Arbeitsbericht NAB 22-02

TBO Stadel-2-1: Data Report

Summary Plot

September 2022

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for the Disposal of
Radioactive Waste

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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 report was finalised in June 2023.

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: F. Casanova (Dossier I), M. Gysi (Dossier II), H.P. Weber (Dossier III and V), G. Deplazes (Dossier IV), R. Garrard (Dossier VI), A. Pechstein (Dossier VII), D. Traber (Dossier VIII), S. Giger (Dossier IX) and J.K. Becker (Dossier X).

Editorial works: M. Unger and P. Blaser

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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 Stadel-2-1 borehole.

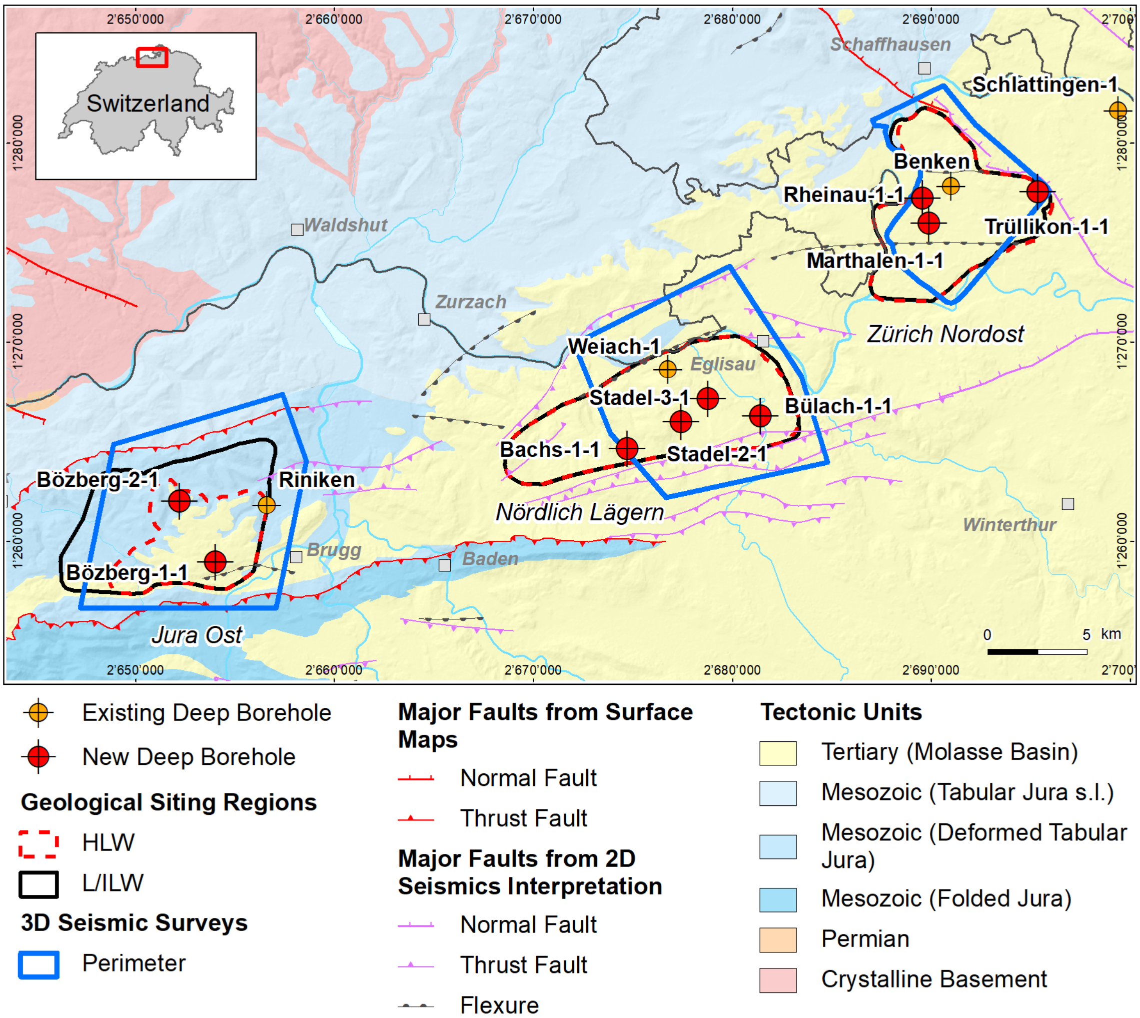

Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Stadel-2-1 (STA2-1) exploratory borehole is the seventh borehole drilled within the framework of the TBO project. The drill site is located in the central part of the Nördlich Lägern siting region (Fig. 1-2). The vertical borehole reached a final depth of 1'288.12 m (MD)[1]. The borehole specifications are provided in Tab. 1-1.

