1'022.85 m Very fossiliferous limestone containing an increasing proportion of iron-oids. A further hardground is located below at 1'022.42 m, followed by a layer rich in *Gryphae arcuate* ("gryphid conglomerate"); the rock can be addressed as limestone (iron-oolitic, partly chamositic) (wackestone and grainstone, biosparite), beige grey (thin sections BUL1-1-2022.08 and BUL1-1-2022.64). Its lower boundary is an erosional surface
- Besides gryphid oysters, the fossil record of this upper part (from 1'019.82 to 1'022.85 m) includes belemnites, bivalves, gastropods, brachiopods, echinoderms and others.
- 1'022.85 – 1'023.49 m Micaceous, claystone (slightly silty) interval
- 1'023.49 – 1'024.15 m Fine-bedded alternation of limestone (argillaceous) (mudstone, biomicrite) and argillaceous marl. The tops of the various limestone beds are strongly bored
- 1'024.15 – 1'025.42 m Alternation of iron-oolite (in the upper part) and marl (iron-oolitic) (in the lower part) with thicker and thinner limestone (sandy) (grainstone, biosparite) beds (thin sections BUL1-1-1024.54 and BUL1-1-1025.00), with variable content of iron-oids, some of them with crinoid breccias or bivalve coquinas showing repeated normal grading. Gryphid oysters are absent and *Cardinia sp.* dominate the bivalve fossil record. From 1'024.30 to 1'024.40 m they form a coquina. Additionally, ammonites were found at 1'020.21 and 1'022.82 m

Most of the tops of the beds are erosional surfaces or hardgrounds, often strongly bored. Distinct burrows often introduce younger sediments into the underlying rock for several centimetres. These burrows and bioturbation are nearly omnipresent; boring of fossils and lithoclasts is common

At 1'025.30 m, close to the base of the section, a very distinct erosional surface is found on the top of a calcareous marl with abundant iron-oids

3.6.1.7 Schambelen Member, 1'025.42 – 1'030.51 m (5.09 m)

The Schambelen Member is dominated by dark silty to sandy claystone with a sparse fossil content.

The upper boundary is set at 1'025.42 m at the base of an argillaceous marl with increased iron-oolite content. Below this level iron-ooids still occur but are disperse and rare.

The lower boundary is set at 1'030.51 m at the top of the dolomitic marl. It is overlain by 26 cm of medium to dark grey fossiliferous, argillaceous marl. The presence of ammonites is evidence for Early Jurassic age (rather than Late Triassic), although there are lithological affinities to rocks addressed as "Rhaetian" (now the Belchen Member) in other locations. Another argument in favour of the Schambelen Member is the presence of crinoids (Kiefer et al. 2015) and bivalves excluding typical Triassic genera such as, e.g. (*Rhaet-*) *Avicula*.

Lithology

1'025.42 – 1'028.16 m At the top, from 1'025.42 to 1'025.84 m, wavy-bedded calcareous marl and limestone (argillaceous) (wackestone and packstone, biomicrite), grey to beige and ochre, fairly limonitic, with distinct echinoderm coquinas, dispersed biotritus, very few iron-ooids and decreasing sand content

From 1'025.84 to 1'027.90 m, alternation of bioclastic sandy marl, calcareous marl and a bed (from 1'027.49 to 1'027.90 m) of limestone (argillaceous) (mudstone, micrite), light grey, with burrow

From 1'027.90 to at 1'028.16 m, argillaceous marl, dark grey

1'028.16 – 1'030.51 m Bituminous (slightly), laminated claystone with framboidal pyrite and several thin (up to 3 cm) silty to sandy interlayers including fossil detritus, showing small-scale foresets

At the base from 1030.25 to 1'030.51 m, argillaceous marl (sandy), medium to dark grey, with an ammonite (1030.41 m in BUL1-1), bivalves, crinoids and burrows (thin section BUL1-1-1030.57, number refers to depth in parallel BUL-1-1 core section)

3.7 Keuper Group

3.7.1 Klettgau Formation, 1'030.51 – 1'067.35 m (36.84 m)

The Klettgau Formation is a heterogeneous succession dominated by variegated playa sediments with mostly silty shale and dolocretes. Fine-grained to coarse-grained calcareous or siliciclastic sediments are found in channels and overspill layers.

In Bülach-1-1B, the Belchen Member is missing, and the Gruhalde Member is separated by the heterogeneous Seebi Member.

The upper boundary is set at 1'030.51 m at the top of a dolomitic marl. It is overlain by 26 cm of medium to dark grey fossiliferous, argillaceous marl of the basal Staffelegg Formation.

The lower boundary is set at 1'067.35 m at the top of the uppermost anhydrite (argillaceous) of the Bänkerjoch Formation.

3.7.1.1 Gruhalde Member (upper part), 1'030.51 – 1'041.70 m (11.19 m)

The upper part of the Gruhalde Member is characterised by its light grey to light pale violet colour, as opposed to the lower part of the Gruhalde Member with its intense and variegated colours. Surface outcrop analyses yield a flood plain origin documented by an alternation of channel and overbank sediments. This differentiation is not possible in the present core.

The upper boundary corresponds to the upper limit of the Klettgau Formation. It is set at 1'030.51 m at the top of dolomitic marl which is overlain by 26 cm of medium to dark grey fossiliferous, argillaceous marl of the basal Staffelegg Formation. The boundary is an erosional surface. Fine tubes (boreholes or root structures?) bring younger sediment into the underlying rock.

The lower boundary is set at 1'041.70 m at the top of a prominent dolostone bed. The boundary is marked by reworked lithoclasts of the underlying sediment.

Lithology

1'030.51 – 1'041.70 m Besides gradual changes in rock colour there is a rather homogeneous succession of dolostone (argillaceous, silty) to dolomitic marl (thin section BUL1-1-1034.81). In the upper part the rock colour is predominantly very light to light grey. From 1'035.50 m onwards, the rock colour gradually changes to pale violet. Reduction seams and halos are pale yellowish green

Pedogenic calcareous nodules are found at different levels from 1'032.27 to 1'035.50 m. At various levels, desiccation cracks and synsedimentary to early diagenetic collapse breccias are visible

3.7.1.2 Seebi Member, 1'041.70 – 1'044.42 m (2.72 m)

The Seebi Member unifies a broad range of different sediments that were formed in the channels of the «Stubensandstein» alluvial system, in surrounding ponds and on floodplains. In the present section, a channel fill (or proximal overbank sediment) can be observed from 1'043.42 to 1'043.72 m.

The upper boundary is set at 1'041.70 m at the top of a prominent dolostone bed. The boundary is marked by reworked lithoclasts of the underlying sediment.

The lower boundary is set at 1'044.42 m and is marked by the offset (in a downward direction) of silt and sand content and the onset of reddish inclusions (burrows? intraclasts?).

Lithology

1'041.70 – 1'042.92 m Dolostone, very light grey to beige, showing micritised remains of various sedimentary features such as (freshwater?) oncoids, biotritus and diagenetic breccias, and possibly channels, indicating an origin as a limestone which was later dolomitised. Argillaceous marl (dolomitic), is found in cracks and in small (cm) nodules

1'042.92 – 1'044.42 m Dolostone to dolostone (argillaceous). From 1'043.42 to 1'043.72 m the succession is interrupted by a coarse-grained to very coarse-grained dolostone (sandy) to dolomitic sandstone, light grey to beige, moderately sorted, subangular. Some structures may be interpreted as initial fluvial foresets or ripples which were later altered by diagenetic processes

3.7.1.3 Gruhalde Member (lower part), 1'044.42 – 1'050.82 m (6.40 m)

The lower part of the Gruhalde Member is characterised by its usually intense, variegated colour. The section from 1'045.00 to 1'047.45 m can be correlated with the «Rote Wand», an important regional marker throughout north-eastern Switzerland and southern Germany.

The upper boundary is set at 1'044.42 m where (in a downward direction) silt and sand disappear and the occurrence of reddish inclusions (burrows? intraclasts?) begins.

The lower boundary is set at the top of the uppermost dolostone layer of the Gansingen Member at 1'050.82 m. Reworked lithoclasts of the underlying sediment highlight the erosional character of this boundary.

