# Arbeitsbericht NAB 22-48

## Long-term monitoring system of the Marthalen-1-1 borehole: Installation Report

February 2023

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

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[1] Nagra
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KEYWORDS
Tiefbohrungen, TBO, Langzeitbeobachtung, LZB, Zürich Nordost, ZNO, Marthalen-1, MAR1, Installation report

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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 |

# 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 Marthalen-1-1 borehole. The details of the drilling and characterization of the borehole are given in (Hinterholzer-Reisegger & Garitte 2021).

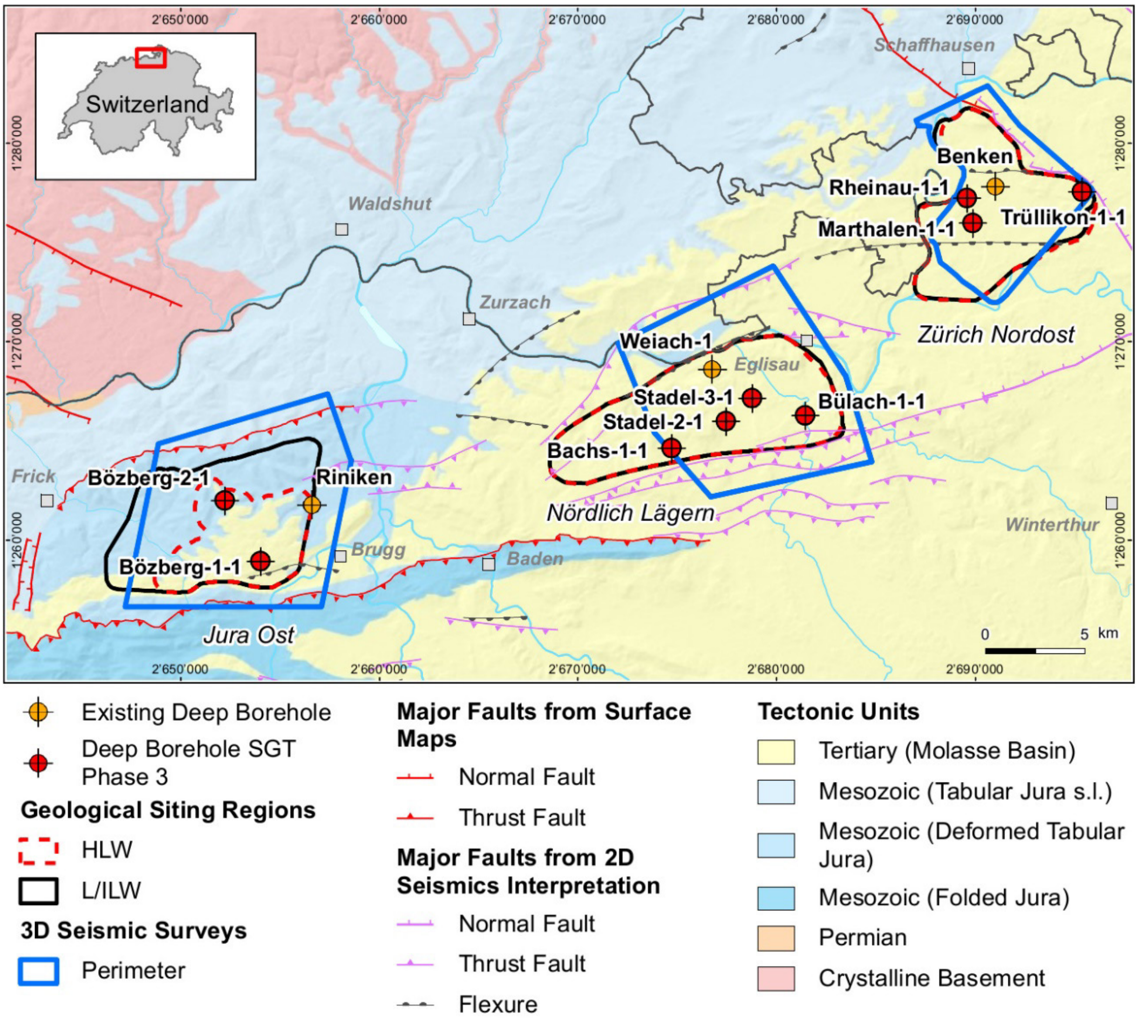


Fig. 1-1: Tectonic overview map with the three investigated siting regions

## 1.1 Borehole Marthalen-1-1

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 stabilised with a telescopic casing system and liner hanger to 858 m MD (Fig. 1-3). After drilling, the borehole was cemented back to 943.5 m and a bridge plug was set at 900.0 m depth.

Tab. 1-1: General borehole information

| **Borehole name** | **Marthalen-1-1 (MAR1-1)** |
|---|---|
| Siting region | Zurich Nordost, Switzerland |
| Wellhead longitude / latitude (WGS84) | E 8° 38' 4.39" N 47° 37' 41.22" |
| Wellhead coordinates (for log headers) | X (m) 2'689'894.533<br>Y (m) 1'275'956.307<br>(Geodetic Datum: CH1903+/LV95) |
| Ground level | 399.483 m AMSL (top of rig cellar) |
| Drilling period (start – end rig release) | 09.02.2020 – 14.07.2020 |
| Drilling company and rig | Daldrup, workover rig |
| Borehole maximum total depth | 1'099.25 m MD |
| Maximum deviation | 3° at 921.7 m MD (borehole is vertical) |

