

Arbeitsbericht NAB 22-03

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

June 2023

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

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

June 2023

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description, drill cores, cuttings

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Nagra Arbeitsberichte ("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.

December 2023: Replacement of Tab. 1-3 with an updated version.

This Dossier was prepared by a project team consisting of:

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

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- 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. In the printed version the appendices are on a flash drive enclosed with the report.

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 ("Tiefbohrungen", TBO) 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 Rheinau-1-1 borehole located in the siting region Zürich Nordost (Fig. 1-2). In the following, the unique exploration objective of this specific borehole is further outlined.

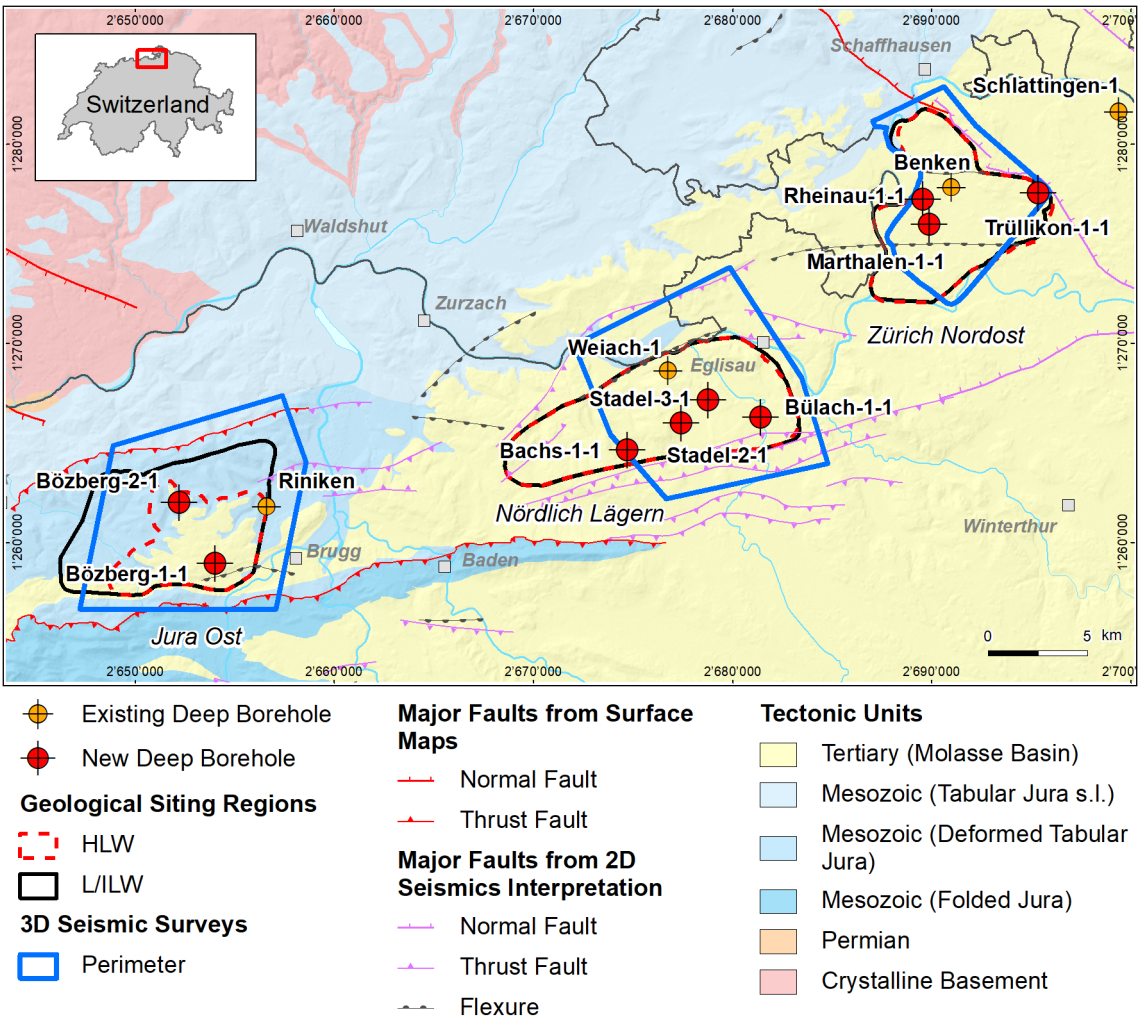


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

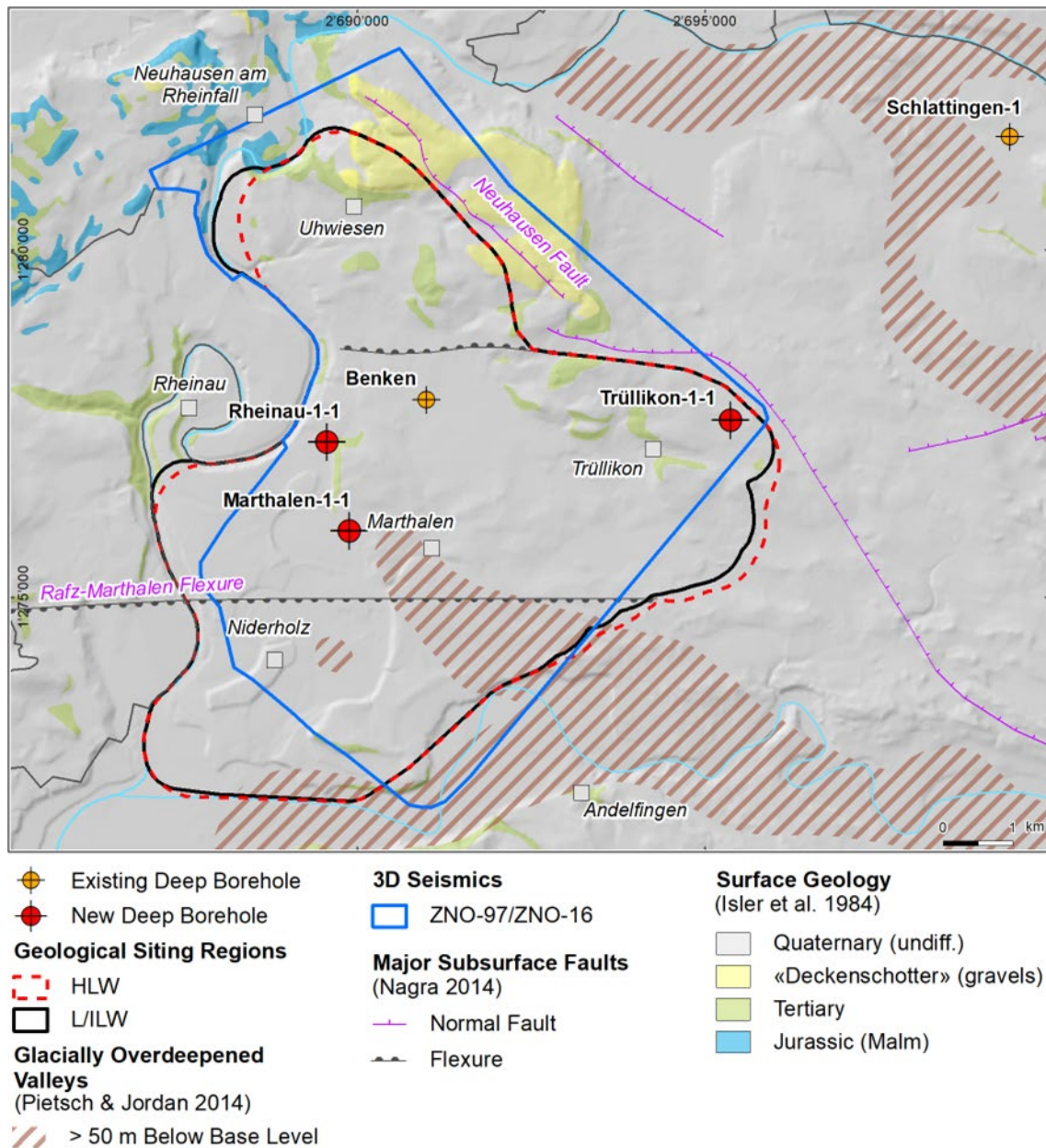


Fig. 1-2: Overview map of the investigation area in the Zürich Nordost siting region with the location of the RHE1-1 borehole in relation to the Benken, TRU1-1 and MAR1-1 boreholes

Exploration objective of the Rheinau-1-1 borehole

In the context of Nagra's TBO project, the Rheinau-1-1 (RHE1-1) borehole is the only deviated borehole. It was planned as a case study with the primary objective of characterising the structural geology of the Opalinus Clay in the area of a steeply dipping fault. Furthermore, dedicated hydrological packer testing and investigations of natural tracers in porewater were conducted to investigate the self-sealing capacity of the Opalinus Clay. More specifically, a stepped constant head injection test was performed in addition to the standard hydraulic packer test to investigate the evolution of transmissivity as a function of effective stress in a fractured interval (*cf.* Dossier VII, Hydraulic Packer Testing for details).

To enable hydraulic testing in the Opalinus Clay with its relatively low strength and high swelling capacity, the maximum borehole deviation (with respect to vertical) was limited to approximately 35° (borehole plunge of 55°). Hence, for the absolute deviation, a trade-off had to be made between maximising the lateral coverage for fracture frequency statistics (large deviation desired) and robust in-situ testing (small deviation desired).

Given the above-outlined scientific goals and related technical requirements, the Rheinau Fault, located immediately east of the Rheinau-1 drill site, was selected for this case study. It is an NNE-SSW trending, steeply dipping fault showing only very minor indications of vertical offsets in seismic amplitude sections. Nevertheless, it was already identified in seismic attribute horizon slices during initial interpretation of Nagra's 3D seismic campaign in the Zürich Nordost siting region (Birkhäuser et al. 2001) and later confirmed during the analysis of follow-up seismic processing products (e.g. Nagra 2019). Fig. 1-3 shows that this fault has a clear seismic attribute expression along the boundaries of the formations below the Opalinus Clay and also along some of the more brittle units above (see horizon slices of the Top Bänkerjoch and Top Villigen Formations shown in Fig. 1-3). However, within the Opalinus Clay, no clear seismic expression is observed. Fig. 1-4 shows the 3D-seismic interpretation considered for trajectory planning of the RHE1-1 borehole together with the discussed and executed borehole trajectories.

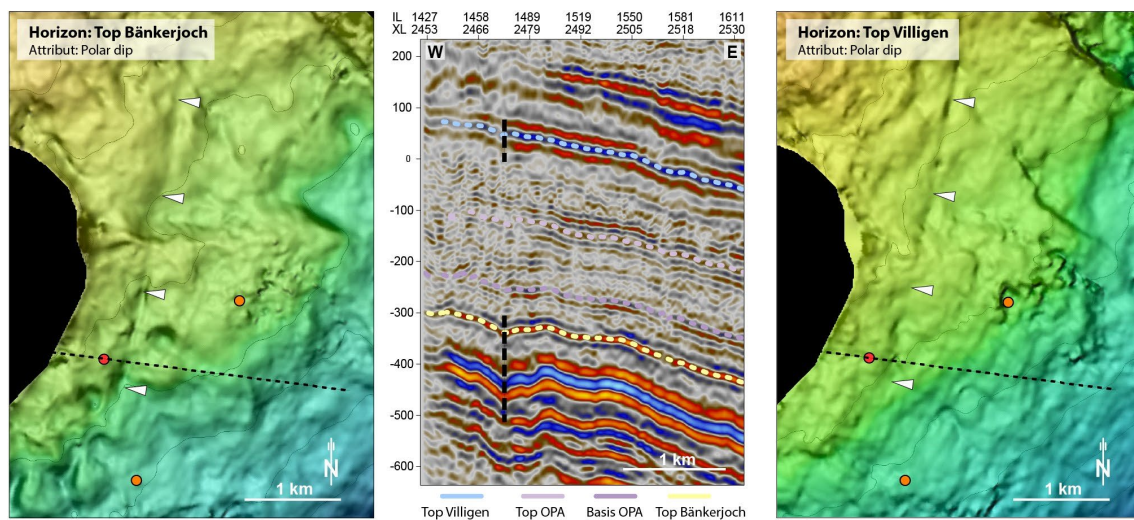


Fig. 1-3: Seismic amplitude cross-section and seismic attribute maps showing the Rheinau Fault

Left and right panels: Seismic attribute maps (polar dip) of a depth-migrated seismic cube (PSDM-A) overlain with depth values (yellowish and blueish colors indicate shallower and larger depths, respectively). The dashed black line indicates the position of the seismic section shown in the central panel. Red and orange dots show the position of the RHE1-1 borehole and neighbouring boreholes, respectively. White triangles mark the lineament representing the Rheinau Fault.

Central panel: Corresponding seismic amplitude section crossing the Rheinau Fault. The vertical axis indicates depth above sea level, and the horizontal axis shows the inline and crossline positions. The approximate trace of the Rheinau Fault above and below the Opalinus Clay is indicated by dashed black lines.

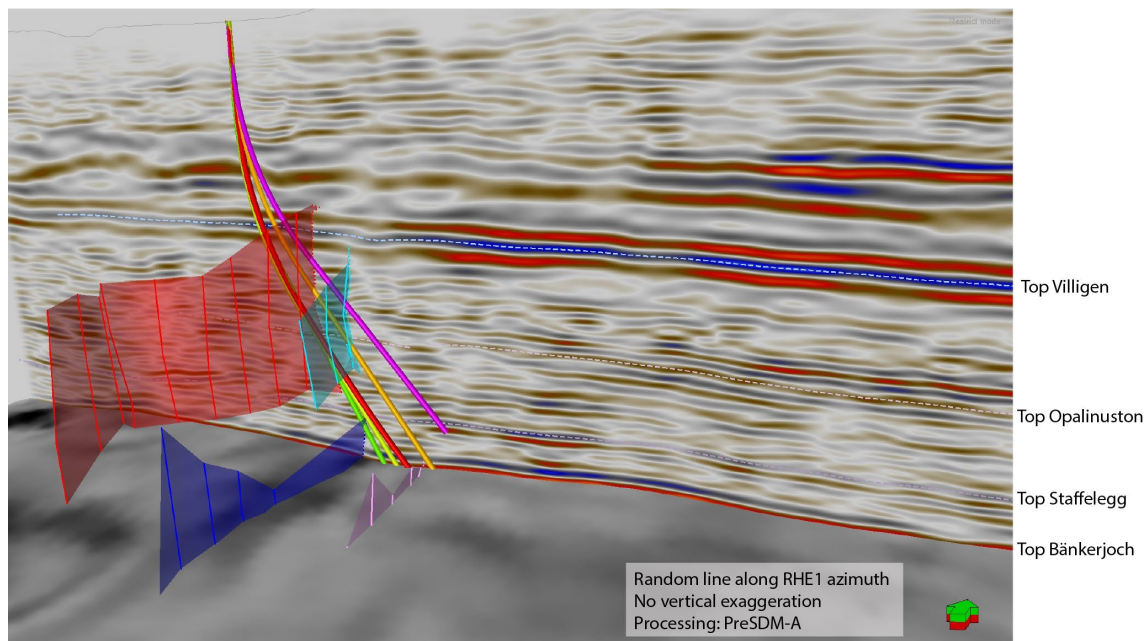


Fig. 1-4: Detailed seismic fault interpretation available for trajectory planning and discussed/executed well trajectories

Cross-section shows seismic amplitude (seismic processing: pre-stack depth migration PDSM-A). The north direction is indicated by a green-and-red arrow. The vertical distance between the Top Opalinus Clay and Top Staffelegg is ~ 120 m and shows no vertical exaggeration. The horizon slice shows polar dip attribute. Semitransparent subvertical surfaces indicate interpreted faults. The final planned and the drilled trajectories are shown in light green and red, respectively. Other discussed trajectories are shown in yellow, orange and red.

Fig. 1-5 shows a conceptual structural model for the Rheinau Fault incorporating both 3D-seismic interpretations and observations from other exploration boreholes as well as from outcrop studies. This conceptual model shows a pronounced mechanical stratigraphy of Northern Switzerland's Mesozoic sedimentary sequence with more focused deformation in the competent units, and distributed deformation in the incompetent units (Roche et al. 2020). Prior to drilling, three hypotheses were formulated on what the RHE1-1 borehole is likely to encounter in the Opalinus Clay. These hypotheses ranged from 1) absence of a distinct fault zone, likely due to a strong degree of strain partitioning within the rheologically weak Opalinus Clay, 2) one or several prominent fault zones, for example revealing cataclastic fault rock or scaly clay as it has been described to occur along larger faults within the Opalinus Clay (Jäggi et al. 2017) and 3) the former, but including the occurrence of secondary mineralisations.

As this report represents a data documentation, it deliberately avoids engaging in a synthesis of the observations and test results. Nevertheless, the following results can already be highlighted:

- The drilled trajectory was within close limits compared to the planned well path (see Dossier I for a detailed comparison).
- The borehole did not yield any evidence of a larger-scale fault zone within the Opalinus Clay. However, a number of fault planes have been encountered (*cf.* Dossier V).
- In-situ hydraulic packer tests across these features (*cf.* Dossier VII) yielded hydraulic conductivities similar to undisturbed Opalinus Clay.

- The stepped constant head test demonstrated that a significant enhancement of the flow rate can only be achieved in existing fractures if the fluid pressure is raised considerably and the magnitude of elevated fluid pressure can be maintained (*cf.* Dossier VII).
- Excursions in the profiles of natural tracers can indicate past fluid flow. No such irregularities are seen for the RHE1-1 borehole in the Opalinus Clay (*cf.* Dossier VIII). The stable isotope porewater profiles show characteristics similar to the neighbouring vertical boreholes MAR1-1 and Benken.

