Arbeitsbericht NAB 21-20

TBO Marthalen-1-1: Data Report

Dossier I
Drilling

September 2021

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for the Disposal of
Radioactive Waste

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Keywords:
MAR1-1, Zürich Nordost, 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:
B. Garitte and P. Hinterholzer (project management, writing)
F. Casanova (QC

Editorial work: Geomecon, P. Blaser and M. Unger

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
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
RDIT	Ready to drill integration test
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 Marthalen-1-1 borehole.

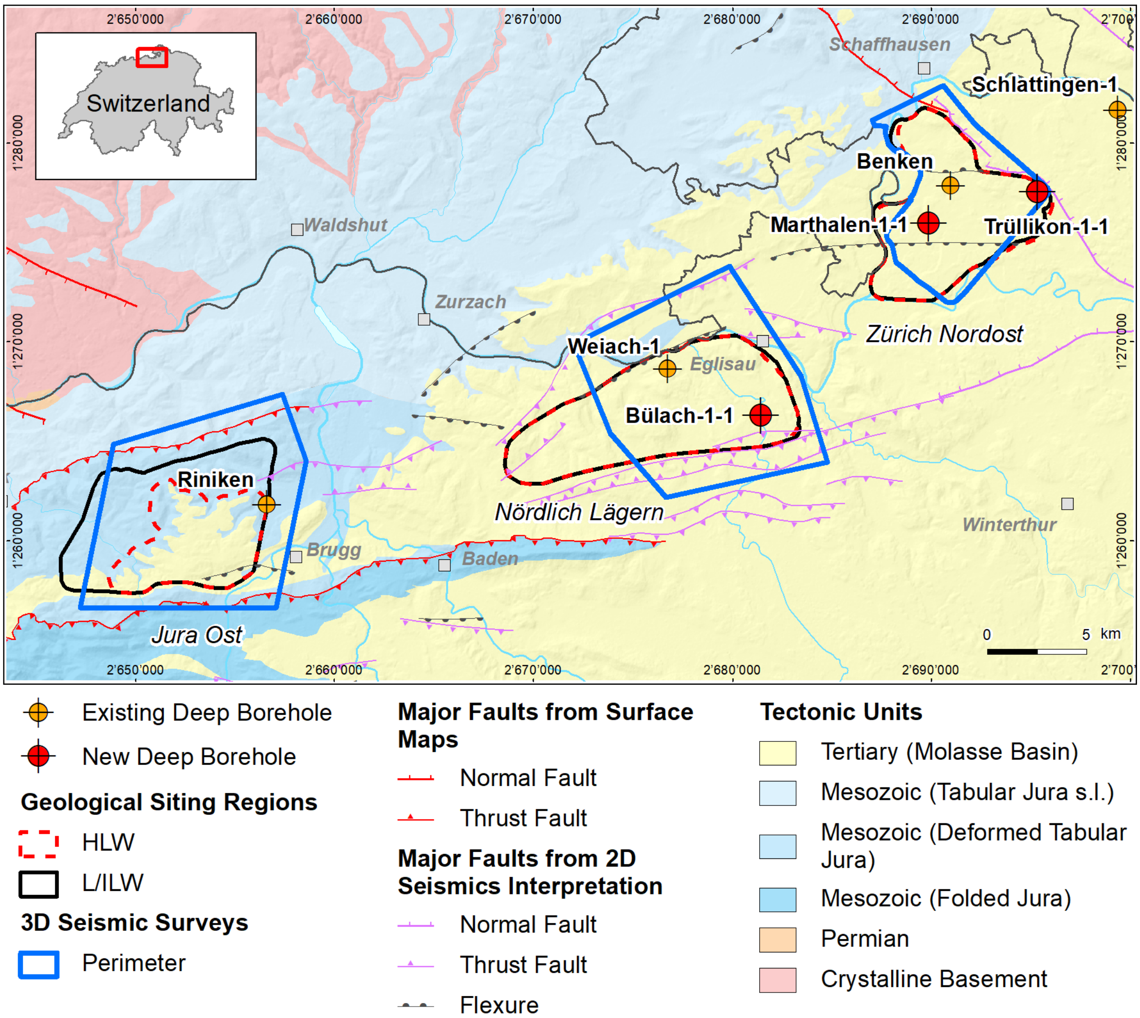

Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Marthalen-1-1 (MAR1-1) exploratory borehole is the third borehole drilled within the framework of the TBO project. The drill site is located in the western part of the Zürich Nordost siting region (Fig. 1-2). The vertical borehole reached a final depth of 1'099.25 m (MD)[1]. The borehole specifications are provided in Tab. 1-1.

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

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

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. The comparison of the core versus log depth[3] of the main lithostratigraphic boundaries in the MAR1-1 borehole is shown in Tab. 1-2.

---

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

2 For detailed information see 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.

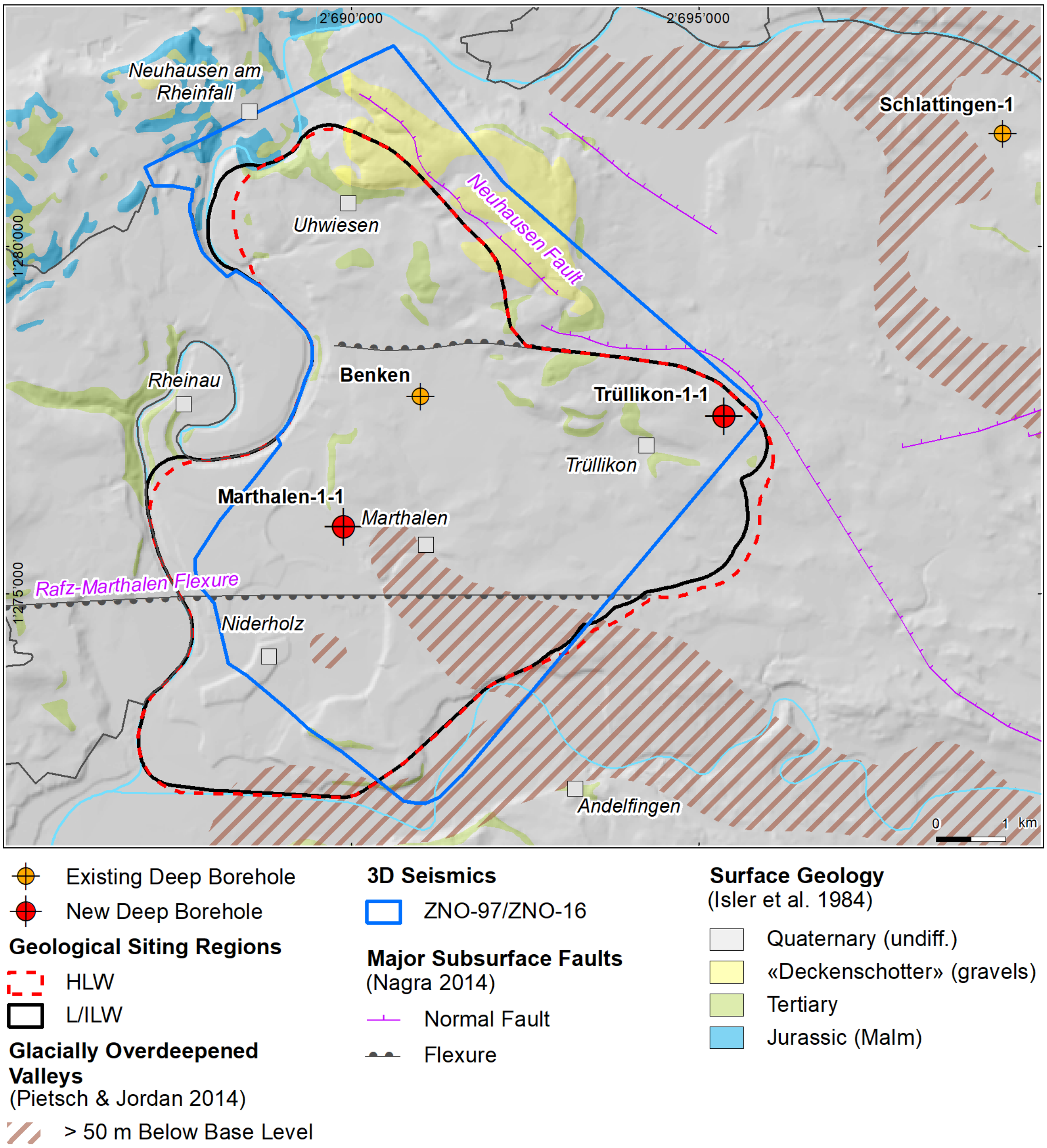

Fig. 1-2: Overview map of the investigation area in the Zürich Nordost siting region with the location of the MAR1-1 borehole in relation to the boreholes Benken, Schlattingen-1 and TRU1-1

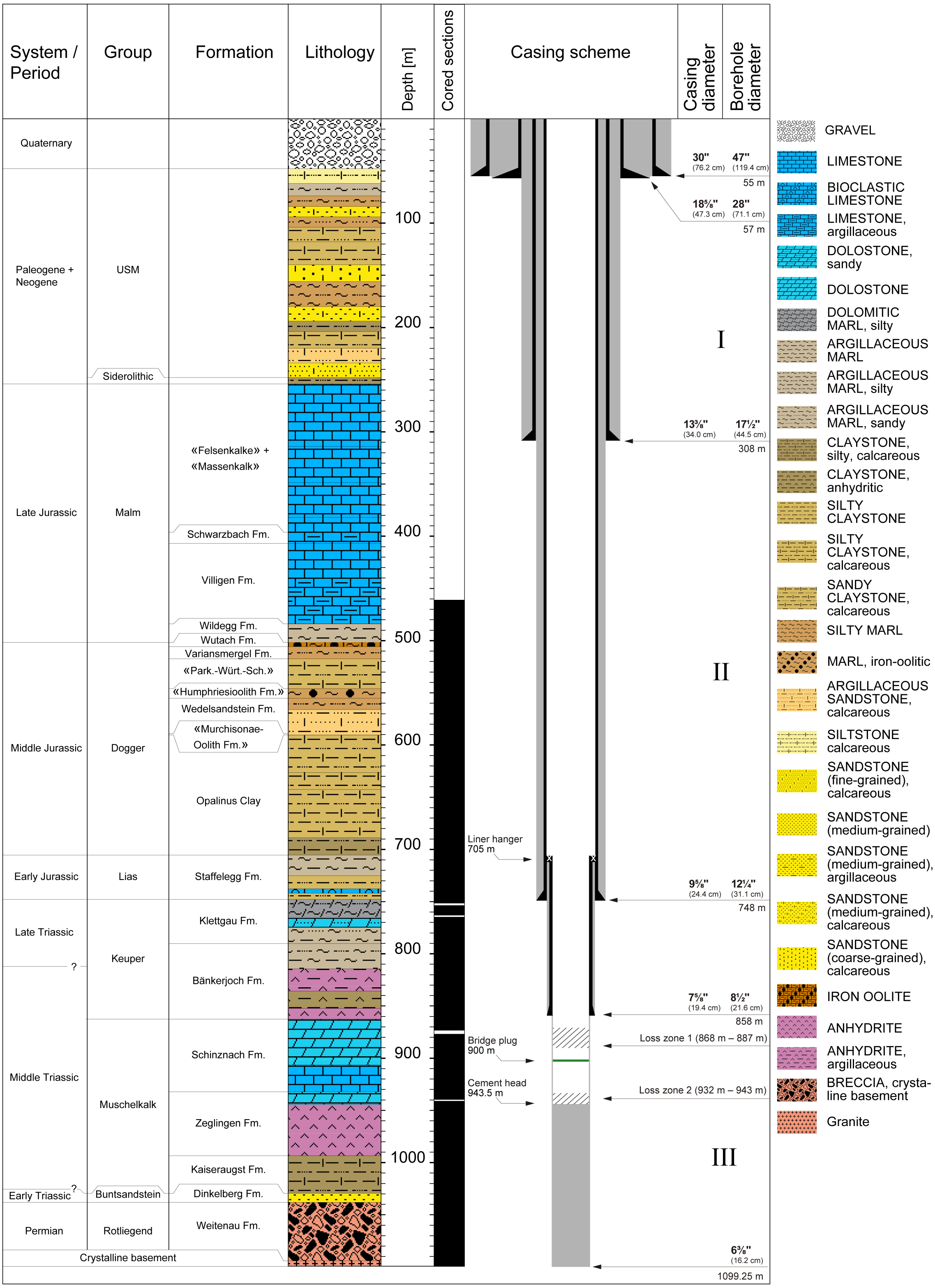

Fig. 1-3: Lithostratigraphic profile and casing scheme for the MAR1-1 borehole[4]

[4] For detailed information see Chapter 3 and Dossier III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the MAR1-1 borehole[5]

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

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

1.3 Documentation structure for the MAR1-1 borehole

NAB 21-20 documents the majority of the investigations carried out in the MAR1-1 borehole, including laboratory investigations on core material. The NAB comprises a series of stand-alone dossiers addressing individual topics and a final dossier with a summary composite plot (Tab. 1-3).