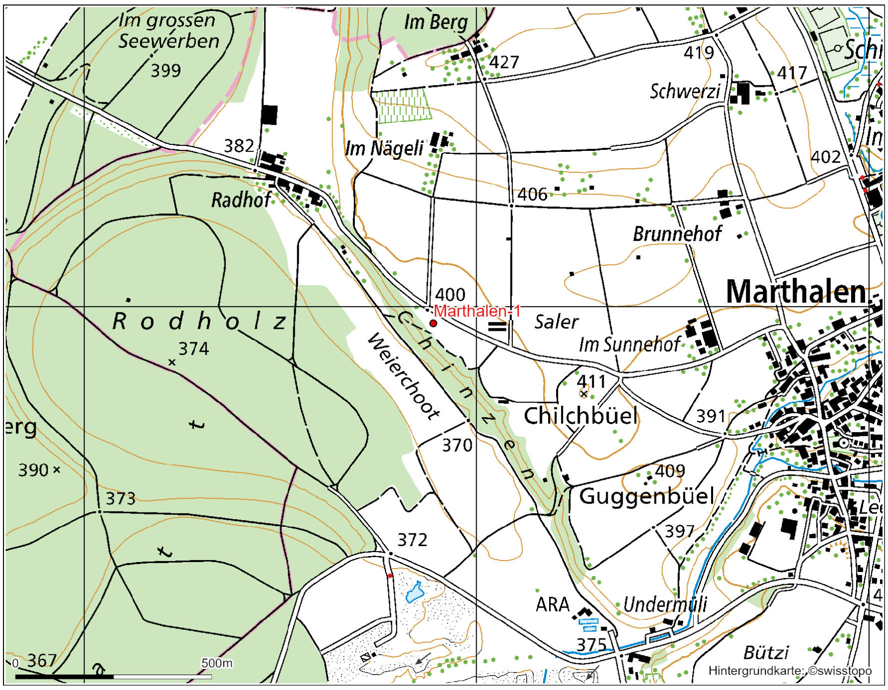


Fig. 1-2: Location of the drill site MAR1-1

## 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, Keuper and Muschelkalk), three zones in the Opalinus Clay sections and three zones in the rock units surrounding the Opalinus Clay: Parkinsoni-Württembergica and Wedelsandstein formation of the Dogger group and the Staffelegg formation in Lias (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.

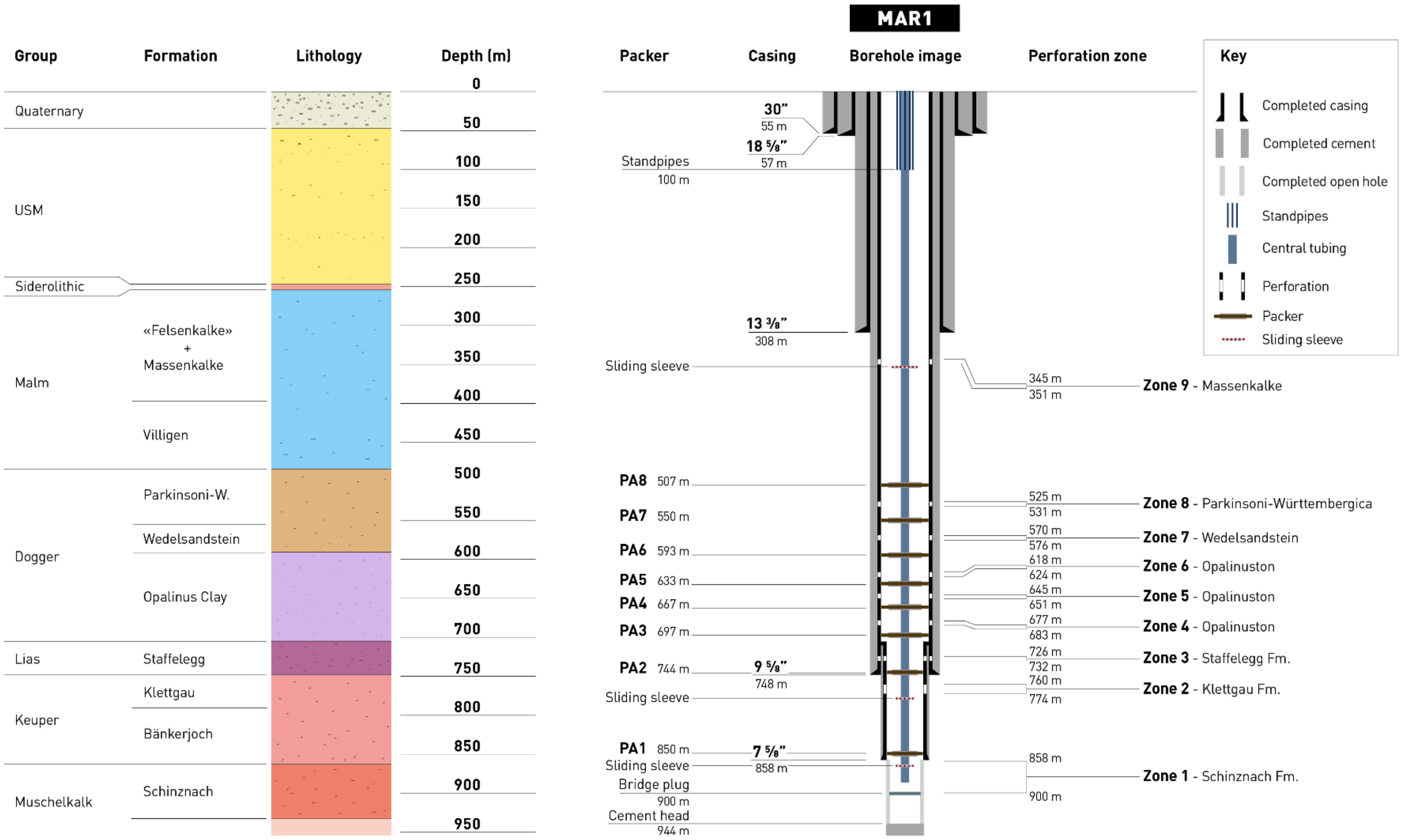


Fig. 1-3: Simplified lithostratigraphic profile, casing scheme and summary of the MPS for the MAR1-1 borehole
All depths are rounded to full meters.

