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Arbeitsbericht NAB 22-50

Long-term Monitoring System of the Stadel-3 Borehole: Installation Report

March 2023

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National Cooperative for the Disposal of Radioactive Waste

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KEYWORDS
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List of Acronyms

AISI	American Iron and Steel Institute
API	American Petroleum Institute
BTC	Buttress thread connection
DAS	Data acquisition system
DTS	Distributed temperature sensing
ELB	Disposal canister
FO	Fibre optics
HLW	High-level waste
ID	Inner diameter
L/ILW	Low- and intermediate level waste
LTMS	Long-term monitoring system
MPS	Multi-packer system
OD	Outer diameter
OPA	Opalinus Clay
OTDR	Optical time-domain reflectometry
POOH	Pull out of hole
RIH	Run in hole
TBO	Nagra deep borehole
TU	Tubing
USIT	UltraSonic Imager Tool

1 Introduction

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 in Northern Switzerland. The aim of the drilling campaign was to characterise the Mesozoic sediments of the three remaining siting regions located at the edge of the Northern Alpine Molasse Basin (Fig. 1-1).

In this report, we describe the installation of a multi-packer-system (MPS) for long-term observation in the Stadel-3-1 borehole. The details of the drilling and characterisation of the borehole are given in Ammen & Palten (2023).

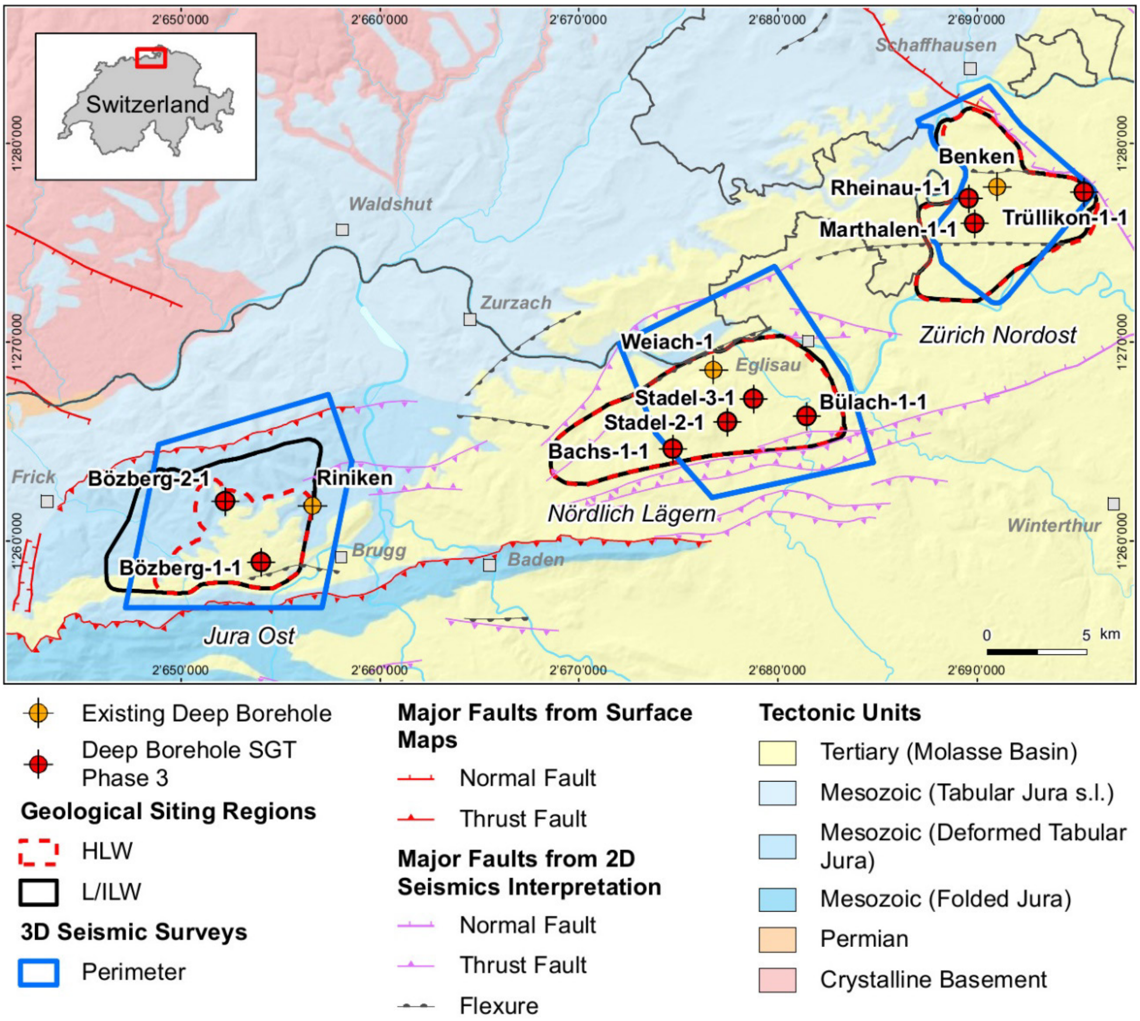

Fig. 1-1: Tectonic overview map with the three investigated siting regions

1.1 Borehole Stadel-3-1

The general information on the borehole is given in Tab. 1-1, Fig. 1-2 shows a map with the location of the drill site.

The borehole was drilled destructively to 438.5 m with a 17½" drill bit and cored below that to a final depth of 1'280.88 m. The planned work and investigation programme was fully implemented, and the drilling work was carried out successfully without any major changes.

After drilling, the borehole was cemented back to 1'100.0 m depth. The borehole was stabilised with a telescopic casing system and liner hanger to 1'033.5 m MD (Fig. 1-3).

Tab. 1-1: General borehole information

Borehole name	**Stadel-3**
Siting region	Nördlich Lägern
Wellhead coordinates	X (m) 2'678'792.885 Y (m) 1'267'161.988 (Geodetic Datum: CH1903+/LV95)
Ground level	408.74 m above sea level (top of rig cellar)
Drilling period (start – end rig release)	17.12.2020 – 25.06.2021
Drilling company	PR Marriott Drilling Ltd.
Drilling rig	Rig-16 Drillmec HH102
Borehole maximum total depth	1'280.88 m
Maximum deviation	1.29° at 1'162.96 m MD (borehole is vertical)
Maximum dogleg severity	5.78°/30 m at 445.01 m MD

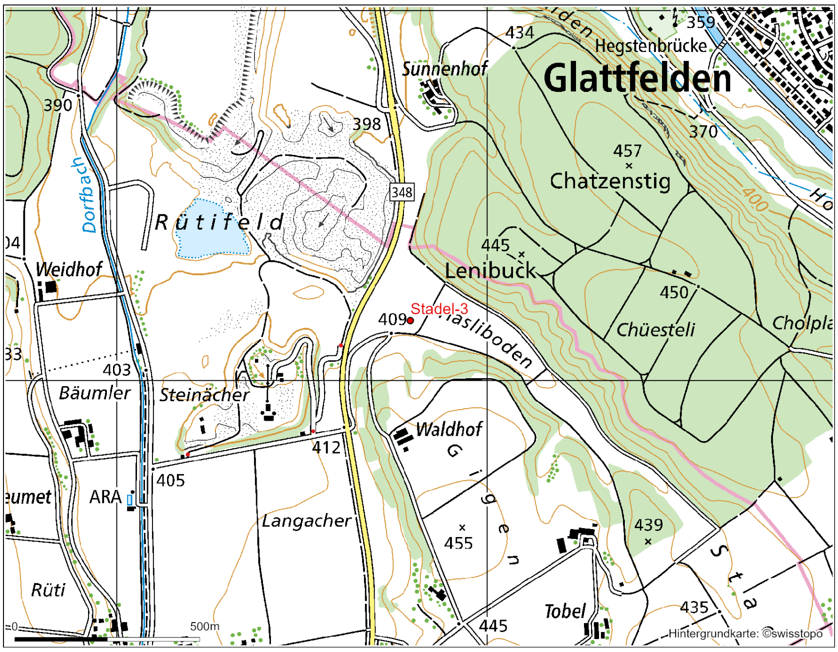

Fig. 1-2: Location of the drill site Stadel-3

1.2 Planning of the Multi-Packer System

The MPS is intended to measure the undisturbed hydraulic heads and their temporal fluctuations in the Opalinus Clay, its surrounding rock units and the deep aquifers. The measurements represent a part of the environmental baseline monitoring according to Fanger et al. (2021).