Lithology

1'044.42 – 1'045.00 m Dolostone with characteristic reddish inclusions which may be interpreted as intraclasts or former burrows

1'045.00 – 1'047.45 m Dolomitic marl (sandy) with an intense pale violet to dark reddish-brown colour. Pedogenic nodules (micritic dolostone, light green to beige, and limestone, light grey) and folded calcitic sedimentary dykes are found at several levels. The base is marked by a disconformity

1'047.45 – 1'050.82 m Dolomitic marl (sandy / silty) like the section from 1'045.00 to 1'047.45 m. The colour is less intense and pedogenic nodules are more prominent and abundant. The lowermost few centimetres are characterised by a dolomitic marl containing reworked lithoclasts from the underlying dolostone

3.7.1.4 Gansingen Member, 1'050.82 – 1'052.03 m (1.21 m)

The Gansingen Member is present with a very reduced thickness but in fully calcareous facies.

The upper boundary is set at a distinct contact at the top of the uppermost dolostone layer at 1'050.82 m. It is overlain by a thin dolomitic marl horizon with reworked components of the topmost Gansingen Member.

The lower boundary is defined by a sharp contact at 1'052.03 m separating light grey to dark beige dolostone from grey violet to grey green dolomitic marl.

Lithology

- 1'050.82 – 1'051.65 m Dolostone, light grey to beige. The repeated occurrence of microbial mats suggests a cyclic genesis
- 1'051.65 – 1'052.03 m Below an irregular contact another microbial mat follows. It is underlain by dolostone, grey to pink, with dissolved ooids, giving the rock a porous look locally ("Schaumkalk", Geyer et al. 2011)

3.7.1.5 Ergolz Member, 1'052.03 – 1'067.36 m (15.33 m)

The Ergolz Member encompasses channel sediments («Schilfsandsteinrinnen», «Schilfsandstein» sensu stricto) and overbank sediments including pedogenic horizons. The black silty claystone layer at the base (from 1'066.89 to 1'067.35 m) may correlate with the «Obere Estherien-schichten» at the top of the Grabfeld Formation of the German stratigraphic scheme (*cf.* Jordan & Deplazes 2019).

The upper boundary is defined by an erosional contact at 1'052.03 m, separating a light grey to dark beige dolostone from underlying grey violet to grey green dolomitic marl.

The lower boundary is set at 1'067.36 m at the top of the uppermost anhydrite (argillaceous) of the Bänkerjoch Formation.

Lithology

- 1'052.03 – 1'054.58 m Dolomitic marl (silty), grey violet to grey green, with various pedogenic horizons marked by (partly dolomitised) anhydrite nodules and beds. This succession is interpreted as an (upper) overbank section
- 1'054.58 – 1'055.94 m Sandstone (fine-grained), micaceous, alternating beige grey and reddish brown (in reduction halos green grey), cross-bedded, dolomite cement. Ripples and foresets are common. From 1'055.35 to 1'055.55 m an escape structure is visible giving the impression of a high accumulation rate. This succession is of fluvial origin and represents an upper channel section
- 1'055.94 – 1'058.60 m Dolomitic marl, reddish brown. Dendritic structures possibly result from roots or bioturbation. However, distinct pedogenic horizons are missing. This part is addressed as a lower overbank section
- 1'058.60 – 1'067.36 m Heterogeneous section including both channel deposits as well as overbank sediments. The most prominent channel deposits are found from 1'064.65 to 1'064.85 m and from 1'064.96 to 1'065.19 m. They consist of sandstone (fine-grained, well sorted, dolomite cement), light grey, cross-bedded. The dominant part of the lowermost section, however, can be addressed as crevasse splay deposits, an alternation of siltstone (sandy) and sandstone (silty), micaceous, well sorted, showing ripples, dolomite cement. Bedding is wavy to lenticular. Load casts, burrows and bioturbation can be found throughout the whole section

At the base, from 1'066.89 to 1'067.36 m, silty claystone, black, possibly correlating to the «Obere Estherienschichten» of the German stratigraphic scheme (*cf.* Jordan & Deplazes 2019)

3.7.2 Bänkerjoch Formation, 1'067.36 – 1'132.00 m (64.64 m)

The Bänkerjoch Formation is an evaporitic succession with many complete and incomplete cycles and subcycles including various sulphate sediments, dolomitic marl, dolostone and sandstone (Dronkert et al. 1990).

The upper boundary is set at 1'067.36 m at the top of the uppermost important, i.e. rock (co-)forming, occurrence of anhydrite.

The lower boundary is set at 1'132.00 m at the base of the last significantly anhydritic rock coinciding with the top of the uppermost massive dolostone of the Asp Member of the Schinznach Formation.

Lithostratigraphic subdivision

There is as yet no formal subdivision of the Bänkerjoch Formation. The informal (rather lithological) subdivision based on earlier core records of Nagra was proposed to be used for the actual campaign by Jordan & Deplazes (2019) and can tentatively be applied to the present core:

1'067.36 – 1'085.07 m: «I claystone with anhydrite nodules» (17.71 m) including «Dolomitmergel» bed (from 1080.65 to 1083.05 m) and «Marker Horizon I» («Quarzitische Bank») from 1'084.33 to 1'085.07 m

1'085.07 – 1'109.60 m: «II cyclic sequence» (24.53 m)

1'109.60 – 1'124.14 m: «III thin-layered anhydrite and claystone sequence» (14.54 m) including «Marker Horizon II» («Pseudocorbula-Bank», from 1'116.74 to 1'117.55 m)

1'124.14 – 1'128.67 m: «IV banded massive anhydrite» (4.53 m); the «Grundgips» of the German stratigraphic scheme

1'128.67 – 1'132.00 m: «V dolomite and anhydrite» (3.33 m) including a characteristic bed (from 1'128.67 to 1'129.60 m) which correlates to the «Mauchach- or Mya-concha-Bank» or the «Myaconcha-Bank»

Lithology

«I claystone with anhydrite nodules», 1'067.36 – 1'085.07 m (17.75 m)

1'067.36 – 1'074.60 m At the top, from 1'067.36 to 1'068.50 m, claystone to claystone (anhydritic), dark grey, with very abundant white anhydrite nodules and beds

From 1'068.50 to 1'074.60 m, as above but with less abundant anhydrite nodules organised in isolated layers

- 1'074.60 – 1'080.65 m As above, with more abundant anhydrite nodules and nodular beds. Some of the beds have a chicken-wire texture. Others consist of dolomite crystals which replaced detritic gypsum crystals. At 1'072.75 m inclined pink anhydrite veins are found
- 1'080.65 – 1'083.05 m Dolostone (argillaceous), white, fine-layered to nodular prevails. At some levels initial layering seems to be disturbed by bioturbation. The dolostone (argillaceous) layers are separated by medium to dark grey claystone. Additionally, nodular anhydrite is found mainly in two distinct horizons. The section can be correlated with the «Dolomitmergel» found in the Weiach borehole from 753.20 to 755.20 m (Matter et al. 1988)
- 1'083.05 – 1'085.07 m Dolomitic marl to claystone with few anhydrite nodules, interrupted by two thin, porous layers of sandstone (fine-grained), well sorted with dolomitic cement from 1'084.33 to 1'084.35 m and from 1'085.04 to 1'085.07 m. They are identified as «Marker Horizon I» (Jordan at al. 2016) which corresponds to the «Quarzitische Bank» of Schalch (1916)

«II cyclic sequence», 1'085.07 – 1'109.60 m (24.53 m)

1'085.07 – 1'098.17 m Complete and incomplete cycles of the following scheme (from top):

- claystone (slightly silty), dark grey, with thick pink to white anhydrite veins
- nodular to laminated anhydrite and dolostone (argillaceous) (partly replaced by anhydrite), white, alternating with claystone, dark grey, and thin layers of dolomite crystals (replacing detritic gypsum crystals, thin section BUL1-1B-1091.12 m), often somewhat thicker layers at the base containing quartz grains (silt to fine-sand fraction)
- nodular beds (some few centimetres) of chicken-wire anhydrite, white, with claystone matrix, dark grey

From 1'093.60 to 1'098.17 m, additionally abundant inclined (and often intersecting) pink anhydrite veins

- 1'098.17 – 1'104.75 m As above, except the bedding thickness of claystone and chicken-wire anhydrite increases (up to 1.5 m) and laminated anhydrite virtually disappears from 1'100.45 m on. Characteristic, inclined, pink anhydrite veins are still abundant
- 1'104.75 – 1'109.60 m As above but with a less obvious cyclicity. Chicken-wire anhydrite predominates. At some levels the sediment is deformed (folded) by early diagenetic processes. Characteristic inclined pink anhydrite veins are still abundant

«III thin-layered anhydrite and claystone sequence», 1'109.60 – 1'124.14 m (14.54 m)