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

| Section | Cased hole | Open hole |
|---|---|---|
| 0 – Conductor | OD: 30″; Interval: 0 to 55 mMD<br>Construction steel (ST 52) | OD: 47″; Interval: 0 to 55 mMD |
| 0 – Conductor | OD: 18 5/8″; Interval: 0 to 57 mMD<br>K55, #87.5, Buttress thread connection (BTC) | OD: 28″; Interval: 55 to 57 mMD |
| 1 – Surface casing | OD: 13 3/8″; Interval: 0 to 308 mMD<br>L80, #68.0, BTC | OD: 17 1/2″; Interval: 57 to 309 mMD |
| 2 – Intermediate casing | OD: 9 5/8″; Interval: 0 to 748 mMD<br>J55, #40.0, BTC<br>ID: 224.41 mm, Drift 220.45 mm | OD: 12 1/4″; Interval: 309 to 750 mMD |
| 3 – Liner hanger | OD: 7 5/8″; Interval: 705 to 858 mMD<br>J55, #29.7, BTC<br>ID 174.63 mm, Drift 171.45 mm, | OD: 8 1/2″; Interval: 750 to 861 mMD |
| 4 – Open hole | OD: 6 1/2″; Interval: 834 to 862 mMD<br>OD: 6 3/8″; Interval: 862 to 1’099 mMD<br>Cement backfilled from 1’099 to 943.5 mMD<br>Bridge plug at 900 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 supervisors
- 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 1099.25 m deep borehole MAR-1-1. The borehole MAR1-1 is fully cased until 858 m MD. The open borehole section extends down to 900 m MD to the bridge plug, isolating the lowermost borehole section until borehole end. The casing outer diameter in the section instrumented with the MPS is 7 $^5/_8$" and 9 $^5/_8$". The observation intervals are perforated to create a hydraulic connection to the formations. The casing was perforated immediately before the first MPS installation.

The system consists of the following main components:

- central tubing string;
- hydraulically inflatable packers; each with one 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 2$^7/_8$" 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 9.45 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 ~9.45 m long 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 100 m depth with packer and observation lines and the other type for the upper 100 m of tubing with packer lines and standpipes (Fig. 2-1). The protector couplings above 100 m depth are custom-made for 9 standpipes from the observation intervals, the 8 packer inflation lines and the fibre optic cable.

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

Fig. 2-1: Central tubing with monitoring and inflation lines below the hanger sub and stand-pipes above the hanger sub

**Sliding-end packers**

Two types of sliding end packers are used, 154 mm (6.06″) packer for the 7 $^{5}/_{8}$" diameter casing and 184 mm (7.24") packer for the 9 $^{5}/_{8}$" diameter casing. The packer connections were sealed with Loctite adhesive during installation (Fig. 2-2). 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 pressures lines are run through the mandrels of the upper packers and are connected to a packer pressure maintenance system in the bore cellar. Full 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 (OD ¼");
- The pressure of each packer is kept stable with a pressure maintenance system in the bore cellar.

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

**Packer inflation lines**

Each packer is connected via a packer line to the packer pressure maintenance system installed in the bore cellar. The packer 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. 2-3).

The packer inflation lines were delivered in 250 m rings. Each ring was tested on 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 pressurized 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. 2-3: Connections of monitoring and packer inflate lines on packer 8

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 100 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 pressurized 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. 2-4).

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 100 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. 2-4: 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, three sliding sleeves are installed into the central tubing string (Fig. 2-5 and Fig. 2-6) at the depth of the three aquifers (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. 2-5: Sliding sleeve with a 1 m section of a pup joint behind

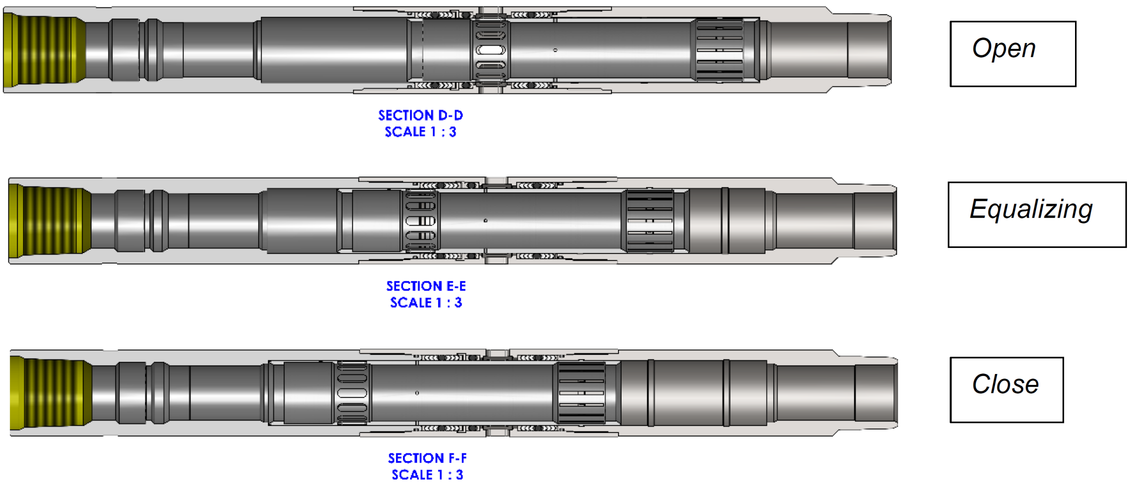


Fig. 2-6: Schematic drawing of a sliding sleeve in open and closed position

**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 cable has to be spliced below each packer using a splice box designed by Solexperts (Fig. 2-7), 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 50 m of cable is mounted to the wall. This can be used for calibration during each measurement.