This documentation aims at early publication of the data collected in the MAR1-1 borehole. It includes most of the data available approximately one year after completion of the borehole. Some analyses are still ongoing (e.g. diffusion experiments, analysis of veins, hydrochemical interpretation of water samples) and results will be published in separate reports.

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

Tab. 1-3: List of dossiers included in NAB 21-20

Black indicates the dossier at hand.

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

1.4 Scope and objectives of this dossier

The 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 MAR1-1
- Chapter 2 is dedicated to drilling technology
- Chapter 3 describes drilling operations and its 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 MAR1-1:

- Nagra
  - Drilling manager: project management, coordination and organisation of the drilling of the borehole, definition of test aims, quality control, technical supervision of all the drilling, coring, casing running, cementing, logging and testing operations performed in the borehole
  - Drilling engineer: technical supervision of all the drilling, 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
- Baker Hughes Company: wireline logging
- Polymetra GmbH: wireline logging
- 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

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.

Before drilling operations started, the drilling rig was inspected by an external service company contracted by Nagra, for a period of three days followed by a one-day ready to drill integration test (RDIT). The purpose of the survey and RDIT was to verify that the drilling rig was in a safe and reliable condition to carry out the planned drilling operations for the MAR1-1 borehole. In general, the rig was in an operational condition with some small issues that were addressed and eliminated immediately before the start. The RDIT was conducted following the survey to determine whether all drilling systems were working in the assumed operating mode. The RDIT was successfully conducted over a period of 6 h.

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), H_2S, CO_2

2.2 Drilling / coring tools

2.2.1 Drill string and wireline coring string

Two different drill strings were used for the MAR1-1 borehole, the same as for the BUL1-1 borehole. A 5½" wireline coring string (SK 5½" B, N80) from the manufacturer MICON-Drilling GmbH (MICON-Drilling 2016) 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 MAR1-1 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 MAR1-1 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 MAR1-1, 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 MAR1-1, 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 MAR1-1 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

Section I of the MAR1-1 borehole was drilled with a 17½" 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 to stay vertical during drilling, create sufficient ROP and to ensure good hole cleaning. Based on lessons learned from the BUL1-1 borehole, it was decided to use a 9⅝" mud motor for drilling Section I (see datasheet for the mud motor in Appendix L).

The upper part of Section II was not required to be cored. Therefore, it was drilled destructively with a 6½" polycrystalline diamond compact (PDC) bit. This bit was not the best choice for drilling through limestone as the cutters were severely worn during drilling, but it was not possible to obtain a TCI bit of the same size in time to start drilling.

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 6⅜" 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 stress relieving 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 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 July 2019. During the construction phase, a 30" (762 mm) conductor casing was installed and cemented down to a depth of 55 m MD (measured depth). This conductor was installed through the Quaternary and several metres into the Untere Süsswassermolasse (USM) to protect the groundwater. Construction of the drill site ended at the beginning of November 2019 and the site was handed over to the drilling contractor on 06.11.2019. Minor correction work on the drill site was carried out by the construction company up to 20.12.2019.

Because the diameter of the 30" conductor casing was too large for upcoming drilling activities, a second 18⅝" (473 mm) conductor casing was installed and cemented down to a depth of 57 m MD by the drilling contractor.

With the drilling permission granted by the Swiss Federal Nuclear Safety Inspectorate (ENSI 2017) on 07.02.2020, drilling operations started on 09.02.2020 and, including the scientific investigations carried out in the borehole, continued until 14.07.2020 (156 days, 24 h operations, 63 days of which were for logging and testing activities).

The borehole was drilled with a tricone bit for the uppermost 308 m. The remaining sections were continuously cored using the wireline coring technique.

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 1'099 m MD was 6⅜" (161.9 mm). The cores had a diameter of 95 mm.

A total of five permanent casings were installed in the borehole and, with the exception of the 7⅝" liner hanger and the 9⅝" technical casing, cemented up to surface. The top of cement behind the 9⅝" casing was found at 390 m MD.

The upper section of the borehole down to the bottom of the Malm limestones 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), it was also necessary to displace the potassium silicate mud first to a sodium silicate mud (for logistical reasons) and then to a saturated salt mud (for logistical reasons and to ensure good core quality in the expected salt layer) in the Muschelkalk formations. Two fractured loss zones were encountered which led to total mud losses. The first loss zone was between 868 m and 887 m MD and the second loss zone between 932 m and 943 m MD. Several attempts to cure the losses by using lost circulation material (LCM) were unsuccessful but allowed coring to be continued until final depth.

Once the final depth of 1'099 m MD had been reached and the active borehole investigations were completed, the borehole was backfilled with cement up to 943.5 m MD, the bottom part of the second loss zone. Afterwards, two open hole bridge plugs were installed to isolate and separate the loss zones. The first bridge plug was installed at around 900 m MD and the second at around 865 m MD. The second bridge plug was pulled after setting the 7⅝" liner hanger to leave the upper loss zone open for potential long-term monitoring.

With pulling the second bridge plug and changing the saturated salt mud to a completion fluid, work was completed within 156 working days (continuous 24 h operation) after spud. Rig down took 17 days. The time used for scientific investigations in the borehole amounted to around 40% and the drilling and coring activities to 60%, including casing and cementing operations. The total duration of the project was 5 days shorter than the original work programme. Non-productive time (NPT) added up to a total of 10 days; 6.4 days were related to drilling activities including 2.8 days waiting time on drilling fluid material at the time of total losses in the Muschelkalk; 3.6 days NPT were related to logging and testing activities.

Continuous gas detection during the execution of the MAR1-1 borehole showed no significant occurrences of hydrocarbon gases, CO_2 or H_2S.

Regarding health, safety and environment (HSE), one first aid case was reported. An external truck driver delivering fresh silicate got silicate in his eyes while connecting his truck to the storage silo for unloading. There were no lost time incidents, no spills and no COVID-19 infections from January 2020 to July 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 27.06.2019)
- Stage 2: in-situ concrete construction of the rig cellar (permission given on 19.08.2019)

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 started on 01.07.2019 (Landolt + Co. AG construction company, Kleinandelfingen). A subcontractor (Bauer Spezialtiefbau Schweiz AG) was hired to drill and install the conductor.

After the upper soil layers were removed and deposited to the east side of the drill site, the foundation work began. The soil was kept beside the drill site for later renaturation as the land is to be farmed on a regular basis afterwards. Excavation work was supported by the cantonal department of archaeology with regard to potential archaeological findings. No findings were recorded. After soil removal, the connection lines for electricity, water and drainage were installed. A larger seepage pit at the east side and a smaller seepage pit at the west side of the drill site were excavated according to the drainage concept. These pits were mainly constructed to drain away the water collected from the asphalted area of the drill site after passing through a scum collector and an oil separator installed below ground level.

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

Because of the good ground conditions, it was not necessary to build a separate foundation for the conductor drilling rig. Conductor drilling operations were carried out on the very stable and pebbly ground (see Fig. 3-1). A 1'194 mm diameter hole was drilled dry through 48.5 m of Quaternary sediments and an additional 6.5 m of solid formations of the Untere Süsswassermolasse. The 30" (762 mm) conductor pipe was welded and equipped with centralisers on the surface and then installed in one piece down to a depth of 55 m MD (see Fig. 3-1). The conductor was adjusted for verticality with several spirit levels while the cementation was performed through the annulus between the formation and the steel pipe. Logging showed a vertical deviation below 0.3° and homogeneous cementation to all sides.

Fig. 3-1: Drilling (left) and installation (right) of the conductor

The foundations of the drilling rig were placed transversally across the rig cellar walls. This setup was verified with additional static calculations. In the final plans the upper base plate was changed to a lower armoured base plate. A sump pump was also integrated into the cellar.

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 one of the most important issues for the local communities. The access roads to the drill site, the Chinzen- and Radstrass, were extended with passing places and the street was also widened.

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 area of the rig site by adding a strip of approximately 4 m
- concrete foundations for container placement
- washing trough for cleaning the cores
- parking lots outside the fenced area
- levelling and building an access path for the visitor containers
- installation of connections with all additional media required
- various area entrances and emergency exits in the fence

The water collected on the drill site was channelled across a pitched roof to the edges of the asphalt where it was drained through the scum collector and oil separator and on to the seepage pit.

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.

Due to the complex triangular shape of the drill site, a second detachable gate section was installed at the broader east side to allow trucks to enter and load or unload equipment.

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 MAR1-1 borehole

Below is a chronology of all working steps of the MAR1-1 borehole. Details can be found in the daily drilling reports (DDR) in Appendix H.

01.07.2019	Start of drill site construction
28.11. – 20.12.2019	Rig down BUL1-1 and start moving to MAR1-1
21.12.2019 – 05.01.2020	Christmas break
06.01. – 29.01.2020	Rig up and installation of drilling rig and all peripheral facilities
30.01. – 09.02.2020	Installation of 18⅝" conductor
09.02. – 10.02.20	RIH (run in hole) 17½" drill string, start of drilling operations
10.02. – 13.02.2020	Drilling 17½" from 57 m to 309 m MD with downhole motor

13.02. – 14.02.2020	RIH 13⅜" surface casing until 308 m MD, cementation with stinger to surface, WOC (waiting on cement)
14.02. – 21.02.2020	WOC, rig up BOP + testing, RIH 12¼" drill string, drilling out shoe track + 3 m new formation, perform FIT (formation integrity test), POOH (pull out of hole) 12¼" drill string
21.02.2020	Technical logging
21.02. – 26.02.2020	RIH 7⅝" auxiliary casing, RIH 6½" drill string, drilling 6½" from 312 m to 460 m MD, perform single shot measurement every 50 m, POOH 6½" drill string
26.02. – 28.02.2020	Mud exchange from bentonite polymer mud to tap water, fluid logging, technical logging, mud exchange from tap water to potassium silicate polymer mud
29.02. – 04.03.2020	Hydraulic test (Malm)
04.03. – 05.03.2020	BOP test, RIH 7⅝" auxiliary casing, RIH coring string
05.03. – 20.03.2020	Coring 6⅜" from 460 m to 750 m MD (two core bit changes), POOH coring string
20.03. – 25.03.2020	Petrophysical logging, MHF (micro hydraulic fracturing), logging after MHF
25.03.2020	POOH 7⅝" auxiliary casing, BOP (blowout preventer) test
25.03. – 06.04.2020	Three hydraulic tests (Bottom Lias, Top Lias, Top Opalinus Clay)
06.04.2020	Roundtrip, mud conditioning
07.04. – 18.04.2020	Three hydraulic tests (Bottom Opalinus Clay, Bottom «Brauner Dogger», middle «Brauner Dogger»)
18.04. – 19.04.2020	BOP test, roundtrip, mud conditioning
19.04. – 29.04.2020	Technical logging, GTPT
29.04. – 03.05.2020	RIH 8½" hole opener, hole opening from 312 m to 750 m MD, POOH 8½" hole opener, BOP test
03.05. – 09.05.2020	Logging prior to MHF, MHF, logging after MHF