If required, simple hydraulic tests and groundwater sampling in the deep aquifers will also be possible during the monitoring phase at selected observation intervals of the MPS. Furthermore, measurements of undisturbed formation temperatures are also foreseen.

Finally, with the long time series, the hydraulic heads in the clay-rich and very low-permeability formations can be recorded very precisely and thus large-scale, undisturbed hydraulic properties of the rock can be mapped. This means that the database for regional and local hydrogeological models can be further expanded.

The MPS was planned considering the hydraulic tests conducted during drilling of the borehole, the recovered core and image logs as well as logs that provide information on the cementation quality.

Nine observation intervals were foreseen: one in each of the aquifers (Malm and Muschelkalk), three zones in the Opalinus Clay sections and four zones in the rock units surrounding the Opalinus Clay: Herrenwis Unit and Wedelsandstein of the Dogger group, the Staffelegg formation in Lias and the Klettgau formation in Keuper (Fig. 1-3).

The details of the borehole casing are given in Tab. 1-2 and had to be considered for the planned perforation and selection of suitable packer elements. Perforation of the casing prior to MPS installation was required to create a hydraulic connection to the formations behind the casing where observation intervals of the MPS were planned.

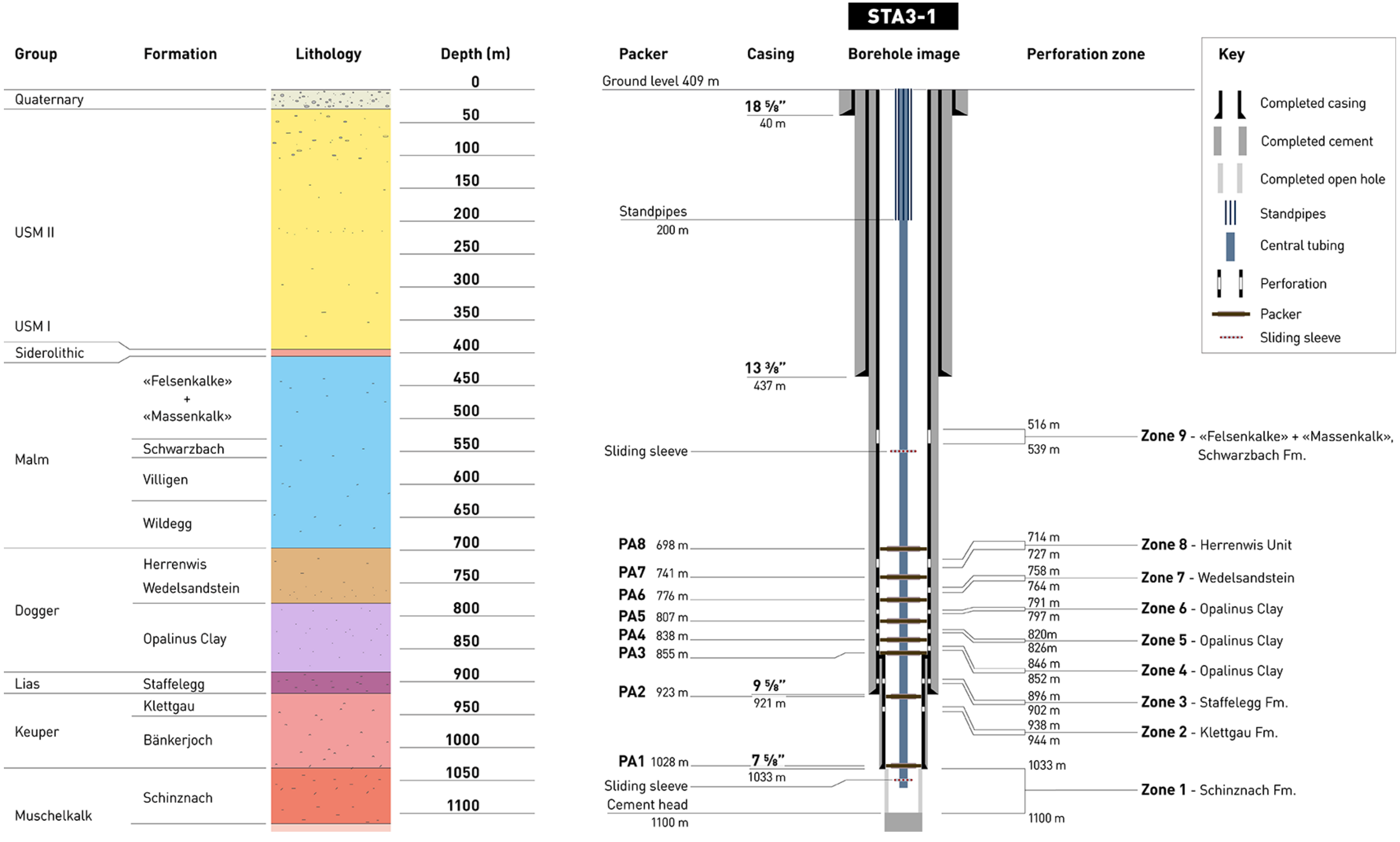

Fig. 1-3: Simplified lithostratigraphic profile, casing scheme and summary of the MPS for the Stadel-3 borehole

All depths are rounded to full meters.

Tab. 1-2: Casing scheme and open hole intervals

Section	Cased hole	Open hole
0 – Conductor	OD: 18⅝"; Interval: 0 to 40 mMD K-55, 87.5 lbs/ft, BTC	1'180 mm; Interval: 0 to 41.6 mMD
1 – Surface casing	OD: 13⅜"; Interval: 0 to 437.4 mMD K-55, 68.0 lbs/ft, BTC	OD: 17½"; Interval: 41.6 to 438.5 mMD
2 – Production casing	OD: 9⅝"; Interval: 0 to 921.0 mMD K-55, 40.0 lbs/ft, BTC ID: 224.41 mm, Drift 220.45 mm	OD: 12¼"; Interval: 438.5 to 924.2 mMD
3 – Liner hanger	OD: 7⅝"; Interval: 859.27 to 1'033.5 mMD K-55, 29.7 lbs/ft, BTC ID 174.63 mm, Drift 171.45 mm,	OD: 9½"; Interval: 924.2 to 1'035.0 mMD
4 – Open hole	OD: 6⅜"; Interval: 1'035.0 to 1'280.9 mMD Cement backfilled from 1'280.9 to 1'033.5 mMD	

1.3 Companies involved

The following companies were involved in the installation activities:

- Nagra: project management, coordination, and organisation of the well site
- Daldrup & Söhne AG: drilling contractor
- Schlumberger: wireline logging and perforation
- Société Suisse des Explosifs: supervising work with explosives during perforation
- Solexperts: Installation of the MPS
- Well Engineering Partners BV (WEP): drilling supervisor
- AFRY Switzerland Ltd: Quality control of the installation work performed in the borehole
- Ad Terra Energy: technical supervision of all the perforation and logging work performed in the borehole

2 Description of the Multi-Packer-System

The MPS isolates nine observation intervals in the 1'280.88 m deep borehole Stadel-3. The borehole is fully cased until 1'033.5 m MD. The open borehole section extends down to 1'100.0 m MD to the cement head, isolating the lowermost borehole section. The casing outer diameter in the section instrumented with the MPS is 7⅝" and 9⅝". The observation intervals are perforated to create a hydraulic connection to the formations.

