

Arbeitsbericht NAB 21-22

**TBO Bözberg-2-1:
Data Report**

**Dossier I
Drilling**

April 2022

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

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P. Hinterholzer-Reisegger

Keywords:

BOZ2-1, Jura Ost, TBO, deep drilling campaign, end-of-well report, drilling, drill site, drilling technology, drilling tools, sections, casing, cementing, drilling fluid, mud system, mud losses, coring system, hole opening, potassium silicate, HSE, non-productive time

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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:

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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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Note: In the digital version of this report Appendices A – R can be found under the paper clip symbol. In the printed version the appendices are on a flash drive enclosed with the report.

Abbreviations

ALAP	As low as possible
API	American Petroleum Institute
APS	Accelerator porosity sonde
ATEX	EU directives describing the minimum safety requirements of the workplace and equipment used in an explosive atmosphere (Appareils destinés à être utilisés en ATmosphères EXplosives)
BB	Big bag
BGL	Below ground level
BHA	Bottom hole assembly
BOP	Blowout preventer
BTC	Buttress thread connection
CBL	Cement bond log
CCL	Casing collar locator
CHH	Casing head housing
DDR	Daily drilling report
DETEC	Federal Department of the Environment, Transport, Energy and Communications
DMR	Daily mud report
DMT	Deutsche Montan Technologie
ECS	Elementary capture spectroscopy
EDTC	Enhanced digital telemetry cartridge
EMS	Electronic multishot system
EMW	Equivalent mud weight
ENSI	Swiss Federal Nuclear Safety Inspectorate (Eidgenössisches Nuklearsicherheitsinspektorat)
FBST.E	Full bore scanner – E
FIT	Formation integrity test
FMI	Formation micro imager tool
FOEN	Federal Office for the Environment
FOPH	Federal Office of Public Health
GLA	General license application
GPIT	General purpose inclinometer tool
GR	Gamma ray
GTPT	Gas threshold pressure test
GTS	General Tubular Services GmbH

HLW	High-level waste
HMR	High magnesium resistant cement
HNGS	Hostile gamma ray neutron sonde
HRLA	High resolution laterolog array tool
HRLT	High resolution laterolog array tool
HSE	Health safety environment
HVP	High viscosity pill
IADC	International Association of Drilling Contractors
IBC	Intermediate Bulk Container
JIH	Junk in hole
L/ILW	Low- and intermediate-level waste
LCM	Lost circulation material
LEH.QT	Logging equipment head with tension
LEL	Lower explosive level
LV95	National survey 95 (Landesvermessung 95)
Mb.	Member
MBT	Methylene blue test
MD	Measured depth
MDT	Modular formation dynamic tester
MHF	Micro-hydraulic fracturing
MSIP	Modular sonic imaging platform
MW	Mud weight
NPT	Non-productive time
NSG	Application for exploration permits (Nagra Sondiergesuch)
OCMA	Oil Company Materials Association
OD	Outdiffusion
PDC	Polycrystalline diamond compact
POOH	Pulling out of hole
PPC	Powered positioning caliper
PPE	Personal protective equipment
RIH	Run in hole
ROP	Rate of penetration
RPM	Revolutions per minute
RT	Roundtrip
SBT	Segmented bond tool

SG	Specific gravity
SGT	Sectoral Plan for Deep Geological Repositories
SHO	Staged hole opener
SLB	Schlumberger N. V.
SP	Spontaneous potential
SPM	Strokes per minute
SPP	Standpipe pressure
SR	Sulfate resistant
TBO	Tiefbohrungen
TCI	Tungsten carbide insert
TD	Target depth of section or hole / total depth
TLD	Three-detector lithology detector
TOC	Top of cement
TSD	Thermally stable diamond
TVD	True vertical depth
UBI	Ultrasonic borehole imager
USIT	Ultrasonic imager tool
USRS	Ultrasonic rotating sub
USM	Untere Süsswassermolasse
VDL	Variable density log
VSP	Vertical seismic profile
WEP	Well Engineering Partners BV
WOB	Weight on bit
WOC	Waiting on cement
WP	Work programme
ZNO	Zürich Nordost

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 Bözberg-2-1 borehole.

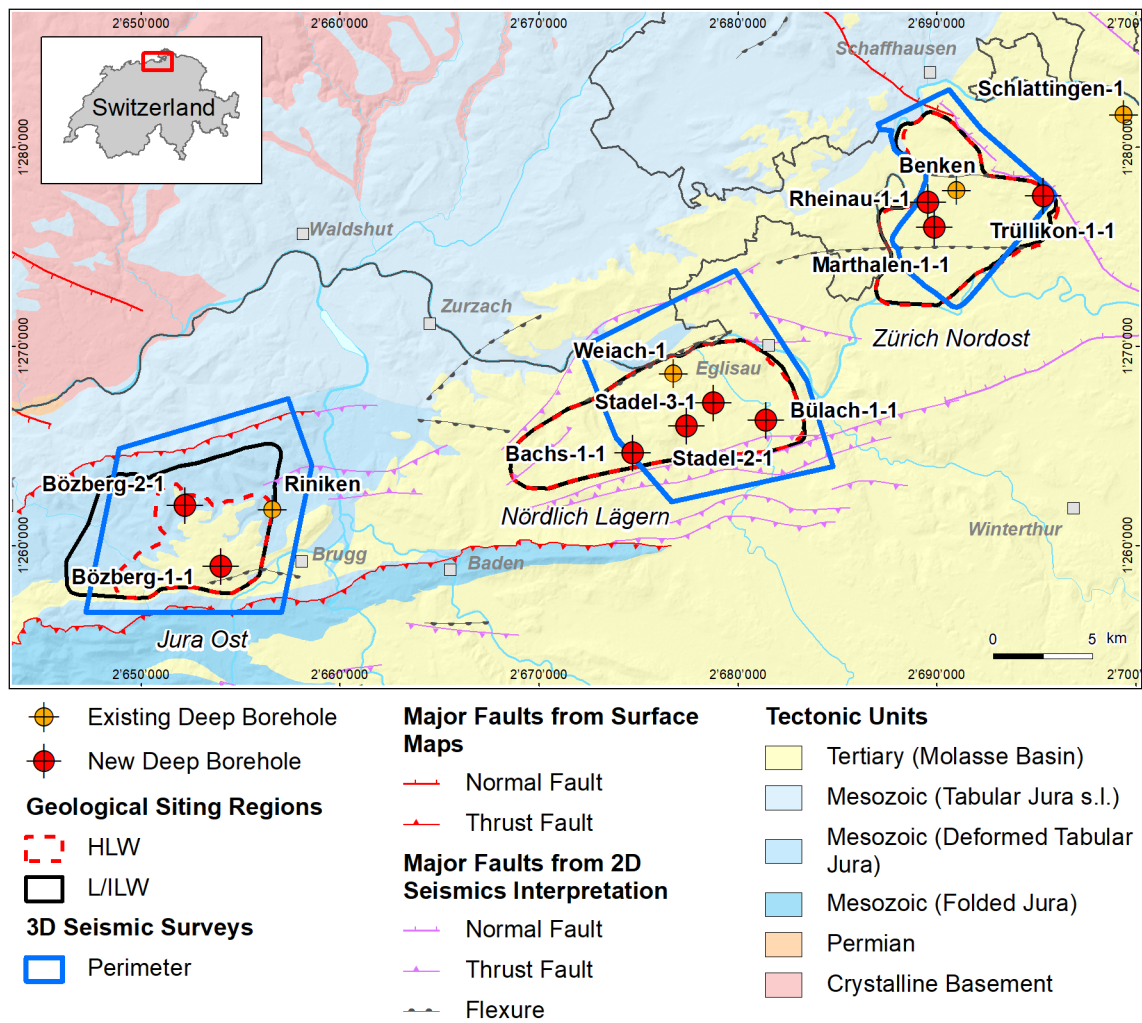


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Bözberg-2-1 (BOZ2-1) exploratory borehole is the fifth borehole drilled within the framework of the TBO project. The drill site is located in the northern part of the Jura Ost siting region (Fig. 1-2). The vertical borehole reached a final depth of 829.11 m (MD)¹. The borehole specifications are provided in Tab. 1-1.

Tab. 1-1: General information about the BOZ2-1 borehole

Siting region	Jura Ost
Municipality	Bözberg (Canton Aargau / AG), Switzerland
Drill site	Bözberg-2 (BOZ2)
Borehole	Bözberg-2-1 (BOZ2-1)
Coordinates	LV95: 2'652'218.764 / 1'261'985.437
Elevation	Ground level = top of rig cellar: 624.33 m above sea level (asl)
Borehole depth	829.11 m measured depth (MD) below ground level (bgl)
Drilling period	11th August – 14th December 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 : 0 – 370 m: Bentonite & polymers 370 – 615 m: Potassium silicate & polymers 615 – 829.11 m: Pure-Bore®

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 BOZ2-1 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 Chapter 3.

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.

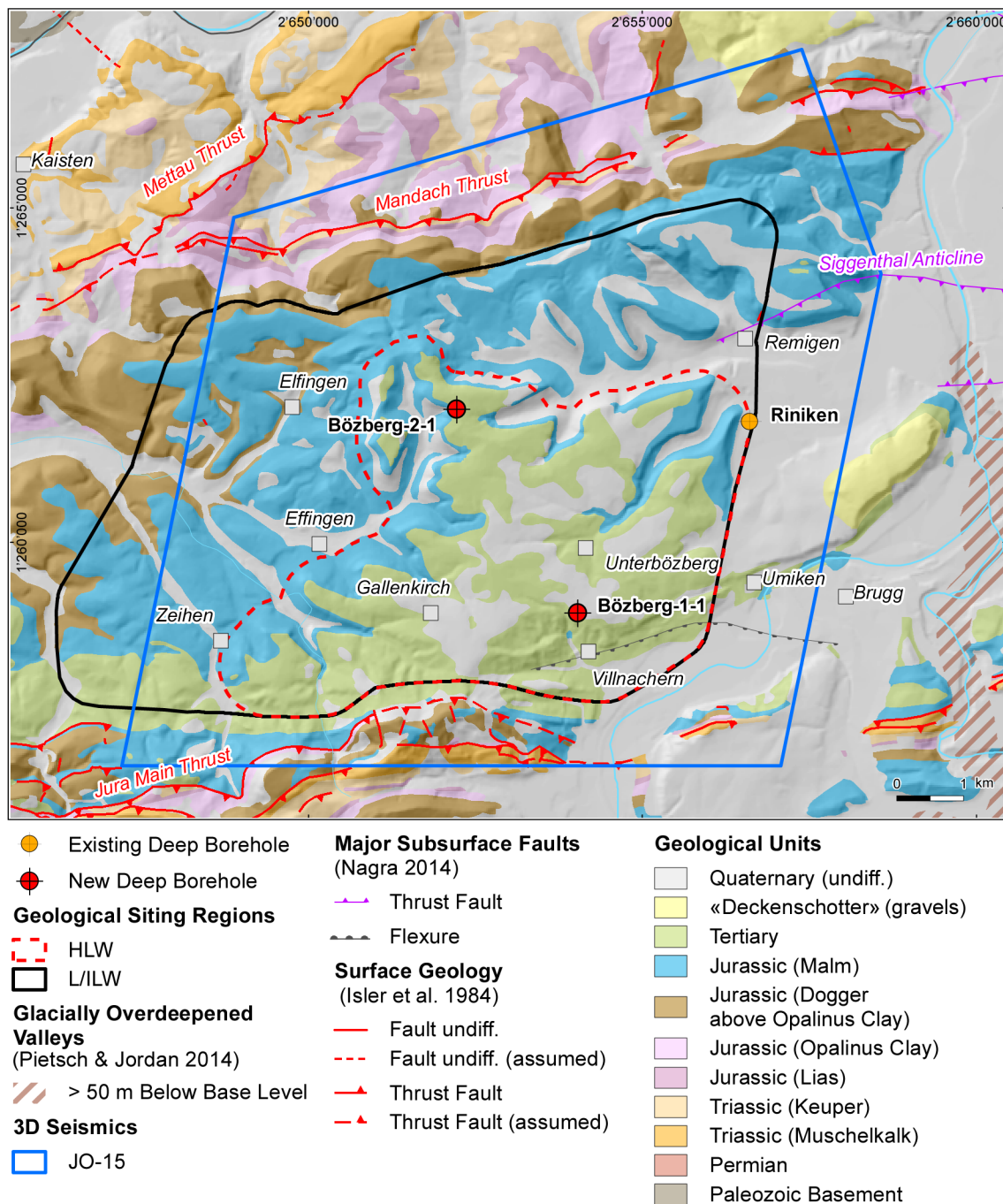


Fig. 1-2: Overview map of the investigation area in the Jura Ost siting region with the location of the BOZ2-1 borehole in relation to the boreholes Riniken and BOZ1-1