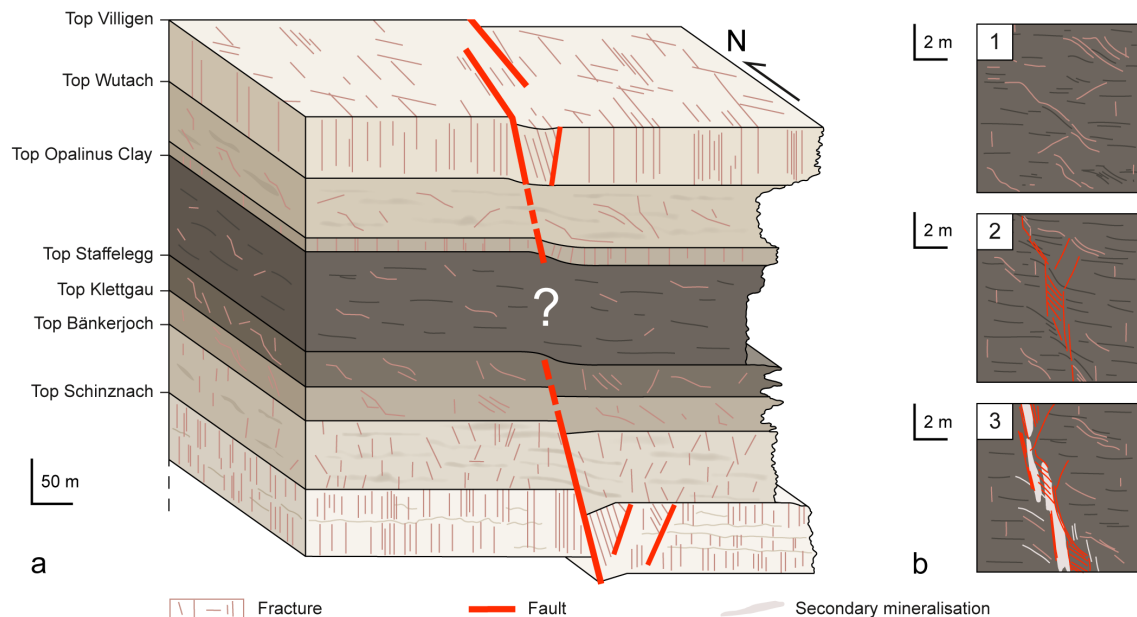


Fig. 1-5: Conceptual structural model of the Rheinau Fault

(a) Conceptual block model. The pronounced mechanical stratigraphy of the Mesozoic sequence in the area is stressed via a schematic weathering profile. The RHE1-1 borehole aimed at characterising the deformation style in the Opalinus Clay constituting a mechanically weak layer in between rheologically stiffer units (e.g. under- and overlying Schinznach/Bänkerjoch and Villigen/Wutach Formations). According to outcrop records and previous borehole results, these units show a significantly higher frequency of fault planes compared to the Opalinus Clay. In 3D seismics, the Rheinau Fault is also only clearly recognisable at the horizons related to stiffer formations.

(b) Hypothetic deformation characteristics of the Opalinus Clay to be encountered in the RHE1-1 borehole: 1) No exceptional deformation features besides small-scale fault planes as previously observed in vertical boreholes outside of seismically recognised faults. 2) One or several localised zones associated with cataclastic fault rock (e.g. scaly clay) as described for larger fault zones elsewhere (e.g. Jäggi et al. 2017). 3) The above, but also including secondary mineralisation (not to scale on picture).

1.2 Location and specifications of the borehole

The Rheinau-1-1 (RHE1-1) exploratory borehole is the eighth borehole drilled within the framework of the TBO project. The drill site is located in the western part of the Zürich Nordost siting region (Fig. 1-2). The deviated borehole reached a final depth of 827.99 m MD = 745.33 m TVD (true vertical depth)¹. The borehole specifications are provided in Tab. 1-1.

Tab. 1-1: General information about the RHE1-1 borehole

Siting region	Zürich Nordost
Municipality	Rheinau (Canton Zürich / ZH), Switzerland
Drill site	Rheinau-1 (RHE1)
Borehole	Rheinau-1-1 (RHE1-1)
Coordinates	LV95: 2'689'563.92 / 1'277'235.06
Elevation	Ground level = top of rig cellar: 387.23 m above sea level (asl)
Borehole depth	827.99 m measured depth (MD) = 745.33 m true vertical depth (TVD) below ground level (bgl)
Borehole deviation at total depth (TD)	Inclination from vertical: 38.93° Azimuth from North: 76.25°
Drilling period	19th July – 10th October 2021 (spud date to end of rig release)
Drilling company	PR Marriott Drilling Ltd
Drilling rig	Rig-16 Drillmec HH102
Drilling fluid	Water-based mud with various amounts of different components such as ² : 0 – 497 m: Polymers 497 – 828 m: Potassium silicate & polymers

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-6. The comparison of the core versus log depth³ of the main lithostratigraphic boundaries in the RHE1-1 borehole is shown in Tab. 1-2.

¹ Measured depth (MD) refers to the position along the borehole trajectory, starting at ground level, which for this borehole is the top of the rig cellar. For a perfectly vertical borehole, MD below ground level (bgl) and true vertical depth (TVD) are the same. In all Dossiers depth refers to MD unless stated otherwise.

² For detailed information see Dossier I.

³ Core depth refers to the depth marked on the drill cores. Log depth results from the depth observed during geophysical wireline logging. Note that the petrophysical logs have not been shifted to core depth, hence log depth differs from core depth.

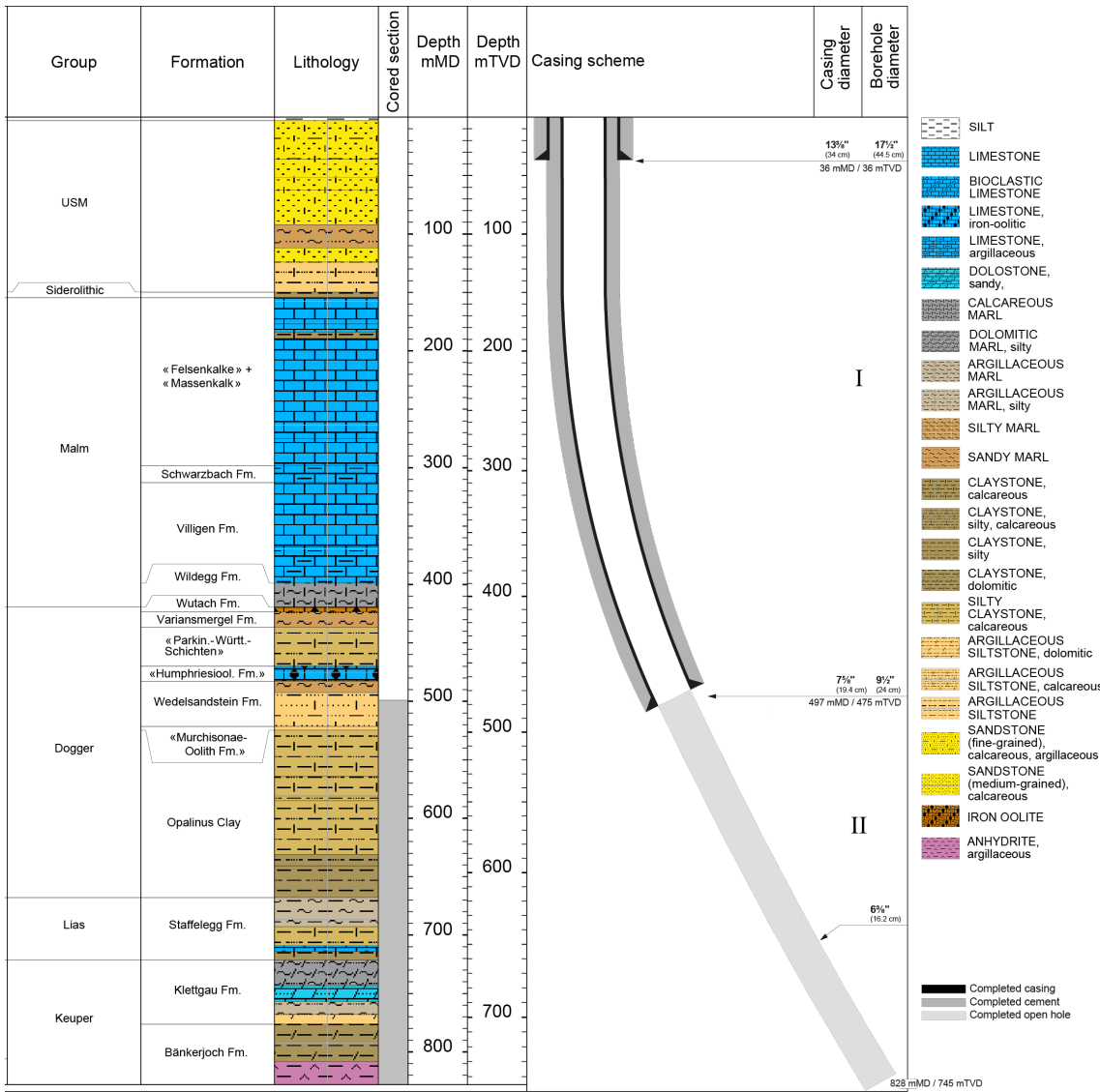


Fig. 1-6: Lithostratigraphic profile and casing scheme for the RHE1-1 borehole⁴

⁴ For detailed information about the casing scheme see Dossier I.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the RHE1-1 bore-hole⁵

System / Period	Group	Formation	Core top depth in m (MD)	Log top depth in m (MD)	Core top depth in m (TVD)	Log top depth in m (TVD)
Quaternary			3	—	3	—
Paleogene + Neogene	USM		149.90	—	149.88	—
	Siderolithic		154.40	—	154.37	—
Jurassic	Malm	«Felsenkalke» + «Massenkalk»	298.10	—	295.71	—
		Schwarzbach Formation	312.70	—	309.70	—
		Villigen Formation	398.80	—	389.75	—
		Wildegge Formation	419.20	—	408.04	—
		Wutach Formation	423.40	—	411.78	—
	Dogger	Variansmergel Formation	436.60	—	423.47	—
		«Parkinsoni-Württembergica-Sch.»	469.80	—	452.23	—
		«Humphriesioolith Formation»	482.80	—	463.20	—
		Wedelsandstein Formation	521.43	521.21	495.83	495.64
		«Murchisonae-Oolith Formation»	524.61	524.33	498.51	498.27
		Opalinus Clay	668.07	668.19	617.65	617.75
		Staffelegg Formation	721.46	721.50	660.95	660.98
Triassic	Keuper	Klettgau Formation	776.42	776.79	704.82	705.11
		Bänkerjoch Formation	827.99	828.24	745.33	745.52
		final depth	827.99	828.24	745.33	745.52

⁵ For details regarding lithostratigraphic boundaries see Chapter 3 and Dossier IV; for details about depth shifts (core goniometry) see Dossier V.

1.3 Documentation structure for the RHE1-1 borehole

NAB 22-03 documents the majority of the investigations carried out in the RHE1-1 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. 1-3).

This documentation aims at early publication of the data collected in the RHE1-1 borehole. It includes most of the data available approximately one year after completion of the borehole. Some analyses are still ongoing and results 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. 1-3: List of dossiers included in NAB 22-03

Black indicates the dossier at hand.

Dossier	Title	Authors
I	TBO Rheinau-1-1: Drilling	M. Ammen & P.-J. Palten
II	TBO Rheinau-1-1: Core Photography	D. Kaehr & M. Gysi
III	TBO Rheinau-1-1: Lithostratigraphy	M. Schwarz, P. Schürch, P. Jordan, H. Naef, R. Felber, T. Ibele & F. Casanova
IV	TBO Rheinau-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 Rheinau-1-1: Structural Geology	A. Ebert, S. Cioldi, E. Hägerstedt, L. Gregorczyk & F. Casanova
VI	TBO Rheinau-1-1: Wireline Logging and Micro-hydraulic Fracturing	J. Gonus, E. Bailey, J. Desroches & R. Garrard
VII	TBO Rheinau-1-1: Hydraulic Packer Testing	R. Schwarz, M. Willmann, P. Schulte, H. Fisch, S. Reinhardt, L. Schlickenrieder, M. Voß & A. Pechstein
VIII	TBO Rheinau-1-1: Rock Properties and Natural Tracer Profiles	J. Iannotta, F. Eichinger, L. Aschwanden & D. Traber
IX	<i>NAB 22-03 does not include a Dossier IX, as no rock-mechanical and geomechanical laboratory tests were conducted.</i>	
X	TBO Rheinau-1-1: Petrophysical Log Analysis	S. Marnat & J.K. Becker
	TBO Rheinau-1-1: Summary Plot	Nagra

1.4 Scope and objectives of this dossier

The dossier at hand 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 as documented in Sections 1.6.2 and 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 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-3

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 sections (microfacies) and chemostratigraphic analyses can be found in Dossier IV.

1.5 Petrophysical logs available at data-freeze

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

- total natural gamma ray corrected for borehole and potassium (GR)
- spectral gamma ray: hostile environment natural gamma ray sonde standard gamma ray (HSGR) and hostile environment natural gamma ray sonde 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 microimager (FMI)

1.6 Work undertaken

1.6.1 Timeline and 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 MAR1-1 borehole (Jordan et al. 2021). 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 almost monthly with all parties involved, including Nagra project managers. This enabled rapid implementation of improvements to the workflow. The 1:100, 1:1'000 and 1:2'500 profiles were drawn using the TerraStation II software (TERRASCIENCES Inc.). To corroborate the lithological identification and representation in the 1:100 profile, the lithostratigraphy experts received regular updates of the petrophysical logs (Section 1.5) and laboratory analyses.

The lithostratigraphic classification in this dossier is based on system / period, group, formation and member boundaries at the data-freeze on 07.01.2022.

All depths in the core descriptions refer to core depth. Depths from the cuttings sections refer to log depth.

1.6.2 Description and representation of cuttings samples

The cuttings samples were taken from the shaker with a sampling interval of 2 m. Below 122 m (kick-off depth, MD), only spot samples were taken due to the high rate of penetration (ROP), i.e. samples do not represent all beds. The samples were then washed, sieved, and roughly described at the drill site by the mud logger for the purpose of operational decisions. The 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 as well as 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 ROP, revolutions per minute (RPM), a quick-look lithological composition of the cuttings from the shale shakers and gas chromatography.

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

1. Fine-grained fractions lost during sample preparation: It was unclear what weight fraction was lost during sampling and sample preparation (washing and sieving) at the drill site. Therefore, the descriptions given in the field logs refer solely to the material in the washed samples and do not consider potentially lost lithologies. Molasse lithologies are often insufficiently lithified and the lost fraction is therefore more likely part of fine-grained clastic lithologies such as siltstone, claystone or marl. As a result, 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. While 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. A detailed description of grain size, sorting, grain shape, colour, cement and accessory minerals was provided for sandstones.
5. No petrophysical logs were available in the cuttings section from 0 m to 34.5 m MD. 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 in Section I of the TerraStation profile correspond to sample boundaries along the 2 m intervals. Depths in the text and on the profile are rounded to full metres (e.g. 22 m).
6. A full suite of petrophysical logs was available in the cuttings section from 36.0 m to 497.0 m MD (log depth). Therefore, it was decided to draw lithological boundaries according to the FMI log. The primary lithology was determined by comparing the sample description with the petrophysical logs, primarily FMI, neutron porosity and density logs. This comparison helped to better distinguish material from cavings and secondary lithologies from the primary lithology. Depths and thicknesses in both the text and the profile for this section are accurate to one significant digit and refer to log depth (e.g. 275.1 m MD log depth).
7. In the core section from 499.10 m MD (core depth) to the final depth of 872.99 m MD (core depth), the lithological boundaries were drawn according to the core description. In this section, depths and thicknesses in both the text and the profile are accurate to two significant digits and refer to core depth (e.g. 524.61 m MD core depth).

1.6.3 Description and representation of cores

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 depth 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 are 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 are 2 mm thick 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. 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. 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, claystone or siltstone. 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 and conglomerate patterns must be used for beds with a thickness of more than 50 cm, otherwise the corresponding breccia or conglomerate 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 log; depth annotations are given with two significant digits

While lithological boundaries were first identified in the core, the FMI often provided additional information to allow the exact depth range of a given lithology to be determined. In such cases, the upper and lower boundaries of a given lithology were taken from the FMI log and lithology from the field log. The shift between log depth and core depth was assessed by comparing FMI logs and core photographs.

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 only. 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 Füchtbauer scheme was divided into two versions that differ slightly in the way lithological terms are written in profiles and in continuous text (see Fig. 1-6).

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, 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 to 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 (Folk 1959, 1962, Dunham 1962) 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 use of the Folk classification was further refined by the Nagra QC team in order to avoid ambiguous terminology. All Folk classifications in this text and in the profile follow Fig. 1-7.

For diagenetically altered limestones composed of small calcite crystals, 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.