The system consists of the following main components:

- central tubing string
- hydraulically inflatable packers; each with a separate packer inflation line
- monitoring lines with ports/filters to measure the hydraulic head in the observation intervals
- sliding sleeves to guarantee individual additional access to aquifers for groundwater sampling
- pressure sensors for pressure measurements in the observation intervals and of the packer pressures
- packer pressure control system at the surface
- data acquisition system

2.1 Components

Central tubing string

A 2⅞" outer diameter L80, 6.5 lbs/ft tubing with API standard connections and an inner diameter of 62 mm is used. The length of the individual tubings is about 9.15 m. Protector couplings are used to protect and guide the packer and observations lines at the position of the couplings. In addition, one banding strap Alloy400 (Monel® 400) was used to fix the lines in the middle of each tubing.

A bullnose with a diameter of 140 mm is mounted as end cap at the bottom of the system and is sealed by Loctite adhesive.

The protector couplings protect and guide the packer and observation lines at the position of the tubing couplings. Two types of protector couplings are used, one type for the tubing below 200 m depth with packer and observation lines and the other type for the upper 200 m of tubing with packer lines and standpipes (Fig. 2-1). The protector couplings above 200 m depth are custom-made for nine standpipes from the observation intervals, the eight packer inflation lines and the fibre optic cable.

For the centralisation of the whole downhole assembly in the borehole, centralisers are installed wherever it is appropriate (Fig. 2-2) to guarantee a smooth installation in critical sections (e.g. in the area of the liner hanger).

Fig. 2-1: Hanger sub with threads for monitoring and inflation lines below and standpipes above, respectively

Here the hanger sub is mounted on the central tubing which is filled with synthetic pore water.

Fig. 2-2: Two centralisers were used to help guide the lowermost section of the MPS

Sliding-end packers

Two types of sliding-end packers are used, 154 mm (6.06") packer for the 7⅝" diameter casing and 184 mm (7.24") packer for the 9⅝" diameter casing. The packer connections were sealed with Loctite adhesive during installation (Fig. 2-3). The packers are individually inflated with water and in the uppermost part of the packer inflation lines with antifreeze (to protect from freezing during cold winter time). All packer inflation lines are run through the mandrels of the upper packers and are connected to a packer pressure maintenance system in the bore cellar. Packer specifications are given in App. A. The packers fulfil the following requirements:

- length of packer sleeve = 1.00 m
- natural rubber type for long-term stability
- integrated steel wire reinforcement in sleeves
- packers hold a differential pressure (pressure difference across a packer element) of 6'000 kPa for the defined casing diameters
- individual hydraulic inflation line for each packer with fluid (OD¼")
- The pressure of each packer is kept stable with a pressure maintenance system in the bore cellar.

Fig. 2-3: Installation of a packer element on the central tubing

Packer inflation lines

Each packer is connected via a packer inflation line to the packer pressure maintenance system installed in the borehole cellar. The packer inflation lines are made of stainless steel 1.4404 (AISI 316 L), with inner diameter (ID): 4.55 mm, and outer diameter (OD) 6.35 mm. They are connected by Swagelok-type (Hy-Lok), stainless steel 1.4401 (316) fittings (Fig. 2-4).

The packer inflation lines were delivered in 250 m rings. Each ring was tested for tightness with 7 bar compressed air in a water basin. Afterwards, the packer inflation lines were wound up on a bobbin and the rings were connected with Swagelok-type compression fittings. The entire line for each packer was saturated with water and pressurised with 100 bar water pressure.

Above each packer inflation port, a burst disc is included in the packer inflation line to avoid packer inflation during system installation (the packer inflation lines are saturated with water before system installation). They were also used to test the tightness of the packer inflation lines and their couplings at the end of the system installation before packer inflation.

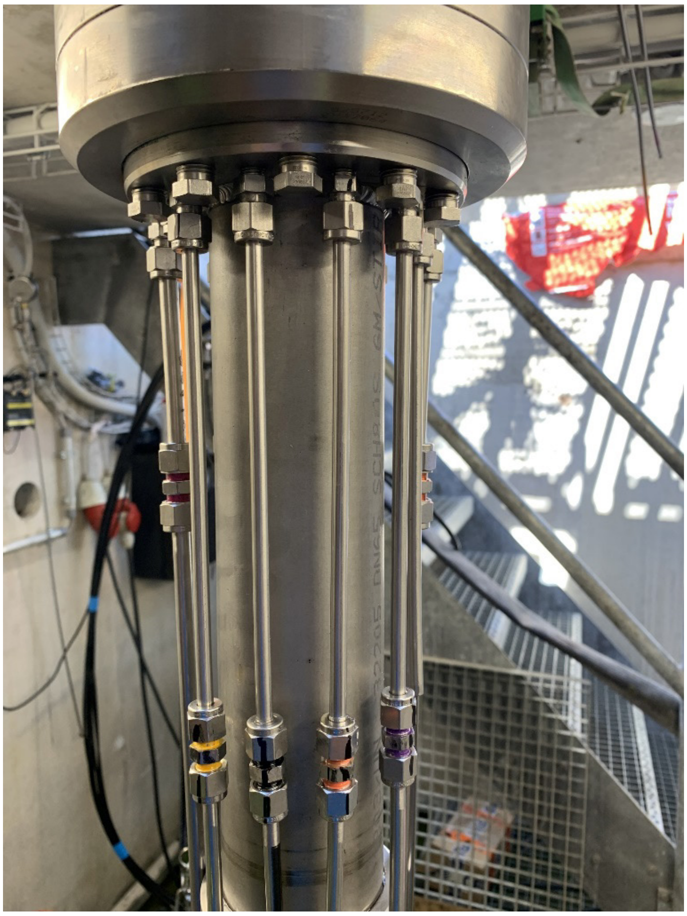

Fig. 2-4: Connections of monitoring and packer inflate lines on a packer

Lines are identified by a colour code.

Monitoring lines with filter ports

Each observation interval is equipped with an individual monitoring line for pressure monitoring. The monitoring lines from the observation intervals until 200 m below ground level have an inner diameter of 6.00 mm and an outer diameter of 8.00 mm.

The monitoring lines were delivered in 350 m rings. Each ring was tested on tightness with 7 bar compressed air in a water basin. Afterwards, the monitoring lines were wound up on a bobbin and the rings were connected with Swagelok-type compression fittings. The entire line for each packer was saturated with water and pressurised with 100 bar water pressure.

Each monitoring line is equipped with a filter piece located in the corresponding observation interval. The filter piece consists of a tube with an outer diameter of 20 mm mounted to the monitoring line with Swagelok-type fittings (Fig. 2-5).

Above each filter piece, a burst disc is included in the monitoring line. They were used for pressure testing the monitoring lines with water up to 20 bar.

At about 200 m below ground level, each monitoring line is connected to a stainless-steel standpipe up to the wellhead. A specific hanger sub was used to connect the monitoring lines and the standpipes (Fig. 2-1). The standpipes have an ID of 16.05 mm and an OD of about 19.05 mm and a standard length of 6 m. They are connected by ¾" Swagelok fittings. For artesian conditions, the monitoring standpipes have a valve at the top end such that the pressure transmitter and manometer can be removed without outflow or pressure decrease in the standpipe.

Fig. 2-5: Filter port with burst disc above, installed on the central tubing with metal banding straps

Sliding sleeves

To be able to take water samples from selected aquifers, two sliding sleeves are installed along the central tubing string (Fig. 2-6 and Fig. 2-7) at the depth of the Malm and Muschelkalk observation intervals (Tab. 2-1). The connection is sealed by Loctite adhesive. By opening the sliding sleeve, the access to the observation interval is established and the water can be pumped to the surface by installing a 2"-pump or similar into the central tubing string.

The sliding sleeve has an opening and closing mechanism which is activated by a wireline operation tool. The operation tool is designed to be run using wireline methods. The sliding sleeve has the ability to operate numerous times over a long period of time.

