

Arbeitsbericht NAB 21-20

**TBO Marthalen-1-1:
Data Report**

**Dossier III
Lithostratigraphy**

September 2021

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

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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.

This Dossier was prepared by a project team consisting of:

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

M. Schwarz (cuttings and core description and QC)

R. Felber (cuttings and core description)

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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: The appendices are only included in the digital version of this report and can be found under the paper clip symbol.

1 Introduction

1.1 Context

To provide input for site selection and the safety case for deep geological repositories for radioactive waste, Nagra has drilled a series of deep boreholes ("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 Marthalen-1-1 borehole.

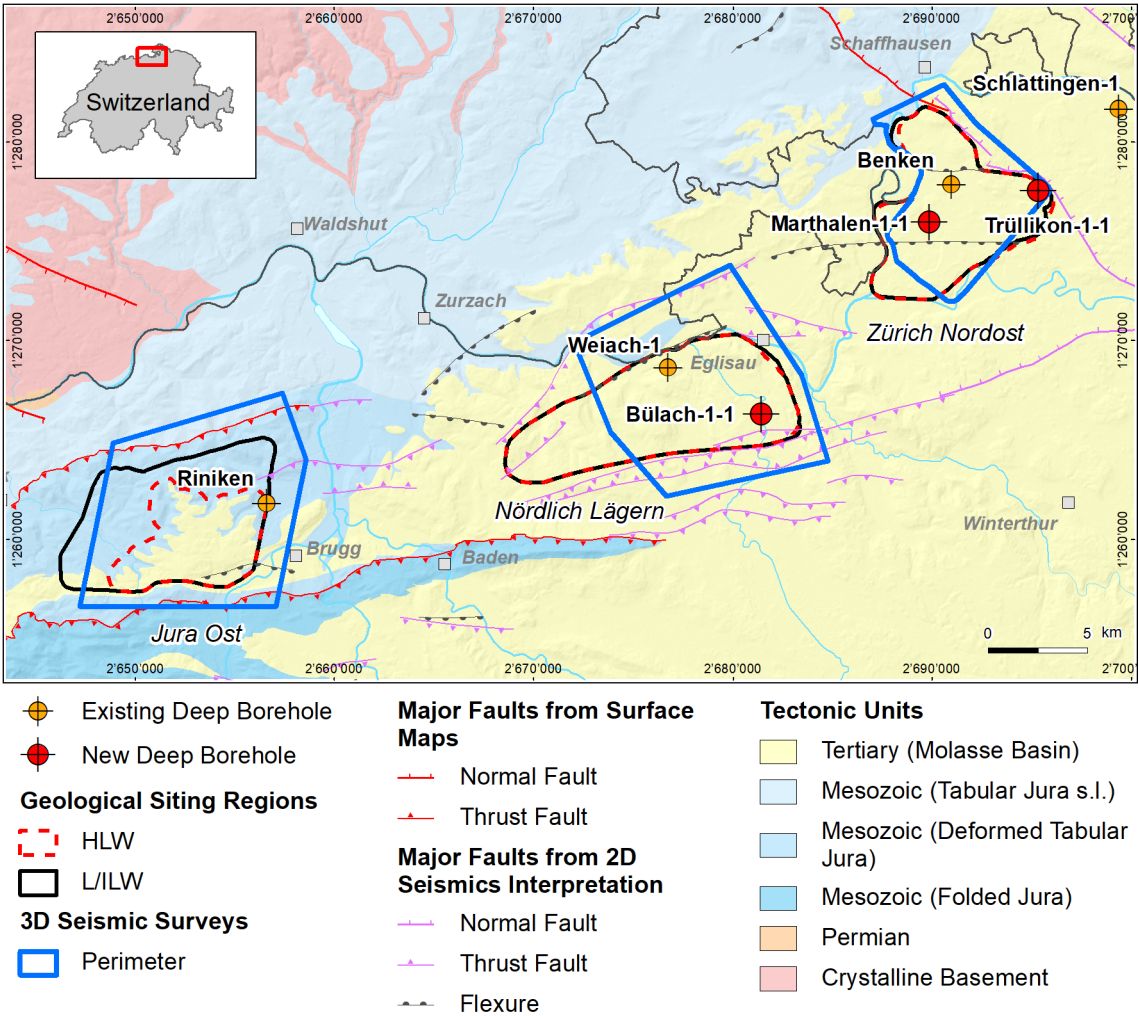


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Marthalen-1-1 (MAR1-1) exploratory borehole is the third 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 vertical borehole reached a final depth of 1'099.25 m (MD)¹. The borehole specifications are provided in Tab. 1-1.

Tab. 1-1: General information about the MAR1-1 borehole

Siting region	Zürich Nordost
Municipality	Marthalen (Canton Zürich / ZH), Switzerland
Drill site	Marthalen-1 (MAR1)
Borehole	Marthalen-1-1 (MAR1-1)
Coordinates	LV95: 2'689'889.946 / 1'275'956.932
Elevation	Ground level = top of rig cellar: 399.48 m above sea level (asl)
Borehole depth	1'099.25 m measured depth (MD) below ground level (bgl)
Drilling period	9th February 2020 – 14th July 2020 (spud date to end of rig release)
Drilling company	Daldrup & Söhne AG
Drilling rig	Wirth B 152t
Drilling fluid	Water-based mud with various amounts of different components such as ² : 55 – 460 m: Bentonite & polymers 460 – 881 m: Potassium silicate & polymers 881 – 961 m: Sodium silicate & polymers 961 – 1'099.25 m: Sodium chloride & polymers

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. The comparison of the core versus log depth³ of the main lithostratigraphic boundaries in the MAR1-1 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.

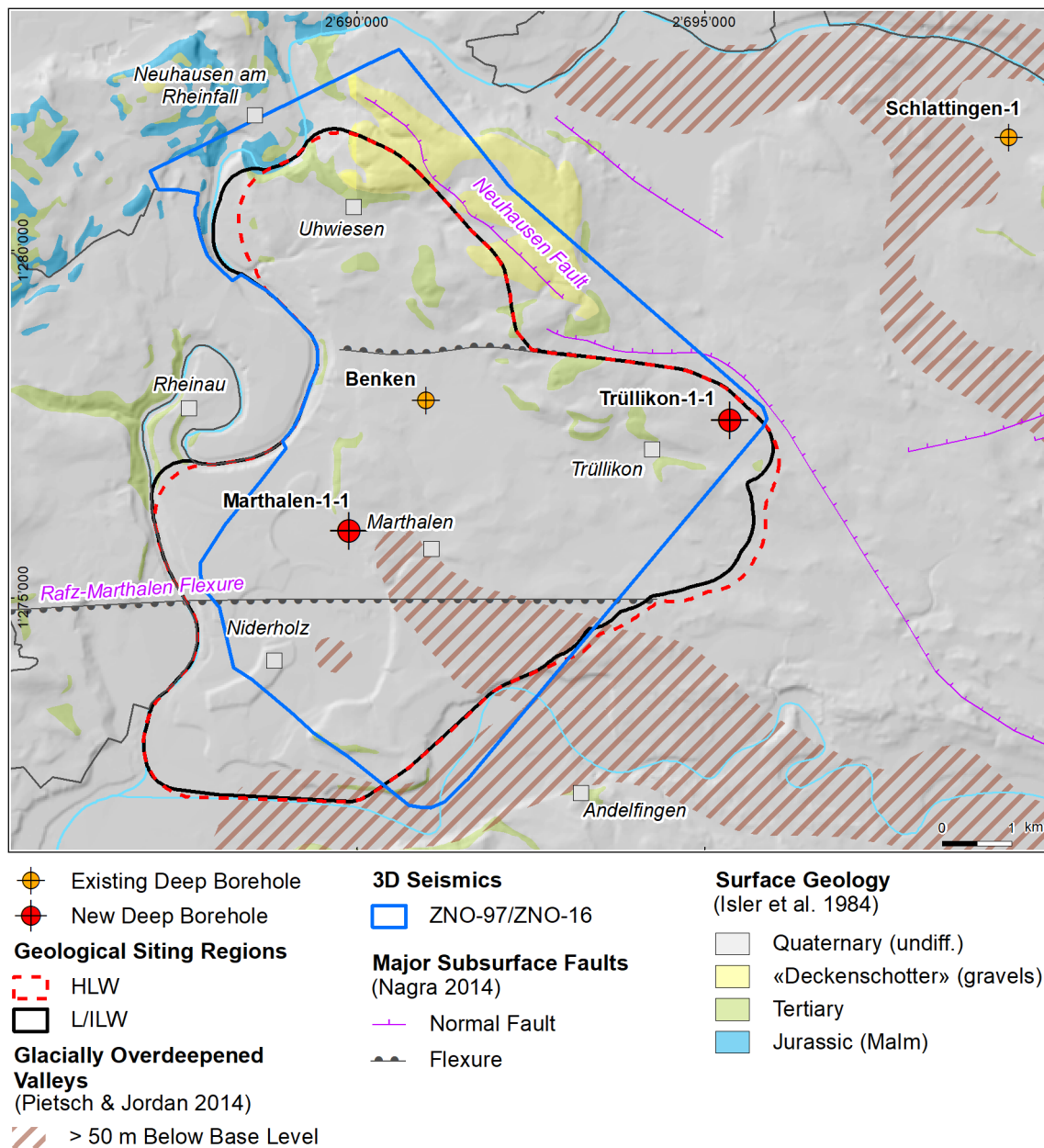


Fig. 1-2: Overview map of the investigation area in the Zürich Nordost siting region with the location of the MAR1-1 borehole in relation to the boreholes Benken, Schlattigen-1 and TRU1-1

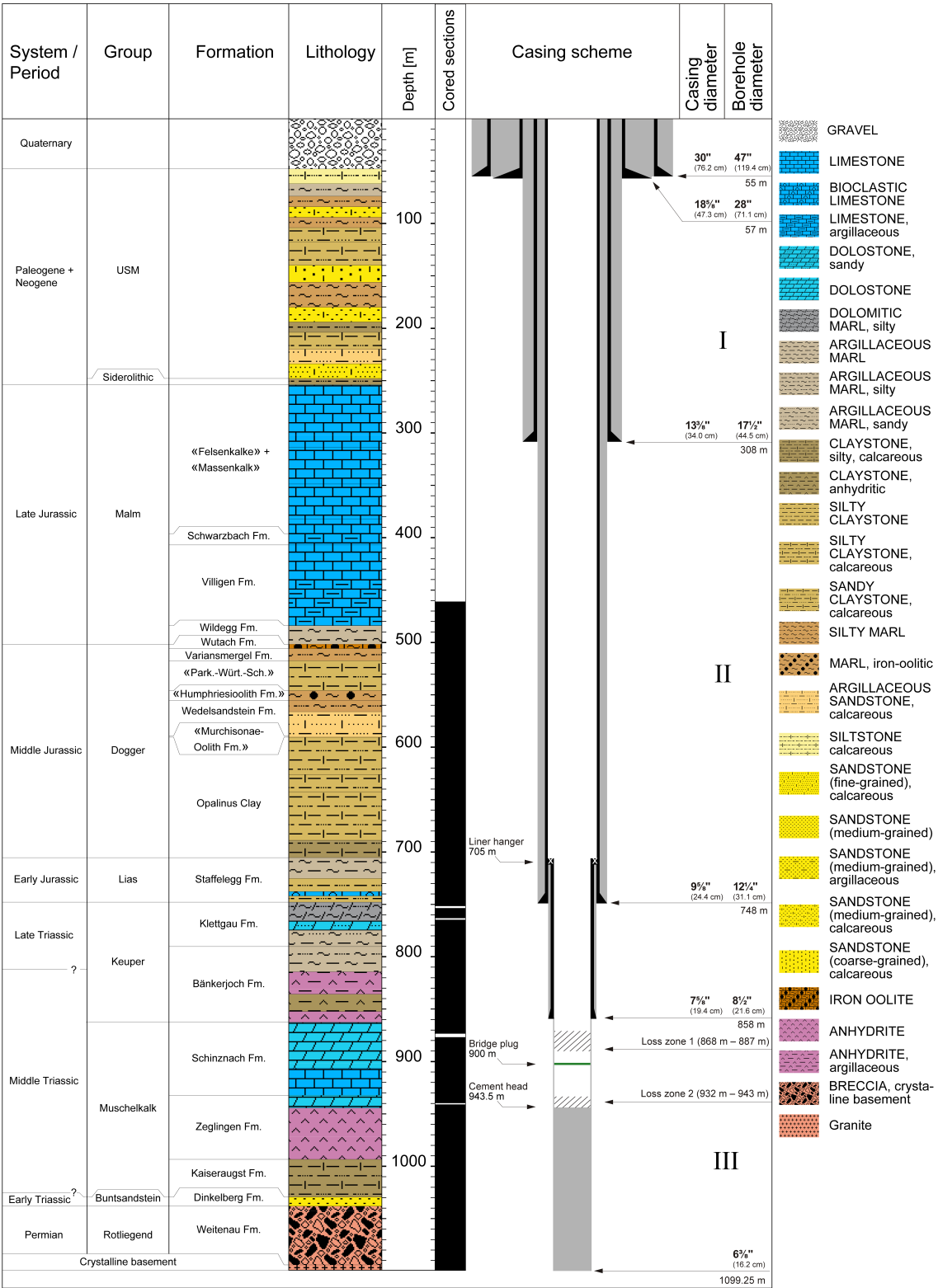


Fig. 1-3: Lithostratigraphic profile and casing scheme for the MAR1-1 borehole⁴

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 MAR1-1 bore-hole⁵

System / Period	Group	Formation	Core depth in m (MD)	Log
Quaternary			48	—
Paleogene + Neogene	USM		248	—
	Siderolithic		254	—
		«Felsenkalke» + «Massenkalk»	396.1	—
	Malm	Schwarzbach Formation	406.9	—
		Villigen Formation	484.02	484.22 —
		Wildeggen Formation	501.80	501.92 —
		Wutach Formation	505.75	506.03 —
		Variansmergel Formation	517.43	517.57 —
Jurassic		«Parkinsoni-Württembergica-Schichten»	545.93	546.12 —
	Dogger	«Humphriesioolith Formation»	555.23	555.47 —
		Wedelsandstein Formation	589.17	589.19 —
		«Murchisonae-Oolith Formation»	590.35	590.37 —
		Opalinus Clay	705.40	705.52 —
	Lias	Staffellegg Formation	747.83	747.89 —
	Keuper	Klettgau Formation	790.12	790.34 —
		Bänkerjoch Formation	862.52	862.77 —
		Schinznach Formation	932.24	932.47 —
Triassic	Muschelkalk	Zeglingen Formation	993.50	993.97 —
		Kaiseraugst Formation	1029.45	1029.95 —
	Buntsandstein	Dinkelberg Formation	1037.98	1038.23 —
Permian	Rotliegend	Weitenau Formation	1094.08	1094.08 —
		Crystalline Basement	1099.25	final depth

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 MAR1-1 borehole

NAB 21-20 documents the majority of the investigations carried out in the MAR1-1 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 MAR1-1 borehole. It includes most of the data available approximately one year after completion of the borehole. Some analyses are still ongoing (e.g. diffusion experiments, analysis of veins, hydrochemical interpretation of water samples) and 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 21-20

Black indicates the dossier at hand.

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

1.4 Scope and objectives of this dossier

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

- complete, detailed and consistent documentation of the cuttings samples and cores according to the guidelines set out in Naef et al. (2019) and modifications and additions to the procedures 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 laboratory analyses (XRD mineralogy; *cf.* Dossier VIII), thin sections (*cf.* Dossier IV), biostratigraphy (*cf.* Dossier IV) and borehole geophysics (*cf.* Dossier VI) made available up to data cut-off
- detailed description of lithology and lithostratigraphic units down to member and bed level (if applicable), with the focus on special features and deviations from current knowledge and understanding (Jordan & Deplazes 2019)
- visualisation of lithostratigraphic data as profiles:
 - 1:2'500: Appendix A
 - 1:1'000: Appendix B
 - 1:100: Appendices C-1 to C-4

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) can be found in Dossier IV.

1.5 Petrophysical logs available at data cut-off

The logs listed below were available at data cut-off 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 micro imager (FMI)

1.6 Work undertaken

1.6.1 General workflow

Four lithostratigraphy experts worked in turns on the cuttings samples and cores following the procedures detailed in Naef et al. (2019). All findings were originally documented in DIN A3 field logs (manuscript), including a detailed drawing of the lithological column. Following this initial description of the samples, the field logs were checked internally by a second expert and compared to logs of the nearby Benken borehole (Nagra 2001a, 2001b). 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 closely monitored this process and progress was discussed monthly with all parties involved, including Nagra project managers. This enabled rapid implementation of improvements to the workflow. The 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 report is based on system / period, group, formation and member boundaries at the data cut-off on 14.09.2020.

All depths from the core descriptions refer to metres measured depth (MD) core depth. Depths from the cuttings sections, where a full suite of petrophysical logs was available, refer to metres measured depth (MD) log depth.

1.6.2 Description and representation of the cuttings samples

The cuttings samples were taken from the shaker with a sampling interval of 2 metres. They were then washed, sieved, and roughly described at the drill site by the mud logger for the purpose of operational decisions. The washed and dried cuttings samples were packed in transparent plastic boxes, labelled, and delivered to Nagra's core storage facility in Würenlingen. The different lithologies of a single sample were identified using a microscope, hydrochloric acid 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 rate of penetration (ROP), revolutions per minute (RPM), a quick-look lithological composition of the cuttings of the shale shakes and gas chromatography (for more details on drilling operations, see Dossier I).

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

1. Fine-grained fractions lost during sample preparation: It was unclear which weight fraction was lost during sampling and sample preparation (washing and sieving) at the drill site. Molasse lithologies are often insufficiently lithified and the lost fraction is therefore more likely part of fine-grained clastic lithologies such as silt-, claystone or marl. Therefore, the descriptions given in the field logs refer solely to the material in the washed samples and do not consider potentially lost lithologies. Thus, the lithologies presented for the Molasse cuttings sections are systematically overestimated with respect to coarser-grained lithologies such as sandstones.
1. 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.
2. 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.
3. From 0 – 314 m, no petrophysical logs were available. 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. 188 m).
4. From 314 m onwards, a full suite of petrophysical logs was available. Therefore, it was decided to draw lithological boundaries according to the FMI also in the remaining cuttings section down to 460 m. The primary lithology was determined by comparison of the sample description with the petrophysical logs, primarily FMI, neutron porosity and density. This comparison helped to better distinguish cavings material and secondary lithologies from the primary lithology. Depths in the text and in the profile in this section are accurate to one significant digit and refer to log depth (e.g. 330.2 m).

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 is feasible using patterns, symbols and plain text as indicated in Naef et al. (2019). The general objective of the field notes was to ensure a comprehensive documentation of all relevant features visible in the core. The subsequent representation of the field logs in the TerraStation profile at a scale of 1:100 required substantial graphical generalisations and, to some extent, also summaries of lithological descriptions. Beds of 20 cm thickness 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 (e.g. 782.46 m to 784.02 m, Gansingen Member). Nevertheless, within the weathering plot, this may still be a desired visual effect for depicting argillaceous interlayers within more competent rock (e.g. limestone) or thin limestone beds in successions of marl, clay- or siltstones. Therefore, the following rules were defined:

- limestone beds within the Opalinus Clay are always recorded and represented in the profile with actual depths, irrespective of their thickness
- hardgrounds and iron-oolites within the Opalinus Clay are always recorded with actual depths, irrespective of thickness; thin iron-oolite layers may be represented with the corresponding symbol instead of a lithological pattern
- breccia 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; depth annotations are given with two significant digits

While lithological boundaries were first identified in the core, the FMI often provides extra information to allow the exact depth range of a given lithology to be set. In such instances, 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 is assessed by comparison between 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 lithological terms differ slightly for use in profiles compared to continuous text in the report (see Fig. 1-4).

While the implementation of the detailed Füchtbauer scheme as defined for the TBO project in Naef et al. (2019) results in more than 60 lithologies and corresponding patterns, 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).