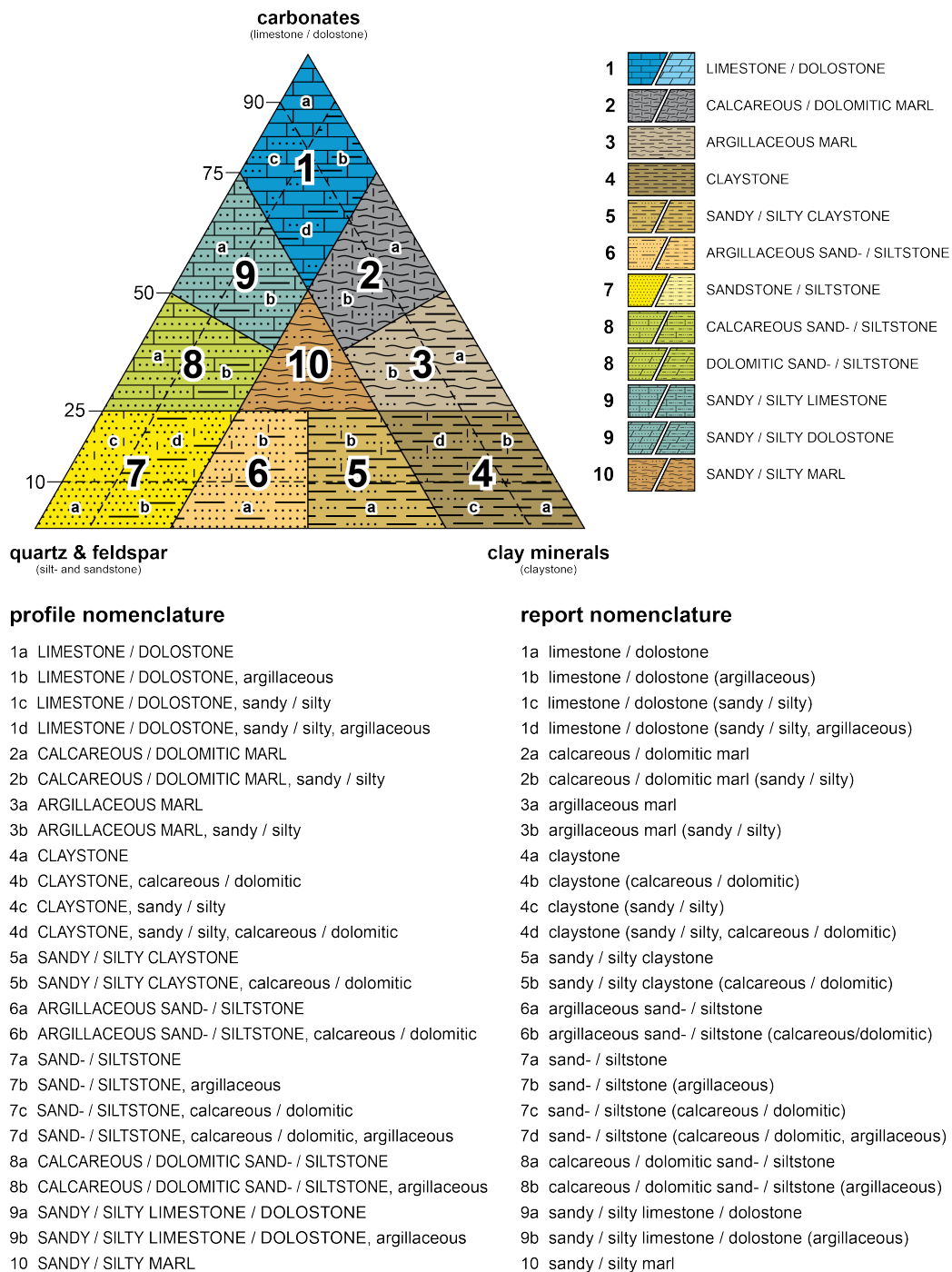


Fig. 1-7: Füchtbauer scheme for lithology names in geological profiles

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

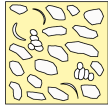
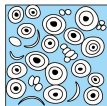
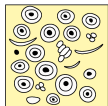
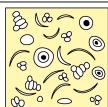
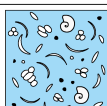
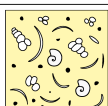
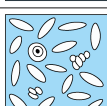
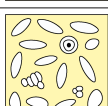
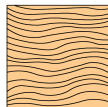
Classification of Carbonate Rocks after Folk (1959, 1962) slightly modified after Flügel (1982) and Lokier & Junaibi (2016)												
		> 10% Allochems (grains): Allochemical Rocks				< 10% Allochems		In situ organic growth structures				
		Sparry Allochemical rocks		Microcrystalline Allochemical rocks		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 (Intracrasts dominate)				
		> 25% Ooids		Oosparite (median grains < 2mm) Oosparrudite (median grains > 2mm)			Oomicrite (median grains < 2mm) Oomicrudite (median grains > 2mm)			Ooid-bearing micrite (Ooids dominate)		
	< 25% Intracrasts	Volume ratio of Fossils to Pellets	Volume ratio of Fossils : Oncoids	> 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			Disomicrite (Disturbed by processes such as bioturbation, soft-sediment deformation or traction currents)	
				1:2	Oncosparite (median grains < 2mm) Oncosparrudite (median grains > 2mm)			Oncomicrorite (median grains < 2mm) Oncomicrorudite (median grains > 2mm)			Oonoid-bearing micrite (Oncoids dominate)	
 Micrite (< 1% grains)										 Biolithite (Undisturbed bioherm rocks such as algal, coral, sponge biolithite, ...)		

Fig. 1-8: Folk classification as applied to the description of carbonate rocks in RHE1-1

Pers. comm. S. Wohlwend & H.R. Bläsi

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 (see Fig. 1-6) 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.

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 other three columns contain symbols representative of the whole bed 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. They 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 terms of lithostratigraphic investigation was good overall (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 terms of lithostratigraphic investigation 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 discs
3. poor core quality = many cracks / fractures throughout the core, intense core discing, discs have a highly variable core diameter

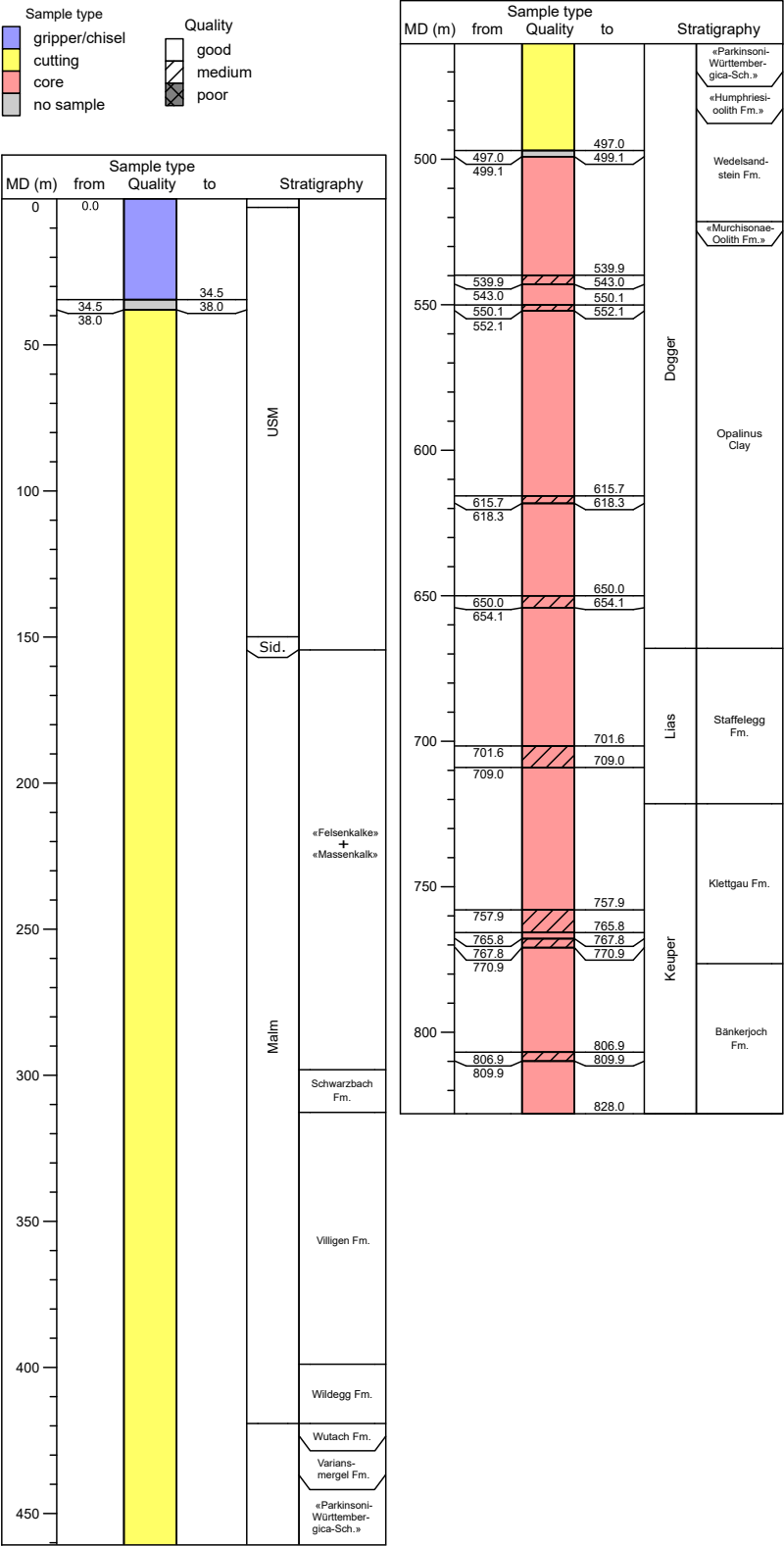


Fig. 2-1: Cuttings and core quality in RHE1-1

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 m – 3 m (about 3 m) [0 m – 3 m TVD, about 3 m TVT]

Unconsolidated rocks were only encountered in the conductor pipe excavation (see Dossier I).

Lithology

0 m – 3 m

The section from 0 m to 3 m is composed of silt and clay (slightly to moderately sandy, moderately to strongly gravelly, slightly cobbly)

Overall, the succession is light brownish-grey and poorly sorted. The gravel particles and cobbles are subangular to rounded, with smooth and polished or rough surfaces. They are polymict and of alpine origin

3.2 Lower Freshwater Molasse Group, 3 m – 149.9 m (about 146.9 m) [3 m – 149.9 m TVD, about 146.9 m TVT]

The Lower Freshwater Molasse Group crops out some 150 m to the east of the RHE1-1 borehole where it can be traced some 30 m above the altitude of the drilling site. This is well below the base of the Upper Marine Molasse Group. In the RHE1-1 borehole, the absence of minerals typical of marine environments (e.g. glauconite) corroborates the classification of the entire Molasse sediments as part of the Lower Freshwater Molasse Group.

The *upper boundary* is set at 3 m with the first occurrence of sandstone cuttings.

The *lower boundary* is set at 149.9 m. The cuttings document a distinctive change from the argillaceous siltstone of the Lower Freshwater Molasse Group to the claystone with iron-pisoids of the Siderolithic Group. The change of lithology to the Siderolithic Group at 149.9 m is also reflected in the signature of the petrophysical logs, i.e. by the onset of a low resistivity in the FMI log and a sharp increase in the GR readings.

Lithostratigraphic subdivision

The succession is subdivided in a sandstone-dominated upper part (down to 124.0 m) with intervals of sandy marl and a siltstone-dominated lower part (to the base at 149.9 m) with silty marl and silty claystone (calcareous). The entire succession shows the characteristic "granitic composition" of the «Obere Bunte (Granitische) Molasse» and reflects different architectural elements of a fluvial setting (e.g. Keller 1992). Marl-dominated successions which could be indicative of the «Oberaquitane Mergelzone» at the top of the «Obere Bunte Molasse» and the «Untere Bunte Molasse» at the base of the Lower Freshwater Molasse Group were not encountered.

Lithology

The Lower Freshwater Molasse Group is composed of three major lithologies.

Sandstone

Mostly fine- to medium-grained, always calcareous and mostly non-argillaceous or slightly argillaceous. It is very light grey and dark beige to beige. The main component is quartz (variegated, angular to subangular), while other components include feldspar, claystone fragments, hornblende, lithic fragments (black, prolate to stalky, sand-sized) and mica (sparse to moderate). It is well sorted and poorly to moderately cemented.

Deviations from the general description above are:

- The sandstone is argillaceous in three intervals between 3 m and 144.2 m, with the longest interval from 3 m to 28 m.
- In some short intervals, the coarse-grained fraction of sandstone prevails.
- The sorting is moderate in only two intervals down to 58 m.

No specific combinations of lithology, mineral content, grain size, colour, sorting and cementation were recognised in the sandstone intervals, with the exception of a non-argillaceous sandstone with quartz, feldspar, partly mica and hornblende. This composition roughly corresponds to the mineralogy of a lithology regionally known as "Granitischer Sandstein". Due to its poor degree of cementation, the rock chips were milled to loose sand while drilling. The "Granitischer Sandstein" occurs in three intervals (28 m to 34 m, 38.0 m to 50.6 m and 62.3 m to 92.0 m) with sharp boundaries to the adjacent lithologies.

Argillaceous siltstone and argillaceous sandstone

Argillaceous siltstone (calcareous) and, subordinately, argillaceous sandstone (calcareous), mainly dark beige and micaceous, occurring almost exclusively below 124.0 m and alternating with sandstone but in transition to silty and sandy marl as well as to silty claystone (calcareous).

Silty and sandy marl

Mostly containing quartz sand up to the medium-grained fraction, light brown to ochre brown, grey violet and dark beige, sparsely micaceous to micaceous. They mainly occur in alternation with sandstone beds from 92.0 m to 112.0 m. Below 124.0 m, intervals of argillaceous siltstone or argillaceous sandstone grade into silty and sandy marls.

Intervals of silty claystone (calcareous) are common but always represent a subordinate lithology. At greater depths, argillaceous siltstone and silty marl grade into silty claystone (calcareous), frequently reddish-brown and containing sparse mica crystals.

3.3 Siderolithic Group, 149.9 m – 154.4 m (about 4.5 m) [149.9 m – 154.4 m TVD, about 4.5 m TVT]

The argument for the delineation of the Siderolithic Group is the presence of non-calcareous claystone and of iron-pisoids («Bohnerz»).

The *upper boundary* is set at 149.9 m. The cuttings document a distinctive change from the argillaceous siltstone of the Lower Freshwater Molasse Group to the claystone with iron-pisoids of the Siderolithic Group. The change of lithology to the Siderolithic Group at 149.9 m is also reflected in the signature of the petrophysical logs, i.e. by the onset of a low resistivity in the FMI log and a sharp increase in the GR readings.

The *lower boundary* is set at 154.4 m with the first occurrence of limestone cuttings which are typical of the underlying Malm Group. The boundary coincides with a distinct drop in the GR readings and a switch to high to very high resistivities in the FMI log. Cuttings with iron-pisoids are sampled again at 186 m and at 188 m; they could either result from cavings or represent karst infills.

Lithology

149.9 m – 154.4 m	Claystone (silty, calcareous), reddish-brown, grading into non-calcareous claystone, ochre brown towards the base. Abundant iron-pisoids, dark reddish-brown
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3.4 Malm Group

3.4.1 «Felsenkalke» + «Massenkalk», 154.4 m – 298.1 m (about 143.7 m) [154.4 m – 295.7 m TVD, about 141.3 m TVT]

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 «Felsenkalke» + «Massenkalk», regarded, in combination, as an informal unit in the rank of a formation. The term alludes to the two interfingering facies units replacing each other laterally and vertically: the mostly massive sponge bioherms («Massenkalk») and the mostly well bedded limestone deposits where sponges are rare or absent («Felsenkalke») between the bioherms. This scheme also includes a unit which was known formerly as "Plattenkalke" on top of the «Felsenkalke» *sensu stricto* (e.g. Hofmann et al. 2002).

In the «Massenkalk», dolomitisation and dedolomitisation processes produce a saccharoidal fabric in the limestone. These processes may also spread to the «Felsenkalke» in the vicinity of the «Massenkalk» (e.g. Lang 1964 and Fritz 1966).

Stylolites are common in the «Felsenkalke» + «Massenkalk». They occur as solitary features at regular intervals or concentrate in clusters at irregular intervals. This results in a diagenetic stylobedding (Logan & Semeniuk 1976, Pawellek & Aigner 2002) for both the «Felsenkalke» and the «Massenkalk». Therefore, the term "bedded" alone does not allow a differentiation between the «Felsenkalke» and the «Massenkalk» units.

In RHE1-1, the top of the Malm Group from 154.4 m to 176.9 m is distinguished from the rest of the unit. The FMI log shows a thin- to medium-bedded alternation of limestone and limestone (argillaceous) with a lower average resistivity than in the rest of the unit, where the succession is

mainly a thick-bedded to massive limestone. The thin- to medium-bedded alternation could be recognised in the adjacent Benken borehole, also at the top of the Malm Group. There, this alternation was classified as the "Plattenkalke".

Rock chips of claystone were found where the bedded succession can be recognised in the FMI log. The chips are often peg-shaped, suggesting claystone coatings of stylolitic bedding planes.

The *upper boundary* is set at 154.4 m where the cuttings document a change from claystone to limestone. The boundary coincides with a distinct drop in the GR readings and a switch to high to very high resistivities in the FMI log. Cuttings with iron-pisoids are sampled again at 186 m and at 188 m; they could result from cavings or represent karst infills.

The *lower boundary* is set at 298.1 m at the top of the first marl bed of the Schwarzbach Formation exceeding a thickness of 10 cm (recognised in the FMI log). Here, the transition from the «Felsenkalk» + «Massenkalk» to the Schwarzbach Formation is characterised by a change from high to lower resistivities with a concomitant increase in the GR readings.

Lithostratigraphic subdivision

The «Felsenkalk» + «Massenkalk» of the RHE1-1 borehole is fully within the cuttings section. The proposed lithostratigraphic subdivision is based on the analysis of the cuttings and on a combined analysis of the GR and FMI logs. The terms "massive" and "saccharoidal" are indicative of but not conclusive for the occurrence of the «Massenkalk» facies. Similarly, the term "bedded" is not conclusively indicative for the «Felsenkalk» facies.

154.4 m – 176.9 m	Probably «Felsenkalk» facies
176.9 m – 189.3 m	Probably «Massenkalk» facies with karstic features
189.3 m – 210.0 m	Transition between «Felsenkalk» facies and «Massenkalk» facies
210.0 m – 268.0 m	Probably «Massenkalk» facies
268.0 m – 298.1 m	Probably «Felsenkalk» facies

Lithology

154.4 m – 176.9 m	Mostly medium-bedded alternation of limestone (mudstone, micrite), white to light grey, and limestone (argillaceous) (mudstone, micrite), dark beige and beige grey. Limestone (argillaceous) dominates in the central part, whereas limestone prevails elsewhere. The FMI log indicates both gradual transitions and sharp bed boundaries between the two lithologies
176.9 m – 183.8 m	Massive succession of limestone (mudstone, micrite), white to light grey, with a minor karstic feature around 180.0 m filled with claystone (calcareous)
183.8 m – 189.3 m	Major karstic feature filled with claystone, ochre brown, grading downwards into claystone (silty, calcareous), reddish-brown. The host rock is limestone (mudstone, micrite), white to light grey

189.3 m – 210.0 m	Thick-bedded to massive succession of limestone (mudstone, micrite), rarely sparitic or slightly saccharoidal, whitish-beige and beige to beige grey
210.0 m – 268.0 m	Massive succession of limestone (mudstone, micrite), partly saccharoidal, mainly white to light grey down to 250.0 m. Beneath, beige and beige grey hues prevail. Glauconite was found at 230.0 m
268.0 m – 275.1 m	Massive succession of limestone (mudstone, micrite), mainly beige grey; subordinately in transition to limestone (argillaceous) (mudstone, micrite), medium light grey. At the base of the succession, an interbed of argillaceous marl, dark grey, is visible both in the petrophysical logs and in the cuttings
275.1 m – 298.1 m	Thick-bedded succession of limestone (mudstone and wackestone, micrite and pelmicrite), beige grey, with peloids; in some intervals transitioning to limestone (argillaceous) (mudstone, micrite), medium light grey. Thin claystone coatings (black, platy) are considerably more frequent than in the successions above. At the base of the unit, frequent fragments of calcite crystals, up to several millimetres in size, are found, which may be remnants of fossils.

3.4.2 **Schwarzbach Formation, 298.1 m – 312.7 m (about 14.6 m) [295.7 m – 309.7 m TVD, about 14.0 m TVT]**

The Schwarzbach Formation represents a marl interval within the predominantly limestone formations of the Malm Group. Following the lithostratigraphic definition of Jordan & Deplazes (2019), the identification and delimitation of the Schwarzbach Formation are based on the colour of the cuttings (darker), on petrography (higher clay mineral content) and on GR (higher radiation) and FMI (relatively low resistivity compared to overlying and underlying sediments) logs. A higher fossil content compared to the formations above and below is also characteristic for the Schwarzbach Formation.