Fig. 2-6: Installation of a sliding sleeve on the central tubing

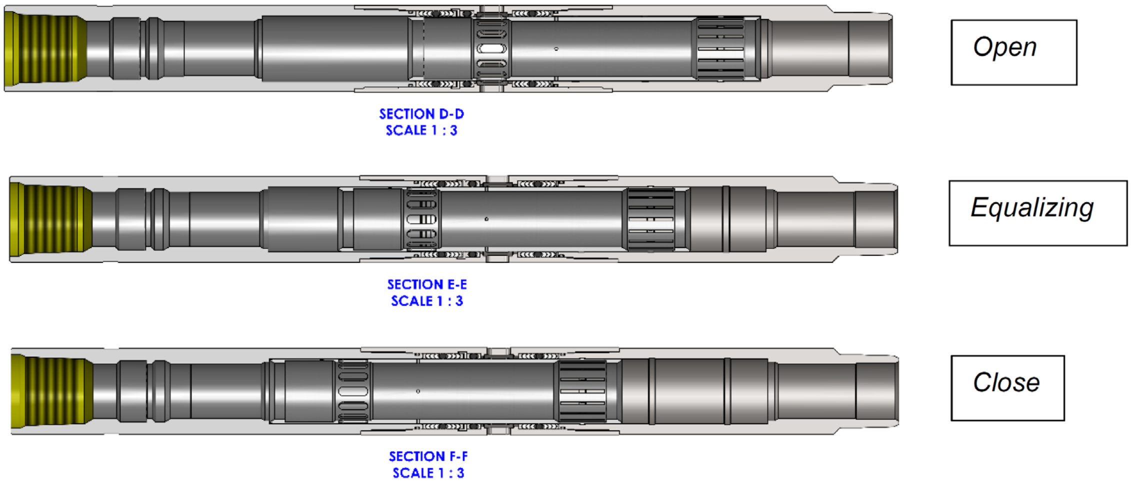

Fig. 2-7: Schematic drawing of a sliding sleeve in open and closed position.

Fibre optic cable

A fibre optic cable is run along the multi-packer-system along with the packer and monitoring lines. The used fibre-optic cable is a stainless-steel loose tube-in-tube sensing cable, with carbon-coated fibres. One single-mode fibre and two multi-mode fibre strands are integrated. The multi-mode fibres are connected at the bottom at 1'031.23 m depth to make one continuous loop.

The cable has to be spliced below each packer using a splice box designed by Solexperts (Fig. 2-8), which is tightly sealed with sealing glands (CONAX compression seal fittings). Before installation of the splice box in the borehole, the quality of each splice was verified with an OTDR-measurement. Additionally, the exact position of each splice box and the cable meters deployed in the borehole were documented during the installation.

In the borehole cellar a reference box with thermal isolation material and about 100 m of cable is mounted to the wall. This can be used for calibration during each measurement.

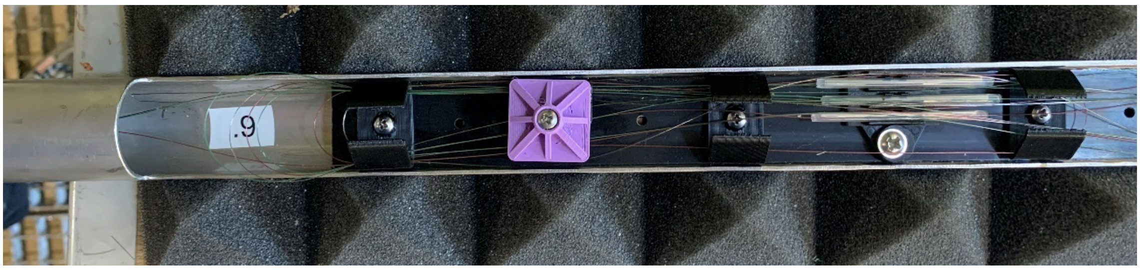

Fig. 2-8: View of the opened splice box with three splices of the FO cable

Landing Spool – Wellhead flange

The wellhead flange is a standard 11" API flange (3'000 psi) with a soft iron ring as seal (Fig. 2-9). Two 2⅞" EU pup joints (0.5 m at the top, 0.89 m at the bottom; both screwed in with optimum torque) are screwed in the landing spool, together with NPT connections for the eight packer inflation lines, one FO cable and 9 monitoring standpipes (through-hole tube fitting for the ¾" observation standpipes).

Fig. 2-9: Lowering of the landing spool with fittings for standpipes and packer inflate lines

Deployed sensors

Different sensors were deployed in the system. A barometric sensor to measure atmospheric pressure and a temperature sensor for ambient temperature are installed in the borehole cellar. The sensor specifications are given in Tab. A-2. In case the hydraulic head lies below ground level, the fluid level in the interval observation lines is monitored by submersible pressure sensors, which are installed in the standpipes below the expected hydraulic head (water level), see Fig. 2-10. The fluid level in the standpipes can lie between 0 – 200 m below ground level. The standpipe is open to the atmosphere. If a pumping test with groundwater sampling will be performed in one of the aquifers, the probe depth can easily be adjusted.

If an observation interval shows artesian conditions, the hydraulic head is measured at the wellhead level at the end of the standpipe with a artesian pressure sensor and with a manometer, see Fig. 2-10. In case of sensor failure, both, the submersible pressure sensors and the artesian pressure sensors are easily replaceable.

The downhole sensors are slim, short and very light. To avoid any problems with the lowering of the downhole sensors in the standpipes to the desired depths, sinker bars are available which can be screwed to the bottom end of each sensor. The sinker bars have a length of 0.5 m and a weight of 0.3 kg each. Several sinker bars can be connected together, if necessary.

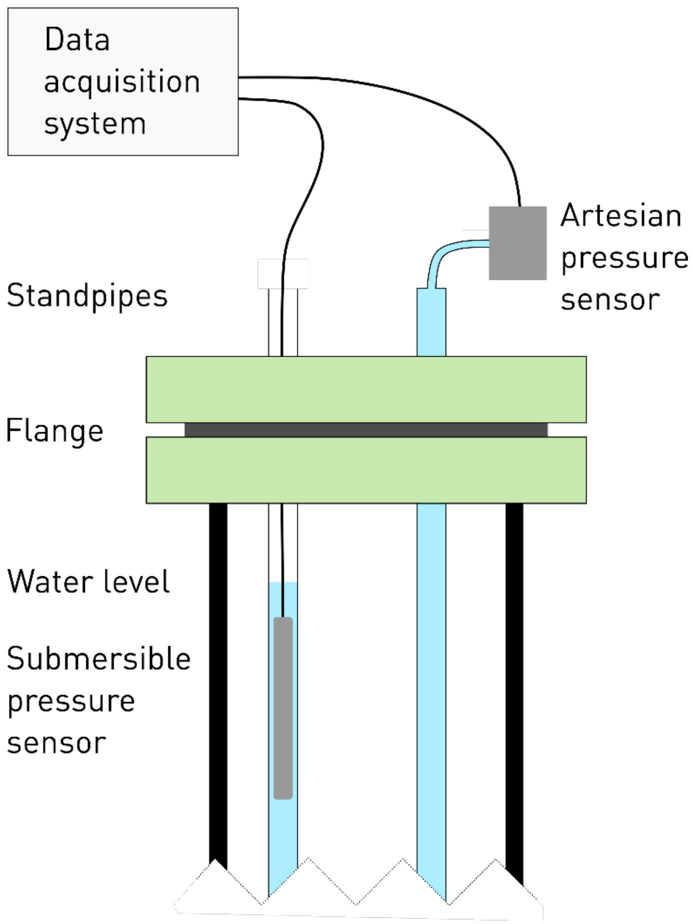

Fig. 2-10: Sketch of the configuration for two standpipes and pressure sensors with sub-artesian conditions (left) and artesian condition (right), respectively

Packer pressure control system

The pressure of each packer should be kept constant with a pressure vessel connected to a 20-litre nitrogen gas bottle with high precision pressure reduction valve. The vessel is filled up to ⅔ with water and ⅓ with gas and the pressure is monitored with a pressure sensor. The nitrogen gas bottle contains a small amount of a non-toxic tracer gas with a strong odour, so that leakages in the high-pressure maintenance system can be detected easily when entering the bore cellar.