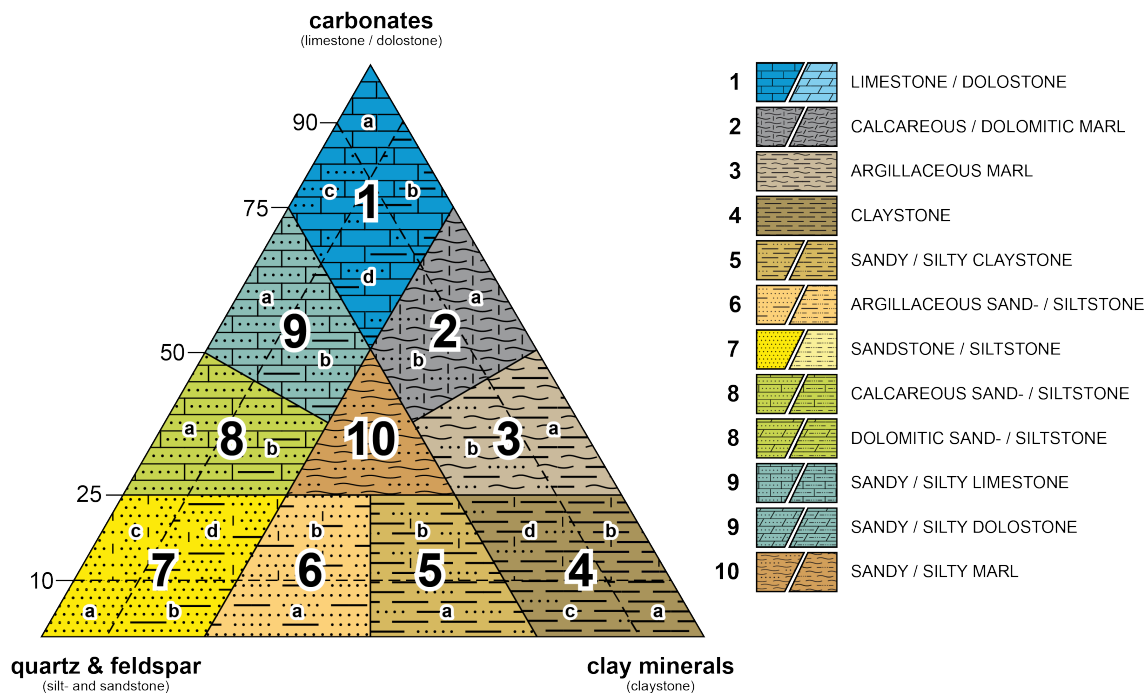
For the description of limestones, the Folk and Dunham classifications were also applied in the best possible manner (see also Naef et al. 2019). However, neither classification is fully suited for a macroscopic classification, because they rely heavily on the distinction of very small components and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

For diagenetically altered limestones, composed of small calcite 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.

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. 1-4) as well as drawn as patterns based on the graphical representation according to Naef et al. (2019). No patterns were used for small-scale interbedding.



profile nomenclature

- 1a LIMESTONE / DOLOSTONE
- 1b LIMESTONE / DOLOSTONE, argillaceous
- 1c LIMESTONE / DOLOSTONE, sandy / silty
- 1d LIMESTONE / DOLOSTONE, sandy / silty, argillaceous
- 2a CALCAREOUS / DOLOMITIC MARL
- 2b CALCAREOUS / DOLOMITIC MARL, sandy / silty
- 3a ARGILLACEOUS MARL
- 3b ARGILLACEOUS MARL, sandy / silty
- 4a CLAYSTONE
- 4b CLAYSTONE, calcareous / dolomitic
- 4c CLAYSTONE, sandy / silty
- 4d CLAYSTONE, sandy / silty, calcareous / dolomitic
- 5a SANDY / SILTY CLAYSTONE
- 5b SANDY / SILTY CLAYSTONE, calcareous / dolomitic
- 6a ARGILLACEOUS SAND- / SILTSTONE
- 6b ARGILLACEOUS SAND- / SILTSTONE, calcareous / dolomitic
- 7a SAND- / SILTSTONE
- 7b SAND- / SILTSTONE, argillaceous
- 7c SAND- / SILTSTONE, calcareous / dolomitic
- 7d SAND- / SILTSTONE, calcareous / dolomitic, argillaceous
- 8a CALCAREOUS / DOLOMITIC SAND- / SILTSTONE
- 8b CALCAREOUS / DOLOMITIC SAND- / SILTSTONE, argillaceous
- 9a SANDY / SILTY LIMESTONE / DOLOSTONE
- 9b SANDY / SILTY LIMESTONE / DOLOSTONE, argillaceous
- 10 SANDY / SILTY MARL

report nomenclature

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

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

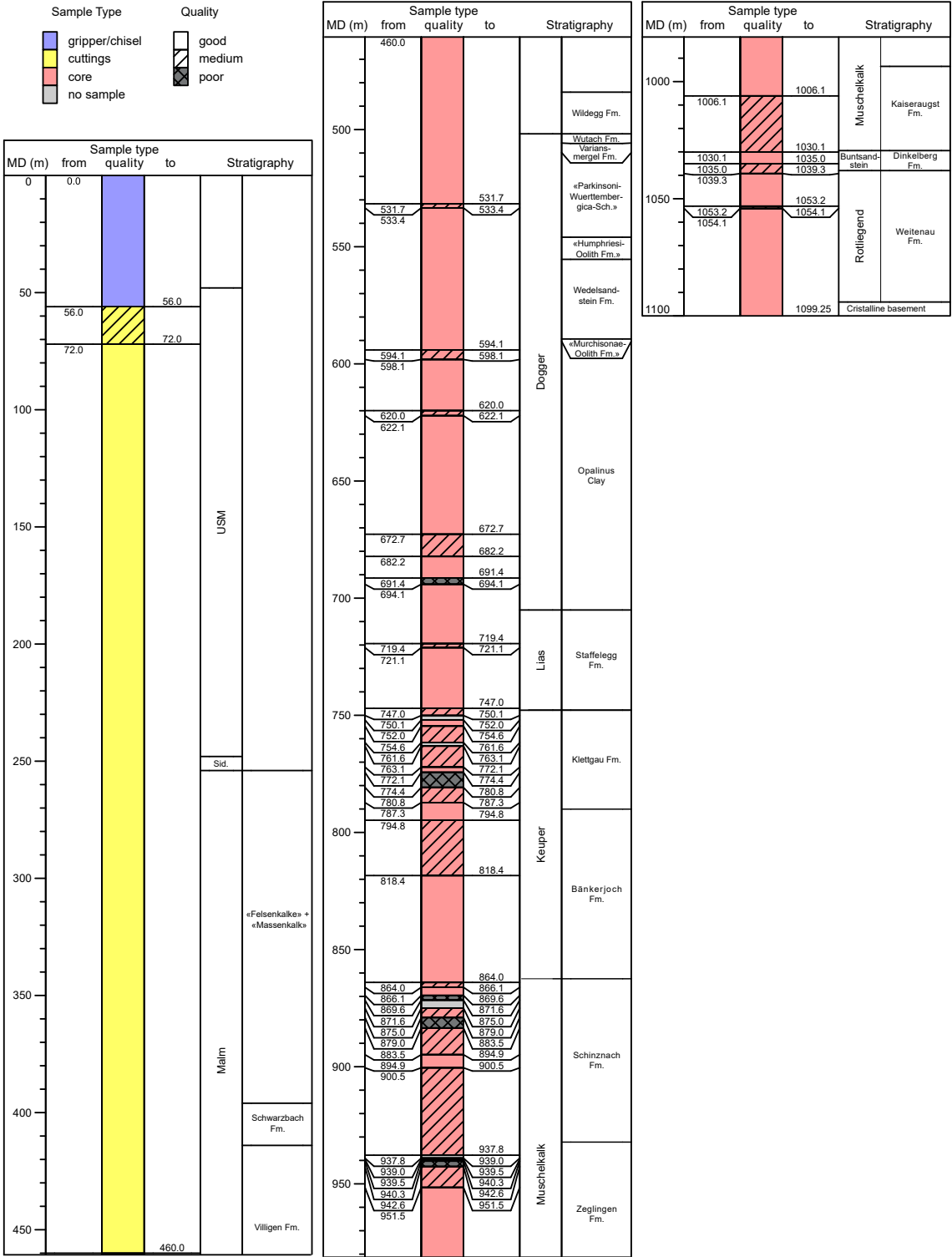
Pers. comm. S. Wohlgend modified after Naef et al. (2019).

2 Inventory and quality of cores and cuttings samples

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

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

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



MD (m)	from	Sample type	quality	to	Stratigraphy
1000	1006.1	gripper/chisel	good	1006.1	Muschelkalk
1030.1	1030.1				
1035.0	1035.0	cuttings	medium	1035.0	Buntsandstein
1039.3	1039.3				
1053.2	1053.2	core	poor	1053.2	Dinkelberg Fm.
1054.1	1054.1				
1099.25	1099.25	no sample		1099.25	Weitenau Fm.
1100					Cristalline basement

Fig. 2-1: Comparison of cuttings and core quality in MAR1-1

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 – 48 m (about 48 m)

Unconsolidated rocks were only encountered in the conductor pipe excavation.

Lithostratigraphic subdivision

The first two metres were not studied as no useful sample could be collected.

The interval from 2 m to 48 m is composed of polymict gravel of alpine origin (including carbonates) with a subordinate interval (samples from 6 m to 10 m) of gravely sand, silt and clay.

Lithology

The section from 2 m to 6 m is composed of gravel (slightly argillaceous, silty and sandy), pale brown, well sorted, subangular to rounded with sporadic blocks. It is probably of fluvial origin.

The section from 6 m to 10 m consists of clay, pale brown, which is underlain by sand (argillaceous, silty), light grey, both with some, well sorted, angular to rounded gravels. It probably documents finer-grained sediments within a fluvial environment.

The section from 10 m to 18 m is composed of gravel (argillaceous, silty and sandy), light grey, poorly to very poorly sorted, angular to rounded, with striated blocks. It probably originates from a periglacial fluvial environment.

The lowermost section, from 18 m to 48 m, consists of gravel (slightly argillaceous, silty and sandy), light grey to pale brown, well to poorly sorted, subangular to rounded, with sporadic blocks. It probably originates from a fluvio-glacial environment.

3.2 Lower Freshwater Molasse Group, 48 – 248 m (about 200 m)

The top of the MAR1-1 borehole is located significantly below the mapped regional base of the Upper Marine Molasse Group (Hofmann 1967). Addressing the entire encountered Molasse sediments as part of the Lower Freshwater Molasse Group is also confirmed by the absence of minerals typical of marine environments (e.g. glauconite).

The upper boundary is set at 48 m, at the first occurrence of sandstone cuttings, although gravel and sand debris from the overlying unconsolidated rock was found down to 62 m.

The lower boundary is set at 248 m. It is located below a succession of three cuttings samples free of iron-pisoids and dominated by sandstone (fine-grained), calcareous, argillaceous. The first iron-pisoids in a silty claystone matrix are already found in the 240 m to 242 m sample. The argument for placing the boundary at 248 m is that sandstone as found in the 242 m to 248 m samples is not known from the Siderolithic Group (but is common in the Lower Freshwater Molasse Group). The occurrence of iron-pisoids and silty claystone in the 240 m to 242 m sample

may simply result from mixing of cuttings during the drilling process. Alternative explanations are the reworking of Siderolithic sediments during early Molasse sedimentation. However, there are no further indications to support these hypotheses.

Lithostratigraphic subdivision

The whole section shows the characteristic "granitic composition" of the «Obere Bunte (Granitische) Molasse». It consists of a succession of mostly fine- to medium-grained terrestrial sediments (predominantly silt- and sandstones) of variable thickness. There is no marl-dominated succession which would be indicative of both the «Oberaquitane Mergelzone» as the topmost part of the «Obere Bunte Molasse» and the «Untere Bunte Molasse» at the base of the USM.

Lithology

In the whole section from 48 m to 248 m, three main lithologies of variable abundance were identified:

- sandy to silty marl, variegated (light green grey, medium grey, beige to dark beige, reddish orange and dark reddish brown). It dominates from 74 m to 180 m
- argillaceous sandstone to siltstone, silty claystone and claystone (silty), all calcareous, predominantly (dark) beige, grey pink and reddish brown, partly micaceous to very micaceous. These lithologies dominate from 180 m to 234 m. An interval of claystone (silty, calcareous), is found from 194 m to 204 m.
- Sandstone (predominantly fine- to medium-grained) (partly silty), light to medium grey, beige, and reddish brown, subrounded quartz, sparse mica, poorly to moderately sorted, partly in mm-thick lamination with siltstone, moderately to well cemented by calcite.
- sandstone (mostly medium- to coarse-grained) (calcareous), (very) light grey and beige, subangular to subrounded, variegated quartz, a minor fraction of plagioclase, sparse mica, moderately to well sorted, very poorly to poorly cemented.

In many samples there are almost no rock chips of this lithology because it was milled to loose sand. This rock type is known as "Granitischer Sandstein" because its grain composition roughly corresponds to the mineralogy of granite. The whole section contains four intervals of "Granitischer Sandstein" (from 84 m to 94 m, 104 m to 108 m, 140 m to 156 m and 180 to 186 m) with sharp boundaries to the adjacent lithologies

3.3 Siderolithic Group, 248 – 254 m (about 6 m)

The argument for the Siderolithic Group is the presence of iron-pisoids («Bohnerz»).

The upper boundary is set at 248 m, although the first iron-pisoids are already found in the 240 m to 242 m cuttings sample.

The lower boundary is set at 254 m with the occurrence of cuttings of limestone which are typical of the underlying Malm Group. Cuttings with iron-pisoids appear continuously down to 266 m and again in the 268 m to 270 m sample, and from 274 m to 280 m. The iron-pisoids could be either cavings or karst infill. There are no other arguments for setting the boundary between the Siderolithic and Malm Groups as there is no petrophysical logging or FMI available for the section in question.

Lithology

The interval comprises, on one hand, rather small amounts of claystone, greyish green, laminated, and iron-pisoids up to some millimetres in diameter, both indicative for the Siderolithic Group. On the other hand, claystone (silty), to silty claystone (calcareous), reddish brown, is abundant in all three samples. Sandstone (fine-grained) becomes quite dominant from 250 m to 252 m. The strong presence of these two lithologies may be the result of caving or mixing of cuttings during transport to the surface. Alternatively, the whole interval must be addressed rather as Siderolithic deposits reworked during early Molasse sedimentation.

3.4 Malm Group

3.4.1 «Felsenkalke» + «Massenkalk», 254 – 396.1 m (about 142 m)

According to the informal stratigraphic scheme for the current deep drilling campaign (Jordan & Deplazes 2019), the Jurassic carbonate rocks above the Schwarzbach Formation are summarised as «Felsenkalke» + «Massenkalk», an informal unit in the rank of a formation. The term alludes to the two interfingering facies realms replacing each other laterally and vertically: the mostly massy sponge bioherms («Massenkalk») and the mostly well bedded limestone deposits in between where sponges are rare or absent («Felsenkalke»).

In the «Massenkalk» facies, dolomitisation and dedolomitisation processes entail a saccharoidal texture in the limestone. These processes may also spread to the «Felsenkalke» in the vicinity of the «Massenkalk» (e.g. Lang 1964, 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 stylo-bedding (Logan & Semeniuk 1976, Pawellek & Aigner 2002) of both the «Felsenkalke» and the «Massenkalk». In consequence, the term "bedded" alone does not allow a differentiation between «Felsenkalke» and «Massenkalk».

The *upper boundary* is set at 254 m with the occurrence of cuttings of limestone which are typical of the underlying Malm Group. Cuttings with iron-pisoids appear continuously down to 266 m and again in the 268 m to 270 m sample, and from 274 m to 280 m. The iron-pisoids could be either cavings or karst infill. There are no other arguments for setting the boundary between the Siderolithic and Malm Groups as there is no petrophysical logging or FMI available for the section in question.

The *lower boundary* is set at 396.1 m. Although still in the cuttings section, the top of the first argillaceous marl bed of the underlying Schwarzbach Formation exceeding some centimetres in thickness was localised based on FMI. There, the change, generally from «Felsenkalke» + «Massenkalk» to Schwarzbach Formation, is characterised by a change from high resistivity to lower resistivity. In detail, the boundary was set at the top of the first thicker lower resistivity interval.

Lithostratigraphic subdivision

The «Felsenkalke» + «Massenkalk» of MAR1-1 is fully in the cuttings section. The proposed lithostratigraphic intervals are based on cuttings analysis and, from 314 m, where petrophysical logging sets in, on a combination with GR and FMI analysis.

254 – 284 m	Probably «Felsenkalke» facies
284 – 294 m	Probably «Massenkalk» facies
294 – 312 m	Probably «Felsenkalke» facies
312 – 314 m	Intermediate facies
314 – 330.2 m	Probably «Massenkalk» facies
330.2 – 336 m	Heterogeneous interval
336 – 348.6 m	Probably «Felsenkalke» facies
348.6 – 368 m	Probably «Massenkalk» facies
368 – 382 m	Probably «Felsenkalke» facies, thick-bedded
382 – 396.1 m	Probably «Felsenkalke» facies, thin-bedded

Lithology

Detritus from overlying Molasse sediments are found in samples down to 280 m. Iron-pisoids appear continuously down to 266 m and again in the 268 m to 270 m sample and from 274 m to 280 m. Whether they are also detritus or document local karstification cannot be decided.

254 – 268 m	Limestone (mudstone, micrite), dark beige to beige, between 266 m and 268 m also brown, iron-pisoids appear continuously down to 266 m
268 – 284 m	Limestone (mudstone, micrite), very light grey, partly recrystallised giving the cuttings a bright white marble look, iron-pisoids appear again in the sample from 268 m to 270 m and from 274 m to 280 m
284 – 294 m	Limestone (saccharoidal) to limestone (mudstone, micrite), abrupt change in rock colour to white
294 – 312 m	Two different types of limestone, possibly an alternation of limestone (mudstone, micrite), light grey to beige, and limestone (mudstone, micrite), white. In the lower part of the section, GR shows first small variations, possibly indicating marl or claystone interlayers
312 – 314 m	GR indicates a decrease in the clay fraction at the top. A change in rock colour from light grey to beige to white only occurs from this to the underlying cuttings sample
314 – 330.2 m	Limestone (mudstone, micrite) to limestone (saccharoidal), white, chalk-like, with spares limestone (mudstone, micrite), beige.

330.2 – 336 m	Heterogeneous section with two types of limestone, claystone and small objects that may be addressed as iron-pisoids. The two types are the lithologies already known from above: limestone (saccharoidal), white, and limestone (mudstone, micrite), beige. Additionally, claystone, beige grey to light greenish grey. GR and FMI indicate thick bedding in the upper part. Claystone may originate from interlayers separating beds.
336 – 348.6 m	Together with GR and FMI evidence, the three recognised lithologies may indicate a probably thick bedded alternation of limestone (mudstone, micrite), beige, limestone (mudstone, micrite) to limestone (saccharoidal), white, and claystone, light greenish grey to beige grey. Claystone, dark reddish brown, found in the 346 m to 348 m sample may be associated with a structure recognised in GR and FMI as indicating a distinct claystone or marl interval from 347.9 m to 348.6 m
348.6 – 368 m	Limestone (mudstone, micrite) to limestone (saccharoidal), beige to white; FMI indicates a massy section with some thin claystone drapes. The few claystone, light greenish grey to beige, may originate from such drapes if not detritus. In the sample from 364 m to 366 m, idiomorph calcite crystals were found which may originate from vug fills
368 – 382 m	Thick bedding is indicated from FMI and GR. Cuttings evidence documents three lithologies: limestone (mudstone, micrite), beige, spotted (small grey nodules), limestone (argillaceous) (mudstone, micrite), limestone (grainstone, sparite), medium grey, with pyrite. The limestone (argillaceous) may represent the interlayers, if they are not formed by marl or claystone which, in this case, would be missing in the sample due to washing out
382 – 396.1 m	Alternation of limestone (mudstone, micrite), beige at the top and increasingly more medium grey towards the bottom and limestone (argillaceous). GR and FMI point to medium- to thick-bedded interval.

3.4.2 Schwarzbach Formation, 396.1 – 406.9 m (10.8 m)

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

The *upper boundary* of the Schwarzbach Formation is set at 396.1 m, at the top of the first thick argillaceous marl interval.

The *lower boundary* is set at 406.9 m, based primarily on FMI (abrupt change to higher resistivity) but also confirmed by GR (decrease in radiation).