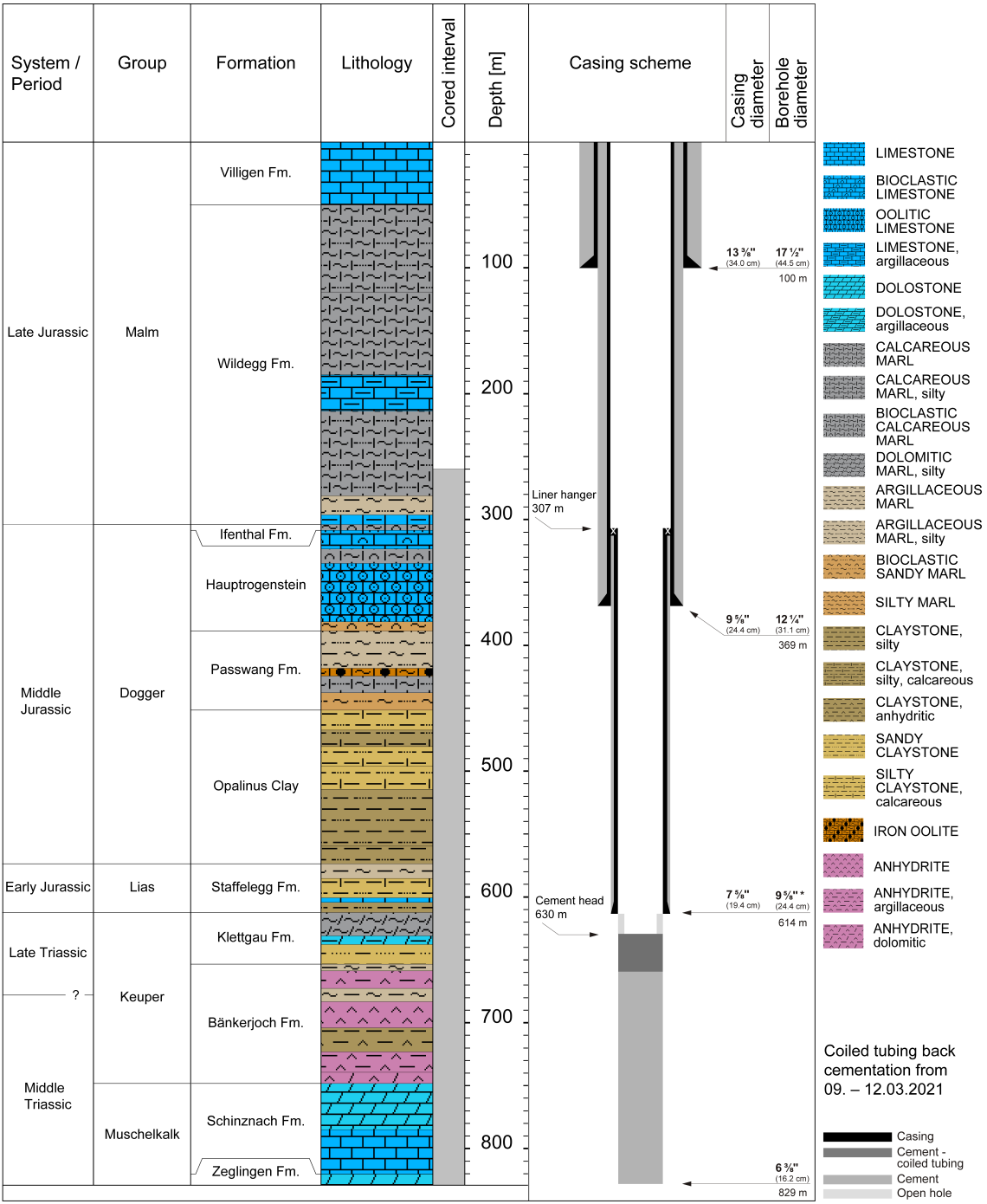


Fig. 1-3: Lithostratigraphic profile and casing scheme for the BOZ2-1 borehole⁴

⁴ For detailed information see Chapter 3 and Dossier III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the BOZ2-1 bore-hole⁵

System / Period	Group	Formation	Core depth in m (MD)	Log
Jurassic	Malm	Villigen Formation	50.0	—
		Wildegge Formation	303.95	304.38 —
	Dogger	Ifenthal Formation	308.70	309.07 —
		Hauptrogenstein	388.54	388.97 —
		Passwang Formation	451.54	451.90 —
		Opalinus Clay	573.68	573.89 —
	Lias	Staffellegg Formation	612.46	612.76 —
Triassic	Keuper	Klettgau Formation	653.45	654.70 —
		Bänkerjoch Formation	748.27	749.52 —
		Schinznach Formation	820.32	821.09 —
	Muschelkalk	Zeglingen Formation	829.11	829.88 —
			final depth	

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 BOZ2-1 borehole

NAB 21-22 documents the majority of the investigations carried out in the BOZ2-1 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 BOZ2-1 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 21-22

Black indicates the dossier at hand.

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

1.4 Scope and objectives of this dossier

The objective of this report is to provide a summary of the drilling operations, including rig site construction, casing tallies, cement bond quality, coring parameter and recovery.

The report is organised as follows:

- Chapter 1 presents the general overview of the drilling campaign and the vertical borehole BOZ2-1
- Chapter 2 is dedicated to the drilling technology
- Chapter 3 describes the construction phase, drilling operations and their chronology
- Chapter 4 discusses the health, safety and environmental topic
- Finally, this report includes a set of appendices, which present relevant general project information and further investigation details

1.5 Involved companies

The following companies were involved in the drilling activities of the borehole BOZ2-1:

- Nagra
 - Drilling manager: project management, coordination and organisation of the drilling of the borehole, definition of test aims, quality control, technical drilling supervision, coring, casing running, cementing, logging and testing operations performed in the borehole
 - Drilling engineer: technical drilling supervision, coring, casing running, cementing, logging and testing operations performed in the borehole
 - Health safety & environment (HSE) manager
- Daldrup & Söhne AG: drilling contractor
- GEO-data GmbH: mud logging and core handling
- AKROS Oilfield Services GmbH: mud engineering
- Fangmann Energy Services: cementing service and liner hanger systems
- GTS General Tubular Services GmbH: casing running / float equipment service
- Schlumberger (SLB) Ltd.: wireline logging and testing
- Solexperts AG: hydraulic testing
- Deutsche Montan Technologie (DMT) GmbH & Co KG and SLB: seismic service
- Well Engineering Partners BV (WEP): night and day drilling supervisors and HSE specialist
- MICON-Drilling GmbH: wireline coring string and RVDS system
- Baker Hughes: coiled tubing service

2 Drilling technology

2.1 Overview

The rig and all peripheral facilities were operated electrically. The rig itself was connected to a separate electro-hydraulic main drive unit, and the mud pumps were operated by a variable frequency drive unit.

The nominal pulling force of the system was 175 t. Technical data of the system and its associated components can be found in Appendix C.

The drilling rig of the contractor Daldrup & Söhne AG was a Wirth B 152t (152 t operational hook load with ten lines) semi-trailer with moveable mast. The draw works had a power of 300 kW. The top drive was a B 152 with 255 kW drive system power (1'520 kN torque dynamic capacity). Mud pumps were two triplex pumps IDECO T-1000 with a 750 kW power rating for each pump. Three Falcon shale shakers, one centrifuge and one flocculation unit were provided by the mud service company. An overview of the general drilling rig data can be found in Tab. 2-1 and a detailed description of the equipment in Appendix C.

Tab. 2-1: General drilling rig data

Drilling rig manufacturer	Wirth Maschinen- und Bohrgeräte GmbH, Erkelenz
Type of drilling rig	Universal rig
Construction	Semi-trailer with moveable mast
Type	B 152t
Original	B 12 SH 30000 / DS 05
Construction year	1980, modified 2007
Total height above ground level	21.3 m
Height of rotary table	2.83 m
Rig floor area	24 m ²
Rig floor load capacity	1'500 kg/m ²
Hook load dynamic (10 lines)	1'520 kN
Hook load static (10 lines)	1'750 kN
Crown block load	2'000 kN
Maximum torque	50 kNm
Continuous torque	12.5 kNm
Maximum rotational speed	390 RPM
Drill pipe handling	Single drill pipe handling
Drive	Electro-hydraulic
Drive power	2 × 174 kW
Lifting drive	Hydrostatic
Lifting – input power	300 kW

Tab. 2-1: continued

Rotary system	Top drive
Maximum allowable wind force (operation)	80 km/h
Total trailer weight	54'000 kg
Maximum shaft load	12'000 kg
Maximum width	2'750 mm
Trailer length	17.89 m
Transport height	3.45 m

The top drive had been in operation since 1981 and was purchased by the drilling contractor in 2003. Records showed that the unit had completed a total of 79'655 m of drilling up to 2016. The deepest borehole was drilled to a depth of 3'005 m MD.

The load of the entire semi-trailer was transferred to four supports. The maximum vertical load on each support at the rig cellar supporting the mast was 950 kN. At the shaft end of the trailer the load on each support was 150 kN.

All drilling activities were continuously recorded by the mud logging service using real-time monitoring. The following parameters were recorded:

- suction pit levels
- mixing pit levels
- trip tank level
- desilting pit level
- sand trap level
- top drive torque
- make-up torque
- revolutions per minute (RPM) of bit and string
- flowrate OUT
- strokes per minute (SPM) of the two mud pumps
- standpipe pressure (SPP)
- hook load
- annular pressure
- hook height
- mud weight (MW) IN/OUT
- mud temperature IN/OUT
- wind speed and direction – anemometer
- gas detection: total hydrocarbons (C1 to iC5), lower explosive limit (LEL), H₂S, CO₂

2.2 Drilling / coring tools

2.2.1 Drill string and wireline coring string

Two different drill strings were used for the BOZ2-1 borehole, the same as for the BUL1-1 and MAR1-1 borehole. A 5½" wireline coring string (SK 5½" B, N80) from the manufacturer MICON-Drilling GmbH (MICON-Drilling 2021) was mainly used for coring operations, and a 5" drill string (S135, #19.5) was mainly used for destructive drilling, hole opening and drilling out cement and float equipment.

Wireline core barrels are designed for reliable, complete recovery of the core without pulling out the drill string. This technique speeds up core retrieval, reduces time-consuming drill rod handling and helps to maximise coring efficiency. The catching assembly is attached to a wireline winch system and lowered into the wireline drill string. The overshot securely interlocks with the latching head. Subsequently, the core-filled inner tube system can be hoisted out through the wireline drill string.

The wireline coring system used for the BOZ2-1 borehole consisted of a core bit, inner and outer core barrel, core catcher, drill pipes, stabilisers, as well as crossovers and other spare parts and consumables. The drilling diameter was 6⅜" (161.9 mm), resulting in a core diameter of 95 mm. All cores were drilled with plastic liners for protection and higher quality of the cores. These plastic liners allowed simplified handling of the cores, eliminating mechanical impacts such as hammering or pumping out the core from the inner core barrel. It enabled transport of the cores to the core handling table in one piece. The core was then removed from the plastic liner by pushing it out by hand or cutting the liner along the longitudinal axis. Core lengths up to 6 m could be reached with the wireline coring system, but to decrease the exposure time of the core to the drilling fluid and during sampling, the core length was fixed to 3 m.

Compared to conventional drill pipes, the wireline coring pipes with an average length of 9 m have slick tool joints, which means that the outer diameter of the pipe body and the tool joint are identical. Tool joints have no shoulders and the diameter of 5½" is the same along the entire drill string. This prevents flow restrictions and improves hole cleaning during coring within the small annulus between the formation and the coring string.

For drilling operations other than coring, conventional 5" drill pipes were used as they have standard connections which make assembling the BHA much easier compared to the coring string, which has non-standard connections. The outer diameter of the tool joint is larger (168 mm) than the body of the 5" drill pipe to accommodate the threads. Furthermore, these shoulders provide stiffness to prevent bending and breaking. Due to the large diameter at the tool joint, the 5" drill pipes with an average length of 9.6 m did not fit into the 6⅜" borehole.

A hydrocarbon-free and metal-free pipe grease was used for all tool and pipe connections to prevent the drilling mud from contamination with traces of hydrocarbons, which was very important for hydrotesting and fluid sampling. The datasheet for the pipe grease can be found in Appendix J.

2.2.2 Core bits

Two different types of core bits (see Fig. 2-1) were used in the BOZ21-1 borehole:

- Thermally stable diamond (TSD) core bit, also called 'synset' core bit:

This type of core bit is designed for medium hard to hard and medium abrasive formations. TSD cutters consist of multiple layers of synthetic diamond fragments. This feature gives TSD cutters a self-sharpening behaviour.

Synset core bits were mainly used in the clay-rich formations of BOZ2-1, such as the Opalinus Clay.

- Diamond-impregnated matrix core bit:

This type of core bit is designed for medium hard to extremely hard formations, but also for less to very abrasive rocks. Multiple layers of synthetic diamond fragments are sintered into a hard metal matrix. This compound behaves self-sharpening during progressive abrasion. Worn diamonds are released and replaced by new ones, until the matrix compound is completely eroded. This core bit is available with different types of matrix.

For BOZ2-1, impregnated core bits with a medium to soft matrix were chosen mainly for coring limestone, dolostone, anhydrite and sandstone. This type of matrix is designed for less abrasive but hard, fine-grained and homogeneous formations.



Fig. 2-1: Synset core bit (left) and impregnated core bit (right)

Four new impregnated and four new synset core bits were used for coring the borehole. Used core bits were usually run in hole to execute roundtrips and condition the mud. A bit summary including bit grading for BOZ2-1 can be found in Appendix K. All bit grading given in this report refers to the IADC dull grading system.

Coring operations do not usually require a complex BHA design due to the small clearance between the formation and the drill string. The list of BHA components for coring is therefore limited to core bits and stabilisers.

2.2.3 Drilling and hole opening bits

The upper part (until 260 m MD) of Section I of the BOZ2-1 borehole was drilled with an 8½" tungsten carbide insert (TCI) tricone bit, which showed very good performance. Especially for this section, the drill bit selection, hydraulics and BHA design were key factors for staying vertical during drilling, creating a sufficient rate of penetration (ROP) and ensuring good hole cleaning. Based on lessons learned from the BUL1-1 and MAR1-1 boreholes, it was decided to use a 7¾" RVDS from the manufacturer MICON-Drilling GmbH (MICON-Drilling 2021) for drilling Section I (see Appendix L for the RVDS brochure).

Drilling out cement and float equipment of the individual sections was mostly done with milled tooth tricone bits without any problems. These bits are a type of rolling cutter bit that has tooth cutters made up of steel which have been assembled as part of the bit cone.