09.05. – 14.05.2020	RIH 12¼" hole opener, hole opening from 312 m to 750 m MD, POOH 12¼" hole opener
14.05. – 15.05.2020	Technical logging, RIH 9⅝" intermediate casing until 749 m MD, cementation with stinger (no cement to surface), WOC
16.05. – 17.05.2020	RIH 8½" drill string, drilling out cement, shoe track + 2 m new formation, perform FIT, POOH 8½" drill string, magnet run, RIH coring string
18.05. – 22.05.2020	Coring 6⅜" from 752 m to 796 m MD, single shot measurement, wiper trip, POOH coring string
22.05. – 25.05.2020	Hydraulic test (Klettgau Formation)
25.05. – 29.05.2020	RIH coring string, coring 6⅜" from 796 m to 877 m MD, POOH coring string
29.05. – 04.06.2020	Technical logging, hydraulic test (Muschelkalk)
04.06. – 08.06.2020	Attempt to cure total mud losses
08.06. – 13.06.2020	Coring 6⅜" from 877 m to 888 m MD, mixing new mud and pumping LCM pills in between
13.06. – 15.06.2020	Petrophysical logging
15.06. – 26.06.2020	Continue to cure total mud losses, coring 6⅜" from 888 m to 961 m MD, mixing new mud and pumping LCM pills in between
26.06.2020	Exchange potassium silicate polymer mud to NaCl polymer mud
26.06. – 30.06.2020	Coring 6⅜" from 961 m to 1'054 m MD, POOH coring string
30.06. – 02.07.2020	Petrophysical logging, VSP
02.07. – 04.07.2020	RIH coring string, coring 6⅜" from 1'054 m to 1'099 m MD, POOH coring string
04.07.2020	Petrophysical logging
04.07. – 07.07.2020	Back-cementation from 1'099 m to 943.5 m MD, WOC, tag cement, RIH first bridge plug, set bridge plug at 900 m MD, RIH second bridge plug, set bridge plug at 865 m MD, fill up several metres with sand
07.07. – 08.07.2020	RIH 8½" hole opener, hole opening from 752 m to 861 m MD, POOH 8½" hole opener, 9⅝" scraper run

08.07. – 09.07.2020	Technical logging, RIH 7⅝" liner hanger until 858 m MD (liner head at 705 m MD), plug cementation, POOH setting tool
09.07. – 11.07.2020	RIH 6½" drill string, drilling out shoe track, circulate out sand, POOH 6½" drill string, attempt to pull second bridge plug (unsuccessful)
11.07.2020	Technical logging
11.07. – 13.07.2020	Continued attempts to pull second bridge plug (successful)
13.07. – 14.07.2020	Circulate in completion fluid, deinstallation of BOP, installation of wellhead, rig release – start of rig down

3.4 Time analysis

The MAR1-1 borehole was completed within 156 working days (continuous 24 h operation) after spud on 09.02.2020, followed by 17 days rig down (and rig up in parallel at the next drilling location).

Before starting the drilling phase, 151 h were spent on installing the 18⅝" conductor within 11 days, beginning on 29.01.2020. This was done in 12 h dayshifts until drilling permission was granted, as it was still part of the construction phase.

The time analysis in Appendix I shows that the total time for completing the borehole adds up to around 40% for scientific investigations and 60% for drilling and coring activities, including casing and cementing operations. The project was finalised five days earlier than predicted by the original work programme.

NPT added up to a total of 10 days:

- 5.9 days of waiting time:
  - 1.7 days during logging and testing activities
  - 4.2 days during drilling activities (including 2.8 days waiting for mud and LCM during losses in Muschelkalk)
- 1.3 days of repair time:
  - 0.1 days during logging and testing activities
  - 1.2 days during drilling activities
- 2.9 days due to problems with equipment:
  - 1.9 days during logging and testing activities
  - 1 day during drilling activities

3.5 Drilling process

The drilling operations combined wireline coring and rotary drilling techniques.

Because the upper groups Untere Süsswassermolasse and Malm were not required to be cored, they were drilled destructively. Section I was drilled with a mud motor to increase the rate of penetration (ROP). Because there was no directional control of the drill bit, a good balance between drilling speed and verticality had to be achieved and the bottom hole assembly (BHA) had to be designed in such a way to keep the drill bit straight (see Appendix N, BHA Report 17½"). 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. Additionally, it also results in a shorter exposure time of the cores to the drilling fluid. In the MAR1-1 borehole, the core length was mostly kept at 3 m for better handling at the surface and to obtain good core quality. In total, 58% (639 m) of the entire borehole length was cored. Core recovery was 99%: 630.4 m were recovered out of 637.1 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 MAR1-1 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 borehole. 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 two major fracture zones led to total mud losses in the Muschelkalk. 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 section.

An overview of the main drilling parameters of the MAR1-1 borehole can be found in the drilling engineering plot in Appendix D.

3.5.1 30" conductor to 55 m MD and 18⅝"conductor to 57 m MD

Starting on 23.07.2019, the conductor was drilled by a subcontractor (BAUER Spezialtiefbau GmbH) with the BG 39 drilling rig using auger-type drilling during the construction phase. Temporary double-walled casings were used while drilling in segments of 1.0 m to 6.0 m with a diameter of 1'194 mm. These temporary casings are used to stabilise boreholes in unstable soil formations. They are designed specifically for the transmission of high torques and crowd forces generated during the drilling process. A double-wall construction of the temporary casing gives additional rigidity and strength and provides a continuously flushed drill string (preventing jamming of drilling tools during insertion and extraction). No drilling fluids were used, which means that drilling was performed dry. Verticality was continuously checked using spirit levels.

The double-walled temporary casings were screwed into the ground at the same time as the drilling operations until a final depth of 55 m MD was reached. Afterwards, the borehole was reamed, cleaned and prepared for running the 30" (762 mm) permanent conductor casing in hole with a wall thickness of 11.0 mm.

The conductor pipe segments had a length of around 14 m and were welded together at the surface before installation. Four centralisers (flat steel, 2 cm wide and 5 mm thick) spaced at angles of 90° were welded onto the outer surface of the casing every 2.5 m to centre the conductor within the borehole. Additionally, four pieces of 1" (25.4 mm) steel pipe were mounted along the conductor for cementation. Two of them were installed to a depth of 37.5 m MD and the other two to a depth of 15 m MD below ground level.

Before running in hole and orientation of the conductor casing, 1.5 m^3 cement were pumped into the bottom of the borehole to seal off the conductor casing shoe. Verticality was measured with two electrical spirit levels and the conductor was fixed against the temporary casings using wooden wedges.

On the following day, the main cementation was performed through the 1" steel pipes into the annulus. The cement was pre-mixed and pumped from a separate storage container until it reached the surface. The temporary casings were pulled directly after pumping the cement. Some additional cement was pumped for metal displacement. The cement type used was a CEM III B 42.5 N-LH/SR with a density of 1.8 SG.

The density and borehole deviation logs performed after the cement job showed homogeneous cement behind the conductor casing. Absolute deviation from vertical was 0.18 m (south direction) at 54.64 m MD (extrapolation from 42.00 m MD – last measured point).

Conductor installation was completed on 08.08.2019.

After rig up of the drilling rig by the contractor Daldrup & Söhne AG and before starting Section I, a smaller 18⅝" (473 mm) conductor had to be installed because the 30" (762 mm) conductor would have been too large for the upcoming 17½" drilling operations in terms of annular flow velocity (hole cleaning) and verticality. The reason for installing a smaller conductor was the decision to start drilling with a smaller diameter (Appendix A) compared to the original work programme (Appendix B). This was not clear at the time the 30" conductor was installed.

The cement shoe (cement head at 48 m MD) within the 30" conductor was drilled out with a 23" tricone bit using freshwater as a drilling fluid. The setup of the BHA was inappropriate and the installation of the 18⅝" casing was not successful. The 23" drill string had no centralisation within the large diameter conductor because the BHA did not include any stabilisers. The cement shoe was drilled corkscrew-like, which led to jamming of the 18⅝" casing and prevented it from reaching the desired depth. It had to be pulled again, followed by drilling down to 57 m MD with a 28" tricone bit and a 26" near-bit stabiliser which had a smaller clearance than the 30" conductor. Afterwards, the 18⅝" casing (see casing tally in Appendix M) was installed successfully with all its centralisers and could be cemented with the same technique as used for the 30" conductor. Cement was pumped through 1" pipes into the annulus until surface.

Specifications regarding cement and casing can be found in Chapter 3.8 and Chapter 3.9. The BHA setup #1 and #2 can be found in Appendix N.

The installation of the 18⅝" conductor was done mostly on dayshifts because it was still part of the construction phase. The drilling permission, and therefore the permission for continuous operations day and night, was given by ENSI on 07.02.2020.

Installation of the 18⅝" conductor was completed on 09.02.2020.

3.5.2 Section I: 57 m – 309 m MD 17½" destructive drilling

The main drilling operations started on 09.02.2020.

Section I was drilled destructively with a 17½" (444.5 mm) tricone bit and a 9⅝" mud motor (see Fig. 3-3). BHA #3 used for this section can be found in Appendix N. Cement was first drilled from 46 m to 57 m MD. Afterwards, the Untere Süsswassermolasse was drilled until 256 m MD and finally the upper part of the Malm until 309 m MD. Single shot measurements were taken every 50 m to check the verticality of the borehole. All measurements were below 1° inclination.

Average drilling parameters were as follows:

- ROP: 4.7 m/h
- WOB: 6.2 t
- string revolutions: 31 RPM
- torque: 298 daNm
- flowrate: 2'873 L/min
- SPP: 58.7 bar

The mud system used was a freshwater bentonite polymer drilling fluid with an increasing mud weight from 1.04 SG in the beginning to 1.09 SG at TD. Details can be found in Chapter 3.6.

As soon as section TD was reached, the borehole was circulated shakers clean (i.e. until no more cuttings were seen on the shaker screens) and a wiper trip was performed during which the borehole was reamed from 213 m to 205 m MD and from 176 m to 147 m MD. POOH the drill string was performed dry without any overpulls or restrictions.

Fig. 3-3: 17½" tricone bit and 9⅝" mud motor after POOH

13⅜" casing and cementing

The 13⅜" casing was installed with bow-spring centralisers to a depth of 308 m MD without any major problems. From 306.5 m MD to 308 m MD, it was washed down with a pumping rate of 600 L/min. The casing tally can be found in Appendix M. The cementation of the 13⅜" casing was performed with a stinger until surface. A volume of 17.5 m^3 cement/mixing zone came to surface and had to be disposed of. In total, 39 m^3 of cement were pumped. Cement return at surface was measured with a MW of 1.7 SG at the flowline.

Specifications regarding cement and casing can be found in Chapter 3.8 and Chapter 3.9. Cementing programme, service report and laboratory measurements can be found in Appendix O.

Section I was completed on 14.02.2020. No well control unit was installed for drilling operations in this section.

Non-productive time and remarks

- For this section, the old shale shakers were used (same as for BUL1-1) as the delivery of the new shakers was delayed. The drilling mud had to be cleaned above the centrifuge most of the time because the old shakers were not working properly. The centrifuge broke down once for one day and the mud weight increased instantly. This problem was solved as soon as the centrifuge was working again.
- During drilling operations, a new wireline core cable was wound onto the winch. This could have already been done during the rig move. In total, 2.5 h of NPT were recorded.

3.5.3 Section II: 309 m – 750 m MD

After completing Section I, the 13⅝" 3K casing head housing (CHH) was installed on the 13⅜" casing and a BOP was mounted on top for borehole control. The 13⅝" BOP stack consisted of a 13⅝" 10K double ram preventer (blind rams and 5½" fixed rams) and a 13⅝" 5K annular preventer. The BOP was tested successfully according to the BOP testing protocol (low: 500 psi and high: 3'000 psi).