There is no formal subdivision of the Schwarzbach Formation.

Lithology

396.1 – 406.9 m Limestone (mudstone, micrite), medium grey, limestone (argillaceous) (mudstone, micrite), medium grey, argillaceous marl, medium grey. FMI and GR suggest that the interval consists of limestone (argillaceous) with three thicker limestone interbeds, one of them at the top of the formation, and a thicker and thinner argillaceous marl interlayer near the top and the base of the formation, respectively

3.4.3 Villigen Formation, 406.9 – 484.02 m (about 77.1 m)

In the Villigen Formation, well bedded micritic limestone prevails. Other forms of limestone are rare. Calcareous or even argillaceous marls are restricted to thin interlayers and some thicker beds.

The *upper boundary* is set at 406.9 m based primarily on FMI (abrupt change to higher resistivity from overlying to underlying sediments), but also confirmed by GR.

The *lower boundary* is set at 484.02 m, at the top of the uppermost thicker (44 cm) argillaceous marl bed, marking the change from a limestone-dominated facies above to a marl-dominated facies below. This delimitation is supported by resistivity logging (FMI, RLA).

Lithostratigraphic subdivision

According to Gygi (e.g. 2000), in the eastern realm to which the ZNO region and consequently MAR1-1 belong, the Villigen Formation is subdivided into three members. These are, from the top, the Wangental, the Küssaburg and the Hornbuck Members. However, this scheme cannot be applied to MAR1-1. On one hand, the limit between the Wangental and Küssaburg Members is expected in the cuttings section, which reaches down to 460 m. This limit between the two lithologically quite similar formations is marked by decimetre thick glauconitic «Knollen Bed». This typical nodular marker bed could not be recognised in MAR1-1. On the other hand, the difference between the Küssaburg and Hornbuck Members is the content of sponges and the thicker marl interbeds of the latter. These two features are found throughout the whole cored section from 460 m to 484.02 m. These 24.02 m correspond exactly to the thickness of the Hornbuck Member in the nearby Benken borehole (Nagra 2001a). However, we refrain from delimiting the Hornbuck Member from the rest of the formation at this artificial and coincidental break.

Lithology (cuttings section)

406.9 – 414.1 m Limestone (mudstone, micrite), medium grey, some limestone (argillaceous) (mudstone, micrite), medium grey, some beds of calcareous marl, medium grey. FMI points to medium-bedded limestone with thin interlayers of calcareous marl, becoming more abundant and possibly thicker in some intervals, especially from 412.00 m to 412.40 m

414.1 – 439.9 m Alternation of limestone (mudstone, micrite), light grey to medium grey, calcareous marl, medium grey to dark grey; grading downwards into limestone (mudstone, micrite), medium grey, and limestone (argillaceous) (mudstone, micrite). FMI documents an increase in layer thickness from thin-bedded at the top to medium-bedded at the bottom (with some thicker interlayers of calcareous marl, medium grey to dark grey)

439.9 – 460 m Gradual change to more argillaceous facies: limestone (argillaceous) (mudstone, micrite) medium grey, and limestone (mudstone, micrite), light grey to medium grey, with more prominent interlayers of calcareous marl, medium grey to dark grey, than in the section above. From 456 m to 460 m, abundant pieces of calcite crystals, up to several millimetres in size are found. These may result from echinoderms or other fossils

Lithology (core section)

460.00 – 461.90 m	Limestone (mudstone and wackestone, micrite), beige grey to light beige, medium-bedded, with interlayers (up to 20 cm) of limestone (argillaceous) (mudstone, micrite), medium grey, sporadic sponges, crinoids and bioturbation. The base of the section is marked by a bed (23 cm) of calcareous marl, medium grey
461.90 – 471.44 m	Limestone (mudstone, micrite), beige grey, mostly bioturbated, with sponges. From 465.46 m to 466.32 m, and from 467.93 m to 468.08 m, sponge bioherms have formed. Echinoderm detritus including crinoids are found at distinct horizons, e.g. at 462.65 m. The section is medium-bedded with several cm thick interlayers of argillaceous to calcareous marl, medium to dark grey, with flat components at the base. Pyrite occurs in the lowermost beds (from 470.10 m to 471.44 m)
471.44 – 475.76 m	In the upper part (from 471.44 m to 472.00 m), calcareous marl, medium grey, fossiliferous: echinoderms, fossil fragments (mm-size), alternating with limestone (mudstone, biomicrite), beige grey, bioturbated In the lower part (from 472.00 m to 475.76 m), limestone (mudstone, micrite), dark beige to light grey, medium-bedded, bioturbated, fossiliferous (mostly fragments (bioclasts), some sponges), with 0.5 to 15 cm thick interlayers of argillaceous to calcareous marl, dark grey, bioclasts, and, from 473.77 m to 473.89 m, with glauconite
475.76 – 478.13 m	Biohermal limestone (packstone and locally, wackestone, biopelmicrite), beige grey to beige and dark beige, locally glauconitic (at 476.15 m), fossiliferous and strongly bioturbated, medium to thick-bedded, with up to 20 cm thick interlayers of argillaceous marl (silty), dark grey to dark greyish brown; glauconite, bioclasts. Sponges are abundant in limestone beds, often forming bioherms. Pellets are prominent at 476.80 m and 477.89 m
478.13 – 482.07 m	Limestone (wackestone, micrite) to limestone (wackestone, pelmicrite), beige grey, bioturbated, with patchy (up to some cm in diameter) tuberous areas (interpreted as micritised sponges), thick-bedded, with up to 20 cm thick interlayers of argillaceous marl (silty), dark grey to dark greyish brown, glauconite, fossiliferous, bioclasts (mainly echinoderms including crinoids). Belemnites are found from 479.21 m to 479.38 m, and at 480.76 m

482.07 – 484.02 m Limestone (wackestone and packstone, biopelmicrite), beige-grey, fossiliferous (mainly echinoderms and sponges), medium-bedded, with interlayers of argillaceous to calcareous marl (silty) (thin section MAR1-1-483.04), dark greyish brown, glauconite, fossiliferous (sponges, echinoderms, bivalves and belemnites e.g. at 482.12 m). Sponges occur as bioherms but also as reworked parts. Additionally, 20 to 40 cm thick dark grey to black silicified beds are found

3.4.4 Wildegg Formation, 484.02 – 501.80 m (17.78 m)

The Wildegg Formation is made up of the Effingen Member and the Birnenstorf Member at its base. The Effingen Member consists of calcareous marl with limestone interbeds. In contrast, the Birnenstorf Member has a similar lithology but is enriched in fossils and usually with a somewhat higher carbonate content. It is usually only a couple of metres thick (e.g. Gygi 2000). For practical reasons, the thin oncolitic-stromatolitic and silty-glaucinitic marl beds at its base are included in the Birnenstorf Member (Jordan & Deplazes 2019).

In MAR1-1, the section is unusually marly. This is also true for the basal Birnenstorf Member, which can be separated solely based on its fossil content. However, sponges that are typical elsewhere for this member do not occur.

The *upper boundary* is set at 484.02 m, at the top of the uppermost thicker (44 cm) argillaceous marl bed, marking the change from limestone-dominated facies with sponges above to a marl-dominated facies below. This delimitation is supported by resistivity logging (FMI, RLA).

The *lower boundary* is set at 501.80 m, at a pronounced hardground. The hardground marks the lowermost occurrence of glauconite of the Wildegg Formation above. This coincides with a marked increase in content of iron-oids below the hardground which form the top of the iron-oolitic Wutach Formation.

3.4.4.1 Effingen Member, 484.02 – 500.69 m (16.67 m)

Usually, the Effingen Member is a predominantly calcareous marl section with beds of limestone (argillaceous). A continuous content of silt and sand (fine-grained) is characteristic of this unit (Deplazes et al. 2013).

In MAR1-1, the marly sections are argillaceous rather than calcareous, while the occurrence of beds of limestone (argillaceous) matches expectations, both in abundance and thickness.

The *upper boundary* is set at 484.02 m, at the top of the uppermost thicker (44 cm) argillaceous marl bed, marking the change from a limestone-dominated facies with sponges above to a marl-dominated facies below. This delimitation is supported by resistivity logging (FMI, RLA).

The *lower boundary* is set at 500.69 m, at the top of a conspicuous nodular glauconitic limestone underlain by argillaceous marl (silty) to sandy marl, with glauconite.

Lithology

484.02 – 487.36 m	Succession of argillaceous marl, dark grey From 484.46 m to 486.02 m, interrupted by a fine-bedded alternation of calcareous marl, partly silty, dark to medium grey, and limestone (argillaceous) (mudstone, micrite), beige grey to dark grey (cloudy), bioturbated, some peloids, and, from 484.02 m to 484.64 m, a layer with abundant burrows
487.36 – 490.36 m	Medium- to thick-bedded alternation of limestone (argillaceous) (mudstone, micrite), beige grey to dark grey (cloudy), bioturbated, and calcareous marl, dark to medium grey. Pyrite is found in both lithologies. Below a bored surface at 489.74 m, bioclastic layers (mainly echinoderms) are common until 490.36 m
490.36 – 491.72 m	Argillaceous to calcareous marl, dark grey, with pyrite and burrows, slightly fossiliferous, belemnites at 490.43 m and at 491.00 m, pellets at 491.35 m
491.72 – 494.34 m	Limestone (argillaceous) (mudstone and wackestone, biomicrite), beige grey, locally medium grey, bioturbated, thick-bedded, with interlayers (up to 27 cm) of calcareous marl to argillaceous marl, dark grey, bioclastic, with glauconite (abundant from 492.84 m to 493.08 m), pyrite in both lithologies, ammonite at 494.10 m. The surfaces of limestone beds are often bored At the base, from 494.17 m to 494.34 m, firmground with abundant ammonites (e.g. at 494.27 m), belemnites and lithoclasts. The matrix is formed by calcareous marl, dark grey, bioclastic
494.34 – 497.15 m	Alternation of calcareous and argillaceous marl, light grey and dark grey, respectively, bioclasts originating mainly from echinoderms, bioturbated From 496.36 m to 496.72 m, bed of limestone (argillaceous) grading into limestone (mudstone), medium grey, bioturbated, pyrite in both lithologies, followed by two thin beds of argillaceous marl and calcareous marl
497.15 – 500.19 m	Argillaceous marl, dark grey, with thin beds of limestone (silty, argillaceous) (mudstone, micrite), light grey, bioclasts (in the upper part, from 497.15 m to 497.50 m, mainly echinoderms), bioturbated, some belemnites At the base, from 499.97 m to 500.19 m, two beds of limestone (argillaceous) (mudstone, micrite), light grey, separated by calcareous marl, dark grey
500.19 – 500.69 m	Argillaceous marl to, locally, calcareous marl (silty), dark grey, bioclasts, fossiliferous: belemnites, crinoids

3.4.4.2 Birmenstorf Member and «Glaukonitsandmergel Bed» sensu Gygi (1977, 2000, 2012), 500.69 – 501.80 m (1.11 m)

From its type locality in the Aargau area towards the ZNO region, the Birmenstorf Member is gradually replaced, from its base upwards, 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-ooids in variable proportions.

In MAR1-1, all units seem to be present, but an unambiguous distinction between them is not possible without further analysis. The following description is therefore purely lithological.

The *upper boundary* is set at 500.69 m, at the top of a conspicuous nodular glauconitic limestone underlain by argillaceous marl (silty) to sandy marl, with glauconite.

The *lower boundary* is set at 501.80 m, at the base of the lowermost occurrence of glauconite and above a conspicuous hardground at the top of a limestone (iron-oolitic).

Lithology

500.69 – 501.57 m	At the top, from 500.69 m to 500.77 m, nodular bed of limestone (argillaceous, silty) (wackestone, micrite), light grey, distinctly rich in glauconite
	In the middle, from 500.77 m to 501.49 m, argillaceous marl (silty) to sandy marl (at the base), dark grey, glauconite, belemnites, echinoderms, with oncoids from 500.90 m to 501.49 m. The thin section MAR1-1-501.51 documents the transition from this to the next layer below. The interval from 500.69 m to 501.49 m correlates closest to what is known as the «condensed Birmenstorf Member» (sensu Gygi 2000, <i>cf.</i> Gygi 2012, Figure 8.3)
	At the base, from 501.49 m to 501.57 m, oncolitic limestone, light grey, glauconite. The oncoids have formed around lithoclasts (some of them iron-oolitic) and bioclasts (mainly ammonites). Ammonites are found, e.g. at 501.49 m, 501.50 m and 501.52 m
	This interval, from 501.49 m to 501.57 m, correlates closest to what is known as the «Mumienkalk Bed» (<i>cf.</i> Gygi 2012, Figure 8.3)
501.57 – 501.80 m	Argillaceous marl (silty), with glauconite, oncoids and belemnites (e.g. at 501.60 m) continuing downwards into sandy marl with glauconite and iron-ooids (thin section MAR1-1-501.62). The hardground at the base is overlain by reworked sediments of the underlying strata
	The upper and lower part of this interval correlate closest to what is known as the «Mumienmergel Bed» and «Glaukonitsandmergel Bed», respectively (<i>cf.</i> Gygi 2012, Figure 8.3)

3.5 Dogger Group

3.5.1 Wutach Formation, 501.80 – 505.75 m (3.95 m)

The Wutach Formation is a highly condensed succession dominated by iron-oolites and enriched 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 MAR1-1, a subdivision into two parts can be identified: the upper part (from 501.80 m to 504.15 m) is characterised by a sequence of hardgrounds formed predominantly by iron-oolites and limestone (iron-oolitic). In the lower part (from 504.15 m to 505.75 m), marl (iron-oolitic) prevails.

The *upper boundary* is set at 501.80 m, at the base of the lowermost occurrence of glauconite and above a conspicuous hardground at the top of a thicker bed (27 cm) of limestone (iron-oolitic).

The *lower boundary* is set at 505.75 m, at the top of a non-iron-oolitic, fossiliferous limestone (coquina). Some iron-oolites are also found below this 8 cm thick limestone layer in the underlying argillaceous marl (silty) interval.

Lithology

501.80 – 504.15 m	Succession of hardgrounds:
	From 501.80 m to 502.17 m, limestone (iron-oolitic) (grainstone and boundstone, biomicrite to biosparite), medium light grey, bioclasts, with a hardground at the top
	From 502.17 m to 502.30 m, iron-oolite, dark reddish brown, ammonites, bivalves, bioclasts, with a hardground at the top
	From 502.40 m to 502.87 m, marl (iron-oolitic), medium grey and reddish brown, locally intraclasts, ammonites, belemnites, bivalves, echinoderms, bioclasts (thin sections MAR1-1-502.33 and MAR1-1-502.81)
	From 502.87 m to 503.39 m, iron-oolite, dark reddish brown, ammonites, belemnites, bivalves, echinoderms, bioclasts, with a hardground at the top
	From 503.39 m to 503.53 m, limestone (iron-oolitic), medium light grey and dark reddish brown, belemnites, bivalves, echinoderms, bioclasts
	From 503.53 m to 503.76 m, marl (iron-oolitic) to limestone (iron-oolitic, silty) (grainstone and boundstone, biosparite), dark greyish brown and reddish brown, locally lithoclasts with a hardground at the top, belemnites, echinoderms, bivalves, bioclasts (thin section MAR1-1-503.60)

From 503.76 m to 503.93 m, limestone (iron-oolitic) (grainstone and boundstone, biomicrite to biosparite), medium light grey and dark reddish brown, belemnites, echinoderms, bivalves, bioclasts

From 503.93 m to 504.15 m, iron-oolite, dark reddish brown, ammonites, belemnites, echinoderms, bivalves, bioclasts

504.15 – 505.75 m Marl (iron-oolitic), dark reddish brown and dark greyish brown, ammonites, belemnites, echinoderms, bivalves, gastropods, bioclasts with a hardground at the top. Iron-oolites make up to 50 vol.-% but become less abundant below 504.72 m

3.5.2 Variansmergel Formation, 505.75 – 517.43 m (11.68 m)

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 MAR1-1, three sections can be distinguished: the upper part is slightly less silty and more argillaceous than the middle and lower parts. Additionally, the upper part is characterised by quite abundant limestone (argillaceous, silty) to calcareous marl (silty) interlayers, often related to coquinas. The lower part differs from the middle part by an increase in fossil abundance and two thin bioclastic limestone layers.

The *upper boundary* is set at 505.75 m, at the top of a non-iron-oolitic, fossiliferous limestone (coquina). Some iron-oolites are also found in the underlying marly layer (from 505.83 m to 506.16 m) of the Variansmergel Formation.

The *lower boundary* is set, in analogy to the Benken borehole (Nagra 2001a and b), at 517.43 m below a gradual transition from a distinctly more calcareous and fossiliferous to a poorly fossiliferous marl.

Lithology

505.75 – 509.80 m Argillaceous marl (silty) to claystone (silty, calcareous) and silty claystone (calcareous), bioarenitic, dark grey, pyrite, increasingly micaceous with depth, some siderite nodules, abundant single shells of bivalves and brachiopods, disperse and in coquinas, echinoderms, belemnites, bioturbated, burrows (in the claystone [silty, calcareous])

From 507.10 m to 508.03 m, with interbeds (up to 20 cm) of limestone (argillaceous, silty) (wackestone and packstone, biomicrite) to calcareous marl (silty), medium grey, pyrite, fossiliferous (often coquinas), including echinoderms, bivalves and brachiopods (thin section MAR1-1-505.85)

509.80 – 515.09 m	Silty to bioclastic sandy marl to silty claystone (calcareous), dark grey, mica, pyrite, siderite nodules (mm to some cm), fossiliferous, mostly small to medium sized bivalves (mm to cm) and other small shell fragments, ammonite (at 511.90 m), large bivalve (<i>Goniomya</i>) at 512.84 m, bioturbated, thin bedded to laminated
515.09 – 517.43 m	Bioclastic sandy marl, dark grey, mica, pyrite, siderite nodules, fossiliferous (belemnites, bivalves, echinoderms, bioclasts), locally bioturbated with nodular interbeds (up to 12 cm thick) of bioclastic limestone (sandy) (grainstone, biopelsparite)

3.5.3 «Parkinsoni-Württembergica-Schichten», 517.43 m – 545.93 m (28.50 m)

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 MAR1-1, the main lithology throughout the entire unit is a silty claystone (calcareous), micaceous, with partly bioclastic (and thus marly) sandy intervals. In the lower part, around 1.2 m above the base, an iron-oolitic, fossiliferous interval can be observed.

The *upper boundary* is set, in analogy to the Benken borehole (Nagra 2001a and b), at 517.43 m below a gradual transition from a distinctly more calcareous and fossiliferous to a poorly fossiliferous marl.

The *lower boundary* is set at 545.93 m, at the top of a 12 cm thick iron-oolitic hardground, underlain by limestone (iron-oolitic). The iron-oolites including the limestone lithoclast with iron-oolids found above this hardground are suggested to be reworked from the underlying sediments.

