Arbeitsbericht
NAB 22-03

TBO Rheinau-1-1:
Data Report

Summary Plot

June 2023

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

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RHE1-1, Zürich Nordost, TBO, deep drilling campaign, wireline, cores, cuttings, casing, lithostratigraphy, structural geology, logging, petrophysics, mineralogy, packer testing, pore water chemistry, natural tracers, laboratory testing, geomechanics, rock properties, stress indicators

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

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

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

The composite plot was set up and designed by D. Arndt, M. Gysi, H.R. Müller and M. Schnellmann based on the information contained in Dossiers I to X.

The following Nagra project managers, responsible for the individual dossiers, provided technical input: P. Hinterholzer-Reisegger (Dossier I), M. Gysi (Dossier II), F.Casanova (Dossier III and V), G. Deplazes (Dossier IV), R. Garrard (Dossier VI), A. Pechstein (Dossier VII), D. Traber (Dossier VIII) and J.K. Becker (Dossier X).

Editorial works: M. Unger and P. Blaser

Table of Contents

List of Tables

List of Figures

List of Appendices

Note: In the digital version of this report the appendix 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 Rheinau-1-1 borehole located in the siting region Zürich Nordost (Fig. 1-2). In the following, the main exploration objectives of this specific borehole are further outlined.

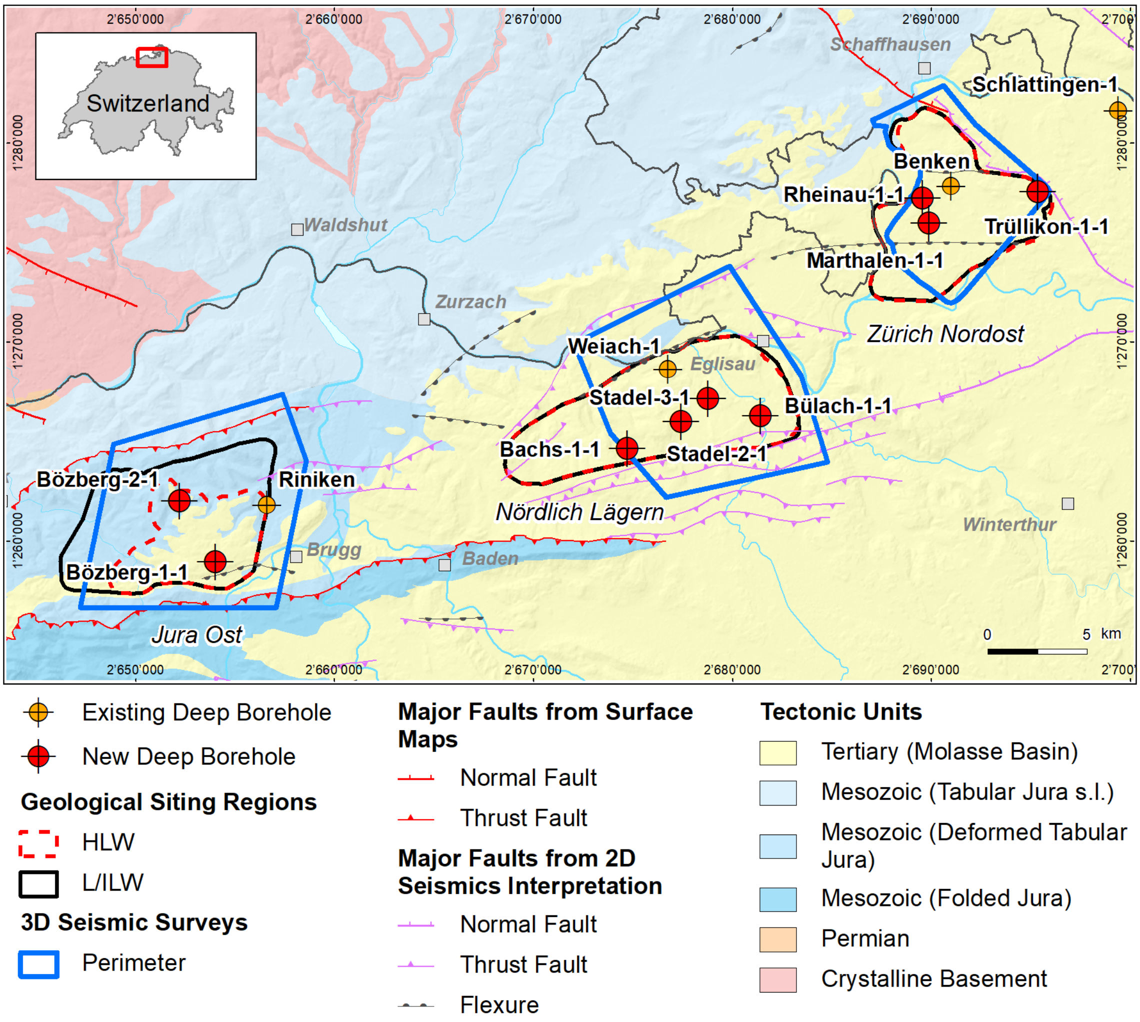

Fig. 1-1: Tectonic overview map with the three siting regions under investigation

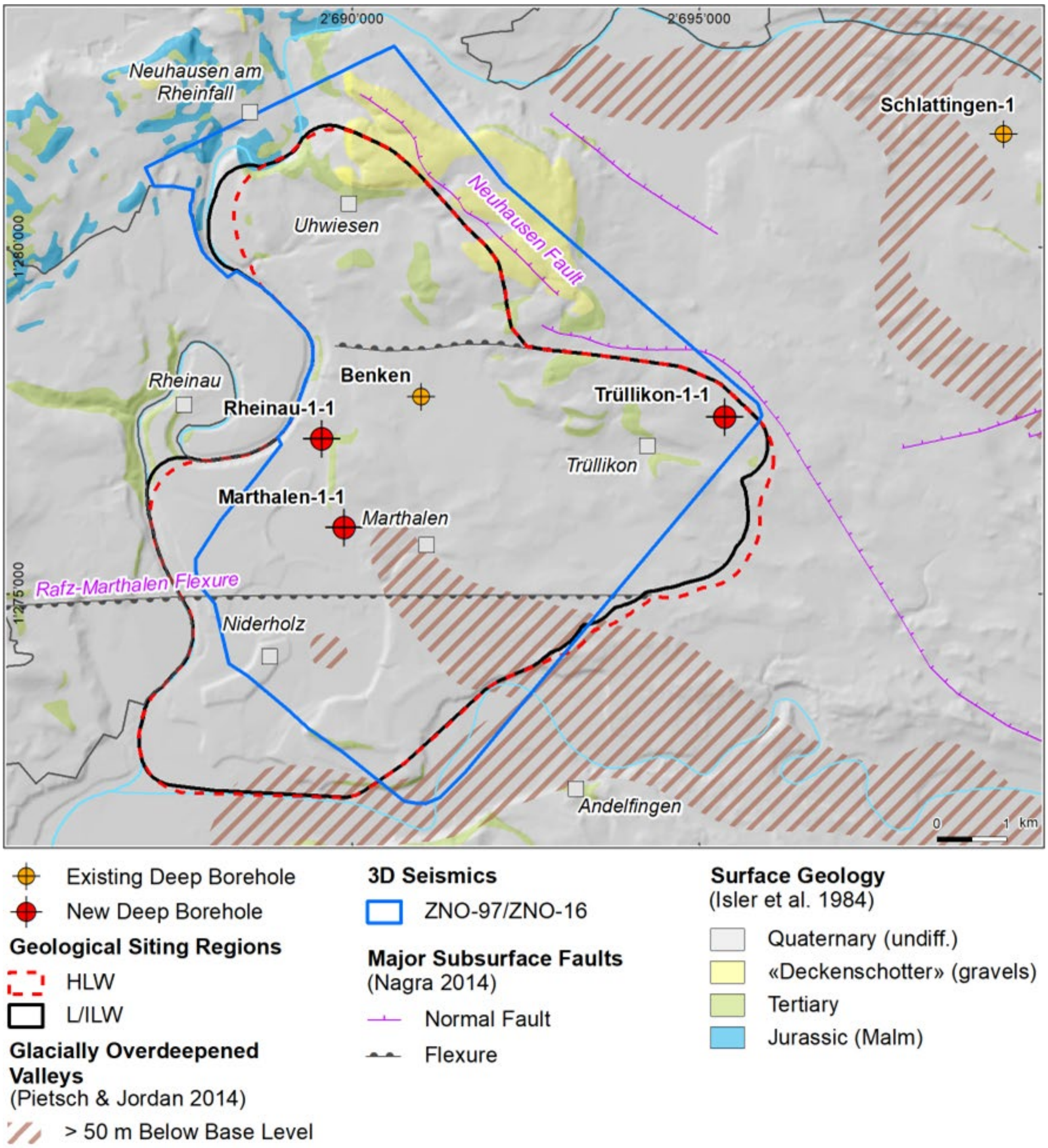

Fig. 1-2: Overview map of the investigation area in the Zürich Nordost siting region with the location of the RHE1-1 borehole in relation to the Benken, TRU1-1 and MAR1-1 boreholes