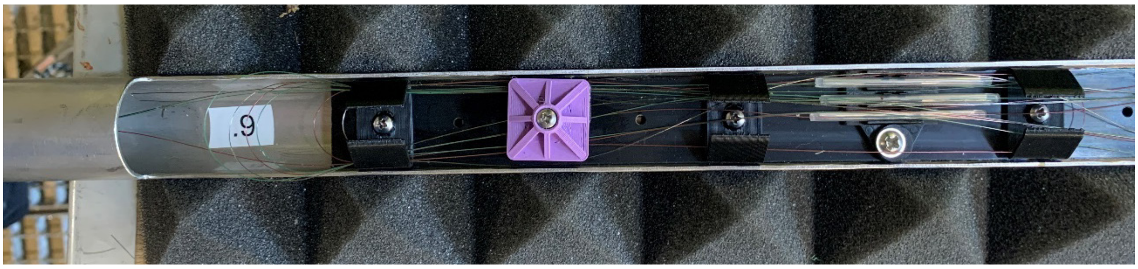


Fig. 2-7: View of the opened splice box with three splices of the FO cable

**Landing Spool – Wellhead flange**

The wellhead flange is a standard 13 $^{5}/_{8}$″ API flange (3'000 psi) with a soft iron ring as seal (Fig. 2-8). Two 2$^{7}/_{8}$" EU pup joints (0.5 m at the top, 1.0 m at the bottom; both screwed in with optimum torque) are screwed in the landing spool, together with NPT connections for the 8 packer inflation lines, one FO cable and 9 monitoring standpipes (through-hole tube fitting for the ¾" observation standpipes).

Fig. 2-8: Landing spool with fittings for standpipes and packer inflate lines

**Deployed sensors**

Different pressure sensors were deployed in the system. A barometric sensor to measure atmospheric pressure and a temperature sensor for ambient temperature are installed in the bore 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 water level probes (downhole pressure probes), which are installed in the standpipes below the expected hydraulic head (water level), see Fig. 2-9. The fluid level in the standpipes can lie between 0 – 100 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. Moreover, sensors can be easily repaired or replaced when they have a problem.

If an observation interval shows artesian conditions, the hydraulic head is measured at the wellhead level at the end of the standpipe with a pressure transmitter and with a manometer, see Fig. 2-9. In case of sensor failure, both, the submersible water level probes and the pressure transmitters 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, ten 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.

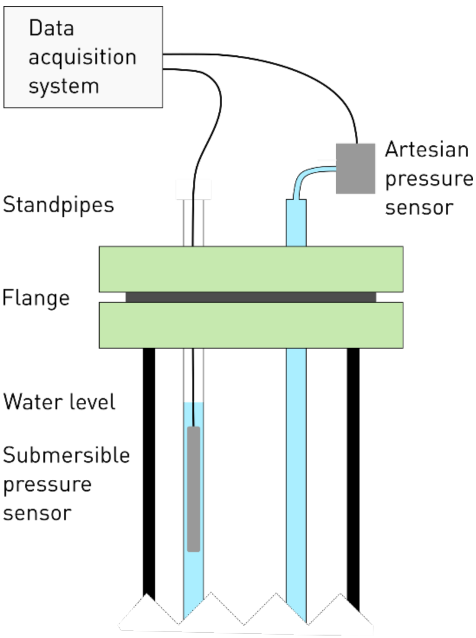


Fig. 2-9: Sketch of the configuration for two standpipes and pressure sensors with sub-artesian conditions (left) and artesian condition (right), respectively

**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 $2^7/_8$" 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 summarizes 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 realized according to the planned depth with an accuracy of around 0.1 m and confirmed by logs. Fig. 2-10 contains the detailed installation record and schematic layout of the MPS, and Fig. 2-11 provides further detail on the centralizers 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 | Massenkalke (Malm) | 0 – 507.17 | 507.17 | 351.37-352.28 | 344.99 – 350.99 |
| Packer 8 | | 507.17 – 508.17 | 1.0 | | |
| Interval 8 | Parkinsoni-Württembergica (Dogger) | 508.17 – 551.07 | 41.9 | | 524.96 – 530.96 |
| Packer 7 | | 550.07 – 551.07 | 1.0 | | |
| Interval 7 | Wedelsandstein (Dogger) | 551.07 – 591.05 | 39.98 | | 570.01 – 576.01 |
| Packer 6 | | 591.05 – 592.05 | 1.0 | | |
| Interval 6 | Opalinus Clay (Dogger) | 592.05 – 632.00 | 39.95 | | 617.98 – 623.98 |
| Packer 5 | | 632.00 – 633.00 | 1.0 | | |
| Interval 5 | Opalinus Clay (Dogger) | 633.00 – 665.56 | 32.56 | | 645.00 – 651.00 |
| Packer 4 | | 665.56 – 666.56 | 1.0 | | |
| Interval 4 | Opalinus Clay (Dogger) | 666.56 – 697.08 | 30.52 | | 676.99 – 682.99 |
| Packer 3 | | 697.08 – 698.08 | 1.0 | | |
| Interval 3 | Staffelegg Fm. (Lias) | 698.08 – 743.06 | 44.98 | | 726.06 – 732.06 |
| Packer 2 | | 743.06 – 744.06 | 1.0 | | |
| Interval 2 | Klettgau Fm. (Keuper) | 744.06 – 849.54 | 105.48 | 775.99 – 776.90 | 760.48 – 766.48<br>767.49 – 773.49 |
| Packer 1 | | 849.54 – 850.54 | 1.0 | | Open hole |
| Interval 1 | Schinznach Fm. (Muschelkalk) | 850.54 – 900.0 | 49.46 | 860.63 – 861.54 | |

