

Arbeitsbericht NAB 22-01

**TBO Stadel-3-1:
Data Report**

**Dossier VII
Hydraulic Packer Testing**

June 2022

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

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Hydraulic Packer Testing**

June 2022

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hydraulic head, fluid logging, gas threshold pressure test
equipment

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This NAB aims at reporting drilling results at an early stage. Additional borehole-specific data will be published elsewhere.

In the event of inconsistencies between dossiers of this NAB, the dossier addressing the specific topic takes priority. In the event of discrepancies between Nagra reports, the chronologically later report is generally considered to be correct. Data sets and interpretations laid out in this NAB may be revised in subsequent reports. The reasoning leading to these revisions will be detailed there.

This report was finalised in March 2023.

This Dossier was prepared by a project team consisting of:

R. Schwarz (QC of test analyses, QC of test reports, writing)

M. Willmann (performance/analysis of the hydraulic packer tests)

H. Fisch (analysis of the hydraulic packer tests)

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The present report is based on the mobilisation report for the test equipment and on the reports for the performance and analysis of the hydraulic packer tests. These reports were written by the testing companies Solexperts AG (U. Rösli, M. Willmann) and AFRY Switzerland Ltd (R. Brauchler, H. Fisch, A. Maqueda, S. Reinhardt, P. Schulte).

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The Dossier has greatly benefitted from technical discussions with, and reviews by, external and internal experts. Their input and work are very much appreciated.

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1 Introduction

1.1 Context

To provide input for site selection and the safety case for deep geological repositories for radioactive waste, Nagra has drilled a series of deep boreholes ("Tiefbohrungen", TBO) in Northern Switzerland. The aim of the drilling campaign is to characterise the deep underground of the three remaining siting regions located at the edge of the Northern Alpine Molasse Basin (Fig. 1-1).

In this report, we present the results from the Stadel-3-1 borehole.

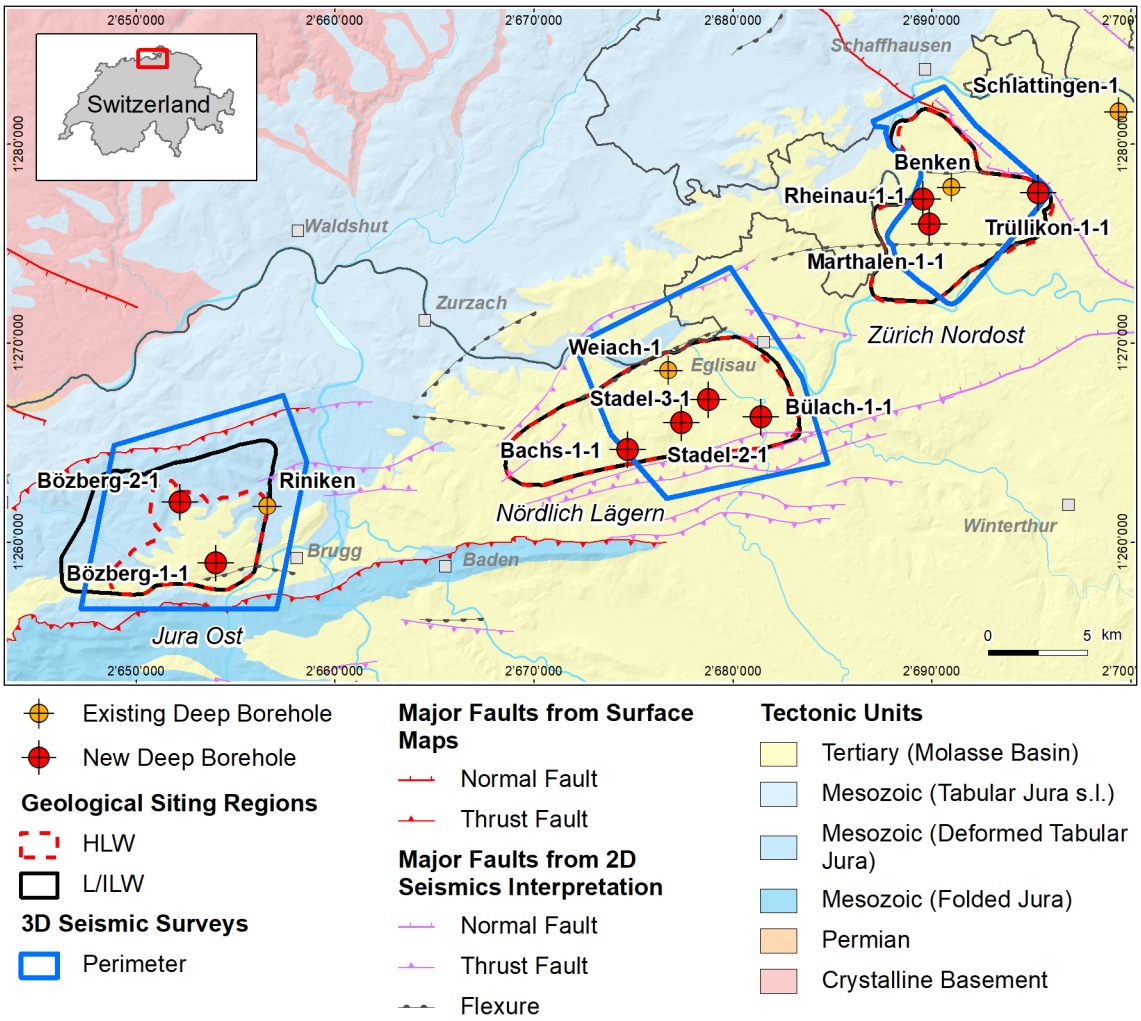


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Stadel-3-1 (STA3-1) exploratory borehole is the sixth borehole drilled within the framework of the TBO project. The drill site is located in the central part of the Nördlich Lägern siting region (Fig. 1-2). The vertical borehole reached a final depth of 1'280.88 m (MD)¹. The borehole specifications are provided in Tab. 1-1.

Tab. 1-1: General information about the STA3-1 borehole

Siting region	Nördlich Lägern
Municipality	Stadel (Canton Zürich / ZH), Switzerland
Drill site	Stadel-3 (STA3)
Borehole	Stadel-3-1 (STA3-1)
Coordinates	LV95: 2'678'792.885 / 1'267'161.988
Elevation	Ground level = top of rig cellar: 408.74 m above sea level (asl)
Borehole depth	1'280.88 m measured depth (MD) below ground level (bgl)
Drilling period	17th December 2020 – 25th June 2021 (spud date to end of rig release)
Drilling company	PR Marriott Drilling Ltd
Drilling rig	Rig-16 Drillmec HH102
Drilling fluid	Water-based mud with various amounts of different components such as ² : 0.0 – 439.0 m: Polymers 439.0 – 640.0 ³ m: Sodium chloride & polymers 640.0 – 1'035.0 m: Potassium silicate & polymers 1'035.0 – 1'101.0 m: Polymers 1'101.0 – 1'280.9 m: Sodium chloride & polymers

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. The comparison of the core versus log depth⁴ of the main lithostratigraphic boundaries in the STA3-1 borehole is shown in Tab. 1-2.

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

² For detailed information see Dossier I.

³ Borehole uncased below casing shoe at 437.4 m after drilling fluid exchange.

⁴ Core depth refers to the depth marked on the drill cores. Log depth results from the depth observed during geophysical wireline logging. Note that the petrophysical logs have not been shifted to core depth, hence log depth differs from core depth.

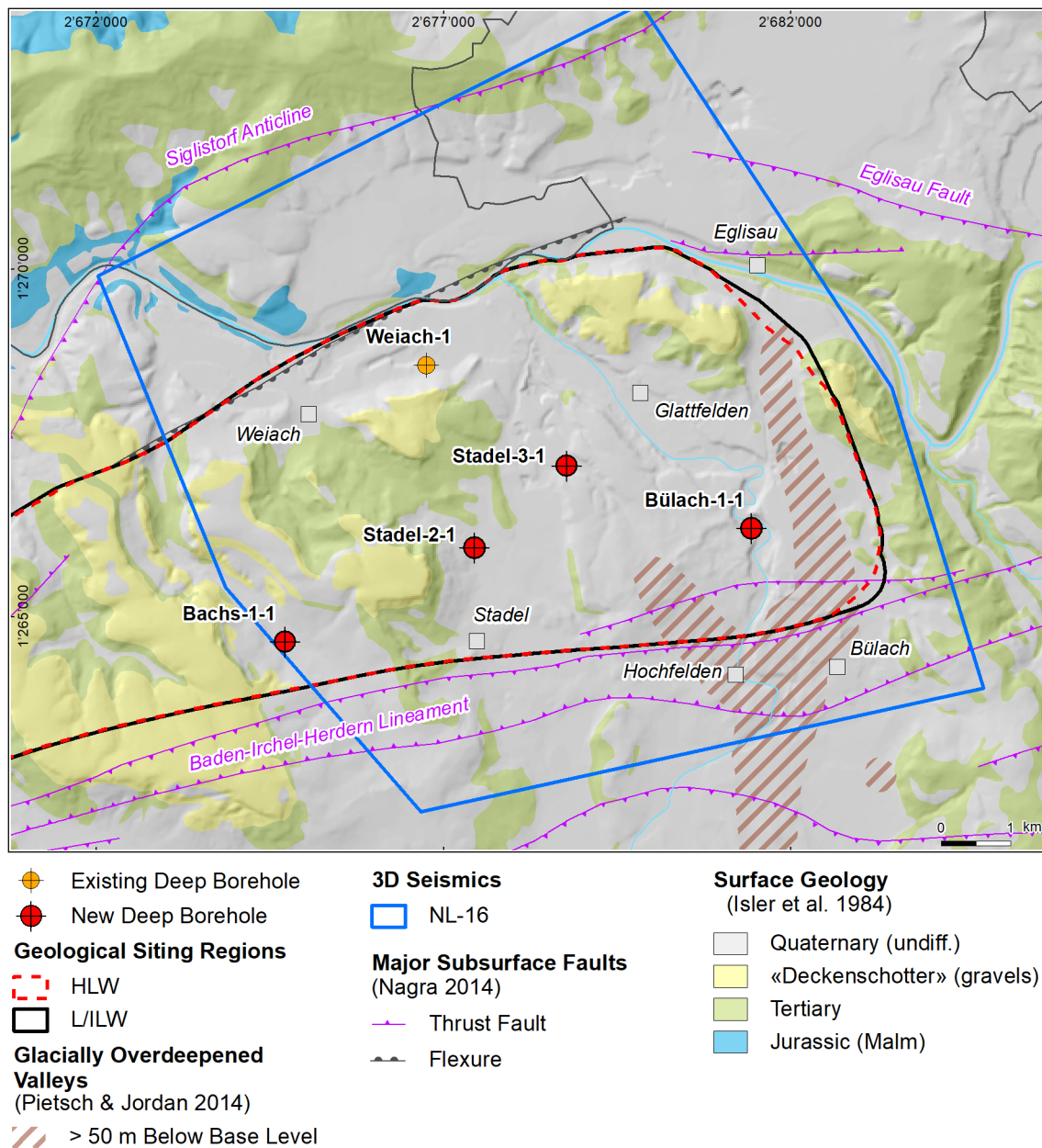


Fig. 1-2: Overview map of the investigation area in the Nördlich Lägern siting region with the location of the STA3-1 borehole in relation to the boreholes Weiach-1, BUL1-1, STA2-1 and BAC1-1

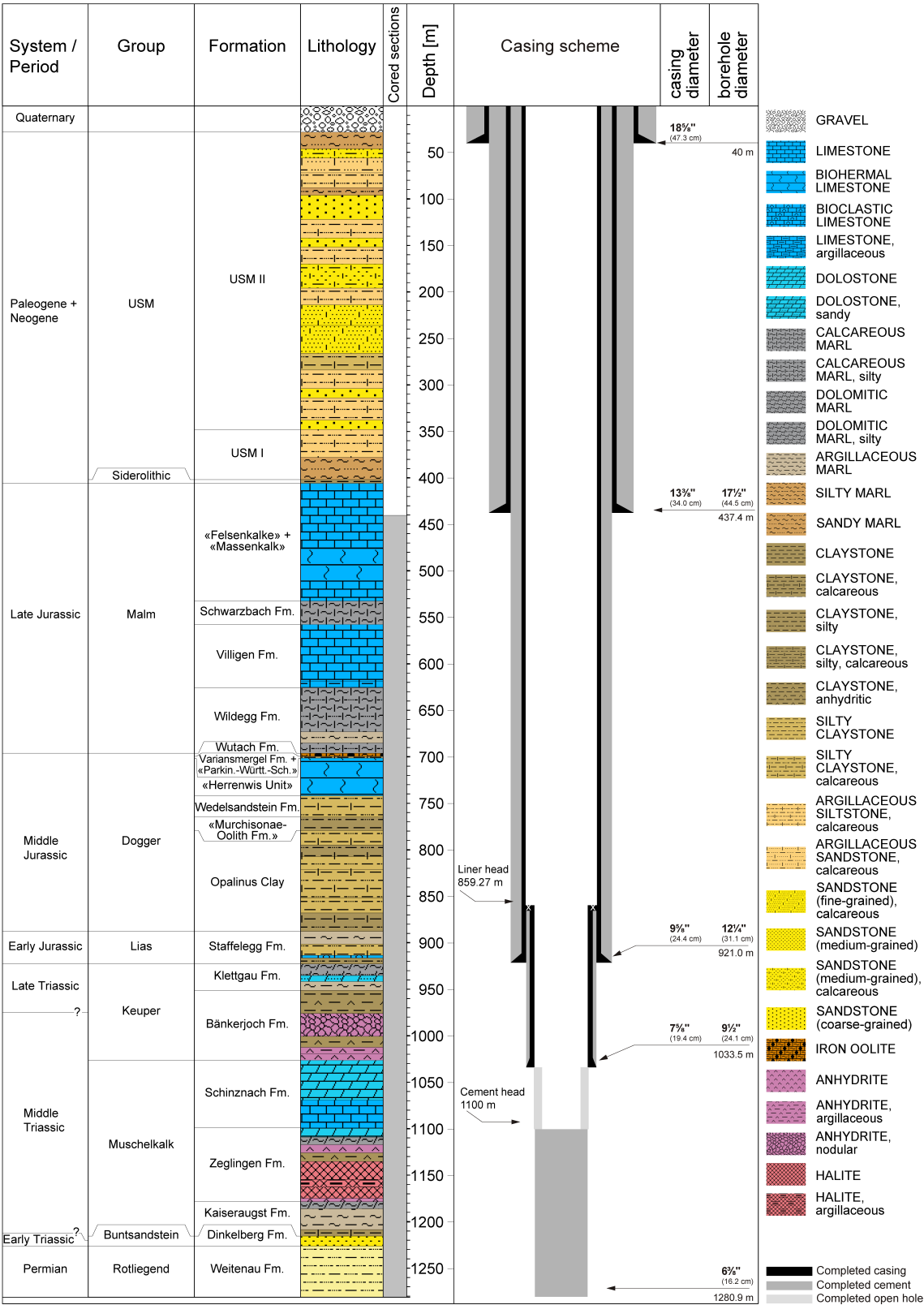


Fig. 1-3: Lithostratigraphic profile and casing scheme for the STA3-1 borehole⁵

⁵ For detailed information see Dossier I and III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the STA3-1 bore-hole⁶

System / Period	Group	Formation	Core depth in m (MD)	Log
Quaternary			28.0	—
Paleogene + Neogene	USM		402.0	—
	Siderolithic		406.0	—
Jurassic	Malm	«Felsenkalke» + «Massenkalk»		
		Schwarzbach Formation	532.55	532.65 —
		Villigen Formation	557.93	558.11 —
		Wildeggen Formation	625.58	625.64 —
		Wutach Formation	696.03	696.15 —
	Dogger	Wutach Formation	699.47	699.59 —
		Variansmergel Formation + «Parkinsoni-Württembergica-Schichten»		
		«Herrenwis Unit»	701.65	701.77 —
		Wedelsandstein Formation	742.00	742.03 —
		«Murchisonae-Oolith Formation»	764.97	764.94 —
		Opalinus Clay	779.26	779.16 —
		Opalinus Clay	887.94	887.72 —
	Lias	Staffelegg Formation	922.71	922.44 —
Triassic	Keuper	Klettgau Formation		
		Bänkerjoch Formation	951.13	951.57 —
	Muschelkalk	Schinznach Formation	1026.62	1026.96 —
		Zeglingen Formation	1099.03	1099.64 —
		Kaiseraugst Formation	1178.43	1178.73 —
	Buntsandstein	Dinkelberg Formation	1215.50	1215.74 —
			1226.38	1226.68 —
Permian	Rotliegend	Weitenau Formation	1280.88	1281.08

⁶ For details regarding lithostratigraphic boundaries see Dossier III and IV; for details about depth shifts (core gonio-metry) see Dossier V.

1.3 Documentation structure for the STA3-1 borehole

NAB 22-01 documents the majority of the investigations carried out in the STA3-1 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 STA3-1 borehole. It includes most of the data available approximately one year after completion of the borehole. Some analyses are still ongoing (e.g. diffusion experiments, analysis of veins, hydrochemical interpretation of water samples) and results will be published in separate reports.

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

Tab. 1-3: List of dossiers included in NAB 22-01

Black indicates the dossier at hand.

Dossier	Title	Authors
I	TBO Stadel-3-1: Drilling	M. Ammen & P.-J. Palten
II	TBO Stadel-3-1: Core Photography	D. Kaehr & M. Gysi
III	TBO Stadel-3-1: Lithostratigraphy	P. Schürch, P. Jordan, M. Schwarz, H. Naef, R. Felber, T. Ibele & M. Gysi
IV	TBO Stadel-3-1: Microfacies, Bio- and Chemostratigraphic Analyses	S. Wohlwend, H.R. Bläsi, S. Feist-Burkhardt, B. Hostettler, U. Menkveld-Gfeller, V. Dietze & G. Deplazes
V	TBO Stadel-3-1: Structural Geology	A. Ebert, S. Cioldi, E. Hägerstedt & M. Gysi
VI	TBO Stadel-3-1: Wireline Logging, Microhydraulic Fracturing and Pressure-meter Testing	J. Gonus, E. Bailey, J. Desroches & R. Garrard
VII	TBO Stadel-3-1: Hydraulic Packer Testing	R. Schwarz, M. Willmann, H. Fisch L. Schlickenrieder, M. Voß & A. Pechstein
VIII	TBO Stadel-3-1: Rock Properties, Porewater Characterisation and Natural Tracer Profiles	L. Aschwanden, L. Camesi, E. Gaucher, T. Gimmi, A. Jenni, M. Kiczka, U. Mäder, M. Mazurek, D. Rufer, H.N. Waber, P. Wersin, C. Zwahlen & D. Traber
IX	TBO Stadel-3-1: Rock-mechanical and Geomechanical Laboratory Testing	E. Crisci, L. Laloui & S. Giger
X	TBO Stadel-3-1: Petrophysical Log Analysis	S. Marnat & J.K. Becker
	TBO Stadel-3-1: Summary Plot	Nagra

1.4 Scope and objectives of this dossier

The dossier at hand aims at providing a summary of the conducted hydrogeological investigations (excluding the detailed analysis of the gas threshold pressure test) and acquired hydrogeological data, including assessments of tests and results, but without interpretation.

Borehole STA3-1 was the fourth borehole in the TBO project in which a gas threshold pressure test (GTPT) was conducted. Because the downhole equipment for the GTPT is part of the packer system used for hydraulic packer testing, a description of the equipment is included in this report. The implementation, data collection and analysis of the GTPT will be reported separately.

This report focuses on fluid logging and hydraulic packer testing, and is organised as follows:

- Chapter 2 presents the general strategy for the hydrogeological investigations in the STA3-1 borehole.
- Chapter 3 is dedicated to fluid logging which was performed in the cored borehole Section II. It discusses all aspects including the test equipment used, general concerns for the analysis, and fluid logging test activities in borehole STA3-1.
- Chapter 4 discusses all aspects of the hydraulic packer tests including planning of test strategies, test equipment used, general concerns for the analysis of tests, test activities and hydraulic packer test results in borehole STA3-1. Selected tests and analyses are presented in detail. The results are summarised in tables and plots, and some assessments are made.
- Chapter 5 summarises and discusses the data and results, mainly for the hydraulic packer tests.
- Finally, this report includes a set of appendices, which present relevant general project information and further investigation details.

2 Strategy for the hydrogeological investigations

2.1 Hydrogeological objectives of the TBO boreholes

The overall objectives of the hydrogeological investigations are the detailed determination of the hydraulic conductivity and hydraulic head in the aquifers, aquicludes and aquitards on the one hand, and the chemistry and isotopic composition of the deep groundwaters in the aquifers and the porewaters in the aquicludes and aquitards on the other. The results of the hydrogeological investigations in the TBO boreholes form an important dataset for site selection and the safety case. They are mainly needed for the characterisation of:

- Hydraulic and hydrochemical properties of the containment-providing rock zone, which consists of the host rock Opalinus Clay and the confining geological units above and below.
- Hydrogeological conditions in the aquifers providing the hydraulic and hydrochemical boundary conditions for the containment-providing rock zone and providing input for the identification of potential release paths as well as for the planning of the future access structures.

2.2 Hydrogeological investigation concept for STA3-1

The hydrogeological investigations for borehole STA3-1 comprised:

- Fluid logging
- Hydraulic packer testing

Given sufficiently high transmissivity, fluid logging was performed in the Malm Group and used to define the test interval for the subsequent hydraulic packer test in Section II of the borehole to investigate the zone of main inflow. Water inflows into the borehole were identified with a series of temperature – electrical conductivity logs and/or flowmeter logs.

Hydraulic packer tests were used for the detailed hydraulic characterisation of selected borehole sections to determine transmissivity (T), hydraulic conductivity (K), hydraulic head (h) and to identify the appropriate flow model. Hydraulic packer tests were performed in scheduled testing phases between drilling phases, and also during drilling phases when potentially highly transmissive features or faults were encountered. Depending on the transmissivity of the test interval, different test methods were applied in STA3-1:

- Pumping tests with constant flow rate
- Slug tests
- Pulse tests

These test methods usually are combined, i.e. executed one after the other as a test sequence in test-specific order.

A gas threshold pressure test (GTPT), extended by an additional hydraulic test sequence, was conducted in the STA3-1 borehole. The analyses of the extended GTPT do not form part of this report. In the siting region Nördlich Lägern, a long-term monitoring system will be installed in STA3-1.

The detailed groundwater sampling, subsequent hydrochemical and isotope analyses (including results) are documented in Lorenz & Stopelli (in prep.). Further porewater investigations are the subject of Dossier VIII. The laboratory permeability measurements on drill-core sections are discussed in Dossier IX.

3 Flowmeter logging and fluid logging

3.1 Description of equipment

Fluid logging was performed with the equipment introduced below. For the pumping test phase of the fluid logging campaign, the equipment of the field test contractor for hydraulic packer testing was used (*cf.* Section 4.2).

3.1.1 Borehole logging winch

The winch features a mechanical cable spooling device, an electronic and a mechanical depth measurement and a cable tension measurement. For specifications, see Tab. 3-1. The borehole logging winch is permanently mounted in the logging van and is powered by a motor. As soon as the motor is stopped, a brake is automatically engaged in the gearbox. Additionally, the winch has a manual brake and a clutch.

Tab. 3-1: Specifications of the borehole logging winch

Manufacturer	HEWA Feinwerktechnik Engineering GmbH, Marie-Curie-Str. 2, D-79211 Denzlingen, Germany
Type	TT2000, Electrical, 220 V
Cable type	Rochester 3/16" 4-conductor cable Type 4-H-181A
Cable breaking strength	14.7 kN
Max. cable length	2'000 m
Logging speed range	0 – 30 m/min
Depth measurement	IVO BAUMER incremental encoder, 2'500 pulse/rotation; 500 mm circumference wheel mounted on the spooling device, mechanical depth counter
Cable tension gauge	External display or input for matrix logger
Safety joint	The cable head is set up to form a weak joint. In the case of a stuck probe, the cable is pulled from the cable head

3.1.2 Matrix logger

The matrix logger is a logging surface unit that interfaces the probe with the acquisition PC, using the Advanced Logic Technology (ALT) Matrix Logger software (for specifications, see Tab. 3-2). It records the data, depth and logging speed and has a digital interface. The unit supports several communication protocols and can therefore be used to run probes built by different manufacturers (among others electromind, Robertson Geologging, ALT). A browser module connects the acquisition software to an ALT WellCAD document and feeds the data directly into WellCAD. The data of several runs are displayed in one document.

The software used to control the unit and the probes is as follows:

- Heat Pulse: Matrix Heat: V3.3 build 2208 © Advanced Logic Technology, 2005 – 2012
- All other probes: Matrix Logger: V 13.2 build 2790 © Advanced Logic Technology, 1995 – 2021
- Processing: WellCAD 5.4 build 1925 © Advanced Logic Technology, 1993 – 2018

The winch features a mechanical cable spooling.

Tab. 3-2: Specifications of the matrix logger

Manufacturer	Advanced Logic Technology, 30H Rue de Niederpallen, Zoning de Solupla, L-8506 Redange, Luxembourg
Type	Matrix borehole logging system
Data transmission	The data are digitised in the probes and sent to the logging system with a resolution of 15 bit (0 – 32'768 cps resolution per channel) and 16 bit (0 – 65'536 cps resolution per channel), respectively, depending on the probe.

3.1.3 Temperature-conductivity-gamma probe with sleeve

The probe measures fluid temperature, electrical fluid conductivity and natural gamma ray (for specifications, see Tab. 3-3). The electrical conductivity is referenced to 25 °C and the temperature-electrical conductivity sensor is mounted at the bottom. In the standard setup, the fluid enters the probe through openings in the bottom, flows through the sensor assembly and leaves the probe through openings on the side of the probe a bit further up. This geometry is optimised for logging going down. To improve the performance while going up, a sleeve can be fitted to the sensor which allows free flow of the fluid while going down and funnels the fluid through the sensor while going up. The sleeve is made from POM (polyoxymethylene).

Tab. 3-3: Specifications of the temperature-conductivity-gamma probe

Manufacturer	Robertson Geologging Ltd., York Road, Deganwy, Conwy, LL31 9PX, UK
Type	TCG
Length	1'690 mm
Weight	4.5 kg
Tool diameter	38 mm
Operational temperature range	0 – 70 °C (up to 80 °C for a limited time)
Max. pressure	20 MPa
Borehole diameter range	> 50 mm (> 96 mm with sleeve)
Temperature sensor range	0 – 70 °C (up to 80 °C for a limited time)
Temperature sensor accuracy	± 0.5 °C (not on data sheet, information from manufacturer)
Temperature sensor resolution	0.04 °C (not on data sheet, information from manufacturer)
Electrical conductivity sensor range	50 – 50'000 µS/cm
Electrical conductivity sensor accuracy	± 2.5% at 500 µS/cm (not on data sheet, information from manufacturer)
Electrical conductivity sensor resolution	4 µS/cm (not on data sheet, information from manufacturer)
Electrical conductivity temperature compensation	25 °C
Gamma Detector	NaI 50 mm × 25 mm crystal
Remark	Sleeve added for up-logs

3.1.4 Borehole geometry gamma probe

The four-arm caliper probe provides two continuous logs of borehole diameter (X+Y; for specifications see Tab. 3-4). The logs are recorded by two independent pairs of linked arms in contact with the borehole wall and the pairs of arms are mounted on the probe with an angle of 90°. The probe is lowered into the borehole with the arms retracted. Once opened at the lowest reachable point of the borehole, the spring-loaded arms respond to borehole diameter variations as the probe is raised. The caliper range is 75 to 700 mm, the vertical sample resolution for the probe is 1 reading/cm.

The X arms are aligned with the axis of the magnetometer package and the measured "magnetic roll" is the angle between magnetic North and the X caliper pair. The probe measures in a clockwise direction from North to the caliper arm when viewed from above. This measurement is required to orientate any eccentricity of the borehole, thus allowing the stress direction to be determined.

The probe is used to identify the state of the borehole by indicating fractures and cavities, diameter reductions and increases, and any ellipticity.

Tab. 3-4: Specifications of the borehole geometry gamma probe

Manufacturer	Robertson Geologging Ltd., York Road, Deganwy, Conwy, LL31 9PX, UK
Type	BGGS
Length	3.54 m
Weight	19.5 kg
Tool diameter	60 mm
Operational temperature range	0 – 70 °C (up to 80 °C for a limited time)
Max. pressure	20 MPa
Borehole diameter range	75 – 700 mm
Caliper accuracy	± 5 mm (not on data sheet, information from manufacturer)
Caliper resolution	0.02 mm (not on data sheet, information from manufacturer)
Gamma detector	NaI 50 mm × 25 mm crystal

3.1.5 Gamma sensors

The probes described above (temperature-conductivity-gamma probe and borehole geometry gamma probe) are equipped with similar gamma-ray detectors. The detectors are of the scintillation type, set up for total count measurements. They consist of a NaI-crystal (50 mm × 25 mm), a photomultiplier tube and a counting circuit. The output is counts per second (cps). No background radiation exists and has to be considered in a borehole.

The range of the sensors is 0 – 65'536 cps (16 bit). In a typical geological context of southern Germany and Switzerland, the count rates normally do not exceed 300 – 400 cps with the given sensors.

Information on the accuracy of a gamma measurement can be found in Richards (1981): There is statistical noise to the data, because it is possible to predict the rate of emission of gamma rays, but not which individual nuclei will disintegrate or not. It is possible to determine the true mean count rate (cps) for a given source of gamma rays quite accurately by counting and averaging for a long time. The statistical noise produces a fluctuation of the readings around the true mean count rate. The expected standard deviation is the square root of the true mean count rate n .

The fractional standard deviation expresses the standard deviation as percentage of the true count rate:

$$\text{fractional std. dev.} = (\text{std. dev.})/n \cdot 100$$

e.g. $n = 10'000 \text{ cps} \rightarrow \text{std. dev.: } 100 \text{ cps, fractional std. dev.: } 1\%$

$n = 100 \text{ cps} \rightarrow \text{std. dev.: } 10 \text{ cps, fractional std. dev.: } 10\%$

This means the precision of the measurement increases as the count rate increases.

3.1.6 Temperature-electrical conductivity meter

The WTW (Wissenschaftlich-technische Werkstätten GmbH) instrument pH/Cond 340i is a hand-held digital instrument to measure fluid pH, electrical conductivity and temperature (for specifications, see Tab. 3-5). This meter is used at the workshop to perform the electrical conductivity calibration of the logging tools, and on-site to check the calibration of electrical conductivity and temperature.

Tab. 3-5: Specifications of the temperature-electrical conductivity meter

Manufacturer	WTW (Wissenschaftlich-technische Werkstätten GmbH), Dr.-Karl-Slevogt-Straße 1, D-82362 Weilheim
Type	pH/Cond 340 i
Temperature sensor range	0 – 105 °C
Temperature sensor accuracy	± 0.1 °C
Electrical conductivity range	0 – 19.99 mS/cm (resolution 0.01), 0 – 199.9 mS/cm (resolution 0.1)
Electrical conductivity accuracy	± 0.5%
Reference temperature	25 °C

3.1.7 Centraliser

When the probes are run in the hole, they are equipped with a set of centraliser blades. The main purpose of the centralisers is to keep the probes off the borehole wall to prevent measurements being influenced by any debris that might be scraped off the borehole wall. For specifications, see Tab. 3-6.

The centralisers are made from brass rings with elastic copper – beryllium blades. The centraliser cage can be set up with different blades to cover different borehole diameter ranges. It is fixed to the probe with grub screws.

Tab. 3-6: Specifications of the centraliser

Manufacturer	LIM Logging / Electromind S.A.
Type	Bow spring centraliser
Length	420 mm at 165 mm diameter, 530 mm at 215 mm diameter
Weight	Approx. 3 kg
Borehole diameter range	70 – 270 mm

3.1.8 Field analysis IT structure

Logging measurements are read directly into a WellCAD document to display previous and current measurements. For specifications of the IT structure, see Tab. 3-7.

Tab. 3-7: Specifications of the IT structure for field analysis

Processing software	WellCAD 5.4 build 1001 © Advanced Logic Technology, 1993 – 2020
Logging software	Matrix Logger: V 13.2 build 2790 © Advanced Logic Technology, 1995 – 2021
Logging software (heat pulse flowmeter only)	Matrix Heat: V3.3 build 2208 © Advanced Logic Technology, 2005 – 2012
Uninterrupted power supply	APC Back-UPS Pro 900 BR900-G, 900 VA / 540 Watt
Data back-up	External hard drive
Acquisition computer	Notebook, Windows 10 Pro

3.2 Performance and analysis

Fluid logging was conducted in borehole STA3-1 on 14 and 15 January 2021 in the cored borehole Section II after a fluid exchange of drilling mud with tap water had been performed. The test is referred to as STA3-1-FL1-MAL. The section was comprised of the «Felsenkalke» + «Massenkalk», the Schwarzbach Formation, the Villigen Formation and the Wildegg Formation of the Jurassic Malm Group. The measurements were performed using the temperature-conductivity-gamma probe described in Section 3.1.3. The objectives of the fluid logging analysis were the detection of inflow zones and their associated transmissivities. The transmissivity values of the inflow zones are summed and compared to the total transmissivity derived from the analysis of the associated pumping test and also the corresponding result of the hydraulic packer test of the interval STA3-1-MAL1.

3.2.1 Description of measurements performed

At the time of the fluid logging STA3-1-FL1-MAL, the drilling depth was 640.00 m MD and the fluid logging was performed in the open borehole between 437.40 m MD and approximately 637 m MD. Tab. 3-8 provides the information on the open borehole section. Tab. 3-9 shows the start and end times of the electrical conductivity and temperature logs (runs) using the probe described in Section 3.1.3. The corresponding pressure drawdown and pumping rates are shown in Fig. 3-1 and Fig. 3-2, respectively.

The first two measurements were performed before pumping: Run 1 before and Run 2 after the installation of the pump. The first pumping phase (RW1) started with a pumping rate of 55 l/min and ended with 24 l/min with a quasi-linear pressure decrease from 1'491.20 kPa to 413.34 kPa. The pumping rate of this first pumping phase was maximised to overcome the wellbore storage effect in reasonable time. It was followed by the technically challenging RW2 with an oscillating pumping rate, mostly below 10 l/min.

Run 3 was conducted during the pumping phase RW3 with a pumping rate decreasing from 16.98 l/min at the beginning to 10.30 l/min at the end, with a quasi-linear pressure decrease from 115.24 kPa to 72.48 kPa. During the 2-minute RW4, the pumping rate was reduced to 3.91 l/min.

Runs 4, 5, 6 and 7 were performed during RW5 with a relatively stable pumping rate. Pumping phase RW5 lasted 5 hours and 19 minutes with an initial pumping rate of 3.91 l/min and a final rate of approximately 1.68 l/min while the water pressure recovered from 56.49 kPa to 62.72 kPa. Testing ended with the recovery phase RWR1.

The following data were recorded and considered for the analysis:

- Seven runs of temperature and electrical conductivity (corrected to 25 °C equivalent conductivity)
- Pumping test data (pressure and flow rate)

Fig. 3-3 shows the recorded electrical conductivity logs. The long-drawn plateaus (e.g., in Run 7 from ~ 480 m MD to ~540 m MD) are due to the probe exceeding its measurement range (Tab. 3-3 of Section 3.1.3).

Tab. 3-8: Fluid logging STA3-1-FL1-MAL: Information on the test interval

¹ Interval assumed in the analysis of the pumping test covering the interval of fluid logging.

Test	Depth		Length [m] ¹	Configuration	Hydraulic testing		
	from [m MD] ¹	to [m MD] ¹			Start date	End date	Duration [h]
STA3-1-FL1-MAL	442.00	640.00	198.00	Open borehole	14.01.2021	15.01.2021	35.20

Tab. 3-9: STA3-1-FL1-MAL: Start and end times of the fluid logging runs performed for STA3-1 and their associated depth range

¹ Bottom of casing (start of open borehole section) is at 437.40 m MD.

Logging run	Hydraulic test sequence	Date	Start time	Start depth [m MD]	End time	End depth [m MD]
1	History	14.01.2021	20:33	420.40 ¹	21:08	636.31
2		15.01.2021	04:48	444.90	05:17	636.01
3	RW3	15.01.2021	10:04	445.08	10:36	636.54
4	RW5	15.01.2021	10:56	445.32	11:28	636.14
5		15.01.2021	11:41	445.45	12:13	636.19
6		15.01.2021	12:40	445.50	13:12	636.99
7		15.01.2021	14:50	445.56	15:21	636.18

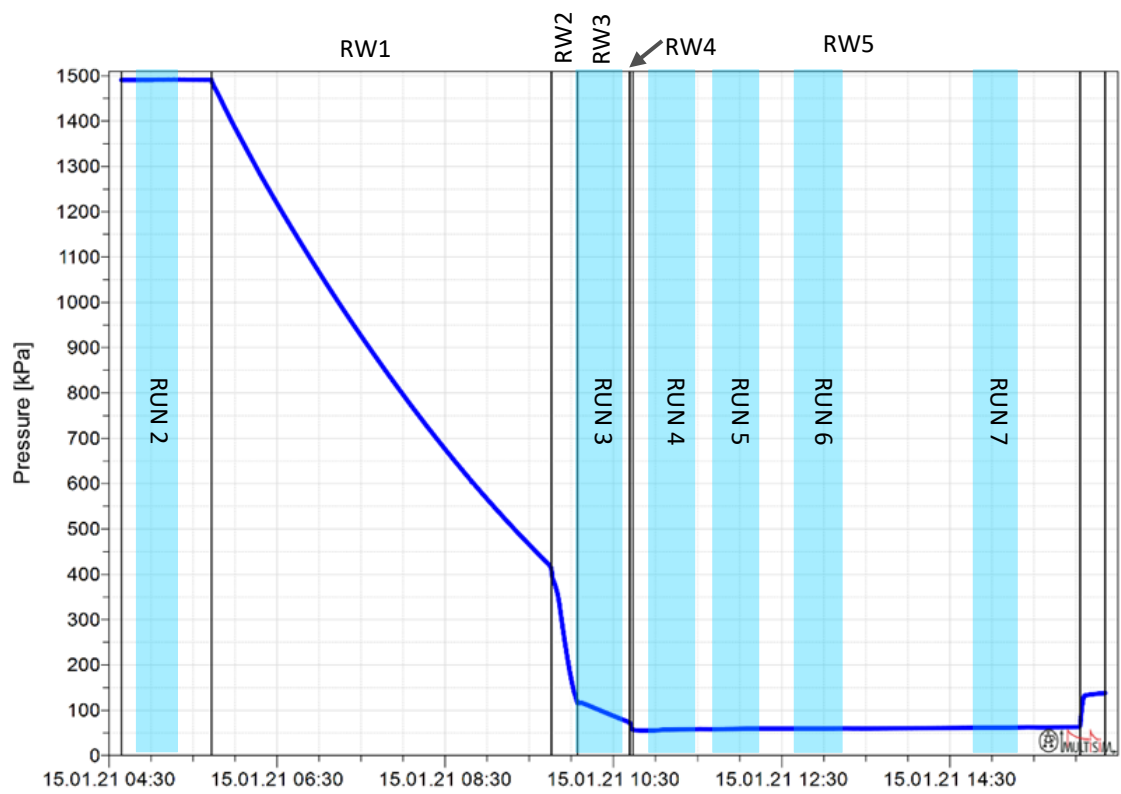


Fig. 3-1: STA3-1-FL1-MAL: Pressure drawdown and the position in time where fluid logging runs were performed

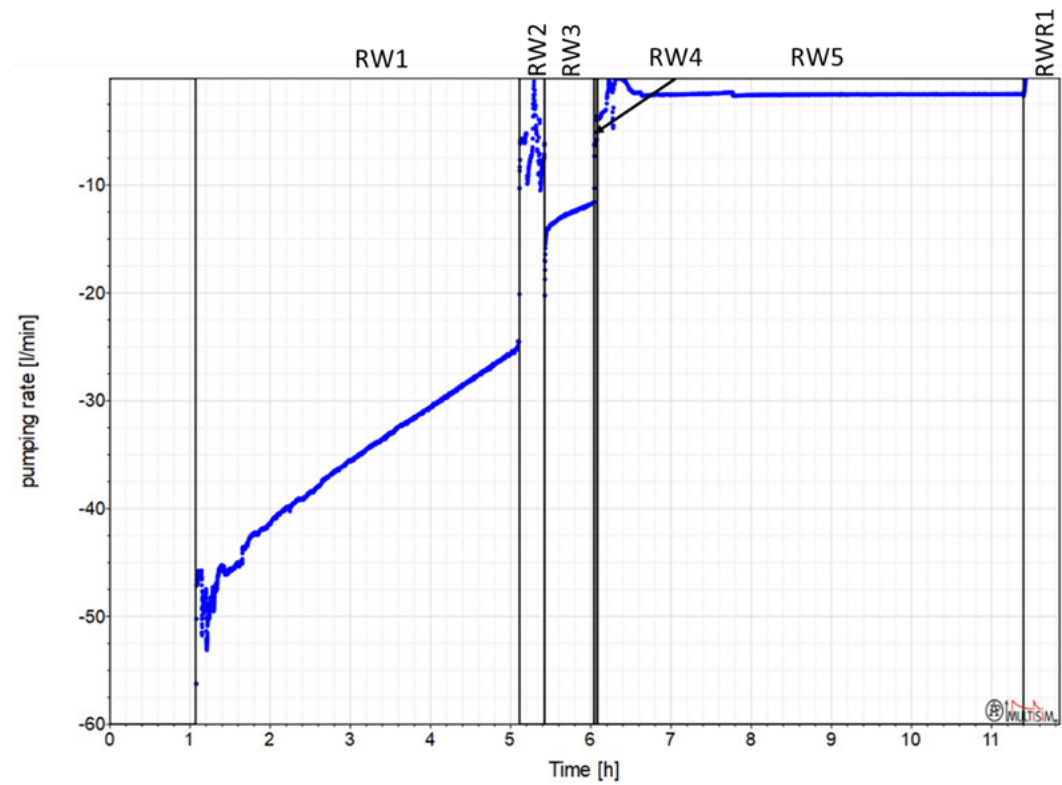


Fig. 3-2: STA3-1-FL1-MAL: Measured pumping rates

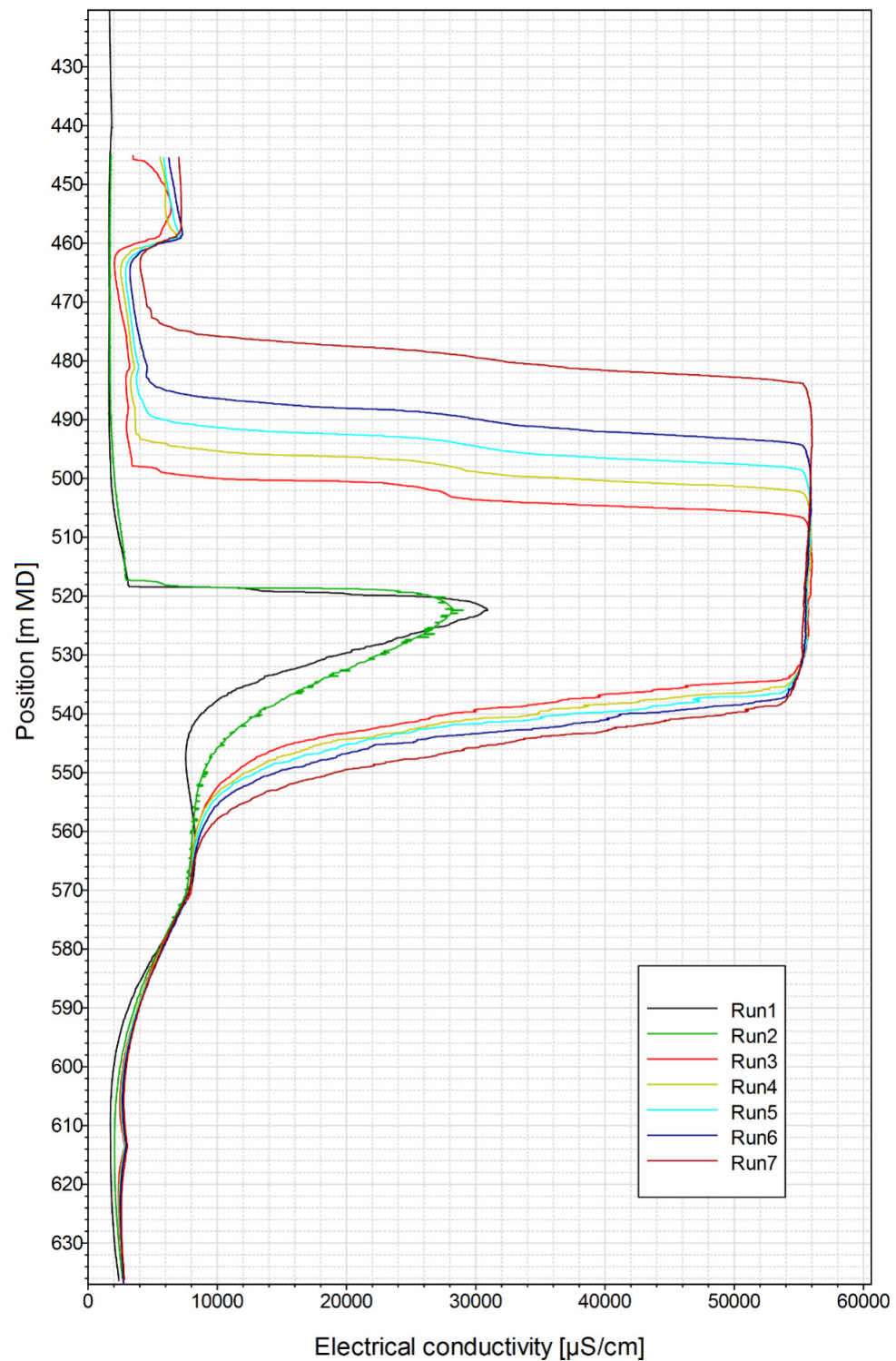


Fig. 3-3: STA3-1-FL1-MAL: Measured electrical conductivity logs (runs), corrected to 25 °C equivalent conductivity

Note, the maximum values of the recorded electrical conductivity of Runs 3 to 7 are underestimated due to the limited measurement range of the probe used, resulting in the "box-car function" shape of these runs.