Exploration objective of the Rheinau-1-1 borehole

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

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

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

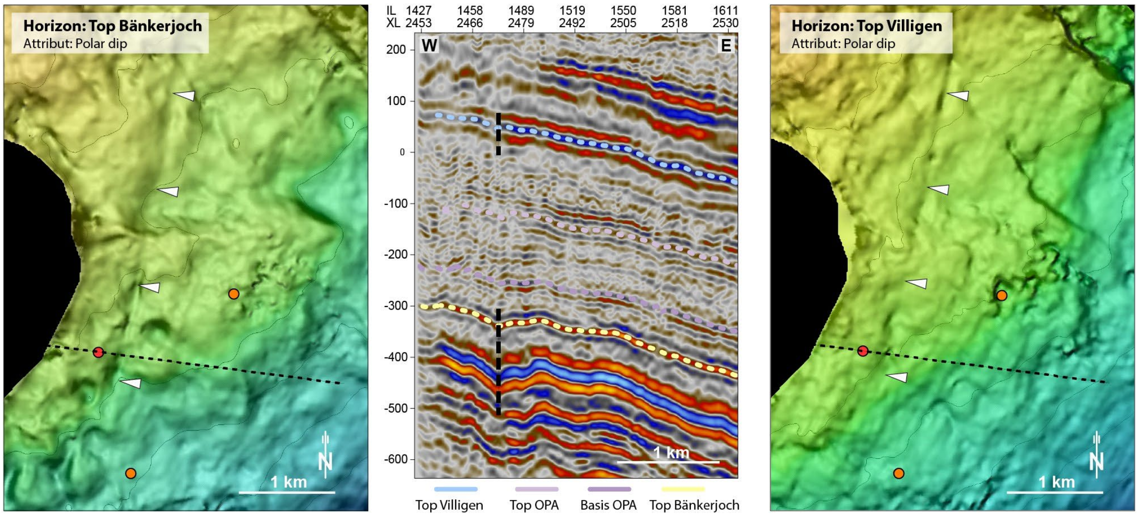

Fig. 1-3: Seismic amplitude cross-section and seismic attribute maps showing the Rheinau Fault