Tab. 1-1: General information about the STA2-1 borehole

Siting region	Nördlich Lägern
Municipality	Stadel (Canton Zürich / ZH), Switzerland
Drill site	Stadel-2 (STA2)
Borehole	Stadel-2-1 (STA2-1)
Coordinates	LV95: 2'677'447.617 / 1'265'987.019
Elevation	Ground level = top of rig cellar: 417.977 m above sea level (asl)
Borehole depth	1'288.12 m measured depth (MD) below ground level (bgl)
Drilling period	25th January – 8th July 2021 (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]: 0 – 670 m: Bentonite & polymers 670 – 1'051 m: Potassium silicate & polymers 1'051 – 1'117 m: Water & polymers 1'117 – 1'288.12 m: Sodium chloride brine & polymers

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. The comparison of the core versus log depth[3] of the main lithostratigraphic boundaries in the STA2-1 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.

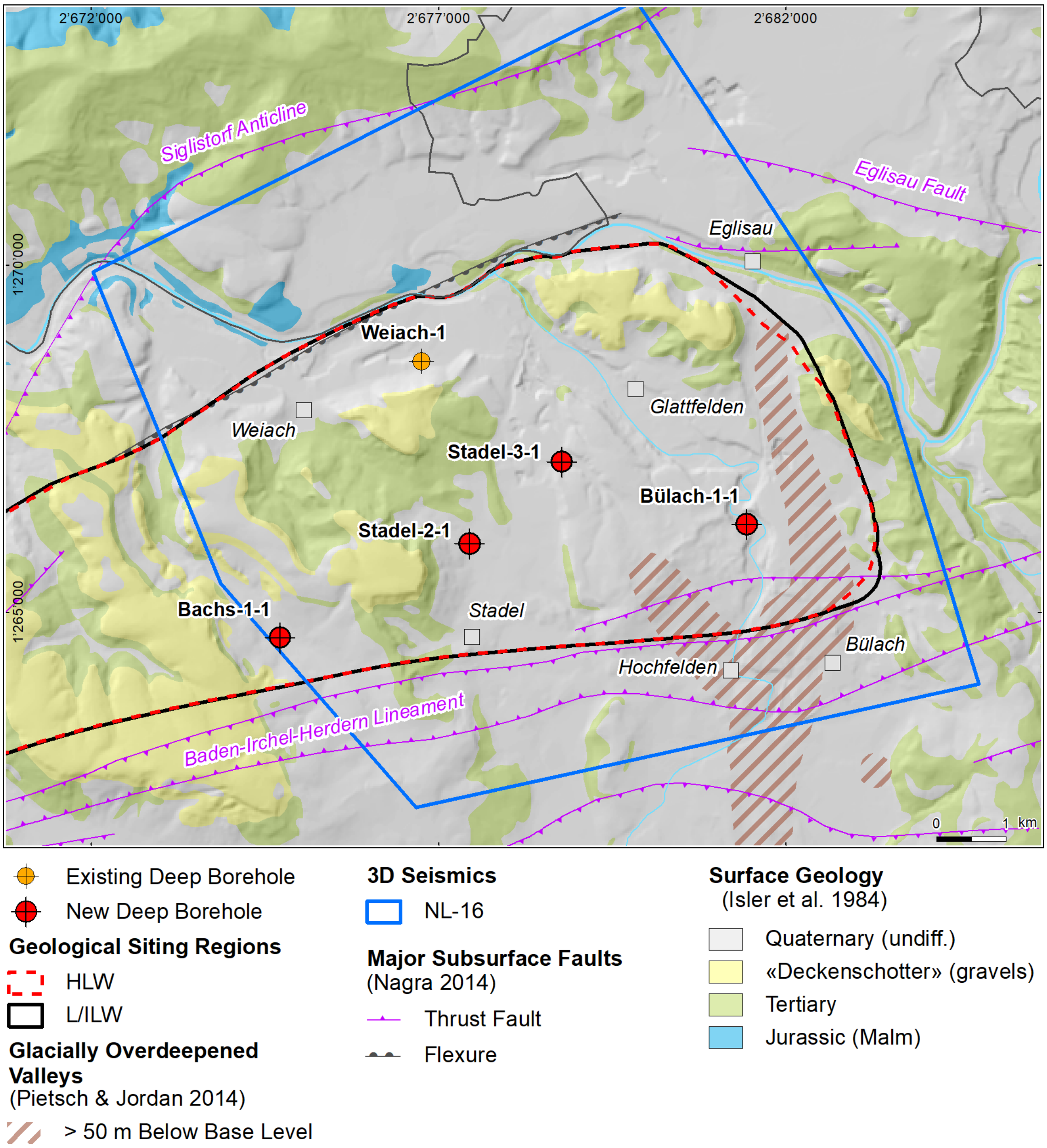

Fig. 1-2: Overview map of the investigation area in the Nördlich Lägern siting region with the location of the STA2-1 borehole in relation to the boreholes Weiach-1, BUL1-1, STA3-1 and BAC1-1