In RHE1-1, the Schwarzbach Formation can be clearly distinguished from the overlying and underlying units as an alternation of limestone, limestone (argillaceous), calcareous marl and argillaceous marl, visible both in the cuttings and in the petrophysical logs. However, fossils could not be identified in the cuttings.

The *upper boundary* is set at 298.1 m at the top of the first marl bed of the Schwarzbach Formation exceeding a thickness of 10 cm (recognised in the FMI log). Here, the transition from the «Felsenkalk» + «Massenkalk» to the Schwarzbach Formation is characterised by a change from high to lower resistivities with a concomitant increase in the GR readings.

The *lower boundary* is set at 312.7 m based on an abrupt switch to higher resistivities observed in the FMI log and confirmed by a decrease in the GR readings typical of the Villigen Formation.

Lithology

298.1 m – 312.7 m

Thin- to medium-bedded alternation of:

- limestone (argillaceous) (mudstone, micrite), beige grey
- limestone (mudstone, micrite), medium light grey
- calcareous marl, medium grey
- argillaceous marl, dark grey

Limestone (argillaceous) and calcareous marl prevail down to 309.40 m. Three beds of pure limestone were encountered in this interval; from 309.4 m to the base, only limestone and argillaceous marl occur. Glauconite was found close to the top of the formation

The occurrence of both calcareous marl and argillaceous marl was deduced from the occurrence of lower resistivities in the FMI log and of higher GR readings but was not observed in the cuttings, in contrast to the limestone lithologies which were also recognised in the cuttings

3.4.3 Villigen Formation, 312.7 m – 398.8 m (about 86.1 m) [309.7 m – 389.7 m TVD, about 80.0 m TVT]

In the Villigen Formation, a well bedded, fossil-poor micritic limestone prevails. Calcareous marl and argillaceous marl are restricted to thin (< 10 cm) interlayers and a few thicker (> 10 cm) beds, often with a somewhat higher content of macrofossils.

The *upper boundary* is set at 312.7 m based on an abrupt switch to higher resistivities observed in the FMI log and confirmed by a decrease in the GR readings typical of the Villigen Formation.

The *lower boundary* is set at 398.8 m at the top of the uppermost thick (ca. 1 m) calcareous marl bed observed in the FMI log, marking the change from the limestone-dominated facies of the Villigen Formation to the marl-dominated facies of the Wildeggen Formation. This delimitation is supported by a subtle but still conspicuous decrease in the resistivities visible in the FMI log and a concurrent increase in the GR readings.

Lithostratigraphic subdivision

In the ZNO siting region, the Villigen Formation is subdivided into three members (Gygi 2000). These are, from the top: the Wangental Member, the Küssaburg Member and the Hornbuck Member. However, this subdivision cannot be applied to RHE1-1.

The Wangental Member and the Küssaburg Member are lithologically very similar. The boundary between the members is normally marked by the glauconitic «Knollen Bed», a few decimetres in thickness. This typically nodular marker bed could not be recognised either in the cuttings or the petrophysical logs of RHE1-1.

The difference between the Küssaburg Member and the Hornbuck Member is the content of sponges and the thicker marl interbeds of the latter. The top and base of the Hornbuck Member are usually drawn at the uppermost and lowermost sponge-bearing limestone beds, respectively. At 367.7 m in the RHE1-1 borehole, a distinct downward change to an alternation of limestone and limestone (argillaceous) takes place, concurrent with the occurrence of thicker and more

abundant marl interbeds. However, a clear delimitation of the Hornbuck Member could not be conclusively defined because sponges (which are its distinguishing feature) could not be recognised in the cuttings.

Lithology

312.7 m – 332.0 m	Limestone (mudstone, micrite), beige grey, below 320.0 m light grey to medium light grey, medium-bedded; claystone coatings (black, peg-shaped to platy) of stylolitic bedding planes. The FMI log indicates seams of claystone coatings from 320.0 m to 332.0 m, in contrast to the section above where more and slightly thicker coatings were observed both in the FMI log and in the cuttings
332.0 m – 367.7 m	Limestone (mudstone, micrite), white to light grey, thin- to medium-bedded; in sections transitioning to limestone (argillaceous) (mudstone, micrite), white to light grey; claystone and argillaceous marl coatings (dark grey to black, peg-shaped to platy) of stylolitic bedding planes. An increase in layer thickness from thin-bedded at the top to medium-bedded towards the base is visible in the FMI log
367.7 m – 398.8 m	Change to more argillaceous facies: medium-bedded alternation of sections dominated by limestone (mudstone, micrite), light grey, less frequently beige grey, and sections dominated by limestone (argillaceous) (mudstone, micrite), medium light grey to medium grey, with interbeds of argillaceous marl, dark grey, and of calcareous marl, medium grey. The marl interbeds are thicker and more abundant than in the intervals above

3.4.4 Wildegg Formation, 398.8 m – 419.2 m (about 20.4 m) [389.7 m – 408.0 m TVD, about 18.3 m TVT]

The Wildegg Formation consists of the Effingen Member and the Birmenstorf Member at its base.

The *upper boundary* is set at 398.8 m at the top of the uppermost thick (ca. 1 m) calcareous marl bed observed in the FMI log, marking the change from the limestone-dominated facies of the Villigen Formation to the marl-dominated facies of the Wildegg Formation. This delimitation is supported by a subtle but still conspicuous decrease in the resistivities visible in the FMI log and a concurrent increase in the GR readings.

The *lower boundary* is set at 419.2 m where the cuttings document a change from a glauconitic to a heterogeneous glauconite-free, iron-oolitic succession of the underlying Wutach Formation. This boundary also corresponds to a switch in mode in the log response, i.e. from an anti-parallel trend (increase in the FMI log and decrease in the GR log and *vice versa*) above to a parallel one (increase or decrease in both logs at the same time) below.

3.4.4.1 Effingen Member, 398.8 m – 418.3 m (about 19.5 m) [389.7 m – 407.2 m TVD, about 17.5 m TVT]

Usually, the Effingen Member is a calcareous marl with beds of limestone and limestone (argillaceous). The most prominent limestone interval is the Gerstenhübel Bed (Gygi 2000). A continuous content of silt and sand (fine-grained) is characteristic of this unit (Deplazes et al. 2013).

In RHE1-1, the member consists of calcareous marl, limestone (argillaceous) and a conspicuous limestone interval from 402.7 m to 406.0 m. The limestone may correspond to the Gerstenhübel Bed. The interval below 406.0 m has a higher clay content with argillaceous marl and calcareous marl prevailing over the limestone lithotypes.

The *upper boundary* is set at 398.8 m. It corresponds to the upper boundary of the Wildeggen Formation.

The *lower boundary* is set at 418.3 m at the top of a bed only discernible on the FMI log but not in the cuttings. It appears to be a glauconitic limestone bed, based on the comparison with a similar interval identified in the cored section of the adjacent borehole MAR1-1 and having the same FMI signature as in RHE1-1.

Lithology

398.8 m – 402.7 m	Calcareous marl (silty), medium light grey to medium grey, with a 90 cm thick interbed of limestone (argillaceous) (mudstone, micrite), light grey to medium light grey
402.7 m – 406.0 m	Limestone (mudstone, micrite), light grey to medium light grey, with glauconite, featureless
406.0 m – 418.3 m	Heterogeneous, medium-bedded alternation of, in decreasing order of abundance: • argillaceous marl (partly silty), dark grey • calcareous marl (partly silty), medium grey • limestone (argillaceous) (mudstone, micrite), medium light grey • limestone (mudstone, micrite), mainly light grey In the upper part of the interval, frequent fragments of calcite crystals, up to several millimetres in size, are found, which may be remnants of fossils. In addition, the interval shows pyrite nodules throughout. Glauconite was found close to the base of the member

3.4.4.2 Birmenstorf Member and «Glaukonitsandmergel Bed» *sensu* Gygi (1977, 2000, 2012), 418.3 m – 419.2 m (about 0.9 m) [407.2 m – 408.0 m TVD, about 0.8 m TVT]

In the ZNO siting region, the fossiliferous and calcareous Birmenstorf Member known from the region of Aargau is replaced by condensed units (Gygi 2012). According to Gygi (1977, 2000, 2012), the condensed units are denoted from top to base as «Mumienkalk Bed», «Mumienmergel Bed» and «Glaukonitsandmergel Bed». Jordan & Deplazes (2019) integrated the oncolitic «Mumienkalk Bed» and «Mumienmergel Bed» as informal units into the Birmenstorf Member. The underlying «Glaukonitsandmergel Bed» *sensu* Gygi (1977, 2000) is characterised by micaceous, argillaceous to calcareous marl (silty). All three units are glauconitic to a varying degree and frequently contain sponges as well as ammonites, the latter partly as cores of oncoids. All three units are condensed and contain iron-oolids in variable proportions.

In RHE1-1, this thin unit was not sampled in the cuttings. The main lithology was assumed to be an argillaceous marl (silty) because the cored sections of the adjacent boreholes Benken and MAR1-1 show no deviation of the main lithology from the overlying Effingen Member (Nagra 2001a, Nagra 2001b, Jordan et al. 2021). Furthermore, the deeper samples of RHE1-1 do not contain any other lithology of cavings which could be assigned specifically to this unit. However, the abundance of glauconite hints at the occurrence of the Birmenstorf Member.

The *upper boundary* is set at 418.3 m at the top of a bed only discernible on the FMI log but not in the cuttings. It appears to be a glauconitic limestone bed, based on the comparison with a similar interval identified in the cored section of the adjacent borehole MAR1-1 and having the same FMI signature as in RHE1-1.

The *lower boundary* is set at 419.2 m where the cuttings document a change from a glauconitic to a heterogeneous glauconite-free, iron-oolitic succession. This boundary also corresponds to a switch in mode in the log response, i.e. from an anti-parallel trend (increase in the FMI log and decrease in the GR log and *vice versa*) above to a parallel one (increase or decrease in both logs at the same time) below this boundary.

Lithology

418.3 m – 419.2 m	Probably an argillaceous marl (silty), dark grey, glauconitic. From the top (418.3 m) to 418.4 m, a glauconitic limestone bed is documented in the FMI log. The presence of this bed was inferred by comparison with the cored section and the FMI log of MAR1-1. The cuttings sample at 418 m contains silty marl with glauconite and limestone with glauconite, light grey
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3.5 Dogger Group

3.5.1 Wutach Formation, 419.2 m – 423.4 m (about 4.2 m) [408.0 m – 411.8 m TVD, about 3.8 m TVT]

The Wutach Formation is a highly condensed succession dominated by iron-oolites and rich in fossils (Dietl 2010). The iron-oolites and fossils are embedded in a matrix of argillaceous marl, more rarely in either calcareous marl or limestone (Frank et al. 1975).

In RHE1-1, the cuttings samples contain all the lithologies encountered in the cored section of the adjacent MAR1-1 borehole, but the pronounced vertical succession identified there could not be reconstructed in RHE1-1, neither from the cuttings nor from the petrophysical logs. However, a common feature in both the MAR1-1 borehole and the Benken borehole (Nagra 2001a, Nagra 2001b) is the occurrence of a 0.5 m thick bed of limestone (iron-oolitic) at the top of the formation, also recorded in the RHE1-1 borehole.

The *upper boundary* is set at 419.2 m. The cuttings document a change from a glauconitic to a heterogeneous glauconite-free, iron-oolitic succession of the Wutach Formation. This boundary also corresponds to a switch in mode in the log response, i.e. from an anti-parallel trend (increase in the FMI log and decrease in the GR log and *vice versa*) above to a parallel one (increase or decrease in both logs at the same time) below this boundary.

The *lower boundary* is set at 423.4 m where the mode in the log response switches back to an anti-parallel one, i.e. a decrease of resistivity coincides with an increase in the GR readings and *vice versa*. It corresponds to the lithological change from the overlying iron-oolitic successions to a non iron-oolitic limestone (silty) below.

Lithology

419.2 m – 423.4 m

Alternation of:

- iron-oolite, dark reddish-brown, with a marl matrix, dark grey
- marl (iron-oolitic), dark grey, with less iron-oolites than in the iron-oolite, embedded in a matrix of argillaceous marl
- limestone (iron-oolitic), sparitic, light grey. A bed at the top of the formation (from 419.2 m to 419.7 m) is clearly visible in the FMI log; a similar bed is located at the same position and has the same thickness in the neighbouring boreholes MAR1-1 and Benken.

The iron-oolites are partly calcified, ochre brown throughout and have sizes of 1 mm to 2 mm. Abundant shell fragments in the cuttings at 420 m indicate that the Wutach Formation is at least partly fossiliferous as observed in neighbouring boreholes.

3.5.2 Variansmergel Formation, 423.4 m – 436.6 m (about 13.2 m) [411.8 m – 423.5 m TVD, about 11.7 m TVT]

The Variansmergel Formation usually consists of silty to sandy marl with a variable carbonate content (Geyer et al. 2011, Bläsi et al. 2013). The marl-dominated succession contains some uneven to nodular interbeds of micritic limestone. Both lithologies display a moderate to high fossil content, especially of brachiopods and bivalves.

In RHE1-1, the upper part of the formation is mainly composed of argillaceous marl with some interbeds of fossiliferous limestone. The whole section is silty to sandy. The lower part contains more quartz, silt and sand. It is a silty to sandy marl with two bioclastic limestone layers close to its base. The vertical sequence closely resembles the cored interval of MAR1-1 in terms of lithology. In light of the findings in MAR1 1, the fossil content of the formation in RHE1-1 is probably underrepresented in the cuttings samples.

The *upper boundary* is set at 423.4 m where the mode in the log response switches back to an anti-parallel one, i.e. a decrease of resistivity coincides with an increase in the GR readings and *vice versa*. It corresponds to the lithological change from the overlying iron-oolitic successions to a non iron-oolitic limestone (silty) below.

The *lower boundary* is set at 436.6 m where a transition from the higher carbonate content of silty to sandy marl above to the lower carbonate content of silty claystone (calcareous) below occurs. This decrease in carbonate content is also reflected by an increase in the average GR readings and a decrease in resistivity on the FMI log.

Lithology

423.4 m – 428.4 m	Argillaceous marl to calcareous marl (silty to sandy), medium grey to dark grey, locally micaceous. In the central part of the interval the marl grades into claystone (silty, calcareous). Some interbeds of limestone (silty to sandy) are intercalated regularly and with constant thicknesses of 20 cm to 30 cm. The limestone (silty to sandy) is micritic, light grey to medium light grey and partly fossiliferous
428.4 m – 436.6 m	Silty to sandy marl, medium light grey to medium grey, mostly micaceous and bioclastic in the lowermost part. The undulating readings in the FMI and GR logs suggest varying contents of clay and carbonate and thus transitions to both silty claystone (calcareous) and calcareous marl. These transitions were also observed as very subtle changes in the cuttings. In the lowermost part, two interbeds of bioclastic limestone occur. They are silty to sandy, micritic and sparitic, light grey to medium light grey as well as beige grey and contain abundant unidentified fossil debris

3.5.3 «Parkinsoni-Württembergica-Schichten», 436.6 m – 469.8 m (about 33.2 m) [423.5 m – 452.2 m TVD, about 28.7 m TVT]

The informal «Parkinsoni-Württembergica-Schichten» represent a uniform succession of silty claystone (calcareous), micaceous, to argillaceous marl (silty to sandy) (Bläsi et al. 2013) with interbeds of calcareous marl (silty to sandy) and limestone (silty to sandy). The fossil content comprises fine bioclasts, ammonites, belemnites, echinoderms and bivalves.

In RHE1-1, the main lithology throughout the entire unit is a silty claystone (calcareous), micaceous. Interbeds of calcareous marl, limestone and bioclastic limestone, all silty to sandy, are quite abundant down to 451.5 m and are rare beneath. An iron-oolitic interval can be observed close to the base of the unit.

The *upper boundary* is set at 436.6 m where a transition from the higher carbonate content of silty to sandy marl above to the lower carbonate content of silty claystone (calcareous) below occurs. This decrease in carbonate content is also reflected by an increase in the average GR readings and a decrease in resistivity on the FMI log.

The *lower boundary* is set at 469.8 m. The boundary is documented by the occurrence of iron-oolids at the top of an iron-oolite, easily discernible in both the cuttings and the FMI log (where a sharp increase in resistivity is observed).

Lithostratigraphic subdivision

Traditionally, the informal «Parkinsoni-Württembergica-Schichten» are subdivided into the «Württembergica-Schichten» (upper part) and the «Parkinsoni-Schichten» (lower part) by an iron-oolite bed, the «Parkinsoni-Oolith». In RHE1-1, rock chips of marl (iron-oolitic) were observed at 468 m. The comparison with the FMI signature of MAR1-1 led to the definition of an iron-oolitic limestone bed from 468.6 m to 468.7 m. This suggests the presence of an iron-oolid-bearing interval at least from 468 m to 468.7 m, at a similar position (close to the base of the unit) as in MAR1-1 and in Benken. In MAR1-1, the iron-oolid-bearing interval may represent the «Parkinsoni-Oolith» (Wohlwend et al. 2021). In RHE1-1 the top of this interval is only roughly set at 468 m based on the cuttings samples. Therefore, in RHE1-1 an exact subdivision of the «Parkinsoni-Württembergica-Schichten» is not possible. Nevertheless, the main part of the unit corresponds to the informal «Württembergica-Schichten» as in MAR1-1.

Lithology

436.6 m – 451.5 m Silty to sandy claystone (calcareous) to argillaceous marl (silty to sandy), dark grey, micaceous, in the central part pyritic, fossiliferous. The section contains, in decreasing order of abundance, interbeds of:

- calcareous marl (silty to sandy), medium grey, micaceous, fossiliferous
- bioclastic limestone (silty to sandy), micritic, beige grey, very fossiliferous
- limestone (silty to sandy), micritic, beige grey

The occurrence of some interbeds is not based on the cuttings description but inferred from the comparison of the FMI log with the findings in MAR1-1

451.5 m – 469.8 m Silty to sandy claystone (calcareous) to sandy marl, throughout dark grey, micaceous, locally pyritic. The section contains only two intervals with thin interbeds of calcareous marl and bioclastic limestone as described in the section above

An iron-oid-bearing interval is suggested by the occurrence of marl (iron-oolitic) in the cuttings at 468 m and a limestone bed (iron-oolitic) from 468.6 m to 468.7 m by comparison of the FMI log with MAR1-1

3.5.4 «Humphriesioolith Formation», 469.8 m – 482.8 m (about 13.0 m) [452.2 m – 463.2 m TVD, about 11.0 m TVT]

The informal «Humphriesioolith Formation» (Bläsi et al. 2013) encompasses a marl interval with limestone beds. It is sandwiched between two iron-oolitic successions at the top and at the base, both very fossiliferous.