Staged hole openers (SHOs) were used to enlarge the existing borehole to the required diameter for casing running and cementing, mostly in steps from 6¾" to 8½" and from 8½" to 12¼". These SHOs run with a bullnose or a pilot bit of the same size as the existing borehole at the bottom, which serves as guidance for the enlarged hole. The pilot section of the SHO itself (lower part of the SHO) consists of one or two rows of cuttings structures to recondition the pilot hole and remove any swelling clays or loose material. Gauge pads provide initial stabilisation as the SHO begins the staged reaming process to reduce stick/slip, whirling or off-centre tendencies. The lower cutters of the SHO are designed to minimise work rates on each cutter position for maximum durability. By relieving stress from the formation with this intermediate stage, larger-hole drilling can be done at a more aggressive ROP. This part of the SHO recentralises the SHO on the given vertical borehole trajectory. The main body of the SHO completes the final hole diameter. With the formation being already stress-relieved, the reaming section remains aggressive, even in more competent formations. Gauge trimmers and spiralled gauge pads ensure good hole quality.

Besides the drilling and hole opening bits, a good stock of various stabilisers, drill collars, heavy weight drill pipes and other BHA components was kept onsite to be able to arrange proper BHA setups for the planned work steps. Appropriate BHA designs are of great importance in drilling operations to effectively load and control the drill bit.

3 Drilling operations

3.1 Overview

Following a licensing procedure, which lasted several years, accessing and construction of the drill site began in April 2020. During the construction phase, no conductor casing was installed because the borehole was expected to start directly in a solid formation. Construction of the drill site ended in mid-July 2020, and the site was handed over to the drilling contractor on 13.07.2020. Minor correction work on the drill site was carried out by the construction company up to 28.07.2020.

With the drilling permit granted by the Swiss Federal Nuclear Safety Inspectorate (ENSI 2017) on 11.08.2020, drilling operations started on the same day and, including the scientific investigations carried out in the borehole, continued until 14.12.2020 (125 days, 24 h operation, 63 days of which were for logging and testing activities). At a final depth of 829 m MD, the borehole passed through 829 m of Neozoic and Mesozoic sediments. The Opalinus Clay was found from 451 m to 574 m MD (123 m thick).

The borehole was drilled with a tricone bit for the uppermost 260 m. The remaining sections were continuously cored using the wireline coring technique. The drilling rig used was a hydraulic rotary drilling rig, type Wirth B 152t.

Because the borehole was unstable within the first 260 m drilled, it was decided to set a 13 $\frac{3}{8}$ " conductor casing down to 100 m MD.

The cored sections were drilled entirely with a wireline coring string using an inner core barrel and plastic liners for core protection. Core recovery was almost 100%. The main coring diameter and the final diameter of the borehole at 829 m MD was 6 $\frac{3}{8}$ " (161.9 mm). The cores had a diameter of 95 mm.

A total of three permanent casings were installed in the borehole and, with the exception of the 7 $\frac{5}{8}$ " liner hanger, cemented up to surface.

The upper section of the borehole down to the bottom of the Hauptrogenstein was drilled using a freshwater bentonite polymer drilling fluid. The Opalinus Clay and its neighbouring formations were drilled using a potassium silicate drilling fluid. This drilling mud showed excellent functioning in inhibiting swelling of clay formations that are sensitive to freshwater. Despite multiple time-intensive hydraulic borehole tests in the target formations, the borehole showed excellent stability with the potassium silicate fluid.

Besides these two types of drilling fluid (bentonite polymer and potassium silicate), Pure-Bore® polymer mud was used in the last section (Keuper and Muschelkalk) because the focus was on improving the hydrogeological and hydrochemical investigations, especially water sampling. Partial mud losses were encountered in the Muschelkalk between 805 m and 829 m MD. Two attempts to cure the losses by using lost circulation material (LCM) were successful and allowed coring to be continued until final depth.

Once the final depth of 829 m MD had been reached and the active borehole investigations were completed, the borehole was backfilled with cement up to 660 m MD and the Pure-Bore® polymer mud was replaced with freshwater.

Work was completed within 125 working days (continuous 24 h operation) after spud. Rig down took 8 days followed by a Christmas break from 22.12.2020 to 04.01.2021. Rig up at the next location, Stadel-2-1, was performed in parallel and finalised on 24.01.2021. The time used for scientific investigations in the borehole amounted to around 52% and the drilling and coring activities to 48%, including casing and cementing operations. The total duration of the project was 9 days shorter than the original work programme. Non-productive time (NPT) added up to a total of 6.4 days; 5.8 days were related to drilling activities and 0.6 days to logging and testing activities.

From 09.03.2021 to 12.03.2021, the borehole was cemented back with a coiled tubing unit from 660 m to 630 m MD at the request of the Swiss Federal Nuclear Safety Inspectorate (ENSI).

Continuous gas monitoring during the execution of the BOZ2-1 borehole showed no significant occurrences of hydrocarbon gases, CO₂ or H₂S.

Regarding health, safety and environment (HSE), no first-aid cases, no lost time incidents, no spills and no COVID-19 infections were reported from August 2020 to December 2020.

Unless mentioned otherwise, depth values indicated in this report should be understood as driller's depth.

3.2 Drill site construction and conductor

Start of execution

Before the start of construction, a technical investigation as well as soil investigations were carried out for the drill site, including extensive profile recordings. Due to the good stability of the foundation soil, the foundation layer was kept rather thin. In accordance with the specifications of the authorities, the building permit was divided into:

- Stage 1: earthworks (permission given on 14.10.2019)
- Stage 2: in situ concrete construction of the rig cellar (permission given on 27.04.2020)

Work preparation

The layout of the drill site was planned and prepared by Nagra with the assistance of the contracted civil engineering company SWR+. After a lengthy permitting procedure, a tight time schedule was followed and respected. A project of a neighbouring landowner could be used to lay power and water cables close to the drill site to speed up preparation work.

Construction engineering of the drill site and conductor

The construction of the drill site (Fig. 3-1) started on 01.04.2020 (ERNE AG construction company, Laufenburg).

Soil moisture was measured with a tensiometer from the beginning of March 2020. Because of bad weather conditions, the construction work could not start before mid-April.



Fig. 3-1: Drill site before (top) and after (bottom) construction

Soil removal was kept to a minimum and most of the drill site was backfilled with gravel, which was placed directly onto the turf. After the upper soil layers had been removed and deposited on the south side of the drill site, the foundation work began. The soil was kept beside the drill site for later renaturation because the land was to be farmed on a regular basis afterwards. After soil removal, the connection lines for electricity, water and drainage were installed. A CO₂ neutralising system with 3 collection tanks was installed at the west side of the drill site according to the drainage concept. These tanks were mainly intended to collect water from the asphalted area of the drill site after it passed through a scum collector and an oil separator installed below ground level.

The drill site consisted primarily of a rig cellar, a surrounding area with an asphalted pavement and other gravel areas that were used to accommodate the testing and office containers.

No conductor casing was installed because drilling operations were expected to start directly in a solid formation (Malm).

The construction company built a special ladder for the protection of amphibians. Amphibians that fell into the rig cellar could use the ladder to climb back to the surface.

Traffic management was an important issue during the construction and drilling phase. The access roads to the drill site were regulated with traffic lights and extended with passing places, especially for trucks.

To avoid bacterial growth in the water lines until the drilling contractor took over from the construction company, the lines were regularly flushed with disinfectant.

The following significant adjustments were implemented on the drill site during construction:

- enlargement of the gravel area of the rig site for parking, truck manoeuvres and accommodation
- enlargement of the soil deposit area because the height of the deposits was reduced (1 m instead of 1.3 m)
- seepage pit (270 m³)
- concrete foundations for container placement
- washing trough for cleaning the cores
- more parking inside and outside the fenced area
- site trail outside the fenced area
- levelling and building an access path for the visitor containers
- installation of connections with all additional required media
- various area entrances and emergency exits in the fence

The water collected on the drill site was channelled across a pitched roof to the edge of the asphalt where it was drained through the scum collector and oil separator and moved to the collection tanks.

The site was fenced off. The main access gate was guarded 24/7 by a security company as soon as construction of the drill site was completed. No incidents, vandalism or other external perturbations occurred during the construction and drilling phase.

A construction plan, including plant management and arrangement of the drilling rig and its peripheral facilities, can be found in Appendix E. Fig. 3-2 shows the fully assembled drill site directly after construction.



Fig. 3-2: Drill site after installation of the drilling rig and peripheral facilities

3.3 Chronology of the BOZ2-1 borehole

Below is a chronology of all working steps of the BOZ2-1 borehole. Details can be found in the daily drilling reports (DDR) in Appendix H.

01.04.2020	Start of drill site construction
14.07. – 31.07.2020	Rig down MAR1-1 and start moving to BOZ2-1
31.07. – 11.08.2020	Rig up and installation of drilling rig and all peripheral facilities
11.08.2020	RIH (run in hole) 12¼" drill string, start of drilling operations
11.08. – 12.08.2020	Drilling 12¼" from 0.5 m to 17.5 m MD
12.08. – 13.08.2020	RIH 9⅝" auxiliary casing, dismantling 30" riser, installation of 9⅝" bell nipple
13.08. – 14.02.2020	RIH 8½" drill string, drilling 8½" from 17.5 m to 32 m MD, POOH (pull out of hole) 8½" drill string

14.08. – 17.08.2020	RIH 8½" drill string with RVDS, drilling 8½" from 32 m to 260 m MD, POOH 8½" drill string with RVDS
17.08. – 19.08.2020	8½" and 6½" check trip, preparations for setting 13¾" conductor casing
19.08. – 21.08.2020	RIH coring string, fill borehole with sand from 260 m to 100 m MD, POOH coring string, dismantle 9⅝" bell nipple, POOH 9⅝" auxiliary casing, install 30" riser
21.08. – 22.08.2020	RIH 12¼" hole opener, hole opening from 17.5 m to 101 m MD, POOH 12¼" hole opener
22.08. – 24.08.2020	RIH 17½" hole opener, hole opening from 0.5 m to 101 m MD, POOH 17½" hole opener, 17½" check trip and wait for casing running and cementing service
24.08. – 25.08.2020	RIH 13¾" conductor casing until 100 m MD, cementing with stinger to surface, WOC (waiting on cement), installation of bell nipple and 13¾" riser
25.08. – 26.08.2020	RIH 12¼" drill string, drilling out shoe track + 1 m new formation, POOH 12¼" drill string, RIH 8½" hole opener, circulate sand out from 102 m to 260 m MD, POOH 8½" hole opener
26.08. – 30.08.2020	RIH coring string, coring 6⅜" from 260 m to 370 m MD, POOH coring string
30.08. – 31.08.2020	RIH 8½" hole opener, hole opening from 260 m to 370 m MD, POOH 8½" hole opener
31.08. – 10.09.2020	Petrophysical logging, hydraulic test (Hauptrogenstein), MHF incl. caliper and UBI (ultrasonic borehole imager)
10.09. – 11.09.2020	Magnet run, roundtrip, mud conditioning
11.09. – 12.09.2020	MHF incl. caliper and UBI, logging after MHF
12.09. – 14.09.2020	Magnet run, RIH 12¼" hole opener, hole opening from 102 m to 370 m MD, POOH 12¼" hole opener
14.09. – 18.09.2020	RIH 9⅝" surface casing until 369 m MD, cementing with stinger to surface, WOC, rig up BOP (blow out preventer), BOP test
18.09. – 19.09.2020	RIH 8½" drill string, drilling out shoe track + 2 m new formation, mud exchange from bentonite polymer to potassium silicate mud, perform FIT (formation integrity test), POOH 8½" drill string
19.09. – 28.09.2020	RIH coring string, coring 6⅜" from 372 m to 615 m MD, POOH coring string

28.09. – 12.10.2020	Petrophysical logging, four hydraulic tests (two in the Opalinus Clay, two in the Passwang Formation)
12.10. – 13.10.2020	BOP test, magnet run, roundtrip
13.10. – 24.10.2020	Three hydraulic tests (one in the Lias, one extended test in the Opalinus Clay)
24.10. – 04.11.2020	Magnet run, roundtrip, caliper log, GTPT (gas threshold pressure test) in the Opalinus Clay
04.11. – 06.11.2020	Magnet run, RIH 8½" hole opener, hole opening from 372 m to 615 m MD, POOH 8½" hole opener
06.11. – 10.11.2020	MHF incl. caliper & UBI, logging after MHF
10.11. – 12.11.2020	Magnet run, RIH 9⅞" underreamer, underreaming from 372 m to 615 m MD, POOH 9⅞" underreamer, caliper log
12.11. – 16.11.2020	Magnet run, RIH 9⅞" underreamer, underreaming from 372 m to 615 m MD, POOH 9⅞" underreamer, caliper log, 9⅝" scraper run
16.11. – 18.11.2020	RIH 7⅝" liner hanger until 614 m MD (liner head at 307 m MD), plug cementation, POOH setting tool, WOC, BOP test
18.11. – 19.11.2020	RIH 6½" drill string, drilling out cement, shoe track + 2 m new formation, mud exchange from potassium silicate to Pure-Bore® polymer mud, perform FIT, POOH 6½" drill string
19.11. – 21.11.2020	RIH coring string, coring 6⅜" from 617 m to 658 m MD, POOH coring string
21.11. – 25.11.2020	Hydraulic test in Keuper
25.11. – 02.12.2020	Magnet run, RIH coring string, coring 6⅜" from 658 m to 805.5 m MD, POOH coring string, roundtrip
02.12. – 07.12.2020	Hydraulic test in Muschelkalk
07.12. – 08.12.2020	RIH coring string, coring 6⅜" from 805.5 m to 829 m MD, POOH coring string
08.12. – 11.12.2020	Petrophysical logging, roundtrip, petrophysical logging, VSP
11.12. – 13.12.2020	Back-cementation from 829 m to 700 m MD, WOC, tag TOC (top of cement), back-cementation from 700 m to 660 m MD, WOC, tag TOC
13.12. – 14.12.2020	Circulate in water, disassembly of BOP, installation of wellhead, rig release – start of rig down

3.4 Time analysis

The BOZ2-1 borehole was completed within 125 working days (continuous 24 h operation) after spud on 11.08.2020. Rig down took 8 days followed by a Christmas break from 22.12.2020 to 04.01.2021. Rig up at the next location, Stadel-2-1, was performed in parallel and finalised on 24.01.2021.