Lithostratigraphic subdivision

Traditionally, the informal «Parkinsoni-Württembergica-Schichten» are subdivided by an iron-oolite bed, the «Parkinsoni-Oolith», into «Württembergica-Schichten» (upper part) and «Parkinsoni-Schichten» (lower part). The iron-oolite beds from 543.73 m to 544.52 m may represent the «Parkinsoni-Oolith». This assumption is supported by ammonite determinations (*cf.* Dossier IV). Consequently, the main part of the section found here will correspond to the informal «Württembergica-Schichten»:

517.43 – 543.39 m	«Württembergica-Schichten»
543.39 – 545.93 m	«Parkinsoni-Schichten» including «Parkinsoni-Oolith» from 543.73 m to 544.52 m

Lithology

517.43 – 534.81 m	Silty claystone (calcareous) and calcareous siltstone (argillaceous), dark grey, mica, pyrite (disperse and in nodules), siderite nodules (mm to some cm), quite numerous scattered belemnites, ammonite (at 530.20 m), some larger bivalves (e.g. at 517.86 m and 522.28 m), echinoderms, driftwood (at 518.78 m), some bioclastic layers and some nodular interlayers (up to 25 cm thick) of bioclastic limestone (sandy) (grainstone, biopelsparite) to calcareous marl (thin section MAR1-1-526.04) and bioclastic sandy marl, beige grey with bioclasts
534.81 – 537.19 m	Bioclastic sandy marl, dark grey, mica, pyrite (disperse and in nodules), siderite nodules, very abundant fossil detritus (> 2 mm, mostly echinoderms) and some scattered macrofossils (ammonite at 537.10 m, belemnites, bivalves, e.g. large <i>Pleuromya</i> at 536.80 m)
537.19 – 543.39 m	Silty claystone (calcareous), dark grey, mica, pyrite (disperse, in nodules and bed-like at 542.77 m), siderite nodules, generally some macrofossils (but several belemnites from 542.77 m to 543.39 m), fossil detritus (rare) and burrows, with two sections (from 539.15 m to 539.60 m and from 540.24 m to 540.40 m) rich in fossil detritus (mostly echinoderms) and bioturbated, resulting locally in a calcareous marl (silty)
543.39 – 544.52 m	Heterogeneous succession comprising: From 543.39 m to 543.73 m, silty claystone, dark grey, mica, with scattered chamositic iron-oids, fossiliferous (echinoderms, bivalves, belemnites and, at 543.61 m, ammonite) From 543.73 m to 543.84 m, marl (iron-oolitic), dark grey and dark reddish brown, very fossiliferous (echinoderms, bivalves, belemnites) From 543.84 m to 544.36 m, silty claystone with iron-oids, very fossiliferous (echinoderms, bivalves, belemnites) From 544.36 m to 544.52 m (offside of yellow reference line down to 544.72 m), nodular limestone (iron-oolitic, silty) (grainstone, biosparite), fossiliferous (echinoderms, bivalves, belemnites, and ammonites at 544.29 m and 544.38 m,); hardground at the top, erosional base
544.52 – 545.93 m	Silty claystone to claystone (silty), medium to dark grey, mica, belemnites From 545.15 m to 545.93 m, silty claystone, medium grey, with iron-oids and belemnites, and, from 545.76 m to 545.79 m, a limestone lithoclast, subrounded, with iron-oids, probably reworked from the underlying layers

3.5.4 «Humphriesioolith Formation», 545.93 – 555.23 m (9.30 m)

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

The *upper boundary* is set at 545.93 m, at the top of a 12 cm thick iron-oolitic hardground, underlain by limestone (iron-oolitic). The iron-oolites including the limestone lithoclast with iron-ooids found above this hardground are suggested to be reworked from the underlying sediments.

The *lower boundary* is set at 555.23 m, at the base of a limestone (iron-oolitic) which represents the lowermost occurrence of iron-ooids. The iron-ooids at 556.55 m are believed to be part of the underlying Wedelsandstein Formation.

Lithostratigraphic subdivision

The «Humphriesioolith Formation» can be divided into three sub-units (Jordan & Deplazes 2019) by the rather sharp onset and offset of iron-ooids. The following subdivision into an upper and lower iron-oolitic interval, sandwiching a marly interval, can be correlated well to the corresponding strata of the nearby Benken and Trüllikon-1-1 boreholes (Nagra 2001a, Bläsi et al. 2013, Schwarz et al. 2021):

545.93 – 550.66 m	Upper iron-oolitic interval (4.73 m)
550.66 – 554.46 m	Marly interval with limestone beds without iron-ooids (3.80 m)
554.46 – 555.23 m	Lower iron-oolitic interval (0.77 m)

Lithology

545.93 – 547.58 m	Iron-oolitic succession comprising: From 545.93 m to 546.50 m, iron-oolite grading into limestone (iron-oolitic) (thin section MAR1-1-546.02) and marl (iron-oolitic), dark grey and dark reddish brown, iron-ooids up to 1 mm, moderately fossiliferous (belemnites, echinoderms, bivalves, ammonite at 546.40 m) From 546.50 m to 547.06 m, rather massive iron-oolite to limestone (iron-oolitic), dark reddish brown, iron-ooids up to 1 mm, large fossils (oysters, belemnites) in the uppermost part, rest moderately fossiliferous (echinoderms, bivalves) (thin section MAR1-1-546.90) From 547.06 m to 547.58 m, argillaceous marl, with iron-ooids grading into marl (iron-oolitic), dark grey and dark reddish brown, iron-ooids up to 1 mm, abundant fossils include bivalves (some with iron-oolite filling), gastropods, belemnites and others
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- 547.58 – 549.81 m Limestone (iron-oolitic) succession comprising:
- From 547.58 m to 548.02 m, below an erosional surface, bioclastic limestone (iron-oolitic, silty) (packstone and grainstone, biomicrite and biosparite), medium to light grey, iron-oolids rather small (< 0.1 mm), very fossiliferous including ammonites (e.g. at 547.66 m), belemnites, gastropods, large oysters and other bivalves (some with iron-oolitic filling) and brachiopods (thin section MAR1-1-547.75), geopetal filling at 547.83 m
- From 548.02 m to 548.42 m, several hardgrounds, argillaceous marl (silty, iron-oolitic to a varying extent), medium grey, mainly with fossil detritus, with irregular interbeds of limestone (iron-oolitic) to iron-oolite, iron-oolids rather small (< 0.1 mm), fossiliferous, including ammonites which are abundant from 548.19 m to 548.35 m and from 547.66 m to 549.78 m, and very large belemnite (diameter > 3.5 cm) at 548.04 m
- From 548.42 m to 549.40 m, succession of three beds of limestone (iron-oolitic to a varying extent), light grey to reddish brown, fossiliferous, separated by thin layers of argillaceous marl (silty), with geopetal filling at 548.51 m
- From 549.40 m to 549.81 m, calcareous marl, dark beige to reddish brown, small iron-oolids, fossiliferous, including ammonites and belemnites (very strongly bored specimen at 549.71 m), with, at the base, limestone (silty, argillaceous), slightly iron-oolitic, light grey, with geopetal filling at 549.68 m
- 549.81 – 550.66 m Argillaceous marl (silty to sandy), medium grey with thin (< 10 cm) interbeds of calcareous marl (silty), light grey, limonitic components, small iron-oolids in both marl and interbeds, increasing abundance of bioclasts and macrofossils with depth, including belemnites, bivalves, echinoderms and brachiopods (thin section MAR1-1-550.47)
- 550.66 – 554.46 m Alternation of argillaceous marl (sandy), dark grey and calcareous marl (sandy), medium grey with interbeds of mostly very thin, in the lower part slightly thicker, layer of sandy limestone (argillaceous) (packstone, biomicrite) to, locally, limestone (sandy, argillaceous) (wackestone, biomicrite), light to medium grey
- All lithologies micaceous and fossiliferous, including echinoderms (abundant above 551.73 m), belemnites (missing in the middle part from 552.32 m to 553.44 m), oysters (abundant below 553.44 m) other bivalves and bioclasts, in the lowermost bed with some iron-oolids
- 554.46 – 555.23 m Succession with iron-oolids comprising:
- From 554.46 m to 554.60 m, sandy limestone (argillaceous, iron-oolitic), medium grey
- From 554.60 m to 554.85 m, argillaceous marl (silty, iron-oolitic), dark grey to dark reddish brown, mica, oyster
- From 554.85 m to 554.98 m, calcareous marl (silty, iron-oolitic), medium grey to reddish grey
- From 554.98 m to 555.12 m, argillaceous marl (silty, iron-oolitic), dark grey to dark reddish brown, with an ammonite at 555.03 m

From 555.12 m to 555.23 m, limestone (iron-oolitic, silty), beige to reddish brown, limonitic components, lithoclasts, echinoderms, with an ammonite at 555.10 m (thin section MAR1-1-555.12)

3.5.5 Wedelsandstein Formation, 555.23 – 589.17 m (33.94 m)

For the Wedelsandstein Formation, a considerable portion of quartz sand and bioclasts and a sparse content of macrofossils are diagnostic and separate it from the formations above and below (Jordan & Deplazes 2019). The main body of the formation is formed by silty to sandy marl with interbeds of bioclasts and sandy limestone.

In MAR1-1, the upper part (from 555.23 m to 566.05 m) of the Wedelsandstein Formation has a higher carbonate content and a lower sand content than the lower part. The background lithology of the upper part is silty marl and interlayers consist of limestone (mostly argillaceous and silty to sandy) and, subordinately, claystone (silty, calcareous). In the lower part, argillaceous siltstone to argillaceous sandstone (both mostly calcareous) dominate. The interbeds are predominantly sandy limestone and, subordinately, calcareous marl (sandy). The «Sowerbyi-Oolith», usually found at the base of the Wedelsandstein Formation, is missing in MAR1-1.

The *upper boundary* is set at 555.23 m, at the base of a limestone (iron-oolitic) which represents the lowermost occurrence of iron-oooids of the «Humphriesiolith Formation», overlying calcareous marl (silty), medium grey.

The *lower boundary* is set at 589.17 m, at the top of the uppermost iron-oolitic, calcareous lithoclast horizon, found at the top of the «Murchisonae-Oolith Formation», similar to the Benken borehole (Bläsi et al. 2013).

Lithology

555.23 – 558.78 m	Succession of claystone (slightly silty to silty, calcareous), dark grey to black, mica, bioclasts, transitional change downwards into argillaceous sandstone (calcareous), dark grey, mica, partly fossiliferous (bivalves [abundant at 556.84 m; thin section MAR1-1-556.84], echinoderms and brachiopods [thin section MAR1-1-558.47]), bioclasts, bioturbated, and sandy limestone (argillaceous), medium grey. Some iron-oooids at 556.55 m
558.78 – 561.85 m	Silty marl, dark grey, mica, burrows, grading downwards into claystone (silty, calcareous), dark grey, mica, pyrite (nodule at 560.40 m), bivalves, burrows, and back into silty marl, dark grey, mica, bivalves, ammonite (at 561.27 m), burrows
561.85 – 566.05 m	Alternation of: • thicker sections of predominantly silty marl mostly poor in fossils, and • thinner sections of mostly fossiliferous limestone In the marly sections, locally sandy marl, siltstone (calcareous, argillaceous) and sandstone (calcareous, argillaceous) occur. Between 561.98 m and 565.11 m, siderite nodules are found The fossiliferous limestone ranges between limestone (sandy, argillaceous, bioclastic) and bioclastic limestone (sandy, argillaceous) (grain-

stone, biosparite), echinoderms, bivalves, bryozoans, bioclasts, bioturbated (thin sections MAR1-1-561.96 and MAR1-1-565.73)

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|-------------------|--|
| 566.05 – 569.99 m | <p>Alternation of:</p> <ul style="list-style-type: none"> • thicker sections of predominantly argillaceous sandstone (calcareous), dark grey, mica, fossiliferous (bivalves, echinoderms, bioclasts), flaserly bedded, and • sections with thin to lenticular beds of calcareous marl (sandy) and calcareous sandstone (argillaceous), fossiliferous (bivalves, serpulids), lenticularly to flaserly bedded (thin section MAR1-1-567.82) |
| 569.99 – 575.07 m | <p>Alternation of:</p> <ul style="list-style-type: none"> • thicker sections of predominantly argillaceous sandstone (calcareous), and argillaceous siltstone (calcareous), dark grey, mica, locally pyrite, fossiliferous (bivalves, echinoderms, bioclasts), flaserly bedded (thin section MAR1-1-571.98), and • thinner sections with thin to lenticular beds of sandy limestone (grainstone, biosparite), fossiliferous (pellets, echinoderms, bivalves), flaser-bedded, thin section MAR1-1-574.66) |
| 575.07 – 579.35 m | <p>Alternation of:</p> <ul style="list-style-type: none"> • thicker sections of predominantly argillaceous sandstone to argillaceous siltstone, medium grey, mica, pyrite, some siderite nodules, bioclasts including echinoderms, below 577.01 m with burrows, flaser- to lenticularly bedded, and • beds, partly nodular, of sandy limestone (grainstone, biosparite), light to medium grey, very small bioclasts, bioturbated, irregularly to lenticularly bedded |
| 579.35 – 589.17 m | <p>Alternation (with mostly gradual boundaries) of:</p> <ul style="list-style-type: none"> • argillaceous sandstone (calcareous) and argillaceous siltstone (calcareous), medium to dark grey, locally also calcareous siltstone (argillaceous) and calcareous sandstone (argillaceous), dark to medium grey, mica, pyrite, siderite nodules, mostly small-scale scattered bioclasts (partly organised in coquinas), echinoderms, bivalves, belemnite (at 584.40 m), burrows (<i>Zoophycos</i> type), bioturbated, flaser- to lenticular-bedded, and • sandy limestone to silty limestone (bioclastic), bivalves, echinoderms (thin section MAR1-1-582.17) and • calcareous marl (sandy to silty), to sandy marl, light to medium grey (thin section MAR1-1-583.88) |

3.5.6 «Murchisonae-Oolith Formation», 589.17 – 590.35 m (1.18 m)

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

In MAR1-1, the «Murchisonae-Oolith Formation» is composed of an argillaceous siltstone below and above a thin fossiliferous hardground with iron-ooids.

The *upper boundary* is set at 589.17 m, at the top of the uppermost iron-oolitic, calcareous lithoclast horizon, found at the top of the «Murchisonae-Oolith Formation», similar to the Benken borehole (Bläsi et al. 2013).

The *lower boundary* is set at 590.35 m, at the base of the lower iron-oolitic calcareous lithoclast hardground. Setting the boundary is strongly corroborated by GR and FMI logs.

Lithology

589.17 – 589.24 m	Argillaceous siltstone, medium to dark grey, with obviously reworked, irregularly shaped lithoclasts of limestone (iron-oolitic), iron-ooids, fossiliferous (belemnites, ammonite) (thin section MAR1-1-589.23)
589.24 – 589.38 m	Limestone (sandy), light grey, fractured, the base is formed by a wavy encrusted firmground (thin section MAR1-1-589.23 including transition from overlying section)
589.38 – 590.26 m	Argillaceous siltstone, dark grey, bituminous, burrows, wavy bedded, from 589.97 m to 589.99 m, firmground
590.26 – 590.35 m	Hardground formed by encrusted calcareous lithoclasts in a matrix of silty marl (iron-oolitic) to iron-oolite (thin section MAR1-1-590.32)

3.5.7 Opalinus Clay, 590.35 – 705.40 m (115.05 m)

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

The findings in MAR1-1 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 590.35 m, at the base of the lower iron-oolitic calcareous lithoclast hardground of the «Murchisonae-Oolith Formation».

The *lower boundary* is set at 705.40 m, at the top of the uppermost calcareous marl of the Staffelegg Formation. It is overlain by a 55 cm thick, very fossiliferous (mainly ammonites) transition zone from claystone (silty, calcareous), dark grey, to silty claystone (calcareous), medium grey.

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:

590.35 – 626.41 m	«Sub-unit with silty calcareous beds» (36.06 m)
626.41 – 642.77 m	«Upper silty sub-unit» (16.36 m)

642.77 – 688.88 m «Mixed clay-silt-carbonate sub-unit» (46.11 m)

688.88 – 705.40 m «Clay-rich sub-unit» (16.52 m)

Lithology

«Sub-unit with silty calcareous beds», 590.35 – 626.41 m (36.06 m)

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

590.35 – 593.36 m Claystone (calcareous), dark grey to black, bituminous flakes, mica (abundant, fine-grained), pyrite (locally as nodules), some small bivalves (a single larger bivalve at 591.28 m), some scattered burrows, with thin (up to 2 cm thick) lenticular to nodular interlayers of calcareous marl, siderite, light grey

593.36 – 597.33 m Silty claystone (calcareous), dark grey, mica, pyrite, little to no bioclasts (thin section MAR1-1-594.13), moderate flaser bedding, laminated, alternating with siltstone (calcareous, argillaceous), medium grey, mica, pyrite, bioclasts, moderate flaser-bedding, and thin interlayers and lenses of calcareous marl (sandy), bioclasts, to limestone (argillaceous), locally siderite and pyrite

597.33 – 600.35 m Silty claystone (calcareous), dark grey, mica (abundant, fine-grained), pyrite (as nodules and strings abundant from 598.20 m to 599.47 m), two ammonites from 597.85 m to 598.09 m, otherwise macrofossils are virtually absent, burrows, bituminous flakes

600.35 – 603.41 m In the uppermost part (from 600.35 m to 600.52 m), bored surface at the top of calcareous marl, with reworked lithoclasts (partly rounded) from underlying calcareous hardground and fossils including belemnites and bioclasts, giving the rock a conglomerate-like appearance. The marl is underlain (from 600.52 m to 600.62 m) by a hardground formed by limestone (mudstone, micrite), light grey, siderite. The thin section MAR1-1-600.50 covers the transition between marl and limestone

From 600.62 m to 603.41 m, silty claystone (calcareous, sandy), dark grey, mica (abundant, fine-grained), pyrite (including nodules and strings) (thin section MAR1-1-602.01), with abundant, very fine, sand flasers and lenses, medium grey, often associated with fine-grained (mm) bioclasts, partly pyritised, burrows; single ammonite at 603.08 m

603.41 – 609.25 m At the top (from 603.41 m to 603.88 m), limestone (silty to sandy) (wackestone, biomicrite), beige grey, base erosional, nodular, bioclasts, in the lower part limestone (silty), siderite, fossiliferous (bivalves, echi-noderms), bioturbated (thin section MAR1-1-603.69)

From 603.88 m to 609.25 m, claystone (calcareous), dark grey to black, partly bituminous, mica (abundant, fine-grained), pyrite (including nodules and strings), some macrofossils (ammonite at 607.19 m, bivalves, crustacean at 606.89 m), very finely laminated; from 607.73 m

	to 607.80 m, interlayer of argillaceous marl (silty) to silty claystone (calcareous), dark and light grey, flaser bedding
609.25– 614.94 m	At the top (from 609.25 m to 609.74 m), two undulating to nodular hardgrounds separated by thin layers of argillaceous marl, beige grey to dark beige; the upper bed is a limestone (mudstone, pelmicrite), fossiliferous (ammonite at 609.34 m), partly bioturbated (thin section MAR1-1-609.27), the lower is a limestone (iron-oolitic where the original iron composition was replaced by calcite; thin section MAR1-1-609.64) to limestone (argillaceous) (packstone and grainstone, biopelmicrite to biosparite), beige grey, with abundant litho- and bioclasts including ammonites (e.g. at 609.69 m), belemnites, bivalves, echinoderms, bivalves, giving the rock a conglomerate-like appearance From 609.74 to 614.94 m, alternation of silty claystone, dark grey, mica, pyrite, siderite nodules, bituminous flakes (down to 614.05 m); with thin lenses of siltstone (calcareous) to calcareous siltstone, light grey, ripples, lenticular- to flaser-bedding, and claystone (calcareous), dark grey to black, mica, pyrite, laminated; in the lower part, from 614.05 m to 614.19 m, bioclastic, nodular layer, and, from 614.19 m to 614.94 m, sandy marl, fossiliferous (echinoderms, bivalves), bioturbated (thin section MAR1-1-614.75), contorted bedding
614.94 – 616.58 m	Claystone (silty, calcareous), dark grey, mica, siderite nodules, bioturbated, contorted bedding
616.58 – 622.43 m	At the top (from 616.58 m to 616.66 m), thin bed of limestone (mudstone, pelmicrite), beige grey, nodular. It is followed by an alternation of silty claystone, dark grey, mica, pyrite, siderite nodules, with thin lenses of siltstone (calcareous), to calcareous siltstone, light grey, ripples, lenticular- to flaser-bedding, and claystone (calcareous), dark grey to black, mica, pyrite, bituminous flakes, laminated. From 618.12 m to 618.30 m, calcareous marl (silty), formed by four layers of small siderite nodules to thin nodular layers of siderite, light grey, in silty claystone matrix, dark grey
622.43 – 626.41 m	At the top (from 622.43 m to 622.54 m), nodular layer of silty limestone, light grey, followed by sandy marl and sandy to silty claystone, dark grey, mica, crinoids, bivalves, belemnites, bioclasts (thin section MAR1-1-623.07), with interlayer (from 623.83 m to 623.92 m) of limestone (sandy, argillaceous), dark grey. At the base (from 625.56 m to 626.41 m), calcareous marl, dark grey, mica

«Upper silty sub-unit», 626.41 – 642.77 m (16.36 m)