## Installation Record

SOLEXPERTS

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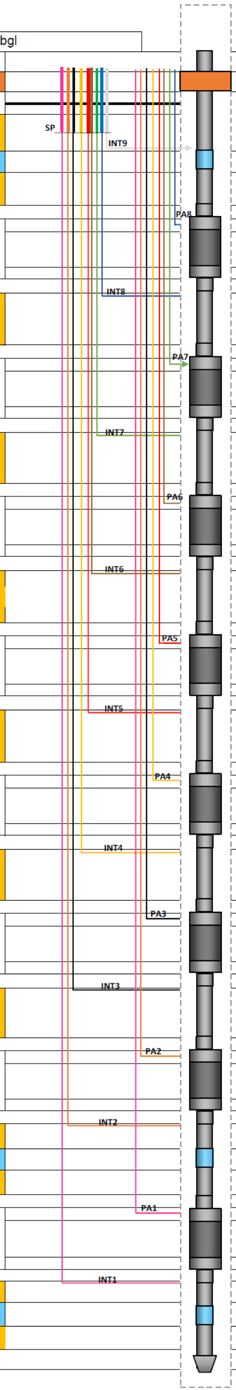
| 8-fold multi-packer system | | | | Location | Marthalen | Date | 30.08.2022 | Engineer | MK |
|---|---|---|---|---|---|---|---|---|---|
| Borehole | MAR1-1 | Direction | vertical | Reference point (= GL) | 399.48 m asl | Intervals | 9 | JOB Nr. | 2828 |
| Borehole Depth | 1099.25 m | System depth | 880.63 m bgl | Water depth | 14.72 m bgl | Sys. Depth (Pa1LS) | 850.54 m bgl | System | 8-fold-Multipacker |
| Borehole Diameter | See layout mm | Stickup MPS | 0.89 m | 13 3/8" casing depth | 308.00 m bgl | 9 5/8" casing depth | 748.00 m bgl | 7 5/8" casing depth | 858.00 mbgl |

Note: All depths shown are not corrected for borehole deviation

Reference point for depth m is ground level (=GL)

Stickup MPS 0.89 m bgl



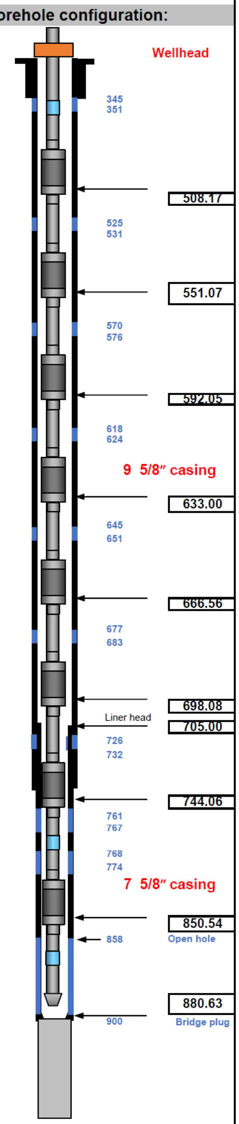

| Interval | Component | Qty - | $L_{unit}$ m | $L_{total}$ m | Depth m | OD mm | ID mm | Wgt kg | Str t |
|---|---|---|---|---|---|---|---|---|---|
| | Pup Joint + X-over | 1 | 0.53 | 350.48 | | 93.2 | 62.0 | 5 | 65.7 |
| | MPS flange | 1 | 0.14 | | 1.56 | 305 | 62.0 | 305 | 65.7 |
| | Top of bottom flange | | | | 1.56 | | | | |
| Interval 9 | Tally list 10 | 38 | 349.81 | | | 93.2 | 62.0 | 3386 | 65.7 |
| Interval 9 | Sliding sleeve | 1 | 0.91 | 0.91 | 352.28 | 93.2 | 58.8 | 23 | 65.7 |
| Interval 9 | Tally list 9 | 17 | 154.29 | 154.89 | | 93.2 | 62.0 | 1494 | 65.7 |
| Interval 9 | Packer Stick Up | | 0.45 | | | 72.8 | 60.0 | | |
| Pa8 | Packer 8 | 1 | 0.15<br>1.00<br>0.18 | 1.00 | 507.17<br>508.17 | 180.3 | 59.0 | 112 | 40 |
| Interval 8 | Packer Stick Down | | 0.46 | | | 72.8 | 60.0 | | |
| Interval 8 | Tally list 8 | 5 | 40.66 | 41.90 | | 93.2 | 62.0 | 394 | 65.7 |
| Interval 8 | Packer Stick Up | | 0.45 | | | 72.8 | 60.0 | | |
| Pa7 | Packer 7 | 1 | 0.15<br>1.00<br>0.18 | 1.00 | 550.07<br>551.07 | 180.3 | 59.0 | 112 | 40 |
| Interval 7 | Packer Stick Down | | 0.46 | | | 72.8 | 60.0 | | |
| Interval 7 | Tally list 7 | 5 | 38.74 | 39.98 | | 93.2 | 62.0 | 375 | 65.7 |
| Interval 7 | Packer Stick Up | | 0.45 | | | 72.8 | 60.0 | | |
| Pa6 | Packer 6 | 1 | 0.15<br>1.00<br>0.18 | 1.00 | 591.05<br>592.05 | 180.3 | 59.0 | 112 | 40 |
| Interval 6 | Packer Stick Down | | 0.46 | | | 72.8 | 60.0 | | |
| Interval 6 | Tally list 6 | 4 | 38.71 | 39.95 | | 93.2 | 62.0 | 375 | 65.7 |
| Interval 6 | Packer Stick Up | | 0.45 | | | 72.8 | 60.0 | | |
| Pa5 | Packer 5 | 1 | 0.15<br>1.00<br>0.18 | 1.00 | 632.00<br>633.00 | 180.3 | 59.0 | 112 | 40 |
| Interval 5 | Packer Stick Down | | 0.46 | | | 72.8 | 60.0 | | |
| Interval 5 | Tally list 5 | 4 | 31.32 | 32.56 | | 93.2 | 62.0 | 303 | 65.7 |
| Interval 5 | Packer Stick Up | | 0.45 | | | 72.8 | 60.0 | | |
| Pa4 | Packer 4 | 1 | 0.15<br>1.00<br>0.18 | 1.00 | 665.56<br>666.56 | 180.3 | 59.0 | 112 | 40 |
| Interval 4 | Packer Stick Down | | 0.46 | | | 72.8 | 60.0 | | |
| Interval 4 | Tally list 4 | 3 | 29.28 | 30.52 | | 93.2 | 62.0 | 283 | 65.7 |
| Interval 4 | Packer Stick Up | | 0.45 | | | 72.8 | 60.0 | | |
| Pa3 | Packer 3 | 1 | 0.15<br>1.00<br>0.18 | 1.00 | 697.08<br>698.08 | 180.3 | 59.0 | 112 | 40 |
| Interval 3 | Packer Stick Down | | 0.46 | | | 72.8 | 60.0 | | |
| Interval 3 | Tally list 3 | 6 | 43.74 | 44.98 | | 93.2 | 62.0 | 423 | 65.7 |
| Interval 3 | Packer Stick Up | | 0.45 | | | 72.8 | 60.0 | | |
| Pa2 | Packer 2 | 1 | 0.15<br>1.00<br>0.18 | 1.00 | 743.06<br>744.06 | 146 | 59.0 | 81 | 40 |
| Interval 2 | Packer Stick Down | | 0.46 | | | 72.8 | 60.0 | | |
| Interval 2 | Tally list 2b | 4 | 31.29 | 105.48 | | 93.2 | 62.0 | 303 | 65.7 |
| Interval 2 | Sliding sleeve | 1 | 0.91 | | 776.90 | 93.0 | 58.8 | 23 | 65.7 |
| Interval 2 | Tally list 2a | 9 | 72.04 | | | 93.2 | 62.0 | 697 | 65.7 |
| Interval 2 | Packer Stick Up | | 0.45 | | | 72.8 | 60.0 | | |
| Pa1 | Packer 1 | 1 | 0.15<br>1.00<br>0.18 | 1.00 | 849.54<br>850.54 | 146 | 59.0 | 81 | 40 |
| Interval 1 | Packer Stick Down | | 0.46 | | | 72.8 | 60.0 | | |
| Interval 1 | Tally list 1b | 1 | 9.45 | 30.09 | | 93.2 | 62.0 | 91 | 65.7 |
| Interval 1 | Sliding sleeve | 1 | 0.91 | | 861.54 | 93.0 | 58.8 | 23 | 65.7 |
| Interval 1 | Tally list 1a | 2 | 18.89 | | | 93.2 | 62.0 | 183 | 65.7 |
| Interval 1 | Bottom cap | 1 | 0.20 | | 880.63 | 140 | - | 18 | 65.7 |
| | Open borehole (m bgl): | | | | 900.00 | | | | |