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

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

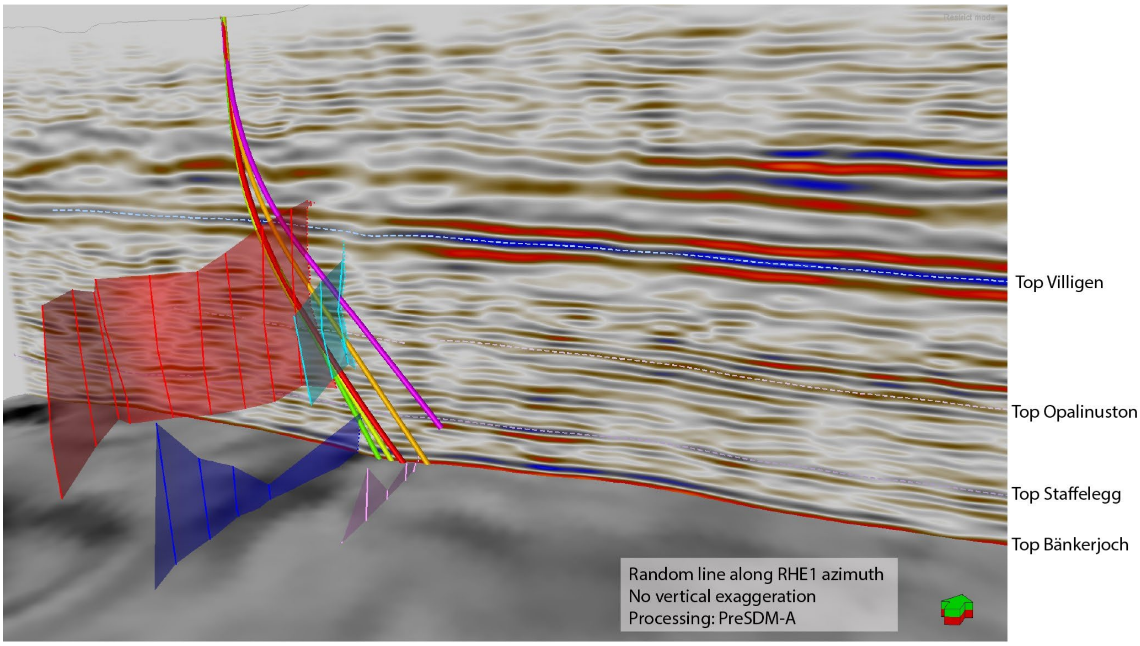

Fig. 1-4: Detailed seismic fault interpretation available for trajectory planning and discussed/ executed well trajectories

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

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

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

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

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

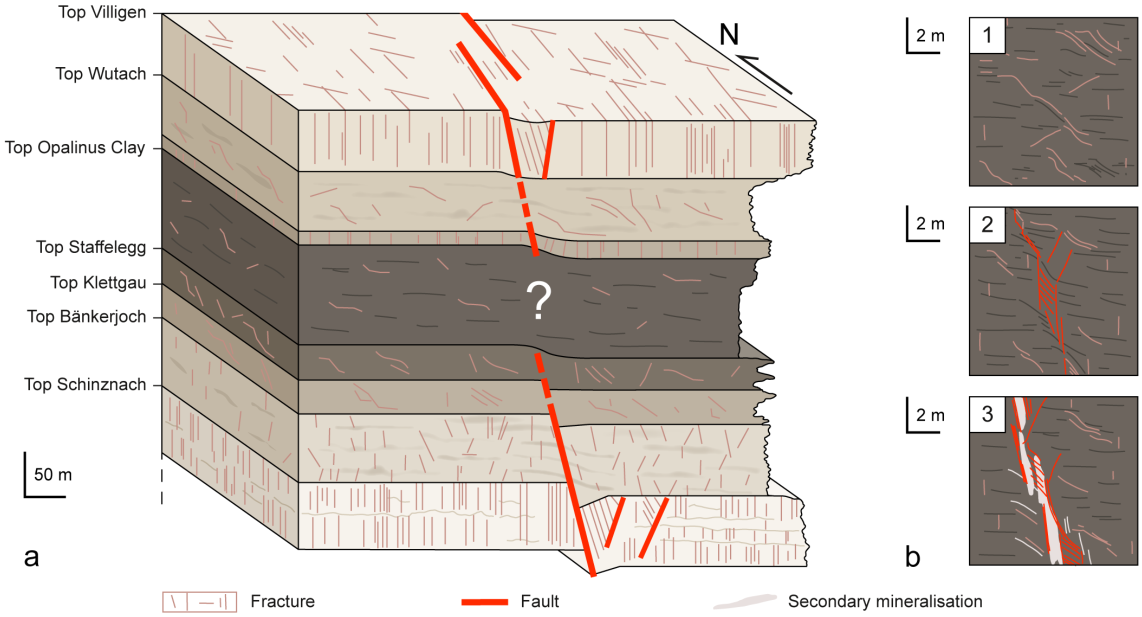

Fig. 1-5: Conceptual structural model of the Rheinau Fault

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

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

1.2 Location and specifications of the borehole

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

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

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

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-6. The comparison of the core versus log depth[3] of the main lithostratigraphic boundaries in the RHE1-1 borehole is shown in Tab. 1-2.

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

[2] For detailed information, see Dossier I.