The cement and float equipment of the 13⅜" casing were drilled out with a 12¼" tricone bit from 295 m to 309 m MD (see BHA #4 in Appendix N). After drilling new formation until 312 m MD, the hole was circulated clean and the mud was conditioned. A FIT was performed at 312 m MD according to protocol (see Appendix P) with an equivalent mud weight (EMW) of 1.42 SG. For a MW of 1.08 SG a surface pressure of 10.5 bar was applied. The FIT was successful without any significant pressure drop.

Wireline logging operations were carried out by the companies Baker & Hughes and Polymetra to evaluate the quality of the cement job and the inclination of Section I. Details can be found in Chapter 3.7 and Chapter 3.10.

6½" destructive drilling

Before starting drilling operations of Section II, a 7⅝" auxiliary casing was installed to a depth of 311.7 m MD (see casing tally in Appendix M). The auxiliary casing was used for centralising the drill string and enabling a better flow regime within the annulus while drilling and coring. Using no auxiliary casing, the volume transition between the 6½" hole and the 13⅜" casing would lead to hole cleaning problems triggered by an instantaneous decrease in annular velocity at the diameter transition zone. The auxiliary casing was set into the CHH with a tubing hanger. Connections between the pipes were welded to protect the casing from unscrewing.

A 6½" PDC bit was used to drill to a depth of 460 m MD through the Malm (see BHA #5 in Appendix N). As the tool joints of the 5½" drill pipes would have been too large, the slick 5½" coring string was used. The ROP was limited in favour of verticality and hole cleaning because the clearance between the bit and the drill string was very small. At a depth of 376 m MD, a check trip was performed into the shoe of the 7⅝" auxiliary casing without any problems. Single shot measurements for 6½" drilling were performed every 25 m. Inclination measurements were always below 1.5°.

Average drilling parameters for 6½" drilling operations were as follows:

- ROP: 2.2 m/h
- WOB: 2.3 t
- string revolutions: 134 RPM
- torque: 169 daNm
- flowrate: 912 L/min
- SPP: 14.6 bar

The 6½" PDC bit was heavily worn after drilling 148 m of limestone, which can be seen in Fig. 3-4.

Fig. 3-4: 6½" PDC bit after POOH

After the 6½" PDC bit and the 7⅝" auxiliary casing were pulled out of hole without any problems, the bentonite polymer mud was exchanged with freshwater (MW 1.00 SG) for fluid logging operations, which were performed by the company Terratec. Terratec also performed a calliper log directly after fluid logging to find appropriate packer seats for the upcoming hydrotest.

The freshwater was then displaced to a potassium silicate mud (MW 1.22 SG) using the coring string. Details about the drilling fluid can be found in Chapter 3.6. Hydrotesting was carried out in the Malm using a double packer assembly with an interval length of 17 m, run on 2⅞" tubing.

After hydrotesting, the 5½" fixed pipe rams within the BOP were changed to 4½" to 7" variable rams because of the different diameters of the drill string (5") used for hole opening and the coring string (5½") used for coring operations. Changing the pipe rams required a full BOP test as soon as the change was complete.

6⅜" coring operations

The 7⅝" auxiliary casing was installed as before to 311.7 m MD (see casing tally in Appendix M) with welded connections. Coring operations started on 06.03.2020 using an impregnated core bit with synthetic diamonds and an outer diameter of 6⅜" (see BHA #9 in Appendix N). Plastic liners within the inner core barrel were used for core protection. Core length was fixed to 3 m. Within the first core (460 m to 463 m MD), non-magnetic copper metal parts were found (see Fig. 3-5). This junk in hole (JIH) was lost during hydrotesting or wireline logging operations carried out before. Further coring proceeded without any problems. The formation change from Malm to «Brauner Dogger» was found at 502 m MD. As the clay content within the «Brauner Dogger» significantly increased, it was decided to change the core bit at 503 m MD to a thermally stable diamond core bit, i.e. synset, see BHA #10 in Appendix N. The impregnated core bit showed normal wear and some teeth were damaged (see yellow marks in Fig. 3-6), most probably due to the JIH. The synset core bit had already been used successfully in the BUL1-1 borehole to core the clayey formations.

Fig. 3-5: Junk in hole recovered from 463 m MD

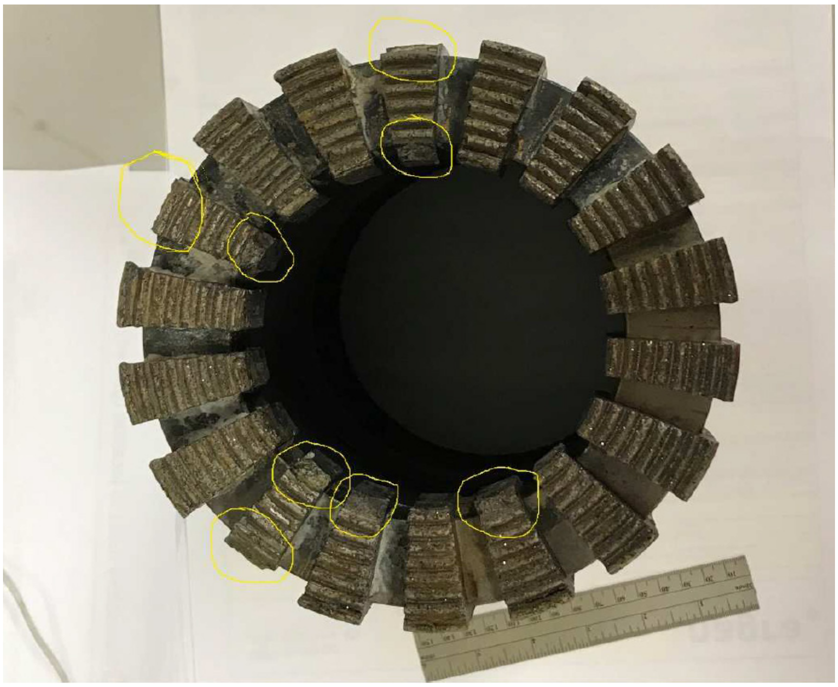

Fig. 3-6: Impregnated core bit after POOH from a depth of 503 m MD

Coring operations continued to a depth of 655 m MD, including an additional bit trip as ROP was dropping constantly towards the end. The synset showed normal wear after POOH (see Fig. 3-7), which led to the decision to run another new synset core bit (see BHA #11 in Appendix N). This bit then cored until section TD at 750 m MD.

In Section II, 99 cores were retrieved: number #1 to #99. 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 1.5°.

Average drilling parameters for coring operations were as follows:

- ROP: 1.59 m/h
- WOB: 2.9 t
- string revolutions: 179 RPM
- torque: 221 daNm
- flowrate: 311 L/min
- SPP: 17.9 bar

The mud weight of the potassium silicate mud was increased in steps of 0.01 SG during coring from 1.22 SG to 1.25 SG to prevent potential hole problems in the bottom part of Section II.

Fig. 3-7: Synset core bit before RIH (left) and after POOH (right) from a depth of 655 m MD

The Opalinus Clay was found at 590 m MD, Lias at 705 m MD and Keuper at 748 m MD. Some problems occurred at the transition from Lias to Keuper because the cores could not be torn off or recovered. The coring string had to be pulled out of hole once, as the core could not be caught. The problem was then solved by using a different type of core lifter.

As Top Keuper is known to be frequently fractured, section TD of Section II was decided to be within the first few metres of the Klettgau Formation, in order to have a competent rock for the 9⅝" casing shoe.

Coring operations were followed by an extended logging and testing programme of the Opalinus Clay and its confining units. Several petrophysical logging runs and MHF stress tests were performed. The results of the MHF tests were not complete and it was decided to perform further MHF tests as soon as the borehole was opened up to 8½". The borehole was found to be in an excellent shape without any breakouts or restrictions (see Appendix F). After finishing wireline operations, the 7⅝" auxiliary casing was pulled for BOP pressure testing.

A series of three hydrotests was carried out in Lias and Opalinus Clay using a double packer assembly with an interval length of 20 m, run on 2⅞" tubing. After keeping the borehole open for more than 17 days without any circulation, a roundtrip was performed using the coring string to check the hole condition 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. The core bit used for the roundtrip showed scratches and deep notches on its teeth after POOH. This indicated JIH from logging or testing activities. A magnet was ordered by Nagra to carry out magnet runs on a regular basis.

After the first roundtrip, three additional hydrotests were performed in the Opalinus Clay and «Brauner Dogger» using a double packer assembly with an interval length of 40 m, run on 2⅞" tubing. The second roundtrip and the regular BOP pressure test (minimum every 21 days) were carried out after another 12 days of open hole. The borehole and drilling fluid were found to be in very good shape.

Due to the good borehole stability with the potassium silicate mud in the hole, it was decided to run a caliper log (see Appendix F) 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 2⅞" tubing. This additional test added another 11 days of open hole time.

In total, the interval of Section II with a length of 442 m had an open hole time of more than 40 days without any borehole stability problems after retrieving the last core.

8½" and 12¼" hole opening

The 6⅜" borehole was opened up to 8½" with an SHO bit (see BHA #17 in Appendix N) starting on 30.04.2020. This SHO bit used a bullnose on bottom as guidance within the already cored borehole.

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

- ROP: 7.36 m/h
- WOB: 0.2 t to 3.6 t
- string revolutions: 60 RPM
- flowrate: 1'700 L/min to 2'400 L/min
- SPP: 38 bar to 72 bar

After 8½" hole opening, wireline logging and an MHF stress test were carried out. A roundtrip to condition the mud was performed in between. The results of the single shot measurements were confirmed by wireline logging as the borehole had an inclination of 1.26° at 748 m MD.

Finally, the borehole was opened up to 12¼" with an SHO bit (see BHA #19 in Appendix N) and shakers circulated clean. POOH the drill string was performed dry without any overpulls or restrictions. Also, the caliper log performed afterwards by Terratec showed no significant wash-outs or restrictions.

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

- ROP: 3.72 m/h
- WOB: 0.2 t to 5 t
- string revolutions: 41 RPM to 60 RPM
- flowrate: 2'650 L/min to 3'000 L/min
- SPP: 44 bar to 71 bar

9⅝" casing and cementing

The 9⅝" casing was installed with bow-spring centralisers to a depth of 748 m MD without any problems. It was set into the CHH with a tubing hanger and return lines were connected to the side outlets below the hanger to allow backflow during circulation and cementation into the cuttings box. There was no other option than to connect hoses to the side outlets of the CHH for return flow as the wellhead was mandrel-type based, which means that the casing can no longer be lifted once it has been set. Before cementing, the borehole was circulated clean through the side outlets to check on proper return flow through the return lines at the side outlets. The casing tally can be found in Appendix M.

Cementation of the 9⅝" casing was performed with a stinger. Cementing operations started by pumping 10.2 m^3 of spacer fluid. While pumping 17.2 m^3 of lead cement (density 1.4 SG), pump pressure was raised constantly at a pumping rate of 600 L/min until it reached almost 90 bar. A low pumping rate of 200 L/min was used to start pumping the tail cement (density 1.7 SG), but pressure continued to increase to over 110 bar. The pumping rate was further reduced in steps of 50 L/min until the total volume of tail cement (2.3 m^3) was pumped. As soon as the freshwater spacer was pumped, there were no longer any returns at the cuttings box and pressure was finally at 115 bar. The cement job had to be stopped to avoid any damage to equipment or formation. Tail cement did not reach the annulus as the cement stinger had a volume of approximately 7 m^3. Therefore, residual amounts of cement within the stinger had to be circulated out from within the casing.

Specifications for cement and casing can be found in Chapter 3.8 and Chapter 3.9.

The reasons for the unsuccessful cementation are not fully clear but could be:

- errors in the cement/spacer recipe (wrong quantities, product quality etc.)
- errors during the mixing process (foam, inhomogeneous slurry etc.)
- contact of cement with potassium silicate mud (instant hardening) due to inadequate displacement of mud by spacer (channeling)

The cementing programme, service report and laboratory measurements can be found in Appendix O.