3.2.2 Analysis of pumping test data

The pumping test data were analysed numerically by the contractor using the borehole simulator Multisim. A radial homogeneous flow model was applied to determine the total transmissivity of the open borehole section.

Two analyses were performed. The first comprised RW1, RW3 and RW5 and showed that the fit quality of RW1 and RW5 was much better than the fit quality of RW3. Therefore, a second fit was performed without matching the RW3 phase, however, prescribing the pressure during this phase. Both analyses have shown that a radial homogeneous model is best suited to honour the recorded pressure and flow data and that the flow rate into the borehole stabilised during RW5. Borehole pressure history data were not considered.

The results of the two pumping test analyses are provided in Tab. 3-10. The transmissivity ranged between $1.47 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ and $1.73 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$. Fig. 3-4 shows a good agreement between the measured and simulated pressure curves for the entire pumping test. Fig. 3-5 presents the resulting estimate of the borehole inflow rate during RW5 from analysis 1. The difference between the early-time pumping and inflow rate in Fig. 3-5 represents the wellbore storage of borehole STA3-1.

Tab. 3-10: STA3-1-FL1-MAL: Estimated hydraulic parameters derived from pumping test analyses 1 and 2 in the framework of fluid logging in borehole STA3-1

The fitted parameters are shown in bold.

Parameter	Analysis 1	Analysis 2
Pumping phases, considered	RW1, RW3, RW5	RW1, RW5
Flow model	Radial homogeneous model	
Length of test interval [m]	198.00	
Total transmissivity (T) [$\text{m}^2 \text{ s}^{-1}$]	1.73×10^{-7}	1.47×10^{-7}
Specific storage (S_s) [m^{-1}]	1.00×10^{-6}	1.00×10^{-6}

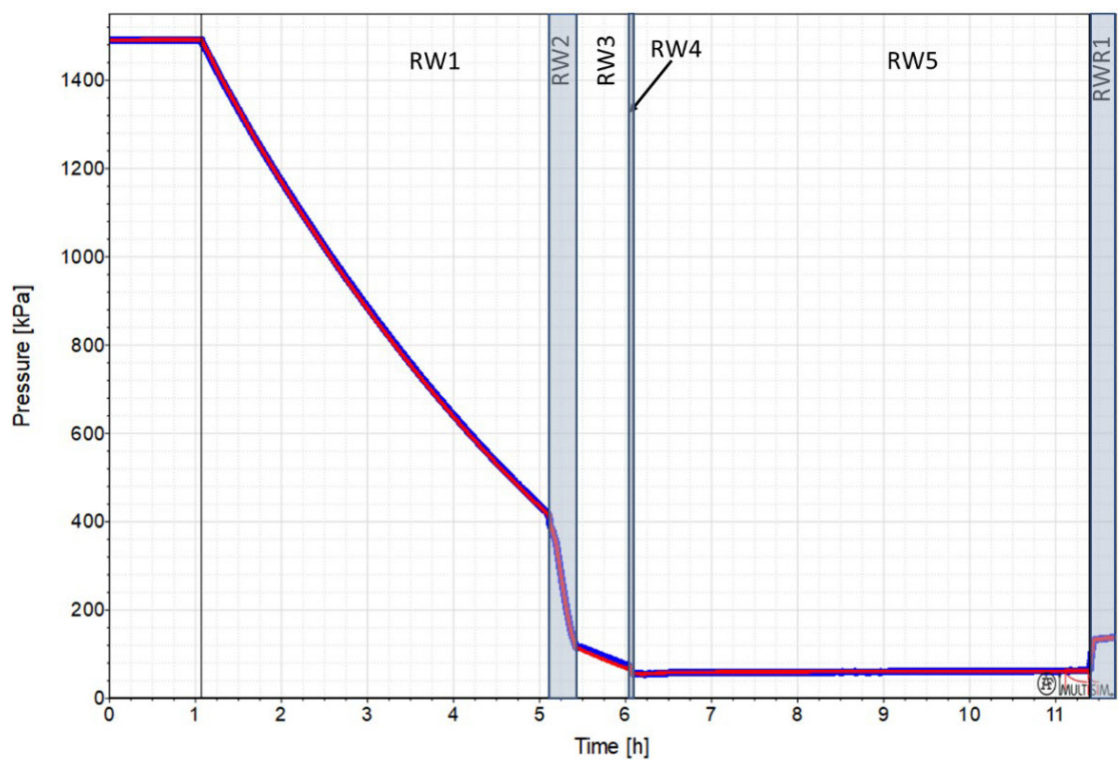


Fig. 3-4: STA3-1-FL1-MAL: Measured pressure (blue) and simulated pressure (red) during the entire pumping test

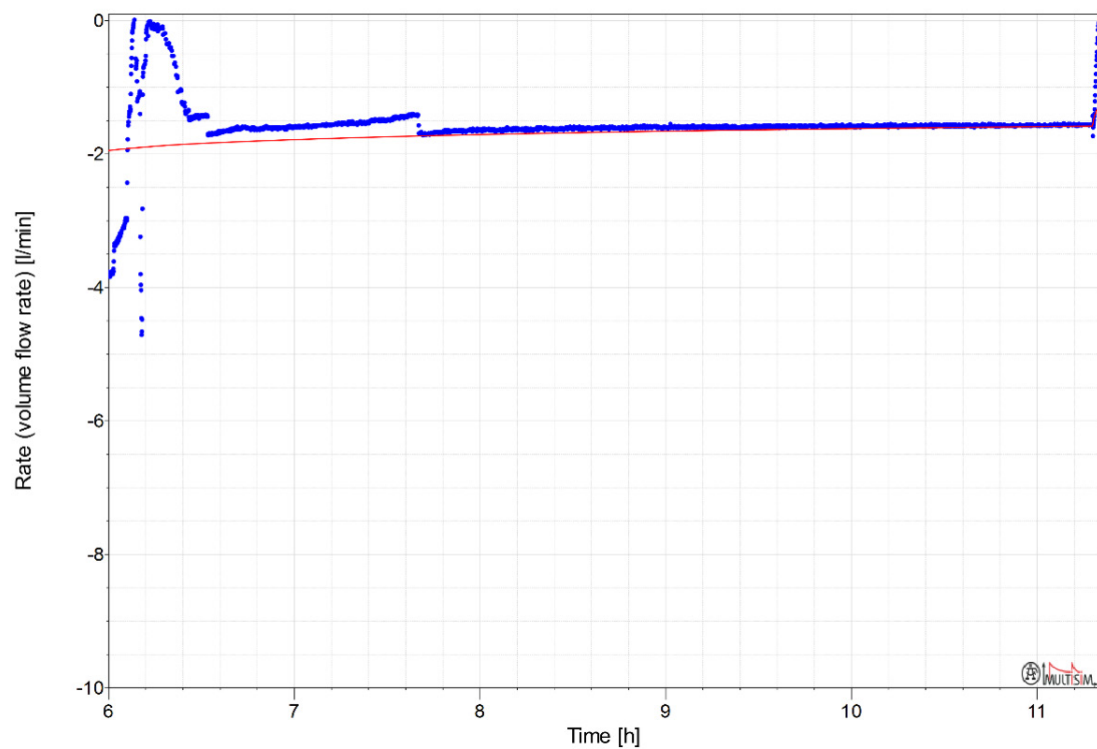


Fig. 3-5: STA3-1-FL1-MAL: Measured pumping rate (blue) and simulated borehole inflow rate (red) during RW5

3.2.3 Fluid logging analysis

The recorded electrical conductivity profiles were converted to concentration profiles and those then analysed numerically by the contractor using the 1D numerical transport model of the simulator Multisim. The inflow rates and their concentrations as well as the concentration calculated from a single fluid logging run were used as the initial conditions. From this, the concentration distributions of the following fluid logging runs were computed. Based on fits of the electrical conductivity / concentration profiles recorded inside the borehole, the inflow zones were determined qualitatively and quantitatively, followed by determination of the transmissivities for the inflow zones using the solution of Cooper & Jacob (1946). The methodology is based on Tsang & Hufschmied 1988, Hale & Tsang 1988 and Loew et al. 1991.

Two prerequisites must be met to simulate the concentration distribution as a function of time inside the borehole by means of a 1D transport model implemented in the simulator Multisim:

- The flow into the borehole must be constant (constant inflow rate).
- The inflow concentration must be constant (implying a constant mass change inside the borehole).

These conditions were expected to be fulfilled for the fluid logging runs during pumping phase RW5 (Runs 4 – 7) where the pumping rate caused merely a minimal change in the water level in the borehole, and the mass change seemed to stabilise. The estimated inflow concentration varied between 49 kg m^{-3} and 43 kg m^{-3} (Fig. 3-6). This is considered a reasonable estimate as the actual concentration is not known. The mud report of 14th January 2021 provides measurements of the chloride concentration of the mud before and after the fluid exchange of approximately 79.2 kg m^{-3} and 3.8 kg m^{-3} , respectively. Therefore, it may be assumed that mainly mud was produced during pumping.

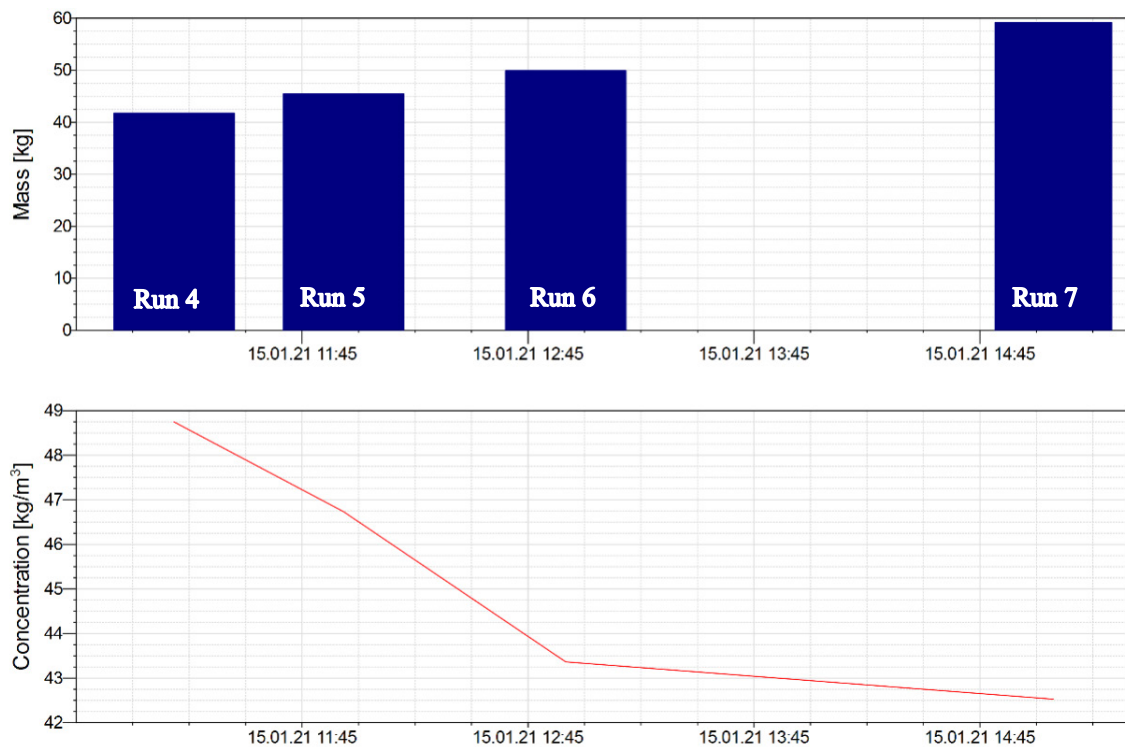


Fig. 3-6: STA3-1-FL1-MAL: Results from the application of the Moment Method (Loew et al. 1991) for Runs 4, 5, 6 and 7

Runs 4 to 7 were analysed with an averaged pumping rate of 1.65 l min^{-1} during pumping phase RW5. During Runs 1 to 3, either the borehole was not in nearly static condition, or the conditions of a constant inflow rate and concentration were not met. Thus, these runs were not considered for further analysis.

The first fluid logging analysis considered Runs 5, 6 and 7 and was based on a conceptual model with 7 inflow zones as presented in Tab. 3-11. Run 4 was considered as the initial condition (initial profile of electrical conductivity / concentration). The position of the main inflow (521.00 – 521.50 m MD) was defined based on the fluid logging Runs 1 and 2. Both runs show a concentration peak which may be associated with an inflow. However, the concentration of the inflow at later times (Runs 3 – 7) leads to a sharp increase in the concentration in the borehole, so that the concentration exceeded the measuring range of the probe (Fig. 3-3).

Fig. 3-7 presents the first result utilising a 1D numerical transport model. The concentration distributions of Runs 5, 6 and 7 were matched by applying a fixed inflow concentration of 49 kg m^{-3} and an equivalent diffusion coefficient of $8.00 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$. The estimated cumulated flow rate for the seven inflow zones is 1.68 l min^{-1} , which corresponds with the averaged flow rate of pumping phase RW5. The sum of transmissivities for all inflow zones is $1.98 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ (Tab. 3-11), which corresponds well with the derived total transmissivity value of $1.47 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ from the pumping test analysis. The calculation of the transmissivity for each zone is based on:

- a specific storage value of $1.00 \times 10^{-6} \text{ m}^{-1}$ (see Section 3.2.2)
- a pressure difference of 1'438 kPa after 5 hours of pumping and
- a zone-specific flow rate

The most important inflow zone characterised by a transmissivity value of $1.19 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ is located between 521.00 m MD and 521.50 m MD. This inflow zone was inferred from fluid logging Runs 1 and 2 as discussed above (see Fig. 3-3). However, its precise location is uncertain due to the electrical conductivity measurements being limited by the range of the probe in the subsequent runs, indicated by the dashed rectangle in Fig. 3-7.

A second fluid logging analysis also considered Runs 5, 6 and 7 for analysis with Run 4 as initial condition inside the borehole. The objective of this second analysis was to explore the feasibility of a single inflow zone within the section where the electrical conductivity exceeded the range of the probe during the initial condition (Run 4). The second simulation was done with five inflow zones as listed in Tab. 3-11 and a different equivalent diffusion coefficient than in the first analysis. The section where the electrical conductivity exceeded the range of the probe is represented by a single inflow zone between 522.00 and 523.00 m MD. The sum of the estimated transmissivities for all inflow zones for the second fluid logging analysis is $2.01 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ (Tab. 3-11).

Tab. 3-11: STA3-1-FL1-MAL: Estimated hydraulic parameters resulting from the analyses of the fluid logging data

Inflow zone	Top [m MD]	Bottom [m MD]	Inflow thickness [m]	Concentration [kg m ⁻³]	Flow rate [l min ⁻¹]	Transmissivity [m ² s ⁻¹]
1 st fluid logging analysis of Runs 5, 6 and 7, equivalent diffusion coefficient $8 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$						
1	459.30	459.50	0.2	49	0.09	1.06×10^{-8}
2	480.50	481.00	0.5	49	0.005	5.90×10^{-10}
3	521.00	521.50	0.5	49	1.01	1.19×10^{-7}
4	537.00	537.20	0.2	49	0.51	6.02×10^{-8}
5	541.30	541.50	0.2	49	0.06	7.08×10^{-9}
6	569.90	570.10	0.2	49	0.002	2.36×10^{-10}
7	613.00	613.50	0.5	49	0.0025	2.95×10^{-10}
2 nd fluid logging analysis of Runs 5, 6 and 7, equivalent diffusion coefficient $1 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$						
1	459.30	459.50	0.2	49	0.09	1.06×10^{-8}
2	480.50	481.00	0.5	49	0.005	5.90×10^{-10}
3	522.00	523.00	1	49	1.6125	1.90×10^{-7}
6	569.5	570.5	1	49	0.001	1.18×10^{-10}
7	613.00	614	1	49	0.001	1.18×10^{-10}

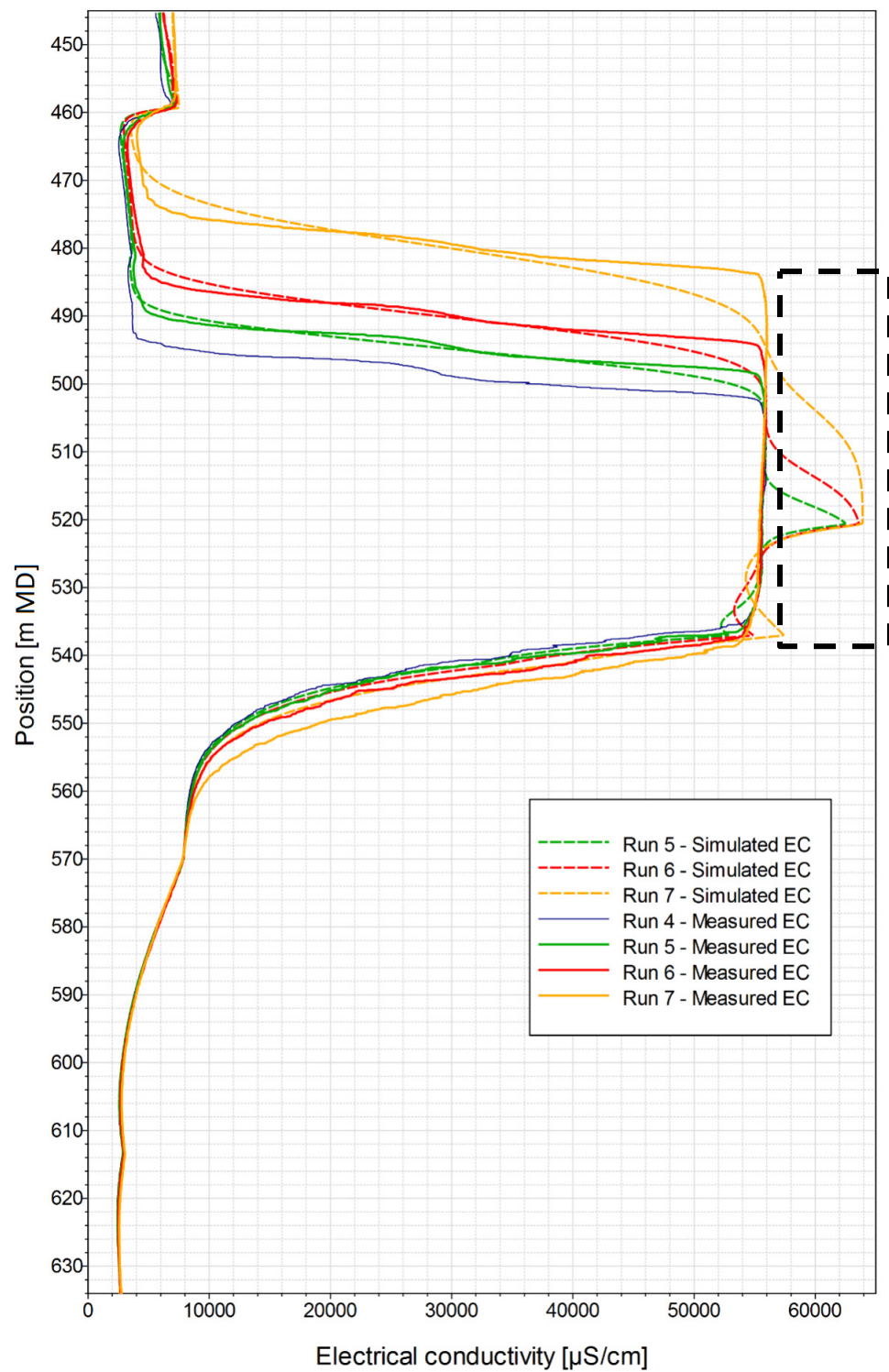


Fig. 3-7: STA3-1-FL1-MAL: Fluid logging analysis of Runs 5, 6 and 7 using Run 4 as initial concentration and considering seven inflows

The dashed rectangle indicates where the concentration exceeded the measuring range of the probe and, therefore, the measurements are unreliable.

3.3 Summary and discussion of fluid logging results

A fluid logging campaign was performed within borehole Section II in order to identify the presence of any inflow zones. The pumping test data comprise five drawdown phases. The analysis of the RW1 and RW5 pumping phases produced the most reliable total transmissivity estimate of $1.47 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$. It is based on a radial homogeneous flow model and a constant specific storage of 1.00×10^{-6} .

For the fluid logging, seven electrical conductivity profiles were recorded in total. For a certain depth range, the electrical conductivity in the borehole exceeded the range of the probe used for Runs 3 to 7, with the corresponding data being deemed unreliable. Nevertheless, two fluid logging analyses were performed, both based on the evaluation of Runs 5, 6 and 7, and using Run 4 as initial concentration profile related to the pumping phase RW5.

The first simulation, matching the measured electrical conductivity distributions of Runs 5, 6 and 7, was based on the conceptual model of seven inflow zones. The quality of the fits is judged as satisfactory, considering seven inflow zones were required to achieve the resulting concentration distribution for the depth intervals where electrical conductivity data are reliable. The sum of transmissivities for all inflow zones is $1.98 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$, which corresponds well with the total transmissivity value of $1.47 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ derived from the analysis of pumping phases RW1 and RW5.

The packer test performed in the Malm Group (STA3-1-MAL1) led to a best estimate of the transmissivity of $3.1 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ based on an interval length of 28.61 m. The results of the analyses of the fluid logging and the associated pumping test are in good agreement with the result of the hydraulic packer testing considering the uncertainty in the electrical conductivity during the fluid logging.

Tab. 3-12 presents an assessment of the quality of the identification of inflow zones.

Tab. 3-12: STA3-1-FL1-MAL: Assessment of inflow zone detection from the analyses of the fluid logging data

¹ Based on the results given by the field test contractor in the corresponding DR.

Inflow zone	Top ¹ [m MD]	Bottom ¹ [m MD]	Transmissivity ¹ [m ² s ⁻¹]	Assessment of results
1	459.30	459.50	1.06×10^{-8}	Certain inflow zones, reliable electrical conductivity data for all runs
2	480.50	481.00	5.90×10^{-10}	
3	521.00	521.50	1.19×10^{-7}	Uncertain position and extension of the inflow zone, reliable electrical conductivity data and indication only for 2 runs prior to pumping
4	537.00	537.20	6.02×10^{-8}	Uncertain inflow zones
5	541.30	541.50	7.08×10^{-9}	
6	569.90	570.10	2.36×10^{-10}	Certain inflow zones, reliable electrical conductivity data for all runs
7	613.00	613.50	2.95×10^{-10}	

4 Hydraulic packer tests

4.1 Test strategy

The geological formations examined in the TBO boreholes exhibit a wide range of transmissivities. The host rock, Opalinus Clay, and its confining units are expected to have very low transmissivities, whilst the regional aquifers in the Malm and Muschelkalk Groups are expected to have relatively high transmissivities.

Nagra has long established hydraulic testing strategies (e.g. Nagra 1997) to extract the maximum information in relation to the hydraulic characteristics of the various geological formations. Two testing strategies are preferred (Tabs. 4-1 and 4-2) depending on the transmissivity of the formation (medium to high, or low to very low). A typical test sequence is divided into different test phases: test preparation, diagnostic and main phase. The test sequence may be concluded with a pulse test (PW/PI) to check if the total test interval compressibility changed during the test. Modifications to the strategies are made according to the preliminarily available information, the specific test conditions encountered, and results obtained while testing. This may lead to the omission of certain test phases, e.g. the diagnostic phase.

The main difference between the two testing strategies is the selection of appropriate test types and phases as well as the duration of the test phases. In a formation with medium to high transmissivity, pressure disturbances due to drilling or temperature effects dissipate relatively quickly. Accordingly, the test preparation phase is short. The main phase delivers results of sufficient accuracy with respect to the hydraulic properties of the formation in a relatively short period. In addition, a water sample may be collected if the hydraulic transmissivity of the formation is sufficient.

In the case of formations with low to very low transmissivity, the test types and their duration are different. For the determination of hydraulic head, the borehole pressure history and test duration are important issues. Depending on the pressure difference between the static formation conditions and the pressure induced in the borehole during the pre-test pressure history, the estimates of hydraulic head can be strongly affected due to non-static pressure conditions in the surrounding borehole area.

A further aspect of the testing strategy is the use of drilling fluid as a test fluid (see Tab. 1-1). In contrast to previous exploration boreholes drilled by Nagra (e.g. Benken), no exchange of drilling fluid in the test interval was performed in the STA3-1 borehole prior to hydraulic testing. The main reason was borehole stability. There was one exception to this, however. The hydraulic test STA3-1-MAL1 was conducted with tap water because it was performed after the fluid logging STA3-1-FL1-MAL for which the mud had to be exchanged with tap water.

The water-based mud used for drilling contained sodium chloride and polymers as additives between 439 and 640 m MD (STA3-1-MAL1) and mainly polymers between 1'035 m MD and 1'101 m MD for drilling the test interval STA3-1-MUK1. For all other intervals the drilling mud was potassium silicate and polymers (*cf.* Dossier I). Only for the interval STA3-1-MAL1 was the mud replaced by tap water to allow the fluid logging campaign to be carried out.

Finally, the model implementation as a skin in the test analysis was assumed to adequately address any issues linked with drilling fluid properties at the borehole wall.

Tab. 4-1: Preferred test sequence for formations with medium to high transmissivity

¹ For an explanation of the abbreviations, see Tab. A-3.

Test phase	Phase ¹	Aims
Test preparation phase	COM	Temperature and pressure equilibration in the test interval
	PSR	Pressure static recovery with closed shut-in tool; create pressure conditions for the initiation of the first test, first estimate of formation pressure; recognition of temperature and pressure trends
Diagnostic phase	PW	First estimates of hydraulic conductivity, which are used to plan the following test sequence
Diagnostic / main phase	SW	Estimation of hydraulic conductivity, which is used to plan the following test sequence, especially the pumping rate and drawdown of the RW phase
	SWS	Estimation of an accurate flow model and hydraulic parameters; hydrostatic pressure for subsequent pumping phase
Main phase	RW	Defined signal with a larger radius of influence; allows a representative groundwater sample of the formation to be taken as well as the detection of boundary conditions
	RWS	Estimation of an accurate flow model and hydraulic parameters as well as boundary conditions
Optional	PW/PI	Estimation of the total test interval compressibility at the end of the test

Tab. 4-2: Preferred test sequence for formations with low to very low transmissivity

¹ For an explanation of the abbreviations, see Tab. A-3.

Test phase	Phase ¹	Aims
Test preparation phase	COM	Temperature and pressure equilibration in the test interval
	PSR	Pressure static recovery with closed shut-in tool; create pressure conditions for the initiation of the first test, first estimate of formation pressure; recognition of temperature and pressure trends
Diagnostic phase	PW	First estimates of hydraulic conductivity, which are used to plan the following test sequence
Main phase Version 1	SW	Estimation of hydraulic formation parameters during a flow phase
	SWS	Estimation of an accurate flow model and hydraulic parameters during shut-in conditions
	PW/PI (optional)	Estimation of the total test interval compressibility at the end of the test
Main phase Version 2	PW/PI	Estimation of hydraulic formation parameters (as an alternative to SW/SWS)

4.2 Test equipment

The most relevant components of the field test contractor's equipment have been drawn from the associated mobilisation report and are presented below.

4.2.1 Downhole equipment

The packer system referred to as the heavy-duty double packer system (HDDP) was used for all hydraulic packer tests in open borehole sections. It consists of a top and bottom inflatable packer (non-inflated outer diameter 114 mm for borehole STA3-1, except for STA3-1-OPA4 with a non-inflated outer diameter of 146 mm) in order to confine a test interval section of appropriate length for the intended test (Fig. 4-1). Inflow and outflow occurred through a perforated filter segment covered by a filter screen mounted on a 2 $\frac{7}{8}$ " tubing above the bottom packer.

Four pressure transducers, mounted in a probe carrier shell above the top packer and referred to as the quadruple sub-surface probe or quadruple probe (QSSP), measured the pressures below (P1), within (interval pressure P2) and above the test interval (annulus pressure P3) as well as in the test tubing above the downhole shut-in tool (P4). In addition, the pressure in the test interval was recorded with an autonomous memory gauge at the bottom of the filter screen (P2*).

Temperatures were measured at the level of the QSSP by the temperature sensors associated with each pressure transducer (referred to as T1, T2, T3, T4, respectively) and additionally by the sensor associated with the memory gauge mentioned above (named T2*).

A hydraulically controlled non-displacement downhole shut-in tool (SIT) placed above the probe carrier shell was used to isolate the test zone from the test tubing (2 $\frac{7}{8}$ " EUE API CT5 N80/L80). A progressive cavity pump (PCP) or Moyno® type pump or a pump housing with a 4" submersible pump, integrated in the test tubing, could be used for production pumping tests.

For testing in a single packer configuration (Fig. 4-2), the system was set up without the bottom packer but with a prolongation of the interval string with the filter at the bottom. Inflow and outflow occurred through a perforated filter segment covered by a filter screen mounted on a 2 $\frac{7}{8}$ " tubing at the bottom of the prolongation.

The quadruple flat-pack consisted of three hydraulic steel tubes of $\frac{1}{4}$ " outer diameter (OD) and one electrical conductor coated in a thermoplastic protective cover. Two steel tubes were used for packer inflation and one for the control of the SIT and the pressure release valve (PRV), which was only used when the packers could not be sufficiently deflated by opening the packer lines at the surface.

Certain parts of the downhole equipment are described below in more detail.

Heavy Duty Double Packer System
Buildup

		API 2 7/8 EU	Stub ACME	max. OD [mm]	min. ID [mm]	Length [m]	Yield Strength [tons]	Weight [kg]
Tubing (2 7/8 inch)		x		93.2 (73.0)	62.0	indiv.	65.8*	
Coupling		x		93.2	62.0	0.15		
PCP Stator (10-60 l/min)				78.6 (93.2)	34.0	2.58	16	53
Stop Pin		x		78.6	62.0	0.40		
Tubing (2 7/8 inch)		x		93.2	62.0	indiv.		
Siphon		x		93.2	62.0	0.185		
X Over						0.14		
Hydraulic Shut In Tool			x	106.0	24.0	1.41		69
Coupling						0.15		
Crown Shaft			x	100.0	40.0	0.378		
						0.178		
Cable Base								
Cable Head and Cable Plug			x	105.0	24.0	1.043	16	
PRV								
Probe Carrier with Quadruple Sub-Surface Probe (QSSP) and Sensor Positions			x	105.0	3 x Ø19	0.525 0.652 0.795 0.992 1.797		132
P3								
P4								
P2 / T2								
P1								
Crown Shaft			x	100.0	40.0	0.22		
X-Over						0.128		
						0.08		
Safety Joint + Pup Joint			x	98.55	63.5		(21.14)**	7.5 (Safety Joint)
X-Over			x	93.0	50.0			
						0.118		
						0.268		
						0.215		
Top Packer (146 mm)				146.0	49.0	1.20		120
						0.225		
						0.164		
			x					
Below Side Entry Sub			x	100.0	30.0	0.435		
X-Over			x			0.108		
Tubing (2 7/8 inch)		x		93.2 (73.0)	62.0	indiv.	16	
X-Over						0.13		
X-Over						0.08		
Filter (Screen length 0.50 m)		x		89.0	73.0	1.18		13
X-Over						0.15		
P1 Seal Sub			x	95.0		0.431		
			x			0.117		
						0.215		
Bottom Packer (146 mm)				146.0	49.0	1.20		98
						0.225		
						0.164		
Bottom Cap				95.0		0.16		

* Tensile strength / ** Shear value with ten shear screws

Fig. 4-1: General configuration and specifications of the HDDP in double packer configuration

Heavy Duty Single Packer System Buildup

			API 2 7/8 EU	Sub ACME	max. OD [mm]	min. ID [mm]	Length [m]	Yield Strength [tons]	Weight [kg]
Tubing (2 7/8 inch)			x		93.2 (73.0)	62.0	indiv.	65.8*	
Coupling			x		93.2	62.0	0.15		
PCP Stator (10-60 l/min)					78.6 (93.2)	34.0	2.58	16	53
Stop Pin			x		78.6	62.0	0.40	0.35	
Tubing (2 7/8 inch)			x		93.2	62.0	indiv.		
Siphon			x		93.2		0.185		
X Over				x					
Hydraulic Shut In Tool				x	106.0	24.0	1.41		69
Coupling				x	100.0	40.0	0.378		
Crown Shaft				x	100.0	40.0	0.378		
Cable Base				x	105.0	24.0	1.043	16	
Cable Head and Cable Plug				x	105.0	24.0	1.043	16	
PRV				x	105.0	24.0	1.043	16	
Probe Carrier with Quadruple Sub-Surface Probe (QSSP) and Sensor Positions				x	105.0	3 x Ø19	1.707		132
P3				x	105.0	3 x Ø19	1.707		
P4				x	105.0	3 x Ø19	1.707		
P2 / T2				x	105.0	3 x Ø19	1.707		
P1				x	105.0	3 x Ø19	1.707		
Crown Shaft				x	100.0	40.0	0.378		
X-Over				x	100.0	40.0	0.378		
Safety Joint + Pup Joint				x	98.55	63.5		(21.14)**	7.5 (Safety Joint)
X-Over				x	93.0	50.0			
							0.268		
							0.215		
Top Packer (146 mm)					146.0	49.0	1.20		120
							0.225		
							0.164		
Below Side Entry Sub				x	100.0	30.0	0.435		
X-Over				x	100.0	30.0	0.435		
Tubing (2 7/8 inch)			x		93.2 (73.0)	62.0	indiv.	16	
X-Over									
X-Over									
Filter (Screen length 0.50 m)			x		89.0	73.0	1.18		13
X-Over									
Bottom Cap									6

* Tensile strength / ** Shear value with ten shear screws

Fig. 4-2: General configuration and specifications of the HDDP in single packer configuration

4.2.1.1 Heavy-duty double packer system

The technical data of the heavy-duty double packer system (HDDP) are provided in Tab. 4-3. A summary of the downhole equipment with the most important component specifications is given in Tab. 4-4.

Tab. 4-3: Specifications for the HDDP

Tool Description	HDDP
Packer configuration	Double packer or single packer
Maximum installation depth	1'400 m (vertical); 1'500 m (inclined) along borehole axis
Maximum fluid pressure	20'000 kPa
Maximum differential pressure	114 mm packer system for 162 mm borehole: ~ 12'200 kPa 146 mm packer system for 216 mm borehole: ~ 8'000 kPa
Maximum downhole temperature	80 °C
Range of interval length	3 – 100 m
Probe	QSSP
Shut-in tool (SIT)	Zero-displacement valve
Control lines	4 core encapsulated flat-pack • Hydraulic line – bottom packer (PA1) • Hydraulic line – top packer (PA2) • Hydraulic line – shut-in tool (SIT) and packer pressure release valve (PRV) • 1/8" (3.175 mm) OD tubing encased single conductor cable

Tab. 4-4: Specifications for the HDDP components

Component	Specifications	Minimum inner diameter (ID) [mm]	Weight
Quadruple flat-pack	3 each ¼" OD × 0.035" WT316L stainless steel welded and cold drawn annealed tubes 25'500 kPa maximum test pressure Incorporating 1 each ⅛" OD × 0.022" WT316L stainless steel 16 AWG solid CU conductor /P/N 024440) encapsulated to ¼" OD in TT200 thermoplastic Encapsulated as 33 mm × 11 mm in TT210 thermoplastic, suitable for maximum 98.9 °C brine service		0.637 kg/m
Tubing	2⅞" EU API CT5 N80/L80	62	9.68 kg/m
Pup joints	2⅞" EU API CT5 L80/N80	62	9.68 kg/m
Shut-in tool (SIT)	Duplex 1.4462	24	69 kg
Pressure release valve (PRV)	Duplex 1.4462	24	132 kg
Cable base	Duplex 1.4462		
Quadruple sub-surface probe (QSSP)	Duplex 1.4462 4 pressure sensors P1, P2, P3 and P4	3 × Ø19	
Coarse thread safety joint	max OD: 3.88" (98.55 mm); min ID: 2.50" (63.50 mm) Thread connection: 2⅞" EUE 8RD with 2⅞" EUE Box × pin connections	63.5	11 kg
Packers for large borehole diameter	IPI 5¾" (146 mm), steel wire reinforced, duplex, natural rubber		
	Packer 1 Packer 2	49 49	98 kg 106 kg
Packers for normal borehole diameter	IPI 4½" (114 mm), steel wire reinforced, duplex, Nitrile Butadiene Rubber (NBR)		
	Packer 1 Packer 2	49 49	78 kg 67 kg
Filter	HP well screen: sand free filter screen mounted on 2⅞" tubing L80		
	Length: 0.50 m Length: 1.00 m	73 73	13 kg 19 kg
Total system weight	At 1'400 m depth including PCP, quadruple flat-pack cable and centralisers		approx. 15.2 t
Maximum applicable tensile force for entire system	Actual system weight at the corresponding depth, plus 16 tonnes (weakest point)		

4.2.1.2 Packers

Two types of packers were available for use, a 114 mm packer for 162 mm diameter boreholes and a 146 mm packer for 216 mm diameter boreholes (Tab. 4-5). The packers were individually inflated with water through the packer inflation line. The inflation lines were integrated in the quadruple flat-pack and operated using a booster pump. Anti-freeze was added to the water. Both packer pressure lines were connected to the packer control board at the winch and equipped with pressure sensors (pressure range 0 – 30'000 kPa) for packer pressure monitoring. The packer pressure sensors were connected to the data acquisition system (DAS) for continuous recording. To keep packer pressures constant, the packers were connected to a pressure-maintenance system (see Section 4.2.2.2).

Tab. 4-5: Specifications for the HDDP packers

Manufacturer	Inflatable Packers International, Perth, Australia	
Packer types	IPI 4½" (114 mm)	IPI 5¾" (146 mm)
Material and type	Duplex, NBR, sliding end (+ 4 natural rubber packer sleeves)	Duplex, natural rubber, sliding end
Reinforcement type	Steel wire reinforced	Steel wire reinforced
Borehole diameter	162 mm	216 mm
Packer diameters	125 – 230 mm (pressure dependent)	162 – 280 mm (pressure dependent)
Outer diameter, not inflated	114 mm max.	146 mm max.
Inner diameter	49 mm min.	49 mm min.
Overall length: Bottom packer Top packer	1.93 m 2.08 m	1.92 m 1.92 m
Rubber sleeve length	1.20 m	1.20 m
Thread connections	2⅞" EU pin × 2⅞" EU box	2⅞" EU pin × 2⅞" EU box
Max. working temperature for a period > 100 h	+80 °C	+80 °C
Packer inflation lines	Quadruple flat-pack, see Tab. 4-4	Quadruple flat-pack, see Tab. 4-4
Inflation method	Surface controlled	Surface controlled
Inflation fluid	Water and anti-freeze (if necessary)	Water and anti-freeze (if necessary)

4.2.1.3 Downhole sensors in the quadruple sub-surface probe

Four Keller PA-27XW transducers (for transducer types and specifications see Tab. 4-6) were used to monitor fluid pressures in the interval below the bottom packer (P1), within the testing interval (P2), in the annulus between the tubing and borehole wall above the top packer (P3) and in the test string (P4) above the downhole SIT. These four transducers were mounted in the QSSP probe, which was integrated in the probe carrier (see Fig. 4-1). The pressure sensors measured absolute pressure and corrected it to atmospheric pressure; the sensor generally showed ± 3 kPa at atmospheric pressure conditions.