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

626.41 – 629.27 m	Silty claystone, dark grey, mica, crinoids, bioclasts, flaser-bedding and ripples, including a firmground from 626.96 m to 627.00 m In the lower part (from 628.49 m to 628.60 m and from 629.00 m to 629.27 m), two beds of calcareous marl (slightly silty to sandy), medium
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	grey, fossiliferous (crinoids, bivalves), separated by silty claystone, dark grey. The lower bed, a hardground, consists of suspected microbial mats and encrusted lithoclasts (from 629.00 m to 629.24 m) and a sedimentary conglomerate (from 629.24 m to 629.27 m) formed by rounded lithoclasts (1 to 5 cm) of calcareous marl in a marly matrix rich in crinoids and pyrite (thin section MAR1-1-629.24)
629.27 – 631.30 m	Silty claystone, dark grey to black, mica, pyrite, siderite nodules, bituminous flakes, some belemnites (e.g. at 630.20 m) and bivalves, burrows, with very thin (mm) lenses of calcareous siltstone, predominately laminated
631.30 – 637.20 m	Sandy claystone (calcareous), dark grey, mica, with thin (cm) siltstone to sandstone lenses, partly bioclastic; towards the base, layers to lenses of calcareous marl (silty), light grey, flaser to lenticular bedding, locally contorted bedding and, at 636.00 m, load cast
637.20 – 642.77 m	Alternation of silty claystone, dark grey, mica, mostly laminated and silty claystone (calcareous), dark grey to black, mica, siderite nodules, in the lower part also bituminous flakes, laminated

«Mixed clay-silt-carbonate sub-unit», 642.77 – 688.88 m (46.11 m)

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

642.77 – 656.37 m	Silty claystone (calcareous), dark grey to black, mica (locally very abundant), siderite, bituminous flakes, laminated, with thin lenses to nodular beds of silty claystone to siltstone (argillaceous), light grey, mica, and interbeds of silty claystone, dark grey, mica, pyrite, mostly laminated. Fossils (mostly bivalves and bioclasts) are concentrated in distinct layers, e.g. from 644.87 m to 645.09 m or from 652.05 m to 652.41 m. The base from 655.92 m to 656.37 m shows a higher abundance of crinoid detritus
656.37 – 665.48 m	Rather uniform succession composed of silty claystone (calcareous), dark grey to black, mica, pyrite (disperse, in nodules and in fine layers, e.g. at 659.28 m, 662.40 m and 664.47 m), siderite, laminated (thin section MAR1-1-662.11), with thin lenses to nodular, partly bioclastic beds of silty claystone to siltstone (argillaceous, calcareous), light grey, and interbeds of silty claystone, dark grey, mica, pyrite, mostly laminated
665.48 – 677.85 m	Continuation of the uniform succession but here slightly more fossiliferous (mainly bivalves, some ammonites): silty claystone and silty claystone (calcareous), dark grey, mica, pyrite (down to 669.32 m), very abundant siderite, fossiliferous, ammonite at 669.07 m
677.85 – 682.20 m	Claystone (silty, calcareous), dark grey, mica, siderite, pyrite, some macrofossils (bivalves from 677.85 m to 679.04 m, ammonite at 677.95 m), bioclasts (enriched at the basal layer from 681.96 m to 682.20 m)

682.20 – 688.88 m Silty claystone (calcareous), dark grey, mica, siderite nodules abundant, pyrite (disperse and in nodules), bioclasts in the upper part (from 682.20 m to 685.15 m), laminated, from 686.48 m to 688.88 m lenticularly bedded

«Clay-rich sub-unit», 688.88 – 705.40 m (16.52 m)

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

688.88 – 705.40 m Claystone (calcareous) to claystone (silty, calcareous), claystone (silty) and silty claystone (calcareous), dark grey, mica, pyrite, rich in ammonites and thin-shelled bivalves and burrows on bedding planes (fucoids)

3.6 Lias Group

3.6.1 Staffelegg Formation, 705.40 – 747.83 m (42.43 m)

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 705.40 m, at the top of a calcareous marl, light grey, which is overlain by a transition zone from claystone (silty, calcareous) to silty claystone (calcareous), medium grey, to, dark grey, of basal Opalinus Clay. The delimitation is based primarily on the offset of silt, a decrease in clay minerals (reflected also in GR record) and a significant increase in carbonate content (all in an upward direction).

The *lower boundary* is set at 747.83 m, at an erosional surface, separating bituminous shale from dolomitic marl.

3.6.1.1 Gross Wolf Member, 705.40 – 712.10 m (6.70 m)

In MAR1-1, the Gross Wolf Member (Reisdorf et al. 2011) can be separated in two parts, both very fossiliferous. The upper part is an alternation (from 705.40 m to 706.74 m) of nodular beds of limestone (argillaceous), calcareous marl and interlayers of argillaceous to calcareous marl underlain by a thicker section of argillaceous marl (from 706.74 m to 707.56 m). The lower part (from 707.56 m to 712.10 m) represents the typical "Jurensismergel" facies with nodular beds of calcareous marl separated by relatively thick interlayers of argillaceous marl.

The *upper boundary* is set at 705.40 m, at the top of a calcareous marl, light grey, which is overlain by a transition zone from claystone (silty, calcareous) to silty claystone (calcareous), medium grey, to, dark grey, of basal Opalinus Clay. The delimitation is based primarily on the offset of silt, a decrease in clay minerals (reflected also in GR record) and a significant increase in carbonate content (all in an upward direction).

The *lower boundary* is set at 712.10 m, at the base of a horizon with large belemnites characteristic of the basal Gross Wolf Member. The boundary coincides with a change to darker colours, the onset of bitumen content and a significant decrease in belemnite abundance, all indicative for the underlying Rietheim Member.

Lithology

705.40 – 707.56 m	Alternation of limestone (argillaceous) (mudstone, biomicrite) to calcareous marl, medium grey, locally also limestone (packstone, biosparite; thin section MAR1-1-705.66), nodular, and argillaceous to calcareous marl (slightly silty), dark grey, fossiliferous (mainly detritus, fine-shelled bivalves, ammonites, e.g. at 705.78 m and belemnites), burrows, fine-bedded and, in the lower part (from 706.74 m to 707.56 m), an argillaceous marl (silty), bioturbated
707.56 – 712.10 m	Argillaceous marl (silty), medium to dark grey, with nodules and nodular beds of calcareous marl to limestone (wackestone, biomicrite, thin section MAR1-1-707.68), light grey, pyrite, fossiliferous (very abundant belemnites, abundant ammonites, e.g. at 708.23 m, 708.90 m, 710.20 m, bivalves, echinoderms, bioclasts), bioturbated

3.6.1.2 Rietheim Member, 712.10 – 721.48 m (9.38 m)

The Rietheim Member is very distinctive due to its bitumen content and its lamination by 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).

In MAR1-1, the Rietheim Member consists of argillaceous marl (silty), bituminous, passing into bituminous shale towards the base. The section contains four beds of calcareous marl and limestone, all bituminous and sometimes laminated.

The upper boundary is set at 712.10 m, at the base of the lowermost belemnite horizon typical of the overlying Gross Wolf Member. It coincides with the uppermost occurrence of claystone (silty, bituminous) of the Rietheim Member.

The lower boundary is set at 721.48 m, at the lowermost cm-thick seam of bituminous shale.

Lithology

712.10 – 713.19 m	Claystone (silty, calcareous), bituminous, dark grey, increasing downwards in carbonate content, underlain (at 712.53 m) by calcareous marl (slightly silty), dark beige to beige, bioclasts grading into coquinas (belemnites, bioclasts)
713.19 – 718.10 m	Claystone (silty, calcareous) to argillaceous marl, dark grey, bituminous, pyrite, siderite, fossiliferous (mainly bivalves of <i>Bositra</i> genus " <i>Posidonia</i> ", mostly pyritised, and, in the upper part down to 715.59 m, belemnites, disperse, many pyritised), fine-layered to laminated
718.10 – 721.48 m	At the top (from 718.10 to 718.33 m), calcareous marl, followed by bituminous shale (slightly silty), dark grey to black, virtually no macrofossils (besides an ammonite at 720.45 m), laminated From 719.10 m to 719.27 m, two thin and, from 719.77 m to 720.02 m, one relatively massive bed of limestone (bituminous) (mudstone, micrite), medium light grey, fine-layered to laminated (microbial mats) (thin section MAR1-1-720.00). The latter represents the «Unterer Stein»

A thin coal seam from 719.43 m to 719.44 m may be plant remains or driftwood

From 720.84 m to 721.48 m, argillaceous marl, medium grey, light greenish hue, glauconite, very fossiliferous (mainly belemnites, very abundant from 720.84 m to 721.10 m, and bivalves), with a thin bituminous layer at the base (from 721.45 m to 721.48 m)

3.6.1.3 Breitenmatt and Rickenbach Members, 721.48 – 724.08 m (2.60 m)

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

As the Grünschoholz Member can be clearly delimited from the overlying sediments at MAR1-1, it will be discussed separately (Section 3.6.1.4). However, current data do not allow a differentiation between the Breitenmatt and Rickenbach Members which will, therefore, be described together.

The *upper boundary* is set at 721.48 m, at the base of the lowermost cm-thick seam of bituminous shale from the hanging Rietheim Member.

The *lower boundary* is the base of a hardground at 724.08 m. It separates a succession of calcareous hardgrounds from a limestone with phosphorite concretions and *Gryphaea obliqua*. Additionally, the boundary coincides with a change in colour from very light grey to dark beige and medium grey.

Lithology

721.48 – 721.65 m	Limestone (argillaceous), medium grey, bored surface at the base
721.65 – 722.02 m	Argillaceous marl with limestone (argillaceous) nodules, intensively bored, as a whole medium grey with large belemnites
722.02 – 722.78 m	Calcareous marl, medium grey, glauconite, fossiliferous (belemnites, bivalves, fossil detritus), burrows
722.78 – 723.76 m	From 722.78 m to 723.29 m, two nodular beds of limestone (argillaceous) (mudstone, micrite), light grey, glauconite, very fossiliferous, including large belemnites Calcareous marl, medium grey, glauconite, abundant fossils partly phosphorised, three levels of belemnites (smaller than in overlying strata); ammonite at 723.40 m
723.76 – 724.08 m	Succession of hard- and firmgrounds formed by limestone (argillaceous) (mudstone, micrite), very light grey, glauconite, fossiliferous (belemnites, bivalves)

3.6.1.4 Grünschoholz Member, 724.08 – 725.13 m (1.05 m)

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

The *upper boundary* is set at 724.08 m, at a hardground at the top of a limestone characterised by phosphorite concretions and *Gryphaea obliqua*.

The *lower boundary* is set at 725.13 m, at a bored surface separating the glauconitic limestone rich in fossils, including *Gryphaea obliqua*, from the macrofossil-poor sandy claystone of the uppermost Frick Member.

Lithology

724.08 – 725.13 m	Succession of encrusted hardgrounds formed by limestone (argillaceous) (packstone and grainstone, biomicrite to sparite), dark beige to medium grey, pyrite, glauconite, abundant fossils (partly phosphorised) include <i>Gryphaea</i> , other bivalves, belemnites (smaller than in the basal Breitenmatt and Rickenbach Members), brachiopods. In the domain of hardgrounds, reworked lithoclasts are found. The base is formed by another hardground
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3.6.1.5 Frick Member, 725.13 – 737.74 m (12.61 m)

The Frick Member is known as a uniform succession of micaceous and silty claystone in various shades of dark grey. Macrofossils are virtually absent (Reisdorf et al. 2011).

The *upper boundary* is set at 725.13 m, at a bored surface separating the glauconitic limestone rich in fossils, including *Gryphaea obliqua*, from the macrofossil-poor sandy claystone of the uppermost Frick Member.

The *lower boundary* is set at 737.74 m, above a strongly bioturbated limestone with bioclasts including echinoderms, peloids and lithoclasts.

Lithology

725.13 – 737.74 m	Monotonous succession of silty claystone, medium grey, mica, with thin lenses of sandstone (argillaceous), light grey, and with almost insignificant changes in fossil content (bivalves, detritus) from modest to virtually absent (in the section from 730.00 m to 732.00 m, where burrows are more common) (thin section MAR1-1-740.44). Pyrite is found in the section from 732.00 m to 734.60 m. In the lowermost 26 cm, a transition to bioclastic sandy marl, medium grey, mica, pyrite, bivalves, slightly enriched fossil detritus can be observed
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3.6.1.6 Beggingen Member, 737.74 – 741.98 m (4.24 m)

In north-eastern 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). The limestone successions are separated by a silty claystone interval, becoming more prominent in the ZNO area (e.g. Nagra 2001a). The upper limestone succession is characterised by the occurrence of *Gryphaea arcuata*. The base of the lower succession is marked by the Schleithem Bed as a regional stratigraphic marker with an erosional surface at its base (Reisdorf et al. 2011). As outlined above, lithologically the Beggingen Member can be divided in MAR1-1 into three intervals: an upper limestone succession (from 737.74 m to 740.66 m) with *Gryphaea arcuata*, a claystone interval (from 740.66 m to 741.73 m) and, below, a calcareous marl interval, slightly iron-oolitic, probably corresponding to the Schleithem Bed (from 741.73 m to 741.98 m).

The *upper boundary* is set at 737.74 m, above a strongly bioturbated limestone with bioclasts including echinoderms, peloids and lithoclasts.

The *lower boundary* is set above a striking, 5 cm thick calcareous hardground at 741.98 m which is overlain by a succession of further hardgrounds including locally limestone (iron-oolitic). The hardground at 741.98 m is underlain by monotonous silty claystone (calcareous) of the Schambelen Member.

Lithology

737.74 – 740.66 m	Limestone succession with <i>Gryphaea arcuata</i> comprising: At the top (from 737.74 m to 737.84 m), limestone (grainstone, biosparite), very light grey, strongly bioturbated, phosphorite, pyrite, lithoclasts, echinoderms, bioclasts, peloids, components are normally graded From 737.84 m to 740.23 m, bioclastic limestone (grainstone, biosparite) to limestone (grainstone, biosparite), medium to light grey, glauconite, pyrite (disperse, nodules and nodular beds, e.g. at 740.55 m), partly (incl. some fossils) phosphorised, some siderite nodules, fossiliferous (<i>Gryphaea</i>, topmost at 738.22 m, bivalves, belemnites, echinoderms and others), fossils often bored, medium-bedded with interlayers (2 to 5 cm) of limestone (argillaceous) (packstone, biomicrite), fossiliferous (same as limestone beds), irregularly bedded, with limestone nodules, locally dolomitised (thin section MAR1-1-739.08) At the base (740.23 m to 740.66 m), hardground formed at the top of the upper of two beds of limestone (packstone, biomicritic), medium light grey, fossil detritus, separated by limestone (silty, argillaceous), medium grey, pyrite, lithoclasts, abundant <i>Gryphaea</i>, bivalves and other fossils, fossil detritus; erosive base
740.66 – 741.98 m	Silty claystone, dark grey, mica (sparse and very small), macrofossils (bivalves and others) restricted to lower part (starting with a coquina at 741.12 m), burrows, laminated From 741.73 m to 741.98 m, very heterogeneous interval starting (from the top) with a breccia, calcareous (polymict), variegated, formed by various lithoclasts including dolostone, followed by an argillaceous marl, dark grey, glauconite, partly porous, followed by a succession of hard-

grounds formed by limestone (grainstone, biomicrite), locally iron-oolitic (from 791.93 m to 791.95 m: thin section MAR1-1–741.95), lithoclasts, fossiliferous (bivalves, echinoderms and others); this interval probably corresponds to the Schleithem Bed

3.6.1.7 Schambelen Member, 741.98 – 747.83 m (5.85 m)

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

In MAR1-1, the Schambelen Member can be divided into three parts. The upper part (from 741.98 m to 744.59 m) consists almost exclusively of silty claystone (calcareous) with virtually no fossils. The middle part (from 744.59 m to 747.03 m) is heterogeneous, fossiliferous, more small-scale and also includes sections with higher carbonate content ranging from argillaceous marl to limestone. In the lower part (746.03 m to 747.83 m), bituminous shale dominates.

The *upper boundary* is set at the top of a calcareous hardground at 741.98 m, at the top of the medium to dark grey silty claystone (calcareous) characteristic for the upper part of the Schambelen Member.

The *lower boundary* is set at 747.83 m, at a microbially encrusted erosional surface separating bituminous shale from dolomitic marl. The boundary is accompanied by probable root tubes in the underlying dolomitic marl.

Lithology

741.98 – 744.59 m	At the top (from 741.98 m to 742.03 m), hardground at the top of a limestone (mudstone and wackestone, biomicrite), light grey, pyrite, fossil detritus, nodular Silty claystone (calcareous), medium to dark grey, mica (sparse and small) with very thin lenses (up to some mm) of argillaceous siltstone (calcareous), mica, very little fossil detritus (except in the basal layer from 744.40 m to 744.59 m), burrows
744.59 – 747.03 m	Heterogeneous and rather fossiliferous section comprising: At the top (from 744.59 m to 744.76 m), hardground formed (from the top) by a claystone layer, a pyrite layer (1.5 cm thick), two beds of claystone to calcareous marl, bioclasts, and, from 744.68 m to 744.76 m, a limestone bed with abundant lithoclasts and fossil detritus, overall colour medium grey, glauconite From 744.76 m to 745.16 m, argillaceous marl (silty), glauconite, coquina, bivalves From 745.16 m to 746.43 m, alternation of silty claystone (calcareous), medium grey, glauconite, fossil detritus, laminated, and calcareous marl, medium to light grey, glauconite, fossiliferous (mainly bivalves, up to 3 cm), disperse and in coquinas, flaser bedding

At the base (from 746.43 m to 747.03 m), calcareous marl (silty), glauconite, coquina, bivalves, underlain, from 746.76 m to 746.86 m, by limestone (packstone, biopelmicrite), light grey, glauconite, bivalves and, at the base (746.86 m to 747.03 m), silty claystone (calcareous), medium grey, glauconite

747.03 – 747.83 m Claystone (silty), dark grey, pyrite, with fine siltstone lenses and virtually no macrofossils, grading, from 747.23 m, into claystone (bituminous) and bituminous shale, black, pyrite, with abundant shell detritus (mainly bivalves), becoming scarcer in the lowermost part

3.7 Keuper Group

3.7.1 Klettgau Formation, 747.83 – 790.12 m (42.29 m)

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

In MAR1-1, the Belchen Member is missing, and the Gruhalde Member is divided into two by the Seebi Member.

The *upper boundary* is set at 747.83 m, at a microbially encrusted erosional surface separating bituminous shale from dolomitic marl. The boundary is accompanied by probable root tubes in the underlying dolomitic marl

The *lower boundary* is set at 790.12 m, at the top of the uppermost anhydrite bed of the Bänkerjoch Formation.

3.7.1.1 Gruhalde Member (upper part), 747.83 – 765.75 m (17.92 m)

The upper part of the Gruhalde Member is characterised by non-laminated dolomitic marl of a grey to reddish and brown colour (Jordan et al. 2016), which shows predominantly grey violet colours in MAR1-1. These overbank sediments can be interrupted by channels often filled with dolomitic marl or dolostone.

The *upper boundary* is set at 747.83 m, at a microbially encrusted erosional surface separating dark grey bituminous shale from light greenish grey dolomitic marl. The boundary is accompanied by probable root tubes in the underlying dolomitic marl.

The *lower boundary* is set at 765.75 m, at an erosional surface at the base of a breccia, dolomitic (monomict), consisting of lithoclasts of the underlying dolostone. The transition is reflected by sharp changes in the petrophysical logs.

Lithology

747.83 – 750.09 m Dolomitic marl, grading from light greenish grey (top) to dark greyish pink, cloudy, at the top (from 747.83 m to 748.30 m) microbially encrusted erosional surface and probably root tubes

750.09 – 752.00 m No core

752.00 – 765.75 m	Dolomitic marl (silty), grey violet, and along some large joints pale yellowish green (reduction halos), massive, with a very fine network of calcite-filled joints (possibly pedogenic features) giving the rock a somewhat breccia-like appearance, with, at 763.56 m, lithoclasts with diameter up to 12 mm, and, from 764.46 m to 764.47 m, a silex nodule From 757.20 m to 758.30 m, nodular section of dolomitic marl, light grey to grey violet From 761.62 m to 763.11 m: no core At 765.06 m, sharp change in colour (oxidation front), followed by dolomitic marl, light greenish grey, and from 765.33 to 765.75 m breccia, dolomitic (polymict), matrix-supported (matrix: dolomitic marl), light greenish grey, angular lithoclasts of underlying dolostone, beige grey, some of the clasts in an upright position, some chert clasts, erosive base
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3.7.1.2 Seebi Member, 765.75 – 774.71 m (8.96 m)

The Seebi Member was deposited on an alluvial plain and covers a wide range of lithofacies types from overbank fines and lacustrine carbonates to fluvial bedload sediments.