- 1'109.60 – 1'112.90 m Very thin-bedded alternation (mm to few cm) of dolomite crystals (replacing detritic gypsum crystals), anhydrite (silty, locally also slightly sandy), and claystone (silty), dark grey to black

From 1'112.30 to 1'112.90 m, characteristic alabastrine anhydrite layer, light to medium grey, separated into two by a thin dolomite crystal layer (replacing detritic gypsum crystals) with grains of quartz sand. Features within the anhydrite resemble micritised bivalves indicating a marine origin

- 1'112.90 – 1'116.74 m Alternation (cm to dm) of grey violet to greyish-blue green and dark grey claystone (dolomitic, slightly silty), and anhydrite which is mostly nodular. At some level dolomite crystals (replacing detritic gypsum crystals), white and pink
- 1'116.74 – 1'117.55 m Two dolostone (argillaceous) layers, light greenish-grey, separated by alabastrine anhydrite, white. This sequence is suggested to correlate to the «Marker Horizon II» (Jordan et al. 2016), which corresponds to the «Pseudocorbula-Bank» sensu Hofmann et al. (2000)
- 1'117.55 – 1'124.14 m Non-cyclic alternation of variegated claystone (anhydritic), and detritic and nodular anhydrite. Total anhydrite content increases with depth. At the base, from 1'123.20 to 1'124.14 m, a succession of thin beds rich in dolomite crystals (replacing detritic gypsum crystals) is found (thin section BUL1-1B-1123.99)

«IV banded massive anhydrite», 1'124.14 – 1'128.67 m (4.53 m)

- 1'124.14 – 1'128.67 m Massive anhydrite, white, partly nodular, separated by thin horizons of argillaceous marl, dark grey, giving the rock a banded appearance

«V dolomite and anhydrite», 1'128.67 – 1'132.00 m (3.33 m)

- 1'128.67 – 1'132.00 m At the top, from 1'128.67 to 1'129.60 m, two anhydrite beds, beige grey, rich in micritised bivalves and ooids. The two beds are separated by anhydrite (dolomitic) to dolomitic marl (anhydritic). The interval can be correlated with the «Myaoncha-Bank» of Schalch (1906), which corresponds to the «Mauchach-Bank» (Zeller 1908) of the German stratigraphic scheme according to Hofmann et al. (2000)

From 1'129.60 to 1'132.00 m, non-cyclic alternation of claystone (anhydritic), anhydrite (dolomitic) (with characteristic black dots), anhydrite (argillaceous) as well as massive and nodular anhydrite. Colour varies between white, light and medium grey

3.8 Muschelkalk Group

3.8.1 Schinznach Formation, 1'132.00 – 1'204.73 m (72.73 m)

The Schinznach Formation recently established by Pietsch et al. (2016) shows some divergences from the various older stratigraphic schemes applied when recording boreholes in earlier Nagra and Nagra-accompanied campaigns. The following record follows this recent formal scheme.

The upper boundary is set at the base of the lowermost significantly anhydritic bed of the Bänkerjoch Formation at 1'132.00 m, coinciding with the top of the uppermost massive dolostone. It proves to be an erosional surface with a fossiliferous crust.

The lower boundary is set at 1'204.73 m. at the base of the Fützen Bed, which is deposited on the top of the first massive dolostone bed.

3.8.1.1 Asp Member, 1'132.00 – 1'135.77 m (3.77 m)

The Asp Member (Pietsch et al. 2016) includes dolomite in the upper part and fossiliferous bituminous shale in the lower part.

The upper boundary is set (in accordance with the upper boundary of the Schinznach Formation) at the base of the lowermost significantly anhydritic bed of the Bänkerjoch Formation at 1'132.00 m, coinciding with the top of the uppermost massive dolostone. At the same time this boundary represents an erosional contact.

The lower boundary is set at 1'135.77 m at the base of the lowest (thin) bituminous claystone layer.

Lithology

1'132.00 – 1'134.60 m Alternating beds of dolostone, beige grey, and bituminous shale, black, fossiliferous. At the top an erosional surface is found which is underlain by a dolostone bed with intercalations of dolostone (argillaceous) showing additional internal erosional surfaces. Small pores or fenestral structures may result from the dissolution of very small anhydrite nodules

The uppermost (thin) fossiliferous (bivalves, fish scales, etc.), bituminous shale bed with pyrite is found from 1'132.61 to 1'132.70 m. It is followed by a thicker dolostone bed with dark pellets and anhydrite nodules from 1'133.35 to 1'134.00 m. After a second thin, fossiliferous, bituminous shale bed with pyrite (from 1'134.19 to 1'134.23 m), another dolostone (argillaceous) bed is found

1'134.60 – 1'135.77 m Bituminous shale, black (with pyrite), including several coquinas (bivalves, fish scales, etc.). The total natural gamma ray log exhibits a very prominent peak (marker horizon)

At the bottom, from 1'135.40 to 1'135.77 m, dolostone, beige grey, porous, with erosional surface atop, underlain by very thin (4 cm) bituminous shale, black

3.8.1.2 Stamberg Member, 1'135.77 – 1'174.24 m (38.47 m)

The Stamberg Member is a thick succession of dolostone in the upper part of the Schinznach Formation. Its definition (Pietsch et al. 2016) follows a purely petrographic approach: its lower boundary is given by the lower boundary of post-sedimentary, persistent, and complete dolomitisation (commonly of an initially at least partly marine limestone). In the present section (Bülach-1-1B), this is the case at 1'174.24 m.

The upper boundary is set, following Pietsch et al. (2016) at 1'135.77 m, at the base of the lowest (thin) bituminous shale layer.

The lower boundary is set at 1'174.24 m at the lower boundary of persistent and complete (secondary) dolomitisation.

Lithology

1'135.77 – 1'151.09 m At the top, from 1'135.77 to 1'136.02 m, conglomeratic dolostone with normally graded rounded dolomitic intraclasts and possibly pellets in a dolomitic matrix in the upper part. This section may correspond to the «Unterer Dolomit» which was regarded as part of the obsolete «Lettenkohle» (for discussion see Pietsch et al. 2016 and Jordan & Deplazes 2019)

From 1'136.02 to 1'151.09 m, dolostone, beige grey to dark beige and pale pink, characterised by numerous porous horizons (becoming very prominent below 1'139 m). At some levels, pores of up to 5 cm in diameter occur. Fine, flasery marl drapes produce a layering from several decimetres to more than 1 m. Dissected layering to brecciation is found at some levels, convolute bedding at others

At two levels located between 1'142.55 to 1'146.05 m, a possible indication of micritised fossils and oolites can be observed. This interval may correspond to the Kaisten Bed

A significant colour change from pale pink to beige at 1'149.35 m correlates with desiccation and brecciation features

1'151.09 – 1'159.60 m Alternation (centimetres to decimetres) of various dolostones, all light to medium grey but differing in their microstructure. The first type is probably a dolomitised limestone (wackestone to packstone, pelmicrite). This type dominates in the lower part from 1'155.60 to 1'159.60 m. The second type is probably originally a limestone (wackestone and packstone, biopelmicrite) with few ooids and a somewhat arenitic look. The third type is a dolostone (micrite). Many beds have erosional surfaces at the top; two very prominent ones are found at 1'153.40 m and at the base of the section (1'159.60 m). Both are overlain by normally graded bioturbitic layers

A high porosity already observed in the overlying section continues down to 1'152.5 m and is observed from 1'155.5 to 1'156 m again

The interval can be correlated to the Eptingen Bed. It is in a similar position but much thicker than the «Oolith-Horizonte» of Weiach (Matter et al. 1988), which were identified as Eptingen Bed by Pietsch et al. (2016)

1'159.60 – 1'167.52 m Dolostone, alternating between light grey and beige grey, medium-bedded (5 to 10 cm). At some levels these beds are laminated, at others the lamination was destroyed, probably by bioturbation. The dolostone beds are separated by dolomitic marl horizons, dark grey to brownish grey, which are a few centimetres thick. There are hardly any macrofossils and only a few oolites (e.g. from 1'166.20 to 1'166.35 m)

- 1'167.52 – 1'169.01 m Very fossiliferous and very porous alternation of various types of dolomite including dolostone coquina, light to medium grey, formed mainly by bivalves and brachiopods, dolomitised initial limestone (wackestone and packstone, biopelmicrite) and dolostone (arenitic), light to medium grey, probably originating from a biomicrite packstone. Lithoclasts are found at two levels above an erosional surface at 1'168.36 m
- 1'169.01 – 1'174.24 m Well bedded alternation (about 0.5 to 1.0 m) of dolostone, beige grey, dolostone, light to medium grey, dolostone, very light grey to beige, with abundant lithoclasts, mainly found above erosional surfaces, and dolostone coquina composed of bivalves and brachiopods. Within this alternation the uppermost crinoid is recorded at 1'171.44 m
- High large-scale porosity is found at around 1172 m showing similarities to the occurrences further above

3.8.1.3 Liedertswil Member, 1'174.24 – 1'176.19 m (1.95 m)

The Liedertswil Member is defined to reach from the lower boundary of post-sedimentary persistent and complete dolomitisation to the uppermost bed consisting of more than 10 % crinoids (Pietsch 2016). In the present section (Bülach-1-1B) this applies to less than 2 m.