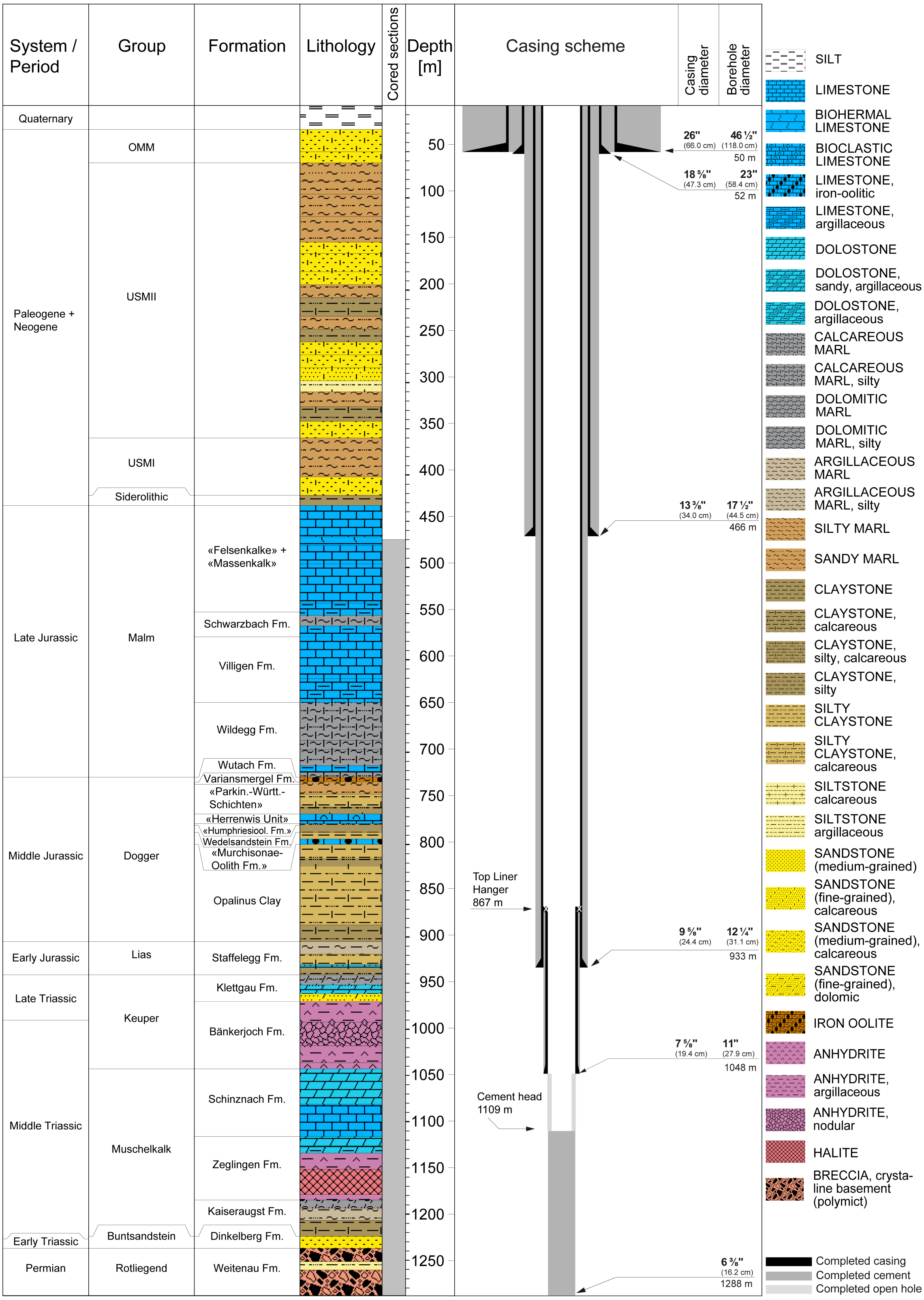

Fig. 1-3: Lithostratigraphic profile and casing scheme for the STA2-1 borehole[4]

[4] For detailed information see Dossier I and III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the STA2-1 borehole[5]

System / Period	Group	Formation	Core depth in m (MD) (base)	Log depth in m (MD) (base)
Quaternary			**26.0**	
Paleogene + Neogene	OMM		62.0	
	USM		422.0	
	Siderolithic		**433.0**	
Jurassic	Malm	«Felsenkalke» + «Massenkalk»	548.35	548.62
		Schwarzbach Formation	575.08	575.45
		Villigen Formation	646.23	646.63
		Wildegg Formation	727.18	728.20
	Dogger	Wutach Formation	732.16	733.25
		Variansmergel Formation	734.92	735.95
		«Parkinsoni-Württembergica-Schichten»	767.02	768.05
		«Herrenwis Unit»	777.54	778.47
		«Humphriesioolith Formation»	779.34	780.27
		Wedelsandstein Formation	786.85	787.79
		«Murchisonae-Oolith Formation»	799.67	800.67
		Opalinus Clay	905.20	906.87
	Lias	Staffelegg Formation	**940.89**	**941.42**
Triassic	Keuper	Klettgau Formation	969.87	970.52
		Bänkerjoch Formation	1043.07	1043.62
	Muschelkalk	Schinznach Formation	1116.01	1116.69
		Zeglingen Formation	1184.72	1185.42
		Kaiseraugst Formation	1224.20	1225.07
	Buntsandstein	Dinkelberg Formation	**1237.01**	**1237.94**
Permian	Rotliegend	Weitenau Formation (final depth)	1288.12	1288.87

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

1.3 Documentation structure for the STA2-1 borehole