Each pressure transducer had an associated temperature sensor (referred to as T1, T2, T3 and T4) for full thermal compensation of the pressure measurement (Tab. 4-6). The temperature sensor was mounted inside the pressure transducer housing. Because the temperature measurements were taken at the positions of the pressure transducers, they may not represent the effective temperature of the test interval fluid.

Tab. 4-6: Specifications for the pressure transmitters mounted in the QSSP

¹ FS = full scale

Pressure transducer type	Keller PA-27XW, custom-made	
Manufacturer	Keller, Winterthur, Switzerland	
Year of commissioning	2018	
Pressure range (full scale)	0 – 20'000 kPa (absolute)	
Accuracy	-0.004...0.005% FS ¹	
Resolution	< 0.0007% FS	
Minimum recording rate	1 Hz	
Temperature range (FS)	-10 °C – 80 °C	
Accuracy (temperature)	1 °C	
Resolution (temperature)	0.01 °C	
Output signal	RS485 (digital)	
		Pressure sensor

4.2.1.4 Autonomous data logger in test interval

Pressures and temperatures were recorded as redundant measurements in the interval at the lower end of the filter screen (referred to as P2* and T2*, respectively) with an autonomous data logger of the type DataCan Memory Pressure Gauges. The specifications are given in Tab. 4-7. The recorded pressure measurement is an absolute measurement.

Tab. 4-7: Specifications for the data logger

¹ FS = full scale

Data logger type	DataCan Memory Pressure Gauge 1.25" Welded Piezo III
Manufacturer	Data Can, Red Deer, Canada
Pressure range (FS ¹)	0 – 20'684 kPa (absolute)
Pressure accuracy	0.022% FS ¹
Resolution	0.0003% FS ¹
Temperature range	0 – 150 °C
Temperature accuracy	0.5 °C
Resolution	0.005 °C
Memory capacity	1'000'000 data sets
Minimum recording rate	10 Hz
Year of commissioning	2018

4.2.1.5 Zero-displacement shut-in tool

The downhole SIT controls the fluid connection between the interior of the test tubing and the test interval. The SIT is a zero-displacement valve that is hydraulically operated via a hydraulic line integrated in the quadruple flat-pack using a hand pump. An axially moveable valve piston opens and closes the valve. The valve piston is moved via the hydraulic (closure) line by applying pressure to close the valve. Releasing the pressure with a pre-stressed spring resets the valve piston and opens the valve (pressure-disturbance free opening).

With a pressure compensation element, the pressure at interval depth (annulus pressure) is used to support the spring and to keep the opening/closing pressure constant for the entire borehole depth. The spring force is high enough to ensure a proper functioning of the valve also at low groundwater levels. The specifications are given in Tab. 4-8.

Tab. 4-8: Specifications for the zero-displacement shut-in tool

Zero displacement shut-in tool (SIT)	Manufactured by Solexperts
Maximum water flow rate	Below 40 l/min without friction loss, max. 350 l/min
Pressure loss caused by SIT at a flow rate of 1 l/min and 10 l/min	± 0 kPa
Closing pressure	9'000 – 10'500 kPa

4.2.1.6 Test tubing

API Spec. 5 CT-05 2 $\frac{7}{8}$ " tubing was used as test rods. The detailed specifications of the test tubing are summarised in Tab. 4-9.

Tab. 4-9: Specifications for the test tubing

Test tubing type	Seamless steel tubing pipes: API 5CT-05 (PSL1), 8 th edition Pup joints: EUE, Tubing & Coupling; API 5CT-05 (PSL1), 8 th edition
Manufacturer	Interpipe Nikopolsky Normec, Celle, Germany
Steel grade	N80/L80 (tubing), N80/L80 (pup joints)
Inner diameter	62.00 mm
Outer diameter	73.02 mm
Coupling outer diameter	93.20 mm
Thread	API 2 $\frac{7}{8}$ " EUE
Weight per metre	9.68 kg
Volume per metre	3.02 l
Individual tubing length	Range 2, approx. 9.5 m
Number of individual tubing lengths	122 (certified) + 35 (newly ordered)
Total length of test tubing	Approx. 1'500 m
Lengths of pup joints	Length, quantity 0.50 m, 2 1.00 m, 2 1.03 m, 1 1.50 m, 2 1.55 m, 1 1.83 m, 1 3.00 m, 3

4.2.1.7 Slim tubing

The rate of pressure increase during the flow phase of a slug test depends on the formation transmissivity and the diameter of the test tubing, which mainly defines the wellbore storage of the test system during the slug. To improve the resolution of the pressure change, a slim tubing was used to reduce the diameter of the test tubing for slug tests in formations with low transmissivity. However, the use of a slim tubing in formations with low transmissivity reduces the dominance of the wellbore storage term that is defined by the diameter. In this case, the wellbore storage term that is determined by the compressibility of the test fluid as well as the equipment (defined by determining the test zone compressibility during a shut-in phase) must be taken into account (Black et al. 1987).

The slim tubing consists of a stiff tube, which is installed into the test tubing. A packer at the bottom of the slim tubing with an outer diameter of 56 mm sealed the annulus between the 2 $\frac{7}{8}$ " tubing and the slim tubing. The water level in the slim tubing was measured with the P4 sensor from the QSSP and additionally with a backup pressure sensor installed at the bottom of the slim tubing packer, referred to as P4-slim. P4-slim has a smaller pressure range and thus a higher precision compared to P4. The technical specifications of the slim tubing are summarised in Tab. 4-10.

After lowering the water level in the 2 $\frac{7}{8}$ " test tubing for a slug withdrawal test to the specified depth, the slim tubing was installed in the tubing below the water level. Afterwards, the slim tubing packer was inflated, and the test was started by opening the SIT valve. The water level only increased in the slim tubing. The use of a stiff tube ensured a constant inner diameter independent of the pressure (fluid level). It should be noted, however, that in the numerical analysis an effective diameter of the slim tubing must be used when using a simulator based on Pickens et al. (1987).

Tab. 4-10: Specifications for the slim tubing

¹ FS = full scale

Slim tubing	Manufactured by Solexperts	
Types	Polyethylene tube	Polyamide tube
Inner diameter	12 mm	6 mm
Outer diameter	16 mm	8 mm
Length	300 m	300 m
Packer specifications	Diameter 56 mm, sealing length 1'000 mm, working pressure 1 – 13.5 MPa	
Packer pressure line	Polyamide OD: 6 mm; ID: 3 mm	
Packer pressure sensor	Keller PAA-33X, 0 – 5'000 kPa, accuracy 0.1% FS ¹	
Pressure sensor (P-slim)	Keller DCX-22, 0 – 5'000 kPa, accuracy 0.05% FS ¹ , resolution 0.0025% FS ¹	
Installation procedure	Wireline system of the drill rig	

4.2.1.8 Submersible pumps

Frequency driven 3" and 4" Grundfos submersible pumps can be used for pumping tests and during open-hole pumping. The specifications are included in Tab. 4-11. The flow rate can be arbitrarily adjusted because of the frequency control of the pump.

Tab. 4-11: Specifications for the submersible pumps

Submersible pump types	4" down-hole pump	3" down-hole pump
Manufacturer	Grundfos, Fällanden, Switzerland	
Type	SP14-27E	SQE1-110
Regulation	Frequency-controlled	Frequency-controlled
Dimensions	101 × 3'040 mm	74 × 852 mm
Pumping rate at 150 m	100 l/min	10 l/min
Range of pumping rates	Max. 300 l/min	Max. 28 l/min
Maximum installation depth	160 m	160 m
Maximum temperature	40 °C	35 °C
Weight	57 kg (pump) 31 kg (motor)	6 kg
Pump housing	Yes	No
Specifications of pump housing	Length: 4.22 m OD max: 180 mm Weight: 130.3 kg	
Purpose	Pumping tests	Pumping tests, fluid logging

4.2.1.9 Progressive cavity pump

For constant rate withdrawal tests (pumping tests) a progressive cavity pump (PCP), a so-called Moyno® type pump, was used. The PCP consists of a helical rotor and a twin helix in a rubber stator. The stator is integrated into the test tubing string and allows for pumping, if necessary, but does not preclude any other test methods. For pumping, a suitable rotor had to be installed by means of the so-called sucker rods until the rotor had fully penetrated the stator. The specifications are listed in Tab. 4-12.

Tab. 4-12: Specifications for the PCP

Type	Progressive cavity pump (PCP)
Manufacturer	Netzsch
Dimensions	Drive head: L × W × H: 1'375 × 767 × 1'263 mm
Pumping rates	1.7 – 60 l/min Pumping rates of < 1.7 l/min can be reached by closing the valve installed in-line at the wellhead
Maximum installation depth	300 m
Temperature	10 °C – 70 °C
Sucker rods, type	¾" × 7.62 m
Sucker rods, quantity	45
Total length	Approx. 300 m
Available stators	1 for pump rates 10.4 – 60 l/min, Temp. 10 °C – 70 °C 1 for pump rates 1.7 – 5.5 l/min, Temp. 10 °C – 70 °C
Available rotors	3 for pump rates 10.4 – 60 l/min, Temp. 10 °C – 30 °C, 30 °C – 50 °C, 50 °C – 70 °C 3 for pump rates 1.7 – 5.5 l/min, Temp. 10 °C – 30 °C, 30 °C – 50 °C, 50 °C – 70 °C

4.2.2 Surface equipment

The surface equipment consisted of the following equipment:

- Winch for quadruple flat-pack cable
- Flow control system
- Injection and pumping head
- PCP drive head and control unit
- Data acquisition system

Most of the surface equipment parts were installed in a mobile measuring trailer.

4.2.2.1 Flow board

For the control and measuring of pump (and injection) rates, a flow board with three flowmeters of the type Yokogawa AXF/ADMAG was available. The flowmeters covered a flow rate range between 0.03 and 100 l/min (Tab. 4-13). The schematic layout of the flow control unit is displayed in Fig. 4-3.

Tab. 4-13: Specifications for the flowmeters

¹ FS = full scale

	Measuring range and accuracy			
	Lower limit		Upper limit	
	[l/min]	[% FS ¹]	[l/min]	[% FS ¹]
AXF 002	0.03	1	2.945	0.35
AXF 005	0.1	1	11.78	0.35
ADMAG SE202	1.0	1	100	0.35

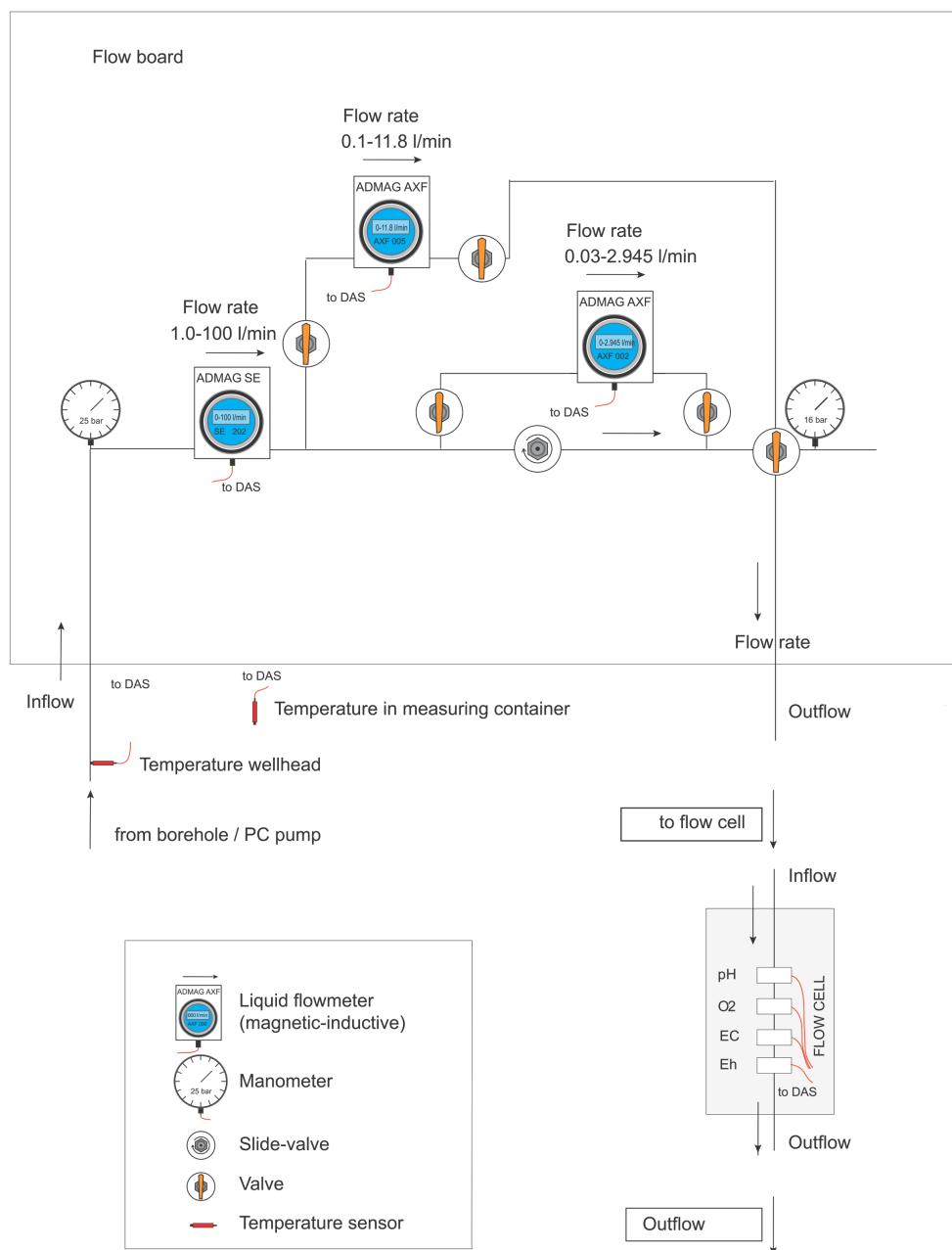


Fig. 4-3: Schematic layout of the flow control unit

4.2.2.2 Packer pressure control unit

Two transducers (type Keller PA-23SY, 30'000 kPa) mounted on the surface inflation control panel were used to monitor the packer inflation pressures (Fig. 4-4). The packer pressure lines are connected to a pressure vessel, which is pressurised by nitrogen. The pressure in the pressure vessel is controlled by a pressure controller for closed volumes. The specifications of the pressure controller are given in Tab. 4-14.

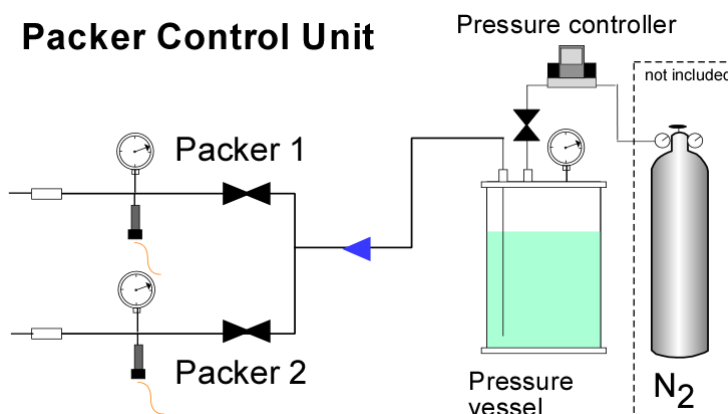


Fig. 4-4: Schematic layout of the packer control unit

Tab. 4-14: Specifications for the pressure controller

¹ FS = full scale

Pressure controller type	Dual-valve pressure controller
Manufacturer	Alicat, USA
Pressure range	0 – 20'684 kPa
Accuracy	0.25% FS ¹
Repeatability	0.08% FS ¹

4.2.2.3 Additionally recorded measurements at surface

A single pressure transducer (type Keller PAA-33X, 80 – 120 kPa absolute) was mounted outside the monitoring trailer and used to monitor barometric pressure and air temperature (Tab. 4-15).

During pumping tests, the physico-chemical parameters (e.g. pH, EC, Eh, temperature and oxygen concentration) and the temperature of the extracted fluid were recorded. The specifications of the physico-chemical sensors are given in Tab. 4-16. The specifications of the temperature sensor are also given in Tab. 4-16. The sensors were calibrated on-site before each use.

Tab. 4-15: Specifications for the atmospheric pressure sensor

[/] FS = full scale

Pressure sensor type	Keller PAA-33X
Manufacturer	Keller, Winterthur, Switzerland
Pressure range	80 – 120 kPa
Accuracy	0.02% FS [/]
Resolution	0.002% FS [/]

Tab. 4-16: Specifications for the physico-chemical sensors

Sensor type	EC	pH	Eh	O ₂	Temperature
Manufacturer	Xylem analytics, Weilheim, Germany				IST AG
Model	WTW TetraCon 325	WTW SensoLyt DW	WTW SensoLyt PtA/Pt	WTW FDO 700 IQ	Pt 1000
Range	1 µS/cm – 2 S/cm	0 – 14	± 2'000 mV	0 – 20 mg/l	-50 – 650 °C
Accuracy	n/a	n/a	n/a	n/a	± 0.15 °C at 0 °C ± 0.35 °C at 100 °C
Resolution	n/a	n/a	n/a	0.01 mg/l (0.01 ppm)	< 0.1 °C
Temperature range	0 – 100 °C	0 – 60 °C	0 – 60 °C	-5 – 50 °C	-50 – 650 °C

4.2.2.4 Data acquisition system

The data acquisition system (DAS) consisted of a Solexperts HDDP interphase for digital and analogue sensors, two industrial PCs, two screens and a keyboard. Data acquisition was performed through the Solexperts GeoMonitor II (GMII) software. The downhole pressures (P1, P2, P3, P4) and temperature measurements (T1, T2, T3, T4) were recorded in real time through the quadruple flat-pack cable assembly. Surface measurements like flowmeter rates, packer pressures, atmospheric pressure and temperature, slim tubing packer pressure and the physico-chemical parameters were recorded either permanently or, if required, with the same scan rate as the downhole pressures from the QSSP.

The scan rates could be adjusted as required between 0.5 s (using a reduced number of sensors) and > 30 s.

The measurements were written to a data file on the PC hard drive in real-time with a continuous data collection and database model. From the PC hard drive, the data were transferred to another network PC continuously for 'online' analysis and data back-up. An uninterruptible power supply was utilised to protect the system from short power interruptions.

4.2.3 GTPT equipment

The test equipment for the GTPT was designed in a modular way to be used together with the HDDP system. Additional equipment parts were provided by Nagra. The individual parts were assembled on-site, together with the HDDP system of the field test contractor.

The additional system parts for the downhole equipment were the following:

- X-over 2 $\frac{7}{8}$ " to 4 $\frac{1}{2}$ "
- Second shut-in tool (SIT1) with crown shaft below the bottom packer to control the displacement of the interval fluid to the exchange chamber
- 4 $\frac{1}{2}$ " exchange chamber of variable length (API 4 $\frac{1}{2}$ " tubing NU; N80, OD 114.3 mm, ID 100.5 mm, 12.6 lbs/ft = 18.75 kg/m; coupling OD: 132 mm) below the HDDP system / lower SIT1 for the collection of exchanged interval fluid, e.g., drilling mud, sodium hydroxide (NaOH) solution
- Bottom cap / bull nose 4 $\frac{1}{2}$ "
- Dip tube (OD 21.3 mm, wall thickness 2.6 mm) inside the exchange chamber, stainless steel with threads and couplings of variable length, with swivel connection and installation tools
- 3 additional $\frac{1}{4}$ " stainless steel lines (910 m, OD 6.35 mm, ID 4.55 mm) on separate coils (SIT1 line, backflow line from exchange chamber, injection line into the interval with a check valve) besides the standard quadruple flat-pack
- 2 pressure sensors Keller PA-23SY to measure the pressure at the injection and backflow lines
- 2 $\times$ 146 mm inflatable packers with a double mandrel including five through-going pieces of $\frac{1}{4}$ " stainless steel lines and fittings

The additional surface equipment encompasses the following components:

- 1 gas flow controller 0 – 5 l/min (injection line to interval) (l = litre normal)
- 2 gas flowmeters 0 – 150 l/min (one connected to back flow line from exchange chamber and one to injection line for NaOH displacement)
- A flow control board for one gas flow controller and two gas flowmeters with valves and manometers
- Closed tanks for NaOH solution for injection via the (gas-) injection line
- An additional high-pressure injection pump instead of a booster to obtain a higher injection rate and to save time

The flow controller and flowmeters, as well as all other sensors of the GTPT system, were connected to the DAS.

The most relevant system parts are described in detail in the following sections.

A schematic overview of the GTPT system is shown in Fig. 4-5. The four diagrams show the planned test phases of the GTPT:

1. Repeatedly pressurising the (empty) exchange chamber with nitrogen (N_2) to avoid any damage during installation
2. Injection of NaOH solution through the injection line to push the interval fluid to the exchange chamber and simultaneous extraction of N_2 from the exchange chamber to the surface via the extraction line, SIT1 open
3. Injection of N_2 through the injection line to push the NaOH solution from the interval to the exchange chamber and extraction of N_2 from the exchange chamber to the surface via the extraction line, SIT1 open
4. Start of GTPT: Relatively slow injection of N_2 at constant rate into the interval, SIT1 and SIT2⁷ closed

⁷ In this section, the usual SIT from the HDDP, which controls the fluid connection between the interior of the test rods and the test interval, is labelled SIT2; in the test string, it was positioned above SIT1, which controls the fluid connection between the exchange chamber and the test interval during a GTPT.

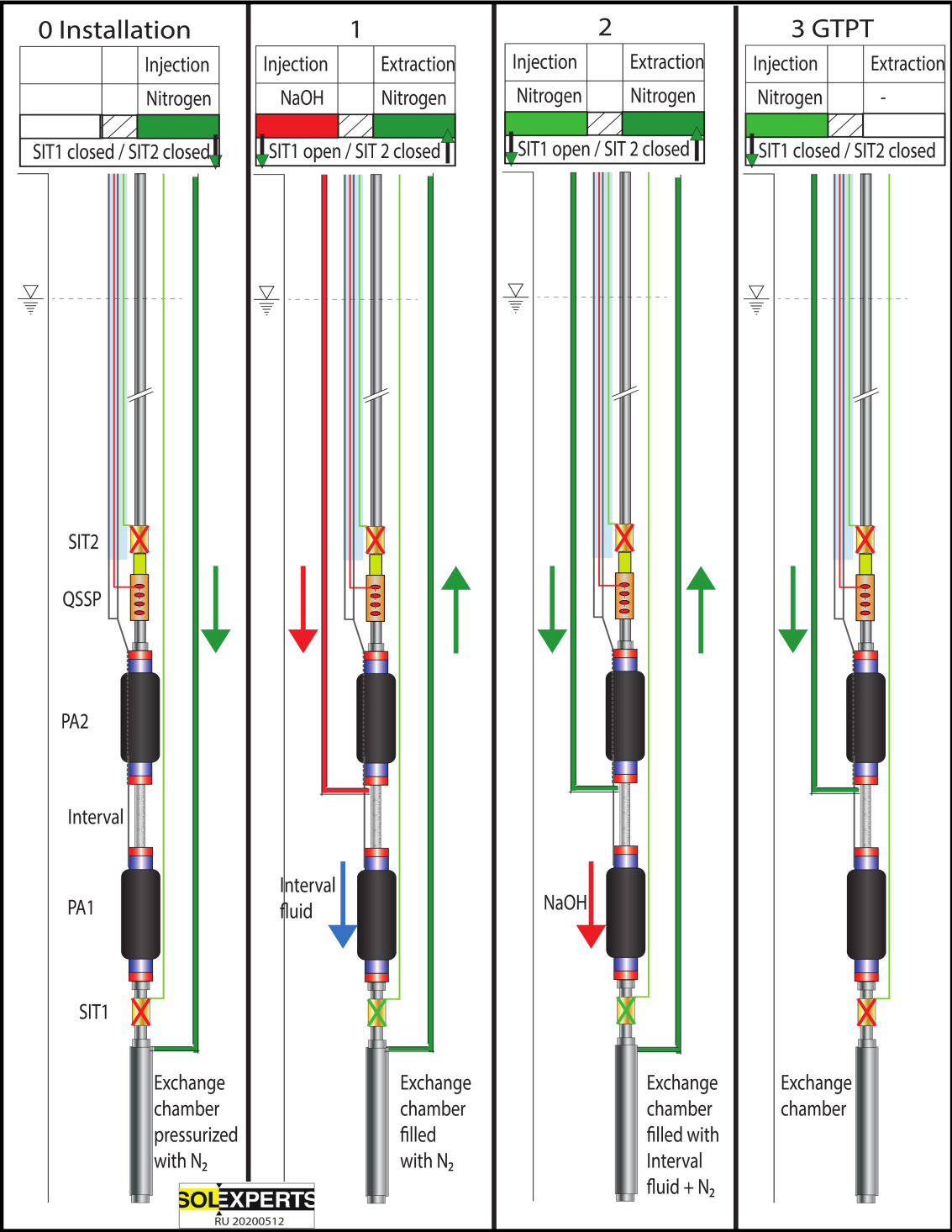


Fig. 4-5: Schematic layout of the modified HDDP system with the four major phases of the GTPT

4.2.3.1 Packers for the GTPT

The system comprised two new packers with a diameter of 146 mm which have a double mandrel including five pieces of ¼" stainless steel lines and the corresponding fittings.

A detailed description of the packers and the use of the ¼" stainless steel lines is given in Tab. 4-17. Before installation, the packers with the corresponding lines were saturated with water and anti-freeze (if necessary).

Tab. 4-17: Specifications for the 146 mm packers for the GTPT

Manufacturer	Inflatable Packers International (IPI), Perth, Australia
Packer types	IPI 5¾" (146 mm)
Material and type	Duplex, 316 ss, Nitrile Butadiene Rubber (NBR), sliding end
Mandrel	Double mandrel with 5 through-going pieces of ¼" stainless steel lines
Use of ¼" stainless steel lines	Packer 1 (lower packer): 1. Not used 2. SIT1 line 3. Backflow line 4. Not used 5. Line to the QSSP sensor P1 Packer 2 (upper packer) 1. Injection line 2. SIT1 line 3. Backflow line 4. Not used 5. Inflation line packer 1 Note: The final allocation of the line ports was defined on-site
Reinforcement type	Steel wire reinforced
Borehole diameter	162 / 216 mm
Packer diameters	162 – 280 mm (pressure dependent)
Outer diameter, not inflated	146 mm max.
Inner diameter	43.7 mm min.
Overall length: Bottom packer Top packer	 2.195 m 2.195 m
Weight	95 kg each
Rubber sleeve length	1.20 m
Thread connections	2⅞" EU pin × 2⅞" EU box
Packer inflation lines	Quadruple flat-pack
Inflation method	Surface controlled
Inflation fluid	Water and anti-freeze (if necessary)

4.2.3.2 Stainless steel lines for the GTPT

Three additional 1/4" stainless steel lines (OD 6.35 mm, ID 4.55 mm), each with a length of 910 m, were installed together with the downhole equipment and used as follows:

- Activation and de-activation of the SIT1 – SIT1 line; marked with white tape
- Gas/fluid injection into the interval – injection line; marked with green tape
- Backflow line from the exchange chamber – backflow line; marked with red tape

The lines were connected to the corresponding stainless steel feed-through, through the top and, if required, through the bottom packer double mandrel. At the surface, the lines were coiled up on the corresponding coils. Each stainless steel line was connected to a valve and a 250 bar manometer. Two coils (injection and backflow lines) were additionally equipped with pressure sensors of the type Keller PA-23SY, 0 – 300 bar.

The outlet port for the injection line at the lower end of the top packer was equipped with a check valve which enabled flow into the test interval but no backflow from the test interval into the injection line. The check valve opened at 4 bar injection pressure.

4.2.3.3 Zero-displacement shut-in tool for GTPT

The new SIT1 used for the STA3-1 GTPT test was similar to the SIT2 (the HDDP SIT used for hydraulic packer testing) which controlled the fluid connection between the interior of the test rods and the test interval. The SIT1 is a zero-displacement valve which controls the fluid connection between the exchange chamber and the test interval. The SIT1 was hydraulically operated over a 1/4" stainless steel line using the booster pump. The opening and closing were performed via an axially moveable valve piston. The valve piston was moved via the hydraulic (closure) line by application of pressure and the valve was closed. The valve piston was reset at pressure release through a pre-stressed spring, and the valve was opened (pressure-free opening).

With a pressure compensation element, the pressure at interval depth (annulus pressure) was used to support the spring and to keep the opening/closing pressure constant for the entire borehole depth. The spring force was high enough to ensure proper functioning of the valve, also at deep groundwater levels. The specifications are given in Tab. 4-18.

Tab. 4-18: Specifications for the zero-displacement shut-in tool (SIT1) for the GTPT

Manufacturer	Solexperts AG
Maximum water flow rate	Below 40 l/min without friction loss, max. 350 l/min
Pressure loss caused by SIT at a flow rate of 1 l/min and 10 l/min	± 0 kPa
Closing pressure	9'000 – 10'500 kPa

4.2.3.4 Flow control board for GTPT

For the control and measuring of gas injection and extraction rates, the high-pressure gas flow controller and flowmeters were mounted to a flow control board. The flow controller for the control of the injection flow rate had a measuring range of 0.1 – 5 l/min. The two flowmeters for the flow rate measurements during the displacement of NaOH with gas and during backflow had a measuring range of 3 – 150 l/min (Tab. 4-19). A schematic drawing of the flow board is included in Fig. 4-6.

In addition to the flow controller and flowmeters, the flow board was equipped with two manometers for 100 bar, two for 160 bar and one for 250 bar maximum pressure. Two needle valves were used to control the flow rates at the injection side and at the backflow side.

Tab. 4-19: Specifications for the gas flow controller / meters for the GTPT

¹ FS = full scale

	Gas flow controller (Flow_G_INJ)	Gas flowmeter (Flow_G_DIS)	Gas flowmeter (Flow_G_BCK)
Manufacturer	Bronkhorst	Bronkhorst	Bronkhorst
Type	IN-FLOW	IN-FLOW	IN-FLOW
Measuring range	0.1 – 5 l/min	3 – 150 l/min	3 – 150 l/min
Accuracy (incl. linearity)	$\pm 0.5\%$ Rd (reading), $\pm 0.1\%$ FS ¹	$\pm 0.5\%$ Rd (reading), $\pm 0.1\%$ FS ¹	$\pm 0.5\%$ Rd (reading), $\pm 0.1\%$ FS ¹
Inlet pressure	50 – 200 bar (calibrated for 125 bar)	70 – 200 bar (calibrated for 135 bar)	50 – 100 bar (calibrated for 75 bar)
Output pressure	1 – 150 bar	–	–
Minimum ΔP	2 bar	–	–
Medium	N ₂	N ₂	N ₂

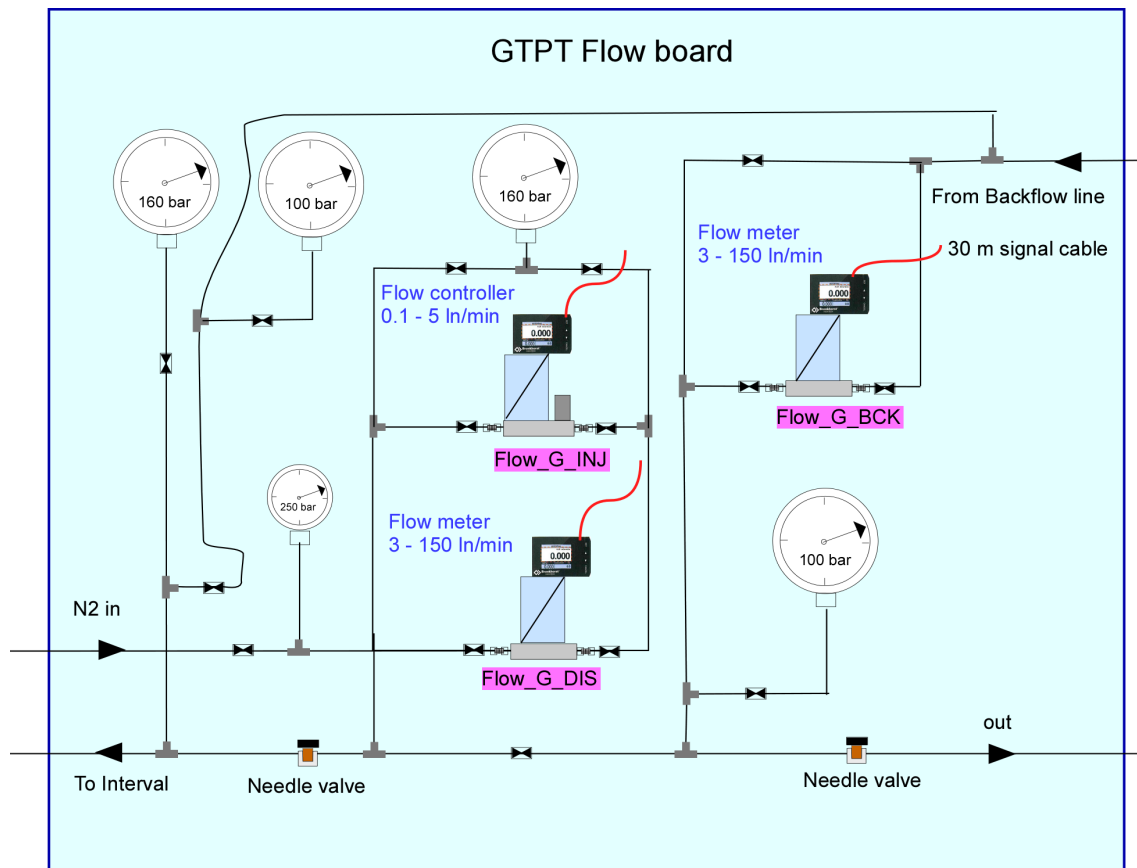


Fig. 4-6: Schematic layout of the flow control unit for the GTPT

4.3 Test analyses

4.3.1 Workflow

For STA3-1, the general on-site analysis approach involved mainly numerical techniques considering the entire borehole pressure history. Analytical solutions and graphical diagnostic representations were used to analyse the flow model selected, to present the results and to conduct more detailed consistency checks between measurements and simulations. This ensured a comprehensive evaluation of the recorded data. The numerical solutions were assessed further with a perturbation analysis. Prior to commencement of the hydraulic tests, the starting input parameters and in particular, the representation of the borehole history period, were defined.

The on-site analysis workflow supported the test design to achieve the quality objectives defined by Nagra:

- Identification of the most appropriate flow model, e.g. by log-log diagnostic plots (Agarwal 1980)
- Numerical simulation of individual test sequences in cartesian coordinates

The suitability of the applied flow model was checked with diagnostic representations of the recorded and simulated pressure data, and a limited perturbation analysis was used to assess the credibility of the numerical solution.

- Assessment of the credibility of the numerical solution and associated uncertainties through perturbation and sampling analysis
- Numerical simulation of the entire test sequence in cartesian coordinates using the optimised parameter set obtained from individual phase analysis
This final step was used to check the consistency of the model with the entire data set.
- Consistency check of the test analysis and the estimated parameters by the technical supervisor

The results were used to continually optimise the test design to achieve the quality objectives within the dedicated time of testing. A general flowchart of the analysis work is provided in Fig. 4-7.

Three programmes were used for the analytical and numerical interpretation: Hugo TM (Solexperts AG), nSIGHTS software (Geofirma Engineering Ltd. & INTERA Inc. 2011) and Multisim (AFRY Switzerland Ltd.). The Cooper-Bredehoeft-Papadopoulos type-curves were used to analyse both slug and pulse tests (Cooper et al. 1967, Bredehoeft & Papadopoulos 1980). Recovery tests were analysed according to Agarwal (1980). A summary of the applied test analysis methods is presented in Tab. 4-20.

Tab. 4-20: Summary of analytical analysis methods / techniques

Test phase	Analysis method	Reference
Pulse test	Type-curve matching	Bredehoeft & Papadopoulos (1980)
	Diagnostics: log-log plot showing dimensionless ΔP and derivative using the deconvolution approach of Peres	Peres et al. (1989)
Slug test (flow phase SW)	Type-curve matching	Cooper et al. (1967) Ramey & Agarwal (1972)
	Diagnostics: log-log plot showing dimensionless ΔP and derivative using the deconvolution approach of Peres	Peres et al. (1989)
Slug test recovery (pressure recovery after slug flow phase, SWS)	Diagnostics: log-log plot showing ΔP and derivative versus "equivalent time" (Agarwal)	Agarwal (1980)
	Straight-line analysis on transient pressure data	Agarwal (1980)
Constant rate test	Diagnostics: log-log plot showing ΔP and derivative versus time	Bourdet et al. (1989)
	Straight-line analysis on transient pressure data	Cooper & Jacob (1946)
Pressure recovery after constant rate tests	Diagnostics: log-log plot showing ΔP and derivative versus "superposition time" (Agarwal)	Agarwal (1980) Birsoy & Summers (1980)
	Straight-line analysis on transient pressure data	Agarwal (1980) Jacob & Lohman (1952)

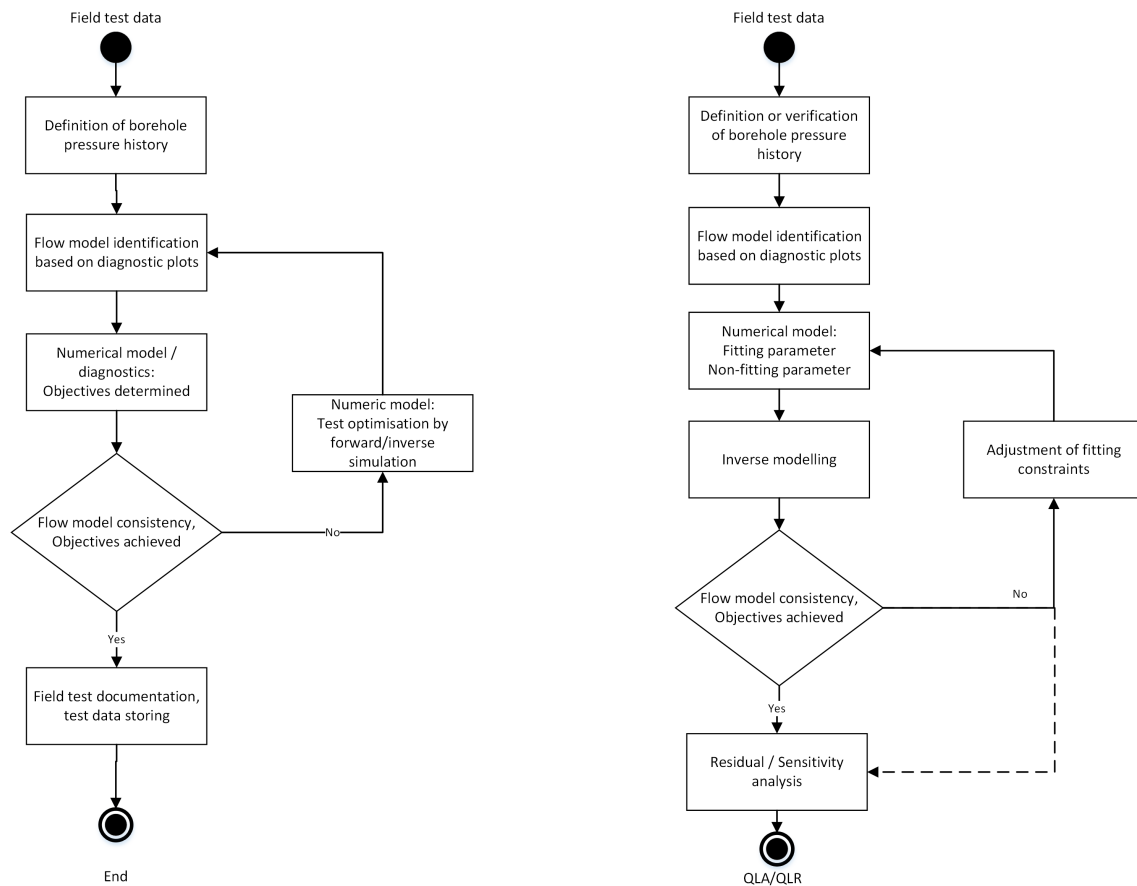


Fig. 4-7: Flowcharts for the on-site hydraulic packer test analysis (left) and Quick Look Analysis (QLA) (right)

The Detailed Analysis (DA) was performed off-site after the test had been completed and is based on the Quick Look analysis (QLA) reported in the Quick Look Report (QLR). The QLR was reviewed as part of the Quality Control (QC) program. During this task, open questions and potential ambiguities of the analysis were defined. Based on the outcome of the QC review, further specifications and, if necessary, further analyses were implemented. Fig. 4-8 provides the general flowchart of the DA, which includes perturbation and non-fitting parameter analysis (of the sampling analysis), to obtain the most reasonable parameter results and ranges of uncertainty. The work is summarised in a Detailed Report (DR), with the QLR included as an Appendix.