The upper boundary is set at 1'174.24 m at the base of a fully dolomitised rock.

The lower boundary is set at 1'176.19 m according to the formal stratigraphic scheme (Pietsch et al. 2016) at the uppermost bed consisting of more than 10 % crinoids. In the present core this bed is found from 1'176.19 to 1'176.37 m.

Lithology

- 1'174.24 – 1'175.40 m Limestone (dolomitic) (mudstone, micrite), medium light grey, bioturbated, slightly porous, is found below an erosional surface
- 1'175.40 – 1'176.10 m Bed (15 cm) of limestone (mudstone, micrite), very light grey, underlain by bioturbated, limestone (dolomitic) (mudstone, micrite), medium light grey
- 1'176.10 – 1'176.19 m Lithoclasts in a claystone matrix, dark grey, overlain by a very thin bed of very light grey limestone (mudstone, micrite)

3.8.1.4 Kienberg and Leutschenberg Members, 1'176.19 – 1'204.73 m (28.54 m)

According to Jordan & Deplazes (2019) the Kienberg and Leutschenberg Members should be combined because a separation is often difficult and of no use. Both members consist of limestone with very little clay content and interlayers.

The upper boundary is set at 1'176.19 m at the top of the uppermost bed which consists of more than 10 % crinoids (Pietsch et al. 2016).

The lower boundary is set at 1'204.73 m. at the base of the Fützen Bed, which is deposited on the top of the first massive dolostone bed.

Lithology

1'176.19 – 1'185.21 m Complete and incomplete cycles of the following scheme (from top):

- limestone (mudstone, micrite), light grey, often strongly bioturbated, with thin (< 1 cm) argillaceous marl interlayers, locally with crinoids
- limestone (partially argillaceous) (wackestone, biomicrite), medium light grey, fossiliferous (mainly crinoids), at some levels graded (increasing size and density of fossils), at some levels (very) porous due to the dissolution of shells
- limestone (packstone, biomicrite), coquina formed by crinoids, brachiopods, bivalves and others, often porous due to the dissolution of shells
- calcareous marl with intraclasts (reworking level) above an erosional surface with borings and sessile hardground bioforms

The thickness of a cycle ranges from a few decimetres to slightly more than 1 m. Locally the limestone is partially dolomitised

1'185.21 – 1'188.87 m As above, but the thickness of the cycles is smaller mainly due to a reduced thickness of the mudstone. Thus, the lower section looks even more fossiliferous than the upper part. Locally, e.g. from 1186.07 to 1186.26 m, lithoclasts are found within the basal (very fossiliferous) layers

1'188.87 – 1'195.35 m Limestone (mudstone, micrite), light grey, macrofossils are virtually absent. Only from 1'190.13 to 1'190.32 m and from 1'192.51 to 1'192.52 m, fossiliferous limestone beds are found. It is noteworthy that the coquinas include brachiopods and bivalves but no crinoids or other echinoderms. This is typical for the boundary zone between the Kienberg Member and Leutschenberg Member (Pietsch et al. 2016). The upper one of the two horizons (from 1'190.13 to 1'190.32 m) can be correlated to the Salhof Bed

At the very base, from 1'195.28 to 1'195.35 m, a fine-grained biotrititic limestone layer, medium grey, is found. It is underlain by a thin, lenticular claystone layer

1'195.35 – 1'199.18 m Succession of fining upward cycles, 0.5 to 0.8 m thick, of the following scheme (from top to bottom):

- limestone (mudstone, micrite), very light grey, bioturbated
- limestone (wackestone, biomicrite), light grey, fossiliferous, mainly crinoids
- limestone (packstone, biomicrite), medium grey, fossiliferous: crinoids (very abundant), brachiopods, bivalves
- breccias, calcareous (polymict), reworked lithoclasts, crinoids and other fossils with calcareous marl matrix, medium grey. These breccias are generally very thin (cm) except from 1'198.45 to 1'198.70 m. At the base, from 1'198.96 to 1'199.18 m the breccia is missing, and the section ends with an echinoderm limestone (grainstone, biosparite) (encrinite, "Echinodermenspatkalk")

- basal erosional surface or hardground, overlain by crinoids, with borings allowing the overlying sediment into the underlying limestone (micrite)
- 1'199.18 – 1'201.75 m Characteristic limestone (mudstone, biopelmicrite) dominated by microbial-encrusted lithoclasts or fossils (oncoids). Within a matrix of dolomitic marl mainly crinoids and other fossils are also found
- 1'201.75 – 1'202.75 m Limestone (dolomitic) (mudstone, micrite), beige grey, with fenestral fabrics and larger pores interpreted as dissolved anhydrite nodules
- 1'202.75 – 1'203.60 m Limestone dolomitic (mudstone, micrite), beige grey, partly fossiliferous. The micritised fossils include bivalves, brachiopods and possibly echinoderms
- 1'203.60 – 1'204.73 m Limestone dolomitic (grainstone and wackestone, micrite, partly recrystallised), beige to light grey, oolite at the top (thin section BUL1-1B-1'203.66), passing to microbial mats at the bottom. Thin section evidently shows secondary crystalline anhydrite inclusions

3.8.2 Zeglingen Formation, 1'204.73 – 1'267.94 m (64.34 m)

The present section (BUL-1-1B) shows an exemplary integral section of the Zeglingen Formation with a thick rock salt layer. Furthermore, it is not affected by early diagenetic or later subsidence (meaning that no subsidence breccia horizons occur although present in many other sections).

The preliminary upper boundary is set at 1'204.73 m at the top of the first massive dolostone bed.

The lower boundary is set at 1'267.94 m at the top of the uppermost dolostone of the Kaiseraugst Formation.

Lithostratigraphic subdivision

There is no formal subdivision of the Zeglingen Formation. The traditional subdivision into four informal units (*cf.* Jordan & Deplazes 2019) can be applied to the present core:

- 1'204.73 – 1'214.00 m: «Dolomitzone» (9.23 m); the boundary between «Dolomitzone» and «Obere Sulfatzone» is set within the core loss section from 1'211.34 to 1'216.00 m based on the high-resolution formation density log and in analogy with surrounding boreholes
- 1'214.00 – 1'245.50 m: «Obere Sulfatzone» (31.5 m); the boundary between «Obere Sulfatzone» and «Salzlager» is set at the uppermost occurrence of rock salt
- 1'245.50 – 1'260.31 m: «Salzlager» (14.81 m); the boundary between «Salzlager» and «Untere Sulfatzone» is set at the lowermost occurrence of rock salt
- 1'260.31 – 1'267.94 m: «Untere Sulfatzone» (7.63 m)

Lithology

«Dolomitzone», 1'204.73 – 1'214.00 m (10.40 m)

1'204.73 – 1211.36 m Dolostone (partly saccharoidal) (micrite), beige to dark beige to beige grey, predominantly laminated (microbial mats), locally disturbed by bioturbation. In the upper part from the top to about 1'207.70 m chert nodules, dark grey to greyish green, are abundant. Their average size increases with depth. In the lower part from 1'208.90 to 1'210.33 m anhydrite nodules, very light to medium grey, are found

1'211.36 – 1'214.00 m no cores available due to drilling out casing shoe

«Obere Sulfatzone», 1'214.00 – 1'245.50 m (31.5 m)

1'214.00 – 1'216.00 m no cores available due to drilling out casing shoe

1'216.00 – 1'221.07 m Alternation of up to 2 cm thick dolostone, beige grey to dark beige, and detritic anhydrite, very light grey. Anhydrite nodules and nodular beds occur in variable sizes and thicknesses. Chert nodules are found at several levels from 1'216.26 m to 1'216.40 m, 1'218.72 m to 1'218.75 m and from 1'221.42 to 1'221.62 m