In MAR1-1, the Seebi Member consists lithologically of two parts. The upper part (from 765.75 m to 772.11 m) comprises a succession of dolostone. The lower part (from 772.11 m to 774.71 m) is composed of terrigenous siliciclastic sediments ranging from claystone (silty) to sandstone (coarse-grained).

The *upper boundary* is set at 765.75 m, at an erosive surface at the base of a breccia, dolomitic (monomict), consisting of lithoclasts of the underlying dolostone. The transition is reflected by sharp changes in the petrophysical logs.

The *lower boundary* is set at 774.71 m, at an erosional surface also showing load casts. It separates argillaceous sandstone of the basal Seebi Member from the variegated argillaceous marl (silty) of the Gruhalde Member. This transition is also documented in GR and FMI logs as well as in a significant change in rock colour from predominantly light grey (with various hues to greenish, yellowish and beige) to dark reddish brown and grey violet.

Lithology

765.75 – 767.68 m	Dolostone, beige grey, with very irregular inclusions (giving the rock a breccia-like appearance), pale green to pale yellowish green, pyrite, with irregularly shaped chert nodules, dark grey to greyish violet. At the base, from 767.30 m to 767.68 m, alternating layering of dolostone, dolomitic marl, and argillaceous marl (dolomitic)
767.68 – 769.73 m	Breccia, dolomitic (monomict), with a dolomitic marl matrix, light grey, components (dolostone) are partly rounded, medium grey, chert nodules abundant from 768.82 m to 769.33 m and, from 769.05 m to 769.20 m, rock almost fully silicified, open vugs from 766.75 to 769.50 m

769.73 – 772.11 m	Dolostone-dominated succession including: From 769.73 m to 770.50 m, dolostone, dark beige, grading into dolostone (argillaceous), dark beige, with irregular relicts of dolostone (calcitic), light beige, layered From 770.50 m to 770.85 m, dolostone (bioclastic), pyrite, bivalves, disperse and in coquina and with pyritised shells From 770.85 m to 772.11 m, dolostone (calcareous), light grey, to dolomitic marl, medium grey, grading into dolostone, dark beige
772.11 – 774.71 m	Detritic succession including: From 772.11 m to 773.50 m, normally graded sandy succession: claystone (silty), pale green to pale yellowish green, grading into argillaceous sandstone (medium- to coarse-grained), pale yellowish green, poorly sorted, well to subrounded, polymict (quartz, feldspar), well cemented (dolomite), with chert clasts up to 15 cm in diameter From 773.50 m to 774.10 m, normally graded, more marly succession: argillaceous sandstone (medium- to coarse-grained) (dolomitic), pale yellowish green, poorly sorted, well to subrounded, polymict (quartz, feldspar), well cemented (dolomite), grading into sandy marl, pale yellowish green, with lithoclasts From 774.10 m to 774.71 m, normally graded, more dolomitic succession: sandy claystone (dolomitic), pale yellowish green grading into argillaceous sandstone (coarse-grained) (dolomitic), pale yellowish green, very poorly sorted, polymict (quartz, feldspar), well to subrounded, well cemented (dolomite), with interbeds showing load casts

3.7.1.3 Gruhalde Member (lower part), 774.71 – 782.46 m (7.75 m)

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 MAR1-1, the lower part of the Gruhalde Member consists lithologically of two parts: the variegated argillaceous marl (silty) of the upper part (from 774.71 m to 778.82 m) comprises a sandy interval but virtually no dolomitic interbeds. The mostly reddish brown and predominantly dolomitic marl (silty) of the lower part (from 778.82 m to 782.46 m) has many dolostone interbeds. It may correlate with the «Rote Wand», an important regional marker throughout north-eastern Switzerland and southern Germany (e.g. Geyer et al. 2011).

The *upper boundary* is set at 774.71 m, at an erosional surface separating the argillaceous sandstone of the basal Seebi Member from the variegated argillaceous marl (silty) below. This transition is also documented in GR and FMI logs as well as in a significant change in rock colour from predominantly light grey (with various hues to greenish, yellowish and beige) to dark reddish brown and grey violet.

The *lower boundary* is set at 782.46 m, at the top of a dolomitic marl (anhydritic) bed which documents the uppermost occurrence of anhydrite and therefore the evaporitic facies of the ZNO region.

Lithology

774.71 – 777.29 m	Argillaceous marl (silty, dolomitic), dark reddish brown to grey violet From 776.08 m to 776.71 m, sandy claystone (dolomitic) grading into argillaceous sandstone (very coarse-grained to coarse-grained) (dolomitic), dark reddish brown, poorly sorted, well to subrounded, polymict (various lithoclasts, quartz, feldspar), well cemented (dolomite), normally graded From 777.20 m to 777.29 m, conglomerate, dolomitic (polymict), very light green, with black grains (up to 2 mm in diameter)
777.29 – 778.82 m	Argillaceous marl (silty), dark reddish brown, with nodular interlayers and nodular beds of dolostone, very light grey
778.82 – 782.46 m	Dolomitic marl (silty), dark reddish brown, with two thin-bedded successions (from 779.28 m to 779.42 m, and from 780.55 m to 780.63 m) of dolostone, very light grey, and argillaceous marl, pale yellowish green

3.7.1.4 Gansingen Member, 782.46 – 784.02 m (1.56 m)

The Gansingen Member testifies to 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 region, the member was predicted to be evaporitic (Jordan & Deplazes 2019).

In MAR1-1, the Gansingen Member is represented by a massive anhydrite bed. It is recognisable in the GR and RLA logs. Two sections may be distinguished: In the upper part (from 782.46 m to 783.19 m), massive alabastrine anhydrite prevails. In the lower part (from 783.19 m to 784.02 m), thin beds (of up to 2 cm) of argillaceous marl (dolomitic), grey violet to reddish, with very small anhydrite nodules are found at irregular distances.

The *upper boundary* is set at 782.46 m, at the top of a dolomitic marl (anhydritic) bed which documents the uppermost occurrence of anhydrite and therefore the evaporitic facies of the ZNO region. Massive anhydrite starts below an erosional surface at 782.64 m.

The *lower boundary* is set at 784.02 m, at the top of the first argillaceous marl interval (with anhydrite nodules). Anhydrite, probably pedogenic, is also found below this boundary.

Lithology

782.46 – 782.64 m	Dolomitic marl (anhydritic), medium grey, underlain
782.64 – 784.02 m	Anhydrite, very light greenish grey to very light grey, slightly transparent, massive to nodular, with thin interlayers, from 783.19 m to 783.23 m dolomitic marl, grey violet, and, from 783.23 m to 784.02 m, of argillaceous marl (dolomitic), medium grey with reddish hue, occasionally, small (max. some mm) anhydrite nodules are found within the marl layers

3.7.1.5 Ergolz Member, 784.02 – 790.12 m (6.10 m)

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

In MAR1-1, the Ergolz Member is composed predominantly of argillaceous marl (sandy [fine-grained], dolomitic) and, subordinately, claystone (silty) representing distal overbank deposits. In the upper part (784.02 m to 785.60 m), nodules and nodular beds of anhydrite and dolomite represent paleosoils. Three thin beds of sandstone (fine-grained) (dolomitic, argillaceous) and a thicker bed of argillaceous sandstone (dolomitic) in the lower part may be addressed as proximal overbank deposits or as deposits in subordinate shallow channels.

The *upper boundary* is set at 784.02 m, at the top of the first argillaceous marl bed. This bed and further beds down to 785.60 m include anhydrite nodules, which could be clearly distinguished from the massive anhydrite of the Gansingen Member.

The *lower boundary* is set at 790.12 m, at the top of the first (slightly nodular) bed of anhydrite. Anhydrite veins are already found between 788.98 m and 790.12 m.

Lithology

784.02 – 785.60 m	Argillaceous marl (partly silty to sandy), greyish green to reddish brown, with flattened nodules of anhydrite, very light grey, which become more prominent with depth From 784.72 m to 784.77 m, dolostone, very light grey
785.60 – 788.98 m	Argillaceous marl (sandy, fine-grained), pale yellowish green and dark reddish brown with thin layers of argillaceous sandstone (fine-grained) and lenses of claystone (silty) and four thicker sandstone intervals: From 786.46 m to 786.57 m: sandstone (fine-grained) (argillaceous, dolomitic), light grey, well cemented, flaserly From 786.86 m to 786.93 m: sandstone (fine-grained) (argillaceous, dolomitic), light grey, well cemented, flaserly From 787.67 m to 788.16 m: argillaceous sandstone (fine-grained) (dolomitic), pale yellowish green and reddish brown, flaserly to irregularly bedded From 789.84 m to 789.98 m: sandstone (fine-grained) (argillaceous, dolomitic), light grey, well cemented, flaserly
788.98 – 790.12 m	Argillaceous marl (sandy [fine-grained]), reddish brown and, in contact with veins, pale yellowish green with a dense network of inclined anhydrite veins, white to light grey, folded by compaction

3.7.2 Bänkerjoch Formation, 790.12 – 862.52 m (72.40 m)

The Bänkerjoch Formation is an evaporitic succession with many complete and incomplete cycles and sub-cycles, 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).

The *upper boundary* is set at 790.12 m, at the top of the first (slightly nodular) bed of anhydrite.

The *lower boundary* is set at 862.52 m, at the top of an anhydrite-free dolostone bed. It is located below the lowermost massive anhydrite bed (864.41 m to 862.52 m) that is more than some cm thick. The very lowest anhydrite bed is found from 862.93 m to 863.00 m.

Lithostratigraphic subdivision

There is as yet no formal subdivision of the Bänkerjoch Formation. The informal subdivision based on earlier core records of Nagra (Dronkert et al. 1990, Nagra 2001a) is proposed to be used for the campaign by Jordan & Deplazes (2019). The upper three of a total of five sub-units could be recognised in MAR1-1. The lowermost part of the formation shows aspects of both «Banded massive anhydrite» and «Dolomite and anhydrite» without a clear vertical differentiation into an upper and lower unit. Rather, there are dolostone beds, dolomitic marl beds, anhydrite (dolomitic) beds and banded massive anhydrite over the whole section.

790.12 – 814.28 m:	«Claystone with anhydrite nodules» (24.16 m) including «Marker Horizon I» («Quarzitische Bank») from 811.08 m to 812.12 m
814.28 – 835.66 m	«Cyclic sequence» (21.38 m)
835.66 – 852.34 m	«Thin-layered anhydrite and claystone sequence» (16.68 m) including the «Marker Horizon II» from 842.38 m to 842.62 m
852.34 – 862.52 m	«Banded massive anhydrite / dolomite and anhydrite» (10.18 m)

Lithology

«Claystone with anhydrite nodules», 790.12 – 814.28 m (24.16 m)

This sub-unit is lithologically the most heterogeneous of the entire formation. In MAR1-1, not claystone but argillaceous marl (silty) is the dominant lithology. Anhydrite nodules are found in the uppermost part (down to 792.11 m), in the interval from 796.87 m to 798.67 m, and in the lower part from 801.78 m to 811.08 m, here mostly within claystone (anhydritic). There are two siliciclastic intervals which, together with relative anhydrite content, allow a certain subdivision:

790.12 – 794.34 m	Anhydrite-dominated interval: anhydrite and anhydrite (argillaceous), mostly light grey to greyish green, mostly nodular, with thin bed of argillaceous siltstone, light grey
	Continuing, at 792.11 m, into a marl-dominated interval: argillaceous marl (partly silty), mostly light grey to greyish green, locally dark reddish brown, with some anhydrite layers, mostly light grey to white

794.34 – 796.87 m	Siliciclastic interval: argillaceous marl (sandy), mostly light grey to greyish green, locally dark reddish brown with several layers of sandstone (fine-grained) (argillaceous) and argillaceous sandstone (fine-grained), well cemented, very light grey, and some anhydrite to anhydrite (dolomitic) layers, mostly light grey to white
796.87 – 803.67 m	Marl-dominated interval: argillaceous marl (silty), mostly light grey to greyish green, with anhydrite nodules and beds of nodular anhydrite, white, thin beds of alabastrine anhydrite and anhydrite veins, pink Continuing at 801.78 m into a fine-layered interval: thin-bedded alternation of partly nodular beds of claystone (anhydritic), greyish green, argillaceous marl (sandy), light grey, anhydrite (dolomitic) to anhydrite, white, crossed by inclined anhydrite veins, pink, at the base thicker nodular bed of dolostone (argillaceous), light grey
803.67 – 807.07 m	Anhydrite-dominated interval: anhydrite, very light grey, partly nodular, partly lenticular, partly alabaster-type, anhydrite (argillaceous, partly silty), claystone (anhydritic), greyish green, inclined anhydrite veins, pink
807.07 – 811.08 m	Marl-dominated interval with anhydrite nodules interval: argillaceous marl to claystone (anhydritic), repeated change in colour from greyish green to dark reddish brown, smaller to larger nodules and nodular beds of anhydrite, light grey, mostly of alabaster-type, dolostone (argillaceous), very light green
811.08 – 812.12 m	Siliciclastic interval: dolomitic sandstone (argillaceous), light greenish grey, bioturbated, with anhydrite nodules, load casts at the base («Marker Horizon I»)
812.12 – 814.28 m	Marl-dominated interval: argillaceous marl, dark reddish and greyish green, anhydrite nodules, from 813.25 m to 813.52 m, fine-layered alternation of dolostone and dolostone (argillaceous), very light grey, underlain by sandy marl to argillaceous siltstone, pale green

«Cyclic sequence», 814.28 – 835.66 m (21.38 m)

The sub-unit consists mainly of anhydrite with varying fabrics and bedding: beds of densely packed nodules, laminated anhydrites with thin claystone intervals, massive anhydrite that lacks internal structures, and anhydrite nodules organised in a chickenwire structure. Solitary nodules as in the sub-unit above are much less abundant. Veins of anhydrite are exclusively developed in thicker interbeds of claystone (anhydritic). The sub-unit can be described as follows (from top to base):

814.28 – 817.92 m	Alternation of: anhydrite (argillaceous), greyish green, anhydrite, very light grey, partly nodular, anhydrite, alabaster-type, light grey, partly nodular, claystone (anhydritic), black, inclined anhydrite veins, pink
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817.92 – 821.04 m	Laminated to thin-bedded alternation of: anhydrite (argillaceous, silty) to claystone (anhydritic), medium grey, anhydrite, partly alabaster-type, very light grey, locally also pink, claystone (dolomitic), dark grey, some thin layers of silty to sandy marl
821.04 – 834.00 m	Medium-bedded irregular alternation of: • layered anhydrite: anhydrite (argillaceous, silty), medium grey, anhydrite, very light grey to pink, and claystone (anhydritic, silty), dark grey • heavily veined anhydrite: anhydrite (argillaceous) to anhydrite (dolomitic), dark grey, and anhydrite, very light grey, intersected by abundant inclined veins of anhydrite, pink to very light grey • massive anhydrite: anhydrite, light grey, partly alabaster-type • chickenwire anhydrite: anhydrite (nodular to micro nodular), very light grey to light grey, sparse matrix
834.00 – 835.66 m	Anhydrite to anhydrite (argillaceous), light grey to medium grey, laminated, banded, with sand layers, normally graded, ripples

«Thin-layered anhydrite and claystone sequence», 835.66 – 852.34 m (16.68 m)

This sub-unit comprises three intervals which differ in their lithology and textures:

835.66 – 842.62 m	Thin-layered anhydrite and claystone interval: irregular, from 838.68 m to 840.66 m, rather cyclic alternation of argillaceous marl (silty) to claystone (anhydritic, silty), dark grey, anhydrite (argillaceous, silty), dark grey, with abundant anhydrite veins, anhydrite, very light grey, partly primordial chevron-type gypsum and anhydrite (nodular), light grey, massive From 840.66 m to 841.96 m, the thin-layered alternation is interrupted by a thicker interval of argillaceous marl (silty) grading into claystone (anhydritic), dark grey, with some arenitic anhydrite layers At the base, from 841.96 m to 842.62 m, anhydrite, light grey massive, dolomitic marl, dark grey and anhydrite (dolomitic), medium grey with coquina including <i>Lingula</i> sp. The interval from 842.38 m to 842.2 m represents the «Marker Horizon II»
842.62 – 849.75 m	Interval of massive dolomitic marl beds with anhydrite interlayers and nodules: dolomitic marl (in some layers sandy), greenish grey and dark reddish brown, grading into interlayers of sulpharenitic anhydrite, light grey to pink, and interlayers of dolostone, light grey, and anhydrite nodules, light grey to white. Pedogenic features, e.g. from 845.75 m to 845.91 m and various deformation features (e.g. from 849.16 m to 849.43 m) including tepee structures are present in this interval
849.75 – 852.34 m	Fine-layered to laminated anhydrite interval (with some thicker beds): anhydrite (dolomitic) to dolostone (anhydritic), light greenish grey to pink and dark pink, and dolomitic marl (partly silty), dark greyish brown

«Dolomite and anhydrite» and «Banded massive anhydrite», 852.34 – 862.52 m (10.18 m)

This sub-unit shows by far the highest amount of anhydrite in the entire Bänkerjoch Formation. It contains the thickest beds of massive (i.e. featureless or slightly banded) anhydrite. The succession of anhydrite is interrupted by two sections where dolostone (argillaceous) to dolomitic marl (locally silty) dominate. Thus, the unit can neither be addressed as «Dolomite and anhydrite» nor as «Banded massive anhydrite».

852.34 – 856.00 m	Below a non-erosive boundary, a fine-layered to laminated sequence showing various shades of grey is formed by: anhydrite (locally silty to sandy) grading into anhydrite (dolomitic), dolostone (anhydritic), dolostone (argillaceous, locally silty), dolostone; locally slightly bituminous, some anhydrite nodules
856.00 – 859.67 m	Anhydrite, light and medium grey, laminated, banded, with thin detrital layers formed by fine dolostone lithoclasts or quartz sand
859.67 – 861.41 m	Succession of dolostone (argillaceous, anhydritic, sandy), light grey, dolomitic marl (silty), medium grey, and dolostone (argillaceous), medium grey, abundant anhydrite nodules, very light grey
861.41 – 862.52 m	Anhydrite (dolomitic), very light grey, massive, with selenite interlayers

3.8 Muschelkalk Group

3.8.1 Schinznach Formation, 862.52 – 932.24 m (69.72 m)

The formal Schinznach Formation and its members are not consistently congruent with the stratigraphic units «Lettenkohle», «Trigonodus-Dolomit» and «Hauptmuschelkalk» used when recording boreholes in earlier Nagra and Nagra-accompanied campaigns. Pietsch et al. (2016) and Jordan & Deplazes (2019) give a correlation between the actual formal scheme and older litho-stratigraphic concepts.

The *upper boundary* is set at the base of the lowermost significantly anhydritic bed of the Bänkerjoch Formation at 862.52 m, coinciding with the top of the uppermost massive dolostone without anhydrite.

The *lower boundary* is set at 932.24 m, at the base of the lowermost limestone bed.

3.8.1.1 Asp Member, 862.52 – 867.61 m (5.09 m)

The Asp Member consists mainly of dolostone with intervals of *rauhwacke* in the upper half of the member and fossiliferous bituminous shales with thin dolostone interbeds in the lower half (Pietsch et al. 2016).

The *upper boundary* is set at 862.52 m, at the base of the lowermost significantly anhydritic bed of the Bänkerjoch Formation, coinciding with the top of the uppermost massive dolostone without anhydrite.

The *lower boundary* is set at 867.61 m, at the base of the lowest (thin) bituminous shale layer overlying the erosive top of the lower Stamberg Member.