In RHE1-1, the expected three-part subdivision of the formation was encountered with minor deviations from MAR1-1. In the iron-oolitic interval at the top, both boreholes show a marl succession, underlain by limestones. However, in RHE1-1 the marl unit in the central part of the formation is more calcareous towards its base than in MAR1-1. Nevertheless, both the downward transition from calcareous marl to sandy limestone and the lithology of the interbeds are similar in the two boreholes. The basal iron-oolitic interval consists of bioclastic limestone in RHE1-1, while it is marl-dominated in MAR1-1.

The *upper boundary* is set at 469.8 m. The boundary is documented by the occurrence of iron-oids at the top of an iron-oolite, easily discernible in both the cuttings and the FMI log (where a sharp increase in resistivity is observed).

The *lower boundary* is set at 482.8 m. The boundary is documented by the disappearance of iron-oids at the base of an iron-oid-bearing bioclastic limestone and by a concurrent sharp drop in the resistivity in the FMI log towards the underlying Wedelsandstein Formation.

Lithostratigraphic subdivision

The «Humphriesioolith Formation» can be subdivided into three sub-units (Jordan & Deplazes 2019). An interval of argillaceous marl with interbedded calcareous marl and limestone is accompanied by iron-oolitic, fossiliferous sequences of varying lithology at both its top and base. The three-part subdivision can also be established in all surrounding boreholes (Nagra 2001a, Bläsi et al. 2013, Schwarz et al. 2021, Jordan et al. 2021) and consists of:

469.8 m – 474.9 m	Upper iron-oolitic interval (about 5.1 m)
474.9 m – 481.8 m	Marl interval with sandy limestone beds without iron-oids (about 6.9 m)
481.8 m – 482.8 m	Lower iron-oolitic interval (about 1.0 m)

Lithology

469.8 m – 474.9 m	Bioclastic limestone (limonitic), slightly silty, iron-oolitic, beige grey to dark reddish-brown and light grey to medium light grey, bioclasts with limonitic crusts. A considerable fossil content is further corroborated by the occurrence of frequent calcite crystals up to several millimetres in size. The bioclastic limestone is interbedded by thin argillaceous marl (silty to sandy), medium grey to dark grey, with a few iron-ooids, micaceous The bioclastic limestone (limonitic), iron-oolitic, is overlain by a thinner succession of marl (iron-oolitic, silty to sandy), dark grey, and iron-oolite, dark reddish-brown, with a marl matrix (silty to sandy), medium grey to dark grey, micaceous The iron-ooids are ochre brown and large (maximum 2 mm)
474.9 m – 479.4 m	Argillaceous marl (silty to sandy), dark grey. The interval contains three interbeds of calcareous marl (silty to sandy), medium grey, and one of sandy limestone, light grey to medium light grey
479.4 m – 481.8 m	Calcareous marl (silty to sandy), medium grey, micaceous. This interval contains three interbeds of sandy limestone as described above
481.8 m – 482.8 m	Bioclastic limestone (silty) with some iron-ooids, light grey to medium light grey. The iron-ooids are ochre brown but on average smaller than in the upper iron-oolitic interval

3.5.5 Wedelsandstein Formation, 482.8 m – 521.43 m (about 38.6 m) [463.2 m – 495.83 m TVD, about 32.6 m TVT]

A distinct portion of quartz sand and sand-sized bioclasts combined with a sparse content of macrofossils are diagnostic for the Wedelsandstein Formation (Jordan & Deplazes 2019). The background lithology of the formation varies from silty and sandy marl to argillaceous siltstone and sandstone, both mostly calcareous. Interbeds of sandy limestone to limestone (sandy, argillaceous) occur at regular intervals. In contrast to the background lithology, they often have a considerable content of macrofossils.

In RHE1-1, the background lithology in the upper part (from 482.8 m to 492.6 m) is more heterogeneous than in the lower part of the Wedelsandstein Formation. It varies from claystone (silty to sandy, calcareous) to argillaceous sandstone and to silty and sandy marl. Some interbeds of silty to sandy limestone and bioclastic limestone (sandy) occur. Below 492.6 m, the background lithology is almost exclusively argillaceous siltstone or argillaceous sandstone, both calcareous and with gradual transitions between each other. In contrast, the frequency and lithology of the interbeds varies in this section. From 499.10 m to 508.98 m (in the cored section), interbeds of limestone (sandy) and sandy limestone, both argillaceous, occur, whereas above and below the interbeds are sparse and mostly consist of calcareous marl (sandy).

On the whole, the succession closely resembles the Wedelsandstein Formation in MAR1-1 with respect to both background lithology and presence of interbeds. However, the basal part of the formation is missing in MAR1-1. The «Sowerbyi-Oolith», usually found at the base of the Wedelsandstein Formation, is missing in both boreholes. Cuttings samples were collected down to 497 m. In the light of the findings in MAR1-1, the fossil content of the formation in RHE1-1 is probably under-represented in the cuttings samples.

The *upper boundary* is set at 482.8 m. The boundary is documented by the disappearance of iron-oids at the base of an iron-oids-bearing bioclastic limestone and by a concurrent sharp drop in the resistivity in the FMI log towards the underlying Wedelsandstein Formation.

The *lower boundary* is set at 521.43 m. It corresponds to the top of several layers of bored and encrusted limestone clasts containing partly fossils and iron-oids as in MAR1-1.

Lithology (cuttings section)

482.8 m – 487.9 m	Claystone (silty to sandy, calcareous), dark grey to black, micaceous. The quartz content initially increases downwards and then decreases again, leading to a central interval composed of argillaceous sandstone (calcareous), dark grey, and of silty to sandy limestone, medium grey
487.9 m – 492.6 m	Silty to sandy marl, medium grey to dark grey, micaceous, with three interbeds of bioclastic limestone (sandy), medium light grey to medium grey
492.6 m – 497.0 m	Argillaceous sandstone (calcareous), in transition to argillaceous marl (silty to sandy, calcareous), medium grey to dark grey, micaceous, with two interbeds of calcareous marl (sandy), white to light grey
497.0 m – 499.10 m	Neither cores nor cuttings collected

Lithology (core section)

499.10 m – 508.98 m	Argillaceous siltstone (sandy, calcareous), below 503.91 m grading into argillaceous sandstone (silty, calcareous), dark grey, micaceous, partly bioturbated. At regular intervals, interbeds of limestone (sandy, argillaceous), and of sandy limestone (locally argillaceous), both light grey and medium grey to dark grey. Some of the beds may be described as bioclastic limestone (sandy) with limonitised peloids (thin section RHE1-1-500.75). At the base, an interbed of calcareous marl (sandy), medium grey The whole interval is micaceous, mostly flaser-bedded and often containing sand-sized crinoids, locally of considerable abundance, in the partly bioclastic interbeds (thin section RHE1-1-505.88)
508.98 m – 521.43 m	Argillaceous sandstone (silty, calcareous), to argillaceous siltstone (sandy, calcareous), dark grey, pyritic in the lower part, bioclastic throughout and with solitary belemnites

The thin interbeds consist of only two beds of sandy limestone (the lower one argillaceous), light grey to medium grey, and one bed of calcareous marl (sandy), light grey to medium grey

The interval is micaceous throughout but flaser-bedding, pyrite and siderite nodules as well as burrows of *Zoophycos* type are restricted to the background lithologies

In the uppermost part of the interval, the background lithology of sandy claystone (calcareous) grades into argillaceous sandstone (calcareous) and argillaceous siltstone (calcareous). Towards the base, the background lithology grades into sandy marl (silty)

3.5.6 «Murchisonae-Oolith Formation», 521.43 m – 524.61 m (3.18 m) [495.83 m – 498.51 m TVD, 2.68 m TVT]

In boreholes in the ZNO siting region, the «Murchisonae-Oolith Formation» is generally strongly reduced in thickness or even missing (Albert et al. 2012, Bläsi et al. 2013, Schwarz et al. 2021).

In RHE1-1, the «Murchisonae-Oolith Formation» is composed of an argillaceous siltstone framed by thin fossiliferous hardgrounds with iron-ooids and lithoclasts. The hardgrounds stand out due to their high resistivity on the FMI log.

The *upper boundary* is set at 521.43 m. It corresponds to the top of several layers of bored and encrusted limestone clasts containing partly fossils and iron-ooids as in MAR1-1.

The *lower boundary* is set at 524.61 m. It corresponds to the erosional base of a thin, fossiliferous interval rich in encrusted limestone clasts and containing iron-ooids, encrusted lithoclasts and bioclasts.

Lithology

521.43 m – 524.61 m Three-part subdivision consisting of:

From 521.43 m to 521.79 m, an upper condensed section with limestone (silty, argillaceous), light grey, as encrusted and bored clasts forming four nodular beds. The clasts are densely packed in the second and third bed, each with a hardground at the top (at 521.50 m and at 521.63 m). The maximum thickness of the beds is 12 cm. Sandy marl (as described for the basal part of the overlying Wedelsandstein Formation) occurs down to the third bed. It is enriched in bored clasts of bioclastic limestone (sandy) (packstone, biomicrite), medium grey to beige. The clasts contain calcified iron-ooids (thin section RHE1-1-521.47), bivalves, crinoids and an ammonite at 521.54 m. Below the third bed, the limestone clasts of the fourth bed are embedded in the argillaceous siltstone which prevails in the underlying interval.

From 521.79 m to 524.51 m, argillaceous siltstone, dark grey, micaceous, with some large pyrite nodules, lenticular-bedded by sandstone lenses, light grey

From 524.51 m to 524.61 m, a lower condensed section with an argillaceous siltstone as the matrix of encrusted clasts of bioclastic limestone (limonitic) (packstone, biomicrite), medium grey to beige. The clasts

are sideritic and pyritic. They contain calcified iron-oids (thin section RHE1-1-524.57), limestone clasts and bioclasts of bivalves and crinoids. Encrusted clasts of limestone (mudstone, micrite; thin section RHE1-1-524.52), medium grey, occur subordinately

3.5.7 Opalinus Clay, 524.61 m – 668.07 m (143.46 m) [498.51 m – 617.65 m TVD, 119.14 m TVT]

The Opalinus Clay is generally a monotonous succession of dark grey silty claystone grading towards the base into claystone. In its upper part, the formation is interbedded very sparsely by thin layers of sandstone and limestone (Wetzel & Allia 2003). Fossils are usually rare except in a few limestone beds and enriched intervals, mainly in the lowermost section. The subtle changes of the background lithology and the frequency of silty and sandy lenses are used for a lithostratigraphic subdivision of the unit (Mazurek & Aschwanden 2020; see below). Layers and nodules of both siderite and pyrite are abundant in some sections.

The findings in RHE1-1 confirm the uniform lithology of the Opalinus Clay. The facies and subdivisions are in line with the concept of Mazurek & Aschwanden (2020).

The *upper boundary* is set at 524.61 m. It corresponds to the erosional base of a thin, fossiliferous interval enriched in encrusted limestone clasts and containing iron-oids, encrusted lithoclasts and bioclasts.

The *lower boundary* is set at 668.07 m at the top of the uppermost calcareous marl of the Staffel-egg Formation. The boundary is also visible in the GR log and in the FMI log, where a sharp increase in resistivity (with respect to the readings in the claystone from the basal Opalinus Clay) is observed.

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 apply to the present section as follows:

524.61 m – 564.30 m	«Sub-unit with silty calcareous beds» (39.69 m)
564.30 m – 584.91 m	«Upper silty sub-unit» (20.61 m)
584.91 m – 640.86 m	«Mixed clay-silt-carbonate sub-unit» (55.95 m)
640.86 m – 668.07 m	«Clay-rich sub-unit» (27.21 m)

Lithology

«Sub-unit with silty calcareous beds», 524.61 m – 564.30 m (39.69 m)

This sub-unit consists mainly of silty claystone (calcareous) grading in some intervals into claystone (silty, calcareous). It is defined by the presence of fossiliferous calcareous beds. These latter are also well expressed as excursions in petrophysical logs (Mazurek & Aschwanden 2020). Laminae and thin lenses of siltstone and sandstone occur in varying density, producing an irregularly wavy or lenticular fabric in the sub-unit. Sideritic layers and siderite nodules are also enriched in some sections.

- | | |
|---------------------|---|
| 524.61 m – 527.68 m | Claystone (silty, the lower half calcareous), dark grey, scattered bituminous flakes, micaceous, pyritic. The interval is slightly irregularly wavy-bedded by some mm-thick siltstone lenses and laminae. Some sideritic layers and siderite nodules occur |
| 527.68 m – 540.40 m | <p>Silty claystone (calcareous), dark grey, micaceous, pyritic, occasionally large pyrite nodules, burrows below 536.64 m. In contrast to above, the interval contains more thicker (maximum 3 cm) lenses and laminae of sandstone (fine-grained), light grey, resulting in a lenticular bedding. The thickest lenses are occasionally pyritised and sideritic. Furthermore, siderite layers and siderite nodules are frequent from the top (527.68 m) to 532.25 m. Beneath, sideritic layers are considerably less frequent and siderite nodules are virtually absent. The interval contains some interbeds:</p> <p>From 531.97 m to 532.25 m, calcareous marl (silty), medium grey, bioturbated</p> <p>From 536.40 m to 536.64 m, above an erosional surface, bioclastic calcareous marl, dark grey with micritic nodules or intraclasts (thin section RHE1-1-536.60) with bored rims, sparse calcified iron-ooids, sideritic, pyrite nodules, with abundant belemnites and bivalves</p> <p>From 539.10 m to 539.35 m, limestone (silty), micaceous, pyritic, bioturbated</p> <p>From 540.08 m to the erosional base (540.40 m), bioclastic calcareous marl, light grey and dark grey with round nodules of limestone and/or intraclasts and bioclasts concentrating above the erosional base, with bivalves and crinoids</p> |
| 540.40 m – 548.49 m | <p>Claystone (silty, calcareous), below 542.45 m grading into silty claystone (calcareous), dark grey, bituminous flakes, micaceous, pyritic (locally as large nodules), with burrows below 542.45 m. The interval is irregularly wavy-bedded by some mm- to cm-thick lenses and laminae of sandstone (fine-grained), light grey. Sideritic layers and siderite nodules are virtually absent</p> <p>From 548.08 m to 548.49 m, several beds of bioclastic calcareous marl with calcified iron-ooids (thin section RHE1-1-548.41) are present. They are conspicuously sideritic and pyritic and contain round nodules and/or intraclasts of limestone (mudstone, micrite) and of bioclastic limestone. The whole interval is very fossiliferous with bivalves and crinoids and represents a firmground</p> |

- 548.49 m – 554.60 m Silty claystone (partly calcareous), dark grey, micaceous, pyritic below 553.53 m, bituminous flakes, locally with burrows. The calcareous parts are lenticular-bedded by thick (maximum 1 cm) lenses and laminae of sandstone (fine-grained), light grey. Sideritic layers and siderite nodules are virtually absent
- From 553.38 m to 553.53 m and from 554.07 m to the base (554.60 m), two intervals of silty marl, dark grey and beige grey, are present. The lower bed is micaceous, pyritic, irregularly wavy-bedded and contains bivalves and crinoids
- 554.60 m – 556.49 m Claystone (silty), dark grey, micaceous, pyritic, with two sideritic layers and at the base a layer (6 cm in thickness) of crinoids, bivalves and bioclasts
- 556.49 m – 564.30 m Silty claystone (calcareous), below 559.61 m grading into claystone (silty, calcareous); both lithologies are dark grey, micaceous, pyritic (locally as large nodules) and contain bituminous flakes. The macrofossil content is restricted to a belemnite at 560.62 m and a layer with crinoids at the base (ca. 30 cm in thickness). The interval is mostly lenticular-bedded by lenses (maximum 3 cm thick) and laminae of sandstone (fine-grained), light grey. Some sideritic layers and siderite nodules occur throughout the interval
- From 561.21 m to 561.28 m a thin layer can be interpreted as a firm-ground consisting of an argillaceous marl, dark grey, pyritic, bioclasts of crinoids and bivalves with bored and encrusted nodules of limestone and/or intraclasts (mudstone, micrite; thin section RHE1-1-561.26), light grey

«Upper silty sub-unit», 564.30 m – 584.91 m (20.61 m)

This sub-unit consists mainly of silty claystone (calcareous). It is characterised by frequent lenses, typically a few centimetres wide and several millimetres thick, consisting of silt- to sand-sized quartz and calcite cement, resulting in a flaser to lenticular fabric (Mazurek & Aschwanden 2020). The sub-unit is approximately cut in half by an interval of silty claystone which is almost lens-free and therefore presents no fabric. An interval of sandy marl at the top of the sub-unit (from 564.30 m to 567.87 m) represents the highest density of siltstone and sandstone lenses of the entire Opalinus Clay.

- 564.30 m – 572.46 m Succession with lenses and laminae of sandstone decreasing downwards:
- From 564.30 m to 567.87 m, sandy marl, dark grey, micaceous, scattered crinoids
- From 567.87 m to 572.46 m, silty claystone (calcareous), dark grey, micaceous, a few crinoids, locally convoluted bedding, at the base (from 572.40 m to 572.46 m) a thin sideritic and pyritic layer with belemnites, gastropods, bioclasts

The entire interval is lenticular-bedded by lenses (maximum 2 cm thick) and laminae of sandstone (fine-grained), light grey. Within the sandy marl, the lenses partly contain abundant bioclastic components and are well cemented by calcite

- 572.46 m – 575.06 m Succession almost lens-free:
Silty claystone, dark grey, bituminous flakes, micaceous, scattered burrows, only a few thin lenses and laminae of siltstone to sandstone (fine-grained), light grey
- 575.06 m – 584.91 m Succession with a reoccurrence of lenses:
Silty claystone (calcareous), dark grey, micaceous, pyritic, lenticular-bedded by frequent lenses (maximum 3 cm thick) and laminae of siltstone to sandstone (fine-grained), light grey, often pyritic
From 582.31 m to 582.35 m, layer of calcareous sandstone, medium grey, micaceous, lenticular-bedded

«Mixed clay-silt-carbonate sub-unit», 584.91 m – 640.86 m (55.95 m)

This sub-unit mainly consists of silty claystone (calcareous) grading into claystone (silty) towards the base. It represents the section of the Opalinus Clay which is devoid of marked characteristics typical for the other sub-units (Mazurek & Aschwanden 2020). Laminae and lenses of siltstone and sandstone do occur, but they are sparse (in contrast to the overlying sub-unit) and mostly only mm-thick. The sub-unit contains several intervals with frequent to abundant siderite nodules.