Section II was completed on 15.05.2020.

NPT and remarks

- New shale shakers were installed, resulting in very good mud cleaning and a much better condition of the mud.
- 10K BOP was not necessary because the wellhead only had a 3K pressure rating. A 3K BOP would have been sufficient.
- Single shot measurements were only a very rough estimation for verticality. The mechanical single shot tool had to be repaired because most of the measurements were failing in this section. Accurate inclinometer measurements were taken during logging operations.
- ROP was limited during 6½" drilling to remain vertical. This could have been optimised using directional drilling tools in combination with a mud motor, eliminating the single shot measurement.
- The use of potassium silicate required many additional safety measures to comply with HSE standards.
- While coring, servicing the top drive by exchanging the wash pipe led to several hours of NPT.
- The 2⅞" tubing for the hydrotests was screwed by hand, which is not ideal because the maximum pulling force is not known. A power tongue should be used.
- After having JIH it was agreed to always run a magnet before starting coring.

3.5.4 Section III: 750 m – 1'099 m MD

The cement and float equipment of the 9⅝" casing were drilled out with an 8½" tricone bit from 718 m to 750 m MD (see BHA #21 in Appendix N). After drilling 2 m of new formation until 752 m MD, the hole was circulated clean and the mud conditioned. An FIT was performed at 752 m MD according to protocol (see Appendix P) with an EMW of 1.60 SG. For a MW of 1.24 SG, a surface pressure of 27 bar was applied. The FIT was successful without any significant pressure drop.

6⅜" coring operations

After performing a magnet run without any significant metal recovery, coring of Section III started using a synset core bit (see BHA #22 in Appendix N). Core length was fixed to 3 m as in the previous section. The synset bit cored until 796 m MD with constantly dropping ROP and was fully worn out after these 44 m (see Fig. 3-8).

Fig. 3-8: Synset core bit after POOH from the depth of 796 m MD

Coring operations were stopped to carry out a hydrotest in the Klettgau Formation using a double packer assembly with an interval length of 34 m, run on 2⅞" tubing. After hydrotesting, the periodical BOP pressure test and a magnet run were performed. The magnet run was without any significant recovery.

For further coring operations, an impregnated core bit was used (see BHA #24 in Appendix N). Additionally, the mud weight was increased to 1.29 SG while RIH the coring string.

On 29.05.2020 total mud losses (no returns) occurred in the Schinznach Formation of the Muschelkalk at a depth of 869.8 m MD. The fluid level within the coring string was measured at approximately 180 m MD. Coring was continued until 877 m MD with dynamic losses of

320 L/min to 650 L/min, adding up to 55 m^3 in total. While pumping fresh mud, the mud weight was decreased from 1.29 SG to 1.25 SG. Fig. 3-9 shows the vertical fracture hit by the borehole trajectory which led to the encountered losses.

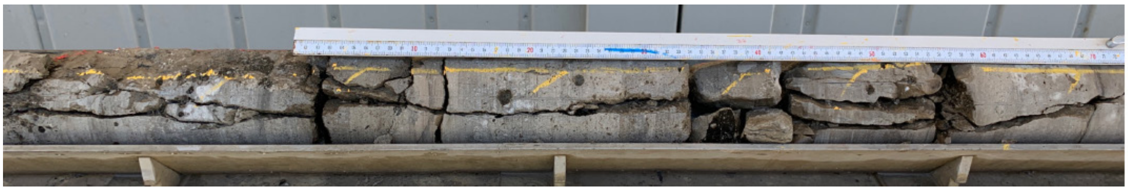

Fig. 3-9: Core picture of the vertical fracture in first encountered loss zone

The coring string was POOH to perform a caliper log before starting an unplanned hydrotest for further investigations of the loss zone. A single packer assembly was installed and run on 2⅞" tubing. After the test, the fluid level within the borehole was measured at 140 m MD.

After the hydrotest, loss control operations using LCM started as soon as the coring string was back in the borehole. A total of 12 LCM pills had to be pumped before backflow and circulation were re-established. Nevertheless, completely sealing off the loss zone was not successful and the subsequent coring attempts failed. The surface and downhole equipment was contaminated and plugged with LCM (see Fig. 3-10) and had to be cleaned several times. The coring string also had to be pulled twice because the inner core barrel was not able to land on the outer core barrel and only small rock fragments were recovered after each coring attempt. There was no progress in coring because rock fragments became jammed within the inner core barrel. It was not possible to establish proper circulation due to an increase in the pumping pressure. The core bit was fully destroyed and completely lost its matrix (see Fig. 3-11).

Fig. 3-10: Equipment contaminated and plugged with LCM material

A magnet run could not retrieve any parts of the core bit matrix. Therefore, a new core bit was RIH for another coring attempt (see BHA #26 in Appendix N). This attempt was finally successful. Coring resumed until 881.5 m MD under dynamic losses of 104 L/min to 360 L/min. The coring operations then had to be stopped because there was no longer sufficient drilling mud available due to lacking potassium silicate fluid (COVID-19 conditions further complicated the logistics). Four additional silos for storing fresh silicate were ordered to be prepared for continuous mud losses but delays in the delivery of large quantities of potassium silicate, manufactured in Switzerland, led to almost three days of waiting time. In the meanwhile, it was decided to additionally order sodium silicate, manufactured in Belgium, because there was no possibility to obtain large amounts of silicate on short notice.

Fig. 3-11: Impregnated core bit fully destroyed without any matrix

After receiving the first truckloads of silicate fluid and mixing new drilling mud, coring continued only until 881.9 m MD. The same problems occurred as before, and the coring string had to be POOH again, cleaned and inspected. The core bit showed no damage, but the coring equipment had to be cleaned from LCM contamination. Afterwards, coring resumed until 888 m MD with dynamic losses of approximately 160 L/min and 50% to 60% return flow.

Petrophysical logging operations were performed before pumping another LCM pill and performing the periodical BOP pressure test.

The subsequent coring attempt failed. Another LCM pill was pumped. The coring string was pulled for cleaning, exchanging the inner core barrel and adjusting several core barrel settings.

Afterwards, coring operations continued from 888 m to 961 m MD, pumping several LCM pills in between as soon as the mud losses became significantly higher. At around 932 m MD mud losses increased significantly to 250 L/min due to a second substantial loss zone at the interface between the Schinznach Formation and the Zeglingen Formation of the Muschelkalk. The string had to be pulled once again due to a jammed core. Silicate mud using sodium silicate fluid was mixed on a regular basis while properly monitoring surface volumes to make up for losses. Single shot measurements showed an inclination of around 2°.

Although it was originally planned (see Appendix B) to set a 7⅝" liner after reaching Top Zeglingen Formation, the decision was made to continue the borehole directly to TD because cementing of the liner might have been delicate in the loss environment.

At 961 m MD, the chloride content in the silicate mud suddenly increased from around 3'000 mg/L to 13'000 mg/L. The decision was made to exchange the silicate mud with a saturated salt mud (MW 1.20 SG) and change the impregnated core bit to a synset core bit (see BHA #29 in Appendix N). Potential salt layers were expected in the Zeglingen Formation. It was also expected that silicate mud would fully dissolve this salt. Details about the drilling fluid can be found in Chapter 3.6.

The mud exchange was conducted without any problems and coring operations resumed under dynamic losses of 60 L/min to 100 L/min until 1'054 m MD with fewer problems than before. Although the chloride content rose before the mud exchange, no salt layer was found in the Zeglingen Formation. The synset core bit was fully worn out after pulling out of hole (see Fig. 3-12).

Fig. 3-12: Synset core bit after pulling out of hole at a depth of 1'054 m MD

The provisional final depth was defined at 1'054 m MD within the Rotliegend. Petrophysical logging and VSP were conducted. Inclination measurements during wireline logging showed a borehole deviation of 2.56° from vertical. The two loss zones were located by image logs in combination with the retrieved cores. The first loss zone was specified between 867.6 m and 887.2 m MD and the second loss zone between 932.2 m and 942.6 m MD. After this, it was decided to core further until reaching Top Crystalline Basement under dynamic losses. An impregnated core bit was selected for upcoming formation types. The Crystalline Basement was found at 1'094 m MD and TD was set to be at 1'099 m MD.

In Section III, 119 cores were retrieved: numbers #100 to #218. Detailed parameters for each core can be found in Appendix Q. Some of the cores were 6 m long instead of 3 m to speed up the advance.

Mud losses added up to a total of 1'709 m^3 in 38 days with a daily maximum of 136 m^3 and a daily average of 61 m^3. Coring was performed in nine steps, interrupted by a roundtrip due to core catching problems at 763 m MD, a hydraulic test at 696 m MD and several round/bit trips due to mud loss problems from 869.8 m to 1'099 m MD.

Average drilling parameters for coring operations were as follows:

- ROP: 1.54 m/h
- WOB: 3.0 t
- string revolutions: 182 RPM
- torque: 447 daNm
- flowrate: 322 L/min
- SPP: 15.6 bar

After coring, another short petrophysical logging run was performed but the MHF stress tests were cancelled due to the critical state of the borehole along the two loss zones.

6⅝" backfilling and installation of two bridge plugs

The borehole was backfilled with 3.9 m^3 of cement from 1'099 m to 943.5 m MD on 05.07.2020.

The next step was to set a 5½" open hole bridge plug (with turn release) at approximately 900 m MD (competent formation) above the lower loss zone and a second 5½" open hole bridge plug (with straight pull release, see Fig. 3-13) above the upper loss zone at approximately 865 m MD, also at a competent formation. It was planned to pull the upper bridge plug at a later stage to leave the Schinznach Formation open for potential long-term monitoring. After setting the two bridge plugs, the mud losses stopped immediately.

To protect the pull release tool and the upper part of the bridge plug from cement while cementing the 7⅝" liner hanger, the borehole was filled with 150 kg of fine sand (grain size 0.1 mm to 0.8 mm) to a depth of 860 m MD.

Fig. 3-13: 5½" open hole bridge plug with straight pull release

8½" hole opening

The remaining open 6⅜" section was then opened up to 8½" from 752 m to 858.8 m MD (bullnose at 861 m MD) with the SHO (see BHA #34 in Appendix N).

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

- ROP: 5.66 m/h
- WOB: 1.0 t to 4.0 t
- string revolutions: 60 RPM to 65 RPM
- flowrate: 1'700 L/min to 1'800 L/min
- SPP: 42 bar to 45 bar

7⅝" liner hanger and cementation

A 9⅝" scraper run was performed to clean the inner surface of the 9⅝" casing to properly set the liner hanger head. Afterwards, a calliper log was performed to calculate the expected cement volume.

The 7⅝" liner hanger was run down to 858 m MD on a 5" drill pipe (see BHA #36 in Appendix N). The liner hanger head was located at 705 m MD. An overlap of approximately 40 m to 50 m with the previous casing was chosen as this is known to be good practice. The last nine joints were run with circulation. The liner hanger was then set with one right turn and the setting tool was released. The casing tally of the 7⅝" liner hanger can be found in Appendix M.

The plug cementation of the 7⅝" liner hanger was performed without any problems. In total, 5 m^3 of cement were pumped: 2 m^3 of cement and 3 m^3 of mixing zone with a MW of 1.28 SG were circulated out.

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

The cement and float equipment of the 7⅝" liner hanger were drilled out with a 6½" tricone bit from 834 m to 858 m MD (see BHA #37 in Appendix N). After drilling 4 m of cement until 862 m MD, the sand was circulated out to free the straight pull release tool on top of the bridge plug.