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

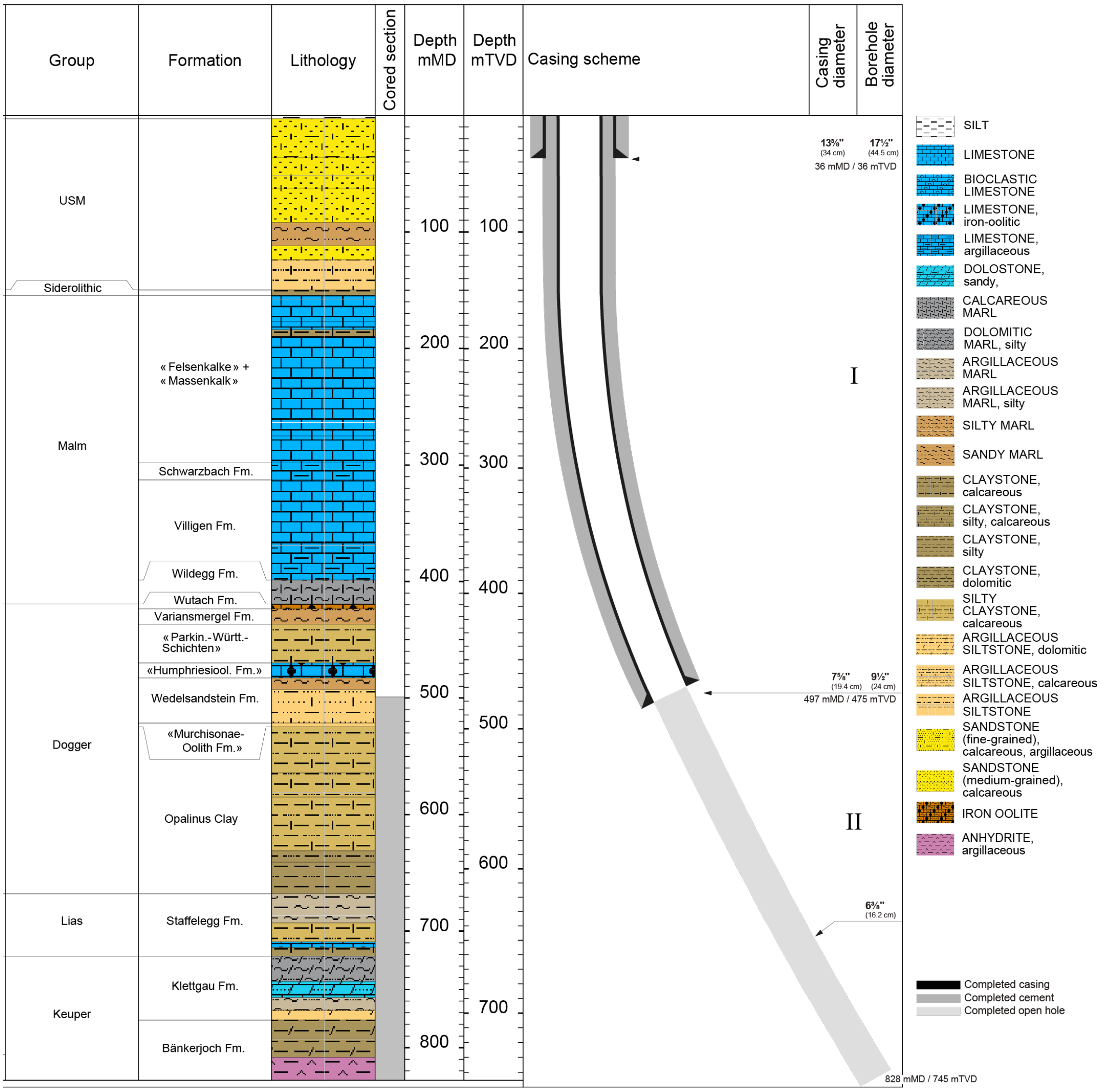

Fig. 1-6: Lithostratigraphic profile and casing scheme for the RHE1-1 borehole[4]

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[4] For detailed information, see Dossiers I and III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the RHE1-1 borehole[5]

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

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[5] For details regarding lithostratigraphic boundaries, see Dossiers III and IV; for details about depth shifts (core goniometry), see Dossier V.

1.3 Documentation structure for the RHE1-1 borehole

NAB 22-03 documents the majority of the investigations carried out in the RHE1-1 borehole, including laboratory investigations on core material. The NAB comprises a series of stand-alone dossiers addressing individual topics and a final dossier with a summary composite plot (Tab. 1-3).

This documentation aims at early publication of the data collected in the RHE1-1 borehole. It includes most of the data available approximately one year after completion of the borehole. Some analyses are still ongoing and results will be published in separate reports.

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

Tab. 1-3: List of dossiers included in NAB 22-03

Black indicates the dossier at hand.