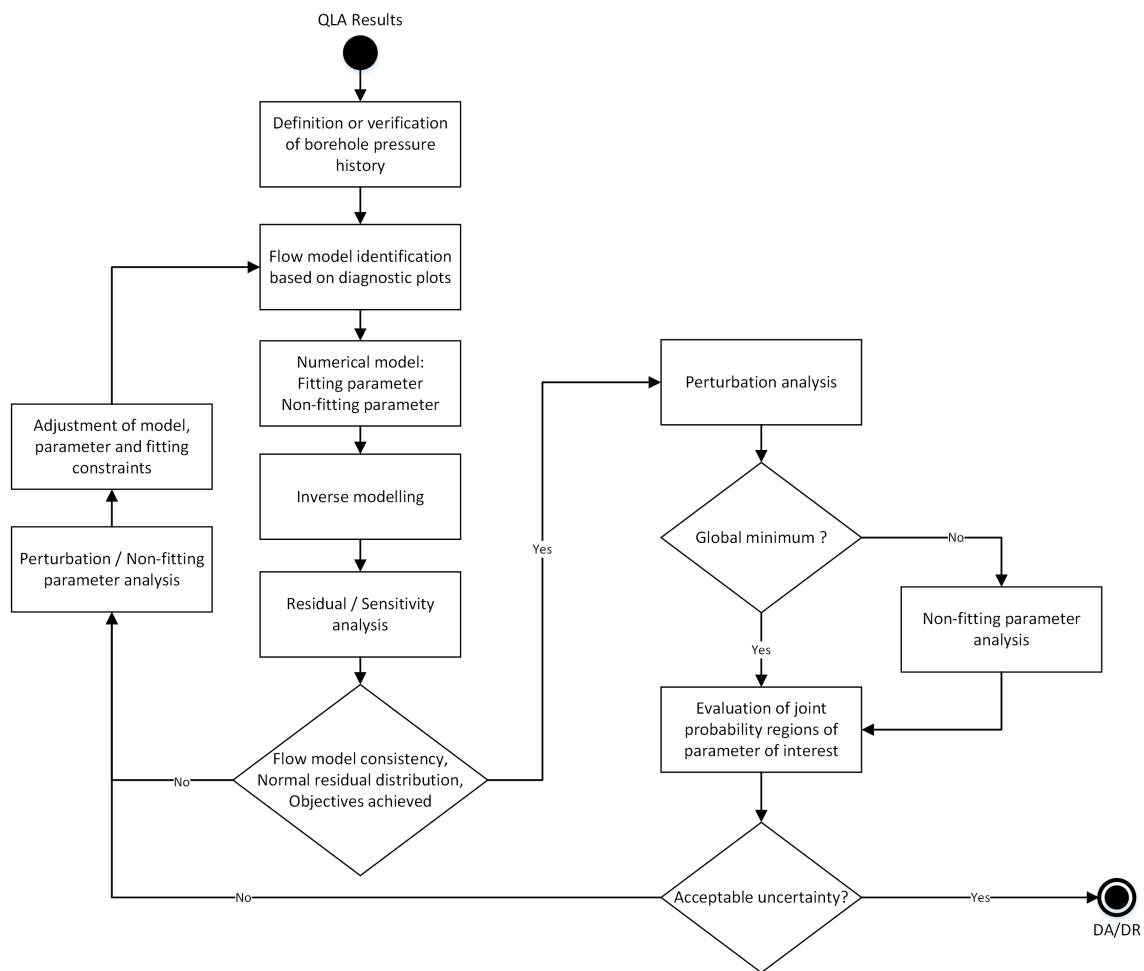


Fig. 4-8: Flowchart for the off-site Detailed Analysis (DA) of a hydraulic packer test

4.3.2 Special effects

The time series measured during hydraulic packer tests are the pressure and temperature inside the test interval. Their development over time was analysed to estimate the hydraulic properties of the formation surrounding the test interval. Various factors affected the recorded time series. All hydraulic tests are affected by factors beyond the test execution and the model used for their analysis (analytical solutions based on assumptions to derive them, numerical models based on the physical processes included in their base equation system). These are referred to as disturbances because they are not considered in the analysis. However, it is possible to describe the development of temperature and pressure signals using the diffusion equation. Disturbances are of short duration in formations with medium to high transmissivity. In formations with low transmissivity, disturbances in the pressure or temperature field can have a significant influence on the pressure signal measured during the test in the test interval (e.g. Nagra 1997, Grauls 1999, Nagra 2001).

Any disturbances of the pressure field during the time before the hydraulic test is started, are summarised under the name 'borehole pressure history'. Disturbances in the pressure and temperature fields can be caused by drilling and other activities before testing. In addition, disturbances can occur even during testing, e.g. mechanical effects (including poroelastic effects) due to

changes in the stress field surrounding the interval, or osmosis due to the chemical interaction of the formation and drilling fluid. However, results from the experiment 'Deep Borehole Hydraulic Testing Experiment' in the Mont Terri Rock Laboratory show that osmotic effects have no significant impact on the determination of transmissivity and hydraulic head (Marschall et al. 2003).

As the TBO boreholes are multi-purpose boreholes with many other objectives besides hydraulic packer testing, there is always a trade-off between disciplines regarding optimal test conditions. Most hydraulic packer tests were performed without exchange of drilling fluid with testing fluid in order to maintain borehole stability. In addition to this preventative measure, the numerical analysis tool can estimate the effect of these influences, so that plausibility ranges for the parameter estimations can be defined. In the following, possible individual special effects that have previously been identified, e.g. for the Benken borehole (Nagra 2001), are discussed in more detail.

4.3.2.1 Borehole history

All numerical analyses took into account the borehole pressure history. The borehole pressure history was constructed based on activities that took place prior to hydraulic testing. Drilling through the midpoint of the test interval was used as the starting point of the pressure history. The borehole pressure history data were incorporated into the numerical analyses. The following information was used:

- Date and time of drilling through the interval midpoint, from drilling logs
- Drilling fluid density
- Mud level in the borehole prior to testing
- Pressure records of preceding hydraulic testing

The drilling fluid densities were measured four times per day and documented in the drilling mud report by the drilling mud engineer from SIRIUS-ES GmbH. In addition, continuous recordings were available from the mud logging company GEODATA during periods of coring and mud circulation, and mud level measurements in the borehole were performed from time to time.

Most affected by the borehole pressure history is the determination of the static formation pressure or the hydraulic head / hydraulic potential (which are derived from the static formation pressure), which in turn depends on the transmissivity of the formation. In formations with low transmissivity, like the Opalinus Clay, the determination of the static formation pressure can be impossible to carry out in a reasonable time due to the long duration of the pressure history. This was proven by measurements carried out using the Benken long-term monitoring system, which demonstrated that the static formation pressures of the Opalinus Clay determined by hydraulic tests were much higher than those subsequently determined by long-term measurements (e.g. Jäggi & Vogt 2020).

The specific periods of the borehole pressure history taken into account for the analysis of the hydraulic packer tests in borehole STA3-1 are provided in Tab. 4-21.

Tab. 4-21: Specific periods of the borehole pressure history

History refers to the period prior to the separation of the test interval from the rest of the borehole through the inflation of the last packer, which marks the beginning of hydraulic testing.

Test name	Drilling through midpoint: date and time	Start hydraulic testing: date and time	Borehole history duration [h]
STA3-1-MAL1	05.01.2021 21:20	17.01.2021 06:35	273.25
STA3-1-LIA1	08.02.2021 09:58	12.02.2021 14:00	100.03
STA3-1-OPA1	06.02.2021 11:45	16.02.2021 14:02	242.28
STA3-1-OPA2	03.02.2021 20:41	19.02.2021 14:43	378.03
STA3-1-OPA3	01.02.2021 23:21	22.02.2021 19:12	499.85
STA3-1-LIA2	07.02.2021 22:43	28.02.2021 11:22	492.65
STA3-1-BDO1	31.01.2021 01:48	03.03.2021 12:44	754.93
STA3-1-BDO2	28.01.2021 22:03	06.03.2021 13:10	879.12
STA3-1-BDO3	27.01.2021 14:59	09.03.2021 10:05	979.10
STA3-1-OPA4	05.02.2021 08:47	15.03.2021 07:20	910.55
STA3-1-KEU1	18.04.2021 04:51	20.04.2021 10:41	53.83
STA3-1-MUK1	18.05.2021 00:34	20.05.2021 20:58	68.40

4.3.2.2 Interval temperature changes during testing

All activities inside the open borehole also affect the temperature field in and around the borehole. In formations with low transmissivity, this temperature disturbance affects the pressure field surrounding the borehole due to coupled thermo-hydraulic processes. The analysis of hydraulic tests using the numerical software packages nSIGHTS, Multisim and WellSi can incorporate temperature changes during the hydraulic test that lead to a change in fluid volume and thus pressure within a confined test interval volume. The fluid volume change in the test interval was calculated using the volumetric thermal expansion coefficient of the interval fluid (water), which itself is temperature-dependent. The pressure change is linearly dependent on the interval fluid volume change using a proportionality factor, the compressibility of the interval.

4.3.2.3 Mechanical effects

The mechanical deformations caused by drilling- and testing-related stress redistribution in the formation can also influence the pressure response during a hydraulic test. Normally, the conceptual model for the description of the storage coefficient used in the underlying hydraulic models assumes a compressible pore volume and an incompressible grain structure. In this model, changes in pore pressure are considered as movement of the fluid into and out of the pore volume. The coupling between fluid volume change and mechanical deformations results in a time-dependent deformation for an elastic medium (Detournay & Cheng 1988). The Opalinus Clay has shown a time-dependent deformation during tunnel excavation in the Mont Terri Rock Laboratory (see Lisjak et al. 2015 for a summary of the observations and for a numerical interpretation of the data). Opalinus Clay time-dependent behaviour is most likely due to the undrained and drained

excavation response, rather than mechanical creep phenomena. In formations with low transmissivity, time-dependent deformations can have an influence on the pressure signal observed in the test interval.

However, there are no data on mechanical deformations available for the tests in borehole STA3-1 that would allow the characterisation of mechanical effects on the tests in formations with low transmissivity. Deformations of the borehole wall can be included in the analysis by all the numerical software packages used by the means of an appropriate parameterisation during the analysis in the same way as for temperature changes inside the interval. The resulting pressure change is caused by volume changes, which can be either linear or quadratic. The proportionality factor between the volume change and the pressure change is the interval compressibility.

4.4 Test activities

In total, twelve hydraulic packer tests were performed in borehole STA3-1 using the HDDP in single and double packer configuration. The most important test specifications are summarised in Tab. 4-22. The hydraulic packer tests were performed in the following geological formations (*cf.* Dossier III):

- Malm Group with a focus on «Felsenkalke» and «Massenkalk» (STA3-1-MAL1); following the fluid logging campaign (STA3-1-FL1-MAL)
- Dogger Group («Brauner Dogger») with «Parkinsoni-Württembergica-Schichten» and mostly «Herrenwis Unit» (STA3-1-BDO3), «Herrenwis Unit» and some Wedelsandstein Formation (STA3-1-BDO2), and «Murchisonae-Oolith Formation» with some Wedelsandstein Formation at the top and some Opalinus Clay at the bottom (STA3-1-BDO1)
- Dogger Group with a focus on Opalinus Clay (STA3-1-OPA3, STA3-1-OPA2, STA3-1-OPA4 and STA3-1-OPA1)
- Lias Group with a focus on the Staffelegg Formation with the Gross Wolf, Rietheim, Grünschholz, Breitenmatt, Rickenbach and Frick Members (STA3-1-LIA2) resp. including also the Beggingen and Schambelen Members and a small part of the Klettgau Formation (STA3-1-LIA1); both with some Opalinus Clay at the top
- Keuper Group with mostly Klettgau Formation including the Gruhalde, Seebi, Gansingen and Ergolz Members and the top of the Bänkerjoch Formation (STA3-1-KEU1)
- Muschelkalk Group with a focus on the Schinznach Formation including the Stamburg, Liedertswil and Leutschenberg Members and a small part of the Zeglingen Formation (STA3-1-MUK1)

Nearly all hydraulic tests were performed in the cored borehole section with a borehole diameter of 6 $\frac{3}{8}$ ", 114 mm (deflated diameter) packers and without any prior fluid exchange, i.e., with the drilling fluid being used as the interval test fluid. The exceptions to this were STA3-1-MAL1 where a fluid exchange with traced tap water was required for the previously performed fluid logging (STA3-1-FL1-MAL), and STA3-1-OPA4 where the hydraulic test was complemented with a GTPT and used 146 mm (deflated diameter) packers.

The density and viscosity of the drilling fluid were recorded by the mud engineer in daily mud reports. Considerable mud losses have not been reported while drilling borehole STA3-1. Minor dynamic losses, hardly at the detection limit, may have occurred in the section where the fluid logging (STA3-1-FL1-MAL) was performed and in the Muschelkalk (STA3-1-MUK1).

The test tubing was typically filled with traced tap water. Sodium-fluorescein at a concentration of approximately 1 ppm was used to trace the drilling mud, while sodium-naphthionate or 1.5-naphthalene disulfonate acid – NDSA (for hydraulic tests in shales) were used as tracers for the water in the test tubing at concentrations of approximately 10 ppm.

The SIT was closed during the entire time the HDDP was lowered to the test depth and also during installation. Therefore, in test intervals with low transmissivity, the interval fluid density was not affected by traced water in the test tubing as mainly withdrawal tests were performed and no or only very little fluid flow occurred. If a pressure increase of more than 100 kPa was observed in the test interval during inflation of the top packer, the SIT was opened and the COM phase started. Due to the higher density of the mud in the test interval, for formations with low transmissivity, it was assumed that no flow occurred from the test tubing into the test interval during the COM phase. Flow from the formation into the borehole by means of a longer test phase of pressure reduction in the interval (i.e. a slug or pumping test phase) was created during all tests.

A swabbing tool was used to create the pressure difference between the test tubing and the test interval. For each of the pumping tests the PCP was used, and the position of the PCP stator in the test string was optimised up to the limit of the allowable pumping head. If two tests were performed sequentially without pulling the HDDP out of the borehole between tests, a stator was already installed for the first test (usually the deeper test).

Drilling stopped shortly before hydraulic testing of the STA3-1-MAL1, STA3-1-LIA1, STA3-1-KEU1 and STA3-1-MUK1 intervals. The time gap between drilling and the start of hydraulic testing was significantly longer for the other test intervals, where a series of hydraulic tests were performed after drilling a longer borehole section. For the tests STA3-1-LIA1 and STA3-1-MAL1, a petrophysical logging campaign and a fluid logging campaign, respectively, were performed between the end of drilling and hydraulic testing. Prior to STA3-1-KEU1 and STA3-1-MUK1 and after pulling out of hole (POOH) the coring string a technical logging (caliper logging) was executed. The measured pressures (measured by the downhole QSSP sensors) and pumping rates (measured by the flow board at the surface) for all tests conducted in borehole STA3-1 are provided in Figs. 4-9 to 4-20. The figures were taken directly from the corresponding analysis reports of the field test contractor.

The interval temperature change was included in the analysis of the hydraulic packer tests for formations without a pumping period (low transmissivity). Interval temperature variation was not considered for hydraulic tests which included a pumping period due to the higher formation transmissivity. The temperature increase in the test interval, from the start of the initial pressure recovery after closing the shut-in valve (PSR) until the end of the test, ranged from 0.16 K to 5.71 K for all tests.

Tab. 4-22: Hydraulic packer testing in borehole STA3-1: Test interval and test specifications

¹ For an explanation of the test names and test phases see Tabs. A-2 and A-3, respectively.² Time between inflation of the last packer and deflation of the first packer.³ FM = flow model, T = transmissivity, h_s = static hydraulic head, WS = water sample.

Test name ¹	Interval depth [m MD]	Interval midpoint [m MD]	Packer configuration	Test phases ¹	Testing period ² (duration)	Geological information [depth and length values are rounded; groups and formations are usually named from top down; for details see Dossier III]	Objectives ³ [secondary aims in brackets ()]
STA3-1-MAL1	499.20 – 527.81	513.51	Double	PSR, SW, SWS, PW, MR (with sub-phases RW1 to RW8), MRS, PW2	17.01. – 21.01.2021 (99.4 h)	Malm Group: Biohermal, bioclastic and biomicrite limestone of «Felsenkalke» + «Massenkalk» including some filled vugs and veins and a few fissures (> 1 cm). This test was conducted after the fluid logging to hydraulically characterise the main inflow zone.	T, h _s , FM, WS
STA3-1-BDO3	697.87 – 720.80	709.34	Double	COM, PSR, SW, SWS, PW	09.03. – 12.03.2021 (67.3 h)	Dogger Group: Iron-oolitic limestone and marl of the Wutach Formation down to 699.47 m MD, followed by the thin Variansmergel Fm. and «Parkinsoni-Württembergica-Schichten» of claystone (silty, calcareous) and argillaceous marl (silty) down to 701.65 m MD and the «Herrenwis Unit» of biohermal and bioclastic limestone. This test was designed as an overview test to include the Variansmergel Fm. and «Parkinsoni-Württembergica-Schichten» as well as the upper part of the «Herrenwis Unit».	T, (h _s), FM
STA3-1-BDO2	721.90 – 744.83	733.37	Double	COM, PSR, SW, SWS, PW	06.03. – 09.03.2021 (61.9 h)	Dogger Group: Bioclastic, biohermal (coral) limestones of the «Herrenwis Unit» down to 742.00 m MD followed by the Wedelsandstein Formation of calcareous marl (sandy), bioclastic limestone and argillaceous siltstone (sandy, calcareous). This hydraulic test was designed to characterise the lower part of the «Herrenwis Unit» that includes fractures identified on the drill cores.	(T), (h _s), FM
STA3-1-BDO1	758.87 – 781.80	770.34	Double	COM, PSR, SW, SWS, PW	03.03. – 06.03.2021 (66.6 h)	Dogger Group: Thin successions of bioclastic and silty marl and limestone, and silty claystone of the Wedelsandstein Formation down to 764.97 m MD, followed by the heterogeneous «Murchisonae-Oolith Formation» to 779.26 m MD with argillaceous marl to claystone (silty, calcareous), limestone (argillaceous) and bioclastic sandy and silty marl, and the silty calcareous top of the Opalinus Clay. This hydraulic test was designed as an overview test for the «Murchisonae-Oolith Formation» and includes fractures identified on the drill cores at about 759.2 and 774.6 m MD.	T, (h _s), FM

Tab. 4-22: continued

¹ For an explanation of the test names and test phases see Tabs. A-2 and A-3, respectively.

² Time between inflation of the last packer and deflation of the first packer.

³ FM = flow model, T = transmissivity, hs = static hydraulic head, WS = water sample.

Test name ¹	Interval depth [m MD]	Interval midpoint [m MD]	Packer configuration	Test phases ¹	Testing period ² (duration)	Geological information [depth and length values are rounded; groups and formations are usually named from top down; for details see Dossier III]	Objectives ³ [secondary aims in brackets ()]
STA3-1-OPA3	782.20 – 813.43	797.82	Double	COM, PSR, SW, SWS, PW	22.02. – 25.02.2021 (65.7 h)	Dogger Group: The test interval is entirely within Opalinus Clay including a sub-unit with silty calcareous beds of claystone down to 807.34 m MD followed by a silty sub-unit of claystone. This hydraulic test was designed as an overview test for the upper part of the Opalinus Clay that small fractures at about 801 m MD.	T, (h _s), FM
STA3-1-OPA2	813.00 – 844.23	828.62	Double	COM, PSR, SW, SWS, PW	19.02. – 22.02.2021 (71.9 h)	Dogger Group: The test interval is entirely within Opalinus Clay with a silty sub-unit of claystone down to 821.09 m MD and a mixed clay-silt-carbonate sub-unit below. This test was designed as an overview test for the middle part of the Opalinus Clay that includes small fractures (at about 830.9 846.2 m MD) and a disturbed bedding zone (823 to 826 m MD).	T, (h _s), FM
STA3-1-OPA4	849.80 – 855.58	852.69	Double	COM, PSR, SW, SWS, PW, PI (GTPT, PSR2, PI2, PW2)	15.03. – 23.03.2021 (58.7 h, 190.3 h incl. GTPT)	Dogger Group: The test interval is entirely within the mixed clay-silt-carbonate sub-unit of Opalinus Clay. The test preceded the realisation of a GTPT in the same interval with a set of fractures (fault zone) at about 851.6 m MD.	T, h _s , FM
STA3-1-OPA1	856.50 – 887.73	872.12	Double	COM, PSR, SW, SWS, PW	16.02. – 19.02.2021 (66.6 h)	Dogger Group: The test interval is entirely within Opalinus Clay with a mixed clay-silt-carbonate sub-unit down to 868.06 m MD, followed by a clay-rich sub-unit. This test was designed as an overview test of the lower sub-unit of the Opalinus Clay and includes a set of fractures at about 868.8 m MD.	T, (h _s), FM
STA3-1-LIA2	885.95 – 908.88	897.42	Double	COM, PSR, SW, SWS, PW	28.02. – 03.03.2021 (66.7 h)	Lias Group: The test interval includes the bottom of the Opalinus Clay down to 887.94 m MD, followed by the heterogeneous succession of mostly marl, claystone and limestone of the Staffelegg Formation consisting of the Gross Wolf (4.85 m), Rietheim (6.51 m), Grünschoholz, Breitenmatt und Rickenbach (2.23 m) Members and 7.35 m of the Frick Member. This test was designed to target the upper parts of the Staffelegg Formation that contains a fault zone between about 892.8 and 894.8 m MD.	T, (h _s), FM

Tab. 4-22: continued

¹ For an explanation of the test names and test phases see Tabs. A-2 and A-3, respectively.

² Time between inflation of the last packer and deflation of the first packer.

³ FM = flow model, T = transmissivity, h_s = static hydraulic head, WS = water sample.

Test name ¹	Interval depth [m MD]	Interval midpoint [m MD]	Packer configuration	Test phases ¹	Testing period ² (duration)	Geological information [depth and length values are rounded; groups and formations are usually named from top down; for details see Dossier III]	Objectives ³ [secondary aims in brackets ()]
STA3-1-LIA1	886.80 – 924.00	905.40	Single	COM, PSR, SW, SWS, PW	12.02. – 15.02.2021 (65.7 h)	Lias Group: The test interval includes the bottom of the Opalinus Clay down to 887.94 m MD, the heterogeneous succession of mostly marl, claystone and limestone of the Staffelegg Formation including the Gross Wolf (4.85 m), Rietheim (6.51 m), Grünschholz, Breitenmatt und Rickenbach (2.23 m), Frick (11.94 m), Beggingen (2.67 m) and Schambelen (6.48 m) Members, followed by 1.29 m of the dolomitic marl of the Gruhalde Member (Klettgau Formation, Keuper Group). This test was designed as an overview test of Lias Group, Staffelegg Formation and includes most of the test interval STA3-1-LIA2.	T, h _s , FM
STA3-1-KEU1	932.20 – 957.00	944.60	Single	COM, PSR, SW, SWS, PW	20.04. – 22.04.2021 (58.1 h)	Keuper Group: approx. 18.93 m of the Klettgau Formation (approx. 4.82 m of the Gruhalde, 6.44 m of the Seebi, 1.82 m of the Gansingen and 5.85 m of the Ergolz Member) consisting of mostly silty claystone, argillaceous marl and dolostone, and approx. 5.87 m claystone of the Bänkerjoch Formation. The aim of this test was to target possible transmissive zones of the Klettgau Formation.	T, h _s , (FM)
STA3-1-MUK1	1054.50 – 1101.00	1077.75	Single	PSR, SW, SWS, MRW (MR with sub-phases RW1, RW2, RW3), MRS, PW, SW2, SWS2	20.05. – 23.05.2021 (63.5 h)	Muschelkalk Group: approx. 44.53 m of the Schinznach Formation (14.68 m of the Stamberg, 1.84 m of the Liedertswil and 28.01 m of the Leutschenberg Member) and approx. 1.97 m of the Zeglingen Formation, all consisting mainly of dolostones and limestones. This test was defined to cover the most permeable parts of the Schinznach Formation.	T, h _s , (FM), WS

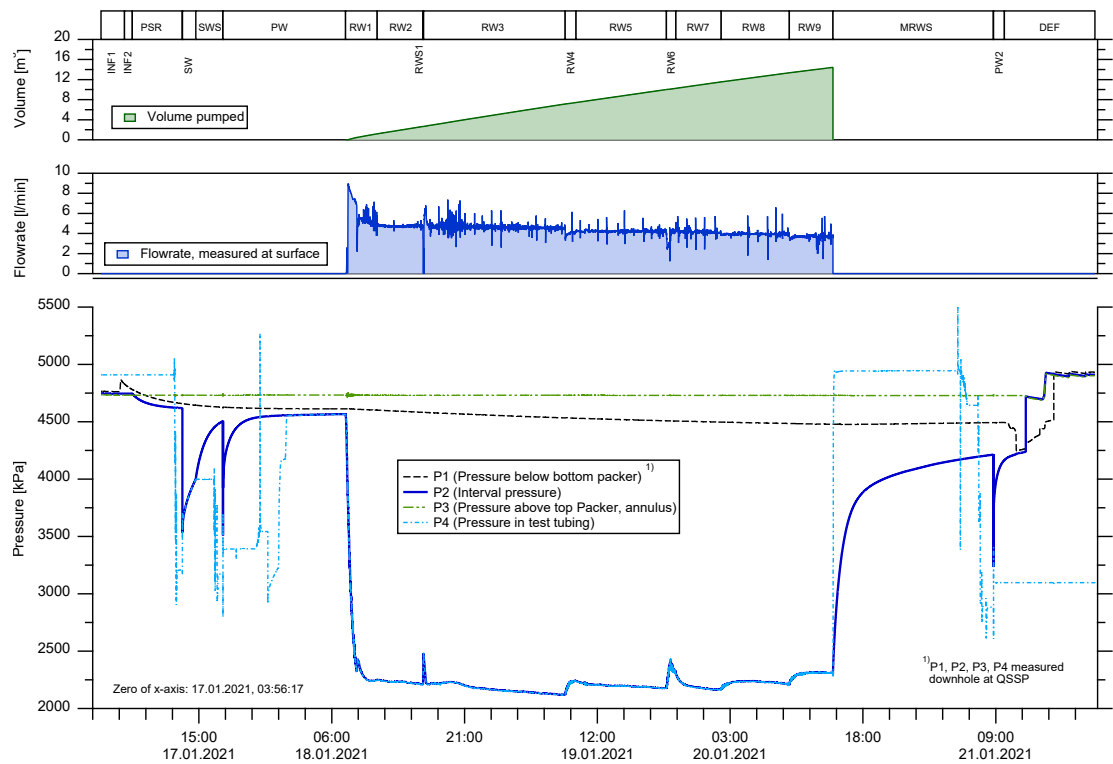


Fig. 4-9: Hydraulic packer test STA3-1-MAL1: Overview plot of pressure and flow rate vs. time and date

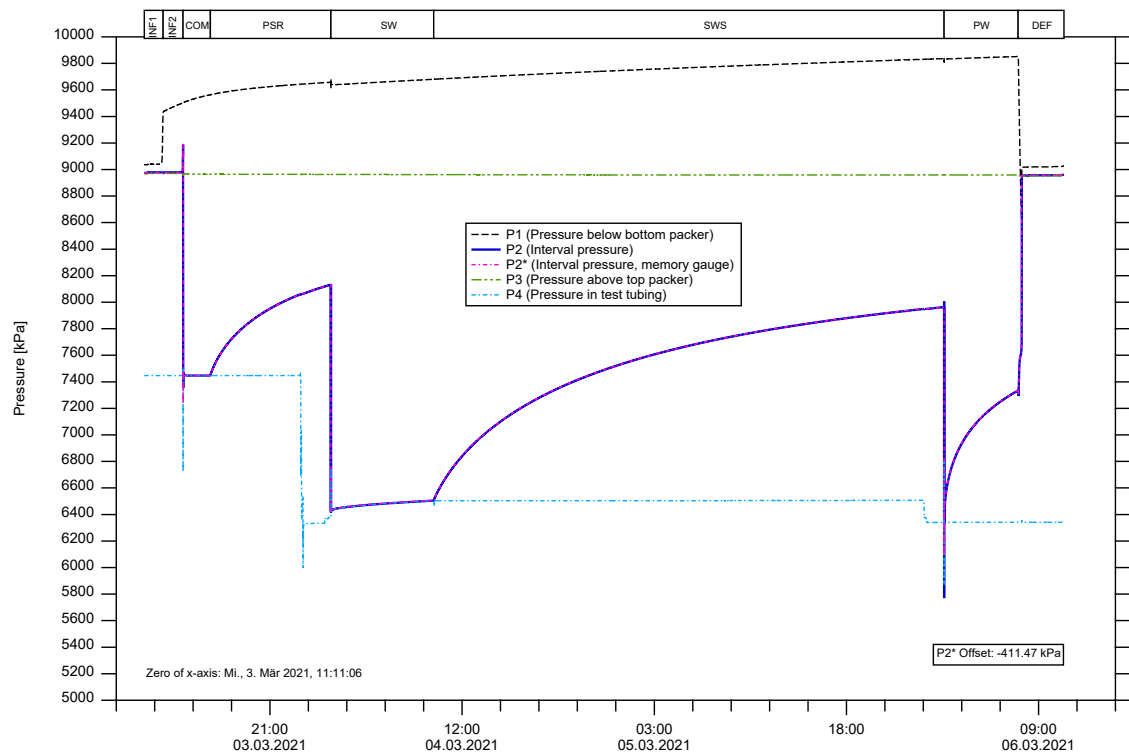


Fig. 4-10: Hydraulic packer test STA3-1-BDO1: Overview plot of pressure vs. time and date

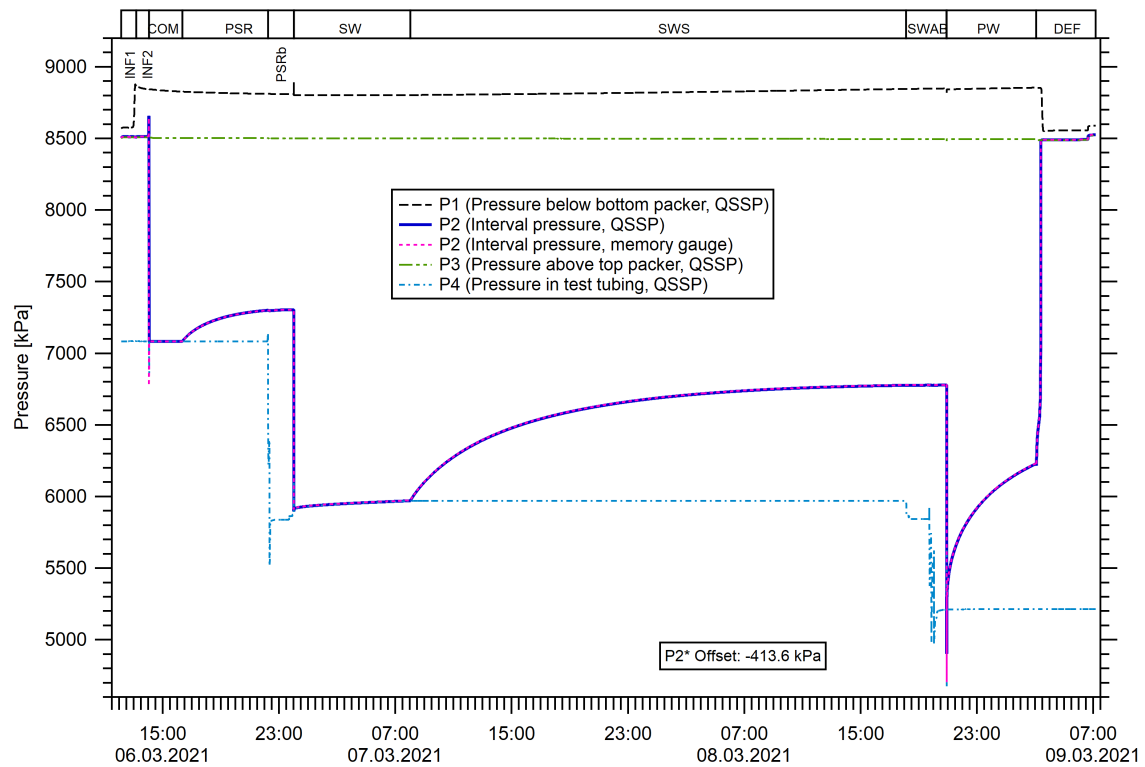


Fig. 4-11: Hydraulic packer test STA3-1-BDO2: Overview plot of pressure vs. time and date

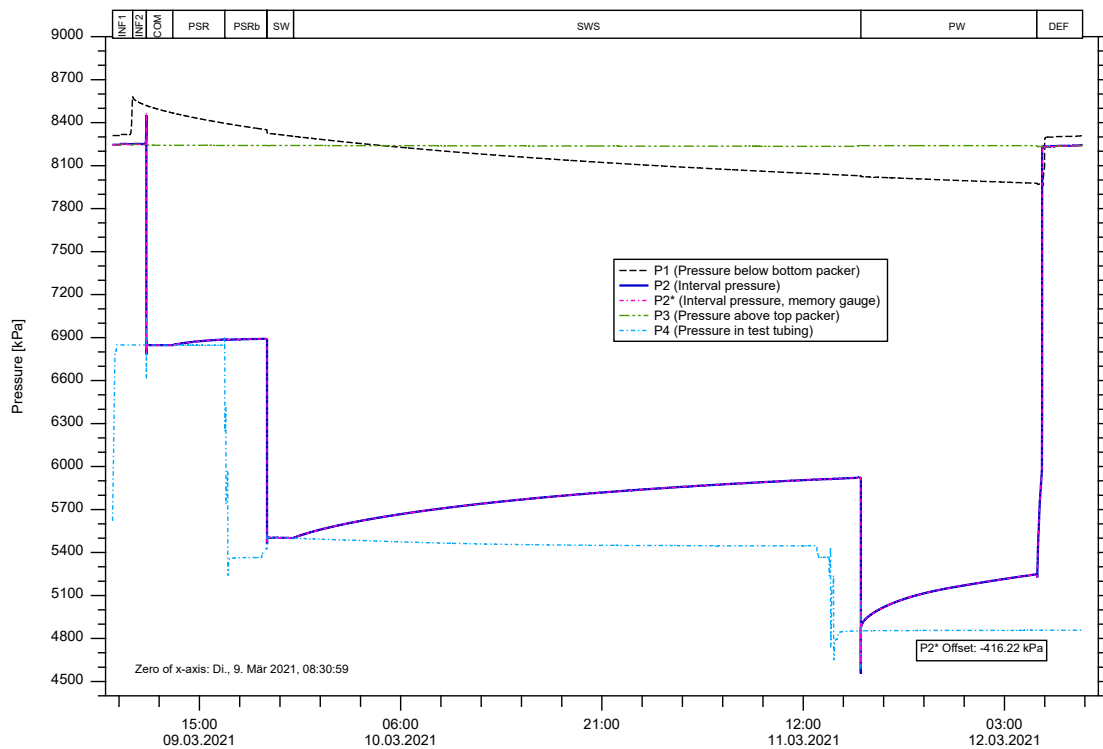


Fig. 4-12: Hydraulic packer test STA3-1-BDO3: Overview plot of pressure vs. time and date

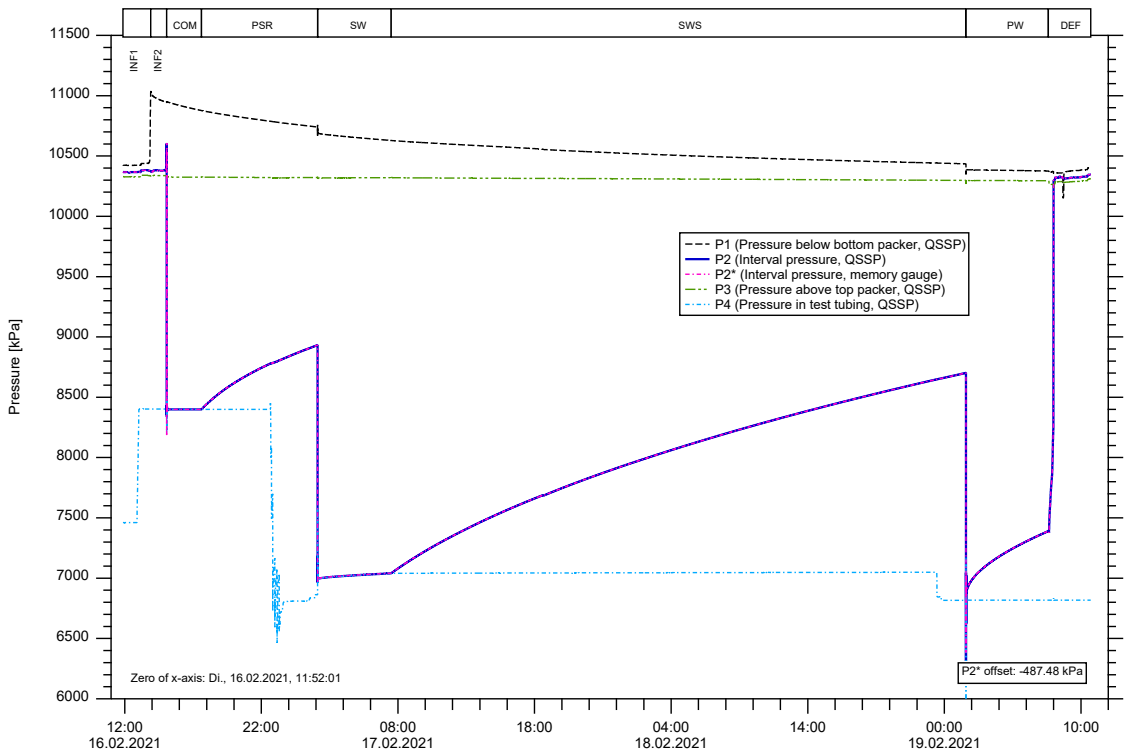


Fig. 4-13: Hydraulic packer test STA3-1-OPA1: Overview plot of pressure vs. time and date

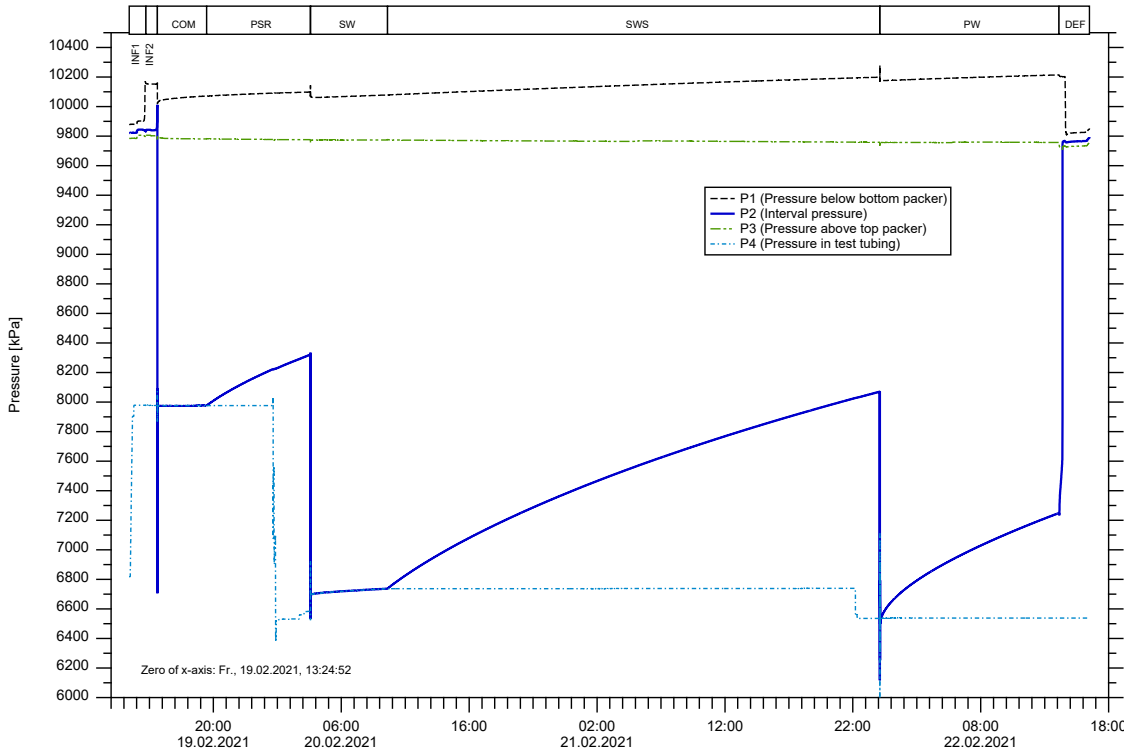


Fig. 4-14: Hydraulic packer test STA3-1-OPA2: Overview plot of pressure vs. time and date

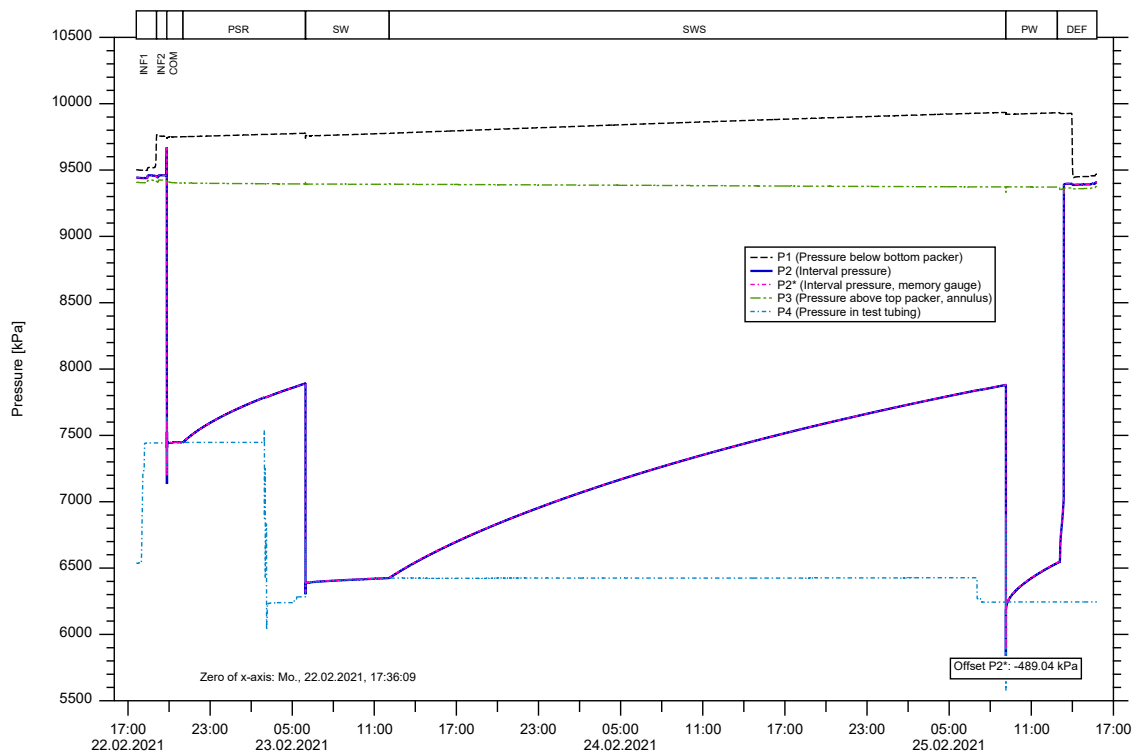


Fig. 4-15: Hydraulic packer test STA3-1-OPA3: Overview plot of pressure vs. time and date

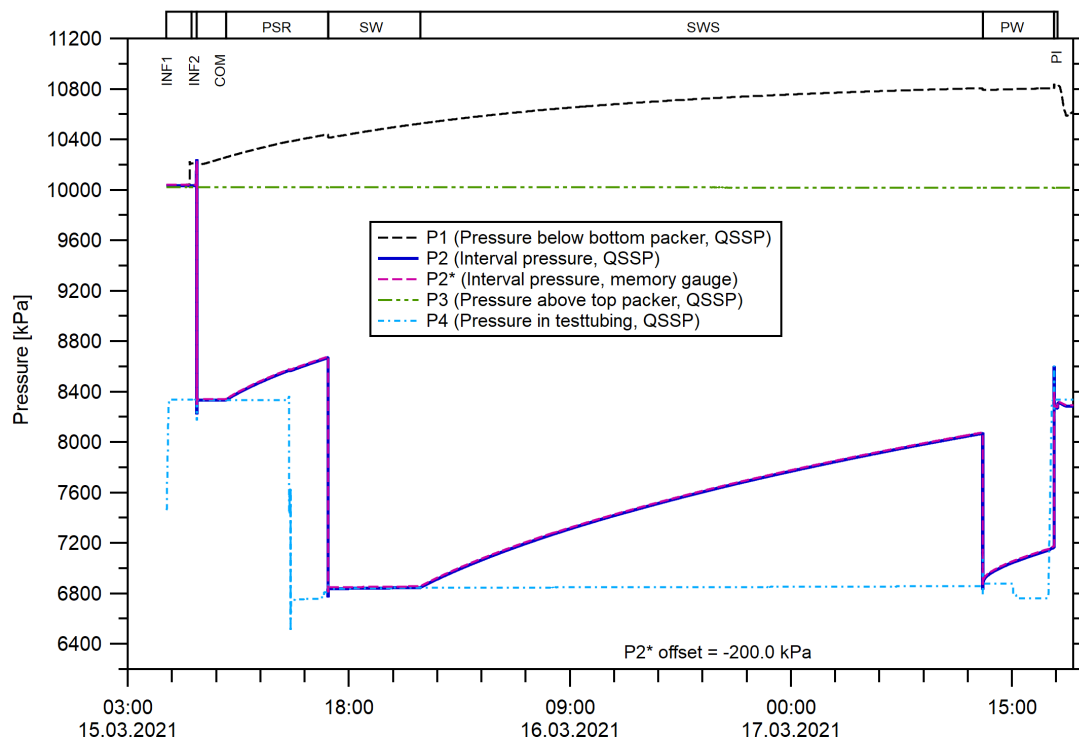


Fig. 4-16: Hydraulic packer test STA3-1-OPA4: Overview plot of pressure vs. time and date