**Lines:**

| | |
|---|---|
| PA# | Packer, ss, ID 4.57 mm, OD 6.35 mm |
| SP | Stand-pipe, ss, about 100 m long, ID: 16.0 mm; OD 19.0 mm<br>Standard individual length: 6 m |
| INT# | Pressure, ss: ID 6.16 mm, OD 7.94 mm |

Depths: bottom of sliding sleeve

**Borehole configuration:**




Total Weight (kg): 9539

Fig. 2-10: Installation record and schematic layout of the MPS, as-built

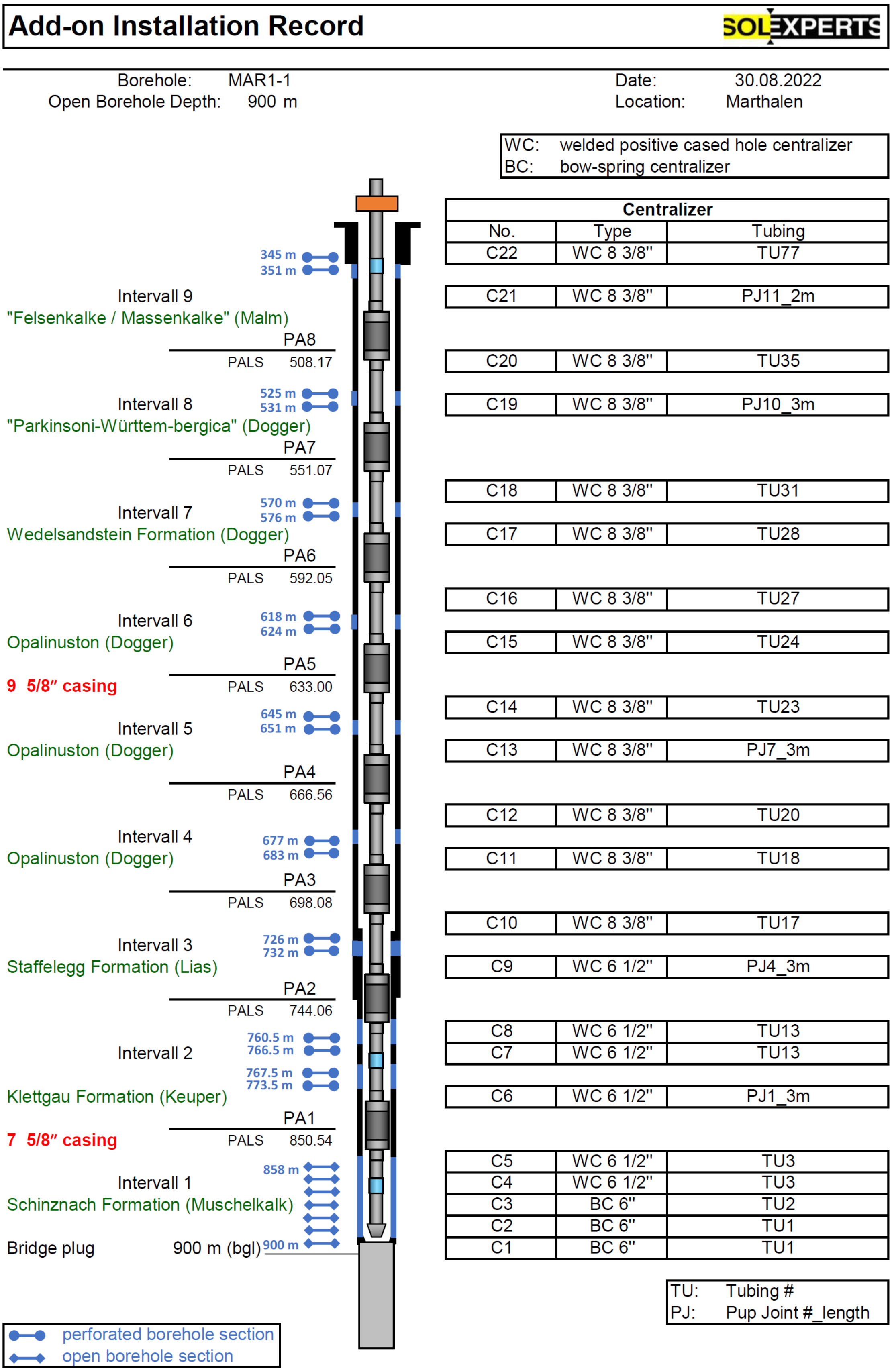



Fig. 2-11: Installation record of centralizers in the MPS, as-built

# 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: 15000 Nm
- Max. RPM: 300 1/min
- Constant Torque: 6000 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: Aerial view of the drill site 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 40 m³ of tap water mixed with salts according to the following list:

- 485.20 kg NaCl
- 7.61 kg KCl
- 74.54 kg $MgCl_2 \cdot 6 H_20$
- 70.04 kg $CaCl_2 \cdot 2 H_20$
- 136.36 kg $Na_2SO_4$
- 1.82 kg $NaHCO_3$

Uranine tracer fluid at 1 ppm concentration was added just before pumping of the brine in order 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).

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

Tab. 3-1: Summary of preparatory work

| Date | Activity |
|---|---|
| 10.07.21 – 18.07.21 | Delivery of workover rig and other equipment<br>Rig-up workover rig |
| 19.07.21 – 21.07.21 | Run in hole (RIH) to 895 m, pumping tap water while in the open hole section.<br>Pumping of mixed brine (rate 19pprox.. 500 l/min) to displace the previous completion fluid until the dyed synthetic pore water was produced at surface.<br>Pull out of hole (POOH) |
| 22.07.21 – 26.07.21 | Preparation for perforations<br>Running Casing Collar Locator log for depth reference during perforations.<br>Nine perforation runs according to Tab. 2-1<br>Confirmation of perforations using USIT log |
| 27.07.21 – 28.07.21 | Scraper runs in 9 $^{5}/_{8}$" casing, then in 7 $^{5}/_{8}$" liner, respectively, to clean the hole.<br>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. |

## 3.3 First system installation

The first installation of the MPS for MAR1-1 was done between 30 July and 11 August 2021. The installation occurred according to the approved installation procedure and each system part was checked and properly documented. After packer inflation and connection to the packer pressure maintenance system, some of the packer pressures suddenly decreased due to packer failure. Therefore, it was decided to retrieve the multi-packer system.

Upon retrieval of the system the failed packers showed the same damage pattern. After an extensive packer failure analysis, it was decided to change the packer design. This involved reworking the packers from fixed-end packers to sliding-end packers.

The borehole fluid was exchanged again after full retrieval. Because of the similar hydraulic heads between the aquifers, it was decided that it was sufficient to close the borehole with the wellhead flange until a new MPS would be installed.