1'221.07 – 1'229.99 m Anhydrite-dominated section: alternation of massive anhydrite, very light grey, and laminated anhydrite to argillaceous anhydrite, light grey, with very fine organic interlayers, dark grey. In the section from 1'228.50 to 1'228.60 m a fine-layered arenitic, slightly dolomitic anhydrite with flat dolomitic pebbles is folded by diagenetic processes

1'229.99 – 1'235.78 m Claystone-dominated section: alternation of claystone (anhydritic), dark grey, and dolostone (argillaceous), beige grey. The claystone (anhydritic) includes dispersed small nodules of anhydrite, pink. The dolomite (argillaceous) is mostly fine layered (microbial mats) and partially brecciated. In the lower part, from 1'232.45 to 1'235.78 m, generally thin and some thicker claystone interlayers, dark grey, are also found. At several levels folding can be observed and is most prominent at 1'231.50 m and at 1'233.25 m

1'235.78 – 1'245.50 m "banded", anhydrite-dominated section: The "banded" appearance results from an alternation of thin layers (mm to few cm) of anhydrite (argillaceous), claystone (anhydritic), dark grey, and dolostone (argillaceous), beige grey. This pattern is interrupted twice by an anhydrite with chicken-wire texture from 1'236.40 to 1'236.80 m, and a predominantly massive anhydrite section from 1'237.75 to 1'239.91 m

The fine-layered sediment is deformed at several levels. Deformation structures include brecciation, geometric (e.g. box folds) and chaotic ("cauliflower") folding, tee pee structures (roof like "folding"), and thrusting. Most prominent and note-worthy examples are found at 1'237.50 m (small scale folding), from 1'238.00 to 1'238.70 m ("cauliflower parasitic folding"), from 1'238.90 to 1'239.13 m (upside down box

fold), at 1240.50 m (lift-off fold), from 1'241.25 to 1'241.50 m ("multi style fold" including blind thrusts and erosion / dissolution) and at 1'242.25 m (flat box fold)

Within the "banded section", from 1'245.02 to 1'245.25 m the uppermost rock salt (halite) inclusions are found within a claystone layer

«Salzlager», 1'245.50 – 1'260.31 m (4.81 m):

1'245.50 – 1'260.31 m Massive rock salt with intraclasts variable in size, frequency, density and nature. The rock salt is very light pink to very light beige, locally also red, partly transparent, and locally coarse-grained with large xenomorphic crystals. The intraclasts include claystone, medium to pale green, fine-layered alternations of anhydrite and claystone (anhydritic), dark and light grey, massive anhydrite, white, and dolostone to dolomitic marl, beige. In some distinct thinner layers small-sized components outnumber the rock salt in terms of volume. From 1'258.10 to 1'258.40 m, a "banded" anhydrite component is larger than the core diameter

«Untere Sulfatzone», 1'260.31 – 1'267.94 m (7.63 m)

1'260.31 – 1'266.06 m Fine-layered ("banded", millimetres to some centimetres) alternation of anhydrite (argillaceous), white to very light grey, claystone (anhydritic), light grey, claystone, dark grey, and massive anhydrite, white. Rock salt (halite) is found in pores and veins, in the latter case partly orange, otherwise transparent to milky. At several levels the fine-layered sediment is deformed. Deformation structures include brecciation, geometric (e.g. box folds) and chaotic ("cauliflower") folding, teepee structures and thrusting. Most prominent and noteworthy examples are found from 1'260.00 to 1'260.25 m ("beheaded" blind thrust folds and "boudin" folding), 1'261.40 to 1'261.70 m (chaotic brecciation), at 1'264.20 m (convolute bedding), and from 1'265.40 to 1'265.70 m (exotic box folding)

1'266.06 – 1'267.94 m Massive almost pure anhydrite, white. In the upper part down to 1'266.95 m the anhydrite is intercalated with thin claystone drapes, medium grey, and shows early diagenetic deformation including a well-developed "synorogenic onlap" (from 1'266.30 to 1'266.60 m). The lower part is a single, massive bed of anhydrite

3.8.3 Kaiseraugst Formation, 1'267.94 – 1'306.17 m (38.23 m)

The Kaiseraugst Formation was encountered in complete and mostly typical facies. Only the chalky nature of the basal «Wellendolomit» was unexpected.

The upper boundary is set at 1'267.94 m at the top of the uppermost dolostone and corresponds to the actual formal definition (Jordan 2016). This definition deviates from arguments used in older campaigns. At the nearby Weiach borehole (Matter et al. 1988), the boundary was set at the base of the lowest anhydrite bed above a thicker interval of bituminous shale. in BUL-1-1B borehole, this would correspond to 1'270.13 m. Note that bituminous sediments are already found from 1268.30 m onwards and that the lowermost anhydrite bed stretches from 1'275.16 to 1'275.95 m.

The lower boundary is set at 1'306.17 m at the top of the uppermost sandstone layer and at the base of a siltstone layer with suspected microbial mats and lenses of claystone and sandstone. It is interpreted as a transgression horizon of the Kaiseraugst Formation.

Lithostratigraphic subdivision

There is no formal subdivision of the Kaiseraugst Formation. The traditional subdivision into three informal units and traditional informal marker beds (*cf.* Jordan & Deplazes 2019) can be applied fairly well to the present core:

- | | |
|------------------------|--|
| 1'267.94 – 1'276.59 m: | «Orbicularismergel» (8.65 m) including «Unterer Dolomit» (from 1'267.94 to 1'269.04 m) and «Geislingen-Bank» (from 1'274.65 to 1'275.95 m) |
| 1'276.59 – 1'300.04 m: | «Wellenmergel» (23.45 m) including «Spiriferina-Bank» (from 1'284.37 to 1'284.98 m), «Obere Terebratelnbank» (from 1'289.85 to 1'290.17 m) and «Buchismergel» (from 1'290.17 to 1'300.04 m) |
| 1'300.04 – 1'305.53 m: | «Wellendolomit» (<i>sensu stricto</i>) (5.49 m), rather a limestone than a dolostone here except for the lowermost bed, including «Bleiglanz-Bank» (in a broader sense) from 1'300.04 to 1'300.17 m |
| 1'305.53 – 1'306.17 m: | Transgression horizon of «Wellendolomit» consisting predominantly of terrigenous sediments, very similar to the underlying sediments of the Dinkelberg Formation. However, the presence of microbial mats at 1'306.00 m points to a peri-marine origin |

Lithology

«Orbicularismergel», 1'267.94 – 1'276.59 m (8.65 m)

1'267.94 – 1'270.13 m Alternation (millimetres to some centimetres) of dolostone (argillaceous, doloarenitic), beige grey, anhydrite (argillaceous), light grey, partly bituminous, few layers of anhydrite (argillaceous, sulpharenitic), white. Anhydrite (argillaceous) predominates in the lower part (from 1'269.04 to 1'269.70 m) and dolostone (argillaceous) is restricted to a few mostly very thin layers. The whole section from 1'267.94 to 1'269.04 m can be correlated to the «Unterer Dolomit»

At the bottom, from 1'269.70 to 1'270.13 m, thin-bedded alternation of bituminous dolomitic marl, beige grey to dark beige, micaceous, and anhydrite (sulpharenitic), white. The base of the lowermost anhydrite bed is found at 1'270.13 m. The following bed of bituminous dolomitic marl bed contains a layer with very small anhydrite nodules (some millimetres) in its centre

1'270.13 – 1'274.65 m Bituminous shale, micaceous. It is calcareous in the upper part and dolomitic in the lower part. In the lowest part (from 1'274.63 m downwards), a nodular and a lenticular bed of calcareous marl rich in fossils (brachiopods, bivalves) is found

1'274.65 – 1'276.59 m Two beds of mostly pure anhydrite (argillaceous), white, micaceous, with chaotic and chicken-wire textures as well as massive layering. This far-ranging marker bed is known as «Geislingen-Bank» in adjacent Southern Germany (e.g. Geyer et al. 2011)

At the bottom, from 1'275.95 to 1'276.59 m, argillaceous marl with anhydrite beds (up to 8 cm)

«Wellenmergel», 1276.59 – 1'300.04 m (23.45 m)

1'276.59 – 1'284.98 m Argillaceous marl, dark grey, with numerous thin limestone interlayers (from a few millimetres to 20 cm), light grey, most of them contain coquinas (brachiopods, bivalves, biotritus) and claystone drapes, partly silty, dark grey to greenish grey. Dispersed fossils including some larger bivalves are also found in the marl between the coquinas. The narrow succession of four coquina beds at the base from 1'284.37 to 1'284.98 m is identified as «Spiriferina-Bank». It shows great similarity to the corresponding interval in the nearby Weiach borehole (Matter et al. 1988)