The time analysis in Appendix I shows that the total time for completing the borehole adds up to around 52% for scientific investigations and 48% for drilling and coring activities, including casing and cementing operations. The project was finalised 9 days earlier than predicted by the original work programme.

NPT added up to a total of 6.4 days:

- 3.5 days of standby or waiting time:
 - 2.8 days of waiting time related to the retrospective setting of a 13 $\frac{3}{8}$ " conductor casing
 - 0.7 days spent waiting for logging tools or geology personnel
- 0.3 days of repair time:
 - only related to drilling activities
- 2.6 days due to problems with equipment:
 - 0.3 days during logging and testing activities
 - 2.3 days during drilling activities

3.5 Drilling process

The drilling operations combined wireline coring and rotary drilling techniques.

Because most of the Malm did not require to be cored, it was drilled destructively. Section I was therefore drilled with a rotary vertical drilling system (RVDS) to ensure the verticality of the borehole. The RVDS is a pre-programmable, self-steering device for drilling vertical boreholes. It consists of two modules which are integrated into the lower part of the bottom hole assembly (BHA) between the drill bit and the first string stabiliser (see Appendix N, BHA Report 8½"). The lithostratigraphy of the intersected formations was determined by analysing the drilled rock fragments (cuttings) (*cf.* Dossier III).

The wireline coring process was driven by the top drive from the surface with specific drilling parameters. The main advantage of the wireline coring technique is that the coring string can remain in the borehole while retrieving the core, meaning that the string does not have to be pulled for every core. The inner core barrel, which contains the core, is pulled to the surface with a special core catcher on a wireline. Wireline coring is faster and involves fewer tripping operations. Therefore, less deterioration of the borehole occurs compared to conventional coring. It also results in a shorter exposure time of the cores to the drilling fluid. In the BOZ2-1 borehole, the core length was mostly kept at 3 m for better handling at the surface and to obtain good core quality. In total, 69% (565 m) of the entire borehole length was cored. Core recovery was 100%: 565.11 m were recovered out of 565.00 m targeted.

After borehole stability problems in the BUL1-1 borehole mainly in the clay-rich sections such as the Opalinus Clay, where a conventional water-based drilling fluid (combination of polysaccharides and polymers) proved to be unsuccessful, potassium silicate mud was used in the BOZ2-1 borehole. Selection of this mud system was done on the basis of tests in the Mont Terri Rock Laboratory and confirmed by the good well behaviour in the TRU1-1 and MAR1-1 boreholes. This mud system showed excellent performance in terms of borehole stability, core quality and coring advance rate and the full investigation programme could be executed without any major issues.

In the lower part of the borehole, the drilling and coring process was characterised by difficult hydraulic and geometric borehole conditions because a Pure-Bore® polymer mud without inhibition was used to improve hydrogeological and hydrochemical investigations. Nevertheless, the planned work and investigation programme was almost fully implemented, and the coring work was carried out successfully without any major changes. Only the in-situ stress tests were cancelled in the last borehole section.

An overview of the main drilling parameters of the BOZ2-1 borehole can be found in the drilling engineering plot in Appendix D.

3.5.1 Section Ia: 0.5 m – 260 m MD

The drilling operations started on 11.08.2020.

8½" destructive drilling

Section I started with a 12¼" (311.15 mm) pilot hole, which was drilled destructively with a tricone bit from 0.5 m to 17.5 m MD. Afterwards, a 9⅝" auxiliary casing was installed to stabilise the open hole for the upcoming drilling activities.

Average drilling parameters were as follows:

- ROP: 2.3 m/h
- WOB (weight on bit): 2.6 t
- string revolutions: 48 rpm
- torque: 288 daNm
- flowrate: 665 l/min
- SPP: 4.1 bar

In a second run, the borehole was pre-drilled with an 8½" (215.9 mm) tricone bit to 32.5 m MD. This was done to make sure the borehole was deep enough for the BHA and to generate enough WOB for the RVDS in the next run.

- ROP: 2.1 m/h
- WOB: 2.3 t
- string revolutions: 65 rpm
- torque: 467 daNm
- flowrate: 1'567 l/min
- SPP: 19.2 bar

In the third run, Section Ia was drilled destructively with an 8½" (444.5 mm) tricone bit and a RVDS (see Fig. 3-3) down to the lower part of the Malm at 260 m MD. Due to a decreasing ROP at a depth of 200 m MD, a roundtrip was performed followed by pumping a high viscosity pill (HVP) to clean the borehole. No further problems occurred.

The BHAs (#1 to #13) used in Section Ia can be found in Appendix N. The inclination at 32.5 m MD was 0.5° and could be corrected to 0.0° by the RVDS within the first metres. All following measurements down to 260 m MD had an inclination of 0.0°.

Average drilling parameters for the RVDS were as follows:

- ROP: 4.6 m/h
- WOB: 7.0 t
- string revolutions: 62 rpm
- torque: 1'215 daNm
- flowrate: 1'224 l/min
- SPP: 30.9 bar

The mud system used was a freshwater bentonite polymer drilling fluid with a mud weight increasing slightly from 1.04 SG in the beginning to 1.05 SG at TD. Details can be found in section 3.6.



Fig. 3-3: RVDS after delivery (left) and RVDS with 8½" tricone bit before RIH (right)

As soon as section TD was reached, the borehole was circulated until cuttings were no longer seen on the shaker screens. POOH the drill string was performed while rotating and circulating. A check trip was planned afterwards but could not be executed because the 8½" drill string became stuck at the shoe of the 9⅝" auxiliary casing. After successfully performing a 6½" check trip it was decided to RIH the 8½" drill string again. In the upper part of the borehole, several restriction zones were encountered which had to be reamed. TD could be reached but it was not possible to POOH dry due to several overpulls. POOH the 8½" drill string was performed while rotating and circulating.

Due to unstable conditions in the upper part of the borehole, especially in the zone directly below the rig cellar, it was decided to set a 13⅜" conductor casing down to 100 m MD. The borehole was filled with sand from 260 m to 100 m MD with the coring string. Afterwards, the 9⅝" auxiliary casing was POOH without any problems. The zone below the rig cellar was inspected for washouts and found to be very loose. Additionally, seepage water from the hillside flowed continuously into the borehole causing loose material to fall into the borehole.

12¼" and 17½" hole opening

The 8½" borehole was first opened up to 12¼" and then to 17½" with SHO bits (see BHA #14 and BHA #15 in Appendix N), starting on 21.08.2020. These SHO bits used tricone bits (8½" for 12¼" and 12¼" for 17½") on the bottom of the string as guidance within the already drilled borehole.

Average drilling parameters for 12¼" and 17½" hole opening from 0.5 m to 101 m MD were as follows:

- ROP: 4.6 m/h
- WOB: 1.5 t to 3 t
- string revolutions: 44 rpm
- torque: 1'120 daNm
- flowrate: 2'500 l/min
- SPP: 15 bar to 32 bar

13⅜" conductor casing and cementing

On 24.08.2020, the 13⅜" conductor casing was installed with bow-spring centralisers to a depth of 100 m MD without any major problems. The casing tally can be found in Appendix M. The cementing of the 13⅜" casing to surface was performed with a stinger. A volume of 5.0 m³ cement / mixing zone came to surface and had to be disposed of. In total, 14.6 m³ of cement (density 1.63 SG) were pumped.

Specifications regarding the cement and casing can be found in sections 3.8 and 3.9. The cementing programme, service report and laboratory measurements can be found in Appendix O.

Non-productive time (NPT) and remarks

- Drilling the 12¼" pilot hole from 0.5 m to 17.5 m MD was complicated and time-consuming because the BHA had to be rearranged several times to ensure verticality and to generate enough WOB. The bell nipple and riser had to be adjusted twice due to changing diameters and because no conductor casing was installed.
- Drilling operations with the RVDS proved successful as a perfectly vertical borehole was obtained.
- Since the upper part of the borehole was not as stable as expected and drilling operations started directly from surface, a 13⅜" conductor casing had to be installed retrospectively. A total of 30 h of NPT was recorded during the preparation for setting the conductor. Sand to backfill the borehole, sufficient BHA for hole opening and the 13⅜" casing had to be organised at short notice. Additionally, 38 h of NPT were recorded while waiting for the casing being run and the cementing service.

3.5.2 Section Ib: 260 m to 370 m MD

After installing and cementing the 13⅜" conductor casing, the cement and float equipment were drilled out with a 12¼" tricone bit from 87 m to 102 m MD and the sand in the already drilled borehole was circulated out using an 8½" drill string (see BHA #17 and BHA #18 in Appendix N). Additionally, a HVP was pumped to clear the borehole from any remaining debris.

6⅜" coring operations

Coring operations started on 26.08.2020 using a thermally stable diamond core bit (Synset) and an outer diameter of 6⅜" (see BHA #19 in Appendix N). Plastic liners within the inner core barrel were used for core protection. The core length was fixed to 3 m. Due to an insufficient ROP, the

coring assembly was changed to an impregnated core bit with synthetic diamonds (see BHA #20 in Appendix N) at 271 m MD. The Synset core bit showed abrasive wear (broken inserts) due to hard formation (see Fig. 3-4). The impregnated bit showed a much better ROP performance and cored to section TD at 370 m MD without any problems. Fig. 3-5 shows the impregnated core bit with little wear after POOH.

On 31.08.2020, mud losses occurred at a depth of 351.5 m MD while coring with an average rate of 2.1 m³/h (static 0.7 m³/h). In the core from the same depth, a fracture was observed. Nevertheless, coring operations could be completed successfully despite ongoing mud losses. The mud loss persisted until the section TD was reached with an average of 2 m³/h, resulting in a total of 83 m³ at the end of coring.



Fig. 3-4: Synset core bit after POOH from a depth of 271 m MD

In Section Ib, 37 cores were retrieved (number #1 to #37). Detailed parameters for each core can be found in Appendix Q. One single shot measurement was carried out at 300 m MD, showing an inclination of 0°.

No coring problems, pressure or circulation problems, stand-ups, overpulls or reaming problems were observed in Section Ib.



Fig. 3-5: Impregnated core bit after POOH from a depth of 370 m MD

Average drilling parameters for coring operations were as follows:

- ROP: 1.9 m/h
- WOB: 1.6 t to 4.6 t
- string revolutions: 185 rpm
- torque: 466 daNm
- flowrate: 320 l/min
- SPP: 13 bar

8½" and 12¼" hole opening

Starting on 30.08.2020, the 6⅜" borehole was opened up to 8½" with an SHO bit (see BHA #21 in Appendix N). This SHO bit used a bullnose as guidance within the already cored borehole. Mud losses occurred during hole opening (up to 3.2 m³/h dynamic and 0.7 m³/h static). A total mud loss of 93.0 m³ (including the 83 m³ while coring) was observed in this Section Ib (including casing running).

Average drilling parameters for 8½" hole opening were as follows:

- ROP: 18.4 m/h
- WOB: 0.9 t
- string revolutions: 65 rpm
- torque: 1'232 daNm
- flowrate: 1'480 l/min
- SPP: 24 bar

After 8½" hole opening and wireline logging, a hydraulic test in the Hauptrogenstein and MHF stress tests were carried out. Fluid logging was cancelled due to the ongoing mud losses. A magnet run and a roundtrip to condition the mud were performed between the MHF tests.

Finally, the borehole was opened up to 12¼" with an SHO bit (see BHA #24 in Appendix N) and the shakers circulated clean. POOH the drill string was performed dry without any overpulls or restrictions.

Average drilling parameters for 12¼" hole opening were as follows:

- ROP: 7.7 m/h
- WOB: 1.6 t
- string revolutions: 65 rpm
- torque: 1'630 daNm
- flowrate: 1'515 l/min
- SPP: 16 bar

9⅝" casing and cementing

The 9⅝" casing was installed with bow-spring centralisers to a depth of 369 m MD without any problems. The casing tally can be found in Appendix M.

Because cementing of the 9⅝" casing was planned with a cement stinger, the stinger was RIH inside the casing down to the float equipment. The stinger was found to be leaking after a leak test. It was therefore decided to POOH the stinger and change the O-rings. After inspecting and exchanging the O-rings, the stinger was RIH again but continued to leak slightly. A metal plate was welded onto the annulus between the 5" drill pipe (the cement stinger) and the 9⅝" casing to generate backpressure during cementing, preventing the cement from leaking inside the casing. This metal plate has the same function as a cementing head.

The 9⅝" casing was successfully cemented to surface. A volume of 20.8 m³ of lead cement (density 1.35 SG) and 3.0 m³ of tail cement (density 1.63 SG) were pumped. Due to continuing losses, 60 kg of fibres were added to the lead slurry as lost circulation material (LCM). During the cement job 2.0 m³ of losses occurred.

Specifications regarding the cement and casing can be found in sections 3.8 and 3.9. The cementing programme, service report and laboratory measurements can be found in Appendix O.