## 3.4 Second system installation

The MPS as detailed in Section 2 was installed in Spring 2022. Before installation, the borehole fluid was exchanged according to the same recipe of added salts used in 2021.

Tab. 3-2: Summary of the installation activity

| Date | Activity |
|---|---|
| 29.04.22 – 06.05.22 | Delivery of workover rig and other equipment<br>Rig-up workover rig |
| 07.05.22 – 10.05.22 | RIH to 860 m; pumping of mixed brine (total volume 20pprox.. 33 $m^3$, rate 20pprox.. 500 l/min) until the freshly dyed synthetic pore water was produced at surface; POOH<br>Finish of other preparatory work for the MPS installation (e.g. measuring of tubing, setup of scaffolding for steel lines, preparation of tools) |
| 11.05.22 | Installation to tubing (TU) 13, incl. packers 1 and 2 |
| 12.05.22 | Installation to TU23, incl. packers 3 and 4 |
| 13.05.22 | Installation to TU31, incl. packers 5 and 6 |
| 16.05.22 | Installation to TU35, incl. packers 7 and 8 |
| 17.05.22 | Installation to TU72 |
| 18.05.22 | Installation to TU83, incl. standpipe series 1 to 8 |
| 19.05.22 | Installation to landing spool, incl. remaining standpipes |
| 20.05.22 | Connect lines to pressure vessels and data acquisition in borehole cellar |
| 23.05.22 | Inflation of packers 8 to 5 (top to bottom)<br>Performed DTS measurement |
| 24.05.22 | Re-inflation of packers 8 to 5<br>Inflation of packers 4 to 1 |
| 25.05.22 | Finish of installation work in the borehole cellar |

## 3.5 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 the 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 2-$^{7}/_{8}$" 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 – comprises the following procedures:

- Each 2-$^{7}/_{8}$" 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 proved 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: 2250 lbf-ft = 3050 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 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 $^1/_8$" 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 part and the casing was covered during any actions at the system with thin slotted plywood discs movable between each other and with rags.
- 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 pressurized 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 25 August 2022, the scale weights are automatically recorded by the DAS.

# 4 Operation

Fig. 4-1 contains an overview of the system installation in the borehole cellar. The packers were inflated on 24-25 May 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 25 August 2022) and ambient air temperature and air pressure in the bore 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 DAS, entrance, wellhead with inflate and monitoring lines and the pressure control system with pressure vessels and gas bottles

For verification and initial data recording, a DTS measurement was conducted after installation on 23 May 2022. No calibration was applied to this measurement, since this was conducted primarily to validate that the fibre optic cable fully functional.