Data acquisition system

The DAS consist of an industrial PC, screen and keyboard. Data acquisition is performed through the Solexperts GeoMonitor II software. The connected sensors include packer pressure, interval pressure, ambient pressure and temperature and weight readings from the scales with the pressure vessels. Data is transmitted via FTP to a database for remote access to the monitoring data.

2.2 As-built record

The lengths of the 2⅞" central tubing vary slightly from one piece to another. Hence, there are minor deviations in the geometry as-built over the planned location of all elements of the MPS. Tab. 2-1 summarises the as-built record for the sub-surface components, i.e. the depths of packers and sliding sleeves together with the perforation zones. The perforation zones were realised according to the planned depth with an accuracy better than 0.1 m and confirmed by logs. Fig. 2-11 contains the detailed installation record and schematic layout of the MPS, and Fig. 2-3 provides further details on the centralisers deployed.

Tab. 2-1: Summary of the observation intervals and packer locations of the MPS

	Formation	**Interval** [m MD]	**Length** [m]	**Sliding sleeve** [m MD]	**Perforation** [m MD]
Interval 9	«Felsenkalke» + «Massenkalk», Schwarzbach Fm. (Malm)	0 – 697.23	697.23	527.47 – 528.38	516.00 – 522.00 523.00 – 529.00 533.00 – 539.00
Packer 8		697.23 – 698.23	1.00		
Interval 8	Herrenwis Unit (Dogger)	698.23 – 740.67	42.44		714.01 – 720.01 721.01 – 727.01
Packer 7		740.67 – 741.67	1.00		
Interval 7	Wedelsandstein (Dogger)	741.67 – 775.97	34.30		758.01 – 764.01
Packer 6		775.97 – 776.97	1.00		
Interval 6	Opalinus Clay (Dogger)	776.97 – 806.70	29.73		791.00 – 797.00
Packer 5		806.70 – 807.70	1.00		
Interval 5	Opalinus Clay (Dogger)	807.70 – 837.64	29.94		820.00 – 826.00
Packer 4		837.64 – 838.64	1.00		
Interval 4	Opalinus Clay (Dogger)	838.64 – 854.11	15.47		846.00 – 852.00
Packer 3		854.11 – 855.11	1.00		
Interval 3	Staffelegg Fm. (Lias)	855.11 – 922.15	67.04		896.01 – 902.01
Packer 2		922.15 – 923.15	1.00		
Interval 2	Klettgau Fm. (Keuper)	923.15 – 1'027.29	104.14		938.00 – 944.00
Packer 1		1'027.29 – 1'028.29	1.00		Open hole
Interval 1	Schinznach Fm. (Muschelkalk)	1'028.29 – 1'100.00	71.71	1'038.21 – 1'039.12	