NAB 22-02 documents the majority of the investigations carried out in the STA2-1 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 STA2-1 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 22-02

Black indicates the dossier at hand.

Dossier	Title	Authors
I	TBO Stadel-2-1: Drilling	P. Hinterholzer-Reisegger
II	TBO Stadel-2-1: Core Photography	D. Kaehr & M. Gysi
III	TBO Stadel-2-1: Lithostratigraphy	P. Jordan, P. Schürch, H. Naef, M. Schwarz, R. Felber, T. Ibele & H.P. Weber
IV	TBO Stadel-2-1: Microfacies, Bio- and Chemostratigraphic Analysis	S. Wohlwend, H.R. Bläsi, S. Feist-Burkhardt, B. Hostettler, U. Menkveld-Gfeller, V. Dietze & G. Deplazes
V	TBO Stadel-2-1: Structural Geology	A. Ebert, S. Cioldi, E. Hägerstedt & H.P. Weber
VI	TBO Stadel-2-1: Wireline Logging and Microhydraulic Fracturing	J. Gonus, E. Bailey, J. Desroches & R. Garrard
VII	TBO Stadel-2-1: Hydraulic Packer Testing	R. Schwarz, R. Beauheim, S.M.L. Hardie & A. Pechstein
VIII	TBO Stadel-2-1: Rock Properties, Porewater Characterisation and Natural Tracer Profiles	C. Zwahlen, L. Aschwanden, E. Gaucher, T. Gimmi, A. Jenni, M. Kiczka, U. Mäder, M. Mazurek, D. Roos, D. Rufer, H.N. Waber, P. Wersin & D. Traber
IX	TBO Stadel-2-1: Rock-mechanical and Geomechanical Laboratory Testing	E. Crisci, L. Laloui & S. Giger
X	TBO Stadel-2-1: Petrophysical Log Analysis	S. Marnat & J.K. Becker
	TBO Stadel-2-1: 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.