1'284.98 – 1'289.85 m Fine-bedded alternation of claystone, dark grey, and argillaceous marl, medium grey, both slightly silty. The latter dominates in the upper part, the former in the lower part (below about 1'288.60 m). Dispersed fossils (brachiopods, single shells of bivalves, some of them quite large) are found throughout the section. However, they are more abundant in some parts, and less abundant in other parts of the section. Bioturbation is evident at some levels

1'289.85 – 1'291.46 m Two successions of coquinas at the top (from 1'289.85 to 1'290.17 m) and at the bottom (from 1'291.11 to 1'291.46 m) are separated by a claystone (slightly silty), dark grey and micaceous. The upper coquina interval includes beds of limestone (packstone and grainstone, biomicrite to biosparite), light grey, and of calcareous marlstone, medium grey separated by claystone as below. This upper succession is identified as «Terebratelnbank». The lower succession comprises only limestone beds (packstone and grainstone, biomicrite to biosparite), light grey

1'291.46 – 1'300.04 m Claystone, dark grey, micaceous and fossiliferous prevails. It is interrupted by few cross-bedded coquina horizons (brachiopods, bivalves) from 1'296.87 to 1'297.06 m and again from 1'299.29 to 1'299.41 m. Limestone (packstone and grainstone, biomicrite to biosparite), light grey, with galena. The section can be correlated to the «Buchimer gel»

«Wellendolomit», 1'300.04 – 1'306.17 m (6.13 m)

1'300.04 – 1'303.61 m At the top, from 1'300.04 to 1'300.17 m, four thin limestone (argillaceous) (grainstone, biosparite) beds, light grey, with galena. The uppermost can be identified as «Bleiglanz-Bank», sensu stricto

From 1'300.17 to 1'303.61 m, alternation of calcareous marls, dark grey, fossiliferous (bivalves, brachiopods, dispersed) with very thin (1 to 3 cm) interlayers of limestone (slightly sandy) (wackestone and packstone, micrite), medium to light grey. Most but not all of these interlayers are coquinas (brachiopods, bivalves). Most of them show ripples and fore-sets. The abundance of limestone layers varies throughout the section to the point that limestone is the main lithology in some intervals. Mica and pyrite are omnipresent in this interval, galena virtually absent

1'303.61 – 1'306.17 m Limestone (mudstone and packstone, biomicrite) is increasingly dolomitised with depth. The rock colour changes from very light grey to medium grey. Galena is found in the two coquinas (brachiopods, bivalves) from 1'301.61 to 1'303.73 m and from 1'303.95 to 1'304.08 m

From 1'305.53 to 1'306.17 m, siltstone, light grey to beige, with lenses of claystone and sandstone (medium-grained) overlying an erosional surface. At 1'306.00 m features resembling microbial mats are found. This points to a peri-marine origin. This section can then be interpreted as a basal transgressive layer of the Kaiseraugst Formation consisting mainly of reworked sediment of the underlying strata

3.9 Buntsandstein Group**3.9.1 Dinkelberg Formation, 1'306.17 – 1'319.63 m (13.46 m)**

The siliciclastic Dinkelberg Formation was encountered in a rather unexpected form. The typical silty «Rötton» found in most other boreholes and outcrops is absent.

The upper boundary is set at 1'306.17 m at the top of the uppermost sandstone layer and the base of a siltstone layer with suspected microbial mats and lenses of claystone and sandstone. It is interpreted as a transgressional horizon of the Kaiseraugst Formation.

The lower boundary is set at 1'319.63 m at an erosional surface overlain by a conglomerate including an angular quartz pebble of more than 6 cm in diameter. Large ventifacts ("Windkanter") were reported to mark the base of the Mesozoic at several places (*cf.* Jordan & Deplazes 2019). A further argument for the formation boundary is the significant drop of the total natural gamma ray log at that depth.

Lithology**«Plattensandstein» (?), 1'306.17 – 1'311.29 m (5.12 m)**

1'306.17 – 1'307.25 m Sandstone (fine-grained), light grey to beige grey, well sorted, subangular to well rounded, siliceous cement, with lenses of claystone and sandstone (medium-grained)

1307.25 – 1'311.29 m Sandstone (medium-grained), medium-sorted, subangular to well rounded, quartz and dolomite cement. In the upper part the rock colour is mostly light greenish grey, but also light grey, white, pale yellow and grey violet. From 1'309.60 m on a reddish hue appears and prevails increasingly. At the base of the section from 1'311.22 to 1'311.29 m a layer of coarser sandstone with reworked intraclasts of the substrate and Fe-rich impregnation is found, representing a weathering surface and subsequent fluvial transgression

«Karneolhorizont VH2» (?), 1'311.29 – 1'313.37 m (2.08 m)

1'311.29 – 1'311.46 m Siltstone (sandy), grey violet and pale yellow, with chert

1'311.46 – 1'313.37 m Sandstone (coarse-grained), pale yellowish green (above 1'312.39 m also reddish grey), poorly sorted, subangular, with an argillaceous matrix, within initially dolomitic and now almost fully silicified nodules at two levels (from 1'312.20 to 1'312.39 m and from 1'313.16 to 1'313.37 m)

«Vogesensandstein» (?), 1'313.37 – 1'319.63 m (6.26 m)

1'313.37 – 1'315.21 m Conglomerate, siliciclastic (polymict), pale yellowish green, poorly sorted, subangular, argillaceous sandstone matrix

1'315.21 – 1'315.86 m Alternation of sandstone (coarse-grained), grey violet, poorly sorted, subangular, argillaceous matrix, with lithoclasts, fining upward, and claystone (sandy), pale yellowish green with dolomite nodules. It probably represents a further palaeosol succession

1'315.86 – 1'319.63 m Three normally graded cycles of conglomerate, siliciclastic (polymict), light greenish grey to pale pink, mostly quartz, few lithoclasts and feldspar, poorly sorted (maximum size: pebbles), subangular, argillaceous sandstone matrix. The lowest cycle from 1'318.25 to 1'319.63 m ends on top of an erosional surface with a large quartz clast / pebble followed by normally graded sandstone (coarse- to fine-grained), light yellowish grey to reddish brown, moderately sorted and rounded

3.10 Permo-Carboniferous sediments

3.10.1 Weitenau Formation, 1'319.63 – 1'370.19 m (> 50.56 m)

Although the borehole penetrated about 50 m into the siliciclastic pre-Mesozoic sediments the layers cannot be unambiguously identified, either in terms of the traditional informal Swiss scheme or the formal German stratigraphic scheme.

The upper boundary is set at 1'319.63 m at an erosional surface overlain by a conglomerate including an angular quartz pebble of more than 6 cm in diameter. Large ventifacts ("Windkanter") were reported to mark the base of the Mesozoic at several places (*cf.* Jordan & Deplazes 2019). A further argument for the formation boundary is the significant drop of the total natural gamma ray log at that depth.