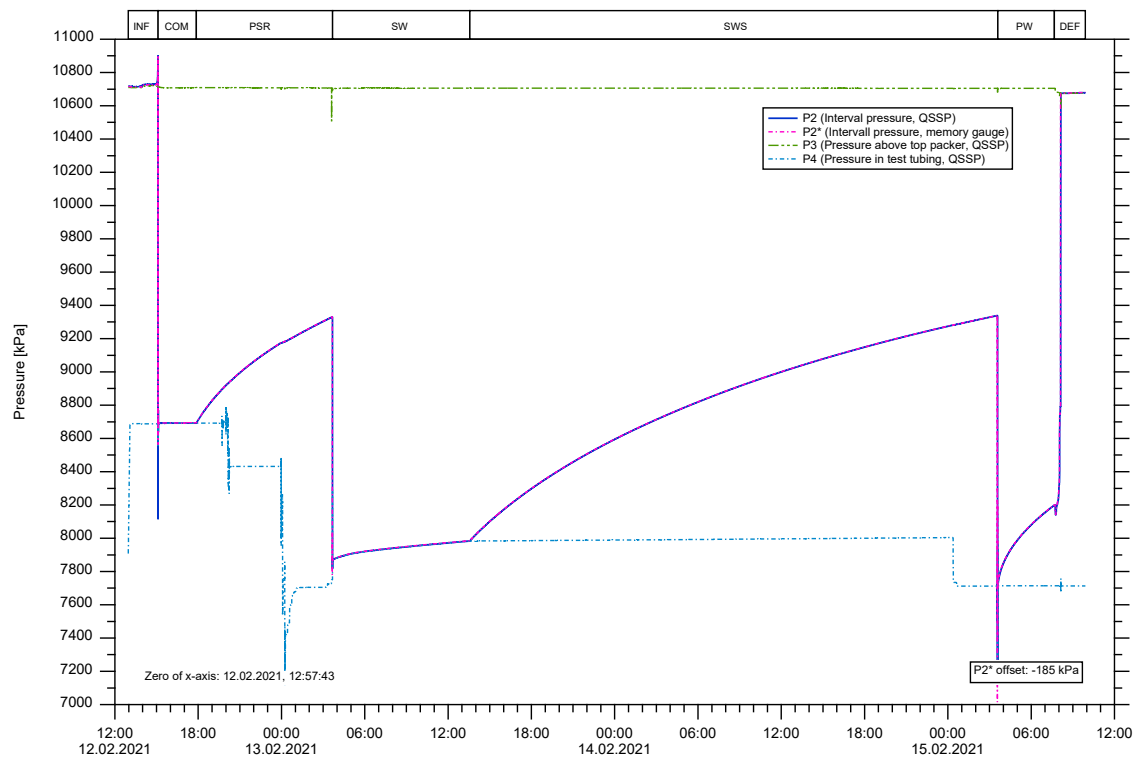


Fig. 4-17: Hydraulic packer test STA3-1-LIA1: Overview plot of pressure vs. time and date

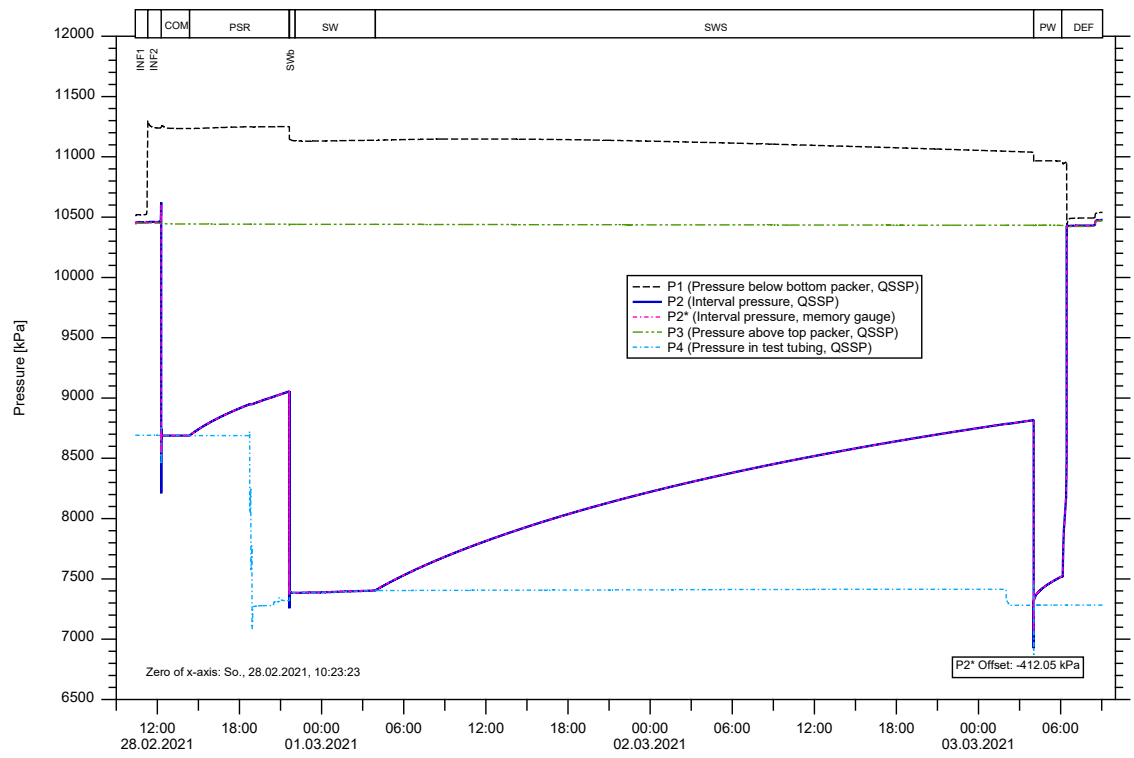


Fig. 4-18: Hydraulic packer test STA3-1-LIA2: Overview plot of pressure vs. time and date

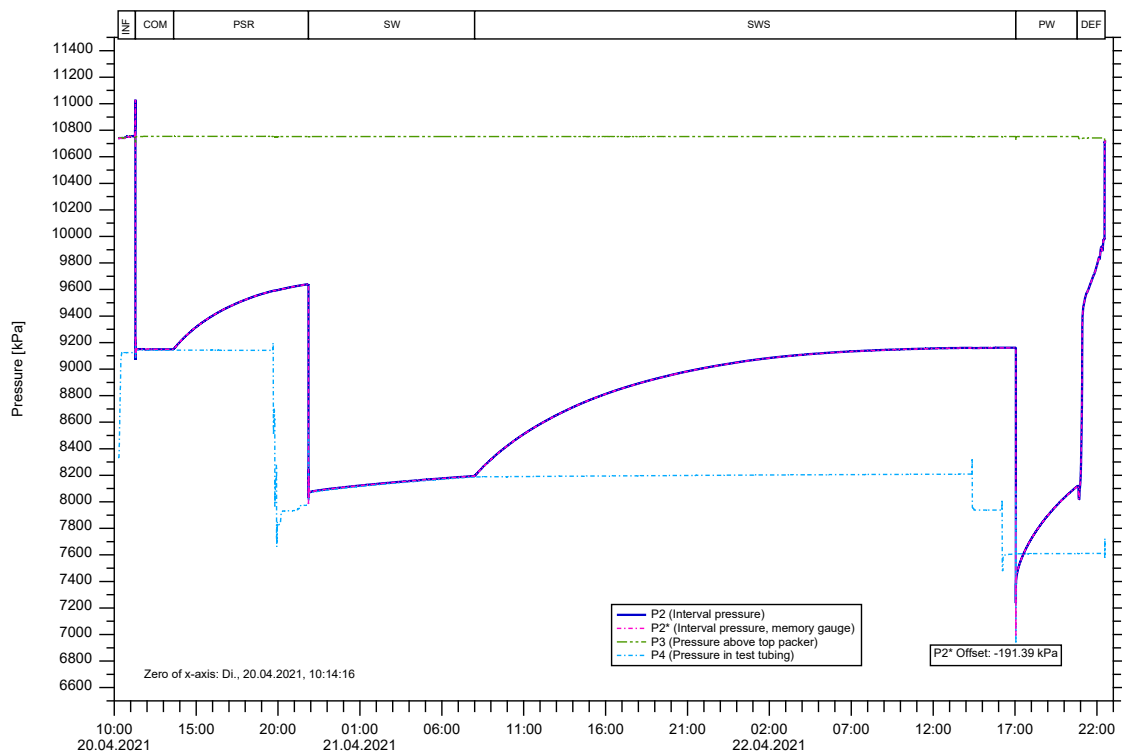


Fig. 4-19: Hydraulic packer test STA3-1-KEU1: Overview plot of pressure and flow rate vs. time and date

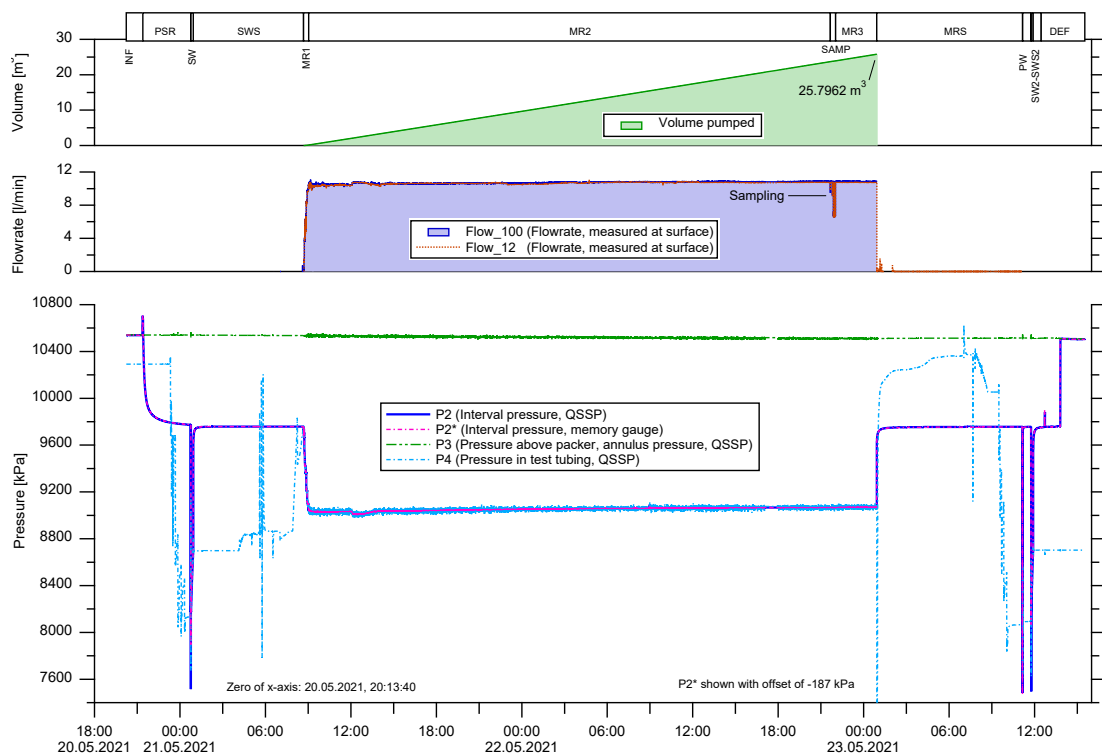


Fig. 4-20: Hydraulic packer test STA3-1-MUK1: Overview plot of pressure and flow rate vs. time and date

4.5 Details of selected tests

Two of the hydraulic packer tests are presented below in more detail: STA3-1-LIA1 and STA3-1-OPA1. Both hydraulic tests were performed in a sequence of slug withdrawal, slug recovery and pulse withdrawal phases, STA3-1-OPA1 in a double packer configuration and STA3-1-LIA1 as single packer test. The chosen test procedure represents the preferred test strategy for formations with very low to low transmissivity (*cf.* Tab. 4-2 in Section 4.1).

The two test examples demonstrate the application of the main approach used to provide estimates of the formation parameters including the associated ranges of uncertainty. The results of the two test analyses are provided in Section 4.6 along with the results of all other tests performed.

4.5.1 Hydraulic packer test STA3-1-LIA1

The hydraulic packer test STA3-1-LIA1 represents an example of testing in a formation with low transmissivity, a moderate pressure history duration (100.03 h) and a short hydraulic test duration of 65.67 hours⁸. For the analysis, the QSSP P2 sensor measurements at 882.32 m MD were used.

4.5.1.1 Interval characterisation

The hydraulic test STA3-1-LIA1 was performed in a single packer configuration. The main part of the interval (886.80 – 924.00 m MD) was located in the Staffelegg Formation of the Lias Group (including the Gross Wolf, Rietheim, Grünschholz, Breitenmatt, Rickenbach, Frick, Beggingen and Schambelen Members), the top part (886.80 – 887.94 m MD) belonged to the Opalinus Clay of the Dogger Group and the bottom part (922.71 – 924.00 m MD) to the Klettgau Formation of the Keuper Group. The primary test objectives were to obtain reliable estimates of the hydraulic transmissivity (hydraulic conductivity) of the formation and the freshwater hydraulic head based on an evaluation of the most appropriate flow model. Details of the interval and test duration are provided in Tab. 4-23. The test fluid was the potassium silicate & polymers mud with which the borehole section was cored. The borehole pressure history is presented at the beginning of Section 4.5.1.3.

Tab. 4-23: Hydraulic test STA3-1-LIA1: Test interval information

¹ Time between packer inflation and deflation

Test	Depth		Length [m]	Packer configuration	Hydraulic testing		
	from [m MD]	to [m MD]			Start date	End date	Duration ¹ [h]
STA3-1-LIA1	886.80	924.00	37.20	Single	12.02.2021	15.02.2021	65.67

⁸ The duration refers to the time between packer inflation and deflation.

4.5.1.2 Test execution

Fig. 4-21 shows the system installation record as provided by the field test contractor. The equipment components were those described above, in Section 4.2. The test in interval STA3-1-LIA1 was performed after the following procedures had been completed:

- Coring down to a depth of 924.00 m MD
- Petrophysical logging
- Testing of the blow out preventer (BOP) of the borehole
- Installation of the HDDP system

The HDDP was installed in borehole STA3-1 for the STA3-1-LIA1 test on 12.02.2021. After the installation of two pieces of test tubing, the tubing was filled with traced tap water (1.5-NDSA solution with a concentration of approximately 10 ppm), pulled back approximately 9 m and then the shut-in tool (SIT) was opened to release the air. During the subsequent placement of the HDDP, the SIT was closed, and the tubing was regularly filled to the top with traced tap water. The QSSP pressure sensors were regularly checked during the run in hole (RIH) of the HDDP. The installation was completed 100.03 hours after drilling through the interval midpoint with the inflation of the packer. The SIT was opened for 2.8 hours after packer inflation (COM) to reduce the pressure rise induced by the squeeze effect which occurred during inflation when the packer started attaching to the borehole wall. The SIT was then closed and the initial pressure recovery phase (PSR) commenced and lasted around 9.8 hours. The following slug withdrawal phase (SW) lasted for 9.9 hours, and the subsequent pressure recovery (SWS) was recorded for 38.0 hours. Finally, a pulse withdrawal test PW was performed, lasting for 4.1 hours. After the subsequent deflation (DEF) of the packer, the SIT was closed and the entire HDDP system was removed from the borehole while the SIT remained closed.

HDDP Packertests						Location	Stadel	Date	11.02.2021	Engineer	MaW
Borehole	STA3-1	Direction	vertical	Reference point (= GL)	408.736 m asl	Interval	LIA1	JOB Nr.	2666-5		
Borehole Depth	924.0 m	Casing Depth	440.5 m bgl	Interval length	37.20 m	Test depth (UPLS)	886.80 m bgl	System	HDDP 114		
Borehole Diameter	161.9 mm	Stickup b. Reference	-0.99 m	Water depth	0.00 m bgl	Test file	STA3_1_LIA1.DA	Quadro Probe	QSSP 3		

Note: All depths shown are not correct for borehole deviation

Reference	Qty	L _{unit} m	L _{total} m	Depth m	OD mm	ID mm	Wgt kg	Str t	Comments:
Wellhead, Wellhead equipment (not shown)									
Stickup									
Ground level (GL)									
Tubing 2"7/8 EU									
Moyno-Pump									
Tubing 2"7/8 EU									
SIT 2"7/8 DAS									
Cable Base incl. Coupling + Crown Shaft									
Probe Carrier with Quadruple Probe									
Crown Shaft									
Safety Joint incl. X-Over and 1 PJ (0.96 m)									
Packer Stick Up / Above Side Entry Sub									
UPUS									
Upper Packer									
Packer Stick Down									
Below Side Entry Sub (BSES)									
X-Over									
Tubing 2"7/8 EU (Tally list 1)									
X-Over									
Filter									
X-Over									
Bottom Cap									

End of Borehole (m bgl): 924.0

Total Weight (kg): 9049

Ground level: 0.00

Casing depth: 440.50

Moyno-Pump: 0.00

UPLS: 886.80

End of System: 889.16

Bottom of Borehole: 924.0

Fig. 4-21: Hydraulic test STA3-1-LIA1: Downhole equipment installation record with system layout as used in the field test

4.5.1.3 Analysis

Borehole pressure history

The borehole history used for the analysis of the STA3-1-LIA1 test is shown in Fig. B-1 and summarised in Tab. 4-24. The mean fluid density for the interval was calculated using the P2 and P2* pressure sensor measurements (prior to packer inflation) and resulted in a value of $1'298.5 \text{ kg m}^{-3}$. This value is slightly larger compared to the documented drilling mud density recorded at surface during drilling ($1'240 \text{ kg m}^{-3}$; see Dossier I). For the numerical simulations, a pressure history was ascribed that assumed a constant drilling mud level at the level of the drain pipe (-3.27 m MD) and a drilling fluid density of $1'234 \text{ kg m}^{-3}$ for the period from drilling through the interval midpoint until drilling termination. During the petrophysical logging, no mud table measurement was recorded. For the history periods without further information, the pressure was estimated between 10'719 and 10'720 kPa depending on the stated density, and assuming the drilling mud level at drain pipe level. Prior to RIH of the packer system, however, the mud level was measured at the level of the drain pipe (-3.27 m MD). Once the HDDP system was at test depth, data acquisition of the STA3-1-LIA1 hydraulic test started with direct measurement of the downhole pressures.

Tab. 4-24: Hydraulic test STA3-1-LIA1: Borehole pressure history

¹ Interval pressure at the level of the P2 sensor (882.32 m MD) with a pressure offset of 3.18 kPa as calculated from the history information, i.e. fluid level and density.

² Drilling through the interval midpoint (905.40 m MD).

³ Pressure measured when the borehole was filled with mud (e.g. when P2 was at test depth but before packer inflation).

⁴ Start of the inflation of the packer. The DAS had been started before (12.02.2021 12:57).

Description	Start date and time	Duration [h] Total: 100.03	Pressure ¹ [kPa]	
			Start	End
Drilling ²	08.02.2021 09:58	27.21	10'720	10'720
POOH core string	09.02.2021 13:11	7.57	10'720	10'719
Petrophysical logging	09.02.2021 20:45	44.25	10'719	10'719
BOP	11.02.2021 17:00	8.25	10'719	10'719
RIH single packer test string	12.02.2021 01:15	12.75	10'720 ³	10'720
Start testing STA3-1-LIA1	12.02.2021 14:00 ⁴	-	10'720	-

Flow model evaluation

The hydraulic test sequence was analysed using a 2-zone radial composite flow model. This flow model approach was based on the analysis of the shut-in phase (PSR) and the slug recovery phase (SWS) using Agarwal superposition time, the de-convolved slug phase (SW) as well as numerical investigations (residual analysis). Figs. B-2, B-3 and B-4 show the diagnostic plots for the PSR, SWS and the SW phases, respectively. The log-log plots of the PSR phase (Fig. B-2) and the SWS phase (Fig. B-3) show a long-lasting period dominated by wellbore storage. Towards the end of the PSR, the pressure and derivative curves indicate the beginning of a transition phase towards

a possible infinite acting radial flow (IARF) phase. The late time increase of the pressure and derivative curves in Fig. B-3 is most probably related to uncertainties in the production time, because the production history was limited to the slug flow phase (SW), while the previous test phases and the borehole pressure history were not considered. The de-convolution plot (Fig. B-4) of the slug phase provides no further conclusive information on the formation flow model.

A comparison between a radial homogeneous and a radial composite flow model (with the inner zone representing a thin skin zone around the borehole) indicated that the latter is characterized by a better representation of the measured pressure by the simulation. Therefore, a radial composite flow model with infinite lateral extent as outer boundary condition was favoured as a conceptual flow model for the analysis.

Analysis of the slug and slug-recovery (SW-SWS) sequence

Temperature changes that occurred inside the closed test interval during the test phases were considered in the analysis. Fig. B-5 shows the development of the downhole temperature (T_2^* and T_2) and pressure as measured by the memory gauge and the QSSP, respectively. The slug and the slug recovery phase were selected as test sequence (SW-SWS) to focus on the optimisation of the formation hydraulic parameters. The slug phase was performed using a 6 mm diameter slim tubing with a small packer at the bottom end which was lowered into the 2 $\frac{7}{8}$ " tubing. Once in position, the packer of the slim tubing was expanded to provide a seal against the 2 $\frac{7}{8}$ " tubing. For the simulation, a corrected slim tubing radius was used considering the physical slim tubing and the contribution of the system compliance (i.e. the compressibility of the test zone of $4.5 \times 10^{-10} \text{ Pa}^{-1}$ and the compressibility of the water column between the SIT and the packer of the slim tubing) according to Black et al. (1987).

The results, derived from the parameter optimisation on the cartesian pressures of the sequence SW-SWS, are shown in Tab. 4-25. Fig. B-6 illustrates the simulation using the optimised formation parameters of Tab. 4-25.

Tab. 4-25: Hydraulic test STA3-1-LIA1: Formation parameter estimates based on the parameter optimisation for the SW-SWS sequence using a radial composite flow model considering both the borehole pressure history and temperature changes inside the test interval

¹ Static formation pressure at the depth of the P2 sensor (882.32 m MD).

SW-SWS results (radial composite flow model)	K [m s ⁻¹]	Ss [m ⁻¹]	P _f ¹ [kPa]
Best estimate	1.06×10^{-13}	1.88×10^{-6}	10'411

Detailed views of the adjustment to the pressure curve of the slug test are shown in a log-log plot for the SWS phase and for the de-convolved pressure data of the SW phase in Fig. B-7. The fit quality of the simulation is judged as very good for the SW and SWS phases.

As described above, the possibility to represent the measured pressure curve with a less complex flow model (radial homogeneous flow model) cannot be excluded by the flow model diagnostics of the measurements. Therefore, an optimisation of the formation parameters using a radial homogeneous flow model was performed. Fig. B-8 shows the simulation result based on the optimised formation parameters of Tab. 4-26 and the radial homogeneous flow model. For comparison reasons, Fig. B-8 includes the simulations of both flow models.

Tab. 4-26: Hydraulic test STA3-1-LIA1: Formation parameter estimates based on the parameter optimisation for the SW-SWS sequence using a radial homogeneous flow model considering both the borehole pressure history and temperature changes inside the test interval

¹ Static formation pressure at the depth of the P2 sensor (882.32 m MD).

SW-SWS results (radial homogeneous flow model)	K [m s ⁻¹]	S_s [m ⁻¹]	P_f ¹ [kPa]
Best estimate	1.05×10^{-14}	3.58×10^{-5}	10'889

The quality of the representation of the measured pressure curve by the simulation was judged as poor. In addition, the resulting estimate of the formation specific storage exceeded the plausibility range derived from the mechanical properties of the Lias Group.

The existence of the inner/skin zone is also supported by the residual analysis. Fig. B-9 provides the probability distribution functions of the simulations using both flow models. It can be concluded that a normal distribution of the pressure residuals confirms the chosen conceptual model being a radial composite flow model.

Joint parameter regions for the SW-SWS sequence

Based on the results of the parameter optimisation using a radial composite flow model for the SW-SWS sequence, an estimate of the joint parameter regions was possible. Tab. 4-27 provides the 95% uncertainty ranges for the results. The calculated ranges are unrealistically small due to the existence of well-defined and well-constrained minima of the objective function. Therefore, further investigations were performed to better estimate the uncertainty ranges for the formation parameters.

Tab. 4-27: Hydraulic test STA3-1-LIA1: 95% uncertainty range associated with the result of the parameter optimisation using a radial composite flow model for the SW-SWS sequence

¹ Increased resolution to be able to display a range

² Static formation pressure at the midpoint of the test interval (882.32 m MD).

SW-SWS results (joint parameter region)	K ¹ [m s ⁻¹]	S_s ¹ [m ⁻¹]	P_f ² [kPa]
95% uncertainty range	$1.059 - 1.060 \times 10^{-13}$	$1.879 - 1.883 \times 10^{-6}$	10'410.2 – 10'411.0

Estimates and uncertainty ranges for the formation parameters

An analysis to assess the uncertainty in the formation parameters by varying the pressure history in terms of measured level or mud density uncertainties was considered unnecessary due to the fact that prior analysis results in the TBO borehole campaign showed merely an insignificant influence of variations of the borehole history on the test simulation results in intervals of comparable hydraulic transmissivity (e.g. in both the BUL1-1 and MAR1-1 boreholes). However, the analysis result could be affected by the uncertainty associated with the parameter optimisation

procedure and any inaccuracies in the determination of the wellbore storage. Previous studies had shown an impact of this aspect on the result during the TBO borehole campaign. The impact of the optimisation procedure and parameters (chosen parameter ranges and process parameters like the number or termination criteria of the iterations) can be estimated by a perturbation analysis. Also, in this analysis, the bandwidth of the parameters is determined based on several individual optimisations, which can, for instance, identify whether the result corresponds to a global minimum in the parameter space. The possible influence of uncertainties in the determination of the wellbore storage is assessed by a sampling analysis. In this analysis, the parameters are optimised depending on a representative bandwidth for the wellbore storage.

A perturbation analysis with 500 runs was carried out in which the radius of the discontinuity (equals borehole radius plus skin thickness) was defined between 0.091 m and 0.181 m. Fig. B-10 presents two simulations of the perturbation analysis, i.e. the simulation with the lowest sum of squared errors (SSE) solution and a selected simulation with inferior fit quality, and the previously presented initial simulation (Tab. 4-25) for comparison. Note that the initial simulation (reference simulation) and the best estimate simulation virtually overlap in the graph of Fig. B-10. The parameter results of each single parameter optimisation of the perturbation runs are shown against increasing values of the objective function/SSE in Fig. B-11. The first 201 runs (run #0 to run #200) cover an SSE range between 318'038 and 860'130 (Fig. B-11). Within this range the matches of the SW-SWS sequence were of a good to moderately good quality and therefore used for the estimation of the parameter uncertainty ranges. The upper limit was chosen due to the visible start point of a strong increase in the SSE value (*cf.* Fig. B-11). Tab. 4-28 shows the resulting best estimates of the formation parameters and the associated uncertainty ranges for the simulation with the lowest SSE. The upper limit of resulting parameter ranges was limited through the plausibility range (parameter optimisation range) of the specific storage, which could affect the ranges of the other formation parameters due to the observed correlation between them. The plausibility range of the specific storage was estimated based on the bandwidth of the mechanical properties of the Lias Group.

Tab. 4-28: Hydraulic test STA3-1-LIA1: Uncertainty ranges and best estimates for the formation parameters estimated by the perturbation analysis

¹ Static formation pressure at the depth of the P2 sensor (882.32 m MD).

² Reached the upper limit of the plausibility range.

Perturbation analysis results	K [m s ⁻¹]	S_s [m ⁻¹]	P_f ¹ [kPa]
Best estimate	1.08×10^{-13}	1.72×10^{-6}	10'400
Uncertainty range	$0.32 - 2.77 \times 10^{-13}$	$0.42 - 3.58 \times 10^{-6}$ ²	10'032 – 10'961

Scatter plots of the formation parameters are shown in Fig. B-12. The two upper plots show a clear negative correlation between the formation hydraulic conductivity and both the formation specific storage (outer zone) and the static formation pressure for all selected results. Nearly no correlation could be observed near the lowest SSE (parameter sets marked with red circle). Hence, the plot of the formation specific storage against the static formation pressure is positively correlated and again there is no obvious correlation near the lowest SSE.

The sampling analysis for the test zone compressibility was performed for a maximum suitable range of values between 4.3×10^{-10} Pa⁻¹ and 1.0×10^{-9} Pa⁻¹. The resulting parameter sets in combination with the resulting objective function value/SSE value as a function of the value of the

test zone compressibility are represented in Fig. B-13. Tab. 4-29 shows the resulting best estimates for formation parameters and the associated uncertainty ranges for the simulation with the lowest SSE (test zone compressibility of $4.76 \times 10^{-10} \text{ Pa}^{-1}$). The uncertainty range was defined between the value of $4.36 \times 10^{-10} \text{ Pa}^{-1}$ for the test zone compressibility as a lower limit, which is slightly higher than the fluid compressibility, and a corresponding upper value of $4.99 \times 10^{-10} \text{ Pa}^{-1}$ associated with an SSE value equal to that associated with the smallest test zone compressibility value.

Tab. 4-29: Hydraulic test STA3-1-LIA1: Uncertainty ranges and best estimates for the formation parameters as a result of the sampling analysis for the test zone compressibility

¹ Static formation pressure at the depth of the P2 sensor (882.32 m MD).

Sampling analysis results	K [m s ⁻¹]	Ss [m ⁻¹]	P_f ¹ [kPa]
Best estimate	1.13×10^{-13}	1.81×10^{-6}	10'395
Uncertainty range	$1.05 - 1.18 \times 10^{-13}$	$1.75 - 1.85 \times 10^{-6}$	10'390 – 10'399

Parameter optimisation for the SW-SWS-PW sequence

To validate the results of the SW-SWS sequence, the entire test sequence SW-SWS-PW was investigated. The same conceptual model was used to numerically simulate the test data for the SW-SWS-PW sequence, i.e. a radial composite flow model (representing a thin skin zone) with a wellbore storage as the inner boundary condition in an infinitely extended reservoir. However, the test zone compressibility was assigned to a value of $4.76 \times 10^{-10} \text{ Pa}^{-1}$ corresponding to the result of the sampling analysis. The results derived from the parameter optimisation are shown in Tab. 4-30. The cartesian fit for the pressure measurement is displayed in Fig. B-14. During the optimisation process the discontinuity radius reached the lower limit of the optimisation range of 0.091 m. The resulting value of the specific storage also represents the previously defined upper limit of the plausibility range (calculated based on the mechanical properties of the Lias Group).

Tab. 4-30: Hydraulic test STA3-1-LIA1: Formation parameter estimates based on the parameter optimisation for the SW-SWS-PW sequence

¹ Reaching the upper limit of the plausibility range (optimisation range).

² Static formation pressure at the depth of the P2 sensor (882.32 m MD).

SW-SWS-PW results	K [m s ⁻¹]	Ss [m ⁻¹]	P_f ² [kPa]
Best estimate	7.08×10^{-14}	3.58×10^{-6} ¹	10'364

The SWS phase slightly underestimates the early time pressure data but is still judged as good because the fit of late times is excellent. The fit quality of the SW and PW phases is judged as poor. The poor quality of the reproduction of the measured pressure curve by the simulation during the SW and PW phases might be explained by the fact that early time measurements were still affected by the interval and near borehole conditions which seem to differ between phases. Furthermore, the PW phase was rather short with 4 hours.

Summary of the analysis

The best estimates for the hydraulic properties are derived from the sampling analysis of the SW-SWS sequence, and the results are listed in Tab. 4-31. The parameter set was chosen according to the lowest SSE value as no criterion other than the SSE value is available to rank between the results. All parameter optimisations led to almost the same formation parameter set. The uncertainty ranges from the perturbation analysis represent the overall ranges from the entire analysis with respect to the formation parameters.

Tab. 4-31: Hydraulic test STA3-1-LIA1: Best estimates and associated uncertainty ranges for the formation parameters

¹ Static formation pressure at the midpoint of the test interval (905.40 m MD) considering the sensor offset of 3.18 kPa.

² Range limited by the upper limit of the plausibility range based on the mechanical parameters of the Lias Group.

STA3-1-LIA1	K [m s ⁻¹]	Ss [m ⁻¹]	P _s ¹ [kPa]
Best estimate	1.13×10^{-13}	1.81×10^{-6}	10'689
Uncertainty range	$0.32 - 2.8 \times 10^{-13}$	$0.42 - 3.6 \times 10^{-6}$ ²	10'323 – 11'252

4.5.2 Hydraulic packer test STA3-1-OPA1

The hydraulic packer test STA3-1-OPA1 represents an example of testing formations with very low transmissivity after a longer pressure history duration (242.28 h) and using a short hydraulic test execution duration (66.62 h). The analysis is based on the measurements of the P2 sensor inside the QSSP at 852.02 m MD.

4.5.2.1 Interval characterisation

The hydraulic test STA3-1-OPA1 was performed in a double packer configuration. The entire interval (856.50 – 887.73 m MD) was located in the Opalinus Clay of the Dogger Group (779.26 – 887.94 m MD).

The HDDP used was described in Section 4.2. The hydraulic test was conducted with the drilling fluid (potassium silicate & polymers) as test fluid. The primary test objectives were to obtain reliable estimates of the hydraulic transmissivity (conductivity) for the formation, and to determine the most appropriate flow model. The estimation of the freshwater hydraulic head was defined as an objective of second priority due to the longer pressure history and shorter testing duration, and uncertain influence of possible mechanical coupled processes. Details of the tested interval and test duration are provided in Tab. 4-32. The borehole pressure history is presented at the beginning of Section 4.5.2.3.

Tab. 4-32: Hydraulic test STA3-1-OPA1: Information on the test interval

¹ Time between packer inflation and deflation

Test	Depth		Length [m]	Packer configuration	Hydraulic testing		
	from [m MD]	to [m MD]			Start date	End date	Duration ¹ [h]
STA3-1-OPA1	856.50	887.73	31.23	Double	16.02.2021	19.02.2021	66.62

4.5.2.2 Test execution

Fig. 4-22 shows the system installation record as provided by the field test contractor. The equipment components are those described in Section 4.2. The hydraulic test in interval STA3-1-OPA1 was performed after the following procedures had been completed:

- Coring to a depth of 924.00 m MD
- Petrophysical logging
- Testing of the blow out preventer (BOP) of the borehole
- Hydraulic test STA3-1-LIA1
- Pull out of hole (POOH) of the single packer equipment
- Installation of the HDDP in a double packer configuration

The HDDP was installed in borehole STA3-1 for STA3-1-OPA1 on 16.02.2021. After the installation of the first two test tubing rods, the tubing was filled with traced tap water (1.5-NDSA of a concentration of approx. 10 ppm) and the system was pulled back approximately 9 m from rig floor. The shut-in tool (SIT) was opened to release the air. The SIT was then closed during the following run-in hole (RIH) of the HDDP. During installation of the test tubing, the test tubing was regularly filled up to the top with traced tap water and the QSSP pressure sensors were checked. The installation was completed 242.28 hours after drilling through the interval midpoint, by inflation of the upper packer (PA2). Due to the squeeze effect that occurred in the interval during inflation of the upper packer, the SIT was opened to initiate the compliance phase (COM) that lasted 2.5 hours. Next, the SIT was closed, and the initial pressure recovery phase (PSR) commenced, lasting around 8.5 hours. After completion of the PSR phase, the slim tubing was installed, and a slug withdrawal test (SW) was performed that lasted for 5.4 hours. The SW test was terminated with the closure of the SIT valve. The subsequent pressure recovery (SWS) was recorded for 42.1 hours. Finally, a pulse withdrawal test (PW) was performed over the course of 6.0 hours. After this phase, the hydraulic test was terminated. And, after a sufficient backflow of the packer fluid during its deflation (DEF), the system was moved to the new position for the subsequent test STA3-1-OPA2. The SIT was closed during relocation.

Installation Record - Double Packer									
AC20210105NaD									
SOLEXPERTS									
HDDP Packertests				Location	Stadel	Date	15.02.2021	Engineer	NaD
Borehole	STA3-1	Direction	vertical	Reference point (= GL)	408.736 m asl	Interval	OPA1	JOB Nr.	2666
Borehole Depth	924.0 m	Casing Depth	440.5 m bgl	Interval length	31.23 m	Test depth (UPLS)	856.50 m bgl	System	HDDP 114 ▼
Borehole Diameter	161.9 mm	Stickup b. rig floor	-1.29 m	Water depth	-3.35 m bgl	Test file	STA3_1_OPA1.DAT	Quadro Probe	QSSP 3 ▼
Note: All depths shown are not correct for borehole deviation									
Rig floor									
Wellhead, Wellhead equipment (not shown)				Qty	L unit	L total	Depth	OD	ID
Stickup				-	m	m	m	mm	mm
Ground level (GL)				0	0.00		0.00	93.2	62.0
Tubing 2"7/8 EU				0	0.00		0.00	93.2	62.0
Tally list 3				0	n.a.	853.13		n.a.	n.a.
Tubing extension				0	n.a.			n.a.	n.a.
Moyno-Pump				0	n.a.			n.a.	n.a.
Stop Pin				0			-6.24		
Tubing 2"7/8 EU				74	853.13		846.89	93.2	62.0
X-Over				1	1.20		847.37	93.2	51.0
SIT 2"7/8 DAS				1	0.66			106.0	24.0
DAP				1	1.22			105.0	24.0
Cable Base incl. Coupling + Crown Shaft				1	1.26			105.0	24.0
QSSP P3					0.53		851.75		
QSSP P4					0.13		851.88		
QSSP P2				1	0.14		852.02	105	3 x Ø19
QSSP P1					0.20		852.22		
Crown Shaft incl. 1 X-Over				1	0.41			100.0	40.0
Safety Joint incl. X-Over and 1 PJ (0.96 m)					1.565			93.0	62.0
Packer Stick Up / Above Side Entry Sub					0.37			85	eccentri c Ø30
UPUS					0.20		855.30		
Upper Packer				1	1.20			114.0	32.0
UPLS					0.26		856.50		
Packer Stick Down					0.05				
Packer Stick Up / Below Side Entry Sub					0.20			58.5	eccentri c Ø25
X-Over				1	0.08			80.0	60.0
Tubing 2"7/8 EU (Tally list 1)				1	28.14			93.2	62.0
X-Over				1	0.15			93.5	51.2
X-Over				1	0.05			80.0	50.0
Filter				1	0.97			89.0	73.0
Screen				1	0.21		886.81	80.0	50.0
X-Over				1	0.20			78	n.a.
P1-Seal Sub					0.32				
Packer Stick Up					0.11				
LPUS					0.26		887.73		
Lower Packer				1	1.20			114.0	32.0
LPLS					0.26		888.93		
Packer Stick Down					0.11				
Bottom Cap					0.16		889.46	95.0	n.a.
End of Borehole (m bgl): 924.00									
Total Weight (kg): 9086									

Fig. 4-22: Hydraulic test STA3-1-OPA1: Downhole equipment installation record with system layout as used in the field test

4.5.2.3 Analysis

Borehole pressure history

The borehole pressure history, calculated for the P2 sensor position and used for the analysis of the STA3-1-OPA1 test, is shown in Fig. B-15 (see Appendix B) and summarised in Tab. 4-33. Calculation of the mean interval fluid density (prior to packer inflation) using the P2 pressure measurement and P2* (memory gauge) pressure measurements gave a density of $1'233 \text{ kg m}^{-3}$. This value corresponds well with the documented density for the drilling mud ($1'240 \text{ kg m}^{-3}$; see Dossier I). For periods without a mud level measurement, the mud level was assumed to be at the level of the drain pipe, -3.27 m bgl. For periods with no active mud circulation, the drillers generally kept the borehole filled with mud up to the level of the drain pipe. Therefore, the pressure value was between 10'367 and 10'371 kPa depending on the stated density for the history periods without further information, when the borehole was filled with drilling mud. During the previous hydraulic testing, namely for STA3-1-LIA1 in the next interval below, the pressure was measured by the P3 QSSP sensor and extrapolated to the depth of the P2 transducer at STA3-1-OPA1. Once the HDDP was at test depth and data acquisition began, the P2 QSSP sensor measured pressure directly (Fig. 4-13).

Tab. 4-33: Hydraulic test STA3-1-OPA1: Borehole pressure history

¹ Interval pressure at the level of the P2 sensor (852.02 m MD) with a pressure offset of 20.52 kPa as calculated from the history information, i.e. fluid level and density.

² Drilling through the interval midpoint (872.12 m MD).

³ P3 sensor measurement during testing corrected to the P2 sensor level (852.02 m MD). Time corresponding to the start of the DAS recording for STA3-1-LIA1.

⁴ Start of the inflation of the last/upper packer (PA2). The DAS had been started earlier (16.02.2021 11:52).

⁵ Pressure measured when the borehole was filled with mud (i.e. when P2 was at test depth but before packer inflation).