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. All information shown in the summary plot refers to MD.

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, red for cross-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 / Temperature

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.

The temperature measurement during petrophysical wireline logging gives the temperature of the fluid-filled borehole in degrees Celsius (degC) (Dossier VI). Whilst the temperature recorded during petrophysical logging is needed for performing certain quality control checks on the measurements, it is not representative of the true formation temperature. Temperatures measured during logging runs are generally cooler than that of the formation, but the temperature of the static borehole fluid is assumed to converge to the formation temperature after a certain time period. It is recommended that true formation temperature is either calculated using Horner plot method to correct the measured temperatures for the effects of fluid circulation, or to either run temperature re-logs post completion and/or complement by installing a fibre optic sensing technology in order to obtain an as undisturbed temperature profile as possible. The temperature measurements shown were performed after the completion of the borehole in order to obtain an as undisturbed temperature profile as possible.

2.17 Clay mineral content

The filled circles in black show the clay mineral content in weight percent (wt.-%) obtained from laboratory measurements on rock samples; for details see Dossier VIII.

The curve in dark grey represents the clay mineral content in weight percent (wt.-%) obtained from a combined interpretation ("multi-mineral interpretation") of several geophysical wireline logging measurements and available laboratory measurements on core samples. In the case of data gaps in the geophysical wireline logging, data from a Multi-Sensor-Core-Logger (MSCL) were taken into account; 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 geophysical wireline logging and laboratory measurements on core samples as well as measurements with a Multi-Sensor-Core-Logger (MSCL) are taken into account; for details see Dossier X.

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

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[6] Quartz and feldspars.

2.19 Clay mineralogy

Displayed is the content of the individual clay minerals in weight percent (wt.-%) obtained from laboratory measurements on core samples; for details see Dossier VIII.

Displayed are the clay mineral end-members: chlorite (CM _CHLORITE), kaolinite (CM_KAOLINITE), smectite (CM_SMECTITE) and illite (CM_ILLITE).

2.20 Porosity

This track combines the porosities derived from "multi-mineral interpretation" and laboratory measurements.

The filled circles in black represent the water loss porosity, calculated based on the gravimetric water content (oven dried at 105 °C) and the bulk wet density. All laboratory measurements were performed on core samples and are given in percent (%); for details see Dossier VIII.

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.

2.21 Chloride

The circles in black show the chloride content in mg/L of porewater (based on aqueous extraction scaled to anion-accessible porosity); horizontal lines represent the propagated analytical error. The filled squares in blue indicate the results from water samples taken from the borehole during pumping tests; vertical blue lines mark the length of the test interval. For details see Dossier VIII.

2.22 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. The filled squares in blue indicate the results from water samples taken from the borehole during pumping tests; blue vertical lines mark the length of the test interval. For details see Dossier VIII.

2.23 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 bore-hole. 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.

The circles in dark orange denote values obtained from constant head tests at a single effective stress value (typically 10 or 15 MPa), performed in the oedometric laboratory tests. The circles in blue denote values obtained from advective displacement tests on core samples. For details see Dossier IX.

2.24 (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.

2.25 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.

These logging results from the sonic scanner are compared to ultrasonic measurements on rock samples in the laboratory (perpendicular to bedding). Besides velocity (Vp) measurements (indicated by circles in brown), uniaxial compressive strength test results (indicated by filled squares in black) in Megapascal (MPa) are shown for comparison. Typically, higher values correlate with higher velocities and indicate stronger lithologies; for details see Dossier IX.

2.26 Stress magnitudes

The blue curve represents the vertical stress (SV) in Megapascal (MPa) from integrated density according to Dossier VI.

The circles indicate the position of micro-hydraulic fracturing measurements in the borehole giving closure pressures in Megapascal (MPa) with error bars, which under certain conditions can be interpreted as the minimum principal stress magnitudes. Additionally, the closure pressure in relation to the vertical stress can give an indication of the stress regime; for details see Dossier VI.

2.27 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

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