- 584.91 m – 606.78 m Two intervals of silty claystone (calcareous), separated by claystone (silty, calcareous) from 589.72 m to 592.63 m; both lithologies are dark grey, micaceous
The whole interval is slightly irregularly wavy-bedded by sparse, mm-thick lenses and laminae of siltstone and sandstone (fine-grained), light grey. Siderite nodules concentrate in the upper interval of silty claystone (calcareous). In contrast, burrows, pyrite nodules and pyritic layers concentrate close to the base of the lower interval of silty claystone (calcareous)
- 606.78 m – 619.21 m Silty claystone (calcareous), dark grey, micaceous, mostly bioturbated. Laminae and lenses of siltstone and sandstone are slightly more frequent than above. Nodules and layers of both siderite and pyrite occur much more frequently than above
- 619.21 m – 623.41 m Silty claystone (calcareous), dark grey, micaceous, in the lower part bioturbated. Lenticular-bedded by the highest number of laminae and lenses (still only mm-thick) of siltstone and sandstone within the sub-unit
- 623.41 m – 631.07 m Silty claystone (calcareous), dark grey, micaceous, bioturbated, laminated. In contrast to above, the interval is almost devoid of laminae and lenses but contains abundant sideritic layers and some siderite nodules (e.g. at 628.63 m and at 630.41 m)

- 631.07 m – 640.86 m Claystone (silty), dark grey, micaceous, bioturbated, laminated, some pyrite nodules, abundant sideritic layers and frequent siderite nodules as well as an ammonite at 636.38 m
- From 639.61 m to 639.72 m a thin bed of limestone (silty, argillaceous) (mudstone, micrite), light grey

«Clay-rich sub-unit», 640.86 m – 668.07 m (27.21 m)

This sub-unit mainly consists of thick alternating intervals of dark claystone (silty) and minor claystone (calcareous) with gradual transitions between each other. Fabrics are virtually absent apart from lamination. The fossil content is the highest of all sub-units. Ammonites and bivalves are especially enriched in the central part of the sub-unit, even forming some coquina layers which are classified as bioclastic argillaceous marl or as bioclastic calcareous marl. The fossils content is not associated with a distinct lithology.

- 640.86 m – 649.18 m Claystone (silty, locally calcareous), dark grey to black, micaceous, laminated. This interval is almost macrofossil-free
- 649.18 m – 657.00 m Claystone (silty), dark grey to black, micaceous, laminated; a few thin siltstone lenses, light grey and beige grey, close to the top; some siderite nodules and layers mainly in the central part and some calcareous concretions close to the base (at 655.02 m, at 656.10 m and at 656.44 m). Frequent macrofossils include ammonites, bivalves and belemnites as well as bioclasts starting at 651.80 m, with well-preserved specimens of ammonites at 651.95 m, at 653.58 m and at 655.16 m. Ammonites, bivalves and bioclasts are enriched in coquinas resulting in the following intervals of different lithology:
- From 653.03 m to 653.10 m, bioclastic calcareous marl, consisting mainly of ammonite fragments (ammonite shill layer)
- From 654.21 m to 654.33 m and from 655.09 m to 655.24 m, bioclastic argillaceous marl, consisting mainly of bivalves and bioclasts
- 657.00 m – 664.06 m Claystone (silty, calcareous), dark grey to black, micaceous, laminated, with burrows. This interval contains bioclasts (mainly bivalves) down to 661.54 m and frequent ammonites with a well preserved one at 663.67 m
- 664.06 m – 668.07 m Claystone, dark grey to black, micaceous, laminated, with burrows. From 667.88 m to the base (668.07 m), an interval of silty claystone (calcareous), dark grey, micaceous is present This interval is bioclastic at the top. In the lowermost part, there is a continuous increase in the fossil content (bioclasts, belemnites, bivalves) towards the base. Some scattered ammonites occur throughout the interval with a well preserved one at 667.61 m (diameter 12 cm)

3.6 Lias Group

3.6.1 Staffelegg Formation, 668.07 m – 721.46 m (53.39 m) [617.65 m – 660.95 m TVD, 43.30 m TVT]

The Staffelegg Formation (Reisdorf et al. 2011, Kiefer et al. 2015) is a heterogeneous succession dominated by marl and claystone, some of it bituminous, and including various thin limestone horizons, some of them iron-oolitic.

The *upper boundary* is set at 668.07 m at the top of the uppermost calcareous marl of the Staffelegg Formation. The boundary is also visible in the GR log and in the FMI log, where a sharp increase in resistivity (with respect to the readings in the claystone from the basal Opalinus Clay) is observed.

The *lower boundary* is a bored erosional surface at 721.46 m. It separates the overlying marine, fossiliferous claystone of the basal Schambelen Member from the underlying barren dolomitic marl of the Klettgau Formation. The boundary also shows a pronounced colour change from dark grey hues above to variegated ones below.

3.6.1.1 Gross Wolf Member, 668.07 m – 675.84 m (7.77 m) [617.65 m – 623.99 m TVD, 6.34 m TVT]

The Gross Wolf Member is usually composed of argillaceous to calcareous marl, in sections silty to sandy. It is interbedded by mainly thin, nodular layers with a higher carbonate content than the background lithology, mostly calcareous marl or limestone (Reisdorf et al. 2011). A further characteristic is the specific abundance of belemnites, ammonites and benthic fauna (Jordan & Deplazes 2019).

In RHE1-1, the Gross Wolf Member can be subdivided into two parts. The background lithology from the top (668.07 m) to 671.01 m consists of claystone (calcareous) and argillaceous marl with some nodular interbeds of calcareous marl. The lower part from 671.01 m to the base (675.84 m) represents the typical "Jurensismergel" facies. It contains abundant nodular interbeds of calcareous marl and limestone (argillaceous). The marl interbeds partly coalesce into thick intervals of calcareous marl, thereby displacing the argillaceous marl to thin interlayers. The limestone (argillaceous) of the lower part is silty to sandy in contrast to the upper part. The whole member is fossiliferous but with a higher content of macrofossils in the lower part.

Generally, the cores from RHE1-1 show a similar succession as in MAR1-1 in terms of lithology, fabric and fossil content. In detail, the unit differs from that in MAR1-1 in the upper part because it contains a lower number of interbeds. Furthermore, it mainly consists of marl instead of limestone. Conversely, in RHE1-1 the succession shows a higher carbonate content in the lower part due to a higher number of marl and limestone interbeds than in MAR1-1.

The *upper boundary* is set at 668.07 m. It is identical to the upper boundary of the Staffelegg Formation.

The *lower boundary* is set at 675.84 m with the (downward) onset of bitumen and the disappearance of both quartz and belemnites, abundant in the Gross Wolf Member.

Lithology

- 668.07 m – 671.01 m Claystone (calcareous) and argillaceous marl (slightly silty), dark grey, bioclastic; with nodular interbeds of calcareous marl (slightly silty), dark grey, and bioclastic calcareous marl, medium grey, bioturbated. The whole interval contains solitary belemnites, subordinately ammonites (e.g. at 670.01 m) and small siderite nodules
- 671.01 m – 675.84 m Calcareous marl (silty to sandy), medium grey, and intervals of argillaceous marl (silty to sandy), dark grey, several large pyrite nodules, bioclastic throughout. The section is interspersed with many nodular interbeds and large nodules of limestone (argillaceous) (mudstone and wackestone, micrite and biomicrite), light grey, bioclastic, bioturbated and with burrows. The whole section contains abundant belemnites, bivalves and ammonites with well-preserved specimens at 671.46 m, at 672.75 m and at 674.70 m. Crinoids are rare

3.6.1.2 Rietheim Member, 675.84 m – 687.81 m (11.97 m) [623.99 m – 633.74 m TVD, 9.75 m TVT]

The Rietheim Member is very distinctive due to its bitumen content and its lamination of very fine bioclasts (e.g. Kuhn & Etter 1994). Usually, the total organic content is highest in the lower part of the member, reflected by the presence of bituminous shale in this section (e.g. Röhl et al. 2001, Wohlwend et al. 2021).

In RHE1-1, the Rietheim Member consists of pyritic argillaceous marl with a bitumen content continuously increasing downwards. It finally grades into bituminous shale with some interbeds of calcareous marl and limestone, all bituminous and partly pyritic. Except for the lowermost part, the whole member is laminated, in sections due to bivalve detritus.

The *upper boundary* is set at 675.84 m with the (downward) onset of bitumen and the disappearance of both quartz and belemnites, abundant in the overlying Gross Wolf Member.

The *lower boundary* is set at 687.81 m at the base of the lowermost seam of bituminous shale (3 cm thick) from the Rietheim Member.

Lithology

- 675.84 m – 677.24 m Interval with a downward increasing content of bivalves and bioclasts and therefore of carbonate, resulting in transitions from claystone (silty, calcareous), dark grey to black, via argillaceous marl, dark grey, into bioclastic calcareous marl, medium grey. Whole succession laminated with shell layers (from 677.08 m to 677.24 m). Single jet layer ("gagate" or coal), 2 cm thick, at 677.16 m
- The interval also shows a gradual downward increase in bitumen content from slightly to distinctly bituminous in the claystone and in the bioclastic calcareous marl, respectively

677.24 m – 683.71 m	Argillaceous marl, bituminous, below 681.45 m gradually transitioning to bituminous shale, dark grey to black and dark greyish-brown, pyritic, frequent bivalve detritus and solitary, pyritised fossil fragments, including belemnites, laminated; at 677.47 m a jet layer (0.5 cm thick)
683.71 m – 686.98 m	Bituminous shale, mainly dark grey to dark greyish-brown. The interval contains several interbeds: From the top (683.71 m) to 683.81 m, calcareous marl, medium light grey, sand-sized bioclasts From 684.87 m to 685.05 m, two thin layers of limestone (argillaceous), medium light grey to medium grey separated by a thin layer of bituminous shale from 684.96 m to 685.00 m. The upper limestone bed is pyritic From 685.69 m to 685.99 m, limestone, light grey to medium light grey, sand-sized bioclasts, pyritic. The layer represents the marker bed «Unterer Stein» All lithologies of the interval are bituminous and laminated. This interval correlates well with the findings in the MAR1-1 and in Benken boreholes
686.98 m – 687.81 m	Argillaceous marl, mainly medium grey to dark grey, slightly bituminous, very pyritic with large flakes in the lower half, fossiliferous (bioclasts, bivalves, belemnites), partly with burrows At the base of the member (from 687.78 m to 687.81 m), a layer of bituminous shale (3 cm thick), dark grey

3.6.1.3 Breitenmatt Member and Rickenbach Member, 687.81 m – 691.63 m (3.82 m) [633.74 m – 636.84 m TVD, 3.10 m TVT]

Throughout Northern Switzerland, the Breitenmatt Member, the Rickenbach Member and the Grünschholz Member represent a strongly condensed succession (Reisdorf et al. 2011). Jordan & Deplazes (2019) recommend describing the Breitenmatt Member and the Rickenbach Member (together with the thin underlying Grünschholz Member) as one informal stratigraphic unit, because the delimitation of the two (or three) thin and predominantly calcareous and fossiliferous members was expected to be difficult.

Because the Grünschholz Member can be clearly delimited from the overlying sediments in RHE1-1, it will be discussed separately (Section 3.6.1.4). However, current data do not allow a differentiation between the Breitenmatt Member and the Rickenbach Member, which will therefore be described together.

In RHE1-1, the succession can be subdivided lithologically into two parts. The upper part mainly consists of calcareous marl with some limestone interbeds. The lower part is an argillaceous marl with only two thin limestone layers.

The *upper boundary* is set at 687.81 m, at the base of the lowermost seam of bituminous shale (3 cm thick) from the overlying Rietheim Member.

The *lower boundary* is set at 691.63 m at the top of a succession of encrusted hardgrounds with limestone clasts and beds.

Lithology

- 687.81 m – 689.59 m Calcareous marl, medium grey, micaceous close to the base but glauconitic throughout. The interval contains three limestone interbeds (mudstone, micrite), maximum 22 cm in thickness, very light grey to light grey, all glauconitic. The two uppermost beds show burrows, the lowermost one is bioturbated
- The top part of the interval (from 687.81 m to 688.12 m) is lithologically different from the rest. It is an argillaceous marl, medium grey, pyritic but bitumen-free, with one belemnite and intensely burrowed
- The fossil content is restricted to sections of calcareous marl. They contain sand-sized bioclasts, large bivalves and, especially in the upper part, abundant belemnites as well as an ammonite at 689.46 m
- 689.59 m – 691.63 m Argillaceous marl, medium grey to dark grey, micaceous, pyritic, very glauconitic. It is enriched in large and abundant belemnites, as well as in bivalves, sand-sized bioclasts and contains an ammonite at 690.97 m. The argillaceous marl is interbedded by two limestone beds: from 690.52 m to 690.63 m, limestone (mudstone, micrite), medium light grey, and from 691.41 m to 691.54 m, limestone (wackestone, biomicrite), beige grey, glauconitic, bioturbated, only the lower limestone bed being fossiliferous (bivalves and belemnites)

3.6.1.4 Grünschoholz Member, 691.63 m – 692.89 m (1.26 m) [636.84 m – 637.86 m TVD, 1.02 m TVT]

The Grünschoholz Member is the lowermost member of the highly condensed, calcareous and often phosphoritic section framed by the more argillaceous and thicker Rietheim Member and Frick Member. Due to the presence of *Gryphaea obliqua*, it can be distinguished from the similarly condensed beds of the overlying members.

The *upper boundary* is set at 691.63 m at the top of a succession of encrusted hardgrounds with limestone clasts and beds.

The *lower boundary* is set at 692.89 m at an erosional surface. It separates the calcareous hardgrounds with glauconite and abundant macrofossils above from the macrofossil-poor but pyrite-rich silty claystone of the underlying Frick Member.

Lithology

- 691.63 m – 692.89 m Succession of encrusted hardgrounds formed by limestone (argillaceous) to bioclastic limestone (wackestone and packstone, biomicrite), medium light grey, beige grey. Both lithologies occur as beds and as clasts which cover the hardgrounds
- Limestone clasts are embedded in a matrix of bioclastic calcareous marl, which additionally occurs as beds at the top and at the base of the member. It is medium grey to dark grey, in some horizons very pyritic, sparsely glauconitic and very fossiliferous (small bivalves, belemnites, bioclasts, rarely brachiopods). Close to the erosional base, specimens of *Gryphaea obliqua* are found between 692.78 m and 692.87 m

3.6.1.5 Frick Member, 692.89 m – 709.21 m (16.32 m) [637.86 m – 651.08 m TVD, 13.22 m TVT]

The Frick Member is known as a uniform succession of micaceous and silty claystone in various shades of dark grey. The upper part usually shows a slightly higher siliciclastic content. Macro-fossils are virtually absent in contrast to the members above and below (Reisdorf et al. 2011).

In RHE1-1, the member consists of silty claystone which is calcareous in the upper half. Large solitary pyrite nodules and pyrite aggregates are abundant.

The *upper boundary* is set at 692.89 m at an erosional surface. It separates the calcareous hard-grounds with glauconite and abundant macrofossils above from the macrofossil-poor but pyrite-rich silty claystone of the Frick Member.

The *lower boundary* is set at 709.21 m. It separates the macrofossil-poor silty claystone of the Frick Member from the bioclastic succession of limestone and calcareous marl below.

Lithology

692.89 m – 703.31 m	Silty claystone (calcareous), dark grey, micaceous, pyritic (as nodules, in horizons and dispersed), slightly laminated with lenses and laminae with a higher content of quartz silt, light grey
703.31 m – 709.21 m	Silty claystone, dark grey to black, micaceous, slightly pyritic but with some large pyrite nodules and aggregates, slightly laminated with silt-stone lenses, light grey. In the lowermost 11 cm, mm-thick layers of bioclasts occur, increasing in number downwards

3.6.1.6 Beggingen Member, 709.21 m – 714.15 m (4.94 m) [651.08 m – 655.06 m TVD, 3.98 m TVT]

In Northern Switzerland, the Beggingen Member comprises two successions of thin- to medium-bedded fossiliferous limestone (partly iron-oolitic, partly limonitic and phosphoritic), with thin marl interbeds (Reisdorf et al. 2011). In the ZNO siting region, the two successions are separated by a prominent claystone interval (e.g. in the Benken borehole, Nagra 2001a). The upper limestone succession is characterised by the occurrence of *Gryphaea arcuata* which is missing in the lower succession. The base of the lower succession is marked by the Schleithem Bed, a regional stratigraphic marker overlying an erosional surface (Reisdorf et al. 2011).

In RHE1-1, the lithology below the upper limestone succession (from 709.21 m to 712.07 m) is different from that in the adjacent Benken and MAR1-1 boreholes. The claystone interval (from 712.07 m to 713.58 m) includes a thin bioclastic calcareous marl with iron-oooids overlying an erosional surface. Furthermore, the lower succession (from 713.58 m to 714.15 m) is a bioclastic calcareous marl with iron-oooids rather than a limestone.

The *upper boundary* is set at 709.21 m. It separates the macrofossil-poor silty claystone of the Frick Member from the bioclastic succession of limestone and calcareous marl below.

The *lower boundary* is set at 714.15 m. The erosional boundary separates the iron-oooid bearing and fossiliferous calcareous marl from the rather monotonous claystone (silty) of the upper part of the underlying Schambelen Member.