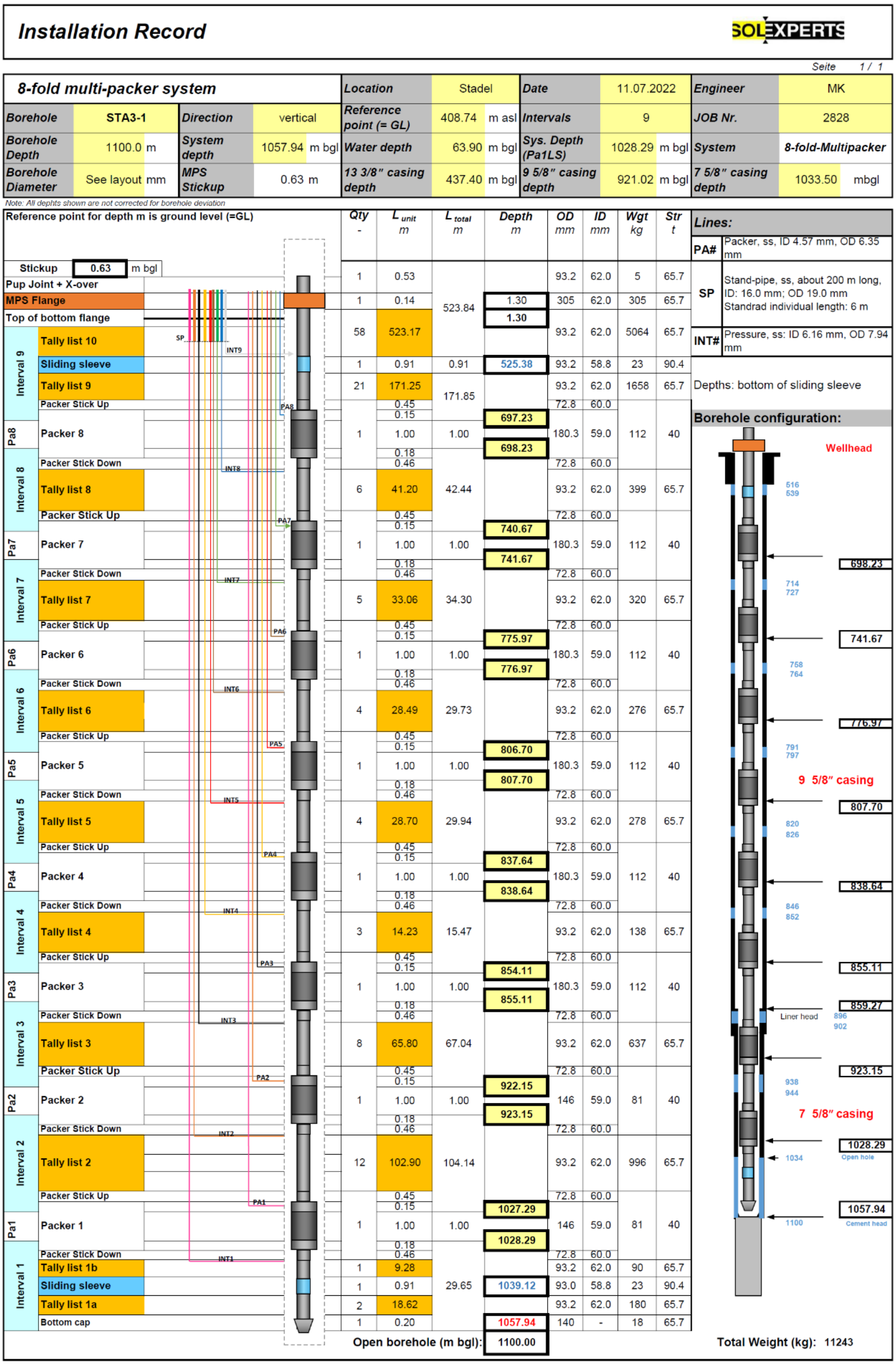

Fig. 2-11: Installation record and schematic layout of the MPS, as built

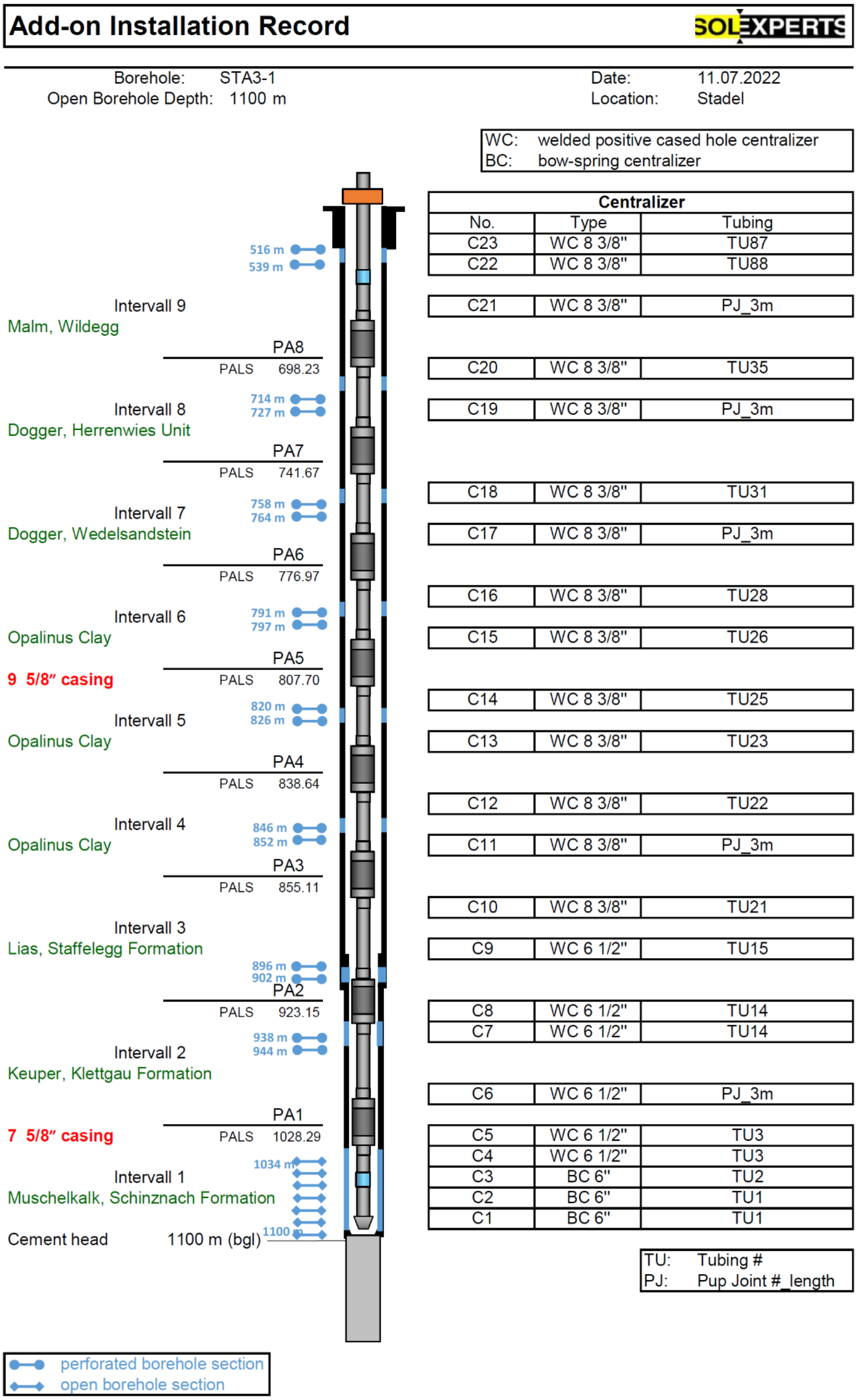

Fig. 2-12: Installation record of centralisers in the MPS, as built

3 Field work

3.1 Workover Rig

The preparation of the borehole and installation of the MPS was conducted using a workover rig Schäfer C14 8.10 operated by Daldrup (Fig. 3-1). The specifications are detailed below.

Work over rig details

General

- max. Load: 470 kN
- working Load: 410 kN
- auxiliary winch: 20 kN
- workover rig height: 13.8 m (overall); 11.8 m (free working)

Top drive hydraulic

- power: 140 kW
- max. torque: 15'000 Nm
- max. RPM: 300 1/min
- constant torque: 6'000 Nm
- constant RPM: 280 1/min

Mud pumps

- power: 84 kW
- max. pressure: 210 bar
- max. flow rate: 500 l/min

Mud mixing system

- volume: 40 m^3 mud tanks + 12 m^3 mixing tank

Fig. 3-1: Setup of the workover rig during installation of the MPS

3.2 Preparation of the borehole

Before installation of the MPS, the borehole had to be prepared. The first step was to replace the completion fluid with a synthetic porewater, that resembles the composition of the pore water found in the Opalinus Clay formation of the borehole. A batch of 10 m^3 of tap water mixed with salts according to the following list:

- 168 kg NaCl
- 1.4 kg KCl
- 39.1 kg Na_2SO_4
- 0.35 kg $NaHCO_3$
- 35.8 kg $MgCl_2$ * 6 H_2O
- 56.3 kg $CaCl_2$ * 2H_2O
- 0.9 kg SrCl2 * 6 H_2O

Uranine tracer fluid at 1 ppm concentration was added just before pumping of the brine to not lose the dying effect which fades with exposure to sunlight.

Subsequently, the borehole was perforated at the selected intervals. Each perforation section was about 6 m long and contained 100 shots of shaped charges (5 shot/ft). Perforation was followed by a scraper run to clean the borehole wall. Perforation was then verified by the means of a USIT log.

The preparation work is summarised in Tab. 3-1.

Tab. 3-1: Summary of preparatory work

Date	Activity
17.06.22 – 22.06.22	Delivery of workover rig and other equipment Rig-up workover rig
23.06.22 – 24.06.22	Run in hole of 3½" drill pipe to 1'053 m depth. The last two drill pipes in the open hole section were installed under circulation. Mixing of 50 m^3 of synthetic pore fluid Pumping until synthetic pore fluid was returned. Stopped pumping after 39 m^3 total volume. Pull out of hole
24.06.22 – 02.07.22	Preparation for perforations Running Casing Collar Locator log for depth reference during perforations Eleven perforation runs according to Tab. 2-1
04.07.22 – 05.07.22	Stand-by due to maintenance of the workover rig
06.07.22 – 07.07.22	Scraper runs in 9⅝" casing, then in 7⅝" liner, respectively, to clean the hole. At the bottom of the scraper the borehole fluid was exchanged again for a fresh batch of synthetic pore water with the composition as detailed above.
08.07.22	Confirmation of perforations using USIT log
09.07.22	Preparation of well site for MPS installation

3.3 System installation

The MPS, as detailed in Section 2, was installed immediately in Stadel-3 after the MPS installation in BOZ1 was finished. Tab. 3-2 gives an overview about the progression of the installation works.

Tab. 3-2: Summary of the installation activity

Date	Activity
11.07.22	Preparatory work for the MPS installation (e.g. measuring of tubing, setup of scaffolding for steel lines, preparation of tools)
12.07.22	Finish of preparatory work Installation to tubing (TU) 14, incl. packer 1
13.07.22	Installation to TU21, incl. packer 2
14.07.22	Installation to TU23, incl. packer 3
15.07.22	Installation to TU26, incl. packers 4 and 5
18.07.22	Installation to TU28, incl. packer 6
19.07.22	Installation to TU35, incl. packer 7
20.07.22	Installation to TU40, incl. packer 8
21.07.22	Installation to TU88
22.07.22	Installation to TU94, incl. standpipe series no. 8
25.07.22	Installation to TU103, incl. standpipe series no. 22
26.07.22	Installation to TU110, incl. standpipe series no. 32
27.07.22	Installation to landing spool, incl. last standpipes series, beginning of installations in the borehole cellar
28.07.22	Breaking of burst discs in monitoring lines Continue installation in borehole cellar Breaking of burst discs and inflation of packers 1 and 2 (bottom to top)
29.07.22	Demobilisation of workover rig Breaking of burst discs and inflation of packers 3 to 8 (bottom to top)
02.08.22 – 05.08.22	Finish of installation work in the borehole cellar
08.08.22 – 10.08.22	Clean-up wellsite

3.4 Quality assurance

The system installation was performed by Solexperts, Nagra provided AFRY for QC and the workover rig from Daldrup (with personnel). Each activity was checked based on the 4-eyes principle by the Solexperts test engineer/Solexperts technician/Solexperts-GTC Geophysicist. In addition, AFRY performed independent QC. All relevant activities were documented by the Solexperts test engineer and by AFRY in separate logbooks. All actions concerning the FO cable installation and verification were made by the FO specialist from the Solexperts subsidiary Solexperts GmbH Karlsruhe (brand name GTC Kappelmeyer).