Description	Start date and time	Duration [h] Total: 242.28	Pressure ¹ [kPa]	
			Start	End
Drilling ²	06.02.2021 11:45	73.43	10'368	10'368
POOH core string	09.02.2021 13:11	7.57	10'368	10'367
Petrophysical logging	09.02.2021 20:45	44.25	10'367	10'367
BOP	11.02.2021 17:00	8.25	10'367	10'371
RIH single packer test string	12.02.2021 01:15	11.70	10'371	10'371
STA3-1-LIA1 ³	12.02.2021 12:57	68.95	10'371	10'339
POOH single packer test string	15.02.2021 09:45	14.85	10'339	10'367
RIH double packer test string	16.02.2021 00:45	13.28	10'367	10'367
Start testing STA3-1-OPA1	16.02.2021 11:52 ⁴	-	10'367 ⁵	-

Flow model evaluation

The hydraulic test sequence was analysed using a 2-zone radial composite flow model. This flow model approach was based on the analysis of the shut-in phase (PSR) and the slug recovery phase (SWS) using Agarwal superposition time as well as the de-convolved slug phase (SW). Figs. B-16, B-17 and B-18 show the diagnostic plots for the PSR, SWS and the SW phases, respectively. The diagnostic plot for the PSR phase shows a long-lasting period dominated by wellbore storage and the log-log plot for the SWS phase shows a similar picture. Towards the end of the PSR, the pressure and derivative curve show a faint beginning of a transition phase to a possible infinite acting radial flow (IARF) phase. The late time increase of the pressure and derivative curves in Fig. B-17 is most probably related to uncertainties in the production time, because the production history was limited to the slug flow phase (SW), as the previous test phases and the borehole pressure history were not considered. The derivative in the de-convolution plot of the slug phase shows a decrease of the slope at late time, indicating a possible transition to IARF. However, a clear formation response confirming IARF conditions cannot be seen in either of these figures. A comparison between a radial homogeneous and a 2-zone radial composite model (with the inner zone representing a thin skin zone around the borehole) indicated that the latter was a better characterisation of the measured pressure curve.

Analysis of the slug, slug recovery and pulse withdrawal (SW-SWS-PW) sequence

Temperature changes during the test within the closed test interval were considered in the analysis. Fig. B-19 shows the development of the downhole temperature (T_2^* and T_2) and pressure, as measured by the memory gauge and the QSSP, respectively. The entire test sequence of SW-SWS-PW was selected for the optimisation of the hydraulic parameters. The slug phase was performed using a 6 mm diameter slim tubing with a small packer at the bottom end which was lowered into the 2 $\frac{7}{8}$ " tubing. Once in position, the packer of the slim tubing was expanded to provide a seal against the 2 $\frac{7}{8}$ " tubing. For the simulation, a corrected slim tubing radius was used considering the physical slim tubing and the contribution of the system compliance (i.e. the compressibility of the test zone of $4.42 \times 10^{-10} \text{ Pa}^{-1}$ and the compressibility of the water column between the SIT and the slim tubing packer) according to Black et al. (1987).

The results, derived from the parameter optimisation based on the measured pressure of the SW-SWS-PW sequence, are shown in Tab. 4-34. The cartesian match for the entire sequence pressure measurement is displayed in Fig. B-20.

Tab. 4-34: Hydraulic test STA3-1-OPA1: Formation parameter estimation based on the parameter optimisation of the SW-SWS-PW sequence using a radial composite flow model considering both the borehole pressure history and temperature changes inside the test interval

¹ Static formation pressure at the depth of the P2 sensor (852.02 m MD).

SW-SWS-PW results (radial composite flow model)	K [m s ⁻¹]	Ss [m ⁻¹]	P _f ¹ [kPa]
Best estimate	4.47×10^{-14}	7.59×10^{-7}	12'450

The resulting discontinuity radius of 0.091 m (thickness of inner zone 10 mm) and the hydraulic conductivity of the inner/skin zone of $1.73 \times 10^{-13} \text{ m s}^{-1}$ may indicate that the inner/skin zone is necessary. To check whether a simplification is possible, a parameter optimisation based on a homogeneous flow model was performed. It confirmed the existence of an inner/skin zone (*cf.* Fig. B-21). Tab. 4-35 shows the results of the parameter optimisation for the homogeneous flow model. In this case, the formation specific storage reached the upper limit of the predefined range of plausibility (parameter optimisation range).

Tab. 4-35: Hydraulic test STA3-1-OPA1: Formation parameter estimation based on the parameter optimisation of the SW-SWS-PW sequence using a homogeneous flow model considering the borehole pressure history and temperature changes inside the test interval

¹ Static formation pressure at the depth of the P2 sensor (852.02 m MD).

SW-SWS-PW results (homogeneous flow model)	K [m s ⁻¹]	S _s [m ⁻¹]	P _f ¹ [kPa]
Best estimate	1.85×10^{-14}	3.75×10^{-6}	13'224

Fig. B-21 shows a comparison of the residuals of the two simulations in the bottom part of the figure. The pressure residuals of the composite flow model remain under 6 kPa while those of the radial homogeneous flow model reach values of more than 20 kPa.

The existence of the inner/skin zone is also supported by the residual analysis. Fig. B-22 provides the probability distribution functions of the simulations with the two flow models. The normal distribution of the pressure residuals confirms the preferred conceptual model being the radial composite flow model.

Joint parameter regions of the SW-SWS-PW sequence

Based on the results of the parameter optimisation using a radial composite flow model, it is possible to estimate the joint parameter regions. Tab. 4-36 provides the 95% uncertainty ranges for the results of the parameter optimisation. The calculated ranges are unrealistically small because of the well-defined and well-constrained minima of the objective function/SSE values. Therefore, further investigations were performed to estimate the uncertainty ranges of the formation parameters.

Tab. 4-36: Hydraulic test STA3-1-OPA1: 95% uncertainty range associated with the results of the parameter optimisation using a radial composite flow model for the SW-SWS-PW sequence

¹ Static formation pressure at the depth of the P2 sensor (852.02 m MD).

SW-SWS-PW results (joint parameter region)	K [m s ⁻¹]	S _s [m ⁻¹]	P _f ¹ [kPa]
95% uncertainty range	$4.46 - 4.48 \times 10^{-14}$	$7.58 - 7.61 \times 10^{-7}$	12'448 - 12'452

Estimates of the formation parameter values and uncertainty ranges

A parameter analysis to assess the uncertainty of the results was considered necessary. However, this does not apply to the influence of variations in the borehole pressure history due to uncertainties in the mud density or mud level. In this sense, it should be noted that the main part of the STA3-1-OPA1 borehole pressure history is described by the annulus pressure (P3) measurements of the previous hydraulic test. Earlier analysis results in the TBO borehole campaign (BUL1-1, MAR1-1) have also shown that variations in mud density in the pressure history period had no significant influence on formation parameter estimates. The analysis of the uncertainty in the results is thus reduced to a consideration of the uncertainty associated with the parameter optimisation procedure and any inaccuracies in the determination of the wellbore storage. The former can be estimated using a perturbation analysis. In this analysis, the bandwidth of the parameters is determined based on several individual optimisations, which can, for instance, identify whether the result corresponds to a global or local minimum in the parameter space. The possible influence of uncertainties in the determination of the wellbore storage is assessed by means of a sampling analysis, in which the parameters are optimised in multiple runs depending on a representative bandwidth for the wellbore storage.

A perturbation analysis with 500 runs was carried out with a fixed radius of discontinuity (skin thickness). Fig. B-23 presents the simulations based on the best estimates for the optimisation parameters and one selected perturbation result in comparison to the previous simulation with a radial composite flow model (Tab. 4-34). The parameter results of each single parameter optimisation of the perturbation runs are shown against increasing values of the objective function/sum of squared errors (SSE) in Fig. B-24. The first 179 runs (run #0 to run #178) cover an SSE range between 426'293 and 935'862 (Fig. B-24). Within this range the matches of the SW-SWS-PW sequence were of a good to excellent quality and therefore used for the estimation of the parameter uncertainty ranges. Tab. 4-37 shows the resulting best estimates of the formation parameters and the associated uncertainty ranges for the simulation with the lowest SSE. The upper limit of resulting parameter ranges was limited by the plausibility ranges (parameter optimisation ranges) of the static formation pressure and specific storage. Thereby, the plausibility range of the specific storage was estimated based on the bandwidth of the mechanical properties of the Opalinus Clay.

Tab. 4-37: Hydraulic test STA3-1-OPA1: Uncertainty ranges and best estimates for the formation parameters estimated by the perturbation analysis

¹ Static formation pressure at the depth of the P2 sensor (852.02 m MD).

² Reached the lower limit of the plausibility range.

³ Reached the upper limit of the plausibility range.

Perturbation analysis results	K [m s ⁻¹]	Ss [m ⁻¹]	P _f ¹ [kPa]
Best estimate	4.32×10^{-14}	7.94×10^{-7}	12'515
Uncertainty range	$1.20 - 6.15 \times 10^{-14}$	$5.35 - 37.4 \times 10^{-7}$ ²	11'743 - 15'000 ³

Scatter plots of the formation parameters are shown in Fig. B-25. The two upper plots show a clear negative correlation between the formation hydraulic conductivity and both the formation specific storage (outer zone) and the static formation pressure. The bottom plot shows a positive correlation of the formation specific storage with the static formation pressure.

The sampling analysis for the test zone compressibility was performed for a maximum suitable range of values between $4.2 \times 10^{-10} \text{ Pa}^{-1}$ and $1.0 \times 10^{-9} \text{ Pa}^{-1}$. The resulting parameter sets in combination with the resulting objective function value/SSE value as a function of the value of the test zone compressibility are represented in Fig. B-26. Tab. 4-38 lists the resulting best estimates for formation parameters and the associated uncertainty ranges for the simulation with the lowest SSE (test zone compressibility of $4.96 \times 10^{-10} \text{ Pa}^{-1}$). The uncertainty range for the test zone compressibility was defined between $4.2 \times 10^{-10} \text{ Pa}^{-1}$ as the lower limit, which corresponds to the fluid compressibility, and an upper limit of $5.8 \times 10^{-10} \text{ Pa}^{-1}$, associated with the approximate inflection point of the SSE distribution.

Tab. 4-38: Hydraulic test STA3-1-OPA1: Uncertainty ranges and best estimates for the formation parameters as a result of the sampling analysis for the test zone compressibility

¹ Static formation pressure at the depth of the P2 sensor (852.02 m MD).

Sampling analysis results	K [m s ⁻¹]	S_s [m ⁻¹]	P_f ¹ [kPa]
Best estimate	5.72×10^{-14}	6.29×10^{-7}	12'251
Uncertainty range	$4.79 - 6.54 \times 10^{-14}$	$5.62 - 7.58 \times 10^{-7}$	12'185 – 12'359

Parameter optimisation for the slug and slug-recovery (SW-SWS) sequence

To validate the results of the entire sequence SW-SWS-PW, the SW-SWS sequence was investigated separately. The same conceptual model was used to numerically simulate the test data for the SW-SWS sequence, i.e. a radial composite flow model (representing a thin skin zone) with a wellbore storage as the inner boundary condition in an infinitely extended reservoir.

The results, derived from the parameter optimisation based on the measured pressure of the SW-SWS sequence, are shown in Tab. 4-39. The cartesian fit for the sequence pressure measurement is displayed in Fig. B-27. During the optimisation process the discontinuity radius reached the previously defined lower limit of the optimisation range of 0.091 m.

Tab. 4-39: Hydraulic test STA3-1-OPA1: Formation parameter estimates based on the parameter optimisation of the SW-SWS sequence with a radial composite flow model considering both the borehole pressure history and the temperature changes inside the test interval

¹ Static formation pressure at the depth of the P2 sensor (852.02 m MD).

SW-SWS results (radial composite flow model)	K [m s ⁻¹]	S_s [m ⁻¹]	P_f ¹ [kPa]
Best estimate	3.19×10^{-14}	1.29×10^{-6}	13'371

It should be noted that the characteristics of the PW phase cannot be reproduced by applying the derived parameter set to the entire sequence (SW-SWS-PW). The simulated PW phase strongly overestimates the measured pressure data for the middle and late times.

Summary of the analysis

Tab. 4-40 presents the results of the analysis of the formation parameters for interval STA3-1-OPA1. The best estimates for the formation parameters were derived from the sampling analysis (with a reliable test zone compressibility of $4.96 \times 10^{-10} \text{ Pa}^{-1}$), relating to the lowest objective function value achieved during the analysis. The uncertainty ranges of the formation parameters from the sampling analysis were smaller than the uncertainty ranges derived from the perturbation analysis, with the exception of the upper limit of the formation hydraulic conductivity. Therefore, the uncertainty ranges for the formation parameters were defined by the results of the perturbation analysis, except for the upper limit of the formation hydraulic conductivity. The formation parameter estimates derived from the SW-SWS sequence are all within the derived uncertainty ranges.

Nevertheless, the best estimate and the wide uncertainty range of the static formation pressure significantly exceed the expected formation pressure. The derived freshwater heads, based on the estimated formation pressures, are therefore judged as unrealistic and considered to represent "apparent" heads.

Tab. 4-40: Hydraulic test STA3-1-OPA1: Best estimates for the formation parameters and associated uncertainty ranges

¹ Static formation pressure at the midpoint of the test interval (872.12 m MD) considering the sensor offset of 20.52 kPa and an interval fluid density of $1'234.9 \text{ kg m}^{-3}$.

² Lower limit defined by the plausibility range (optimisation range).

STA3-1-OPA1	K [m s ⁻¹]	Ss [m ⁻¹]	Ps ¹ [kPa]
Best estimate	5.72×10^{-14}	6.29×10^{-7}	12'474
Uncertainty range	$1.20 - 6.54 \times 10^{-14}$	$0.53 - 3.74 \times 10^{-6} \text{ }^2$	11'966 – 15'223

4.6 Summary and discussion of hydraulic tests

4.6.1 Summary tables and plots

The results of the transmissivity and hydraulic conductivity estimates for all tested intervals are summarised in Tab. 4-41, and the estimated freshwater hydraulic heads and static formation pressures are documented in Tab. 4-42. Both tables present the best estimates along with confidence ranges as determined by the field test contractor and documented in the corresponding analysis reports.

The permeabilities for all tested intervals are summarised in Tab. 4-43 and were calculated based on the hydraulic conductivities provided in Tab. 4-41. An assumed density of $1'000 \text{ kg m}^{-3}$ and a dynamic viscosity of $1 \times 10^{-3} \text{ Pa s}$ were used for the calculation of the hydraulic permeabilities.

The hydraulic parameters T, K, P_f and h_s (in terms of m bgl and m asl) are illustrated with respect to both the borehole depth (in m MD) and the geological profile in Figs. 4-23 to 4-27. The best estimates for these parameters are indicated by vertical lines in the corresponding interval position. The associated confidence ranges are shown as dashed rectangles, delimited vertically by the corresponding interval extent and laterally by the minimum and maximum values.

Tab. 4-41: Summary of the hydraulic packer testing in borehole STA3-1: Transmissivity and hydraulic conductivity

¹ Based on the results presented by the field test contractor. Values are rounded.

Test interval details and hydraulic model							Transmissivity and hydraulic conductivity					
Test name	Interval depth				Interval length [m]	Hydraulic model	Best estimate ¹		Lowest estimate ¹		Highest estimate ¹	
	From [m MD]	To [m MD]	From [m asl]	To [m asl]			T [m ² s ⁻¹]	K [m s ⁻¹]	T _{min} [m ² s ⁻¹]	K _{min} [m s ⁻¹]	T _{max} [m ² s ⁻¹]	K _{max} [m s ⁻¹]
STA3-1-MAL1	499.20	527.81	-90.46	-119.07	28.61	radial-homogeneous	3 × 10 ⁻⁰⁷	1 × 10 ⁻⁰⁸	1 × 10 ⁻⁰⁷	4 × 10 ⁻⁰⁹	6 × 10 ⁻⁰⁷	2 × 10 ⁻⁰⁸
STA3-1-BDO3	697.87	720.80	-289.13	-312.06	22.93	radial-composite	2 × 10 ⁻¹¹	9 × 10 ⁻¹³	4 × 10 ⁻¹⁴	1 × 10 ⁻¹⁵	2 × 10 ⁻¹⁰	8 × 10 ⁻¹²
STA3-1-BDO2	721.90	744.83	-313.16	-336.09	22.93	radial-composite	3 × 10 ⁻¹¹	1 × 10 ⁻¹²	1 × 10 ⁻¹¹	6 × 10 ⁻¹³	6 × 10 ⁻¹¹	3 × 10 ⁻¹²
STA3-1-BDO1	758.87	781.80	-350.13	-373.06	22.93	radial-composite	7 × 10 ⁻¹²	3 × 10 ⁻¹³	6 × 10 ⁻¹²	2 × 10 ⁻¹³	2 × 10 ⁻¹¹	8 × 10 ⁻¹³
STA3-1-OPA3	782.20	813.43	-373.46	-404.69	31.23	radial-composite	2 × 10 ⁻¹²	6 × 10 ⁻¹⁴	5 × 10 ⁻¹³	1 × 10 ⁻¹⁴	4 × 10 ⁻¹²	1 × 10 ⁻¹³
STA3-1-OPA2	813.00	844.23	-404.26	-435.49	31.23	radial-composite	1 × 10 ⁻¹²	4 × 10 ⁻¹⁴	6 × 10 ⁻¹³	2 × 10 ⁻¹⁴	2 × 10 ⁻¹²	5 × 10 ⁻¹⁴
STA3-1-OPA4	849.80	855.58	-441.06	-446.84	5.78	radial-homogeneous	6 × 10 ⁻¹⁴	1 × 10 ⁻¹⁴	5 × 10 ⁻¹⁴	8× 10 ⁻¹⁵	2 × 10 ⁻¹³	3 × 10 ⁻¹⁴
STA3-1-OPA1	856.50	887.73	-447.76	-478.99	31.23	radial-composite	2 × 10 ⁻¹²	6 × 10 ⁻¹⁴	3 × 10 ⁻¹³	1 × 10 ⁻¹⁴	3 × 10 ⁻¹²	7 × 10 ⁻¹⁴
STA3-1-LIA2	885.95	908.88	-477.21	-500.14	22.93	radial-composite	2 × 10 ⁻¹²	9 × 10 ⁻¹⁴	1 × 10 ⁻¹²	5 × 10 ⁻¹⁴	3 × 10 ⁻¹²	1 × 10 ⁻¹³
STA3-1-LIA1	886.80	924.00	-478.06	-515.26	37.20	radial-composite	4 × 10 ⁻¹²	1 × 10 ⁻¹³	1 × 10 ⁻¹²	3 × 10 ⁻¹⁴	2 × 10 ⁻¹¹	3 × 10 ⁻¹³
STA3-1-KEU1	932.20	957.00	-523.46	-548.26	24.80	radial-composite	1 × 10 ⁻¹⁰	4 × 10 ⁻¹²	2 × 10 ⁻¹¹	1 × 10 ⁻¹²	2 × 10 ⁻¹⁰	5 × 10 ⁻¹²
STA3-1-MUK1	1'054.50	1'101.00	-645.76	-692.26	46.50	radial-composite	5 × 10 ⁻⁰⁶	1 × 10 ⁻⁰⁷	2 × 10 ⁻⁰⁶	5 × 10 ⁻⁰⁸	8 × 10 ⁻⁰⁶	2 × 10 ⁻⁰⁷

Tab. 4-42: Summary of the hydraulic packer testing in borehole STA3-1: Hydraulic head estimates

¹ Based on the results presented by the field test contractor.

Test interval details and associated hydraulic model							Hydraulic head [m bgl]			Hydraulic head [m asl]			Formation pressure		
Test name	Interval depth				Interval length [m]	Hydraulic model	Best ¹ h	Lowest ¹ h _{min}	Highest ¹ h _{max}	Best ¹ h	Lowest ¹ h _{min}	Highest ¹ h _{max}	Best ¹ P _s	Lowest ¹ P _{s min}	Highest ¹ P _{s max}
	From [m MD]	To [m MD]	From [m asl]	To [m asl]			[m bgl]	[m bgl]	[m bgl]	[m asl]	[m asl]	[m asl]	[kPa]	[kPa]	[kPa]
STA3-1-MAL1	499.20	527.81	-90.46	-119.07	28.61	radial-homogeneous	48	57	27	361	351	382	4'568	4'477	4'777
STA3-1-BDO3	697.87	720.80	-289.13	-312.06	22.93	radial-composite	104	277	31	305	132	378	5'936	4'244	6'655
STA3-1-BDO2	721.90	744.83	-313.16	-336.09	22.93	radial-composite	118	153	100	291	255	309	6'035	5'689	6'216
STA3-1-BDO1	758.87	781.80	-350.13	-373.06	22.93	radial-composite	-87	-64	-90	496	472	499	8'411	8'180	8'438
STA3-1-OPA3	782.20	813.43	-373.46	-404.69	31.23	radial-composite	-327	-256	-546	736	665	955	11'038	10'340	13'187
STA3-1-OPA2	813.00	844.23	-404.26	-435.49	31.23	radial-composite	-433	-383	-529	842	792	938	12'380	11'889	13'321
STA3-1-OPA4	849.80	855.58	-441.06	-446.84	5.78	radial-homogeneous	-732	-569	-786	1'141	977	1'194	15'548	13'944	16'073
STA3-1-OPA1	856.50	887.73	-447.76	-478.99	31.23	radial-composite	-399	-348	-680	808	756	1'088	12'474	11'966	15'223
STA3-1-LIA2	885.95	908.88	-477.21	-500.14	22.93	radial-composite	-208	-185	-254	616	593	663	10'841	10'616	11'296
STA3-1-LIA1	886.80	924.00	-478.06	-515.26	37.20	radial-composite	-184	-147	-242	593	556	650	10'686	10'323	11'252
STA3-1-KEU1	932.20	957.00	-523.46	-548.26	24.80	radial-composite	16	25	16	392	383	393	9'106	9'017	9'112
STA3-1-MUK1	1'054.50	1'101.00	-645.76	-692.26	46.50	radial-composite	56	57	54	353	352	355	10'028	10'016	10'045

Tab. 4-43: Summary of the hydraulic packer testing in borehole STA3-1: Permeability

¹ The calculation is based on the hydraulic conductivity provided by the field test contractor in the corresponding DR and standard conditions (density: 1'000 kg m⁻³, dynamic viscosity: 1 × 10⁻³ Pa s).

² Based on the results presented by the field test contractor. Values are rounded.

Test interval details						Permeability estimates ¹		
Test name	Interval depth				Interval length [m]	Best ² k [m ²]	Lowest ² k _{min} [m ²]	Highest ² k _{max} [m ²]
	From [m MD]	To [m MD]	From [m asl]	To [m asl]				
STA3-1-MAL1	499.20	527.81	-90.46	-119.07	28.61	1 × 10 ⁻¹⁵	4 × 10 ⁻¹⁶	3 × 10 ⁻¹⁵
STA3-1-BDO3	697.87	720.80	-289.13	-312.06	22.93	9 × 10 ⁻²⁰	1 × 10 ⁻²²	9 × 10 ⁻¹⁹
STA3-1-BDO2	721.90	744.83	-313.16	-336.09	22.93	1 × 10 ⁻¹⁹	6 × 10 ⁻²⁰	3 × 10 ⁻¹⁹
STA3-1-BDO1	758.87	781.80	-350.13	-373.06	22.93	3 × 10 ⁻²⁰	2 × 10 ⁻²⁰	9 × 10 ⁻²⁰
STA3-1-OPA3	782.20	813.43	-373.46	-404.69	31.23	6 × 10 ⁻²¹	1 × 10 ⁻²¹	2 × 10 ⁻²⁰
STA3-1-OPA2	813.00	844.23	-404.26	-435.49	31.23	4 × 10 ⁻²¹	2 × 10 ⁻²¹	5 × 10 ⁻²¹
STA3-1-OPA4	849.80	855.58	-441.06	-446.84	5.78	1 × 10 ⁻²¹	8 × 10 ⁻²²	3 × 10 ⁻²¹
STA3-1-OPA1	856.50	887.73	-447.76	-478.99	31.23	6 × 10 ⁻²¹	1 × 10 ⁻²¹	7 × 10 ⁻²¹
STA3-1-LIA2	885.95	908.88	-477.21	-500.14	22.93	9 × 10 ⁻²¹	5 × 10 ⁻²¹	1 × 10 ⁻²⁰
STA3-1-LIA1	886.80	924.00	-478.06	-515.26	37.20	1 × 10 ⁻²⁰	3 × 10 ⁻²¹	3 × 10 ⁻²⁰
STA3-1-KEU1	932.20	957.00	-523.46	-548.26	24.80	1 × 10 ⁻¹⁹	1 × 10 ⁻¹⁹	5 × 10 ⁻¹⁹
STA3-1-MUK1	1'054.50	1'101.00	-645.76	-692.26	46.50	1 × 10 ⁻¹⁴	5 × 10 ⁻¹⁵	2 × 10 ⁻¹⁴

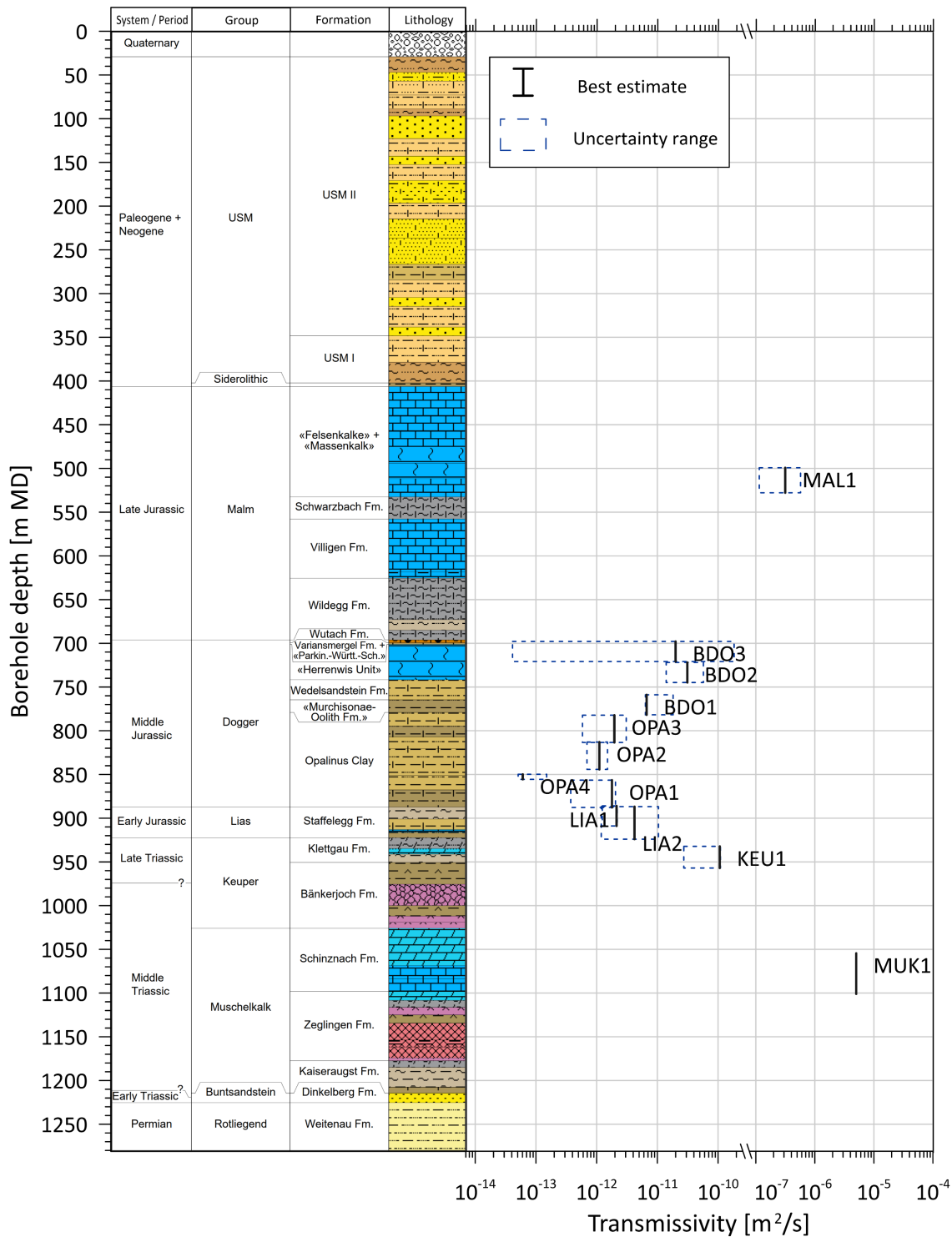


Fig. 4-23: Summary of the hydraulic testing in borehole STA3-1: Formation transmissivity profile

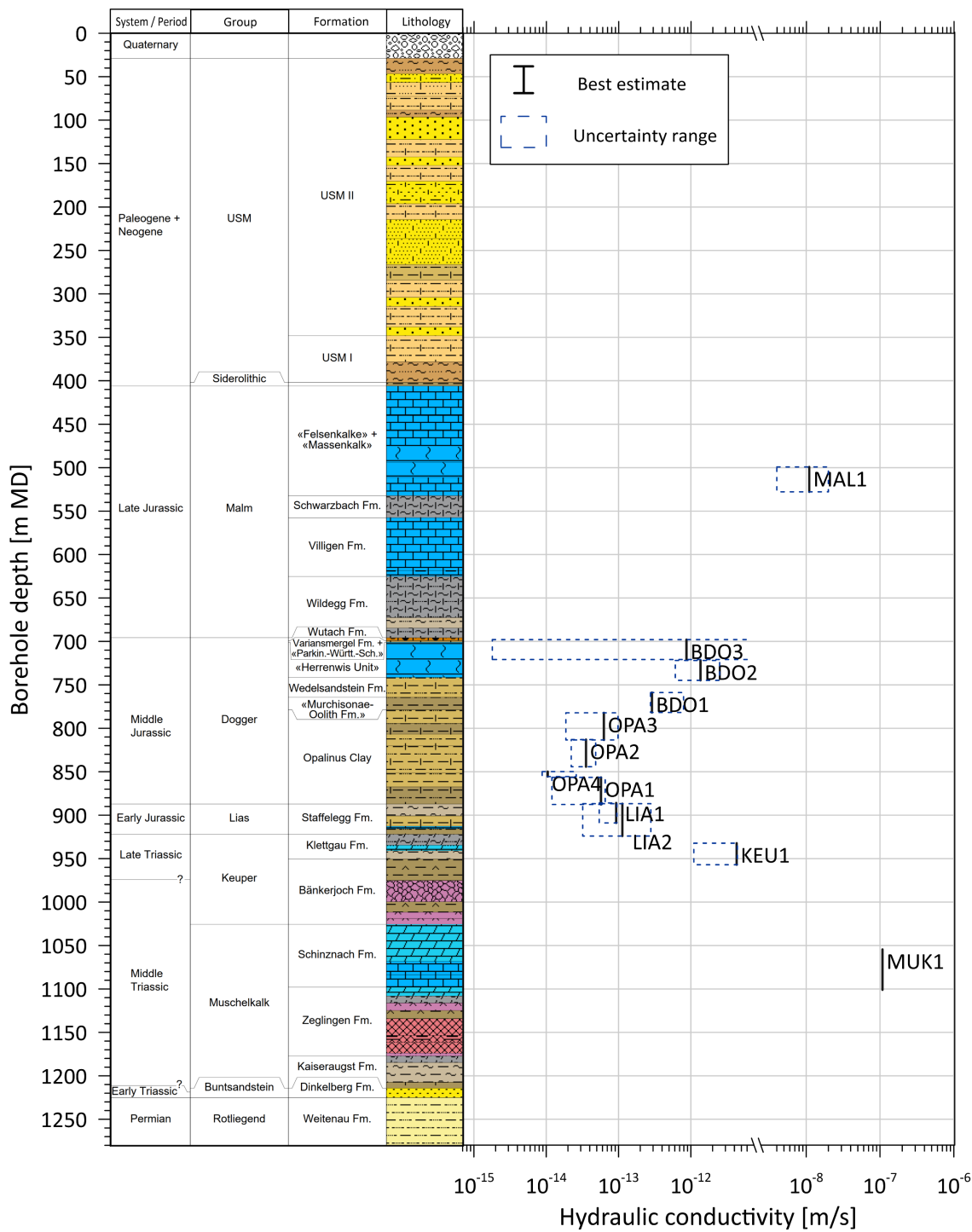


Fig. 4-24: Summary of the hydraulic testing in borehole STA3-1: Formation hydraulic conductivity profile

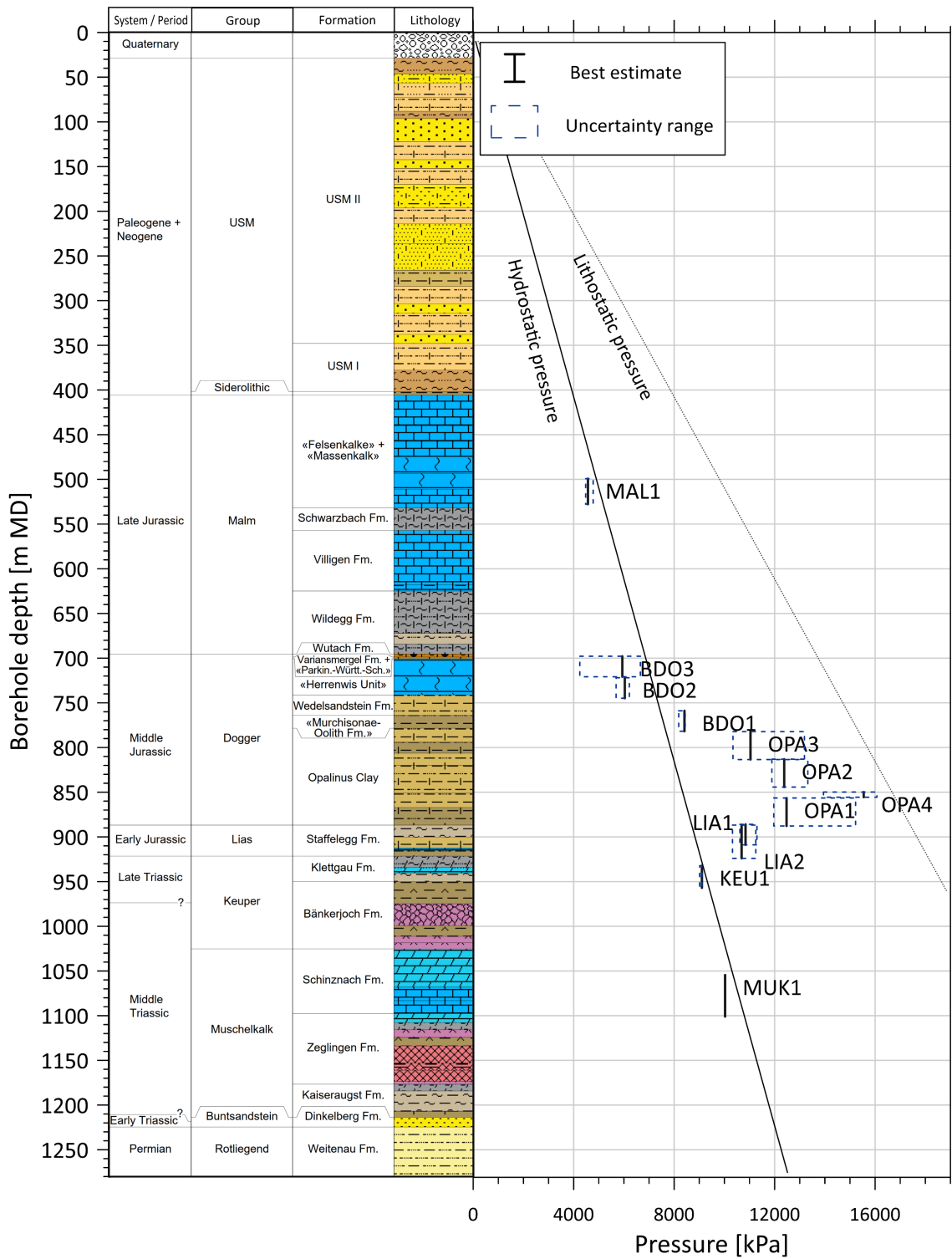


Fig. 4-25: Summary of the hydraulic testing in borehole STA3-1: Static formation pressure profile

The lithostatic pressure is based on the assumption of a mean density of 2'000 kg m⁻³.

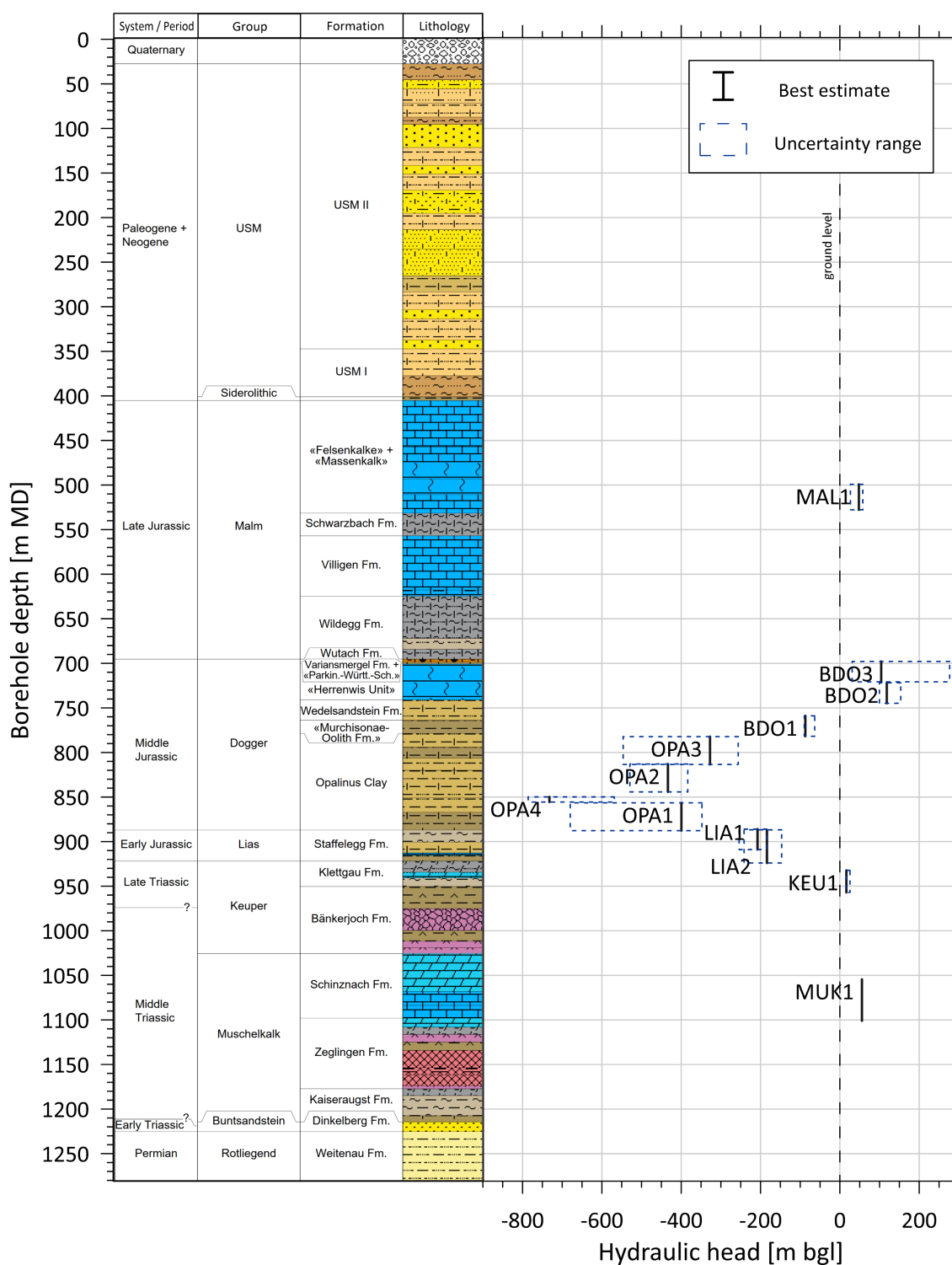


Fig. 4-26: Summary of the hydraulic testing in borehole STA3-1: Formation hydraulic head profile (m bgl)

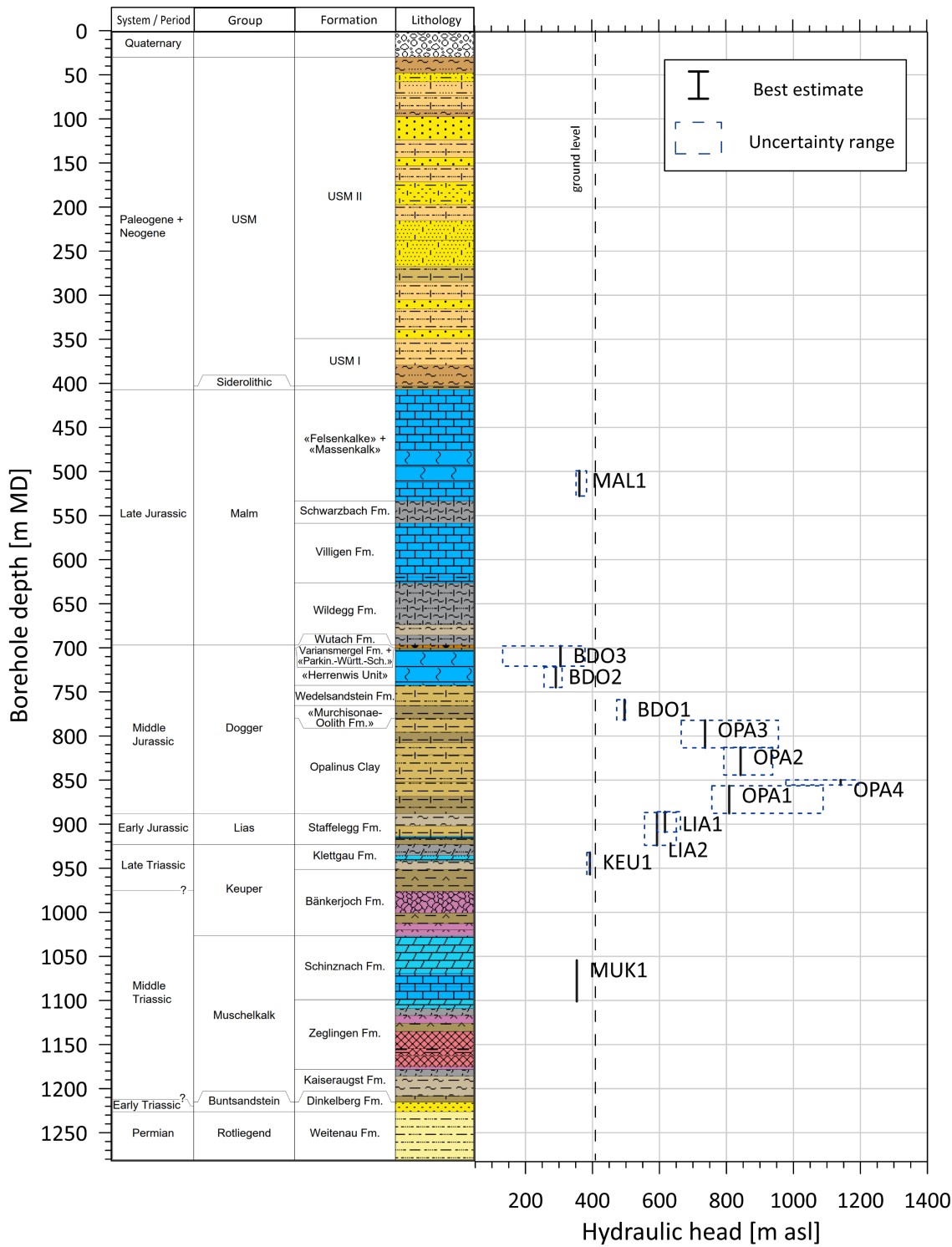


Fig. 4-27: Summary of the hydraulic testing in borehole STA3-1: Formation hydraulic head profile (m asl)

4.6.2 Discussion of data and test results

The first hydraulic test conducted in the STA3-1 borehole focused on the «Felsenkalke» and «Massenkalk» of the Malm Group. The STA3-1-MAL1 test interval (499.20 – 527.81 m MD) was positioned in consequence of the fluid logging campaign STA3-1-FL1-MAL (*cf.* Section 3). STA3-1-MAL1 covers the main inflow zone that was indicated by the fluid logging campaign at approximately 520 m MD. However, fluid logging did not allow an unambiguous positioning because the concentration of the inflow, likely a mixture of the saline drilling fluid and formation water, exceeded the measuring range of the probe. The packer test comprises a limestone section that includes filled vugs and veins and a few fissures (> 1 cm). The best estimate of the hydraulic transmissivity of $3.1 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ (hydraulic conductivity of $1.1 \times 10^{-8} \text{ m s}^{-1}$) that resulted from the analysis of the hydraulic test STA3-1-MAL1 captured the late time hydraulic test response during the infinite radial acting flow. The results correspond well with the result of the analysis of the pump phase during fluid logging (transmissivity of approx. $1.5 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$) which was derived with a simple radially homogeneous analysis approach. The analysis of test STA3-1-MAL1 also used a homogeneous flow model without skin. The uncertainty in the hydraulic conductivity estimate was based on the observed presence of gas as indicated by a measured large test zone compressibility and detected in the samples taken during the production phase. The resulting uncertainty in the hydraulic conductivity estimate ranges over a factor of about 5. This is considered more robust than the results from fluid logging. The hydraulic head was estimated within a 31 m uncertainty range. The interval investigated extended over 28.61 m. Even though the fluid logging did not allow to unambiguously locate the inflow zone for the reasons mentioned above, the hydraulic conductivity of the associated fissures must be higher than the average hydraulic conductivity estimated for the entire test interval STA3-1-MAL1. Test STA3-1-MAL1 allowed for the successful production of a formation water sample.