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

1.4 Scope and objectives of this dossier

The dossier at hand summarises the most important results in the form of a composite plot (Appendix A). A short technical explanation of the information displayed is given in Chapter 2, column by column from left to right.

Due to the specific aims of the deviated borehole RHE1-1, a reduced investigation program has been carried out. This is reflected in the summary plot.

Compared to the standard TBO-program the following measurement types are not available:

- Lab measurements determining total clay mineral contents, clay mineral composition, porosity, hydraulic permeability, porewater chloride content, p-wave velocity and geomechanical properties.
- Groundwater chemistry data (no groundwater sampling)
- MHF-measurements (stress magnitudes)
- Undisturbed temperature profile (no post completion temperature log and no long-term monitoring temperature data available)

2 Short explanation of the attached summary plot

2.1 Metres MD

Measured depth (MD) refers to the position along the borehole trajectory, starting at ground level, which for the TBO boreholes 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. For the deviated borehole RHE1-1, there is a significant difference between MD and TVD. The summary plot refers to MD. For comparison, the calculated depth in metres TVD is also shown (to the left of the column indicating the casing scheme).

2.2 System / Period / Group / Formation / Member

Detailed information regarding the lithostratigraphic classification can be found in Dossier III.

2.3 Depth interval

The numbers in this column refer to the position of the lithological boundaries displayed in the neighbouring columns in metres (m) MD core depth. Core depth refers to the depth marked on the drill cores.

2.4 Lithology

The displayed colours and patterns represent the primary lithology, simplified and upscaled from the original 1:100 to a 1:5'000 profile; for details see Dossier III.

2.5 Weathering plot with GR

The weathering plot visualises the relative resistance of different lithologies to weathering; the larger the bars in black from left to right, the more resistant the lithology to weathering. The different styles of the horizontal separation lines indicate different lithological boundary types; for details see Dossier III.

The total natural gamma ray (GR) measurement, a qualitative indicator for clay content and hence an indicator for weathering, is visualised for comparison in green. Please note that the scale is reversed (decreasing values from left to right) compared to the GR measurement displayed in the column "Natural gamma ray"; for details see Dossier VI.

2.6 Cuttings & core photos

Photos taken from cuttings and drill cores are shown in this column. Please note that the scale of the photos is different for the x- and the y-axis in order to fit the plot; white gaps represent sections where no drill cores were obtained (e.g. for technical reasons). The reference is the core depth as displayed in the column "Lithology". For a high-resolution version of these photos see Dossier II.

2.7 Cored interval

This column indicates which sections of the borehole were (wireline) cored and which were drilled destructively, resulting in cuttings. Please note that smaller core losses are not indicated in this column; for details see Dossier I.

2.8 Tadpole plot (bedding)

A tadpole plot is a graphical method for displaying the orientation of (in this case) bedding planes. The circles indicate the dip angle of the bedding at the respective positions (between 0° = horizontal and 90° = vertical) and the lines originating from the circles indicate the dip direction of the bedding (upwards = north, right = east, down = south, left = west).

Green stands for undifferentiated bedding and magenta for deformed bedding. Unfilled circles show sections where correct core orientation (with the help of the FMI based on core goniometry) was not possible and therefore the dip azimuth, even though displayed, refers to an artificial true north. The dip, however, is correct for these features; for details see Dossier V.

2.9 Fracture density class

Where (parts of) the drill cores were heavily disintegrated it was not possible to accurately assess the density of natural fractures. For these sections, the fracture density was estimated using the classification scheme of Bauer et al. (2016): fracture density class (FDC) 2 in orange (spacing of fractures = 5 – 10 cm), FDC 3 in orange with vertical lines (spacing of fractures = 1 – 5 cm), FDC 4 in red (spacing of fractures < 1 cm); for details see Dossier V.

2.10 P32 fault & fracture density

The parameters displayed in these columns were recorded separately for brittle structures with shear indications and brittle structures without shear or slip indications. The so-called P32 value is obtained by dividing the summarised discontinuity area along the drill cores by the volume. Therefore, the P32 value reflects the area of discontinuities per unit of rock volume (m^2/m^3), possibly highlighting the degree of tectonic overprinting. A high P32 value for fault planes, for example, can indicate the presence and position of a fault zone; for details see Dossier V.