Before delivery of all components, they were tested by the manufacturer or in the lab by Solexperts.

- The 2⅞" central tubing were checked for checked against API requirements and dimensional accuracy (tubing and threads).
- The tightness of threads was verified using the actual hydraulic tongs used during installation with nitrogen gas and water.
- The inflatable packers were checked by the manufacturer as well as Solexperts in pieces of casing provided by Nagra, Tests were run for at least 1 day on each packer.
- Stainless steel lines and standpipes were checked by the manufacturer for conformity with specifications and pressure tested, including necessary couplings, by Solexperts.
- Samples of the burst discs were tested in the lab to verify burst pressure and the burst pattern, to exclude future clogging of potential restrictions.
- The sliding sleeves were pressure tested with nitrogen gas and there opening operation checked.
- The FO cables were checked for attenuation at two different wavelengths.
- The FO splice boxes and feed throughs were pressure tested at 99.5 bar.
- The pressure sensors were calibrated by the manufacturer.

The quality assurance on site – before, during and after system installation – comprised the following procedures:

- Each 2⅞" central tubing rod to be installed was numbered with a permanent marker and was measured with a measuring tape. Each length was documented in the installation list.
- The inner diameter of each tubing rod was checked with a dummy at a fibreglass stick (OD dummy 58 mm).
- Each tubing was cleaned with a high-pressure cleaner, each tubing coupling was cleaned with rags.
- The final installation list with the tally list and the installation record was checked and accepted by AFRY.
- The grease for connecting the system parts was provided by Nagra.
- The tightening torque of each system part connection (central tubing, sliding sleeves, packer) was checked by AFRY (optimum torque: 2'250 lbf-ft = 3'050 Nm).
- The connected system parts did not show a thread turn when connected which corresponds to the measured system part length.

- Each installed system part was protocolled by the Solexperts test engineer and by AFRY.
- Each coupling of the FO cable, packer and interval lines and standpipes was checked by the Solexperts test engineer and by AFRY. Each tightened coupling was marked and photographed by AFRY.
- The couplings of the FO cable were tightened with a torque wrench (30 Nm), the ¼" and 8 mm lines were tightened with suitable spanners and were checked with the corresponding control gauges of the coupling suppliers. The standpipe couplings were mounted onto the standpipes with a hydraulic pre-assembly device and were tightened with suitable spanners and a torque wrench (49 Nm) and were checked with the corresponding control gauge for the specific coupling.
- Each packer was checked on the workbench before installation (visual and coupling check).
- Each packer was tested in test pipes or the topmost section of the borehole immediately before installation in the MPS (Fig. 3-2).
- Each line and the FO cable were visually controlled during the system installation.
- Each burst disc unit was controlled during system installation (if installed in the right direction).
- The colour codes of the lines and standpipes were checked before connecting the lines and standpipes.
- When the lines and the ⅛" FO cable were fixed to the central tubing string with Monel® banding straps, a guide bar made out of corn starch (produced with a 3-D printer) was used to clamp and protect the FO cable. It was also checked that no lines were crossed over while tightening the strap.
- The borehole annulus between the installed system string and the casing was covered during any actions at the system with thin slotted plywood discs movable between each other and with rags (Fig. 3-2).
- The exact position of each installed filter piece and of each splice box was measured with a meter stick.
- The functionality of the FO cable was checked after each splicing and also during system installation. Splicing and verification was made by the FO specialist.
- The tightness of the central tubing was checked by filling up the tubing to the top during and after system installation.
- Packer lines and interval lines/standpipes were pressurised with 20 bar water pressure after system installation and before bursting the burst discs to detect major leaks.
- During packer inflation, the interval pressures were already monitored online with downhole or artesian pressure sensors.
- The inflation pressure of the packer was monitored by a manometer and, when the packer inflation lines were connected to the corresponding pressure vessel, additionally by packer pressure sensors mounted on top of each vessel.
- The weight of each pressure vessel was measured with individual scales. The weights are shown on the displays. In the beginning the scale weights were manually read out. Since 22 August 2022, the scale weights are automatically recorded by the DAS.

Fig. 3-2: Packer inflation for verification of packer performance inside the borehole

The borehole is covered to prevent accidental loss of equipment in the borehole.

4 Operation

Fig. 4-1 shows a panoramic view of the system installation in the borehole cellar. The packers were inflated on July 28 and 29, 2022, which initiated zonal isolation and hydraulic heads between the observation intervals started to separate.

Data is recorded by the DAS. The sampling rate can be adjusted as needed and is set to 5 minutes for long-term monitoring. Daily files include pressure readings (monitoring zones and packers), weights of the pressure vessels (added on August 22, 2022) and ambient air temperature and air pressure in the borehole cellar. They are uploaded via FTP to a server for long-term storage and access. In addition, the sensor depths and any changes performed as part of the system maintenance are recorded in a logbook. This ensures that all necessary corrections can be performed on the recorded raw data for the evaluation of hydraulic heads of the observation intervals.

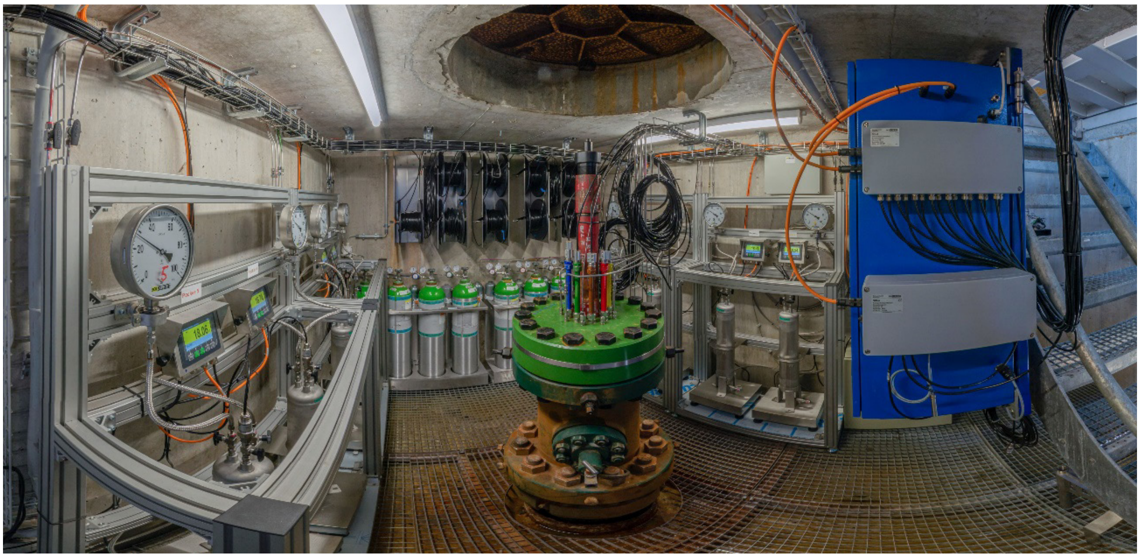

Fig. 4-1: Panoramic view of the borehole cellar with (from left to right): the pressure control system with pressure vessels, nitrogen gas bottle, wellhead and monitoring lines, second set of pressure control units and the DAS

For verification and initial data recording, a DTS measurement was conducted after installation. No calibration was applied to this measurement since this was conducted primarily to validate that the fibre optic cable fully functional.

The packers were inflated and re-inflated in several steps needed to reach stable conditions. Due to transient expansion of the packer sleeve and solution of trapped air in the fluid, pressure decreased and was compensated by re-inflation. After the initial phase most packers have stabilised. Only packers 1 and 8 were reinflated at later times as they fell below 14 bar. All packers appear stable now. An alarm system is implemented that sends out notifications when the packer pressure falls below a certain threshold to allow sufficient mobilisation time for a maintenance intervention. The time series of the packer pressures is shown in Fig. 4-2.