Lithology

- 1'319.63 – 1'322.69 m Crossbedded sandstone (medium- to coarse-grained), beige grey, in fine laminae also reddish brown, with dark opaque minerals, well sorted, sub-angular, siliceous cement, below 1322.45 m micaceous
- 1'322.69 – 1'325.84 m Abundant fining upward cycles (5 to 50 cm) starting with sandstone (fine-grained), well sorted, and ending with claystone, micaceous. In the middle part (from 1'324.35 to 1'325.12 m), the cycles include lithoclasts at the base. In the lower part of the section, from 1'325.12 to 1'325.84 m, the claystone segments of the cycles become dominant. The rock colour of the section from 1'322.69 to 1'325.84 m is predominantly dark reddish brown but also has layers of greenish-grey and beige greyish-green
- 1'325.84 – 1'351.89 m Fanglomeratic cycles (partly incomplete), in general normally graded upward. However, in the lowest part at 1'342.50 m and at 1'351.89 m two inversely graded successions stand out. The ideal cycle starts with a breccia (polymict: mostly granite and quartz, some schists and gneiss), poorly sorted, subangular, argillaceous sandstone cement, followed by a fine-grained conglomerate (monomict: quartz) and sandstone (coarse- to fine-grained), subangular, poorly to very poorly sorted, rarely with pebbles up to 5 cm in diameter, claystone matrix, micaceous, locally cross-bedded, and finally ends with claystone drapes, micaceous, often with pebbles. The rock colour is mostly dark reddish brown, in patches light grey to light greenish grey. Some cycles starting with a medium grain size contain claystone pebbles at the base. In the upper part, from 1'329.10 to 1'330.92 m, some cycle tops are marked by palaeosoils and mud cracks
- 1'351.89 – 1'361.92 m Crossbedded sandstone, subangular, poorly sorted, siliceous cement, micaceous, with medium grain size dominating in the upper part, fine grain size in the lower part. The rock colour varies between reddish brown and dark reddish brown. The two parts are separated by an interval (from 1'355.00 to 1'356.00 m) with prominent gravel beds embedded in coarse-grained sandstone to conglomerate (polymict: mostly granite lithoclasts and quartz, some schists and shales) followed by a siltstone layer, very light grey, micaceous, down to 1'356.16 m
- 1'361.92 – 1'366.94 m Silty to sandy claystone, dark reddish brown, micaceous, very fine-layered, prevails. There are few intercalations and a fairly thicker bed (from 1'366.36 to 1'366.94 m) of sandstone (fine- to medium-grained), subangular, poorly sorted, argillaceous matrix, at the base
- 1'366.94 – 1'370.19 m Fanglomeratic sediment predominantly formed by breccia, siliciclastic (polymict: mostly granite and quartz), dark reddish-brown, poorly sorted with components up to 7 cm, subangular, siliceous cement in upper part, calcareous in the lower, micaceous, with an interbedded layer (from 1'368.24 to 1'368.55 m) of sandstone (medium to coarse-grained), dark reddish brown, subangular, poorly sorted, micaceous, including a claystone drape in the middle

The section from 1'322.69 to 1'325.84 m shows many similarities to the «Playa-Serie» elsewhere. However, the thickness at BUL1-1B (3.15 m) is much smaller compared to e.g. 66.53 m in the nearby Weiach borehole (Matter et al. 1988). An alternative lower delimitation of the «Playa-Serie» at 1'341.86 m would increase the total thickness but include atypical coarse-grained sediments (sandstone and thin beds of conglomerate). A third option is to identify the claystone-rich section from 1'361.92 to 1'366.94 m as a strongly reduced «Playa-Serie». This would lead to the overlying sediments becoming the «Oberer Schuttfächer» which is believed to be missing in the area under investigation either due to non-deposition or to later erosion (*cf.* Jordan & Deplazes 2019).

4 Comparison with the forecast profile

Looking at Fig. 4-1, two significant differences are obvious between the forecast profile and the actual findings in the present Bülach borehole:

- the «Felsenkalke» / «Massenkalk» are significantly thicker (with around 150 m) than expected (around 110 m)
- the succession of coralligenous sediments and crinoidal detritus found in the upper part of the Dogger Group, provisionally referred to as «Herrenwis Unit». The total thickness of the called 'Brauner Dogger' (see Bläsi et al. 2013), is close to expectations (87 m instead of 100 m)

The remaining section shows a good match between the prediction and findings. Moreover, the deviations of the encountered and expected thicknesses of the Mesozoic units are almost balanced: the top of the Mesozoic units was found 14 m deeper than expected at 504 m; the base of the Mesozoic is located 20 m deeper than expected at 1'319.63 m.

In detail, the similarities and differences are as follows:

- The encountered lithofacies and the stratigraphic succession within the Lower Freshwater Molasse Group (USM) are in line with expectations as far as can be assessed by the analysis of the cuttings samples. The thickness of 0 to about 10 m of the Siderolithic Group was only vaguely stated in the forecast. The actual thickness is about 2 m. The base of the Cenozoic sediments is 14 m deeper than expected.
- Although considerably thicker than expected, the lithologies of the «Felsenkalke» / «Massenkalk» correspond to the forecast. This also applies to the Schwarzbach Formation.
- The Villigen Formation developed in transitional facies. Thus, a correlation with the established formal members representing the rather shallower and deeper marine domain (without and with sponges, respectively) could not yet be confirmed. On the other hand, the predominantly marly succession of the Wildegg Formation in the Bülach-1-1 borehole corresponds well to the profile of the Weiach reference section. This also applies to the basal layers of the Malm.
- The Wutach Formation and the Variansmergel Formation could be identified. They are however much thinner (all together less than 3 m) than expected in the forecast profile. This also applies to the following succession, the «Parkinsoni-Württembergica-Schichten», of which probably only the upper part, the «Württembergica-Schichten» and the «Parkinsoni-Oolith», are present in the Bülach-1-1 borehole.
- The following «Herrenwis Unit», mentioned above is underlain by a succession of lithologies which can be correlated to the «Humphriesioolith Formation», the Wedelsandstein Formation and the «Murchisonae-Oolith Formation». While the thickness and facies of the Wedelsandstein Formation match the forecast, the «Humphriesioolith Formation» and «Murchisonae-Oolith Formation» are much thinner than expected and the iron-oolith content is less prominent.
- The thickness and facies of the Opalinus Clay are in good agreement with the forecast and the Weiach borehole. The four sub-units recently proposed by Mazurek & Aschwanden (2020) could be identified.

- A good match between the findings in Bülach-1-1B sections and the forecast is also obvious for most of the lower Mesozoic, Triassic and Liassic formations. The thickness variations of the single formations are mostly less than 5 m. However, significant differences are found regarding the two evaporitic formations: the Bänkerjoch Formation is about 65 m thick, i.e. 10 m less than expected, and the Zeglingen Formation measures about 64 m, i.e. 9 m more than expected. A considerable thickness of rock salt, with 15 m, could be verified. As far as the facies is concerned the formal subdivision of the Klettgau and Schinznach Formation and the informal subdivision of the Bänkerjoch, Zeglingen and Kaiseraugst Formation could be traced.
- Although the Dinkelberg Formation is thicker than expected (13.5 m instead of 10 m), the uppermost informal unit, the characteristic "Rötton", seems to be missing.
- The drilled 50 m of the Weitenau Formation, consisting mostly of coarse-grained sandstones and breccias, do not match the known (informal) lithostratigraphic scheme, in which the characteristic fine-grained "Playa Serie" should be the uppermost unit or be covered only by a very few metres of fanglomeratic sediments.