Bridge plug retrieval and completion

The fishing string with the overshot assembly was run in hole to start fishing the bridge plug. The first fishing attempt failed. While preparing a mule-shoe run, wireline logging was performed to evaluate the quality of the liner hanger cement job. Afterwards, the mule-shoe was RIH, and the borehole was circulated and cleaned again to remove remaining sand or debris around the fishing neck. As the mule-shoe string was pulled out of hole, grinding marks could be seen on the inside along a length of 30 cm. This was a clear indication that the mule-shoe could run over the fishing neck. The second fishing attempt also failed due to a broken grapple within the overshot and a new grapple was ordered. After its arrival, the overshot assembly with the new grapple was run in hole while circulating. At the position of the bridge plug, the pump pressure increased to 19 bar and the overshot was connected to the pull release tool. The bridge plug was pulled several times with 18 t overpull to free the packer element. At 45 t overpull, the string weight immediately dropped to 38 t. The third fishing attempt was successful, and the bridge plug could be retrieved back to surface. Mud losses started again after pulling the bridge plug.

To finalise drilling operations in the MAR1-1 borehole, the saturated salt mud was displaced to a completion fluid (for pH regulation and corrosion protection) with MW 1.00 SG. Afterwards, the BOP stack was demounted and the wellhead (see Fig. 3-14) installed on the 13⅝" CHH (brown colour). This wellhead was equipped with two 4$\frac{1}{16}$" ball valves (blue colour), installed on a 3K double studded adapter flange (green colour) which serves as a crossover from 13⅝" to 4$\frac{1}{16}$".

The rig was released on 14.07.2020, initiating rig down.

Fig. 3-14: Wellhead installed after finishing drilling operations

NPT and remarks

- The original stock of LCM material was not sufficient to cure the total mud losses. A lot of LCM material had to be ordered to provide a wide variety and sufficient quantities onsite.
- Surface equipment such as mud pumps had to be cleaned many times due to heavy contamination with LCM material.
- Due to the total losses, several truckloads of silicate fluid had to be ordered. This led to 67 h of waiting time.
- The silicate from Belgium had a different quality to the silicate from Switzerland. It had a different colour (brownish) and was much more viscous.
- LCM material blocked the inner core barrel from landing within the outer core barrel due to heavy contamination.
- The sand on top of the bridge plug blocked the ports for packer deflation because it was too fine.

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 MAR1-1 borehole. A bentonite polymer mud was used for the Quaternary and two thirds of the Malm Formations, a silicate mud was used for the most relevant Dogger, Lias, Keuper and the upper part of the Muschelkalk Formations, and a sodium chloride mud was used for the lower part of the Muschelkalk Formation until the final depth within the Crystalline Basement. Details about the drilling fluids are listed in Tab. 3-1.

Tab. 3-1: Drilling fluids data

From [m MD]	**To** [m MD]	**Section**	**Type / specification**	**Density**
0	55	0	Dry	-
0	57	0	Water	1.00 SG
0	309	I	Bentonite + polymer	1.09 SG
0	460	II	Bentonite + polymer	1.09 SG
0	750	II	Potassium silicate + polymer	1.25 SG
0	961	III	Potassium/sodium silicate + polymer	1.20 SG
0	1'099	III	NaCl + polymer	1.20 SG
0	900	-	Completion fluid: water, inhibitor Inicor W882, soda ash	1.00 SG

3.6.1 Section I: Bentonite polymer drilling fluid

The cement contamination from drilling out the 18⅝" casing shoe was treated with citric acid to reduce the pH value to below 10. Section I was drilled without any problems with the bentonite polymer mud until 309 m MD. Mud weight was set to 1.09 SG. At 110 m MD polymers were added to reduce the API fluid loss to below 8 ml. The borehole was circulated clean during the roundtrip after reaching TD of Section I using high viscosity pills until the shakers were clean.

Before RIH the cement stinger, the borehole was circulated twice bottom up to prepare the borehole for the upcoming cement job. The drilling fluid parameters of this 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	16	38.8	-
Density	SG	1.02	1.10	1.01 – 1.10
Plastic viscosity	cP	9	18	ALAP (as low as possible)
Yield point	lb/100 ft^2	18	25	20 – 30
Gel strength	10 s	6	15	–
Gel strength	10 min	10	27	–
pH	–	9.4	10.2	9 – 10
Sand content	vol.-%	0.1	0.8	< 1.0%
Methylene blue test (MBT)	kg/m^3	32	49	< 36

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

Product	**Unit size**	**Quantity**
Bentonite OCMA	25 kg	200
Calcium carbonate fine BB	1 MT	3
Calcium carbonate fine	20 kg	20
Citric acid	25 kg	4
Floc cationic	25 kg	4
Sodium carbonate	25 kg	5
Pac LV premium	25 kg	28
Xanthan gum	25 kg	14

Three Akros Falcon shakers and a Brandt Cobra mud cleaner were installed for mud cleaning. Shakers 1 and 2 were equipped with API 70 screens, shaker 3 with API 120 screens and the mud cleaner with API 140 screens. The new 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%.

3.6.2 Section II: Bentonite polymer and potassium silicate drilling fluids

For Section II, the bentonite polymer mud from Section I was used, the parameters of which are represented in Tab. 3-4. The API fluid loss of the drilling fluid was adjusted with polymers in a range between 4 ml and 8 ml. The mud weight was further kept between 1.08 kg/L to 1.10 kg/L by running the mud through the centrifuge.

Tab. 3-4: Drilling fluid parameters of the bentonite polymer mud – Section II

Parameter	Unit	Min.	Max.	Planned
Flowline temperature	°C	20	31	-
Density	SG	1.08	1.09	1.01 – 1.10
Plastic viscosity	cP	12	17	ALAP
Yield point	lb/100 ft^2	16	23	20 – 30
Gel strength	10 s	6	8	-
Gel strength	10 min	9	16	-
pH	–	9.3	10	9 – 10
Sand content	vol.-%	0.25	0.30	< 1.0%
MBT	kg/m^3	35.75	35.75	< 36

After drilling out the shoe track of the 13⅜" casing, the mud was treated with citric acid to regulate the pH value. During drilling, the mud was treated with uranine tracer fluid and analysed for tracer concentration on a regular basis.

At a depth of 460 m MD, the borehole was circulated clean, and part of the surface tank system was cleaned to prepare for the exchange to freshwater. During this time, most of the bentonite polymer mud was already disposed of. The rest of bentonite polymer mud was disposed of after completing the exchange to freshwater. While fluid logging, potassium silicate mud was prepared and mixed according to the programme. The freshwater was displaced to a potassium silicate mud after fluid logging, and the water was disposed of. The drilling fluid parameters of the potassium silicate mud are represented in Tab. 3-5. The product and technical datasheet for the potassium silicate fluid used for mixing the drilling fluid can be found in Appendix R.

During coring, the mud weight was increased in steps from 1.22 SG to 1.25 SG. Furthermore, the drilling fluid was temporarily treated with xanthan gum to maintain the desired viscosity.

Tab. 3-5: Drilling fluid parameters of the potassium silicate mud – Section II

Parameter	**Unit**	**Min.**	**Max.**	**Planned**
Flowline temperature	°C	15	52	-
Density	SG	1.21	1.26	1.20 – 1.25
Plastic viscosity	cP	8	21	ALAP
Yield point	lb/100 ft²	12	19	5 – 20
API fluid loss	mL/30 min	2.2	9.0	4 – 8
Gel strength	10 s	2	6	-
Gel strength	10 min	3	9	-
pH	–	12.5	13.5	9 – 10
Drill solids	wt.-%	1.6	4.0	-
Silicate content	vol.-%	29.65	71.05	-

After reaching TD of Section II at 750 m MD, the borehole was without any circulation for more than 17 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 roundtrip was performed to check on the borehole condition and to circulate fresh mud into the hole. A second roundtrip was performed after a further series of three hydrotests and almost 12 days without circulation. Both roundtrips were carried out without any problems, and the borehole was in very good shape. Another 10 days of testing followed before 8½" hole opening, in-situ stress testing and 12¼" hole opening. The drilling fluid materials used for Section II are listed in Tab. 3-6.

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

Product	Unit size	Quantity
Bentonite OCMA	25 kg	75
Citric acid	25 kg	3
Drispac Superlo	25 kg	15
Drispac Regular	25 kg	1
Floc cationic	25 kg	1
Sodium carbonate	25 kg	21
Sodium bicarbonate	25 kg	8
Pac LV Premium	25 kg	76
Caustic soda	1'000 L IBC	1
K+ silicate	1'000 L	115.32
Xanthan gum	25 kg	24

New Akros Mongoose shakers were installed. 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 phase, but mostly while coring.

3.6.3 Section III: Potassium / sodium silicate and sodium chloride drilling fluid

For Section III the potassium silicate mud from Section II was used. Coring and two hydrotests were carried out without any problems until 870 m MD. At 870 m MD static and dynamic losses of up to 22 m^3/h occurred with no returns to surface.

The loss control began after wireline logging. Various LCM pills with different recipes were pumped down into the loss zone until returns to surface were regained. The dynamic losses were thus significantly reduced but static losses remained unusually unchanged.

At 881 m MD potassium silicate was replaced with sodium silicate because the required quantities could no longer be produced by the local suppliers. The fluid parameters were different because sodium silicate had a higher weight and a higher viscosity than potassium silicate. Therefore, sodium silicate required different treatment to keep the drilling fluid within the required specifications. The drilling fluid parameters of the potassium/sodium silicate mud are represented in Tab. 3-7.

Under fluctuating but reduced losses of about 1 m^3/h to 2.5 m^3/h, coring operations continued. The drilling mud was further treated to reduce the viscosity of the sodium silicate mud down to 9 lb / 100 ft^2 to 11 lb / 100 ft^2 at 25 °C.

From a depth of 916 m MD, the mud losses again increased significantly. At a depth of 932 m MD, the mud losses increased up to 12.5 m^3/h. In this area, three heavy LCM pills with an LCM concentration of 250 kg/m^3 to 300 kg/m^3 and various particle sizes were pumped. The losses were partially stopped, but only for a short time. After two to three hours of coring, the losses started to rise again to 4 m^3/h. Additionally, coring operations had to be stopped several times because the surface and downhole equipment was clogged with LCM material.

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

Parameter	**Unit**	**Min.**	**Max.**	**Planned**
Flowline temperature	°C	24.5	33	-
Density	SG	1.19	1.29	1.15 – 1.30
Plastic viscosity	cP	7	22	ALAP
Yield point	lb/100 ft^2	7	18	5 – 20
API fluid loss	mL/30 min	2.8	9.8	4 – 8
Gel strength	10 s	1	5	-
Gel strength	10 min	2	7	-
pH	–	12.5	14	9 – 10
Drill solids	wt.-%	0.0	1.29	-
Silicate content	vol.-%	44.09	68.43	-

Static and dynamic losses continued to increase with time and depth up to 12 m^3/h to 13 m^3/h. At a depth of 960 m MD, the chloride content in the drilling fluid suddenly increased. After consultation with the geologists, it was decided to switch from silicate mud to a 1.20 SG sodium chloride mud at 961 m MD. The silicate mud was successfully exchanged to sodium chloride mud with a 10 m^3 high viscosity spacer. The silicate mud and the mixing zone that came to surface were disposed of. A total of 966 m^3 silicate mud and 239 m^3 spacers and LCM pills were lost in the borehole by that time.

In total, 19 LCM pills were pumped into the MAR1-1 borehole to treat the two loss zones. Details regarding the LCM pills can be found in Tab. 3-8.