The top part of the Dogger Group, the «Brauner Dogger» above the Opalinus Clay was examined with three hydraulic packer tests. The first test, STA3-1-BDO1, was positioned at the bottom of «Brauner Dogger» and included the topmost meters of the Opalinus Clay. More than half of the interval was addressed to the «Murchisonae-Oolite Formation». The second test, STA3-1-BDO2, was located in a shallower part, and included mostly the «Herrenwis Unit» and the top of the Wedelsandstein Formation. The last test in the Dogger Group, STA3-1-BDO3, covered the topmost parts of the Dogger Group (including also a large section of the «Herrenwis Unit»). The main test sequences for all tests consisted of a slug withdrawal and a slug recovery phase followed by a pulse withdrawal test phase. A radial composite flow model was used in the analysis of all three tests, with the zone near the borehole representing a thin skin layer. The result of STA3-1-BDO1 is a realistic low hydraulic conductivity of $2.9 \times 10^{-13} \text{ m s}^{-1}$. The results of STA3-1-BDO2 and STA3-1-BDO3 differ by less than a factor 2 and are little more than a factor 3 higher than STA3-1-BDO1. The uncertainties were mainly due to the limiting conditions of testing (e.g. duration of history and testing), except for STA3-1-BDO3 where the slug phase could not be used for the analysis because of technical issues during testing. As a result, the subsequent shorter pulse withdrawal phase was included in the main analysis. However, the two shut-in phases (slug recovery and pulse) did not provide a uniform picture of the near-wellbore zone, causing additional uncertainty in the formation parameter estimates. The estimated hydraulic heads for STA3-1-BDO2 and STA3-1-BDO3 are below hydrostatic conditions. For STA3-1-BDO1 the estimated hydraulic head would be considered as “apparent” hydraulic head.

The Opalinus Clay was investigated in borehole STA3-1 using a total of four hydraulic tests. Tests STA3-1-OPA1, STA3-1-OPA2 and STA3-1-OPA3 were conducted sequentially in test intervals of about 31 m length. The hydraulic test STA3-1-OPA4 was conducted separately as it was performed in a test interval of only 5.78 m and preceded the performance of a GTPT, extended by a second hydraulic test sequence. The analyses of the extended GTPT do not form

part of this report. The analysis of the first hydraulic test in the Opalinus Clay, STA3-1-OPA1, is presented in more detail in Section 4.5.2. Based on the experience from previous boreholes in the TBO test campaign, the hydraulic tests were started with an initial pressure recovery phase followed directly by a slug withdrawal phase. Subsequently, the slug pressure recovery phase was started by closing the shut-in valve. On completion of the tests, a pulse withdrawal phase was performed. This procedure was used for all hydraulic tests, except STA3-1-OPA4 where an additional pulse injection phase was performed before completion of the test. For the four tests in the Opalinus Clay, the borehole pressure history ranged from 242 to 911 hours, whereas the actual test durations ranged between 58.7 and 71.9 hours. The best estimates for the hydraulic conductivity varied by a factor of 6, between $1.1 \times 10^{-14} \text{ m s}^{-1}$ for STA3-1-OPA4 and $6.3 \times 10^{-14} \text{ m s}^{-1}$ for test STA3-1-OPA3. The analyses of the three tests in longer intervals were based on a 2-zone radial composite flow model that considered the observed near borehole conditions (skin) as a separate zone. For the analysis of test STA3-1-OPA4, a radial homogeneous flow model was used, since in a radial composite flow model the parameters of the outer/formation zone seemed to be almost insensitive compared to the parameters of the inner/skin zone, which extent over a much larger radius. The uncertainty in the estimates of the hydraulic head was generally high for all tests performed in the Opalinus Clay, particularly for test STA3-1-OPA4 which had the longest borehole history. Like the results for other boreholes in the TBO campaign, the estimates of the hydraulic head from the tests in the Opalinus Clay yielded "apparent" hydraulic heads which are not considered as realistic due to physical processes that cannot be captured by the hydraulic modelling software used, e.g. poroelastic effects.

The Staffelegg Formation of the Lias Group was examined with two hydraulic packer tests. Test STA3-1-LIA1 was performed with a single packer configuration and is discussed in detail in Section 4.5.1. Like most hydraulic tests in borehole STA3-1, test STA3-1-LIA2 was performed with a double packer configuration. STA3-1-LIA2 therefore did not reach the lower parts of the Staffelegg Formation, i.e. the Beggingen and Schambelen Members, and the top of the Klettgau Formation (Keuper Group). Both tests were analysed with a 2-zone radial composite model (representing a skin in terms of a thin zone close to the borehole). The best estimates derived for the formation hydraulic conductivity were consistent $9.3 \times 10^{-14} \text{ m s}^{-1}$ and $1.1 \times 10^{-13} \text{ m s}^{-1}$ for STA3-1-LIA2 and STA3-1-LIA1, respectively. These values are about half an order of magnitude higher than the mean value observed for Opalinus Clay. As with the other tested formations of very low permeability, the high estimated hydraulic pressure is considered not realistic due to physical processes that cannot be captured by the hydraulic modelling software used.

The Klettgau Formation of the Keuper Group was tested with hydraulic test STA3-1-KEU1 using the HDDP system in single packer configuration. No mud losses (potassium silicate & polymers) were observed during coring. For the analysis of this test, a 2-zone radial composite flow model was used where the observed positive skin, also obvious in the flow model diagnostics, was modelled as a zone near the borehole. Test STA3-1-KEU1 consisted of a slug withdrawal and a slug recovery phase followed by a pulse withdrawal phase. Because of the observed low hydraulic conductivity, neither a pumping phase nor water sampling was possible. The hydraulic conductivity was best estimated to be $4.3 \times 10^{-12} \text{ m s}^{-1}$ and the best estimate for the hydraulic head was 392 m asl (16 m bgl) near static conditions. Both estimates have small ranges of uncertainty.

One hydraulic test was performed in the Schinznach Formation of the Muschelkalk Group (including about 2 m of the Zeglingen Formation). Test STA3-1-MUK1 was performed with a single packer configuration after minor mud losses (polymers) had occurred during coring and test preparation. The test consisted of a slug withdrawal and a slug recovery phase, a multi-rate pumping phase followed by a pressure recovery phase and a second slug withdrawal and slug recovery sequence. For the test analyses, a 2-zone radial composite flow model was used where the zone near the borehole represents the observed positive skin. The hydraulic conductivity was

best estimated to be $1.1 \times 10^{-7} \text{ m s}^{-1}$ (with an uncertainty range of $\pm$ factor 2) and the best estimate for the hydraulic head was 353 m asl (56 m bgl). The hydraulic head estimate had a small associated range of uncertainty of 3 m. However, comparable to the Muschelkalk tests in the other TBO boreholes, the core material shows a few steep fractures and dissolution vugs, which probably control the flow in the interval and whose hydraulic conductivity must be higher than the average hydraulic conductivity estimated by the flow models used in the analyses. A groundwater sample was collected successfully.

5 Summary

The Stadel-3-1 (STA3-1) exploratory borehole is the sixth borehole drilled within the framework of the TBO project and the second exploratory borehole drilled in the Nördlich Lägern siting region.

In total, twelve intervals were investigated by hydraulic packer tests in borehole STA3-1 between January 2021 and May 2021. All hydraulic packer tests were performed in cored borehole sections using an HDDP packer system in either single or double packer configuration (*cf.* Tab. 4-22). The test activities were performed in the following geological formations (*cf.* Dossier III):

- Malm Group with a focus on the «Felsenkalke» + «Massenkalk» (STA3-1-MAL1); following the fluid logging campaign (STA3-1-FL1-MAL)
- Dogger Group («Brauner Dogger») with «Parkinsoni-Württembergica-Schichten» and mostly «Herrenwis Unit» (STA3-1-BDO3), «Herrenwis Unit» and some Wedelsandstein Formation (STA3-1-BDO2), and «Murchisonae-Oolith Formation» with some Wedelsandstein Formation at the top and Opalinus Clay at the bottom (STA3-1-BDO1)
- Dogger Group with a focus on Opalinus Clay (STA3-1-OPA3, STA3-1-OPA2, STA3-1-OPA4 and STA3-1-OPA1)
- Lias Group with a focus on the Staffelegg Formation with the Gross Wolf, Rietheim, Grünschholz, Breitenmatt, Rickenbach and Frick Members (STA3-1-LIA2) resp. including also the Beggingen and Schambelen Members and a small part of the Klettgau Formation (STA3-1-LIA1); both with Opalinus Clay at the top
- Keuper Group with mostly Klettgau Formation including the Gruhalde, Seebi, Gansingen and Ergolz Members and the top of the Bänkerjoch Formation (STA3-1-KEU1)
- Muschelkalk Group with a focus on the Schinznach Formation including the Stamberg, Liedertswil and Leutschenberg Members and a small part of the Zeglingen Formation (STA3-1-MUK1)

All hydraulic tests were supported by on-site field analyses to optimise the test procedures. The pressures and flow rates measured during all tests are illustrated in Figs. 4-9 to 4-20. The main results and best estimates of the hydraulic formation parameters are presented in Tabs. 4-41 to 4-43 and Figs. 4-23 to 4-27. The execution of rate withdrawal tests was limited to the hydraulic tests performed in the «Felsenkalke» and «Massenkalk» of the Malm Group (STA3-1-MAL1) and the Schinznach Formation of the Muschelkalk Group (STA3-1-MUK1). The fluid logging analysis (STA3-1-FL1-MAL; *cf.* Section 3.2) and two hydraulic test analyses (STA3-1-LIA1 and STA3-1-OPA1; *cf.* Sections 4.5.1 and 4.5.2) were selected for a detailed description in this report.

The best estimates and uncertainties for the hydraulic conductivities and transmissivities lie within a reasonable range and are within the expected spectrum of values for the investigated formations (e.g. Nagra 2008, Nagra 2014a and b). Operational problems during the STA3-1-BDO3 hampered the generation of data that would allow for a precise determination of the hydraulic formation parameters. In this case, the range of the parameters is relatively large compared to the other estimates of the formation parameters of the other tests. The hydraulic conductivities obtained for the Opalinus Clay are very low and range over one order of magnitude in total.

The extrapolated hydraulic heads are within an expected range (Luo et al. 2014), except for the hydraulic tests carried out in the Dogger Group including the Opalinus Clay and the Lias Group. The hydraulic head estimates from tests STA3-1-BDO2 and STA3-1-BDO3 were lower than the range of the head predicted by Luo et al. (2014) for the «Brauner Dogger» (unit BD5). Due to unavoidable short-term borehole test conditions, the hydraulic heads estimated for STA3-1-BDO1, STA3-1-OPA1, STA3-1-OPA2, STA3-1-OPA3, STA3-1-OPA4, STA3-1-LIA1 and STA3-1-LIA2 appear to be affected by a large overestimation. They are considered as "apparent" hydraulic heads.

General investigations concerning the physical explanation for the overestimation of the hydraulic heads are continuing. The presented analyses consider temperature effects in the test intervals and pressure-induced effects resulting from the high-density drilling mud used after drilling through the interval midpoint. Nagra has installed long-term pressure monitoring systems in borehole STA3-1 and other selected boreholes to study these effects and other findings in more detail.

6 References

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Appendix A: Abbreviations, nomenclature and definitions

Tab. A-1: Lithostratigraphy abbreviations for test names in STA3-1

Lithostratigraphy	Abbreviation
Malm Group	MAL
Brauner Dogger (Dogger)	BDO
Opalinus Clay (Dogger)	OPA
Lias Group	LIA
Keuper Group	KEU
Muschelkalk Group	MUK

Tab. A-2: Test name definitions for hydraulic packer testing

Abbreviation	Example
Drill site abbreviation – lithostratigraphy abbreviation ¹ + number of test	STA3-1-MUK1: First test interval in Muschelkalk aquifer in borehole STA3-1

¹ Based on the preliminary information

Tab. A-3: Test event abbreviations for hydraulic packer testing

Test phase	Abbreviation
Compliance phase	COM
Packer deflation phase	DEF
Filling of test tubing	FILL
Packer inflation phase	INF
Multi-rate pumping test with stepwise constant flow rates	MR
Pressure recovery after multi-rate pumping test (shut-in)	MRS
Pulse injection test	PI
Initial pressure recovery 'static pressure recovery' (SIT closed)	PSR
Pulse withdrawal test	PW
Pumping test with constant flow rate ('rate withdrawal test')	RW
Pressure recovery after pumping test with constant flow rate (shut-in)	RWS
Slug withdrawal test (flow phase)	SW
Slug withdrawal test – pressure recovery with closed SIT (shut-in)	SWS

Tab. A-4: Parameter definitions

Abbreviation / symbol	Description	Unit
c_{tz}	Test zone compressibility	Pa^{-1}
C_i	Concentration (salinity) of one inflow i	g l^{-1}
EC_i	Electrical conductivity of one inflow i	$\mu\text{S cm}^{-1}$
g	Acceleration due to gravity (9.81)	m s^{-2}
h_s	Static hydraulic head (freshwater head) $h_s = z_{\text{ref}} - z_{\text{int}} + \left[\frac{P_f + \rho_{\text{int}} g (z_{\text{int}} - z_2) - P_{\text{atm}} - P_{\text{offset}}}{\rho_w g} \right]$	m asl
k	Intrinsic permeability	m^2
K	Hydraulic conductivity	m s^{-1}
K_{in}	Inner-zone hydraulic conductivity	m s^{-1}
K_{out}	Outer-zone hydraulic conductivity	m s^{-1}
K_s	Hydraulic conductivity of skin zone	m s^{-1}
n	Fractional flow dimension, e.g. Barker (1988)	-
P	Pressure (at QSSP-P2 level, if not otherwise specified)	Pa, kPa
P_1	Pressure below bottom packer / interval P1 (downhole probe)	Pa, kPa
P_2	Pressure in test interval (downhole probe)	Pa, kPa
P_2^*	(Absolute) pressure in test interval (memory gauge)	$\text{Pa, kPa, kPa}_{\text{a}}$
P_3	Pressure in annulus (above top packer, downhole probe)	Pa, kPa
P_4	Pressure in test tubing above SIT (downhole probe)	Pa, kPa
P_{atm}	Atmospheric pressure	Pa, kPa
P_f	Static formation pressure (fitting parameter, at QSSP-P2 level, respectively P_2^* level)	Pa, kPa
P_{int}	Pressure at midpoint of test interval	Pa, kPa
P_{offset}	Offset of a pressure probe at atmospheric pressure	Pa, kPa
P_s	Static formation pressure (at midpoint of test interval if not specified otherwise)	Pa, kPa
ΔP_{packer}	Interval packer pressure changes	bar
q	Flow rate	$\text{m}^3 \text{s}^{-1}$
q_i	Flow rate of one inflow i	$\text{m}^3 \text{s}^{-1}$
Q, Q_{tot}	Cumulative flow volume	m^3
r_d	Radius of discontinuity	m
r_s	Radius of the skin zone extension	m
$r_{w \text{ int}}$	Borehole radius of the test interval	mm

Tab. A-4: continued

Abbreviation / symbol	Description	Unit
ρ_{int}	Density of interval fluid	kg m^{-3}
ρ_{w}	Density of formation water (fluid)	kg m^{-3}
S	Storage	-
s	Skin factor	-
S_{s}	Specific storage	m^{-1}
$S_{\text{s in}}$	Inner-zone specific storage	m^{-1}
$S_{\text{s out}}$	Outer-zone specific storage	m^{-1}
S_{ss}	Specific storage of skin zone	m^{-1}
t_{s}	Thickness of the skin zone extension	m
T	Transmissivity	$\text{m}^2 \text{s}^{-1}$
T_{i}	Transmissivity of one inflow i	$\text{m}^2 \text{s}^{-1}$
t, dt	Time, elapsed time	s
$T_{\text{int}}, T1, T2, T3, T4, T2^*$	Temperature in test interval, temperature triple probe (sensors 1, 2, 3 or 4 associated with specific transducer; sensor T2* associated with memory gauge)	$^{\circ}\text{C}$
ΔV_{int}	Interval volume changes	mL
z_2	Depth of pressure sensor of test interval P2	m MD
z_{int}	Depth interval midpoint	m MD
z_{ref}	Reference point elevation	m asl

Tab. A-5: Non-parameter abbreviations

Abbreviation	Description	Unit
ΔP	Change in pressure	Pa, kPa
ΔV	Change in volume	m ³
1D	One dimensional	
2D	Two dimensional	
3D	Three dimensional	
AG	Aktiengesellschaft (company limited by shares "Ltd.")	
API	American Petroleum Institute	
BHPH	Borehole pressure history	
BOP	Blow out preventer	
STA3-1	Stadel-3 drill site, borehole 1	
cps	Counts per second	
CU	Copper	
DA	Detailed analysis	
DAS	Data acquisition system	
DR	Detailed report	
EU	External upset coupling	
EUE	External upset end	
FM	Flow model	
FS	Full scale	
GmbH	Gesellschaft mit beschränkter Haftung (company with limited liability)	
GTPT	Gas threshold pressure test	
HDDP	Heavy-duty double packer system	
HLW	High level waste	
HTT	Hydraulic test tool	
IARF	Infinite acting radial flow region	
ID	Inner diameter	
IPI	Inflatable Packers International, Perth, Australia	
IT	Information technology	
L/ILW	Low and intermediate level waste	
ln	Litre normal	ln
MAR1-1	Marthalen-1 drill site, borehole 1	
MD	Measured depth	m
MHF	Micro-hydraulic fracturing	

Tab. A-5: continued

Abbreviation	Description	Unit
NBR	Nitrile butadiene rubber	
NDSA	Naphthalene disulfonate acid	
NL	Siting region Nördlich Lägern	
OD	Outer diameter	
PA1	Bottom packer of the hydraulic line of the HDDP	
PA2	Top packer of the hydraulic line of the HDDP	
PCP	Progressive cavity pump	
POOH	Pull out of hole	
PPG	Piston pulse generator	
PRV	Pressure release valve	
QC	Quality control	
QLA	Quick look analysis	
QLR	Quick look report	
QSSP	Quadruple sub-surface probe	
Rd	Reading	
RIH	Run in hole	
SIT	Shut-in tool	
SSE	Sum of squared errors	
TBO	Tiefbohrung(en) (German for deep borehole(s))	
TVD	True vertical depth	m
WS	Water sample	
WT	Water table	
WTW	Wissenschaftlich-technische Werkstätten GmbH	
ZH	Zürich	
ZNO	Siting region Zürich Nordost	

Appendix B: Analysis plots of the hydraulic packer tests STA3-1-LIA1 and STA3-1-OPA1

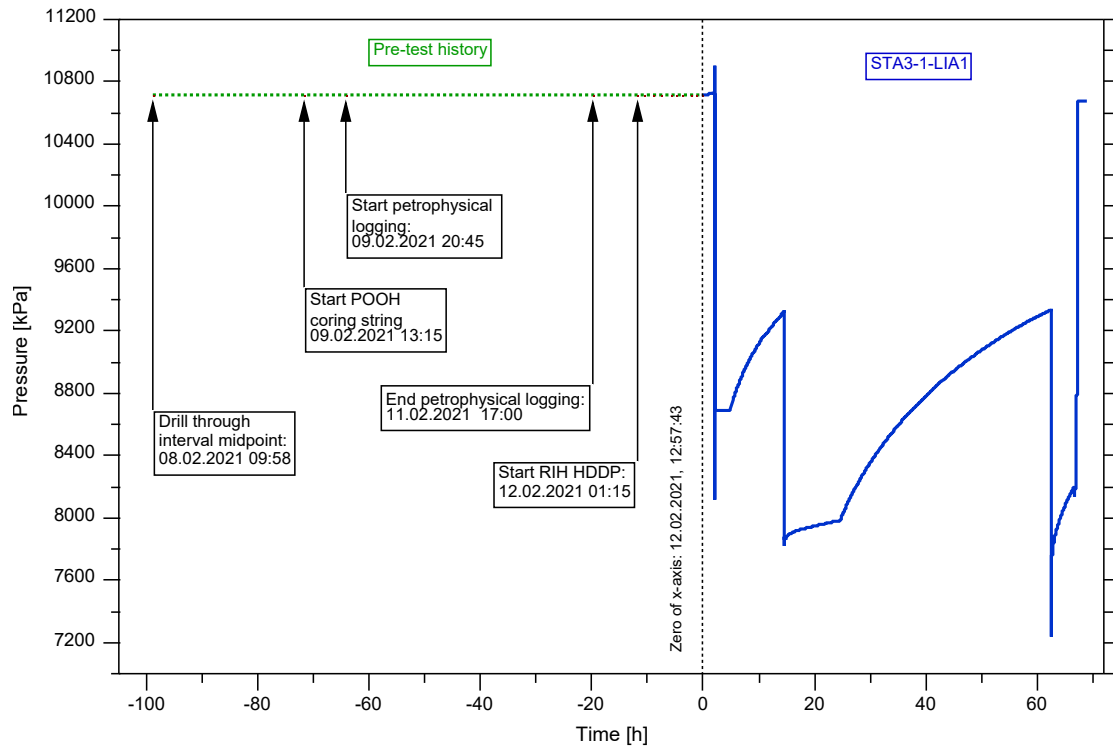


Fig. B-1: Hydraulic test STA3-1-LIA1: Entire record of the borehole pressure history used in the analysis

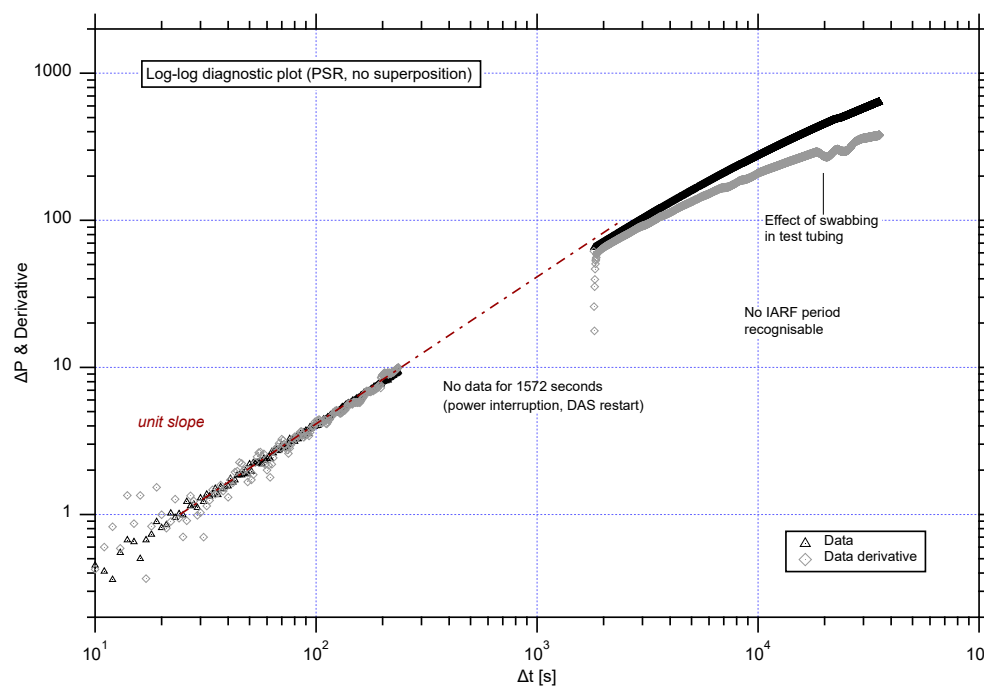


Fig. B-2: Hydraulic test STA3-1-LIA1: Log-log plot of PSR phase (no superposition plot)

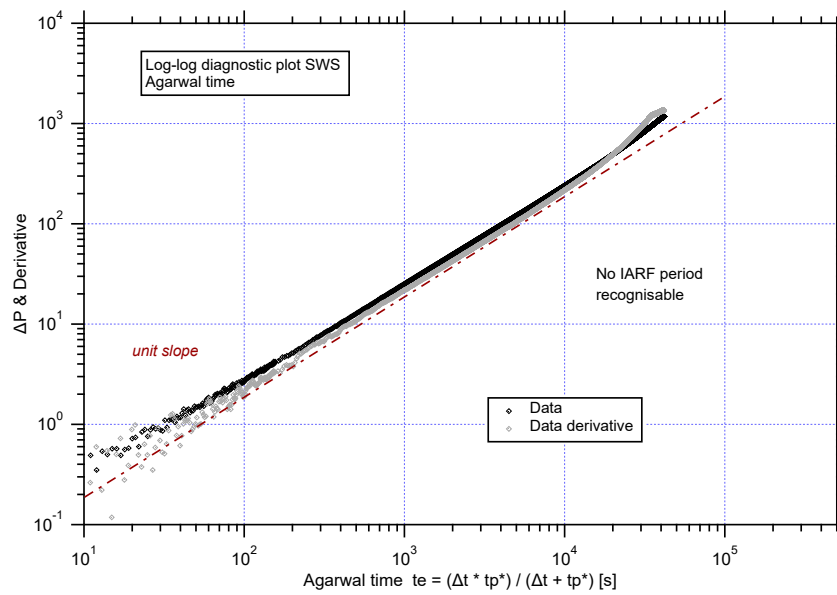


Fig. B-3: Hydraulic test STA3-1-LIA1: Log-log plot of SWS phase (corrected Agarwal time)

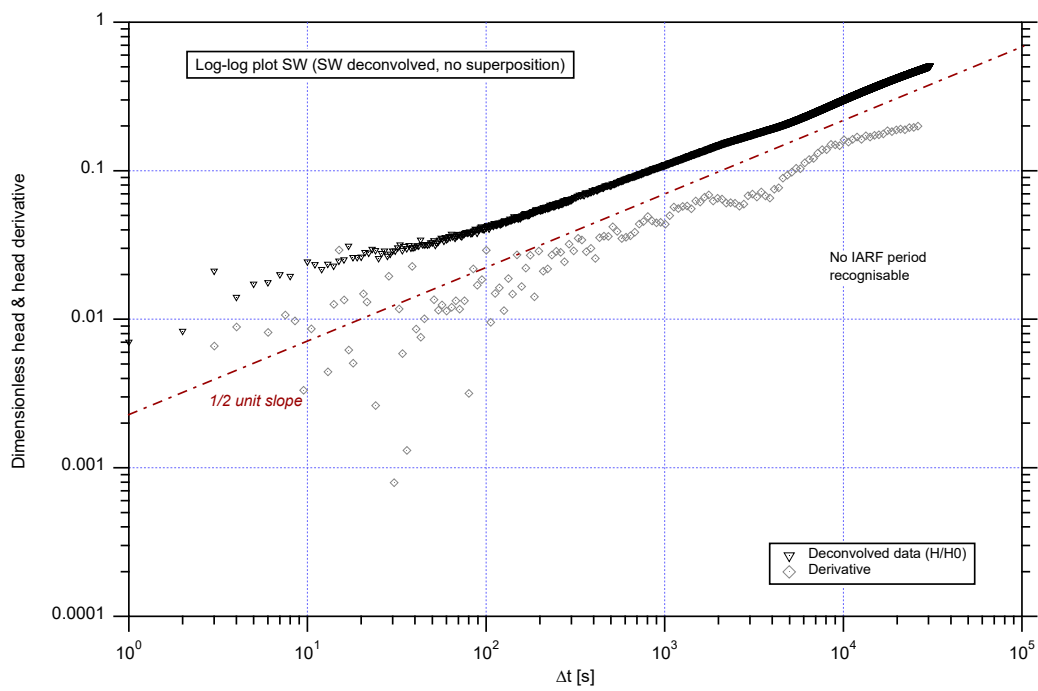


Fig. B-4: Hydraulic test STA3-1-LIA1: Log-log de-convolution plot of SW phase

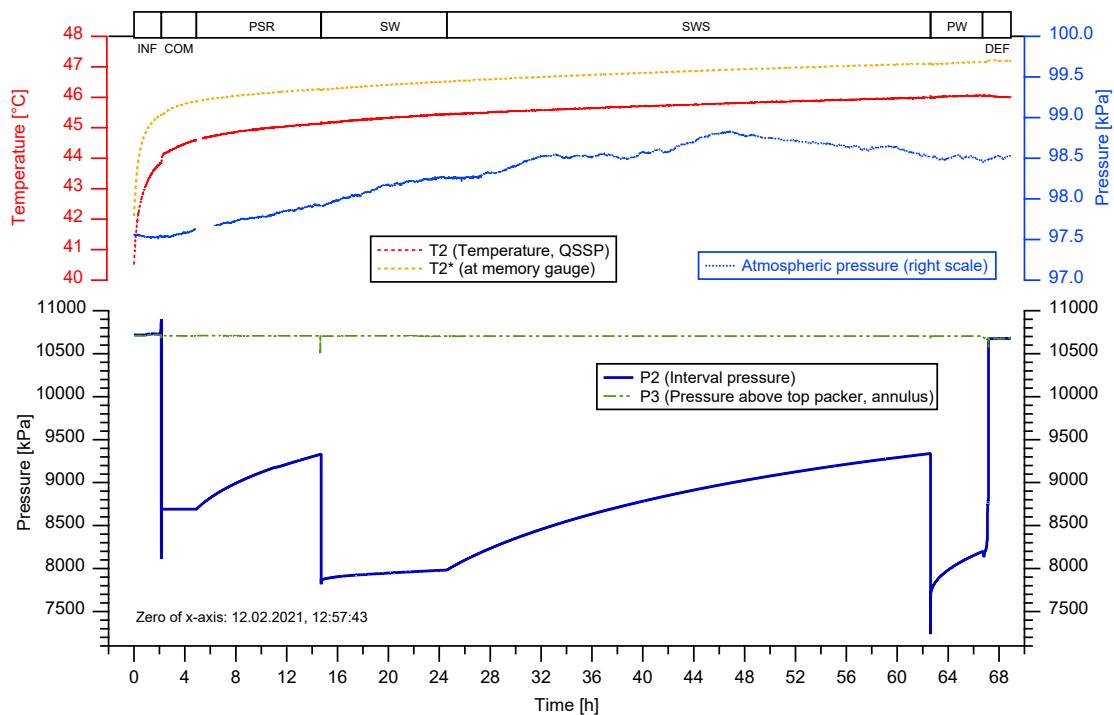


Fig. B-5: Hydraulic test STA3-1-LIA1: Interval temperature ($T2^*$) and QSSP temperature ($T2$) measurements in comparison to the atmospheric and the downhole pressures of the QSSP (P2 and P3)

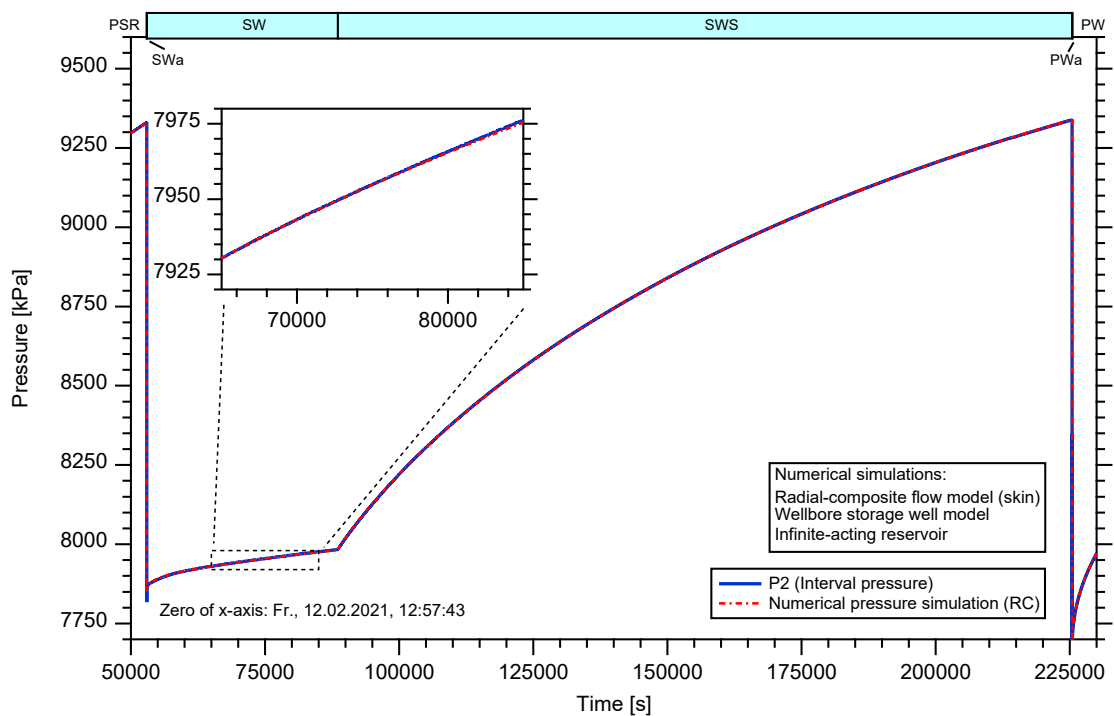


Fig. B-6: Hydraulic test STA3-1-LIA1: Cartesian plot of the simulation using the best parameter estimates resulting from a parameter optimisation of the sequence SW-SWS with a radial composite flow model

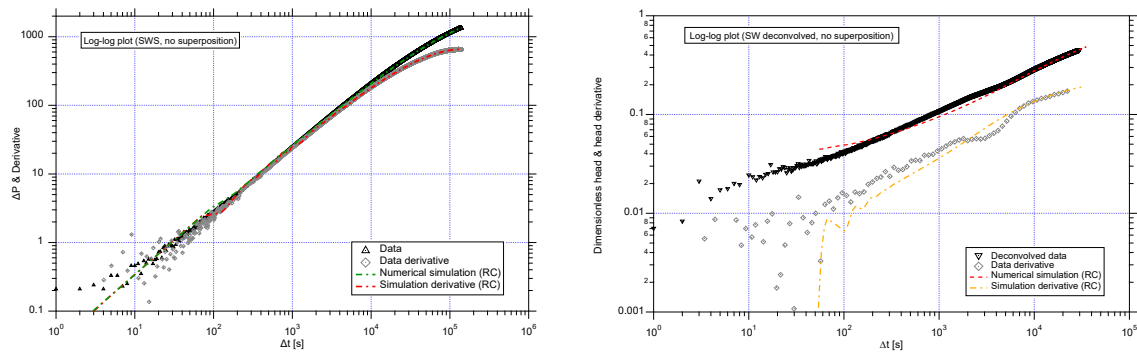


Fig. B-7: Hydraulic test STA3-1-LIA1: Log-log plots of the measured and simulated pressure curve of the SWS phase (left) and de-convolved pressure curve of the SW phase (right) using the best parameter estimates resulting from a parameter optimisation of the sequence SW-SWS with a radial composite flow model

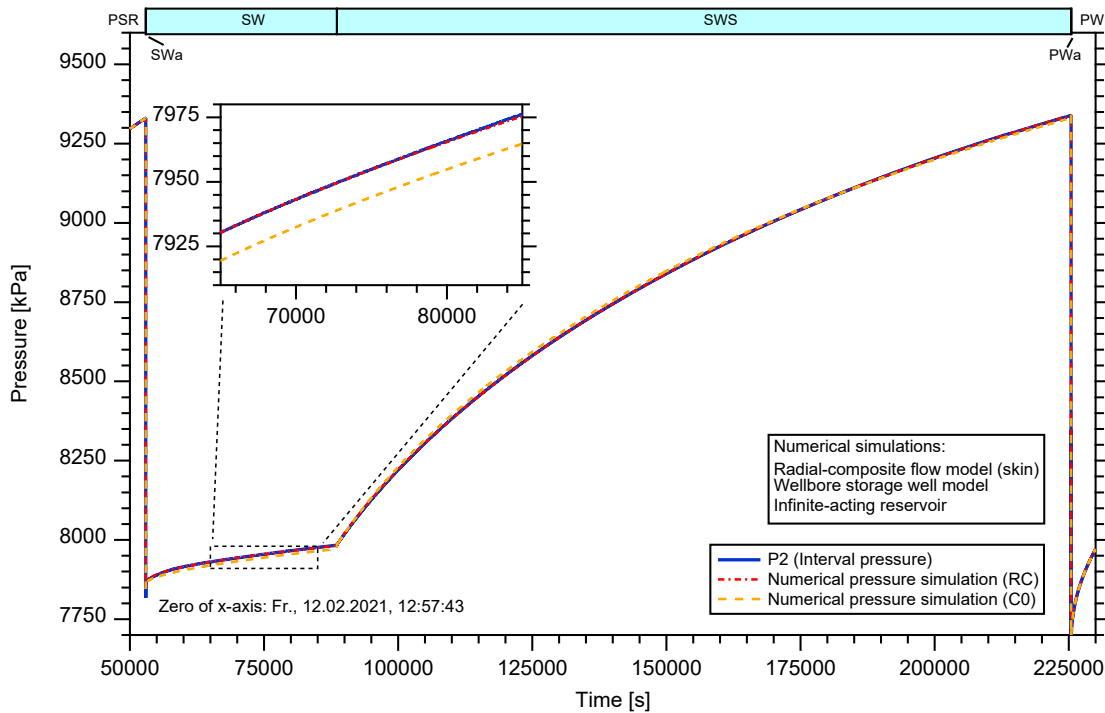


Fig. B-8: Hydraulic test STA3-1-LIA1: Cartesian plot of the simulation using the best parameter estimates resulting from a parameter optimisation of the sequence SW-SWS with a radial homogeneous flow model (C0); and comparison of the simulated pressure curve with the radial composite flow model (reference case – RC)

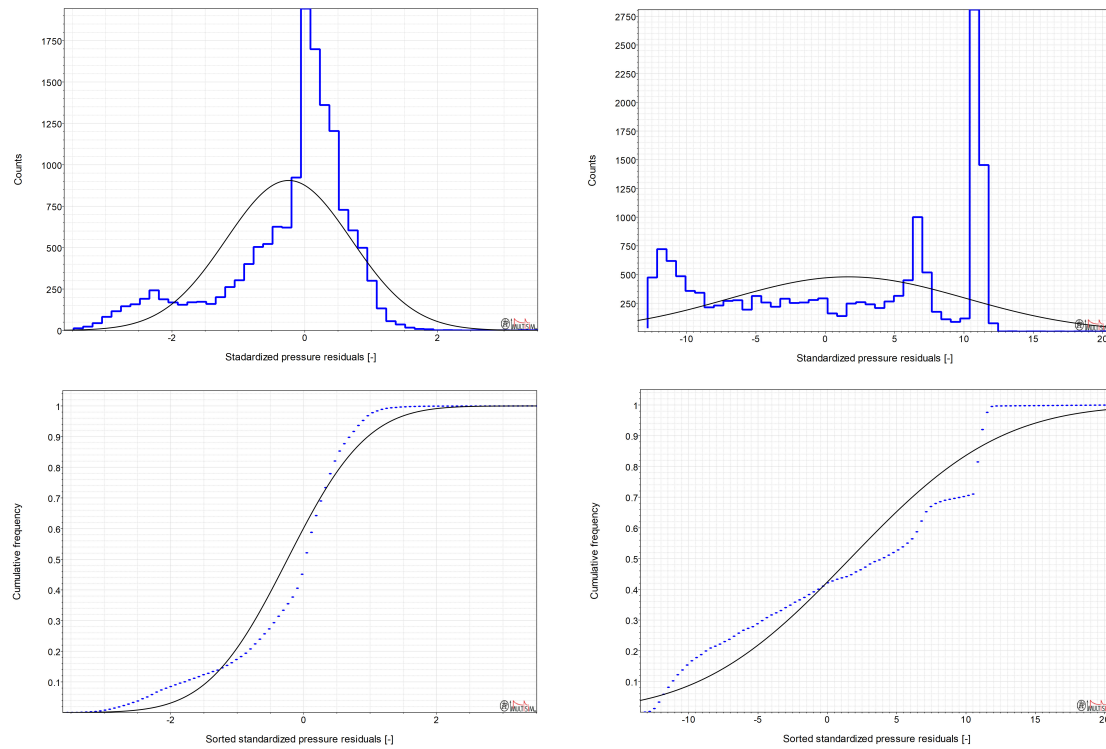


Fig. B-9: Hydraulic test STA3-1-LIA1: Probability distribution function plots (top) and cumulative distribution function plots (bottom) – including the normal distribution as reference – of the simulations using the best parameter estimates for a radial composite flow model (left) and a radial homogeneous flow model (right)