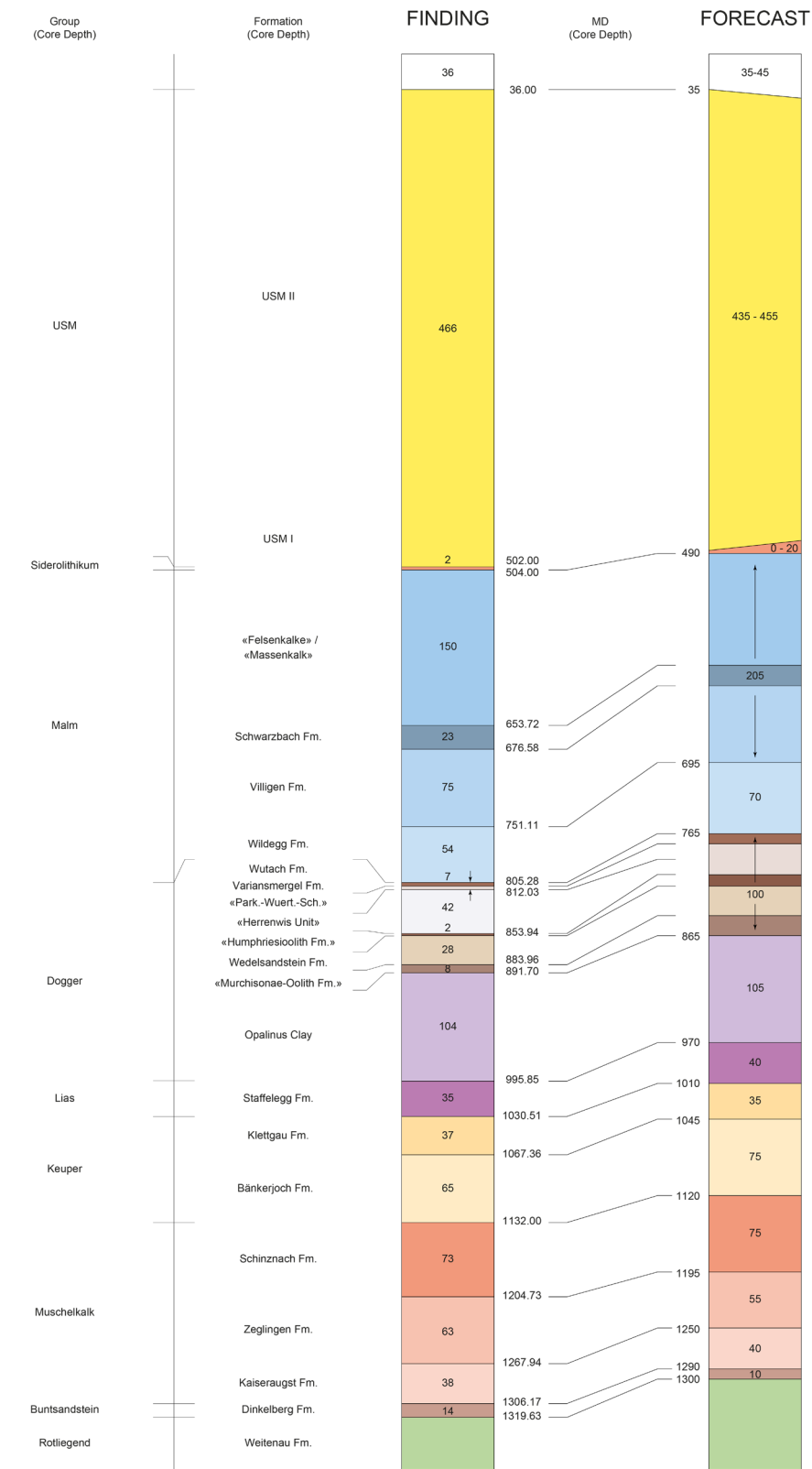


Fig. 4-1: Comparison of the forecast with the actual findings of BUL1-1 and BUL1-1B

5 References

- Bläsi, H.R., Deplazes, G., Schnellmann, M. & Traber, D. (2013): Sedimentologie und Stratigraphie des 'Braunen Doggers' und seiner westlichen Äquivalente. Nagra Arbeitsbericht NAB 12-51.
- Deplazes, G., Bläsi, H.R., Schnellmann, M. & Traber, D. (2013): Sedimentologie und Stratigraphie der Effinger Schichten. Nagra Arbeitsbericht NAB 13-16.
- Dietl, G. (2010): Die Wutach-Formation (clw) des südwestdeutschen Juras – Beschreibung und Gliederung. Jh. Ges. Naturkde. Württemberg, Stuttgart 166, 5-21.
- Dronkert, H., Bläsi, H.R. & Matter, A. (1990): Facies and origin of Triassic evaporites from the Nagra boreholes, Northern Switzerland. Nagra Technical Report 87-02.
- Flügel, E. (1982): Microfacies analysis of limestones. Springer-Verlag Berlin: 633 p.
- Folk, R.L. (1959): Practical petrographic classification of limestones. AAPG Bull., 43/1, 1-38.
- Folk, R.L. (1962): Spectral subdivision of limestone types. In: Classification of Carbonate Rocks – A Symposium (Ed. W.E. Ham), Am. Assoc. Pet. Geol. Mem., 1, 62-84.
- Füchtbauer, H. (ed.) (1988): Sedimente und Sedimentgesteine. 1141 p., 4. Auflage. Schweizerbart, Stuttgart.
- Geyer, M., Nitsch, E. & Simon, T. (2011): Geologie von Baden-Württemberg. 5., völlig neu bearbeitete Auflage. Verlag Schweizerbart Stuttgart, p. 154, p. 287
- Geyer, O.F. & Gwinner, M.P. (1986): Geologie von Baden-Württemberg. 3. Aufl. Schweizerbart. Stuttgart.
- Gygi, R.A. (1977): Revision der Ammonitengattung Gregoryceras (Aspidoceratidae) aus dem Oxfordian (Oberer Jura) der Nordschweiz und von Süddeutschland. Taxonomie. Phylogenie. Stratigraphie. Eclogae geol. Helv. 70/2, 435-542.
- Gygi, R.A. (2000): Annotated index of lithostratigraphic units currently used in the Upper Jurassic of northern Switzerland. Eclogae geol. Helv. 93/1, 125-146.
- Gygi, R.A. (2012): Quantitative geology of late Jurassic epicontinental sediments in the Jura Mountains of Switzerland. Springer, Basel, Heidelberg etc., p. 216.
- Hofmann, F., Schlatter, R. & Weh, M. (2000): Erläuterungen zu Blatt 97: Beggingen (LK 1011) des Geologischen Atlas der Schweiz 1:25'000. Bundesamt für Wasser und Geologie, Bern.
- Isler, A., Pasquier, F. & Huber, M. (1984): Geologische Karte der zentralen Nordschweiz 1:100'000. Herausgegeben von der Nagra und der Schweiz. Geol. Komm.
- Jordan, P. (1983): Zur Stratigraphie des Lias zwischen Unterem Hauenstein und Schinznach (Solothurner und Aargauer Faltenjura). Eclogae geol. Helv. 76/2, 355-379.
- Jordan, P. (2016): Reorganisation of the Triassic stratigraphic nomenclature of northern Switzerland: overview and the new Dinkelberg, Kaiseraugst and Zeglingen formations. Swiss Journal of Geosciences 109/2, 241-255.

- Jordan, P. & Deplazes, G. (2019): Lithostratigraphy of Consolidated Rocks expected in the Jura Ost, Nördlich Lägern and Zürich Nordost Regions. Nagra Arbeitsbericht NAB 19-14.
- Jordan, P., Pietsch, J.S., Bläsi, H.R., Furrer, H., Kündig, N., Looser, N., Wetzel, A. & Deplazes, G. (2016): The middle to late Triassic Bänkerjoch and Klettgau formations of northern Switzerland. *Swiss Journal of Geosciences* 109/2, 257-284.
- Kiefer, L., Deplazes, G. & Bläsi, H.R. (2015): Sedimentologie und Stratigraphie des Frühen Juras in der Nordschweiz: Staffelegg-Formation und sich nach Osten anschliessende Vorkommen. Nagra Arbeitsbericht NAB 14-95.
- Matter, A., Peters, Tj., Bläsi, H.-R., Meyer, J., Ischi, H. & Meyer, Ch. (1988): Sondierbohrung Weiach – Geologie (Textband und Beilagenband). Nagra Technischer Bericht NTB 86-01.
- Mazurek, M. & Aschwanden, L. (2020): Multi-scale Petrographic and Structural Characterisation of the Opalinus Clay. Nagra Arbeitsbericht NAB 19-44.
- Lokier, S.W. & Al Junaibi, M. (2016): The petrographic description of carbonate facies: are we all speaking the same language? *Sedimentology* 63/7, 1843-1885.
- Naef, H., Büchi, M., Bläsi, H.R., Deplazes, G. & Gysi, M. (2019): Lithology Manual – Lithological description of drill cores and cuttings in Northern Switzerland. Nagra Arbeitsbericht NAB 19-11.
- Nagra (2001): Sondierbohrung Benken. Untersuchungsbericht. Nagra Technischer Bericht NTB 00-01.
- Nagra (2014): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage. Geologische Grundlagen. Dossier II: Sedimentologische und tektonische Verhältnisse. Nagra Technischer Bericht NTB 14-02.
- Pietsch, J. & Jordan, P. (2014): Digitales Höhenmodell Basis Quartär der Nordschweiz – Version 2013 (SGT E2) und ausgewählte Auswertungen. Nagra Arbeitsbericht NAB 14-02.
- Pietsch, J., Wetzel, A. & Jordan, P. (2016): A new lithostratigraphic scheme for Schinznach Formation (Upper Muschelkalk of Northern Switzerland). *Swiss Journal of Geosciences* 109, 285-307.
- Reisdorf, A.G., Wetzel, A., Schlatter, R. & Jordan, P. (2011): The Staffelegg Formation: a new stratigraphic scheme for the Early Jurassic of northern Switzerland. *Swiss Journal of Geosciences* 104, 97-146.
- Schalch, F. (1916): Geologische Spezialkarte des Grossherzogtums Baden. Erläuterungen zu Blatt Wiechs-Schaffhausen (Nr. 145). Heidelberg: Carl Winter's Universitätsbuchhandlung.
- Wetzel, A. & Allia, V. (2003): Der Opalinuston in der Nordschweiz: Lithologie und Ablagerungsgeschichte. *Eclogae geol. Helv.* 96, 451-469.
- Zeller, F. (1908): Beiträge zur Kenntnis der Lettenkohle und des Keupers in Schwaben. *N. Jb. Mineral. Geol. Paläont. I* 908. Beilbd. 25, 1-134.