2.11 Casing

Details regarding the drilling process (such as bit size, casing diameter, cementation scheme etc.) can be found in Dossier I.

2.12 Caliper

The caliper measurement performed during geophysical wireline logging gives the diameter of the borehole in inches (1 inch = 2.54 cm) at the time of measurement for several (here 6) azimuthal directions obtained by different measurement arms (RD1 to RD6); for details see Dossier VI.

BS stands for bit size. In a perfect borehole, the measured diameter from the caliper log should equal the bit size. Strongly simplified, variations in the borehole diameter, such as washouts and breakouts, can be associated with the drilling process and/or result from unstable borehole sections. Some borehole measurements can be affected by variations in the borehole diameter.

2.13 Resistivity

The resistivity measurement performed during geophysical wireline logging gives the electrical resistivities at different depths of investigation in the formation in Ohm metres (ohmm). Processing allows the extrapolation of the resistivity measurements far into the formation, providing the true formation resistivity (RT_HRLT), as well as close to the tool, providing the micro-resistivity or resistivity close to the borehole wall (RXO_HRLT).

Less resistive formations, for example, can indicate a higher clay content and/or a higher porosity filled with conductive fluids (such as saline porewater); for details see Dossier VI.

2.14 FMI static

The formation microimager (FMI) provides a high-resolution, micro-resistivity measurement of the borehole wall performed during geophysical wireline logging, showing not only changes in lithology (brighter = more resistive), but (on a smaller scale) also discontinuities in the case of mineral or fluid filling; for details see Dossier VI.

The 360° measurement result from the borehole wall is displayed as an unwrapped, planar plot with the 180° mark indicating the side of the borehole facing towards south. Due to the unwrapping, discontinuities (inclined compared to the borehole axis) can be identified as sinusoidal curves, which can be used to assess the dip direction and the dip angle of the associated discontinuities. For a vertical borehole, the amplitude of the curves is smaller the more horizontal the orientation of the intersecting discontinuity is.

Among others, the FMI was used for the core goniometry (*cf.* column "Tadpole plot – bedding") and the analysis of breakouts and drilling-induced fractures (*cf.* column "Stress indicators").

2.15 Neutron porosity / Density

This column shows results from the geophysical wireline logging using a radioactive neutron source for assessing the porosity and a radioactive gamma source for obtaining bulk densities of the rock formations surrounding the borehole. After corrections, the displayed results are:

- represented as dark blue lines: epithermal neutron hydrogen index (APLC) as a proportion of the total volume (v/v), which times 100 equals a percentage; a measurement of the "neutron porosity", with higher values possibly indicating more porous lithologies (pore-filling water contains hydrogen). The "neutron porosity" is also influenced by the clay content, hydrogen-rich minerals, hydrocarbons and chlorine-rich formation fluids.
- represented as a black line: high resolution bulk densities (RHO8) in grams per cubic centimetre (g/cc), a measurement of the bulk density of the formation (minerals and fluid volumes). Higher values can indicate lower porosity or denser minerals.

Bulk density is usually used in combination with "neutron porosity" to quantify the fluid volume (porosity), as a lithological indicator (e.g. clays, limestone, dolostone, sandstone, anhydrite, salt) and as fluid indicator (pores filled with water, gas or hydrocarbons).

2.16 Natural gamma ray

A standard measurement during geophysical wireline logging, used as an indicator for clay content and for depth calibration by identifying lithological marker horizons, is the natural total gamma ray (GR_KCOR) measurement. By measuring the total natural gamma radiation along the borehole, GR gives an indication of the clay content of the rock formations surrounding the borehole. The further left the line or the higher the number on the American Petroleum Institute calibrated scale (API), the higher the GR measurement, which usually correlates with higher clay contents.

2.17 Clay mineral content

The shown curve represents the clay mineral content in weight percent (wt.-%) obtained from a combined interpretation ("multi-mineral interpretation") of several geophysical wireline logging measurements. For details see Dossier X.

2.18 Multi-mineral interpretation

This column shows the "multi-mineral interpretation" (MM) of the mineral content in weight percent (wt.-%) as a stacked overview plot. For the MM, data from several geophysical wireline measurements are taken into account; for details see Dossier X.

Displayed are the following minerals: pyrite (MM _PYRITE), siderite (MM_SIDER), anhydrite (MM_ANHYDR), calcite (MM_CALCITE), dolomite (MM_DOLOMITE), silicates[6] (MM_QF_SILICATES) and clay minerals (MM_DRY_CLAY).