Lithology

862.52 – 865.72 m	At the top, from 862.52 m to 863.00 m, fine-bedded alternation of laminated dolostone (argillaceous), very light grey, microbial mats, and anhydrite (dolomitic), light grey, dark pellets From 863.00 m to 865.72 m, dolostone, mostly medium grey, with abundant very fine (< 1 mm) claystone drapes, greyish green, sparse pyrite, fossiliferous (coquinas with fish scales and bivalves), horizontal anhydrite veins and amorphous anhydrite impregnations, white, dolomitic marl interbed from 865.21 m to 865.33 m. The interval from 862.52 m to 865.72 m can be addressed as the informal «Grenzdolomit»
865.72 – 867.61 m	Bituminous shale, black, with interbed (from 866.99 m to 867.42 m) of dolomitic marl grading into dolostone, light grey. The lower occurrence of bituminous shale overlies an erosional surface. This interval can be addressed as the informal «Estherienschiefer»

3.8.1.2 Stamberg Member, 867.61 – 906.44 m (38.83 m)

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

The Stamberg Member of MAR1-1 can be divided into two parts by the presence of an oolitic horizon and the texture, which is massive to thick-bedded above this horizon and medium-bedded below. To be highlighted are the numerous coquinas (bivalves, brachiopods) in the lower part, not known in this abundance from corresponding sections of nearby sites (e.g. Nagra 2001a, Schwarz et al. 2021).

The *upper boundary* is set at 867.61 m, at the base of the lowest (thin) bituminous shale layer.

The *lower boundary* is set at 906.44 m, at the lower boundary of the persistent and complete dolomitisation. It coincides roughly with a change in colour from medium grey above to the beige colour of the Liedertswil Member below.

In the formal stratigraphic scheme, two oolitic intervals may be locally included in the Stamberg Member (Pietsch et al. 2016): the Kaisten Bed in the upper part and the Eptingen Bed in the lower part. In the present section, the Kaisten Bed was not recognised. The oolitic interval from 882.58 m to 883.49 m corresponds very well to the section from 823.55 m to 828.53 m of the nearby Benken borehole which was addressed by Nagra (2001a) as «Dögginger Oolith» and thus as the Eptingen Bed following the actual formal scheme.

Lithology

867.61 – 869.56 m	Dolostone, predominantly light grey to beige, partly with rauhwacke features, porous to cavernous, locally fossiliferous to very fossiliferous (bivalves and brachiopods); no core from 868.23 m to 868.48 m
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869.56 – 877.00 m	Dolostone, beige to beige grey, massive, homogeneous, but original fine layering still visible; from 870.55 m to 876.00 m, core in very bad condition or missing, remains of dolostone corroded, rauhwacke-type features (honeycomb calcite lamellae)
877.00 – 882.46 m	Dolostone, beige grey, dense and splintery, porous to varying degrees (pores up to 2 cm in diameter, partly filled with anhydrite or rauhwacke with honeycomb calcite lamellae), core repeatedly in bad condition
882.46 – 885.25 m	Dolostone, dark grey to beige grey, fossiliferous (bivalves, brachiopods), underlain, from 882.58 m to 883.49 m, by dolostone (dolomitic oospa-rite), dark grey with beige hue, with abundant dark allochems (ooids and pellets) followed by fine-layered (mm to cm) alternation of dolostone (dolomitic biopelmicrite), beige grey, and dolostone beige grey, fossiliferous, partly porous
885.25 – 891.92 m	Dolostone, dark beige to medium grey, locally lithoclasts, small chert nodules and peloids, bioturbated, partly porous, locally laminated (microbial mats), elsewhere cloudy to nodular, bedding planes mostly irregular to corroded and accompanied by claystone drapes (up to 5 mm thick)
891.92 – 903.68 m	Dolostone, dark beige to medium grey, in the lower part also light grey, sporadically lithoclasts, abundant coquinas (bivalves, brachiopods), coquinas partly porous (pores locally filled with galena and pyrite) and partly silicified, cloudy to nodular, with claystone interbeds up to 7 cm
903.68 – 905.43 m	Alternation of up to 5 cm thick beds of dolostone, beige grey, and up to 2 cm thick beds of dolostone (slightly argillaceous), medium grey
905.43 – 906.44 m	Dolostone, dark beige, pellets, some shells, coquina near the base, porous

3.8.1.3 Liedertswil Member, 906.44 – 910.27 m (3.83 m)

The Liedertswil Member is defined to reach from the lower boundary of post-sedimentary persistent and complete dolomitisation down to the uppermost bed consisting of more than 10% crinoids as its base (Pietsch et al. 2016).

In MAR1-1, the Liedertswil Member is a well bedded succession of micritic limestone with a repeated variation of abiogenic components, especially peloids. The fossil content is restricted to bivalves, both solitary and in coquinas.

The *upper boundary* is set at 906.44 m, at the lower boundary of the persistent and complete dolomitisation. It coincides roughly with a change in colour from medium grey of the Stamberg Member above to beige.

The *lower boundary* is set at 910.27 m, at the top of the uppermost bed consisting of more than 10% crinoids (Pietsch et al. 2016).

Lithology

906.44 – 910.27 m	Limestone (mudstone, micrite), beige and medium grey, partly silicified coquinas, pellets, with thin, slightly darker limestone interlayers
	From 906.77 m to 907.09 m, dolostone (calcareous), beige, layered, at 907.04 m probably an erosional surface

3.8.1.4 Leutschenberg and Kienberg Members, 910.27 – 932.24 m (21.97 m)

According to Jordan & Deplazes (2019), the Kienberg and the underlying Leutschenberg Members should be combined because separation is often difficult. Generally, both members consist of limestone with very little clay content and a varying content of biogenic components. However, the Kienberg Member is especially enriched in crinoids and shell debris, both concentrated in bioclastic limestone.

The *upper boundary* is set at 910.27 m, at the top of the uppermost bed which consists of more than 10% crinoids (Pietsch et al. 2016).

The *lower boundary* is identical to the lower boundary of the Schinznach Formation. It is set at 932.24 m, at the base of the lowermost limestone bed. Beneath, the succession of laminated dolostone beds with the typical beige to dark beige colour and chert nodules sets in, which is typical of the underlying Zeglingen Formation.

Lithology

910.27 – 922.15 m	Alternation of limestone, complete and incomplete cycles; a full cycle includes (from top): • limestone (mudstone, biopelmicrite), very light grey to light grey, laminated, partly bioturbated • limestone (argillaceous) (mudstone, micrite), beige grey, bioturbated, locally fenestral fabrics with wavy clay drapes between the beds • bioclastic limestone (wackestone and packstone, biosparite), beige grey, fine-grained with white biogenic components (mainly crinoids ["Echinodermenbrekzie"], brachiopods, bivalves). The fossils are normally graded both in size and content • bioclastic limestone as above, but coarse-grained. Locally with crinoids up to 10 mm in diameter, locally lithoclasts, locally oncoids (from 910.60 m to 910.65 m), sporadically silicified • erosional surface From 915.61 m to 916.63 m, four successive fossiliferous basal layers are free of crinoids:
922.15 – 924.95 m	Limestone (mudstone, micrite), light grey to medium grey, bioturbated, showing a pseudo-layering by intense horizontal stylolitisation and resulting claystone drapes, virtually no macrofossils
924.95 – 927.24 m	Limestone (mudstone, micrite), light grey with blueish hue, with inclined claystone drapes, virtually no macrofossils

927.24 – 929.59 m	Three cycles as described above (910.27 m to 922.15 m), fossiliferous basal layers with crinoids up to 5 mm, at the base erosional surface with burrows and borings
929.59 – 932.24 m	Limestone (wackestone, biopelmicrite), beige grey, fine-grained (less than 1 mm) bioclasts, pellets, bioturbated, partly nodular, with some claystone drapes From 932.04 m to 932.24 m, bioclastic limestone (wackestone, biopelmicrite), beige grey to medium grey, porous (up to 2 mm) due to dissolved fossils

3.8.2 Zeglingen Formation, 932.24 – 993.50 m (61.26 m)

The Zeglingen Formation (Jordan 2016) is an evaporate sequence. In MAR1-1, the salt layers are missing. They are common in central Northern Switzerland but absent in eastern Northern Switzerland (Jordan 2016). However, they have been encountered in the nearby Benken borehole further to the east (Nagra 2001a). The chaotic section from 982.76 m to 984.75 m may correspond to the subroded «Salzlager» (cf. Jordan 2016).

The *upper boundary* is set at 932.24 m, at the base of the lowermost limestone.

The *lower boundary* is set at 993.50 m, at the top of the first dolostone (argillaceous) bed. The lowermost anhydrite (dolomitic) bed of reasonable thickness is found from 993.65 m to 993.87 m.

Lithostratigraphic subdivision

There is no formal subdivision of the Zeglingen Formation. The traditional subdivision into four informal sub-units (cf. Jordan & Deplazes 2019) relies on the occurrence of rock salt. It separates the succession of anhydrite into an upper unit above the rock salt section («Obere Sulfatzone») and a lower unit below the salt («Untere Sulfatzone»). As rock salt is missing here, both units are unified to a single «Sulfatzone»:

932.24 – 944.29 m «Dolomitzone» (12.05 m)

944.29 – 993.50 m «Sulfatzone» (49.21 m)

The boundary between the two sub-units is drawn at the top of the uppermost thick (1.30 m) anhydrite bed of the «Sulfatzone».

The lithological composition of the «Sulfatzone» reflects its sedimentation in cycles and sub-cycles. Intervals of massive anhydrite alternate with intervals composed of an internal alternation of anhydrite and claystone. The succession is interrupted by a characteristic interval (from 945.45 m to 951.57 m) of dolomitic marl and dolostone below the massive anhydrite bed at the top (from 944.29 m to 945.45 m).

Lithology

«Dolomitzone», 932.24 – 944.29 m (12.05 m)

932.24 – 933.41 m	Dolostone (calcareous), beige to dark beige, with fossil detritus including crinoids, partly laminated (microbial mats from 932.29 m to 932.45 m), partly porous
933.41 – 937.00 m	Dolostone, beige to dark beige, bird's eyes, partly distinctly porous, irregular bedding marked by thin claystone drapes, black, from 934.40 m to 937.00 m, laminated and less porous
937.00 – 940.27 m	Core missing or in bad condition: in the upper part, core fragments of dolostone, beige to dark beige, laminated (up to 1 mm) by very fine claystone drapes, black; in the lower part, core fragments of dolostone, beige to dark beige, massive, with rauhwacke (honeycomb calcite lamellae)
940.27 – 942.62 m	Dolostone, beige to beige grey, predominantly massive, locally laminated (microbial mats), locally porous (up to 1 mm), from 941.52 m to 941.55 m, silicified sedimentary breccia; from 942.25 m to 942.62 m: core in bad condition
942.62 – 944.29 m	Dolostone to dolostone (argillaceous), beige to beige grey to light grey, laminated to nodular, fenestral structures filled with anhydrite, partly silicified, with anhydrite veins

«Sulfatzone», 944.29 – 993.50 m (49.21 m)

944.29 – 945.45 m	Anhydrite, white, brecciated at the base
945.45 – 951.57 m	Heterogeneous alternation of dolostone, pale pink to beige grey, dolomitic marl (silty), medium grey to light grey, claystone (anhydritic), medium grey to dark grey, anhydrite (argillaceous), medium grey, anhydrite (white), partly nodular and nodules, breccias, anhydritic (polymict), with angular dolostone lithoclasts, anhydrite veins, white to pink
951.57 – 954.37 m	Laminated anhydrite interval: anhydrite, white, with thin interbeds (1 mm to 10 mm) of argillaceous marl, medium to dark grey, claystone (dolomitic), dark grey to black and dolostone, very light grey, medium grey, dark grey, black; partly folded, thin layer of breccia, anhydritic (polymict) at the base
954.37 – 963.87 m	Massive to banded anhydrite interval; anhydrite, white, with interbeds of claystone (anhydritic), medium grey, and anhydrite (argillaceous), light grey; partly folded
963.87 – 971.79 m	Alternation of anhydrite (dolomitic) light grey to grey beige, with interbeds of claystone (anhydritic, silty), anhydrite (argillaceous), dark grey. Below 968.70 m, claystone (anhydritic), light grey to dark grey, thin-bedded to laminated, with interbeds of argillaceous marl (silty) to anhydrite (argillaceous), anhydrite (dolomitic), anhydrite; breccia, anhydritic (polymict) near the base

971.79 – 976.57 m	Interval with an irregular alternation of various types of laminated anhydrite: • anhydrite, laminated to massive, with thin claystone and breccia interbeds (mm to cm) • anhydrite (dolomitic), light grey to beige, banded • anhydrite (argillaceous), dark grey, laminated • anhydrite, white, with by thin argillaceous marl beds, light grey • breccia, anhydritic (polymict), with a matrix of claystone (dolomitic)
976.57 – 982.76 m	Interval with rather massy anhydrite: anhydrite, white, distinctly nodular (chickenwire) at the top to slightly nodular and massive and finally fine-layered with some breccia and dolomitic marl interlayers. At the base, dolostone beds and nodules
982.76 – 984.75 m	Chaotic interval: argillaceous marl (silty), dark grey, partly folded, claystone (anhydritic), dark grey, with small (up to 1 mm) lithoclasts of anhydrite, white, and, from 983.99 m to 984.75 m, breccia, anhydritic (polymict), light grey, including lithoclasts of argillaceous and banded anhydrite. This chaotic, clay-rich interval could be in line with what was formerly known as «Salztun», i.e. a subroded rock salt deposit (<i>cf.</i> Jordan 2016)
984.75 – 986.61 m	Thin-bedded anhydrite interval: anhydrite, white, anhydrite (dolomitic), light grey and claystone (anhydritic), dark grey; massive anhydrite layer at the base
986.61 – 989.94 m	At the top, from 986.61 to 986.94 m, argillaceous sandstone and argillaceous siltstone, dark greyish brown, fine-layered, and claystone (dolomitic, silty), dark reddish brown and greyish green, with anhydrite nodule at the base From 986.94 m to 989.94 m, medium- to fine-scale alternation of anhydrite (argillaceous), white, claystone (dolomitic), dark grey, with anhydrite nodules and lithoclasts of layered anhydrite, white, anhydrite (dolomitic), light grey, and, from 988.99 m to 989.07 m, breccia, anhydritic (polymict)
989.94 – 991.51 m	Massive anhydrite interval: anhydrite, white, predominantly selenite facies with interlayers of laminated, partly graded anhydrite
991.51 – 993.50 m	Fine-layered to laminated dolomitic marl to dolostone, beige to light grey with mostly thin interlayers of anhydrite, white, and anhydrite (argillaceous), light grey with light greenish hue; at the base, from 993.02 m to 993.50 m, anhydrite layers (sulpharenite) dominate

3.8.3 Kaiseraugst Formation, 993.50 – 1'029.45 m (35.95 m)

The Kaiseraugst Formation is a succession of claystone (calcareous, silty) to argillaceous marl (silty, partly bituminous) in the upper part and dolomitic marl in the lower part (Jordan 2016). Interbeds of limestone, dolostone and sandstone can occur throughout the unit, the latter two particularly in the lowermost part of the formation. Some of the interbeds are lithostratigraphic marker horizons.

In MAR1-1, dolomite is only a negligible part of the rock mineralogy; consequently the «Wellendolomit» is much more calcareous and more sandy than corresponding sections in neighbouring boreholes (Nagra 2001a, Schwarz et al. 2021).

The *upper boundary* is set at 993.50 m, at the top of the first massive and (slightly) bituminous dolostone (argillaceous) bed. The lowermost anhydrite (dolomitic) bed of reasonable thickness is found from 993.65 m to 993.87 m.

The *lower boundary* is set at 1'029.45. The interval between 1'028.17 m and 1'029.45 m is formed by an alternation of sandstone (fine-grained, coarse-grained in nests) and calcareous sandstones (fine-grained). This interval is interpreted as a repeated interference between marine and terrestrial facies and thus the base of the Kaiseraugst Formation. The erosional surface at 1'028.17 m is believed to represent a later, intra-formational transgression.

Lithostratigraphic subdivision

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

993.50 – 1'001.90 m «Orbicularismergel» (8.40 m)

1'001.90 – 1'022.44 m «Wellenmergel» (20.54 m)

1'022.44 – 1'029.45 m «Wellendolomit» (7.01 m)

The boundary between the «Orbicularismergel» and the «Wellenmergel» is drawn, correlating with the records of the nearby Benken borehole, at the base of a coquina bed identified there as «Orbicularisbank» (Nagra 2001a).

The boundary between the «Wellenmergel» and the «Wellendolomit» is set at 1'022.44 m, at the top of the uppermost thicker sandy limestone (argillaceous) to limestone (silty, argillaceous) interval.

Lithology

«Orbicularismergel», 993.50 – 1'001.90 m (8.40 m)

- 993.50 – 996.30 m At the top, from 993.50 m to 994.98 m, dolostone, beige grey to dark beige with brownish hue, slightly bituminous, with, from 993.50 m to 994.29 m, thin anhydrite interlayers and very small anhydrite nodules. This section corresponds to the «Unterer Dolomit» (e.g. Jordan 2016)
- From 994.98 m to 996.30 m, calcareous marl, beige grey to dark beige, and dolomitic marl (silty), beige grey to dark beige, both slightly bituminous
- 996.30 – 998.22 m Argillaceous marl, dark grey to black, slightly bituminous, to claystone (dolomitic), black, bituminous, fine crystalline mica, disperse bivalves and brachiopods, and, from 998.08 m to 998.11 m, a coquina, erosional surfaces at 997.16 m, 997.24 m and 997.84 m, dolomitic marl (silty) with compacted soft pebbles at the base
- 998.22 – 1'000.53 m Anhydrite, white, in the upper part nodular (chickenwire), below massive, partly with irregular inclusions of dolomitic marl, pale yellowish green, and, at the base, with lenticular beds of anhydrite (dolomitic), white. This far-ranging marker bed, which is also known from the nearby Benken and Trüllikon-1-1 boreholes (Nagra 2001a, Schwarz et al. 2021), is known as «Geislingen-Bank» in adjacent Southern Germany (e.g. Geyer et al. 2011, Hochuli et al. 2020)
- 1'000.53 – 1'001.90 m At the top, from 1'000.53 m to 1'000.70 m, dolostone (argillaceous), dark grey to black, fine crystalline mica, with four coquina horizons
- From 1'000.70 m to 1'001.90 m, argillaceous marl, dark grey to black, fine crystalline mica, several thicker coquina beds (calcareous marl) and numerous mostly very thin coquinas (bivalves, brachiopods). A characteristic succession of three thicker coquinas with erosive base from 1'001.16 m to 1'001.90 m can be well correlated with the findings in the Benken borehole where the lowermost of the coquinas was identified as «Orbicularisbank», marking the base of the «Orbicularismergel» (Nagra 2001a)

«Wellenmergel», 1'001.90 – 1'022.44 m (20.54 m)

- 1'001.90 – 1'009.97 m Claystone interval with numerous coquinas: claystone (silty to sandy, calcareous), dark grey to black, mica, fossiliferous (brachiopods, bivalves), fine-bedded to laminated, with lenses and thin beds (partly broken) of calcareous marl, medium grey, some with coquinas (bivalves, brachiopods) with erosive base, single or in bundles; with interbed, from 1'008.11 m to 1'008.50 m, of limestone (packstone, biomicrite), medium grey, with large vug

- 1'009.97 – 1'012.18 m Fossiliferous marl interval: calcareous marl (silty), light grey, fossils (brachiopods, bivalves) disperse rather than in coquinas, bioturbation, fine-bedded, with interlayers of argillaceous marl (silty), medium grey, mica, and claystone (calcareous), dark grey to black, and, at the base, thin lenses of siltstone (argillaceous), light grey
- 1'012.18 – 1'015.06m Claystone interval with silt- and sandstone lenses and coquinas, mainly in its lower part: claystone (silty, calcareous), dark grey, mica, fossils (brachiopods, bivalves), fine-bedded to laminated, occasionally bioturbated, numerous lenses and thin layers of silty marl, medium grey, slightly less numerous lenses of siltstone (argillaceous) to sandstone (fine-grained) (argillaceous), light grey, showing foresets (ripples). The coquinas from 1'014.86 m to 1'015.06 m contain galena and may be correlated to the domain of the «Bleiglanzbank»
- 1'015.06 – 1'022.44 m Claystone interval with calcareous nodules and virtually no coquinas: claystone (silty, calcareous), dark grey, mica, fossils (bivalves, brachiopods), bioturbation, many late-diagenetic calcareous nodules, coquina from 1'019.78 m to 1'019.82 m, near the base, from 1'021.96 m to 1'022.08 m, two interlayers, up to 5 cm thick, of sandy limestone, nodular, underlain by a coquina

«Wellendolomit», 1'022.44 – 1'029.45 m (7.01 m)

- 1'022.44 – 1'024.13 m Heterogeneous coarsely siliciclastic and calcareous succession: thinner beds and thicker beds of limestone (silty, argillaceous) (mudstone, micrite), light beige, sandy limestone (mostly argillaceous), very light grey, mica, often associated with coquina and galena, argillaceous marl (silty), medium grey with greenish hue, mica, sandy marl, medium grey, mica, and calcareous sandstone (fine-grained), very light grey with darker lithoclasts, normally graded; most of the beds are bioturbated
- 1'024.13 – 1'026.21 m Predominantly marly interval: argillaceous marl (silty), dark grey, with lenses and layers of limestone (sandy, argillaceous), light grey, and, from 1'025.24 m to 1'025.47 m, interlayer of sandy limestone (argillaceous), very light grey, with lithoclasts
- 1'026.21 – 1'028.17 m Calcareous marl (sandy), medium grey, nodular and silty limestone, medium grey, flaser bedded, and silty marl, medium grey, with limestone nodules
- At the base, from 1'028.15 m to 1'028.17 m, basal conglomerate, calcareous (polymict), with flattened components above erosive surface
- 1'028.17 – 1'029.45 m At the top, from 1'028.17 m to 1'028.41 m, calcareous sandstone, almost fully silicified in the upper part, partly silicified in the lower part, light grey
- From 1'028.41 m to 1'029.45 m, sandstone and calcareous sandstone (fine-grained, coarse-grained in nests), light greenish grey and white, medium-sorted, subangular, polymict (but quartz dominates), well cemented (calcite and quartz), banded

3.9 Buntsandstein Group

3.9.1 Dinkelberg Formation, 1'029.45 – 1'037.98 m (8.53 m)

The Dinkelberg Formation consists of siliciclastics with a preponderance of sandstones. The sandstones display a high degree of compositional as well as textural maturity. Intervals dominated by claystone and conglomerates / breccias also occur. In combination with the lithofacies, they are used to separate sub-units of the formation. However, there is no formal subdivision of the Dinkelberg Formation as yet. Jordan (2016) suggests provisionally maintaining the traditional subdivision (from the top): «Rötton», «Plattensandstein», «Vogesensandstein».