Tab. 3-8: LCM pills pumped

Pill #	Date pumped	Water [m^3]	LCM material
1	05.06.2020	8	AMC-plug, Magma fiber, IPR-007
2	05.06.2020	8	Xanthan gum, AMC-plug, Magma fiber, IPR-007
3	05.06.2020	8	Xanthan gum, AMC-plug, Magma fiber, IPR-007
4	05.06.2020	6	Xanthan gum, AMC-plug, Kwik seal, Mikhart
5	05.06.2020	6	Xanthan gum, AMC-plug, Kwik seal, Mikhart, Magma fiber
6	05.06.2020	6	Xanthan gum, AMC-plug, Kwik seal, Mikhart, Magma fiber
7	06.06.2020	6	Xanthan gum, AMC-plug, Kwik seal, Magma fiber, nutshells coarse, seashells, calcium carbonate fine
8	06.06.2020	8	Xanthan gum, AMC-plug, Kwik seal, nutshells coarse, seashells
9	06.06.2020	8	Xanthan gum, AMC-plug, Kwik seal, Magma fiber, calcium carbonate fine
10	07.06.2020	6	Xanthan gum, AMC-plug, Kwik seal, calcium carbonate fine
11	07.06.2020	10	Xanthan gum, AMC-plug, calcium carbonate fine, cement, nutshells medium, cellophane flakes, mica medium
12	15.06.2020	6	Xanthan gum, AMC-plug, Kwik seal, calcium carbonate, nutshells medium, mica medium
13	16.06.2020	6	Xanthan gum, Magma fiber, calcium carbonate fine, nutshells fine, mica medium
14	19.06.2020	6	Xanthan gum, Magma fiber, calcium carbonate fine, calcium carbonate coarse, nutshells fine, calcium carbonate medium, mica medium
15	20.06.2020	6	Xanthan gum, Magma fiber, calcium carbonate fine, calcium carbonate coarse, calcium carbonate medium, mica medium
16	20.06.2020	6	Xanthan gum, Magma fiber, calcium carbonate fine, calcium carbonate coarse, nutshells fine, calcium carbonate medium, NOV-Carb
17	21.06.2020	10	Xanthan gum, Magma fiber, calcium carbonate fine, calcium carbonate coarse, nutshells fine, calcium carbonate medium, NOV-Carb
18	21.06.2020	8	Xanthan gum, AMC-plug, Magma fiber, nutshells coarse, seashells, calcium carbonate fine, calcium carbonate coarse, nutshells fine, calcium carbonate medium, NOV-Carb
19	25.06.2020	8	Xanthan gum, Magma fiber, calcium carbonate fine, NOV-Carb, mica medium
Total		142	47 t

To save time, new sodium chloride mud was mixed with pre-mixed saltwater brine. The reserve tanks and silos located on site were used to store the large quantities of brine.

After mud exchange, the borehole was cored without problems under creeping losses of 4 m^3/h to 6 m^3/h until the final depth of 1'099 m MD. The sodium chloride mud was constantly treated with polymers for fluid loss and viscosity control.

A total of approximately 755 m^3 of sodium chloride drilling fluid was pumped to finalize the borehole. The drilling fluid parameters of the potassium/sodium silicate mud are represented in Tab. 3-9.

As soon as Section III was completed by installing the liner hanger and retrieving the upper bridge plug, the sodium chloride mud was displaced to 33 m^3 of completion fluid with a 5 m^3 high viscosity spacer. The completion fluid was mixed with freshwater, 200 L inhibitor and 75 kg soda ash. The drilling fluid materials used for Section III are listed in Tab. 3-10.

Tab. 3-9: Drilling fluid parameters of the sodium chloride mud – Section III

Parameter	**Unit**	**Min.**	**Max.**	**Planned**
Flowline temperature	°C	21	32	-
Density	SG	1.19	1.20	1.20 – 1.25
Plastic viscosity	cP	11	22	ALAP
Yield point	lb/100 ft^2	9	16	15 – 25
API fluid loss	mL/30 min	6.8	8.6	< 6
Gel strength	10 s	1	3	-
Gel strength	10 min	2	4	-
pH	–	7.7	12.7	8 – 10
NaCl	g/L	315	318	320

The newly installed 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 phase, but mostly while coring.

Tab. 3-10: Drilling fluid materials – Section III

Product	Unit size	Quantity
Barite BB	1'000 kg/BB	1
Bentonite AMC EURO	25 kg	445
Calcium carbonate fine BB	1 MT	2
Calcium carbonate fine	20 kg	220
Inicor W882	200 L drum	1
Citric acid	25 kg	5
Drispac Superlo	25 kg	145
Drispac regular	25 kg	79
Sodium silicate BE SG 1.54	1 m^3	146.84
Sodium silicate CH SG 1.41	1 m^3	249.56
Nutshells medium	25 kg	32
Mikhart 0.5 to 1.5	25 kg	100
Magma fiber	11.34 kg sx	320
Kwik seal M	18.14 kg sx	100
Barite 1500 kg BB	1.5 MT BB	12
Mica (f/m/c)	25 kg	108
IPR-007	20 kg	10
NOV-Carb 130	25 kg	146
NOV-Carb 0.35-0.7	25 kg	140
NOV-Carb 0.5-1.5	25 kg	50
Calcium carbonate medium	25 kg	294
Calcium carbonate coarse	25 kg	280
Cellophan flakes	10 kg	40
Seashells 2 mm to 4 mm	25 kg	235
Seashells 4 mm to 6 mm	25 kg	135
Nut plug fine	25 kg	90
AMC plug	8 kg pail	139
Nutshells coarse WHSE	25 kg	90
Sodium carbonate	25 kg	89
Pac LV premium	25 kg	246
K+ silicate	1 m^3	101.20
Xanthan gum	25 kg	64

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. 3-11).

Tab. 3-11: Overview of technical logging

Date	**From** [m MD]	**To** [m MD]	**Company**	**Measurement**	**Run**
21.02.2020	310	0	Baker & Hughes	Cement bond log: GR-CCL-VDL-SBT	1.1.1
21.02.2020	307	0	Polymetra	Borehole survey: Gyro	-
28.02.2020	450	308	Terratec	Caliper	-
19.04.2020	750	280	Terratec	Caliper	2.2.1
14.05.2020	750	300	Terratec	Caliper	2.5.1
29.05.2020	870	747	Schlumberger	EMS caliper log: EMS-EDTC-LEH.QT	3.1.1
14.06.2020	748	150	Schlumberger	Cement bond log: PPC-MSIP-PPC-GPIT-EDTC-LEH.QT	3.2.2
15.06.2020	746	155	Schlumberger	Ultrasonic log: USIT-EDTC-LEH.QT	3.2.9
08.07.2020	862	746	Schlumberger	EMS caliper log: EMS-EDTC-LEH.QT	3.5.1
11.07.2020	849	695	Schlumberger	Cement bond log: USIT(USRS-B)-MSIP-EDTC-LEH.QT	3.6.1

A series of caliper logs was performed in the 6⅜" open hole of Section II between the multiple 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 VSP were carried out in Sections 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) was carried out in Section 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. Fluid logging was carried out by Terratec. Details on hydraulic testing and fluid logging can be found in Dossier VII.

3.8 Borehole diameters and casing

Borehole diameter

The borehole diameters are given in Tab. 3-12.

Tab. 3-12: Borehole diameters

From [m MD]	**To** [m MD]	**Diameter**	**Drilling method**	**Comment**
0	55	47"	Auger drilling	For 30" conductor
48	57	23"	Destructive drilling	For 18⅝" conductor
48	57	28"	Destructive drilling	For 18⅝" conductor
46	309	17½"	Destructive drilling	Section I
309	312	12¼"	Destructive drilling	Drilling out cement, shoe track +3 m new formation
312	460	6½"	Destructive drilling	Section II
460	750	6⅜"	Coring	Section II
312	750	8½"	Hole opening	Section II
312	750	12¼"	Hole opening	Section II
718	752	8½"	Destructive drilling	Drilling out cement, shoe track +2 m new formation
752	1'099	6⅜"	Coring	Section III
752	861	8½"	Hole opening	For liner hanger
834	862	6½"	Destructive drilling	Drilling out shoe track

Casing

The casing data are given in Tab. 3-13.

Tab. 3-13: Casing data

From [m MD]	**To** [m MD]	**Diameter**	**Section**	**Specification**
0	55	30"	0 – Conductor	Construction steel (ST 52)
0	57	18⅝"	0 – Conductor	K55, #87.5, Buttress thread connection (BTC)
0	308	13⅜"	I – Surface casing	L80, #68.0, BTC
0	312	7⅝"	II – Auxiliary casing	J55, #29.7, BTC
0	748	9⅝"	II – Intermediate casing	J55, #40.0, BTC
705	858	7⅝"	III – Liner hanger	J55, #29.7, BTC

3.9 Cementing

Cementing data are shown in Tab. 3-14.

Tab. 3-14: Cementing data

From [m MD]	**To** [m MD]	**Casing**	**Amount** [m³]	**Density**	**Type / specification**
0	55	30"	-	1.8 SG	CEM III B 42.5 N-LH/SR
0	57	18⅝"	9.7	1.7 SG	CEM II B-M (T-LL) 42.5 N
0	309	13⅜"	32.0 7.0	1.7 SG 1.88 SG	Lead: CEM III B 32.5 N-LH/HS/NA Tail: HMR+
393	749	9⅝"	17.2 2.3	1.4 SG 1.7 SG	Lead: HOZlite Tail: CEM III B 32.5 N-LH/HS/NA
1'099	943.5	Backfilling	3.7	1.65 SG	CEM III B 32.5 N-LH/HS/NA
Bridge plug at 900 m MD					
705	859	7⅝"	5.0	1.36 SG	HOZlite

For evaluation of the cement jobs in the MAR1-1 borehole, cement bond logs (CBL) and more detailed measurements with an ultrasonic imager tool (USIT) were performed. These measurements are listed in Tab. 3-11 of Chapter 3.7.

In Section I, the 13⅜" casing was successfully cemented to surface. The quality of the cement job shows a good to medium bond above 57.5 m MD. Between 57.5 m and 183 m MD, the CBL showed strong casing arrivals and weak formation arrivals, which indicate poor bonding between casing and cement but good bonding between cement and formation. Below 183 m MD, the logging run showed partial bonding to casing.

The cement job of the 9⅝" casing was planned to be cemented up to 100 m MD below ground level, but, due to technical problems, the top of cement (TOC) only reached 393 m MD. Consequently, the cement did not reach the previous 13⅜" casing and an interval of approximately 85 m open hole and 308 m cased hole was not cemented. Details on what occurred during the cement job can be found in Chapter 3.5.3. The CBL and USIT logging runs showed excellent bonding and zonal isolation across the interval from 507 m to 745 m MD. The short section between 468 m and 507 m MD indicated a free pipe interval. It is possible that cement fell into lower formations. Between 393 m and 468 m MD, the log showed good bonding as deduced from both the sonic and ultrasonic logs, which detected cement bond and formation signals in this interval of bonded lead cement. It was decided to postpone a repair job at the top part of the 9⅝" casing that was not cemented, in view of the long-term monitoring system to be installed.

The cement job of the 7⅝" 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 seemingly moderate quality of the cement jobs, zonal isolation of the different aquifers in MAR1-1 could be achieved. The host rock and its surrounding formations are well isolated and show a good cement bond to the casing as well as to the formation. Furthermore, the Malm aquifer and the two loss zones are isolated from each other.

3.10 Borehole deviation

The inclination and azimuth of the MAR1-1 borehole were measured by performing two survey runs. The survey data filtered at 10 m intervals were spliced from the Polymetra gyro survey (0 m to 307 m TVD [true vertical depth]) through the casing in Section I, and Schlumberger wireline logging (> 307 m TVD). Figs. 3-15 and 3-16 show the borehole survey. Maximum dog-leg severity is 3.09°/30 m at 877 m TVD. Step-out at TD is 16.2 m north and 16.3 m west. The borehole can be considered vertical, and MD values mostly correspond to TVD values.

Changes in deviation occurred in the splice intervals between logging runs, including the 13⅜" casing shoe of Section I at 308 m MD and the severely washed-out interval in the Schinznach Formation where total mud losses were encountered while coring at approximately 870 m to 877 m MD. No such change in deviation is seen at the 9⅝" casing shoe of Section II at 748 m MD. Whether the increase in deviation is a result of changing the BHA, the casing installation, other operational practices or geological effects, or a result of FMI sonde deviation or sensor accuracy affecting measurements variably between logging runs is difficult to determine.