2.19 Porosity

The dark blue curve represents the result of the "multi-mineral interpretation" of porosity as a volume fraction (v/v), which times 100 equals a percentage; for details see Dossier X.

2.20 Stable isotopes of porewater (δ^2H, $\delta^{18}O$)

The circles show the porewater stable isotope composition (δ^2H, $\delta^{18}O$ in ‰ V-SMOW) based on the diffusive-exchange method; horizontal lines represent the analytical error. As no water samples were taken from the borehole, the stable isotope composition of the groundwater is not shown. For details see Dossier VIII.

2.21 Hydraulic conductivity

In this column, the hydraulic conductivity obtained from hydraulic packer testing is presented. Note that hydraulic conductivity was calculated from the measured transmissivity by division by the interval length. The vertical lines indicate the depth of the measurement interval in the borehole. The log (10^{-x}) of hydraulic conductivity is given in metres per second (m/s). The parameter range is shown with horizontal error bars; lower hydraulic conductivities plot on the left and higher hydraulic conductivities plot on the right side of this column; for details see Dossier VII.

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[6] Quartz and feldspars.

2.22 (Apparent) hydraulic head

In this column, the (apparent) hydraulic head obtained from hydraulic packer testing is presented. The vertical lines indicate the depth of the measurement interval in the borehole. The results are given in metres above sea level (m asl) and hydraulic head is shown as freshwater head. The horizontal error bars show the range of parameters. The height of the ground level at the position of the borehole is marked with a dashed vertical line; for details see Dossier VII.

2.23 Sonic / Peak strength

The velocities of seismic waves (Vp) travelling through the different rock formations surrounding the borehole can be derived from sonic measurements performed during geophysical wireline logging. These measurements are used, for example, to assess rock strength properties and to support the calibration of seismic surveys. The results are given in metres per second (m/s) with e.g. porous or fractured lithologies usually showing slower travel times; for details see Dossier VI.

2.24 Stress indicators

Borehole wall images obtained during geophysical wireline logging (i.e. using the FMI) are used in post-processing to identify so-called stress indicators; their position on the 360° borehole wall is shown in this column.

One can differentiate between breakouts (indicated by filled circles in red) and centreline fractures (indicated by filled circles in black). Drilling-induced fractures are typically orientated in the direction of the maximum horizontal stress and breakouts perpendicular to this direction.

3 References

Bauer, H., Schröckenfuchs, T. & Decker, K. (2016): Hydrogeological properties of fault zones in a karstified carbonate aquifer (Northern Calcareous Alps, Austria). Hydrogeology Journal 24, 1147-1170.

Birkhäuser, P., Roth, P., Meier, B. & Naef, H. (2001): 3D-Seismik: Räumliche Erkundung des mesozoischen Sedimentschichten im Zürcher Weinland. Nagra Technischer Bericht NTB 00-03.

Isler, A., Pasquier, F. & Huber, M. (1984): Geologische Karte der zentralen Nordschweiz 1:100'000. Herausgegeben von der Nagra und der Schweiz. Geol. Komm.

Jäggi, D., Laurich, B., Nussbaum, C., Schuster, K. & Connolly, P. (2017): Tectonic structure of the "Main Fault" in the Opalinus Clay, Mont Terri rock laboratory (Switzerland). Swiss Journal of Geosciences 110, 67-84.

Nagra (2014): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage. Geologische Grundlagen. Dossier II: Sedimentologische und tektonische Verhältnisse. Nagra Technischer Bericht NTB 14-02.

Nagra (2019): Preliminary horizon and structure mapping of the Nagra 3D seismics ZNO-97/16 (Zürich Nordost) in time domain. Nagra Arbeitsbericht NAB 18-36.

Pietsch, J. & Jordan, P. (2014): Digitales Höhenmodell Basis Quartär der Nordschweiz – Version 2013 (SGT E2) und ausgewählte Auswertungen. Nagra Arbeitsbericht NAB 14-02.

Roche, V., Childs, C., Madritsch, H. & Camanni, G. (2020): Controls of sedimentary layering and structural inheritance on fault zone structure in three dimensions. A case study from the northern Molasse basin, Switzerland. Journal of the Geological Society 177/3, 493-508.