NPT and remarks

- Filling the borehole with sand did not affect borehole conditions. After circulating out the sand, coring operations could start without any problems.
- Coring and hole opening operations were faster than expected.
- 10 h of NPT occurred because of the waiting time for the core sampling team. The lost time could easily be caught up because coring was very fast.
- Some NPT was recorded during petrophysical logging because the logging truck was not on site in time.
- During the MHF stress test, the pump did not function correctly. Troubleshooting took several hours.

Section I was completed on 16.09.2020. No well control unit was installed for drilling operations in this section.

3.5.3 Section II: 370 m to 615 m MD

After completing Section I, the 9 $\frac{5}{8}$ " casing was cut and TOC was detected 8 m below ground level. A top job was performed with four sacks of cement to fill the annulus up to surface. Afterwards, the 13 $\frac{3}{8}$ " 3K casing head housing (CHH) was installed on the 9 $\frac{5}{8}$ " casing and a BOP was mounted on top for well control. The 13 $\frac{3}{8}$ " BOP stack consisted of a 13 $\frac{3}{8}$ " 10K double ram preventer (5" blind rams and 4 $\frac{1}{2}$ " to 7" variable pipe rams) and a 13 $\frac{3}{8}$ " 5K annular preventer. The BOP was tested successfully according to the BOP testing protocol (low: 500 psi; high: 3'000 psi).

The cement and float equipment of the 9 $\frac{5}{8}$ " casing were drilled out with an 8 $\frac{1}{2}$ " tricone bit from 350 m to 372 m MD (see BHA #26 in Appendix N). After drilling new formation until 372 m MD, the hole was circulated clean. The mud type was then exchanged from bentonite polymer (density 1.05 SG) to potassium silicate (KSil) polymer mud (density 1.20 SG). An FIT was performed at 372 m MD according to protocol (see Appendix P) with an equivalent mud weight (EMW) of 1.75 SG. For an MW of 1.20 SG, a surface pressure of 20 bar was applied. The FIT was successful without any significant pressure drop.

6 $\frac{3}{8}$ " coring operations

Coring operations of Section II started on 19.09.2020 using the impregnated core bit from Section II (see BHA #27 in Appendix N). This core bit drilled 163 m from 372 m to 535 m MD (into the Opalinus Clay) with an excellent performance, coring up to 40 m in one day (24 h). The top of the Opalinus Clay was reached at 451 m MD. At 535 m MD a roundtrip was performed to exchange the impregnated core bit for a Synset core bit (see BHA #28 in Appendix N) because the clay content increased significantly, and ROP dropped to 1 m/h. The impregnated core bit showed normal wear after POOH.

The Synset core bit cored from 535 m until TD at 615 m MD. A picture of the Synset core bit after POOH is shown in Fig. 3-6. At around 583 m MD the pumping pressure constantly increased. While circulating the borehole with 1'500 l/m, dynamic losses of 20 m³/h occurred. Therefore, two joints of the coring string were POOH and the borehole was circulated by reducing the pumping rate to 500 l/m. The pumping pressure stabilised, and mud losses were first reduced to 17 m³/h and finally stopped. Mud losses added up to a total of 24 m³. A reason for the mud losses might have been an unknown clay plug in the annulus. This would also explain why the

pumping pressure constantly increased until the leak-off point had been reached. The losses could be controlled and stopped by keeping the pumping pressure below the critical values. No further coring problems, pressure or circulation problems, stand-ups, overpulls or reaming problems were observed in this section.



Fig. 3-6: Synset core bit after POOH from a depth of 615 m MD

The Lias was found at 574 m MD. The Keuper was found at 612 m MD. As the Top Keuper is known to be frequently fractured, the TD of Section II was decided to be within the first few metres of the Klettgau Formation, in order to have competent rock for the 9 $\frac{5}{8}$ " casing shoe.

In Section II a total of 81 cores were retrieved (number #37 to #118). Detailed parameters for each core can be found in Appendix Q. Single shot measurements were carried out every 50 m. All inclination measurements were below 0.5°.

Average drilling parameters for coring operations were as follows:

- ROP: 1.7 m/h
- WOB: 3.3 t
- string revolutions: 200 rpm
- torque: 491 daNm
- flowrate: 323 l/min
- SPP: 18.3 bar

The mud weight of the KSil polymer mud was kept at 1.20 SG for the entire duration of Section II.

Coring operations were followed by an extended logging and testing programme of the Opalinus Clay and its confining units. Several petrophysical logging runs and hydraulic tests were performed. The MHF tests were performed as soon as the borehole had been opened to 8 $\frac{1}{2}$ ". The borehole was in a very good condition without any breakouts or restrictions.

After finishing petrophysical logging operations, a series of four hydrotests was carried out in the Opalinus Clay and the Passwang Formation using a double packer assembly with an interval length of 20 m, run on 2 $\frac{7}{8}$ " tubing. After keeping the borehole open for more than 14 days without any circulation, the regular BOP pressure test (performed at least every 21 days) and a magnet run were carried out. Afterwards, a roundtrip was performed using the coring string to check the borehole conditions and to recondition the mud. During this roundtrip, no restrictions were observed, and the mud was still in a very acceptable condition without significant depletion.

After the first roundtrip two additional hydrotests were performed: a single packer test in the Lias and an extended test in the Opalinus Clay, which was a double packer test with an interval length of 5 m. These two tests added another 11 days of open hole time followed by a magnet run and the second roundtrip to recondition the KSil polymer mud.

Due to the good borehole stability using the KSil polymer mud in the hole, it was decided to run a caliper log (to find the optimum packer seats) followed by a gas threshold pressure test (GTPT) in the Opalinus Clay using a double packer assembly with an interval length of 5 m, run on 2 $\frac{7}{8}$ " tubing. This additional test added another 11 days of open hole time.

In total, the interval of Section II with a length of 245 m had an open hole time of more than 37 days without any borehole stability problems after retrieving the last core.

8 $\frac{1}{2}$ " hole opening and 9 $\frac{7}{8}$ " underreaming

Starting on 04.11.2020, the 6 $\frac{3}{8}$ " borehole was opened to 8 $\frac{1}{2}$ " with an SHO bit (see BHA #38 in Appendix N). This SHO bit used a bullnose as guidance within the already cored borehole.

Average drilling parameters for 8 $\frac{1}{2}$ " hole opening were as follows:

- ROP: 9.1 m/h
- WOB: 0.9 t
- string revolutions: 64 rpm
- torque: 478 daNm
- flowrate: 1'756 l/min
- SPP: 40 bar

After 8 $\frac{1}{2}$ " hole opening, wireline logging and MHF stress tests were carried out. The results of the single shot measurements were confirmed by wireline logging because the borehole had an inclination of 0.46° at TD of Section II.

Finally, the borehole was opened up with a 9 $\frac{7}{8}$ " underreamer (see BHA #39 in Appendix N) and the shakers circulated clean. Fig. 3-7 shows the underreamer before RIH. After POOH the underreamer (see Fig. 3-8), a caliper log was performed to check the performance of the underreaming operations. This caliper log showed that the underreamer opened up the borehole to only 6.6". Troubleshooting at the surface showed that the hydraulic arms of the underreamer did not function correctly. It was decided to perform another underreaming job with the back-up reamer tool with properly functioning hydraulic arms.



Fig. 3-7: 9 $\frac{7}{8}$ " underreamer before RIH

During the second underreaming job, changes were seen immediately because the ROP was significantly lower and the volume of cuttings running off the shakers was much higher. After finishing the underreaming operations, another caliper log was run on wireline. It performed well overall, with a borehole diameter varying between 9" and 10". The borehole was ready to RIH the 7 $\frac{5}{8}$ " liner hanger.



Fig. 3-8: 9 $\frac{7}{8}$ " underreamer with malfunctioning hydraulic arms after POOH

Average drilling parameters for 9 $\frac{5}{8}$ " underreaming from 370 m to 615 m MD were as follows:

- ROP: 3.1 m/h
- WOB: 1.4 t
- string revolutions: 65 rpm
- torque: 467 daNm
- flowrate: 1'638 l/min
- SPP: 74 bar

7 $\frac{5}{8}$ " liner hanger and cementation

A 9 $\frac{5}{8}$ " scraper run was performed to clean the inner surface of the 9 $\frac{5}{8}$ " casing to properly adjust the head of the liner hanger.

On 16.11.2020, the 7 $\frac{5}{8}$ " liner hanger was run down to 614 m MD on a 5" drill pipe (see BHA #41 in Appendix N). The head of the liner hanger was located at 307 m MD. An overlap of approximately 60 m with the previous casing was chosen because this is known to be good practice. The last nine joints were run with circulation. The liner hanger was then set with a right turn and the setting tool was subsequently released. The casing tally of the 7 $\frac{5}{8}$ " liner hanger can be found in Appendix M.

The plug of the 7 $\frac{5}{8}$ " liner hanger was cemented without any problems. In total, 7.6 m³ of cement were pumped: 2 m³ of cement with a density of 1.34 SG and 12 m³ of mixing zone were circulated out. To avoid the same problems that occurred in the MAR1-1 borehole during the 9 $\frac{5}{8}$ " casing cementation (Nagra 2021), a special procedure was used to clean the annulus from KSil polymer mud and to avoid direct contact of the mud with cement. Therefore, 4.3 m³ of wash pills (usually used for cleaning casing from oil-based muds) with a density of 1.00 SG and 5.1 m³ of spacer with high quantities of retarders and an MW of 1.25 SG were pumped ahead of the cement slurry. This procedure proved successful not only for the cementing itself but also for the cement bond.

Specifications regarding the cement and liner hanger can be found in sections 3.8 and 3.9. The cementing programme, service report and laboratory measurements can be found in Appendix O.

NPT and remarks

- Coring and hole opening went faster than expected. In the Dogger formations it was possible to core up to 40 m per day.
- As in the MAR1-1 borehole, the borehole stability was excellent with the KSil polymer mud, even after long series of logging and testing.
- The first 9 $\frac{5}{8}$ " underreaming job was not successful because the hydraulic arms of the tool did not function correctly. This resulted in almost 2 days of NPT. A back-up underreamer was kept onsite and a second underreaming run could be performed successfully.
- The 7 $\frac{5}{8}$ " liner hanger with KSil polymer mud was cemented without any problems because a special wash pill and spacer were pumped ahead of the cement slurry.

Section II was completed on 17.11.2020.

3.5.4 Section III: 615 m to 829 m MD

After executing the regular BOP test during WOC, the cement and float equipment of the 7 $\frac{5}{8}$ " liner hanger were drilled out with a 6 $\frac{1}{2}$ " tricone bit from 600 m to 617 m MD (see BHA #42 in Appendix N). At the 7 $\frac{5}{8}$ " shoe (614 m MD) no further progress was possible, and ROP dropped to zero. The drill string was POOH and a visual inspection showed evidence of a possible clearance issue between the drill string and the casing due to the presence of jammed aluminium parts in the shoe track. It was decided to RIH the same bit, starting with a low ROP at the beginning to overcome the clearance issues. New formation was successfully drilled from 615 m to 617 m MD. The KSil polymer mud was then changed to a Pure-Bore® polymer mud for Section III because the focus was on hydraulic tests, specifically on water sampling from the Keuper and Muschelkalk aquifers. The 6 $\frac{1}{2}$ " tricone bit after POOH can be seen in Fig. 3-9.



Fig. 3-9: 6 $\frac{1}{2}$ " tricone bit after POOH

An FIT was performed on 19.11.2020 at 617 m MD according to protocol (see Appendix P) with an EMW of 1.70 SG, resulting in a surface pressure of 42 bar. The MW of the Pure-Bore® polymer mud was 1.01 SG.

6 $\frac{3}{8}$ " coring operations

Coring of Section III started on 19.11.2020 using an impregnated core bit (see BHA #43 in Appendix N). The core length was fixed to 3 m as in the previous borehole section. A lot of aluminium parts were recovered with the first core (see Fig. 3-10). The impregnated bit cored until 658 m MD when the decision was made to perform a hydrotest in the Klettgau aquifer. Fig. 3-11 shows the impregnated bit after POOH displaying slight damage from the aluminium of the 7 $\frac{5}{8}$ " shoe track.



Fig. 3-10: Aluminium parts from the 7 $\frac{5}{8}$ " casing shoe recovered from a depth of 617 m MD in the first core of Section III

After hydrotesting, the same impregnated core bit was RIH to core from 658 m to 697 m MD. Weighting up the Pure-Bore® polymer mud with chalk was difficult during coring as the pumping pressure constantly increased and exceeded the limit values. Therefore, coring operations were stopped to condition the mud properly and increase the MW from 1.01 SG to 1.05 SG.

Coring continued until 805 m MD, where dynamic mud losses of approximately 10.7 m³/h were observed at varying flowrates. A flow check was performed to evaluate the static loss rate, which returned values of 1.3 m³/h to 1.5 m³/h. It was decided to continue coring. After coring another 0.5 m, mud losses continued at the same rates and the coring string was POOH for hydrotesting. During POOH the string became stuck at 751 m MD but could be freed with 52 t of overpull. Meanwhile, mud losses of 5.0 m³/h to 7.0 m³/h occurred. A check trip down to 805 m MD was performed with a 6 $\frac{3}{8}$ " TCI bit (see Fig. 3-12) without any problems. Hydrotesting of the Muschelkalk aquifer started on 02.12.2020 with a single packer assembly run on 2 $\frac{7}{8}$ " tubing.