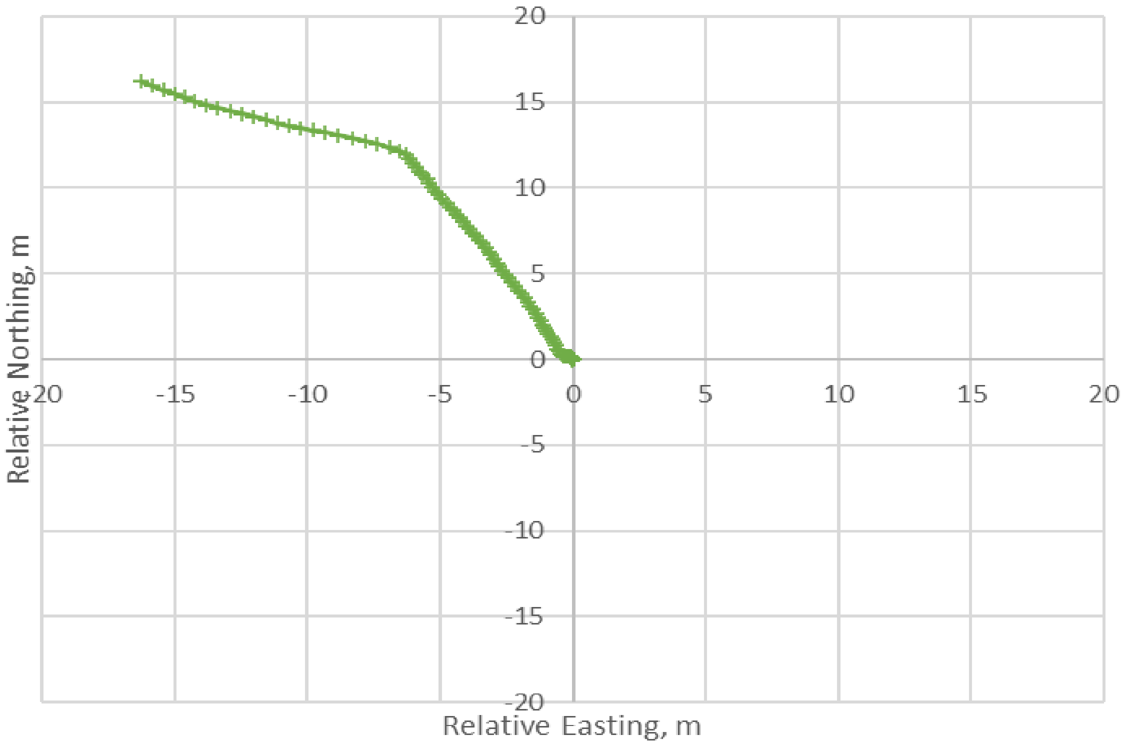

Fig. 3-15: Plan view: relative easting – relative northing

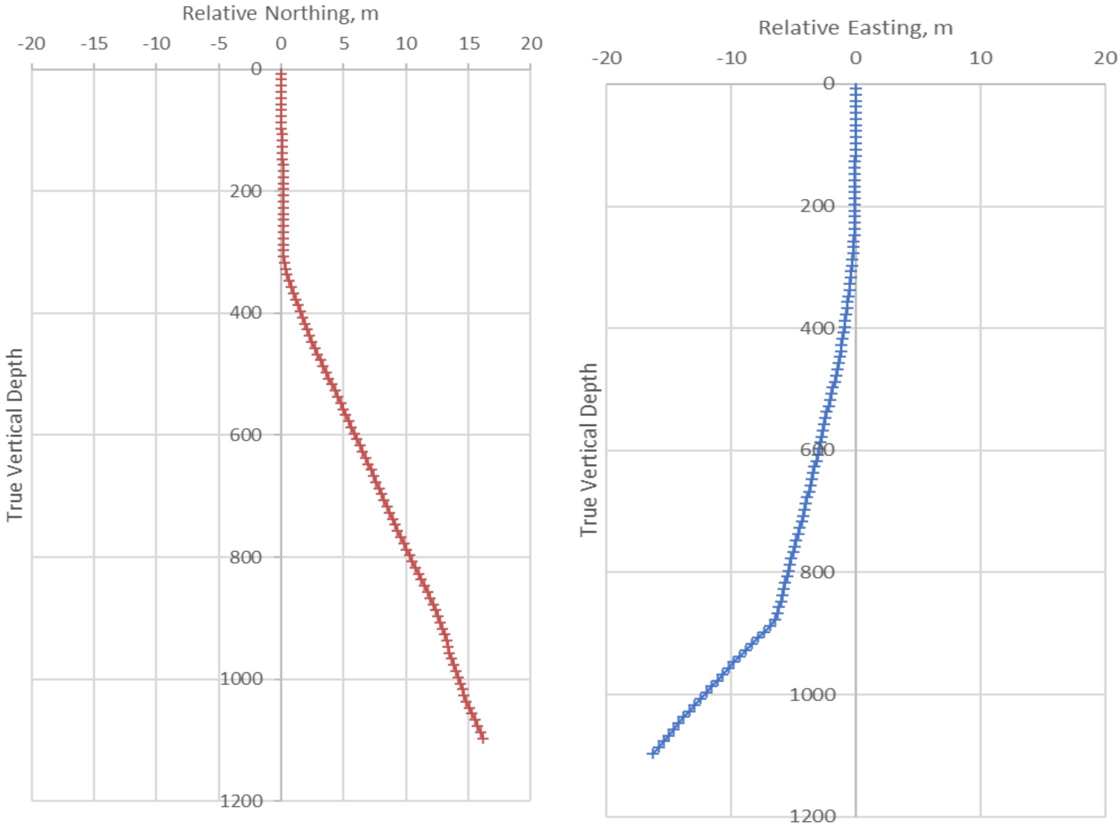

Fig. 3-16: Profile view: relative northing and relative easting – relative elevation (TVD)

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 that are not allowed to access the drill site. Additionally, all drill sites were 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
  - Half high
- 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 on location 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 MAR1-1, one restricted work case and one first-aid case were reported. The restricted work case was related to a rig crew member feeling unwell and being taken to hospital to rule out any serious illness. The first-aid case was related to an external truck driver delivering silicate fluid with a bulk truck. The truck driver got silicate fluid in his eyes while connecting his truck to the storage silo. The very good reaction of the personnel onsite prevented any serious consequences and the truck driver returned to work the following day. This incident proved that emergency training of personnel is of great importance for quick and correct action.

In March 2020 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 about environmental aspects and bringing in external experts if necessary.

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

- communicating transport routes
- verifying whether environmental requirements and protective measures for transports and drilling activities were respected
- checking if the drainage concept was working properly and respected
- checking if the lighting concept was being respected and whether further measures were necessary
- checking the machinery list and particle filters of all vehicles and machines
- checking the storage of hazardous substances
- checking the emergency power generator and its leakage detection system
- conducting leakage tests of wastewater and sewage pipes
- checking storage, separation and disposal of waste at the drill site
- checking 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 and an oil separator and finally seeped away in the two seepage pits constructed on the east and west side of the drill site.

At first, the east seepage pit was found to have an overflow that was installed too low, which was immediately corrected by mounting an additional pipe on top.

During the drilling phase, the dewatering system did not work properly because the seepage pit on the west side was clogged by fine material and the pH of the water at the seepage pit at the east side of the drill site was too high. Both seepage pits were converted to collection pits by filling them with bentonite to seal off the infiltration area. The collected water in the pits was disposed of on a regular basis by suction trucks.

After completing drilling operations, both collection pits were rebuilt to their original state as sewage pits.

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 east 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. During a site visit of the pedological site support in September 2019, it was noticed that the vegetation of the soil depots was not sufficient and had to be improved. Aside from this, all regulations relevant to soil were fulfilled.

4.2.4 Noise measurements

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 MAR1-1 borehole, a three-month long noise monitoring was performed by a specialised company at the nearest house from January 2020 until April 2020 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 56 dB(A) and 49 dB(A) during the night. Because the house where the noise measurements were carried out was in an agricultural zone and sound emissions of agricultural machines could not be filtered out, the results were in the upper range but still below the limits.

4.2.5 Lighting

Besides noise emissions, light emissions were also relevant for the drill site. 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. The target was to protect the light-sensitive mouse-eared bats that had their flight route close to the drill site along the wood. The cantonal department for nature protection found out that the bats were avoiding their original route because of the intensive light emissions of the drilling rig. 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**
Pump/formation water		470 m^3	Neutralisation plant Henggart
Surface water oily		20 m^3	Processing plant Henggart
Drill cuttings and mud	17 05 97 – B	180 t	ESAR Rümlang, Blöchlinger AG Neuhaus, disposal site ASPI, processing plant Strabag Bürglen
Drill cuttings and mud contaminated	17 05 91 – E	380 t	ESAR Rümlang, Blöchlinger AG Neuhaus
Drilling mud	17 05 91 – E	415 t	Processing Mökah, ESAR Rümlang, Blöchlinger AG Neuhaus
Drill cuttings and mud highly contaminated	17 05 05 – S	150 t	Processing Mökah, ESAR Rümlang, Blöchlinger AG Neuhaus
Cement slurries		75 t	Processing Mökah, ESAR Rümlang, Blöchlinger AG Neuhaus

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.

In total, 1'200 t were declared as mineral waste and 490 m^3 as surface and formation water.

In Section I, 144 t of cuttings and 40 t of cement slurry were disposed of.

In Section II, at a depth of 460 m MD, 168 t of bentonite polymer mud were disposed of after changing the fluid to freshwater. After fluid logging the 53 t of freshwater were disposed of after changing the drilling fluid to potassium silicate. In total, 260 t of cuttings and 15 t of cement slurry were dumped. Due to cleaning of the shaker screens and centrifuge on a regular basis from silicate fluid, 73 t of watery drilling fluid had to be disposed of. Additionally, 70 m^3 of surface water were transported offsite with suction trucks because the west seepage pit was converted into a collection pit.

In Section III, the seepage pit on the east side of the drill site was sealed off with bentonite and the surface water was transported offsite with suction trucks. In total, 420 m^3 surface water was collected in these pits. Due to the fast-glazing process of silicate fluids on surfaces that are not directly flushed with freshwater, the disposal site had problems with the filtering system of their treatment plant, but the waste materials from the drill site were still accepted. However, after adding LCM material to the silicate drilling fluid, the disposal site refused to accept the waste materials. Their treatment plant had a full breakdown for several days because of the highly contaminated drilling mud, with LCM material plugging many parts of the machinery. The remaining 61 t of LCM-contaminated waste material had to be brought to another disposal facility because the disposal process was much more complex. In total, 211 t of drilling mud was dumped with high water content due to the many cleaning runs of the surface facilities. Additionally, 39 t of cuttings and drilling mud and 20 t of cement slurry had to be disposed of. After setting the liner hanger, 222 t of sodium chloride drilling fluid was transported offsite.

4.2.7 Mud losses

Mud losses added up to 1'709 m^3, whereas 50% silicate drilling fluid, 10% spacers and LCM pills and approximately 40% of sodium chloride drilling fluid were lost in the two loss zones of Section III.

5 References

ENSI (2017): Sicherheitstechnisches Gutachten des ENSI zum Vorschlag der in Etappe 3 SGT weiter zu untersuchenden geologischen Standortgebiete. Sachplan geologische Tiefenlager, Etappe 2. ENSI 33/540, April 2017. Eidgenössisches Nuklearsicherheitsinspektorat ENSI, Brugg.

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

MICON-Drilling GmbH (2016): Mining bits. MICON-Drilling. https://www.micon-drilling.de/Download/Catalog_Mining%20Bits_EN_170131.pdf

Nagra (2014): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage: Sicherheitstechnischer Bericht zu SGT Etappe 2: Sicherheitstechnischer Vergleich und Vorschlag der in Etappe 3 weiter zu untersuchenden geologischen Standortgebiete. Nagra Technischer Bericht NTB 14-02.

Nagra (2016): Arbeitsprogramm für Tiefbohrungen: Spezifisches Untersuchungsprogramm der Tiefbohrungen Marthalen-1-1. Nagra Sondiergesuch NSG 16-15 AP1 Rev. 2.

Nagra (2020): TBO: Silicate Drilling Fluids Guide. Nagra Arbeitsbericht NAB 20-32.

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