Fig. 4-3 shows the measured hydraulic heads of the observation intervals during the same time period. After an early artesian phase, the Klettgau interval has now returned to sub-artesian conditions. The Herrenwis unit interval shows a very low but stable hydraulic head, more than

100 m below that of the surrounding formations. Note that the pressure sensors had to be moved inside the standpipes several times to adapt to the changing measured heads. For the low permeability formations the displacement by the additional cable length when the sensor depth in a standpipe is adapted resulted in an apparent instantaneous head increase (e.g. in October in observation interval 2) or decrease (e.g. in August in observation interval 4).

A more detailed discussion of the initial observations will be given in the first annual data trend report.

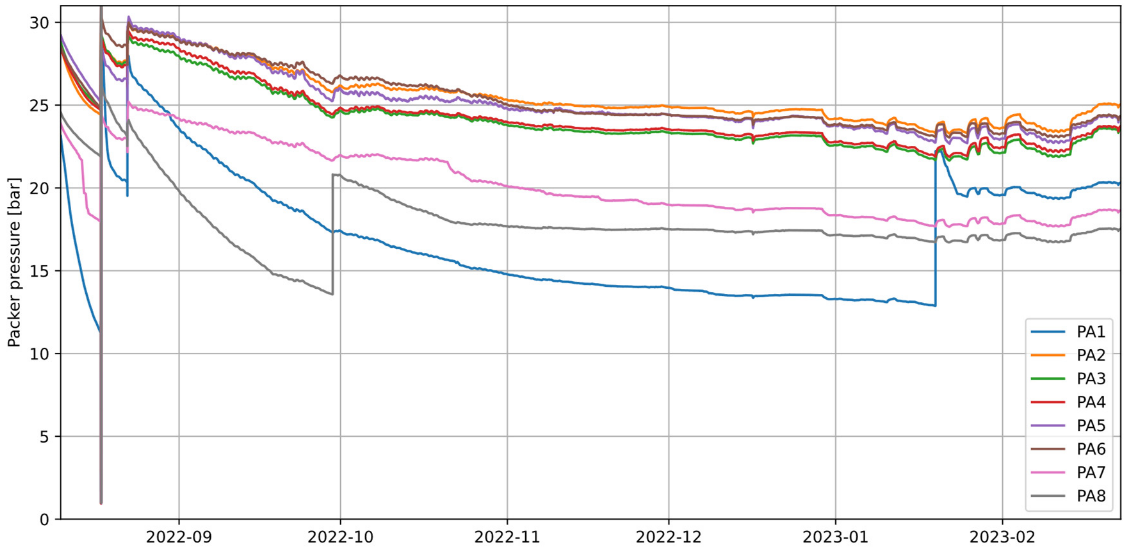

Fig. 4-2: Packer pressures in the first six months of operation

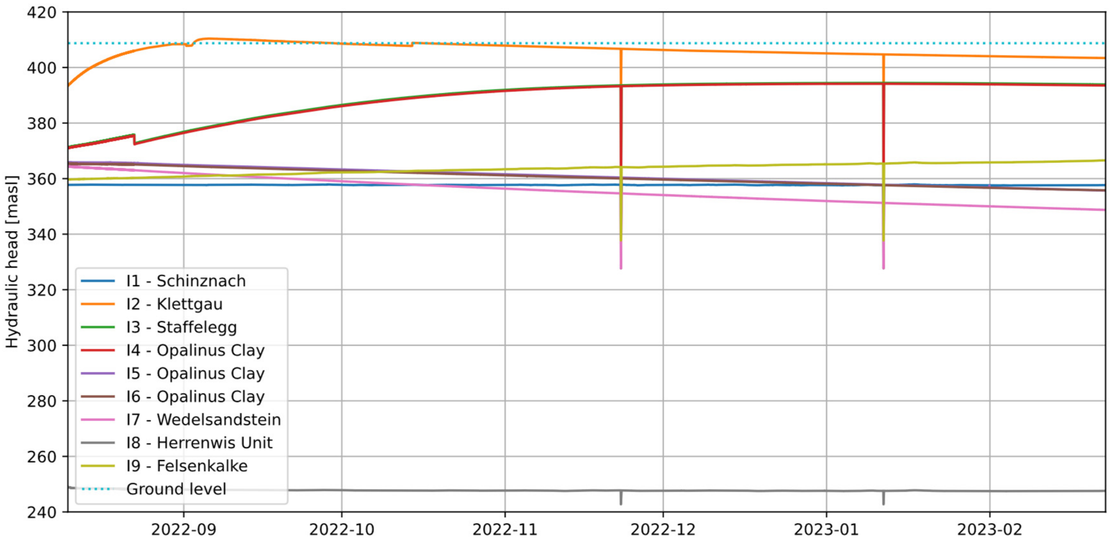

Fig. 4-3: Hydraulic heads in the observation intervals in the first six months of operation

5 References

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App. A Specifications

Tab. A-1: Packer specifications

	Packer for 9⅝" casing	Packers for 7⅝" liner
Manufacturer	Inflatable Packers International, Perth, Australia	
Packer type	IPI 6.06" (154 mm)	IPI 7.24" (184 mm)
Rubber type	Natural rubber, sliding end	Natural rubber, sliding end
Reinforcement	Steel wire reinforced	Steel wire reinforced
Material	Stainless steel	Stainless steel
Drift casing diameter	171.5 mm	220.5 mm
Outer diameter not inflated	154 mm, max.	184 mm, max.
Inner diameter	59 mm, min.	59 mm, min.
Overall length	2.296 m	2.296 m
Installation length	2.239 m	2.239 m
Rubber sleeve length	1.00 m	1.00 m
Thread connections	2⅞" EU pin × 2⅞" EU box	2⅞" EU pin × 2⅞" EU box
Max. number of lines through packer	3 × ⌀ 8 mm 2 × ⌀ 6.35 mm 1 × ⌀ 6.35 mm (inflation)	10 × ⌀ 8 mm 9 × ⌀ 6.35 mm 1 × ⌀ 6.35 mm (inflation)
Packer inflation lines	6.35 mm stainless steel	6.35 mm stainless steel
Inflation method	Surface controlled	Surface controlled
Inflation fluid	Water	Water

Tab. A-2: Sensor specifications

Location	**Interval lines submersible**	**Interval lines submersible**	**Interval lines surface**	**Packer lines**	**Atmosphere**	**Temperature**
Pressure transmitter manufacturer	STS Sensor Technik	STS Sensor Technik	STS Sensor Technik	STS Sensor Technik	STS Sensor Technik	-
Type/model	MTM/N10	MTM/N10	ATM.1ST	ATM.1ST	PTM	PT1000
Pressure range (absolute)	0 – 200 kPa	0 – 600 kPa	0 – 1'600 kPa	0 – 10'100 kPa	85 – 125 kPa	-
Accuracy (characteristic curve deviation)	≤ ±0.1% FS	≤ ±0.1% FS	≤ ±0.1% FS	≤ ±0.1% FS	≤ ±0.1% FS	±0.15 °C at 0 °C ±0.35 °C at 100 °C
Total error band			≤ ± 0.3% FS (max.)		≤ ± 0.3% FS	Class A
Measuring frequency	1 Hz	1 Hz	1 Hz	1 Hz	1 Hz	1 Hz
Temperature compensation	-5…50 °C	-5…50 °C	0…70 °C	0…70 °C	-10…50 °C	-20…70 °C
Outer diameter	10 mm	10 mm	-	-	-	12 mm
Output signal	4 – 20 mA	4 – 20 mA	4 – 20 mA	4 – 20 mA	4 – 20 mA	-
Material	Stainless steel 1.4435					
Cable length	173 m/PUR	210 m/PUR	10 m/PUR	10 m/PUR	1 m/PUR	1 m