Average drilling parameters for coring operations were as follows:

- ROP: 1.9 m/h
- WOB: 4.4 t
- string revolutions: 191 rpm
- torque: 526 daNm
- flowrate: 364 l/min
- SPP: 19.8 bar



Fig. 3-11: Impregnated core bit after POOH from a depth of 658 m MD

After finishing the hydrotest, the same impregnated core bit as in the previous cored interval was used for coring from 805.5 m to 829 m MD, which was also the TD of Section III. The fluid level was measured at 47 m MD before wireline logging started under static mud losses of 1.5 m³/h. Logging was interrupted because of overpulls during POOH at 715 m MD. A roundtrip with the coring string was performed to clean and ream the borehole without any problems. An LCM pill of 5 m³ was also pumped to cure the mud losses. The coring string was POOH under static losses of approximately 2.8 m³/h. The fluid level was measured at 135 m MD. Logging operations continued without filling up the borehole and the fluid level remained at 135 m MD. Since several overpulls were again detected during logging, another roundtrip was performed. No significant pressure or circulation problems, stand-ups, overpulls or reaming problems were observed. Another LCM pill of 3 m³ was pumped because mud losses started to occur during the roundtrip.

Petrophysical logging and VSP were completed on 11.12.2020. MHF stress tests were cancelled due to several overpulls during logging and continuous mud losses during coring.

In Section III, 72 cores were retrieved (number #119 to #191). Detailed parameters for each core can be found in Appendix Q. Single shot measurements were carried out every 50 m. All inclination measurements were below 1.0°. Total mud losses in Section III amounted to 273.2 m³.

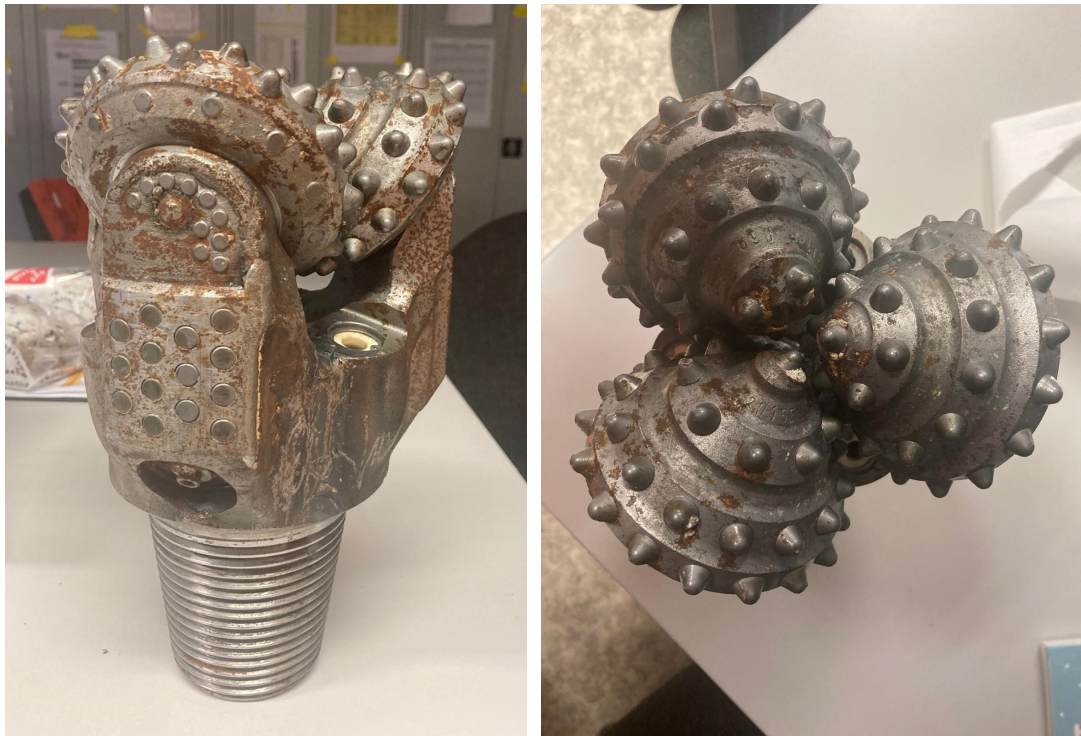


Fig. 3-12: 6 $\frac{3}{8}$ " TCI bit for performing a check trip

6 $\frac{3}{8}$ " back cementation

On 12.12.2020, the borehole was backfilled with cement through a 2 $\frac{7}{8}$ " cement stinger (see BHA #51 in Appendix N) in two steps.

The first plug was set from 829 m to 714 m MD with 3.2 m³ of cement (1.65 SG). A flow check performed afterwards was successful; no losses occurred during the cement job. The cement stinger was slowly pulled back to 700 m MD and 3 m³ of mixing zone were circulated out.

The stinger was pulled further back to 612 m MD to WOC. Cement samples were taken and stored in an oven at downhole temperature to investigate the time required for the cement to harden. There were 8 hours of waiting time before the second cement plug could be pumped.

The cement stinger was RIH and the second plug was set from 714 m to 660 m MD with 3.2 m³ of cement (1.65 SG). A successful flow check was performed afterwards; no losses occurred during the cement job. The cement stinger was pulled back slowly to 660 m MD and 4 m³ of mixing zone were circulated out.

The stinger was pulled back further until 612 m MD to WOC. Again, cement samples were taken and stored in an oven at downhole temperature to investigate the time required for the cement to harden. There were 9 h of waiting time before the top of cement (TOC) could be tagged at 660 m MD.

Specifications regarding the cement and liner hanger can be found in sections 3.8 and 3.9. The cementing programme, service report and laboratory measurements can be found in Appendix O.

To finalise the drilling operations in the BOZ2-1 borehole, the Pure-Bore® polymer mud was exchanged with freshwater with MW 1.00 SG. Afterwards, the BOP stack was demounted and the wellhead (see Fig. 3-13) installed on the 13⁵/₈" CHH (brown colour). This wellhead was equipped with two 4¹/₁₆" ball valves (with handwheels), installed on a 3K double studded adapter flange which serves as a crossover from 13⁵/₈" to 4¹/₁₆".

The rig was released on 14.12.2020, initiating rig down.



Fig. 3-13: Wellhead installed after finishing drilling operations

NPT and remarks

- The shoe track of the 7⁵/₈" liner hanger was drilled out with a 5" drill pipe which created problems because of the low clearance between the drill string and the 7⁵/₈" liner. Large aluminium parts from the shoe track could not be transported to the surface. The use of a 3¹/₂" drill pipe is advisable to improve hole cleaning in small diameter casings.
- Increasing the MW while coring was difficult due to the relatively low pumping rates. Coring had to be stopped to increase the MW and condition the mud.
- Due to very low temperatures (especially during the night), several parts of the rig required permanent or partial heating to continue operations.

3.5.5 Coiled tubing back cementation: 660 m to 630 m MD

The BOZ2-1 borehole was cemented back to 660 m MD, leaving 46 m (7⅞" liner hanger shoe at 614 m MD) open for potential long-term monitoring.

Most of the anhydrite-rich layers of the Bänkerjoch Formation were already below TOC, with the exception of 1.5 m, particularly from 657.39 m to 657.83 m MD (44 cm) and 658.82 m to 659.56 m MD (74 cm). These anhydrite-rich layers were separated by clay layers.

The Swiss regulatory authority ENSI did not accept the TOC being below some of the anhydrite-rich layers and requested subsequent backfilling of the borehole to at least 655 m MD. The reason for this is that anhydrite layers, especially anhydrite-rich claystones or clay-rich anhydrites have the potential to swell or dissolve in contact with freshwater. These swelling and dissolution processes are difficult to stop at shallow depths, even when the contact with water is interrupted.

A coiled tubing unit from Baker Hughes was ordered to perform the back cementation from 09.03.2021 to 12.03.2021. The operations were carried out in dayshift only.

Rigging up the coiled tubing unit took place on the first day (see Fig. 3-14). On the following day (10.03.2021), the borehole was prepared for the cement job. During RIH the 1½" coiled tubing string, the borehole was filled with 6.2 m³ of water (fluid level at around 130 m MD). TOC was found at 660 m MD as expected. Fig. 3-15 shows the coiled tubing unit during RIH. The 1½" tubing runs across the injector head, which is held by a crane, through the BOP into the borehole.

After RIH, cementing operations started by pumping 300 l of high sulphate-resistant API Class G cement. The cement was pumped with two darts, one in front of the cement slurry and one behind. After pumping the cement into the coiled tubing and inserting the second dart, pumping pressure increased rapidly. Several attempts to restart pumping failed. The coiled tubing string was moved up and down and another attempt was made to apply pressure to the cement column within the coil. Finally, the pressure dropped significantly, and the pumping process could be completed without any problems. Displacement of the cement was successful. After POOH the coiled tubing string, it was discovered that only one dart (the first dart, pumped ahead of the cement slurry) could be recovered. The second dart may have already sheared within the tubing when it became stuck within the coil. This could be the main reason why the pressure increased excessively as soon as the second dart was inserted into the tubing. Fig. 3-16 shows the recovered dart and the dart that could not be recovered.



Fig. 3-14: Rigging up the coiled tubing unit from Baker Hughes



Fig. 3-15: Coiled tubing operation during RIH

On the next day, TOC was tagged at around 630 m MD with several metres of soft cement mixing zone on top. The back cementation was successful without any major problems and the coiled tubing unit was released to start rig down.

Rig down was completed as planned on 12.03.2021.



Fig. 3-16: First dart after recovery (left) and second dart that could not be recovered (right)

3.6 Drilling fluids

The drilling fluid engineering service was contracted by the drilling contractor and was permanently onsite during the entire drilling phase.

In total, three different types of drilling fluid were used in the BOZ2-1 borehole. A bentonite polymer mud was used for the Malm, a KSil polymer mud was used for the most relevant borehole sections of the Dogger, the Lias and the upper part of the Keuper, and a Pure-Bore® polymer mud was used for the Keuper and the Muschelkalk until final depth within the upper part of the Zeglingen Formation.

Tab. 3-1: Drilling fluids data

From [m MD]	To [m MD]	Section	Type / specification	Density
0	372	I	Bentonite + polymer	1.05 SG
0	617	II	Potassium silicate (KSil) + polymer	1.20 SG
0	829	III	Pure-Bore® + polymer	1.05 SG
0	630	-	Completion fluid: water	1.00 SG

3.6.1 Section I: Bentonite polymer drilling fluid

Before the drilling operations started, 90 m³ of bentonite polymer mud with a MW of 1.04 SG were mixed and treated with bactericide to protect the mud system from being contaminated with bacteria. Additionally, the mud was treated with uranine tracer fluid and analysed for tracer concentration on a regular basis. As drilling of Section Ia continued, new mud was mixed and added to the active system. Polymers were added from time to time to reduce the API fluid loss and regulate the viscosity.

After drilling out the shoe track of the 13³/₈" conductor casing set in Section Ia, the mud was treated with citric acid and sodium bicarbonate to regulate the pH value. High viscosity pills were pumped to circulate out the sand in steps from 260 m MD to surface. The mud weight increased to 1.06 SG while drilling Section Ib. Dynamic mud losses between 2.1 m³/h and 3.5 m³/h started at a depth of 351.5 m MD and continued until the 9⁵/₈" casing was installed and cemented. New mud had to be mixed during hole opening to compensate for losses and polymers; bactericide and soda ash were added to condition the drilling fluid. Before running the casing, the borehole was circulated clean until the shakers were clean.

After RIH the cement stinger, the borehole was circulated, and the cement stinger was found to be leaking. It was POOH to exchange the sealing rings and RIH again. Although the stinger still leaked slightly, the cementing was performed successfully with dynamic losses which added up to 2 m³ during the cement job.

Sections Ia and Ib were drilled without any problems with the bentonite polymer mud.

The drilling fluid parameters of Section I are given in Tab. 3-2, and the drilling fluid materials are listed in Tab. 3-3.

Tab. 3-2: Drilling fluid parameters – Section I

Parameter	Unit	Min.	Max.	Planned
Flowline temperature	[°C]	27	37	-
Density	[SG]	1.03	1.06	1.01 – 1.10
Plastic viscosity	[cP]	24	30	ALAP (as low as possible)
Yield point	[lbs/100 ft ²]	14	30	20 – 30
Gel strength (10 s)	[lbs/100 ft ²]	4	6	–
Gel strength (10 min)	[lbs/100 ft ²]	4	14	–
pH	–	9.1	10.3	9 – 10
Sand content	[vol.-%]	0.0	0.1	< 1.0
Methylene blue test (MBT)	[kg/m ³]	0	43	< 36

Tab. 3-3: Drilling fluid materials – Section I

Product	Unit size	Quantity
Bentonite OCMA	25 kg	252
Biozid Grotan WS	10 l	23
Citric acid	25 kg	4
Drispac Superlo	25 kg	10
Floc cationic	25 kg	11
Sodium carbonate	25 kg	42
Sodium bicarbonate	25 kg	8
Pac LV premium	25 kg	90
Xanthan gum	25 kg	8

Three AKROS Mongoose shakers and a Brandt Cobra mud cleaner were installed for mud cleaning. Shakers 1 and 2 were equipped with API 120 – 140 screens, shaker 3 with API 120 screens and the mud cleaner with API 140 screens. The centrifuge with flocculation as well as the desander and desilter ran permanently during the drilling phase. The sand content could thus be kept below 1.0 vol.-%.

3.6.2 Section II: Potassium silicate (KSil) drilling fluids

For Section II, the bentonite polymer mud from Section I was used to drill out the shoe track of the 9 $\frac{5}{8}$ " casing and 2 m of new formation. The mud was treated with citric acid and sodium bicarbonate to regulate the pH value. At the same time, some of the surface tanks were cleaned for exchanging the mud and the bentonite polymer mud was transported to the waste treatment facility. In total, 90 m³ of fresh KSil polymer mud with an MW of 1.20 SG were prepared. During mixing, the viscosity was too high which required more water and silicate to be added. Furthermore, the drilling fluid was treated with uranine tracer fluid and analysed for tracer concentration on a regular basis. The product and technical datasheet for the potassium silicate fluid used for mixing the drilling fluid can be found in Appendix R.