Lithology

- 709.21 m – 712.07 m Bioclastic succession with limestone in the centre framed by calcareous marl at the top and at the base:
- From the top (709.21 m) to 709.50 m, bioclastic calcareous marl, medium grey to dark grey, pyritic. The fossils comprise bivalves, echinoderms and bioclasts
- From 709.50 m to 710.31 m, massive bed of bioclastic limestone (grainstone, biosparite) with a basal bed (from 710.25 m to 710.31 m) of bioclastic argillaceous marl with large crinoids and abundant *Gryphaea* sp. The limestone is very light grey. It contains frequent bivalves, crinoids and bioclasts. *Gryphaea* sp. occur just close to the base of the limestone bed.
- From 710.31 m to 711.64 m, thin- to medium-bedded, nodular alternation of bioclastic limestone (grainstone, biosparite), very light grey, and bioclastic limestone (argillaceous) (packstone, biomicrite), medium light grey to medium grey, both very pyritic. Bivalves, bioclasts and *Gryphaea* sp. occur in the whole interval. Iron-ooids and intraclasts as well as phosphorite first occur below 711.15 m and below 711.40 m, respectively. The basal hardground at 711.64 m is studded with intraclasts and *Gryphaea* sp.
- The interval from 711.64 m to the erosional base (at 712.07 m) is described in summary as a bioclastic calcareous marl. The distinct decrease in the abundance of fossils from top to base leads to downward grading from bioclastic limestone, medium light grey, to bioclastic argillaceous marl, dark grey. The interval is pyritic throughout. It contains the same fossils described in the limestone interval above, including *Gryphaea* sp. However, the specimens are smaller and less abundant. Additionally, belemnites and a gastropod at 711.78 m are found
- 712.07 m – 714.15 m A twice repeated succession of a claystone interval with an underlying horizon of bioclastic calcareous marl:
- From the top (712.07 m) to 712.74 m, upper interval of claystone (silty) dark grey to black, pyritic, with a coquina at 712.22 m. The interval contains sparse, isolated sandstone lenses (fine-grained), medium light grey, pyritic, maximum 5 cm thick
- From 712.74 m to 712.95 m, upper horizon of bioclastic calcareous marl, medium grey, scattered iron-ooids, sideritic to limonitic and with phosphoritic nodules. Clasts from the underlying lithology cover the erosional base (712.95 m). The fossil content consists of bivalves (among others of the genus *Cardinia* sp.), belemnites and bioclasts
- From 712.95 m to 713.58 m, lower interval of claystone (silty), similar to the upper one but lenticular-bedded by sandstone lenses, more abundant but smaller than above
- From 713.58 m to the base (714.15 m), lower nodular horizon of bioclastic calcareous marl (silty), in transition to limestone (argillaceous), bioclastic, medium grey, micaceous, pyritic and slightly limonitic. Scattered iron-ooids, some intraclasts and bioclasts are found down to

an internal erosional surface at 713.70 m. Large bivalves are encountered in the whole horizon. Intraclasts are especially abundant at the erosional base (714.15 m). This interval probably corresponds to the Schleithem Bed

3.6.1.7 Schambelen Member, 714.15 m – 721.46 m (7.31 m) [655.06 m – 660.95 m TVD, 5.89 m TVT]

The Schambelen Member is dominated by dark silty to sandy claystone. The fossil content is usually poor. However, the member shows many subtle changes in both lithology and facies throughout Northern Switzerland (e.g. Nagra 1992a, Nagra 1992b, Nagra 2001a, Albert et al. 2012, Jordan & Deplazes 2019). In north-eastern Switzerland, a fossiliferous limestone bed (Hallau Bed) is reported from the lower part or the base of the Schambelen Member (Reisdorf et al. 2011).

In RHE1-1, the Schambelen Member can be subdivided into three parts. The upper part and the lower part consist of a claystone (silty, calcareous). Small siltstone and sandstone lenses are common in the upper claystone interval. Bivalves are ubiquitous in the lower claystone interval. The central part is composed of a fossiliferous and sandy alternation of calcareous marl and limestone. It also contains a conspicuous interbed of argillaceous sandstone (calcareous).

The *upper boundary* is set at 714.15 m. The erosional boundary separates the iron-oooid-bearing and fossiliferous calcareous marl from the underlying, rather monotonous claystone (silty) of the upper part of the Schambelen Member.

The *lower boundary* is a bored erosional surface at 721.46 m. It separates the overlying marine, fossiliferous claystone from the underlying barren dolomitic marl of the Klettgau Formation. The boundary also shows a pronounced colour change from dark grey hues above to variegated ones below.

Lithology

714.15 m – 717.12 m	Upper interval of claystone (silty, calcareous), dark grey, micaceous. Isolated thin (maximum 5 mm) lenses of siltstone to sandstone (fine-grained), medium light grey, pyritic, occur throughout. A coquina (bioclasts, bivalves and belemnites) (5 cm thick) is very noticeable close to the top of the interval in both the core and the FMI log.
717.12 m – 720.07 m	Central limestone dominated interval consisting of: From 717.12 m to 718.65 m, a thin- to medium-bedded alternation of: • limestone (sandy, argillaceous) (mudstone and wackestone, biomicrite), medium light grey to medium grey, scattered iron-oooids and pyritic down to 717.58 m • limestone (sandy) (wackestone, biomicrite), very light grey • bioclastic limestone (sandy) (packstone and grainstone, biomicrite and biosparite), very light grey

The limestone (sandy, argillaceous) forming densely packed nodules in a sparse matrix of calcareous marl (sandy), medium grey, resulting in an irregularly wavy bedding. The alternation is fossiliferous to various degrees with bioclasts and bivalves (large *Cardinia* sp. included)

From 718.65 m to 719.00 m, argillaceous sandstone (fine-grained), calcareous, dark grey to medium grey, irregularly wavy-bedded

From 719.00 m to 720.07 m, an alternation of calcareous marl (sandy), medium grey, and of limestone (packstone, biomicrite), light grey. Some limestone beds are glauconitic and contain calcareous ooids. Below 719.51 m, the limestone grades into bioclastic limestone (packstone, biomicrite). The fossil content comprises bioclasts and bivalves in both lithologies. Bivalves (including *Cardinia* sp.) increase in size and number towards the pyritic base (720.07 m)

720.07 m – 721.46 m Lower interval of claystone (silty to sandy), slightly calcareous, dark grey, pyritic. It differs from the upper claystone interval due to the abundance of bivalves on bedding surfaces and the absence of the siltstone and sandstone lenses

From 721.35 m to the base (721.46 m), silty to sandy claystone (calcareous), medium grey, with some thin (a few mm) sandstone lenses, light grey, and with a cm-thick layer of calcareous sandstone

3.7 Keuper Group

3.7.1 Klettgau Formation, 721.46 m – 776.42 m (54.96 m) [660.95 m – 704.82 m TVD, 43.87 m TVT]

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 RHE1-1, the Belchen Member is missing and the Gruhalde Member is divided in two by the Seebi Member as in MAR1-1. The Ergolz Member is sandier than in MAR1-1.

The *upper boundary* is a bored erosional surface at 721.46 m. It separates the overlying marine, fossiliferous claystone of the Schambelen Member from the underlying barren dolomitic marl. The boundary also shows a pronounced colour change from dark grey hues above to variegated ones below.

The *lower boundary* is set at 776.42 m at the top of the uppermost nodular anhydrite bed of the underlying Bänkerjoch Formation.

3.7.1.1 Gruhalde Member above the Seebi Member, 721.46 m – 743.34 m (21.88 m) [660.95 m – 678.51 m TVD, 17.56 m TVT]

The upper part of the Gruhalde Member (above the Seebi Member) is characterised by non-stratified dolomitic marl of a grey to reddish and brown colour (Jordan et al. 2016). These overbank sediments consist of dolomitic marl or dolostone of pedogenic or pond origin and they can be interrupted by channels often filled with silty to sandy sediments.

In RHE1-1, the dolomitic marl (silty) shows greenish-grey, pale green and grey hues at the contact with the stratigraphic members above and below. In between, it is mainly grey violet. Characteristic features like plant root tubes, dolomitic concretions and pedogenic fissures occur in distinct sections.

The *upper boundary* is set at 712.46 m. It corresponds to the upper boundary of the Klettgau Formation.

The *lower boundary* is set at 743.34 m at a sharp transition from the greenish-grey dolomitic marl of the Gruhalde Member to the light grey and massive or brecciated dolostone of the underlying Seebi Member. The boundary is also conspicuous in the FMI log, where a distinct switch from low resistivities to very high readings is observed.

Lithology

721.46 m – 743.34 m Monotonous succession of dolomitic marl (silty), greyish-green and grey over several metres both at the top and at the base of the unit, in between predominantly grey violet and pale green, scattered pale yellowish and light grey reduction spots, non-stratified. The erosional top contains borings filled with the overlying silty claystone (calcareous). Deviations from the aforementioned main lithology occur only as dolomitic marl to dolostone (argillaceous, silty) from 734.16 m to 734.95 m and as dolomitic marl (silty, calcareous) from 731.79 m to 732.66 m

The interval shows some features often typical for this member: below 722.76 m, it displays a nodular- to breccia-like appearance due to a very fine network of calcite-filled fissures. The commonly occurring plant root tubes are found from 731.79 m to 741.75 m. Moreover, large calcareous dolomitic nodules are observed from 733.75 m to 740.04 m and scattered clasts of dolostone are present below 741.75 m

3.7.1.2 Seebi Member, 743.34 m – 757.16 m (13.82 m) [678.51 m – 689.53 m TVD, 11.02 m TVT]

The Seebi Member was deposited on an alluvial plain and covers a wide range of lithofacies from overbank fine-grained deposits and lacustrine carbonates to fluvial bedload sediments (Hornung & Aigner 2002).

In RHE1-1, a massive to brecciated succession of dolostone with a varying content of quartz silt and sand dominates in the Seebi Member. Other lithologies, again mostly silty to sandy, form the matrix of the brecciated dolostone. Subordinately, they are also found over short intervals in the lower half of the member. As in MAR1-1, most of the member is a partially brecciated dolostone,

although the silt and sand content is higher in RHE1-1. For the lowermost quarter of the member, however, the Seebi Member in MAR1-1 shows a lower carbonate content and more quartz resulting in a wider variety of lithologies than in RHE1-1.

The *upper boundary* is set at 743.34 m, at a sharp transition from the overlying greenish-grey dolomitic marl of the Gruhalde Member to the light grey and massive or brecciated dolostone of the underlying Seebi Member. The boundary is also conspicuous in the FMI log, where a distinct switch from low resistivities to very high readings is observed.

The *lower boundary* is set at 757.16 m at the transition from dolomitic marl and dolostones from the Seebi Member to the underlying argillaceous marl with reddish and violet colours of the Gruhalde Member (lower part). Both the FMI and the GR readings show the gradual transition from the overlying dolomitic marl to the argillaceous marl in the decreasing resistivities and increasing GR readings.

Lithology

743.34 m – 749.43 m	Succession of predominantly brecciated dolostone (sandy): From the top (743.34 m) to 744.83 m, a slightly brecciated dolostone (sandy), very light grey to beige. The fissures are filled with sandy marl (dolomitic), pale green From 744.83 m to the base (749.43 m), a breccia, dolomitic (polymict), overall beige to beige grey and light grey to dark grey, rarely white, with densely packed angular to subangular clasts of dolostone (sandy), variegated. The very sparse to sparse matrix is claystone, pale green, and sandstone. Both the clasts and the matrix are mostly silicified but with some sections still porous. Chert layers also occur in some sections, while scattered chert nodules are restricted to the top part and to some intervals in the lower part of the breccia
749.43 m – 752.60 m	Succession of massive dolostone (partly silty to sandy): Dolostone, beige grey to dark beige, mostly homogeneous, slightly brecciated with calcitic fissures and scattered vugs in some sections. Below 750.73 m, the dolostone becomes increasingly silty and further down even sandy. Concurrent with the downward increase in silt and sand content, the breccia fabric of the dolostone (silty to sandy) disappears and frequent stylolites with claystone coatings emerge
752.60 m – 753.67 m	Succession of sandy dolostone, very light grey to beige and pale green, with quartz (medium-grained to granules, angular to subrounded) and pebbles of lithic fragments (upper part); and of a nodular dolostone (sandy, argillaceous), very light grey to beige, with a matrix of silty to sandy marl, pale green (lower part)
753.67 m – 754.84 m	Sandy marl (dolomitic) as nodules of sandy dolostone, very light grey, in a matrix of argillaceous marl (silty to sandy, dolomitic), pale green. The number of nodules decreases downwards but they are matrix-supported in the whole interval

- 754.84 m – 757.16 m Succession dominated by dolostone (partly silty to sandy) in the upper part and dolomitic marl in the lower part. The colour gradually changes from greyish and greenish hues to grey violet towards the base
- From the top (754.84 m) to 756.42 m, dolostone (silty to sandy above 755.20 m), beige to beige grey and very light grey to beige. Towards the base, the colour turns into grey violet. Below 755.20 m, some fissures occur. They are filled with dolomitic marl (silty to sandy), pale green
- From 756.42 m to the base (757.16 m), dolomitic marl, very light grey to pale green and grey violet which becomes increasingly dominant towards the base. Below 756.68 m, the dolomitic marl grades into a breccia, dolomitic (polymict). Clasts of dolomitic marl and of dolostone (argillaceous) are embedded in a sandstone matrix (coarse-grained). The sandstone contains angular quartz and lithic fragments, among others of dolostone. Below 756.87 m, the sandstone matrix is restricted to fissures. The whole interval contains plant root tubes

**3.7.1.3 Gruhalde Member below the Seebi Member, 757.16 m – 765.67 m (8.51 m)
[689.53 m – 696.30 m TVD, 6.77 m TVT]**

The lower part of the Gruhalde Member is characterised by variegated to reddish-brown argillaceous to dolomitic marl with bright nodular to irregular dolomitic interbeds, partly with a wide variety of components, representing paleosoils.

In RHE1-1, the lower part of the Gruhalde Member consists lithologically of two parts. The upper part occupies roughly three-quarters of the member. It is composed of variegated argillaceous marl (silty) with a few rather thin dolomitic interbeds and two somewhat thicker beds of brecciated dolostone. The lower part is an alternation of argillaceous marl, dolomitic marl and dolostone. The reddish and brownish colours of the marl dominate throughout the interval.

The *upper boundary* is set at 757.16 m at the transition from dolomitic marl and dolostones from the overlying Seebi Member to the underlying argillaceous marl with reddish and violet colours of the Gruhalde Member (lower part). Both the FMI and the GR readings show the gradual transition from the overlying dolomitic marl to the argillaceous marl in the decreasing resistivities and increasing GR readings.

The *lower boundary* is set at 765.67 m at the top of a dolostone bed with ooids ghosts and vugs, some filled with anhydrite. This dolostone grades from slightly nodular to massive anhydrite. In addition, the FMI and the GR readings also clearly mark the transition from the overlying dolomitic marl to dolostone and anhydrite.

Lithology

- 757.16 m – 763.57 m Argillaceous marl (silty to sandy, dolomitic), dark reddish-brown to grey violet and pale green. Plant root tubes and fissures occur down to 761.53 m. The fissures give the interval a slight breccia-like appearance. Solitary dolomitic concretions, very lightly coloured, are found throughout. The interval contains some interbeds (maximum 21 cm thick) of:

- dolostone (argillaceous), very light grey to pale green
- nodular dolomitic marl (silty), very light grey and dark reddish-brown
- two layers of breccia, dolomitic. The upper layer is monomict and comprises dolostone clasts, very light green to pale green. The lower interval is polymict. It contains dolostone clasts, pink, in a matrix of argillaceous marl (silty, dolomitic), dark reddish-brown

763.57 m – 765.67 m Alternation of (in decreasing order of abundance) dolomitic marl (silty to sandy), argillaceous marl (silty to sandy, dolomitic) and dolostone (argillaceous). The succession is mainly dark reddish-brown and pale green, while the dolostone (argillaceous) is very light grey. Based on lithology and colour, this interval may correspond to the «Rote Wand», an important regional marker throughout north-eastern Switzerland and southern Germany (Geyer et al. 2011, Jordan & Deplazes 2019)

3.7.1.4 Gansingen Member, 765.67 m – 767.79 m (2.12 m) [696.30 m – 697.98 m TVD, 1.68 m TVT]

The Gansingen Member provides evidence of a marine ingress from the west, with a strong lateral variation of lithofacies in an E-W direction (Jordan et al. 2016). For the ZNO siting region, the member was predicted to be evaporitic (Jordan & Deplazes 2019).

In RHE1-1, the Gansingen Member is represented by a slightly nodular to massive anhydrite layer. Two dolostone beds with ooid ghosts, one at the top, complete the member. As expected, the member is clearly visible in the petrophysical logs due to extreme readings.

The *upper boundary* is set at 765.67 m at the top of a dolostone bed with ooids ghosts and vugs, some filled with anhydrite. This dolostone grades from slightly nodular to massive anhydrite. In addition, the FMI and the GR readings also clearly mark the transition from the overlying dolomitic marl to dolostone and anhydrite.

The *lower boundary* is set at 767.79 m at the top of the uppermost marl interval of the Ergolz Member below the mainly anhydritic interval of the Gansingen Member. Anhydrite nodules, concentrated in some layers, are also found below this boundary. However, they were interpreted as of probable pedogenic origin.

Lithology

765.67 m – 767.79 m From the top (765.67 m) to 766.10 m, dolostone (calcareous), medium light grey to beige. The bed contains dispersed ooid ghosts and vugs. The vugs are filled with calcite or anhydrite

From 766.10 m to the base (767.79 m), anhydrite, mainly white, sub-ordinately beige grey and dark pink, slightly nodular to featureless, very sparse matrix of dolomitic marl, reddish-orange, in the upper part with ooid ghosts. In the anhydritic interval from 767.22 m to 767.36 m, an interbed of dolostone, beige grey and white, occurs. The bed is slightly laminated on account of microbial mats. Some small, black and white anhydrite nodules are interspersed

3.7.1.5 Ergolz Member, 767.79 m – 776.42 m (8.63 m) [697.98 m – 704.82 m TVD, 6.84 m TVT]

The Ergolz Member comprises a wide variety of lithologies. It reflects the deposition in a fluvial (channel and overbank) to lacustrine depositional environment (e.g. Jordan et al. 2016).

In RHE1-1, the Ergolz Member shows a distinct division into two lithological intervals. The upper interval (767.79 m to 770.13 m) consists of argillaceous marl (dolomitic). It contains anhydrite nodules forming densely packed layers with an argillaceous marl matrix. Most of the member however consists of an argillaceous siltstone interval (770.13 m to 776.42 m). A thick interlayer of sandstone with an erosional base at 773.50 m, underlain by a thin argillaceous marl layer, approximately cuts this interval in half.

Conversely, the whole Ergolz Member in RHE1-1 may consist of two sedimentary successions divided by the erosional base of the sandstone layer at 773.50 m. Both successions consist of siltstone (lower succession) to sandstone (upper succession) at the base, which may be addressed as proximal overbank deposits or as deposits in subordinate shallow channels. These are followed by argillaceous marl (lower succession) to anhydrite, argillaceous (upper succession), representing the distal overbank deposits.