The packers were initially inflated to a pressure of 40 bar. However, the packers were re-inflated several times and have reached stable conditions at pressures below 40 bar. It appears that some packers may require maintenance from time to time. However, the current packer pressures are sufficient for hydraulic isolation of the observation intervals. The time series of the packer pressures is shown in Fig. 4-2. The exact reason why a few packers are stabilizing only at low pressures is unknown.

Some observation intervals were influenced by the re-inflations, e.g. increasing hydraulic head of observation interval 6 or artesian pressure of observation interval 8 following reinflation. However, the influence of the transient packer behaviour on some observation intervals is recovering and reliable measurement conditions have been achieved.

Fig. 4-3 shows the measured hydraulic heads of the observation intervals during the same time period. It is evident that the Schinznach formation and Malm (Massenkalke formation) aquifers are close to equilibrium. The other zones are still declining and recovering from the perturbation by the drilling operations. Zones that showed artesian pressures due to the packer inflation at the beginning have declined to sub-artesian levels and continue to decline.

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

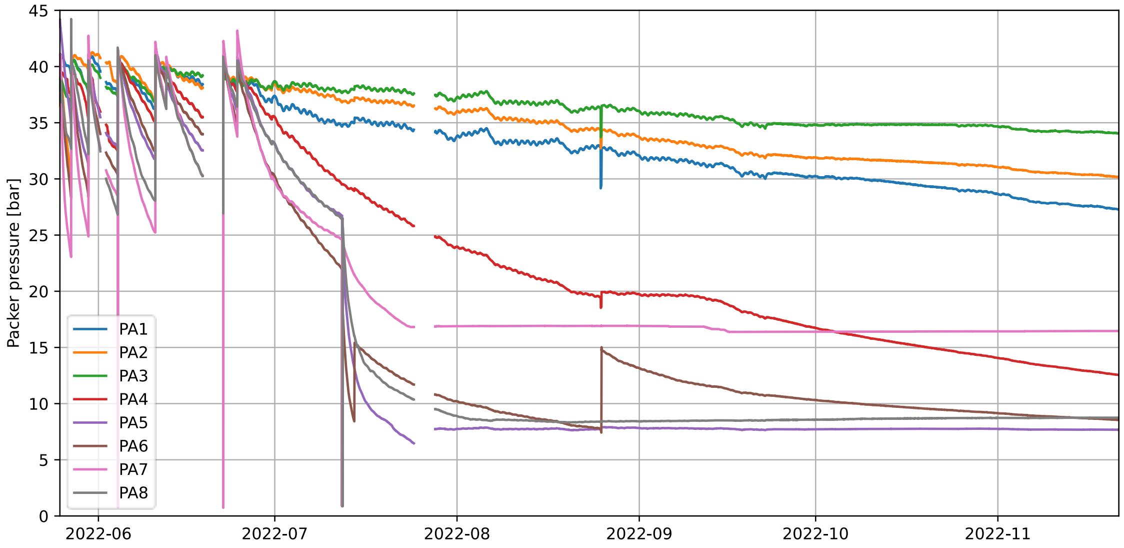



Fig. 4-2: Packer pressures in the first six months of operation

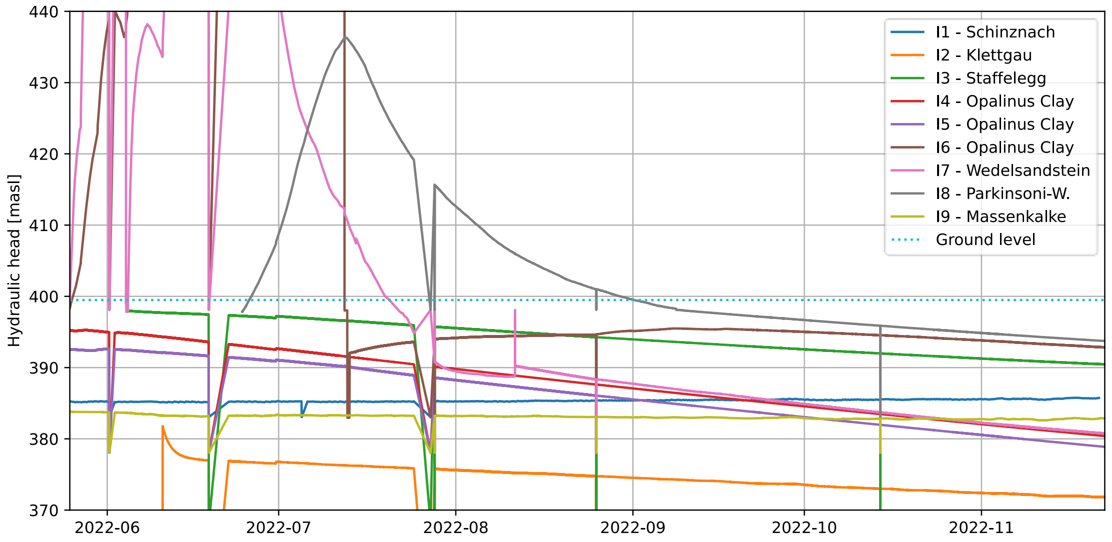



Fig. 4-3: Hydraulic heads of the observation intervals during the first six months of operation

# 5 References

Hinterholzer-Reisegger, P. & Garitte, B. (2021): TBO Marthalen-1-1: Data Report Dossier I Drilling. Nagra Arbeitsbericht NAB 21-20 I.

# App. A Specifications

Tab. A-1: Packer specifications

| | **Packer for 9 5/8" casing** | **Packers for 7 5/8" 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 | 2 7/8" EU pin × 2 7/8" EU box | 2 7/8" EU pin × 2 7/8" EU box |
| Max. number of lines through packer | 3× ⌀ 8 mm<br>2× ⌀ 6.35 mm<br>1× ⌀ 6.35 mm (inflation) | 10× ⌀ 8 mm<br>9× ⌀ 6.35 mm<br>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<br>± 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** | 60 m / PUR | 110 m / PUR | 10 m / PUR | 10 m / PUR | 1 m / PUR | 1 m |