The bentonite polymer mud was exchanged with KSil polymer mud by pumping 8 m³ of high viscosity spacer followed by 17 m³ of fresh drilling fluid. In total, a mixture of 24 m³ of bentonite polymer mud, spacer and mixing zone had to be disposed of until the mud exchange was complete.

As stated in section 3.5.3, dynamic mud losses between 20 m³/h and 17 m³/h occurred at a depth of around 583 m MD while circulating the borehole with a pumping rate of 1'500 l/min, and after the pumping pressure constantly increased during coring. After reducing the pumping rate to 500 l/min, mud losses stopped after 24 m³ of KSil polymer mud had been lost into the formation. Coring could continue without any further problems.

The KSil polymer mud was treated with polymers, xanthan gum and fresh silicate on a regular basis to adjust mud properties.

The drilling fluid parameters of Section II are given in Tab. 3-4 and the drilling fluid materials are listed in Tab. 3-5.

Tab. 3-4: Drilling fluid parameters of the potassium silicate mud – Section II

Parameter	Unit	Min.	Max.	Planned
Flowline temperature	[°C]	23	26	-
Density	[SG]	1.18	1.23	1.20 – 1.25
Plastic viscosity	[cP]	15	25	ALAP
Yield point	[lbs/100 ft ²]	9	17	5 – 20
API fluid loss	[ml/30 min]	3.5	20.0	4 – 8
pH	–	12.5	13.6	12 – 14
Sand content	[vol.-%]	0.0	0.05	< 1
Chloride	[mg/l]	1'060	2'169	-

After reaching the TD of Section II at 615 m MD, the borehole was without any circulation for more than 14 days due to logging and testing. In the meanwhile, the mud in the surface tanks was properly maintained and conditioned to remain within the planned specifications. The first round-trip was performed to check the borehole condition and circulate fresh mud into the hole. A second roundtrip was performed after a further series of three hydrotests and almost 11 days without

circulation. Both roundtrips were carried out without any problems and the borehole was in very good condition. Another 11 days of testing followed before 8½" hole opening, in situ stress testing and 9⅞" underreaming.

As the first 9⅞" underreaming job failed, a second run was performed which was successful. A 6.5 m³ high viscosity pill was pumped afterwards to clean the borehole until the shakers were clean.

Some tanks of the surface system were cleaned from KSil polymer mud for the upcoming cementing and fluid exchange. The KSil mud was properly conditioned and stored in silos for reuse in the next borehole (Stadel-2-1 in Canton Zürich).

Tab. 3-6: Drilling fluid materials – Section II

Product	Unit size	Quantity
Citric acid	25 kg	1
Drispac Superlo	25 kg	32
Drispac Regular	25 kg	32
Sodium carbonate	25 kg	3
Sodium bicarbonate	25 kg	6
Pac LV Premium	25 kg	5
K+ silicate	1'000 l	119.45
Xanthan gum	25 kg	10
Xanthan gum FED	15 kg	1

AKROS Mongoose shakers were installed. Shakers 1 and 2 were equipped with API 200 screens, and shaker 3 with API 120 screens for coring. The centrifuge was partially in use during the drilling and hole opening phases, but mostly used while coring.

3.6.3 Section III: Pure-Bore® polymer drilling fluid

For Section III the potassium silicate mud from Section II was used to drill out the shoe track of the 9⅞" liner hanger and 2 m of new formation. At the same time some of the surface tanks were cleaned for mud exchange and most of the KSil polymer mud was transferred to the storage silos. The rest of the KSil polymer mud was transported to the waste treatment facility. In total, 128 m³ of fresh Pure-Bore® polymer mud with a MW of 1.01 SG were prepared. Furthermore, the drilling fluid was treated with uranine tracer fluid and analysed for tracer concentration on a regular basis.

The KSil polymer mud was exchanged with Pure-Bore® polymer mud by pumping 8 m³ of high viscosity spacer followed by fresh drilling fluid. In total, a mixture of 27 m³ of KSil polymer mud, spacer and mixing zone had to be disposed of until the mud exchange was complete.

Coring and one hydrotest were carried out without any problems down to 805 m MD. The MW increased to 1.03 SG during coring. After completing the hydrotest in the Keuper aquifer, the mud density was slowly increased with calcium carbonate during coring. Because the pumping rate

was too low during coring, the coring operations were stopped to increase the MW from 1.03 SG to 1.05 SG and to properly condition the drilling fluid. The MW increased to 1.06 SG but was brought back to 1.05 SG by switching on the centrifuge.

Due to the high solid content resulting from the addition of calcium carbonate, the API fluid loss decreased to 7 ml/30 min. Viscosity was adjusted by adding polymers and xanthan gum to improve borehole cleaning.

At 805 m MD dynamic losses of up to 10.7 m³/h occurred at varying flowrates; static losses were between 0.0 m³/h and 1.5 m³/h. Coring operations were stopped, and a hydrotest was performed to analyse the Muschelkalk aquifer. Drilling fluid was added to the surface tanks to compensate for losses.

Coring resumed after hydrotesting with fluctuating mud losses from 805.5 m to 829 m MD, which was also the final depth of the BOZ2-1 borehole. In total, 221 m³ of drilling fluid were lost in Section III as soon as TD had been reached.

The drilling fluid parameters of Section III are given in Tab. 3-7 and the drilling fluid materials are listed in Tab. 3-8.

Tab. 3-7: Drilling fluid parameters of the potassium silicate mud – Section III

Parameter	Unit	Min.	Max.	Planned
Flowline temperature	[°C]	11	20.1	–
Density	[SG]	1.01	1.06	1.01 – 1.10
Plastic viscosity	[cP]	13	19	ALAP
Yield point	[lbs/100 ft ²]	14	19	5 – 20
API fluid loss	[ml/30 min]	6.4	13.3	4 – 8
pH	–	8.6	9.2	9 – 10
Chloride	[mg/l]	535	709	–

Wireline logging and VSP were performed under static losses of 1.5 m³/h. Due to several overpulls during logging, a roundtrip was performed to clean and ream the borehole. A 5 m³ pill with LCM was pumped, consisting of 137 kg/m³ calcium carbonate and 110 kg/m³ Mikhart 130 medium. Afterwards, the mud losses stopped (fluid level in the borehole stayed at 135 m MD) and logging operations continued.

Another roundtrip was performed due to overpulls and stand-ups while logging. Mud losses started again during this roundtrip and 3 m³ of LCM pills were pumped, consisting of Mikhart 0.35 to 0.7, Mikhart 130, Nut Plug fine and Nut Plug coarse, having an LCM concentration of 200 kg/m³. Mud losses stopped and the fluid level was back at surface.

A total of approximately 273 m³ of Pure-Bore® polymer drilling fluid were lost in Section III.

As soon as Section III was completed by cementing back to 660 m MD, the Pure-Bore® polymer mud was exchanged with freshwater with a 5 m³ high viscosity spacer.

Tab. 3-8: Drilling fluid materials – Section III

Product	Unit size	Quantity
Calcium carbonate fine	20 kg	1'152
Calcium sx	25 kg	12
Defomex	55 gal	1
Drispac Superlo	25 kg	62
Drispac regular	25 kg	25
Sodium carbonate	25 kg	30
Nut Plug coarse	25 kg	10
Nut Plug fine	25 kg	10
Mikhart 130	25 kg	46
Mikhart 0.35 – 0.7	25 kg	10
Pure-Bore® ULV	25 kg	77
Xanthan gum	25 kg	7
Xanthan gum FED	15 kg	23

AKROS Mongoose shakers 1 and 2 were equipped with API 200 screens, and shaker 3 with API 140 screens for coring. The centrifuge was partially in use during the drilling and hole opening phases, but mostly used while coring.

3.7 Borehole measurements

Borehole measurements planned as per work programme (WP) are described in Appendix B.

Technical logging operations were carried out in all sections (Tab. 3-9).

A series of caliper logging runs were performed in the 6 $\frac{3}{8}$ " open hole of Section III between the logging and testing sequences. A comparison of the borehole conditions and the very small changes in borehole conditions between the runs can be found in Appendix F.

Petrophysical logging operations and vertical seismic profiling (VSP) were carried out in Sections I, II and III by Schlumberger with the assistance of the drilling contractor. Details on petrophysical logging and VSP can be found in Dossier VI.

In situ stress testing (micro-hydraulic fracturing MHF) with the modular formation dynamic tester (MDT) were carried out in Sections I and II by Schlumberger with the assistance of the drilling contractor. Details on MHF can be found in Dossier VI.

Hydraulic packer tests were carried out in Sections II and III by Solexperts with the assistance of the drilling contractor. Details on hydraulic testing can be found in Dossier VII.

Tab. 3-9: Overview of technical logging

Date	From [m MD]	To [m MD]	Company	Measurement	Run
31.08.2020	100	5	Schlumberger	Cement bond log: PPC-MSIP-PPC-GPIT-EDTC- LEH.QT	1.1.2
08.09.2020	369	80	Schlumberger	EMS caliper log: EMS-EDTC-LEH.QT	1.2.1
28.09.2020	340	10	Schlumberger	Cement bond log: PPC-MSIP-PPC-GPIT-EDTC- LEH.QT	2.1.3
30.09.2020	367	5	Schlumberger	Ultrasonic log: USIT-EDTC-LEH.QT	2.1.9
24.10.2020	616	340	Schlumberger	EMS caliper log: EMS-PPC-EDTC-LEH.QT	2.2.1
06.11.2020	614	355	Schlumberger	EMS caliper log: EMS-EDTC-LEH.QT	2.3.1
12.11.2020	614	350	Schlumberger	EMS caliper log: EMS-EDTC-LEH.QT	2.4.1
15.11.2020	614	350	Schlumberger	EMS caliper log: EMS-EDTC-LEH.QT	2.5.1
09.12.2020	827	570	Schlumberger	EMS caliper log: EMS-EDTC-LEH.QT	3.2.1
10.12.2020	613	310	Schlumberger	Ultrasonic log: USIT-EDTC-LEH.QT	3.2.3
10.12.2020	722	600	Schlumberger	Cement bond log: PPC-MSIP-PPC-GPIT-EDTC- LEH.QT	3.2.4

3.8 Borehole diameters and casing

Borehole diameter

The borehole diameters are given in Tab. 3-10.

Tab. 3-10: Borehole diameters

From [m MD]	To [m MD]	Diameter	Drilling method	Comment
0.5	17.5	12¼"	Destructive	Pilot hole for 8½" RVDS drilling
17.5	32.5	8½"	Destructive	Pilot hole for 8½" RVDS drilling
32.5	260	8½"	Destructive	Section I
17.5	101	12¼"	Hole opening	For 13⅜" conductor casing
0.5	101	17½"	Hole opening	For 13⅜" conductor casing
87	102	12¼"	Destructive	Drilling out cement, shoe track + 1 m new formation
102	260	8½"	Reaming	Circulating out sand
260	370	6⅜"	Coring	Section I
260	370	8½"	Hole opening	For 9⅝" casing
102	370	12¼"	Hole opening	For 9⅝" casing
350	372	8½"	Destructive	Drilling out cement, shoe track + 2 m new formation
372	615	6⅜"	Coring	Section II
372	615	8½"	Hole opening	For 7⅝" liner hanger
370	615	9⅞"	Underreaming	For 7⅝" liner hanger
600	617	6½"	Destructive	Drilling out cement, shoe track + 2 m new formation
617	829	6⅜"	Coring	Section III

Casing

The casing data are given in Tab. 3-11.

Tab. 3-11: Casing data

From [m MD]	To [m MD]	Diameter	Section	Specification
0	100	13 $\frac{3}{8}$ "	I – Conductor	L80, #68.0, buttress thread connection (BTC)
0	369	9 $\frac{5}{8}$ "	I – Surface casing	J55, #40.0, BTC
310	614	7 $\frac{7}{8}$ "	II – Liner hanger	J55, #29.7, BTC

3.9 Cementation

Cementing data are shown in Tab. 3-12.

Tab. 3-12: Cementing data

From [m MD]	To [m MD]	Casing	Amount [m ³]	Density	Type / specification
0	101	13 $\frac{3}{8}$ "	14.6	1.63 SG	CEM III B 32.5 N-LH/HS/NA
0	370	9 $\frac{5}{8}$ "	20.8	1.35 SG	Lead: HOZlite
			3.0	1.63 SG	Tail: CEM III B 32.5 N-LH/HS/NA
310	615	7 $\frac{7}{8}$ "	7.6	1.35 SG	HOZlite
829	660	backfilling	5.4	1.65 SG	CEM III B 32.5 N-LH/HS/NA
660	630	backfilling	0.3	1.90 SG	API Class G Grade HSR

For evaluation of the cement jobs in the BOZ2-1 borehole, cement bond logs (CBL) and more detailed measurements with an ultrasonic imager tool (USIT) were performed. These measurements are listed in Tab. 3-9 of section 3.7.

In Section I, the 13 $\frac{3}{8}$ " casing was successfully cemented to surface. The quality of the cement job shows mainly poor bonding throughout the cemented sections of the log, except for the interval from 79 m to 100 m MD. The CBL showed medium to very high amplitudes with strong casing arrivals and weak formation arrivals. The bond index showed the presence of cement but no zonal isolation was achieved. The bottom part showed a medium to high CBL amplitude with strong formation arrivals on the variable density log (VDL) and high acoustic impedance, which results in medium bonding.

The CBL and USIT logging runs of the 9 $\frac{5}{8}$ " casing cement job showed excellent bonding and zonal isolation across the interval from 133 m to 366 m MD. The logs revealed strong formation arrivals with high acoustic impedance and the cement map showed strong cement and no channelling. The section from 133 m MD upwards showed mostly medium bonding with some intervals of poor bonding; cement was, however, still present in these intervals and there were no indications of channelling.