The *upper boundary* is set at 767.79 m at the top of the uppermost marl interval of the Ergolz Member below the mainly anhydritic interval of the Gansingen Member. Anhydrite nodules, concentrated in some layers, are also found below this boundary. However, they were interpreted as of probable pedogenic origin.

The *lower boundary* is set at 776.42 m at the top of the uppermost nodular anhydrite bed of the underlying Bänkerjoch Formation.

Lithology

767.79 m – 770.13 m	Thin- to medium-bedded alternation of argillaceous marl (dolomitic), argillaceous marl (silty, dolomitic) and anhydrite (argillaceous). White anhydrite nodules are found throughout but they are concentrated in some layers resulting in anhydrite (argillaceous) with a matrix of argillaceous marl, dark pink and pale green. The alternation is framed by two different lithologies From the top (767.79 m) to 768.03 m, dolomitic marl, pale green to dark pink, with small anhydrite nodules, thin nodular dolostone layers and dolomitic concretions From 769.89 m to the base (770.13 m), anhydrite bed, white, featureless
770.13 m – 776.42 m	Interval of argillaceous siltstone divided in two by a sandstone inter-layer: From the top (770.13 m) to 772.31 m, an upper interval of argillaceous siltstone (partly sandy, dolomitic), greyish-green to grey violet and dark reddish-brown. The interval contains plant root tubes and some white anhydrite nodules

From 772.31 m to an erosional base at 773.50 m, sandstone interlayer (fine-grained, partly argillaceous), dark pink to medium grey. Close to the base, the sandstone contains flasers of argillaceous marl (silty, dolomitic) and dolomitic marl (silty), dark reddish-brown to medium light grey

Underneath an erosional surface, from 773.50 m to the base (776.42 m), a lower interval of argillaceous siltstone (dolomitic), dark reddish-brown to dark pink and greyish-green. The top consists of argillaceous marl (silty, dolomitic), dark reddish-brown. Close to the base, the interval shows veins and nodules of anhydrite, white, and of dolostone, medium light grey

3.7.2 Bänkerjoch Formation, 776.42 m – 827.99 m (> 51.57 m MD) [704.82 m – 745.33 m TVD, > 40.51 m TVT]

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). Some of the dolostone and sandstone sections represent marine ingressions and may be used as regional marker beds (Jordan et al. 2016).

In RHE1-1, a wide variety of lithologies were encountered in the uppermost sub-unit («Claystone with anhydrite nodules») of the Bänkerjoch Formation, as also encountered in MAR1-1. In contrast, the background lithology of the Bänkerjoch Formation in RHE1-1 is mainly a claystone (dolomitic) and not an argillaceous marl (dolomitic) as in MAR1-1. The second sub-unit («Cyclic sequence») is dominated by anhydrite in nodules, veins and layers in both boreholes. The sulphate sediments are always white.

The *upper boundary* is set at 776.42 m at the top of the uppermost nodular anhydrite bed of the Bänkerjoch Formation.

The lower boundary of the Bänkerjoch Formation was not encountered before the final depth of the borehole at 827.99 m MD.

Lithostratigraphic subdivision

There is still no formal subdivision of the Bänkerjoch Formation. Jordan & Deplazes (2019) propose using the informal subdivision based on earlier core records of Nagra (Dronkert et al. 1990, Nagra 2001a). Due to this informal subdivision, the RHE1-1 borehole ended in the second of a total of five sub-units.

776.42 m – 808.28 m	«Claystone with anhydrite nodules» (31.86 m) including «Marker Horizon I» («Quarzitische Bank») from 804.44 m to 805.90 m
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808.28 m – 827.99 m	«Cyclic sequence» (> 19.71 m)
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Lithology

«Claystone with anhydrite nodules», 776.42 m – 808.28 m (31.86 m)

This sub-unit is lithologically very heterogeneous. On a large scale, claystone (dolomitic) dominates the sub-unit. Investigated more closely, claystone-dominated intervals alternate with lithologically heterogeneous intervals. The whole succession is interbedded with thick layers of argillaceous marl. Close to the base, a siliciclastic interval stands out: it is one of the regional marker beds («Quarzitische Bank», «Marker Horizon I»; Jordan et al. 2016).

776.42 m – 781.00 m	First interval with a wide variety of lithologies: • several layers of anhydrite, white to medium light grey, as nodules (partly with a chicken wire texture) • several layers of argillaceous marl (dolomitic, silty in the lower half), dark grey to black, and of dolomitic marl (silty), medium grey to dark grey • one layer of claystone (dolomitic), dark reddish-brown to black, • a basal nodular bed (44 cm thick) of dolomitic marl and dolostone (silty, argillaceous), medium light grey to medium grey All non-anhydritic lithologies contain sparse anhydrite nodules
781.00 m – 785.40 m	First interval dominated by claystone (mostly silty, dolomitic), black, with some anhydrite veins and nodules. The interval contains, in decreasing order of abundance, interbeds of: • dolomitic marl (silty to sandy), medium grey to dark grey, with a few anhydrite nodules • argillaceous marl (silty to sandy), dark grey to black • anhydrite (dolomitic), white to medium grey, nodular (with a chicken wire texture) • anhydrite (argillaceous, dolomitic), consisting of layered anhydrite and layers of dolomitic marl, medium to dark grey
785.40 m – 789.12 m	Interbedded sequence of: From the top (785.40 m) to 787.54 m, argillaceous marl (silty, dolomitic), dark grey to black, with a few anhydrite veins From 787.54 m to the base (789.12 m), anhydrite (argillaceous), as abundant anhydrite nodules in a sparse claystone matrix, black. The bed is framed by nodular anhydrite layers with a chicken wire texture
789.12 m – 795.19 m	Second interval dominated by claystone (dolomitic), mostly black, with some anhydrite veins. The interval contains, in decreasing order of abundance, interbeds of: • anhydrite (argillaceous), as nodules and, below 792.09 m, additionally as anhydrite veins in a sparse claystone matrix, black • argillaceous marl (dolomitic, partly silty), mainly dark grey to black, with some sparse anhydrite nodules and veins

- 795.19 m – 804.44 m Second interval with a wide variety of lithologies:
- several intervals of anhydrite as nodular layers in a chicken wire texture and of densely packed nodules and veins in a very sparse claystone matrix, black
 - several intervals of anhydrite (argillaceous), anhydrite nodules and veins in a more abundant claystone matrix than in the anhydrite beds
 - several intervals of claystone (below 797.25 m dolomitic), black and dark reddish-brown, anhydrite mostly concentrated in veins and less in nodules
 - four intervals of argillaceous marl (dolomitic), dark grey, with sparse anhydrite veins and nodules
 - three beds (maximum 42 cm thick) of dolomitic marl, medium grey. Two of the three beds are free of anhydrite nodules
- 804.44 m – 805.90 m Siliciclastic interval: dolomitic sandstone (fine- to medium-grained, argillaceous) to sandy dolostone (argillaceous), medium light grey, with a few white anhydrite nodules, bioturbated. This corresponds to the «Marker Horizon I» (Jordan et al. 2016)
- 805.90 m – 808.28 m Interbedded sequence of:
- argillaceous marl (dolomitic), dark grey to black (in upper part also dark reddish-brown), with a few anhydrite nodules
 - a central interval of claystone (dolomitic), black
 - two rather thin intervals, one of anhydrite nodules, and of dolomitic marl, medium grey

«Cyclic sequence», 808.28 m – 827.99 m (> 19.71 m)

The sub-unit consists mainly of anhydrite with varying fabrics and bedding. In the upper part, the anhydrite is mainly found in veins, solitary and densely packed nodules and, partly, with a chicken wire texture. Underneath, layered anhydrite appears more often, and the nodular anhydrite exclusively displays a chicken wire texture. The lowermost part down to the final depth of the borehole resembles the interval above but with less chicken wire anhydrite. Only a few, thin sulpharenitic layers occur throughout the sub-unit, probably corresponding to the sulpharenitic layers in MAR1-1.

- 808.28 m – 813.61 m Alternation of anhydrite in varying fabrics with claystone intervals, in decreasing order of abundance:
- anhydrite, mostly nodular (partly with a chicken wire texture), only a few layers of featureless anhydrite
 - heavily veined anhydrite: anhydrite (argillaceous), with less nodules but abundant veins, both in a matrix of claystone (dolomitic), black
 - a few intervals of claystone (dolomitic) to claystone (anhydritic), black, with sparse anhydrite veins

- 813.61 m – 820.08 m Laminated to thin-bedded alternation of anhydrite organised in layers, veins and in a chicken wire texture without claystone intervals. Anhydrite (argillaceous) prevails in some sections where anhydrite layers and veins are embedded in a matrix of claystone (dolomitic), medium grey to black
- 820.08 m – 827.99 m: Medium-bedded alternation of, in decreasing order of abundance:
 - anhydrite (argillaceous), as anhydrite veins and layers in a matrix of claystone (dolomitic), medium grey to black
 - anhydrite, nodular (with a chicken wire texture)
 - claystone (anhydritic), with less veins and layers of anhydrite in a claystone matrix compared to the anhydrite (argillaceous). One thick claystone layer is almost anhydrite-free

4 Comparison with the forecast profile

For the RHE1-1 borehole, a forecast profile was first prepared in 2016 in connection with the application for an exploration permit (Nagra NSG 16-13; Nagra 2016). This was mainly based on the state of the regional geological 3D model at that time, as well as on the results from the Benken borehole (Nagra 2001a, Nagra 2001b).

During the recent drilling campaign, new insights into the regional geology emerged, in particular due to the findings from the nearby Marthalen-1-1 borehole (MAR1-1; Jordan et al. 2021). As a result, the regional geological 3D model was revised. Consequently, the forecast profile for RHE1-1 was also adapted to the new state of knowledge before the start of the drilling operations and for internal use. The following comparison refers to this revised forecast completed in June 2021.

RHE1-1 was drilled with a progressively increasing inclination. This may lead to different ways in which the actual layer thicknesses can deviate from the forecast during drilling progress. Although measured depth (MD) profiles were prepared for the drilling trajectory as originally planned, comparing them with the actual findings can be misleading, because differences could be attributed either to formation thicknesses that actually contradict the forecast or to deviations from the planned borehole trajectory. The following comparison is therefore made between the calculated true vertical depth (TVD) of the findings and the corresponding TVD forecast from June 2021. The TVD values also allow for an easier comparison with the neighbouring boreholes and the regional model. Tab. 4-1 shows the MD and TVD values of the formation boundaries, as well as the measured and actual true vertical layer thicknesses (TVT).

Tab. 4-1: Measured depth (MD), measured thickness (MT), calculated true vertical depth (TVD) and true vertical thickness (TVT) (all in metres) of the formations in RHE1-1

	Top MD	Base MD	MT	Top TVD	Base TVD	TVT
USM Group	3.0	149.9	146.9	3.00	149.9	146.9
Siderolithic Group	149.9	154.4	4.5	149.9	154.4	4.5
«Felsenkalke» + «Massenkalk»	154.4	298.1	143.7	154.4	295.7	141.3
Schwarzbach Fm.	298.1	312.7	14.6	295.7	309.7	14.0
Villigen Fm.	312.7	398.8	86.1	309.7	389.7	80.0
Wildeggen Fm.	398.8	419.2	20.4	389.7	408.0	18.3
Wutach Fm.	419.2	423.4	4.2	408.0	411.8	3.8
Variansmergel Fm.	423.4	436.6	13.2	411.8	423.5	11.7
«Parkinsoni-Württembergica-Schichten»	436.6	469.8	33.2	423.5	452.2	28.7
«Humphriesoolith Fm.»	469.8	482.8	13.0	452.2	463.2	11.0
Wedelsandstein Fm.	482.8	521.43	38.6	463.2	495.83	32.6
«Murchisonae-Oolith Fm.»	521.43	524.61	3.18	495.83	498.51	2.68
Opalinus Clay	524.61	668.07	143.46	498.51	617.65	119.14
Staffelegg Fm.	668.07	721.46	53.39	617.65	660.95	43.30
Klettgau Fm.	721.46	776.42	54.96	660.95	704.82	43.87
Bänkerjoch Fm.	776.42	827.99	> 51.57	704.82	745.33	> 40.51

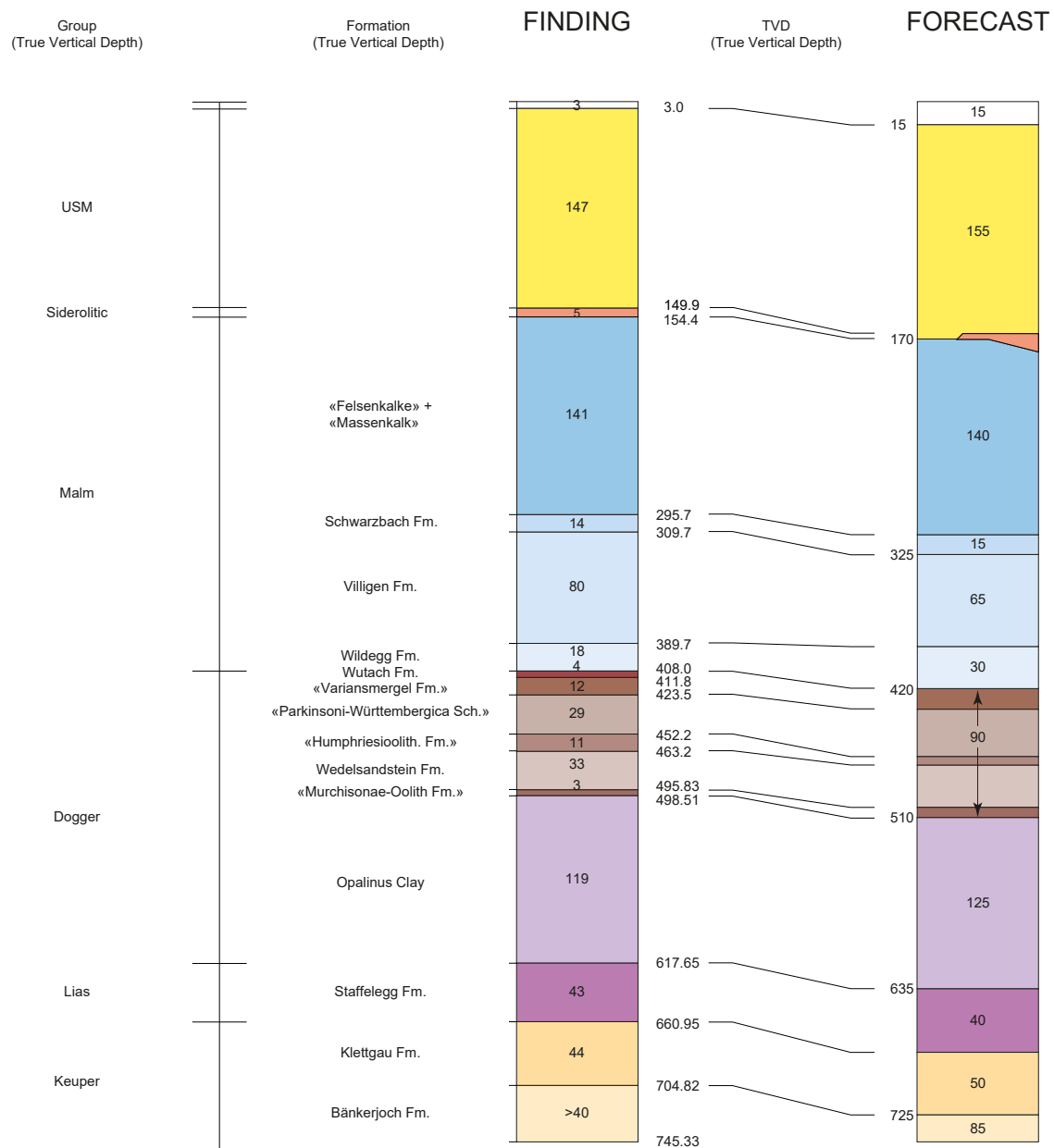


Fig. 4-1: Comparison of the revised forecast (June 2021) with the actual findings of RHE1-1

Generally, there are only minor differences between the findings from RHE1-1 and the June 2021 forecast profile (Fig. 4-1). The difference exceeds 10 m in only four cases (in the unconsolidated rocks, the Molasse sediments, the Villigen Formation and the Wildegge Formation).

The thickness of the unconsolidated rocks is significantly smaller than expected (ca. 3 m instead of 15 m).

The top of the Mesozoic strata was reached at about 154.4 m, 16 m shallower than expected. As a result, the encountered Lower Freshwater Molasse Group (USM) is slightly thinner than predicted (ca. 146.9 m instead of 155 m).

In the forecast profile, the potential presence of rather thin (and stratiform) sediments of the Siderolithic Group was indicated. The actual thickness of these sediments is about 4.5 m which is within the expected thickness range.

The «Felsenkalke» + «Massenkalk» as well as the Schwarzbach Formation fit almost exactly to the predicted thicknesses (ca. 141.3 m TVT and 14.0 m TVT instead of 140 m and 15 m, respectively)

The Villigen Formation proved to be about 15 m thicker than expected (ca. 80 m TVT instead of 65 m). This offsets the cumulative effect of shallower units being thinner than forecast; consequently, the base of the Villigen Formation was found almost exactly at predicted depth (389.7 m TVD instead of 390 m). Despite the unexpected considerable thickness, it is not possible to subdivide the Villigen Formation into its known members.

Remarkably, the Wildegg Formation is significantly thinner than expected (ca. 18.3 m TVT instead of 30 m). However, the total thickness of the Villigen Formation and the Wildegg Formation combined agrees well with the forecast.

The heterogeneous upper part of the Dogger Group (the Dogger Group above the Opalinus Clay) is about 90.5 m TVT thick, almost exactly as predicted (90 m). The forecast profile does not explicitly comment on the thicknesses of the involved formations, which are only indicated graphically. However, it can be noted that the «Humphriesioolith Formation» (ca. 11 m TVT) and the «Murchisonae-Oolith Formation» (2.68 m TVT) are, respectively, thicker and thinner than expected.

The Opalinus Clay proved to be thinner than expected (119.14 m TVT instead of 125 m). However, all four sub-units recently proposed by Mazurek & Aschwanden (2020) could be identified.

The Staffelegg Formation and the Klettgau Formation have almost the same thickness (43.309 m TVT and 43.87 m TVT instead of the predicted 40 m and 50 m, respectively).

The top of the Bänkerjoch Formation was encountered at 704.82 m TVD, about 20 m shallower than expected. Only about 40 m TVT of the Bänkerjoch Formation were drilled before the final depth was reached (745.33 m TVD). A total thickness of 85 m was expected for this formation.

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