In MAR1-1, the «Rötton» is missing, as in the nearby Benken and Trüllikon-1-1 boreholes (Nagra 2001a, Schwarz et al. 2021).

The medium- to thick-bedded sandstone (fine-grained to coarse-grained) of the upper part of the formation can, with reservation, be addressed as «Plattensandstein».

Unusual, compared to the nearby Benken and Trüllikon-1-1 boreholes (Nagra 2001a, Schwarz et al. 2021), is the comparatively thick succession of silicified coarse sandstones, conglomerates and breccias at the base. Irregularly shaped reddish brown chalcedony concretions are already found in the sandstone bed from 1'033.71 m to 1'034.09 m. They become abundant in the very heterogeneous interval from 1'035.07 m to 1'036.06 m that can be addressed as «Karneol-Dolomit-Horizont» (paleosol formation rich in chalcedony and dolomite). If this is the VH2 of the German stratigraphic scheme (e.g. Geyer et al. 2011), on the one hand the assignment of «Plattensandstein» to the overlying sediments would be confirmed and, on the other hand, the conglomerate and coarse sandstones below could be the «Vogesensandstein», which was later partly silicified. Alternatively, the whole sequence from 1'033.71 m to 1'037.77 m can be interpreted as a «Karneol-Dolomit-Horizont».

The *upper boundary* is set at 1'029.45. The interval between 1028.17 m and 1029.45 m is formed by an alternation of sandstone (fine-grained, coarse-grained in nests), and calcareous sandstones (fine-grained). This interval is interpreted as a repeated interference between marine and terrestrial facies and thus the base of the Kaiseraugst Formation.

The *lower boundary* is set at 1'037.98 m, at an erosional surface between two types of sandstone. The boundary is associated with a significant change in colour, grain size and mineral composition.

Lithology

- 1'029.45 – 1'031.15 m Sandstone (mostly medium-grained, locally also fine-grained), light greenish grey, subangular to subrounded, moderately sorted, polymict (> 90% quartz, plagioclase, mica, lithoclasts [granite], argillaceous matrix), moderately cemented (quartz), with small (up to 2 cm) calcareous nodules, locally cross-bedded
- 1'031.15 – 1'033.71 m Sandstone (increase in grain size from coarse-grained at the top to very coarse-grained at 1031.88 m and back to medium-grained at the base), patchy light greenish grey, dark pink and grey violet, subangular to subrounded, moderately sorted, almost monomict (> 90% quartz, sparse feldspar and lithoclasts), moderately (quartz) to poorly cemented (anhydrite), locally cross-bedded

- 1'033.71 – 1'035.07 m Sandstone (fine-grained) (argillaceous), mainly grey-violet, light greenish grey, well rounded, poorly sorted, polymict (quartz dominates), poorly cemented (clay matrix), with irregularly formed aggregates (some mm up to 2 cm) of chalcedony, reddish brown. This interval shows similarities to a «Karneol-Dolomit-Horizont»
- From 1'034.09 m to 1'035.07 m, sandstone (medium-grained), light greenish grey, in patches grey, subangular, moderately sorted, polymict (mainly quartz, some clasts), moderately to well cemented (quartz), with chert concretions, pink, up to 4 cm and cross-bedding at the base
- 1'035.07 – 1'036.06 m Lenticular to irregular alternation of breccia, siliciclastic dolomitic (polymict), reddish brown and greenish grey, dolostone (partly calcareous), white, partly silicified, subhorizontal, slightly undulating beds of chalcedony, very light grey, partly transparent, and sandstone, reddish brown, silicified; this interval can be addressed as «Karneol-Dolomit-Horizont»
- 1'036.06– 1'037.98 m Conglomerate, siliciclastic (polymict), to sandstone (very coarse-grained to coarse-grained), light grey, argillaceous matrix, partly calcite cemented with large quartz pebbles (up to 8 cm), sandstone and crystalline lithoclasts, locally dolomitic, locally silicified and including dolomite / calcite – chalcedony concretion and subhorizontal, undulating veins of chalcedony
- At the base, from 1'037.77 m to 1'037.98 m nodules of sandstone (fine-grained), light grey, silicified in a matrix of sandstone (coarse-grained), well rounded, monomict (quartz), well cemented to silicified, some larger, rounded clasts, vugs

3.10 Permo-Carboniferous sediments

3.10.1 Weitenau Formation, 1'037.98 – 1'094.08 m (56.10 m)

The Weitenau Formation (*cf.* Jordan & Deplazes 2019) was defined to unite the three informal units (from above) «Oberer Schuttfächer», «Playa-Serie» and «Unterer Schuttfächer». They are traditionally regarded as representing the upper part of the Permian in Northern Switzerland (Blüm 1989).

In MAR1-1, the interval between the overlying Dinkelberg Formation and the Crystalline basement is, in a broader sense, fanglomeratic, i.e. it is composed of breccia and predominantly coarse-grained, angular to subangular sandstone with angular blocks, all polymict, subarkosic to arkosic, with claystone matrix. The interval can be divided into three quite homogeneous sections:

- 1'037.98 – 1'049.98 m Sandstone (coarse- to fine-grained), matrix (argillaceous) supported
- 1'049.98 – 1'090.59 m Fanglomerate, successively changing from breccia, Crystalline basement (polymict), predominantly matrix (argillaceous) supported, to breccia, Crystalline basement (polymict), predominantly clast supported
- 1'090.59 – 1'094.08 m Sandstone (coarse-grained), calcareous, matrix (argillaceous) supported

The *upper boundary* is set at 1'037.98 m, at an erosional surface between two types of sandstone. The boundary is associated with a significant change in colour, grain size and mineral composition. The nodular sandstone (fine-grained), light grey, in a coarse-grained matrix, silicified above the erosional surface, is replaced by sandstone, argillaceous (coarse- to fine-grained), subarkosic, reddish brown to dark reddish brown.

The lower boundary is set at 1'090.59 m, at the top of a biotite-plagioclase-gneiss. The boundary is sharp, i.e. a zone of weathered crystalline rock as found in other places, does not exist.

Lithology

1'037.98 – 1'049.98 m Sandstone, argillaceous (coarse- to fine-grained), subarkosic, reddish brown to dark reddish brown, disperse light grey to medium light grey patches (reduction halos), poorly sorted, angular to subangular, sparse mica, polymict (quartz more than 80%, feldspar, lithoclasts), poorly cemented (clay matrix); the lithoclasts (many up to 4 cm) include unaltered granite (quartz, plagioclase, alkali-feldspar, mica), locally thin breccia interlayers

1'049.98 – 1'090.59 m Breccia, Crystalline basement (polymict), matrix (argillaceous) to clast supported, reddish brown to dark reddish brown, some light grey patches (reduction halos)

The larger components comprise exclusively Crystalline basement components, i.e. mesosome biotite-plagioclase-gneiss, medium (light) grey, fine-grained, foliated and melanosome inclusions, dark pink to reddish brown, medium-grained (< 1 cm), equigranular, equal proportions of quartz, alkali-feldspar and plagioclase

There is an irregular change between matrix supported and clast supported sections. The matrix is formed by sandstone (mainly medium-grained, locally fine-grained to silty), subarkosic to arkosic, moderately sorted, angular, polymict (quartz, feldspar, mica [biotite and muscovite], and, possibly, hornblende), moderately cemented (quartz). Within the clast supported sections, occasionally patches with sparitic calcite cement, white, are found

1090.59 – 1094.08 m Sandstone (coarse-grained) (calcareous, locally argillaceous), matrix (argillaceous), mostly pale violet, locally dark reddish brown, reduction halos light grey, with some lithoclasts and, in the lower domain and at the base, two levels of breccia, siliciclastic (polymict)

3.11 Crystalline basement, 1'094.08 – 1'099.25 m (> 5.17 m)

The crystalline rocks consist of an alternation (30 cm to 80 cm) of biotite-plagioclase-gneiss and leucosome, starting with gneiss at the top.

Petrography

Mesosome ("Biotite-Plagioclase-Gneiss")

Overall medium light grey, fine-grained, biotite and plagioclase abundant, foliated, mm-thick banded, mostly unaltered, close to the top of the crystalline rock section, brecciated with amorphous black material along some fractures (fault gouge); some steep veins (width ≤ 1 cm) of leucosome.

Leucosome of granitic composition

Overall variegated from dark pink to reddish brown with schlieren of darker colour, medium-grained (< 1 cm), equigranular, equal proportions of quartz, variegated, alkali-feldspar, reddish orange, and plagioclase, white, small to very small amounts of biotite and hornblende, not foliated, unaltered.

4 Comparison with the forecast profile

Generally, there are only minor differences between the findings from MAR1-1 and the forecast profile (Fig. 4-1; Nagra 2016), which is mainly based on the record of the nearby Benken borehole (Nagra 2001a). Deviations from the forecast profile of 10 m or more in thickness or depth are:

- the thickness of the unconsolidated rock is significantly greater than expected (48 m instead of 30 m)
- the top of the Mesozoic strata was reached at 254 m, 19 m deeper than expected. This shift of about 20 m continues throughout the whole Jurassic and uppermost Triassic into the Bänkerjoch Formation. At the top of the Muschelkalk Formation, the deviation is only +3 m. The sediments of the Muschelkalk and Buntsandstein Groups are about 5 m thinner than expected, so that the base of the Mesozoic was reached 2 m higher than predicted
- the heterogeneous «Brauner Dogger» succession (Dogger Group without Opalinus Clay) is some 88 m thick, 13 m more than predicted. The forecast profile provides only vague information on the thickness and facies of the individual formations and these have been largely confirmed. The «Parkinsoni-Württembergica-Schichten» and the Wedelsandstein Formation make up the main share. Both formations are about the same thickness and the rest of the formations are fairly thin
- the Bänkerjoch Formation is slightly thinner than expected (72 m instead of 85 m). This also applies for the other evaporite sequence, the Zeglingen Formation, showing a similar relative deviation (61 m instead of 70 m). The prognosis that rock salt may be found within the Zeglingen Formation has not been confirmed
- below the Triassic Dinkelberg Formation, some 56 m of Weitenau Formation have been found. Thus, the Crystalline basement was encountered some 55 m lower than expected

The lithofacies within the Lower Freshwater Molasse Group (USM) is in line with expectations as far as can be assessed by the analysis of the cuttings samples. There are no indications regarding the chronostratigraphic age of the encountered sediments and there are also no further arguments to distinguish a younger (Aquitanian) USM I from an older (Chattian) USM II.

In the forecast profile the potential existence of rather thin, stratiform sediments of the Siderolithic Group was indicated. The actual thickness is about 6 m. As all samples also contain calcareous components, it is not clear whether it is the Siderolithic Group in the narrow sense or already Molasse with washed-out Siderolithic components.

In the forecast profile (Nagra 2016), the upper limestone succession of the Malm Group is subdivided into «Bankkalke» + «Massenkalk» and «Felsenkalke» + «Massenkalk». Later it was proposed (Jordan & Deplazes 2019) to summarise all these rocks as «Felsenkalke» + «Massenkalk» and only to distinguish, within this informal unit, between «Felsenkalke» facies and «Massenkalk» facies. Since the section was destructively drilled, only vague statements could be made. FMI and cuttings analysis confirm a multiple change in bed thickness and limestone microfacies.

Also mainly based on the FMI is the demarcation of the Schwarzbach Formation which turns out to be rather thin compared to adjacent boreholes.

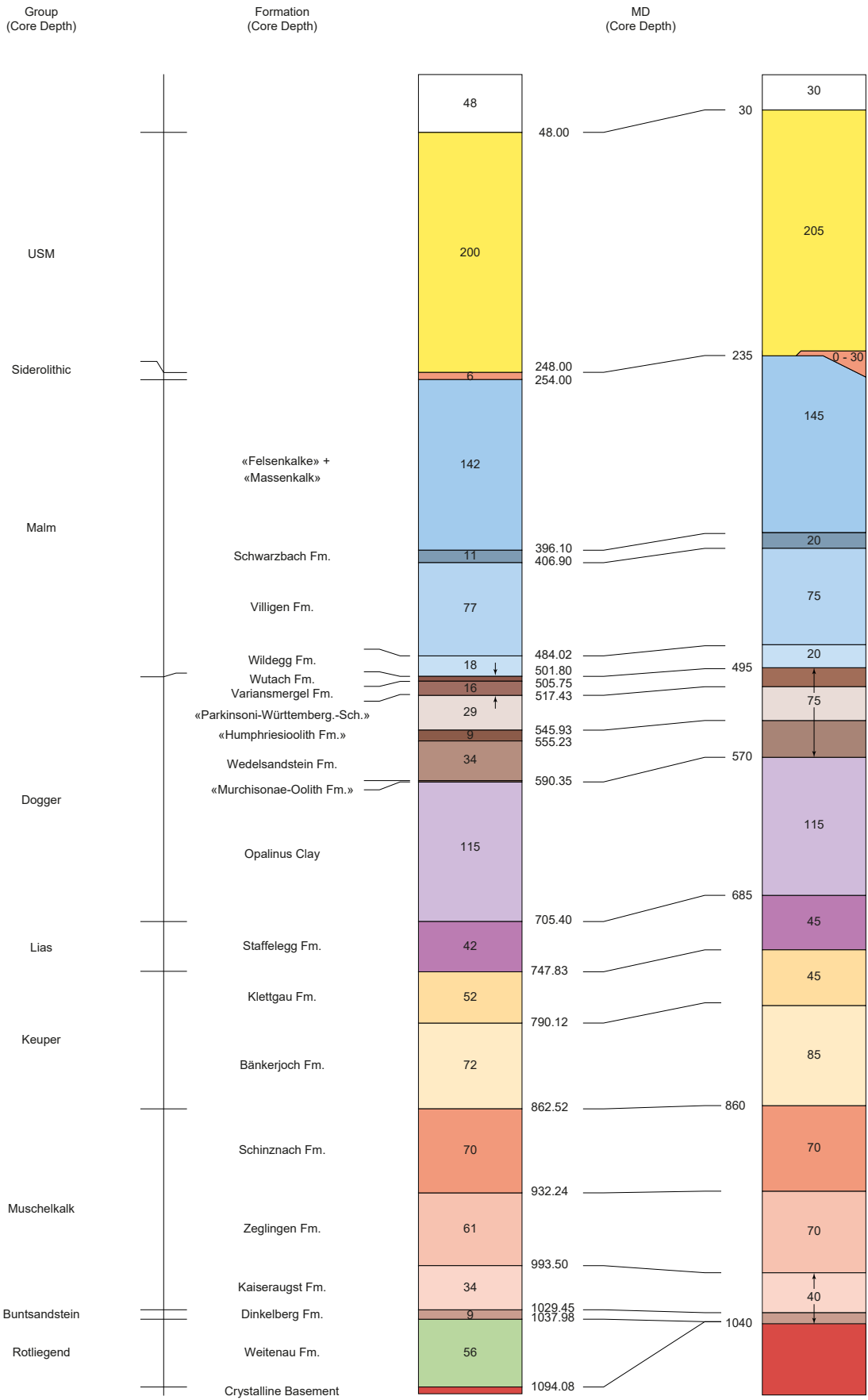


Fig. 4-1: Comparison of the forecast with the actual findings of MAR1-1

In the ZNO siting region, the Villigen Formation is expected to be dividable into (from top) the Wangental, Küssaburg and Hornbuck Members. As the separating «Knollen Bed», a glauconitic and nodular marker interval between the Wangental and Küssaburg Members (which show great affinities to each other), could not be found in the cuttings of MAR1-1, a distinction was not possible. The sediments found below the change from destructive drilling to coring show great affinities to the Hornbuck Member. However, as the boundary to the overlying member is not visible, it was decided to refrain from a subdivision of the Villigen Formation.

The Wildegg Formation matches expectations. This applies also for the largely condensed Birmenstorf Member and the underlying «Glaukonitsandmergel Bed» sensu Gygi (1977, 2000, 2012) at its base.

The thin Wutach Formation and the Variansmergel Formation correspond in thickness and facies to the expectations. There are indications that the «Parkinsoni-Württembergica-Schichten» comprise mainly the «Württembergica-Schichten» and the «Parkinsoni-Oolith», i.e. the «Parkinsoni-Schichten» are very thin. The «Humphriesioolith Formation» shows the same configuration, with two iron-oolitic horizons separated by a thicker marl layer, as in the nearby Benken borehole. The Wedelsandstein Formation and the «Murchisonae-Oolith Formation» were also found in expected thickness.

The thickness (115 m) of the Opalinus Clay exactly matches expectations. Also, its facies is in good agreement with the forecast and the Benken borehole. The four sub-units recently proposed by Mazurek and Aschwanden (2020) could be identified.

The thickness and facies of the Staffelegg Formation correspond largely to the forecast, which is based on the findings from the Benken borehole. The total thickness (124 m) of the Klettgau and Bänkerjoch Formations almost exactly matches the expectations (125 m). However, there is a shift from the Bänkerjoch Formation (slightly thinner than expected) to the Klettgau Formation (slightly thicker than expected). Looking at the facies, there is a good correlation with the Benken borehole.

The overall thickness and facies of the Schinznach Formation match the prognosis. In detail, the Asp Member is thicker (5.1 m) than in the Benken borehole (4.2 m). The post-sedimentary persistent and complete dolomitisation is comparable in MAR1-1 and Benken, resulting in an almost equal thickness of the Stamberg Member at both locations (38.8 m compared to 37.1 m in the Benken borehole). Also, the total thickness of the Liedertswil, Kienberg and Leutschenberg Members corresponds almost exactly to the findings in the Benken borehole.

The Zeglingen Formation (about 61.0 m) proved to be slightly thinner than predicted (90 m) but also thinner than recorded in the Benken borehole (about 67.7 m). This is presumably due to the missing rock salt. In the Benken borehole, about 14 m of pure salt and salt-bearing rock are present.

The Kaiseraugst and Dinkelberg Formations, on the other hand, again meet expectations, although both are slightly thicker than predicted. Below, 56 m of mostly fanglomeratic rocks, interpreted as part of the Weitenau Formation, were found before the Crystalline basement was reached.

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