The cement job of the 7 $\frac{5}{8}$ " liner hanger had good bonding and zonal isolation across the full length.

A graphical overview of the quality of the cement jobs as evaluated by logging can be found in Appendix G. This overview shows that, even with the low quality of the 13 $\frac{3}{8}$ " cement job, zonal isolation of the different aquifers in BOZ2-1 could be achieved. The host rock and its surrounding formations were well isolated and the cement bond to the casing as well as to the formation was good. Furthermore, the aquifers are isolated from each other.

3.10 Borehole deviation

The inclination and azimuth of the BOZ2-1 borehole were measured by survey runs performed by Schlumberger wireline logging. The survey data were filtered at 10 m intervals from 0 m to 829 m TVD (true vertical depth). Figs. 3-17 and 3-18 show the borehole survey. Maximum dog-leg severity is 1.1°/30 m at 300 m TVD. Step-out at TD is 5.58 m north and 3.61 m west. The borehole can be considered vertical, and MD values mostly correspond to TVD values.

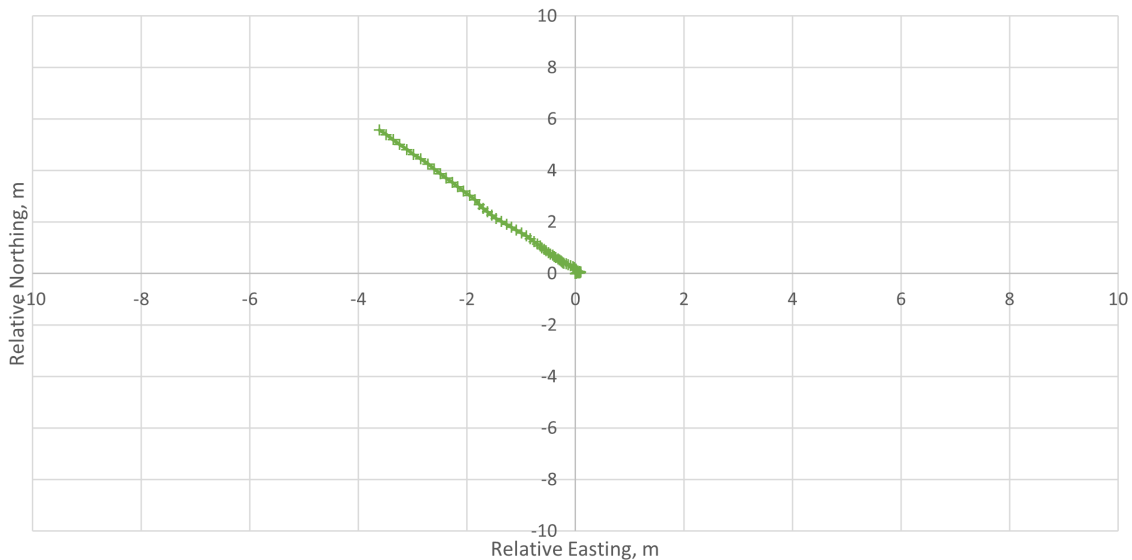


Fig. 3-17: Plan view: relative easting – relative northing

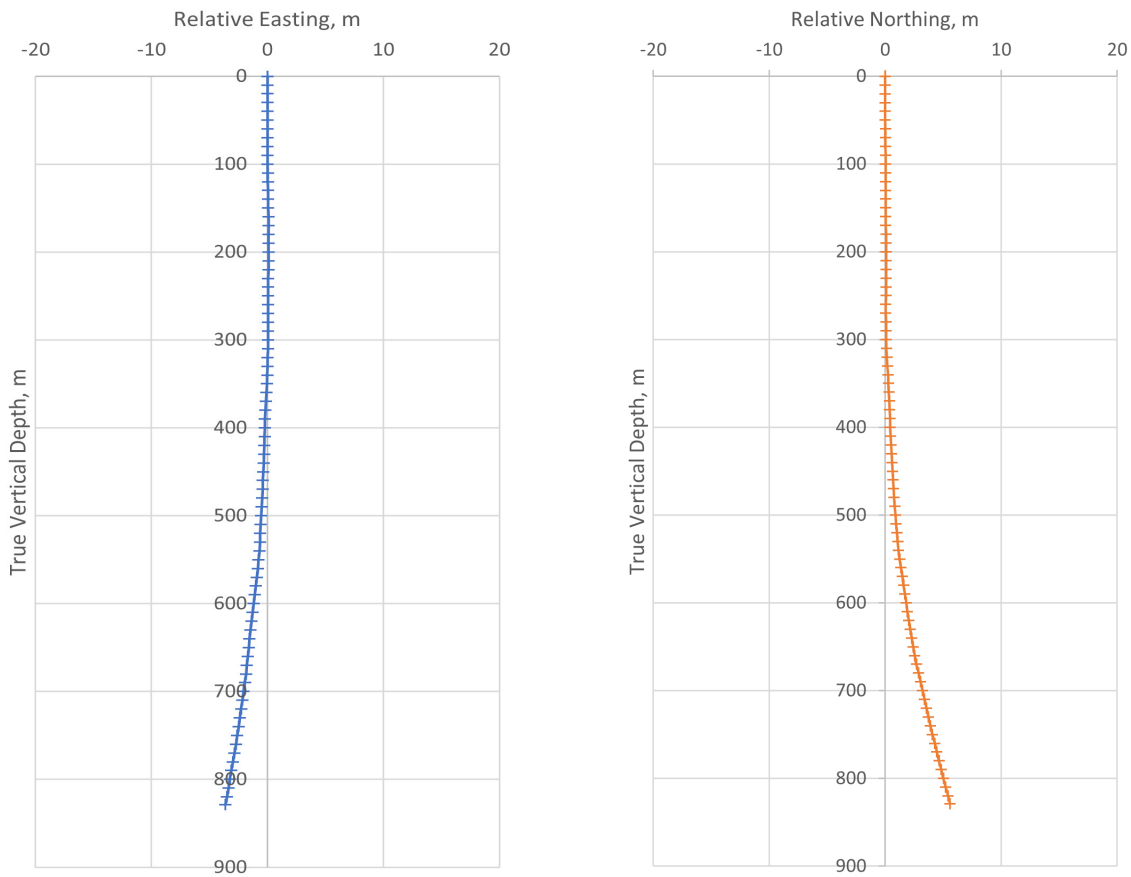


Fig. 3-18: Profile view: relative northing and relative easting – relative elevation (TVD)

4 Health, safety and environment

4.1 Health and safety

The health and safety of employees, contractors and subcontractors of Nagra are of vital importance. Therefore, several measures were taken during planning and performance of the drilling campaign to reduce hazards to a minimum and to create safe working conditions.

All drill sites were fenced to protect workers from external influences and to define a clear barrier for people and animals which are not allowed to access the drill site. Additionally, the drill site was permanently guarded by a security service during the entire drilling phase. The security guards were also responsible for performing detailed access controls.

To respect the different ATEX zones around the drilling rig, the drill site was divided into a restricted area and a non-restricted area. Access to the restricted area was allowed only with the correct personal protective equipment (PPE), consisting of:

- Overall / Jacket
 - anti-flammable
 - anti-static
 - high visibility
- Safety shoes
 - S3
 - mid height
- Safety helmet
- Safety glasses
- Safety gloves

Within the restricted area, it was not permitted to have any non-explosion-proof electrical devices to prevent hazardous sparks within the ATEX zone.

A firefighting and rescue plan with specific procedures for emergency situations was in place for the drill site. Furthermore, the drill site was equipped with emergency exits, muster points, fire-extinguishers, first aid kits and alarm signals. Evacuation drills and trainings were carried out with the onsite personnel on a weekly basis to practice correct behaviour in emergency situations.

Daily shift changes always started with pre-job safety meetings to make the rig crew aware of potential hazards on location. Special jobs such as cementing required additional safety meetings together with subcontractors to address all planned work steps and further safety instructions.

Life-saving rules were implemented which everyone visiting or working at the drill site had to follow. These rules set out the minimum requirements for controlling the risk of serious injury from common activities.

The drilling contractor had a STOP card system in place that allowed all persons onsite to address positive and/or negative observations at the drill site related to HSE. These STOP cards were collected and analysed to pinpoint problems that needed to be addressed and improved for the future. Good cards served as feedback and motivation on excellent performance.

During the entire duration of the drilling phase in BOZ2-1, no restricted work cases and no first-aid cases were reported. Having zero lost time incidents (LTI) proved that the regular emergency training of the personnel onsite was successful.

As for the MAR1-1 borehole, additional safety rules were implemented due to the COVID-19 pandemic. Measures and instructions of the Federal Office of Public Health (FOPH) were strictly followed, not only to be able to continue drilling operations but also to protect the personnel on the drill site. Meetings were held twice a day to communicate current hygiene regulations, discuss the importance of social distancing and how to organise tasks where distance normally cannot be maintained. Body temperature measurements were performed when accessing the site and the number of people onsite was restricted to a minimum. No infections were recorded on the drill site during the entire project.

4.2 Environment

4.2.1 Environmental supervision and monitoring

Due to official regulations, the entire project had to be accompanied by an environmental supervisor. This supervisor was responsible for advising and informing Nagra on environmental aspects and for consulting external experts if necessary.

The tasks of the environmental supervisor during the drilling phase were:

- to communicate transport routes
- to verify whether environmental requirements and protective measures were respected for transporting and drilling activities
- to check if the drainage concept was respected and working properly
- to check if the lighting concept was respected and whether further measures were necessary
- to check the machinery list and particle filters of all vehicles and machines
- checking the storage of hazardous substances
- to check the emergency power generator and its leakage detection system
- the conduction of leakage tests of wastewater and sewage pipes
- to check the storage, separation and disposal of waste at the drill site
- to check if legal noise limits were complied with

The drill site was inspected on a regular basis. No major findings were identified, and official regulations were all fulfilled.

4.2.2 Wastewater

A dewatering concept was prepared according to official regulations and approved by the cantonal authorities. The water collected on the drill site within the asphalted area was originally collected over a roof pitch, passed through a scum collector, an oil separator and finally collected in three tanks (each with a volume of 40 m³) placed on an excavated seepage area below the drill site level at the western side of the drill site. The tanks were connected via an overflow, and it was planned to seep away the collected water into a neighbouring field via the last tank.

During drilling with the KSil polymer mud, the pH value of the water in the dewatering tanks was too high. Therefore, a CO₂ neutralisation system was installed at the third tank to lower the pH value to the desired level for seeping the water away directly into the adjacent field.

The CO₂ neutralisation system was in place for Sections II and III until the project was completed, even when the environmentally friendly Pure-Bore® polymer mud was used, to ensure that the water which seeped away had the correct properties. This way of treating the wastewater was not only environmentally friendly but also economic.

After completing the drilling operations, the dewatering tanks and the CO₂ neutralisation system were removed.

4.2.3 Pedological site support

The drill site was constructed in an agricultural zone. Several official regulations thus had to be fulfilled during the construction and drilling phase. The project was accompanied by a pedological site support, and a soil protection concept was developed to define the pending work steps.

The soil removed during the construction phase was stored in different categories on the southern side of the drill site. This soil was temporarily stored to be reused for the decommissioning phase.

The pedological site support was responsible for maintaining and checking the quality of the soil on a regular basis. No findings were reported during the entire duration of the project.

4.2.4 Noise

During the entire drilling phase, the legal limits of the Noise Abatement Ordinance had to be complied with at the nearest residential properties to the drill site. For the BOZ2-1 borehole, short-term and long-term noise measurements were performed by a specialised company at the two nearest houses to evaluate the average noise emissions of the work carried out.

Because drilling operations were carried out without any interruptions, it was important to stay within the legal limits for day and night. The limit during daytime was 60 dB(A) and 50 dB(A) during the night.

The results of the noise measurements showed that the legal limits were respected. The average noise level during the day was 52 dB(A) and 48 dB(A) during the night at the most noise-intensive measuring point.

4.2.5 Lighting

Besides noise emissions, light emissions were also relevant for the drill site, especially during the night. Proper lighting at the workspace is indispensable in terms of safety for the crew but must not affect the surrounding environment. Therefore, warm-white LED lamps were installed at the site to reduce the harmful blue content in the emitted spectrum, being more environmentally friendly for wildlife and people.

In cooperation with the cantonal department for nature protection, emissions were further reduced by covering the installed LED lamps with special shields to reduce the emission towards the adjoining woods and neighbouring facilities. Light at the drill site was therefore reduced to an absolute minimum.

4.2.6 Waste management

Waste material from the drilling process was categorised and disposed of according to the regulations of the Federal Office for the Environment (FOEN).

Tab. 4-1: Waste classification

Waste type	Waste-code – disposal-type	Total quantities	Disposal site / processing plant
Surface water, oily		9 m ³	Prüser e. K. / Bilfinger & Berger
Drill cuttings and mud	17 05 91 – E	325 t	Imhof / Ehgartner
Drilling mud	17 05 91 – E	120 t	Imhof / Ehgartner
Drilling mud	13 05 08 – S	235 t	Imhof / Ehgartner
Cement slurries	20 03 06 – S	105 t	Fischer / Rosnitz

In every section of the borehole, a detailed analysis of the cuttings and drilling fluid was performed at a specified laboratory to classify the waste materials. For each analysis two samples were taken, first to determine the texture and mechanical modularity and second for eluate investigations.

4.2.7 Mud losses

A volume of 93 m³ of bentonite polymer mud was lost in Section I and a total of 24 m³ of KSil mud and 273 m³ of Pure-Bore® polymer mud were lost in the BOZ2-1 borehole (see Chapter 3).

5 References

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