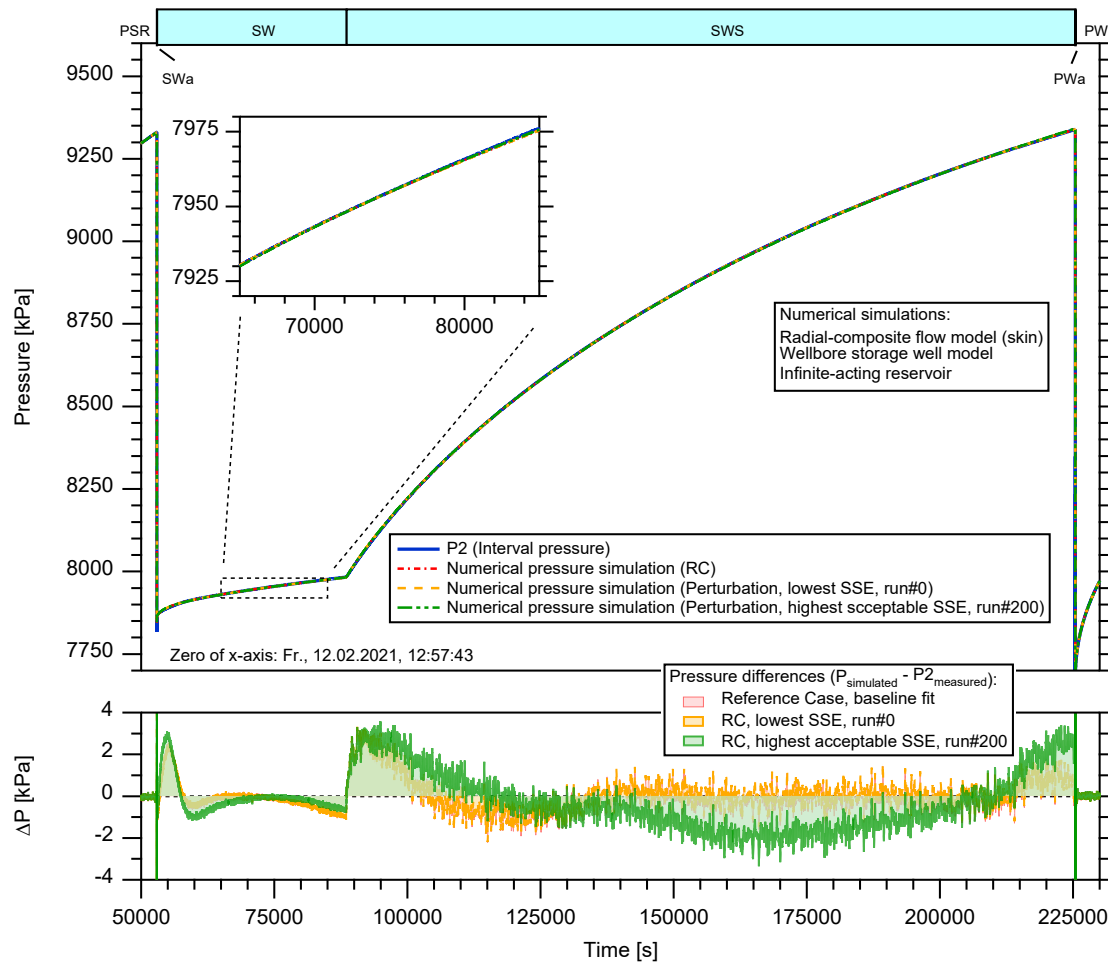


Fig. B-10: Hydraulic test STA3-1-LIA1: Comparison of the simulations associated with the previous single parameter optimisation result (reference case – baseline fit) presented in Fig. B-6, the lowest SSE (run #0) and simulation run #200 of the perturbation analysis for the SW-SWS sequence with a zoom on the SW phase (top) and the corresponding pressure residuals as a function of time (bottom)

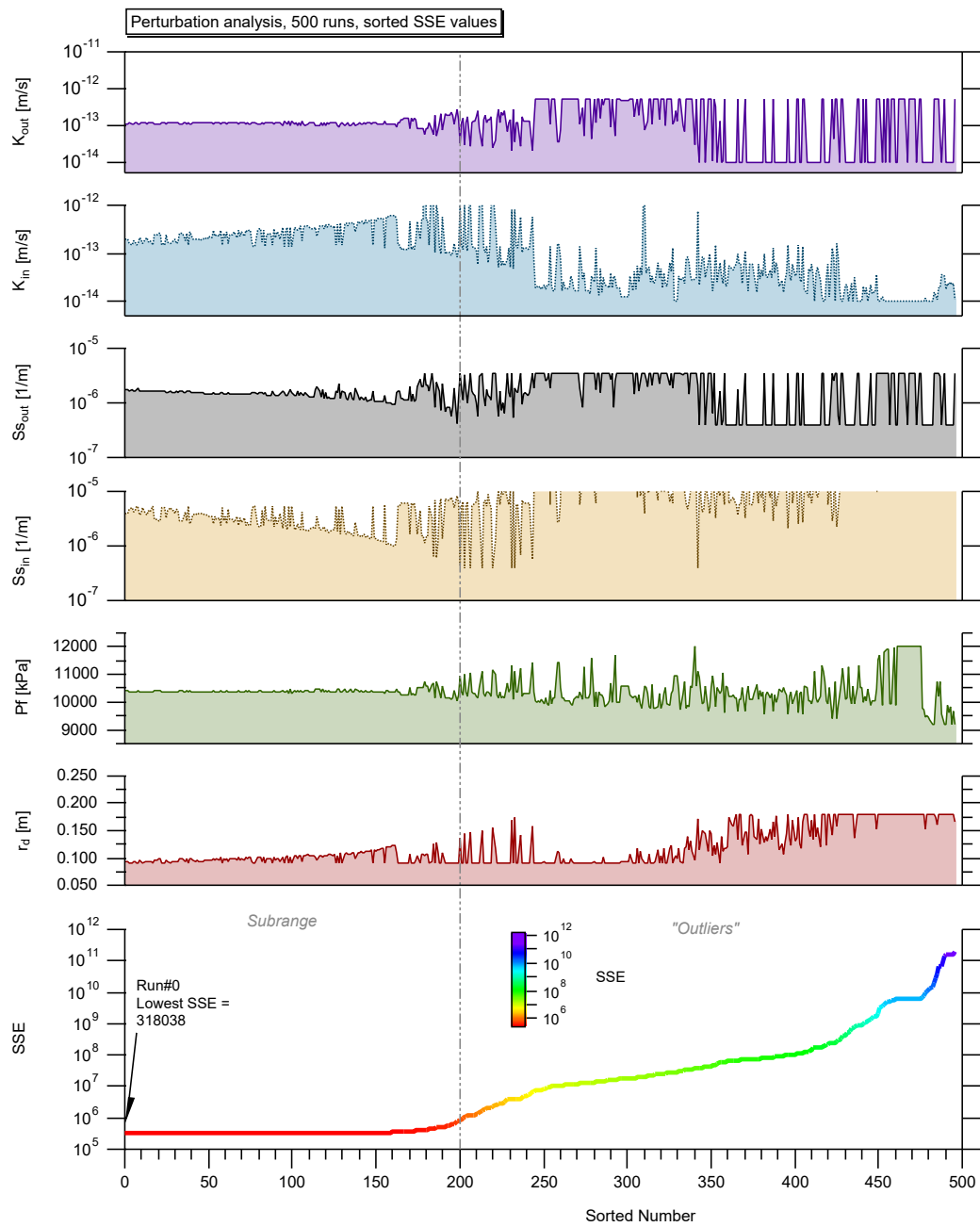


Fig. B-11: Hydraulic test STA3-1-LIA1: Resulting parameter sets of the perturbation analysis sorted by their SSE values used for the selection of the corresponding uncertainty range (exclusion of outliers)

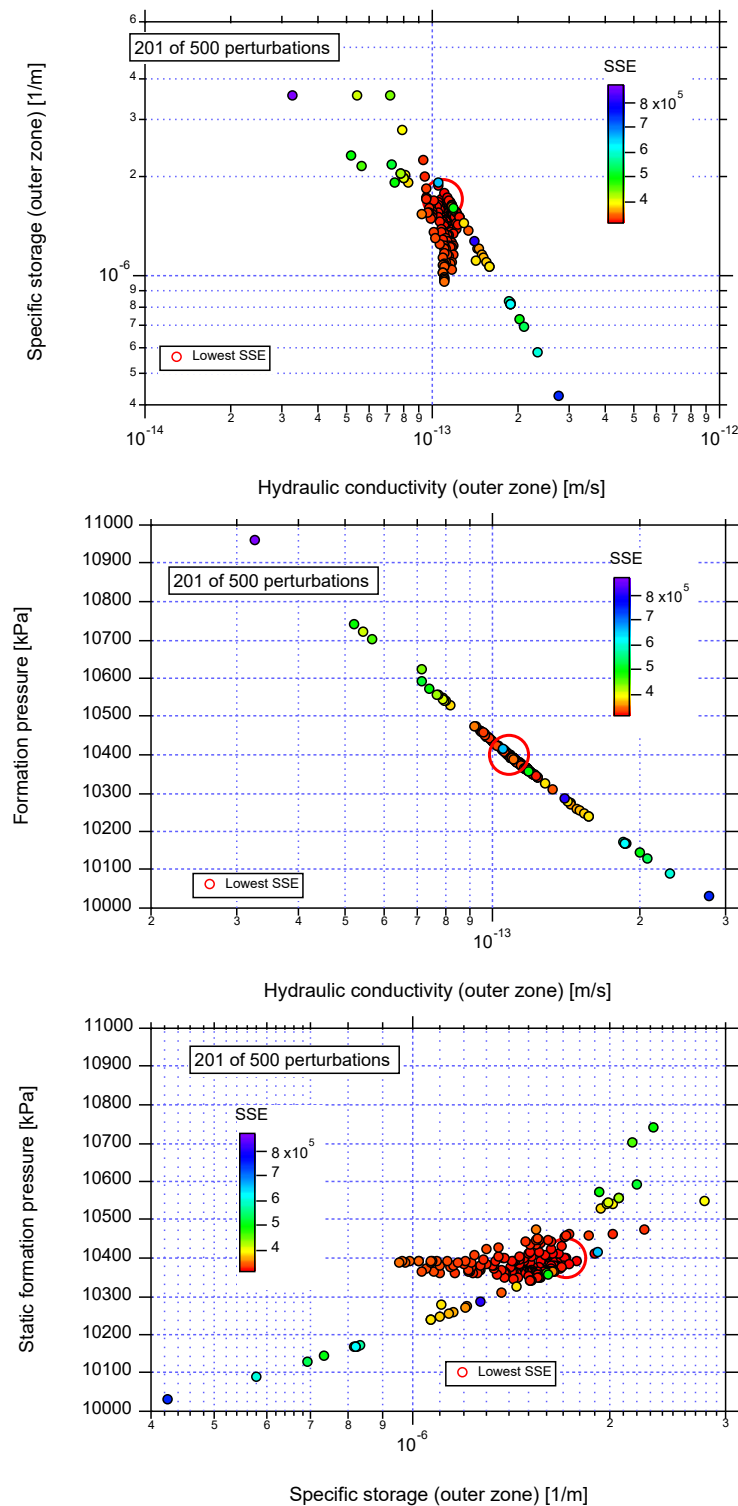


Fig. B-12: Hydraulic test STA3-1-LIA1: Scatter plots of the perturbation parameter sets for the formation parameter associated with their SSE values; $S_{S\ out}$ versus $K_{\ out}$ (top), P_f versus $K_{\ out}$ (middle) and P_f versus $S_{S\ out}$ (bottom)

The red circles mark parameter sets for the simulation with the lowest SSE.

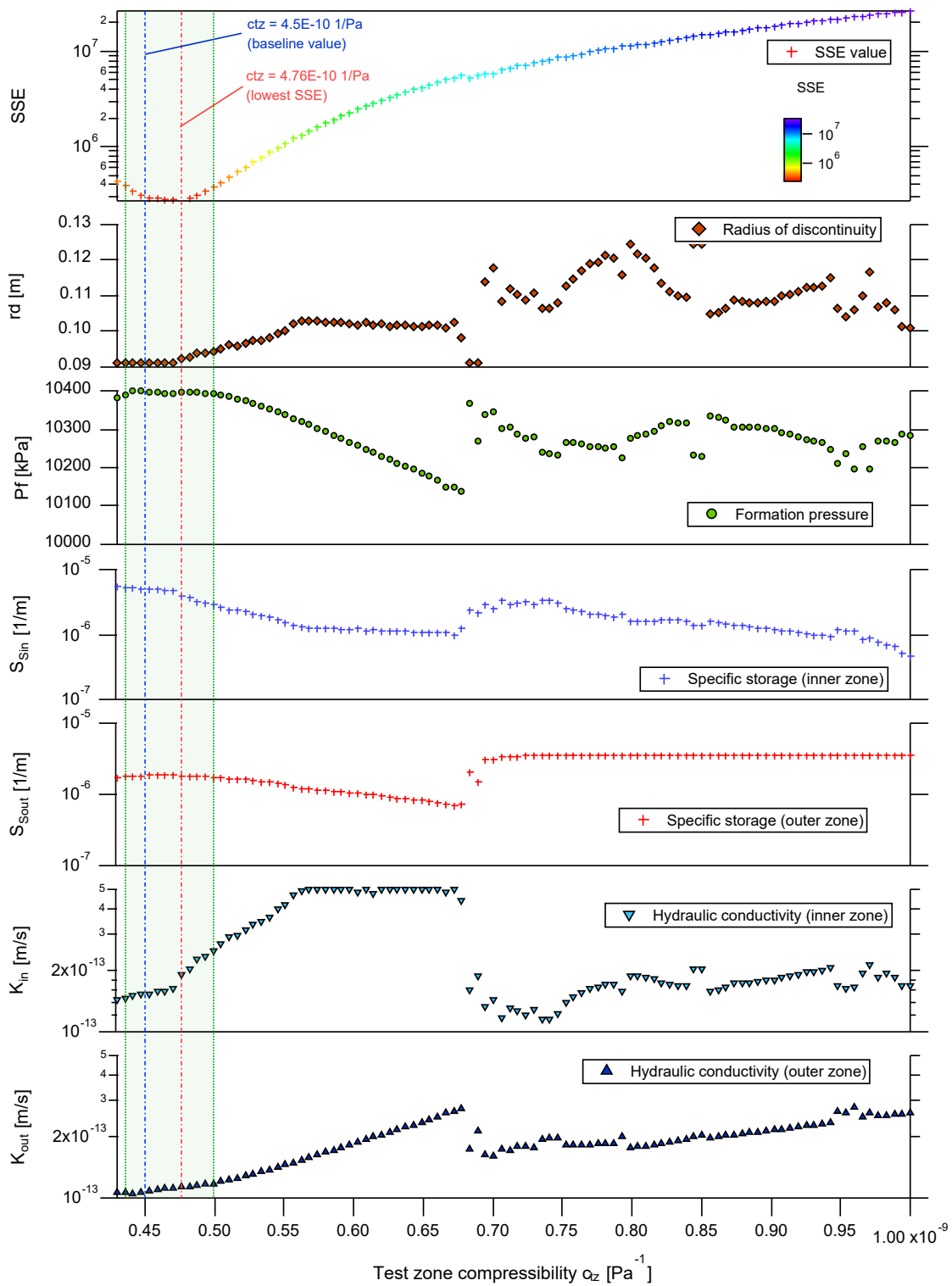


Fig. B-13: Hydraulic test STA3-1-LIA1: Resulting parameter sets of the sampling analysis as function of the test zone compressibility (c_{tz}); the blue dashed line indicates the c_{tz} value used in the entire analysis fit (except the sampling analysis), the red dashed line indicates the parameters associated with the lowest SSE and the green dotted lines indicate the uncertainty range limits

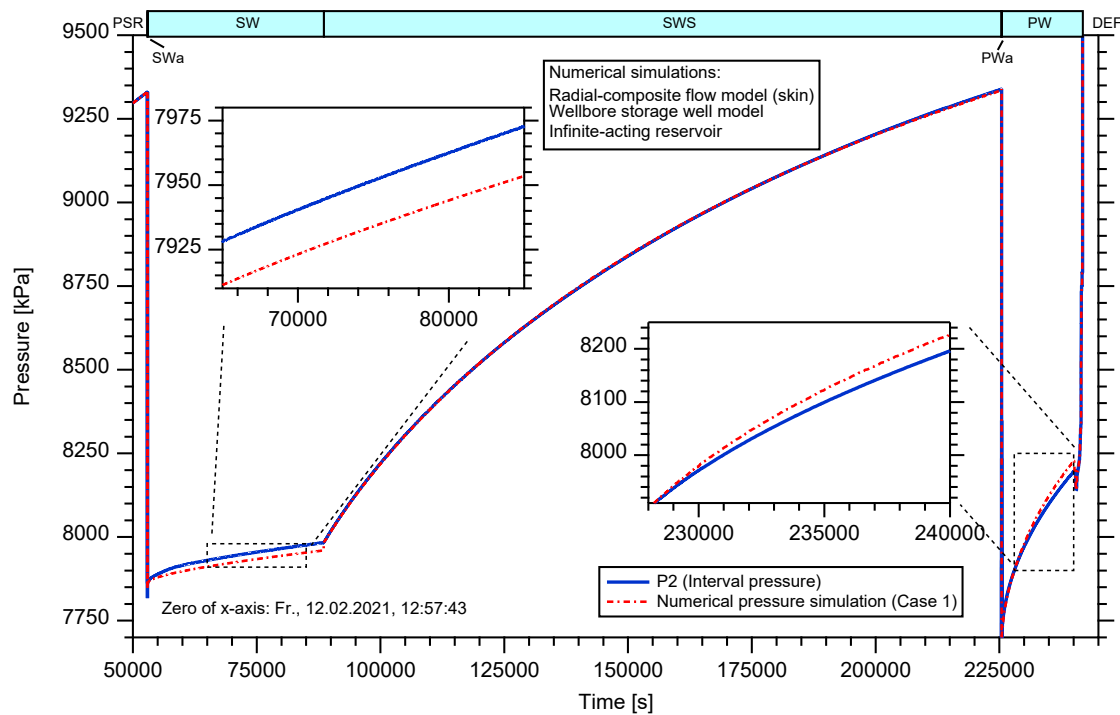


Fig. B-14: Hydraulic test STA3-1-LIA1: Cartesian plot of the simulation using the best parameter estimates resulting from a parameter optimisation of the sequence SW-SWS-PW using a radial composite flow model

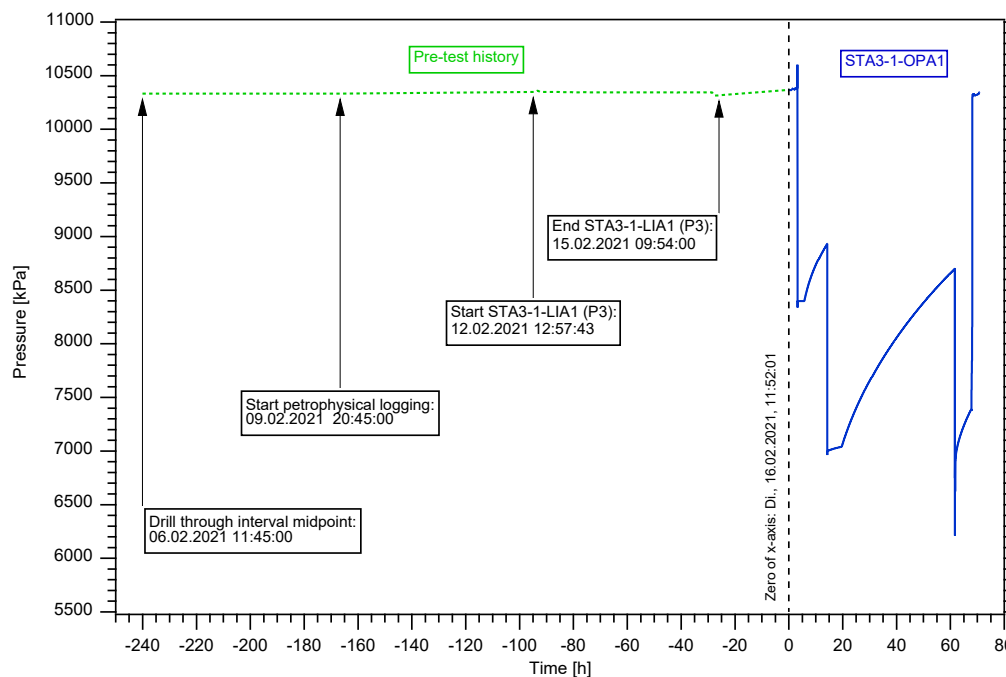


Fig. B-15: Hydraulic test STA3-1-OPA1: Entire record of the borehole pressure history used in the analysis

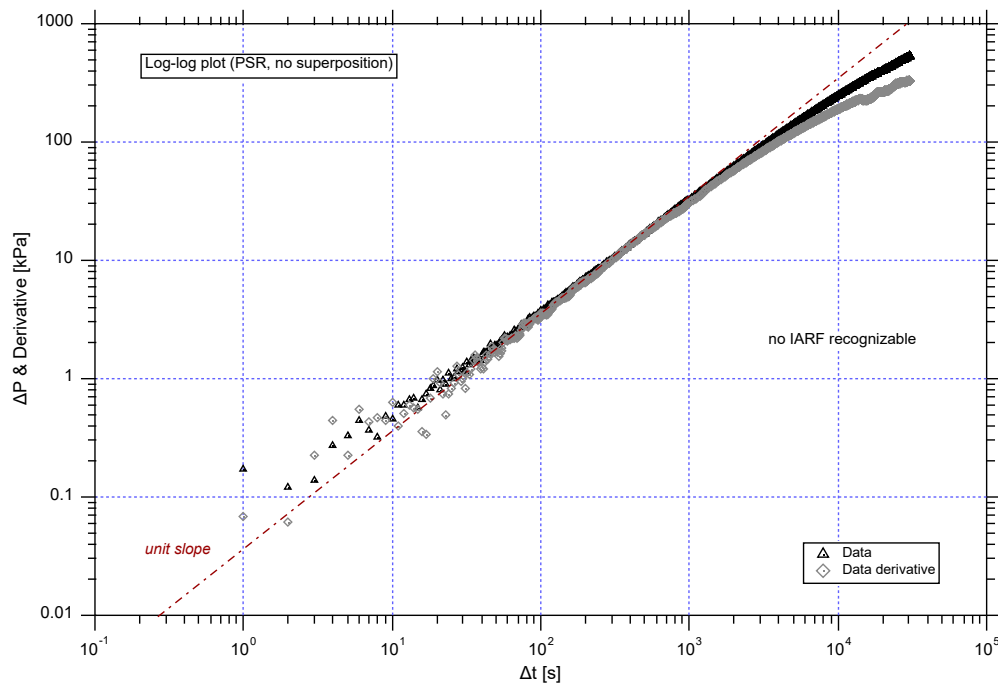


Fig. B-16: Hydraulic test STA3-1-OPA1: Log-log plot of PSR phase (no superposition plot)

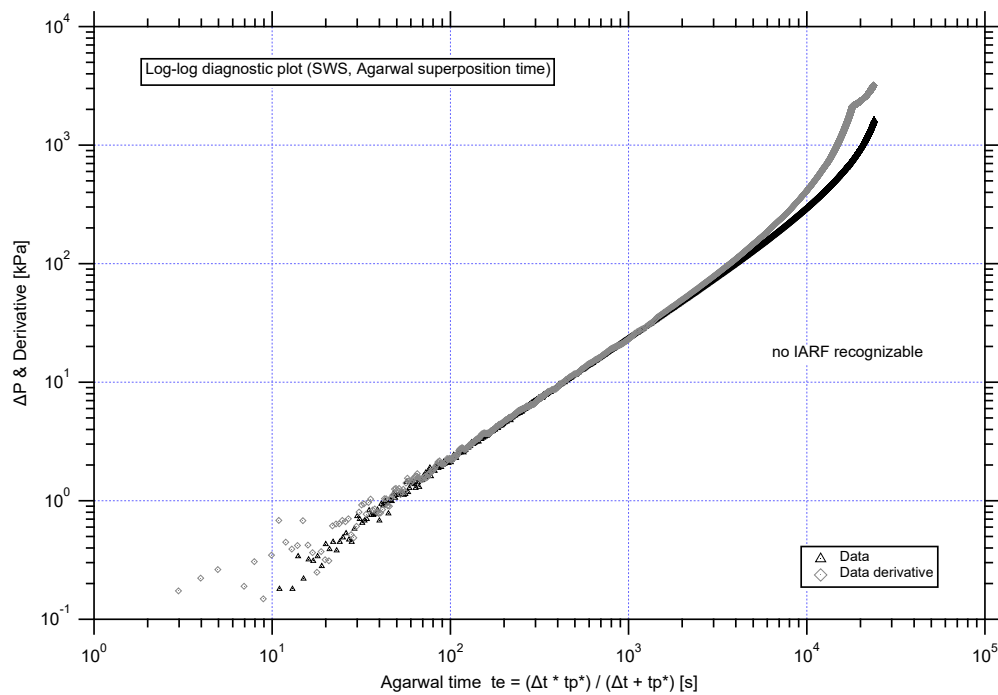


Fig. B-17: Hydraulic test STA3-1-OPA1: Log-log plot of SWS phase (corrected Agarwal time)

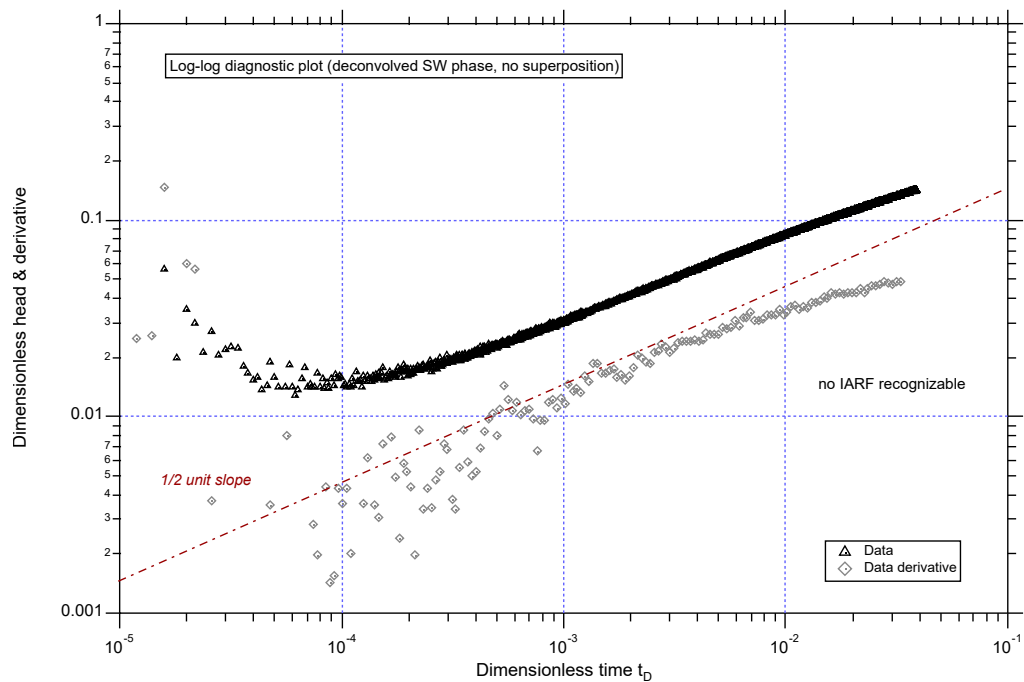
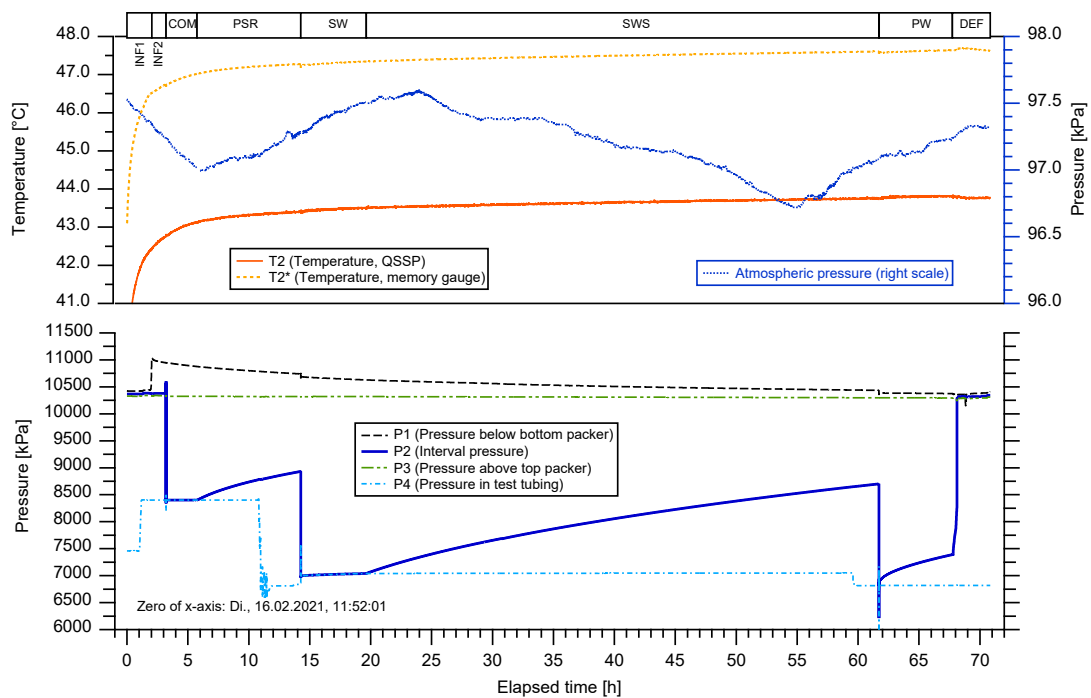


Fig. B-18: Hydraulic test STA3-1-OPA1: Log-log de-convolution plot of SW phase

Fig. B-19: Hydraulic test STA3-1-OPA1: Interval temperature (T_2^*) and QSSP temperature (T_2) measurements in comparison to the atmospheric and the downhole pressures of the QSSP (P1, P2, P3, P4)

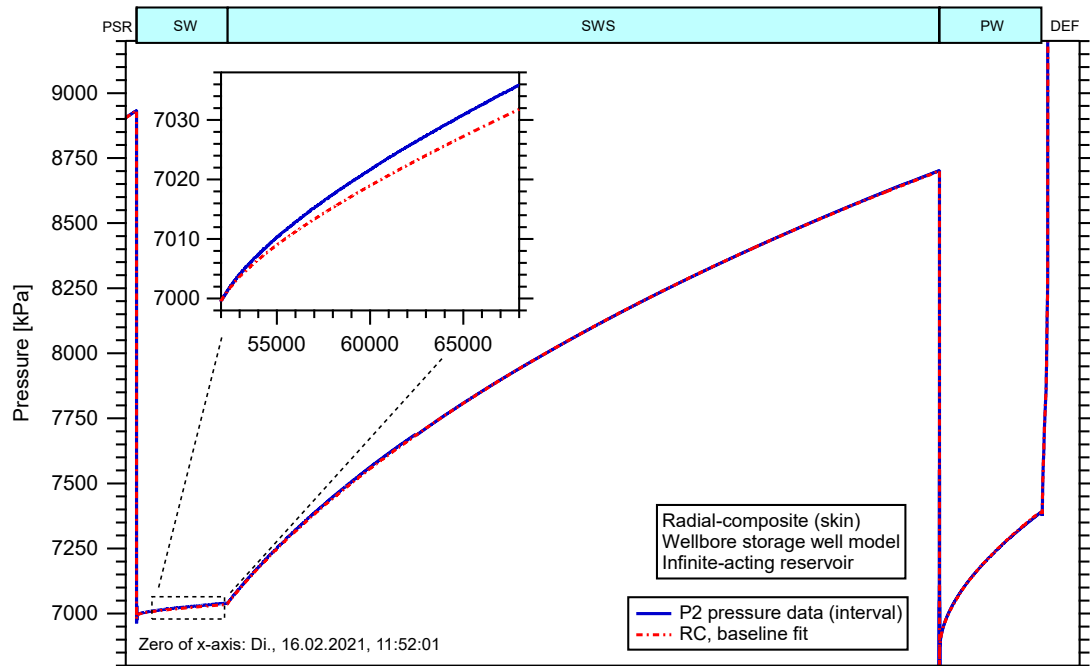


Fig. B-20: Hydraulic test STA3-1-OPA1: Cartesian plot of the simulation using the best parameter estimates resulting from a parameter optimisation of the sequence SW-SWS-PW with a radial composite flow model

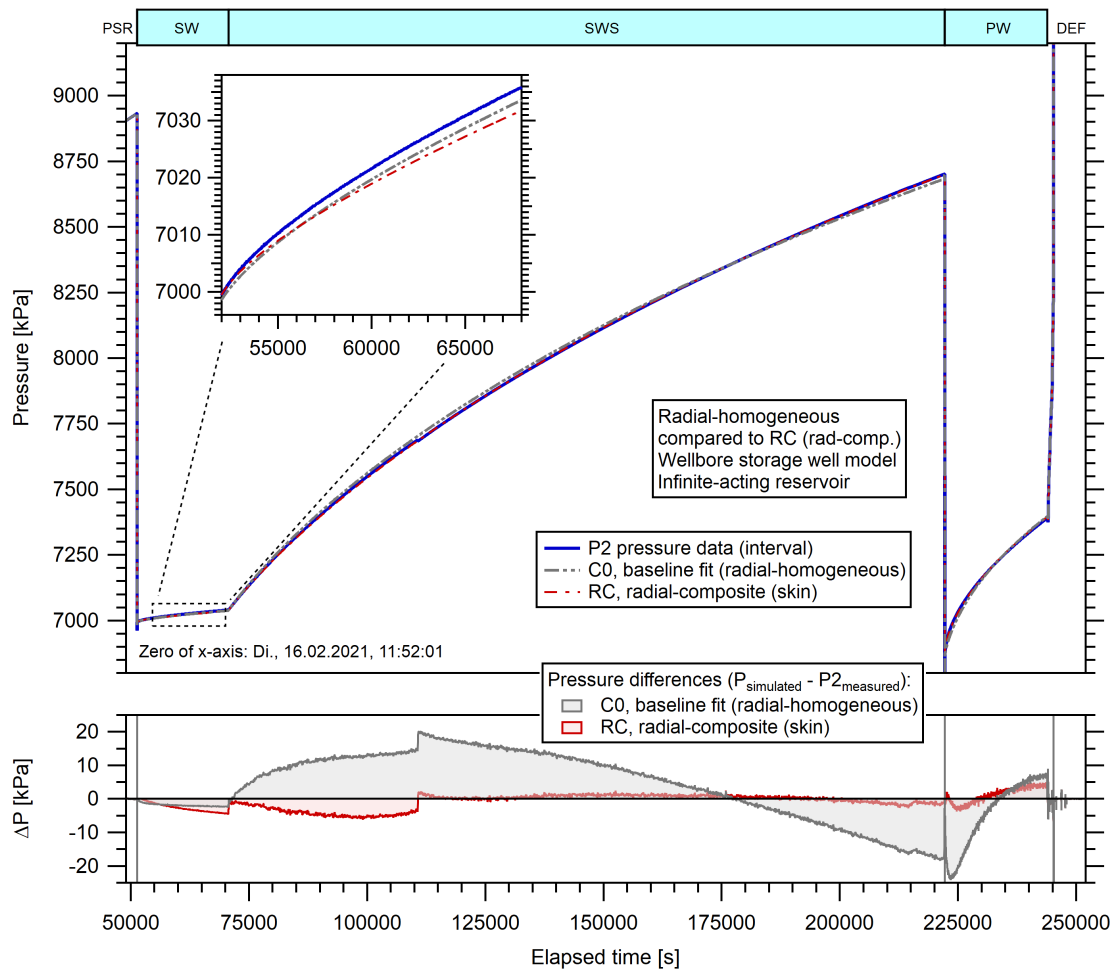


Fig. B-21: Hydraulic test STA3-1-OPA1: Cartesian plot of the simulation using the best parameter estimates resulting from a parameter optimisation of the sequence SW-SWS-PW with a radial homogeneous flow model (C0) compared to the radial composite model (RC) at the top; and comparison of the pressure residuals with respect to the radial composite flow model (bottom)

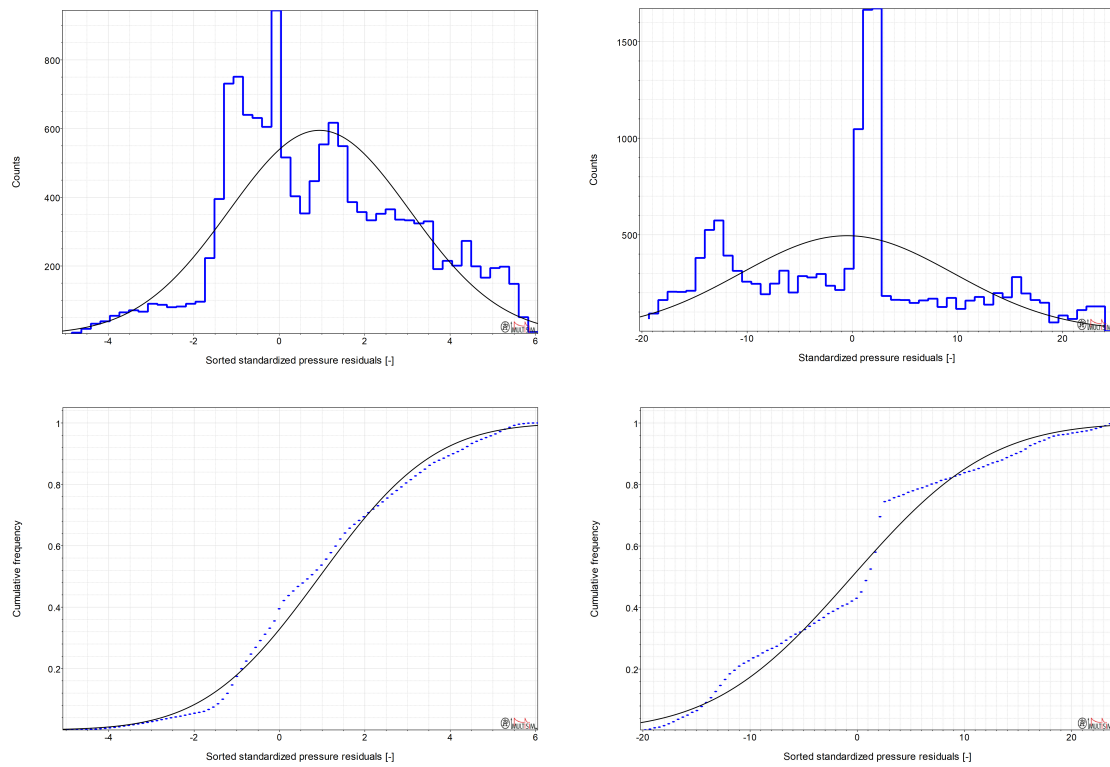


Fig. B-22: Hydraulic test STA3-1-OPA1: Probability distribution function plots (top) and cumulative distribution function plots (bottom) – including the normal distribution as reference – of the simulations using the best parameter estimates for a radial composite flow model (left) and a radial homogeneous flow model (right)

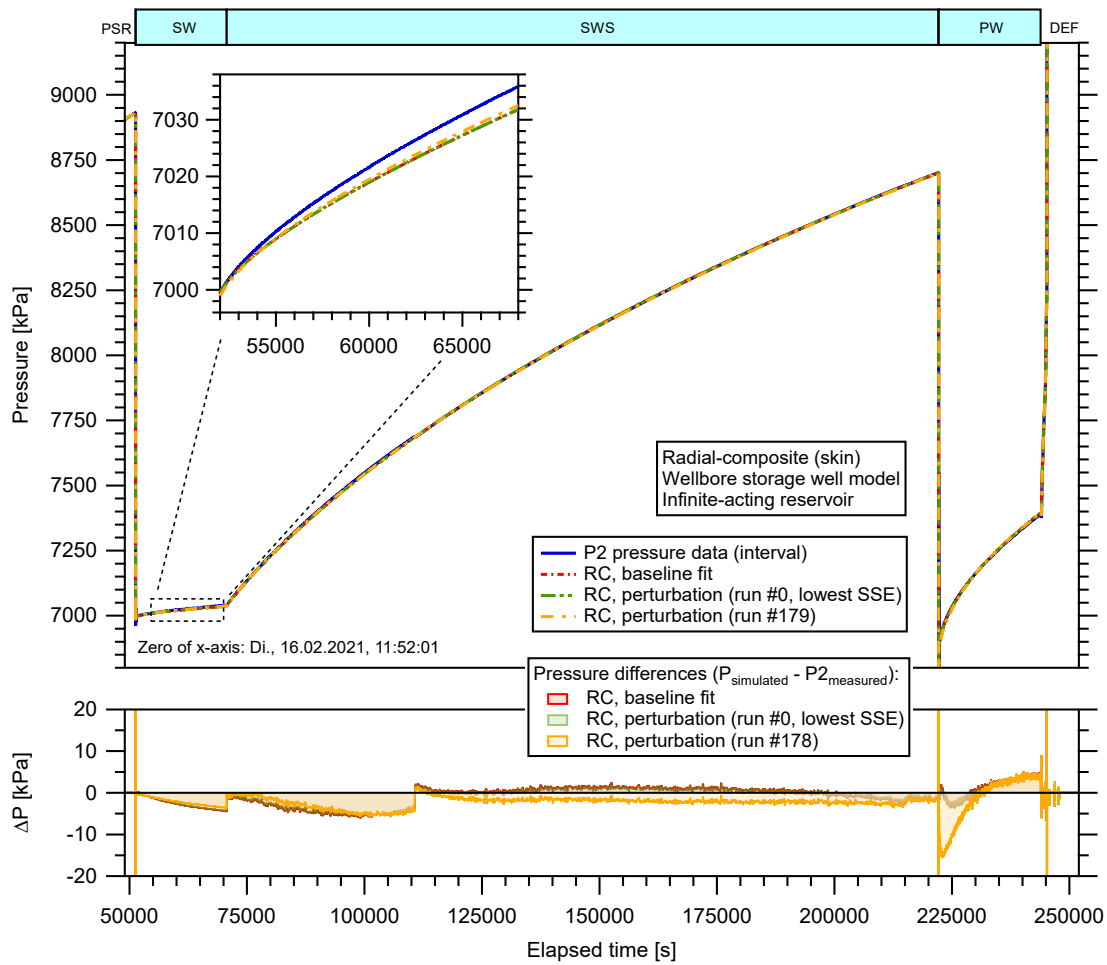


Fig. B-23: Hydraulic test STA3-1-OPA1: Comparison of the simulations associated with the previous single parameter optimisation result (RC, baseline fit) presented in Fig. B-20, the lowest SSE (run #0) and simulation run #178 of the perturbation analysis for the SW-SWS-PW sequence with zoom on the SW phase (top) and their corresponding pressure residuals as a function of time (bottom)

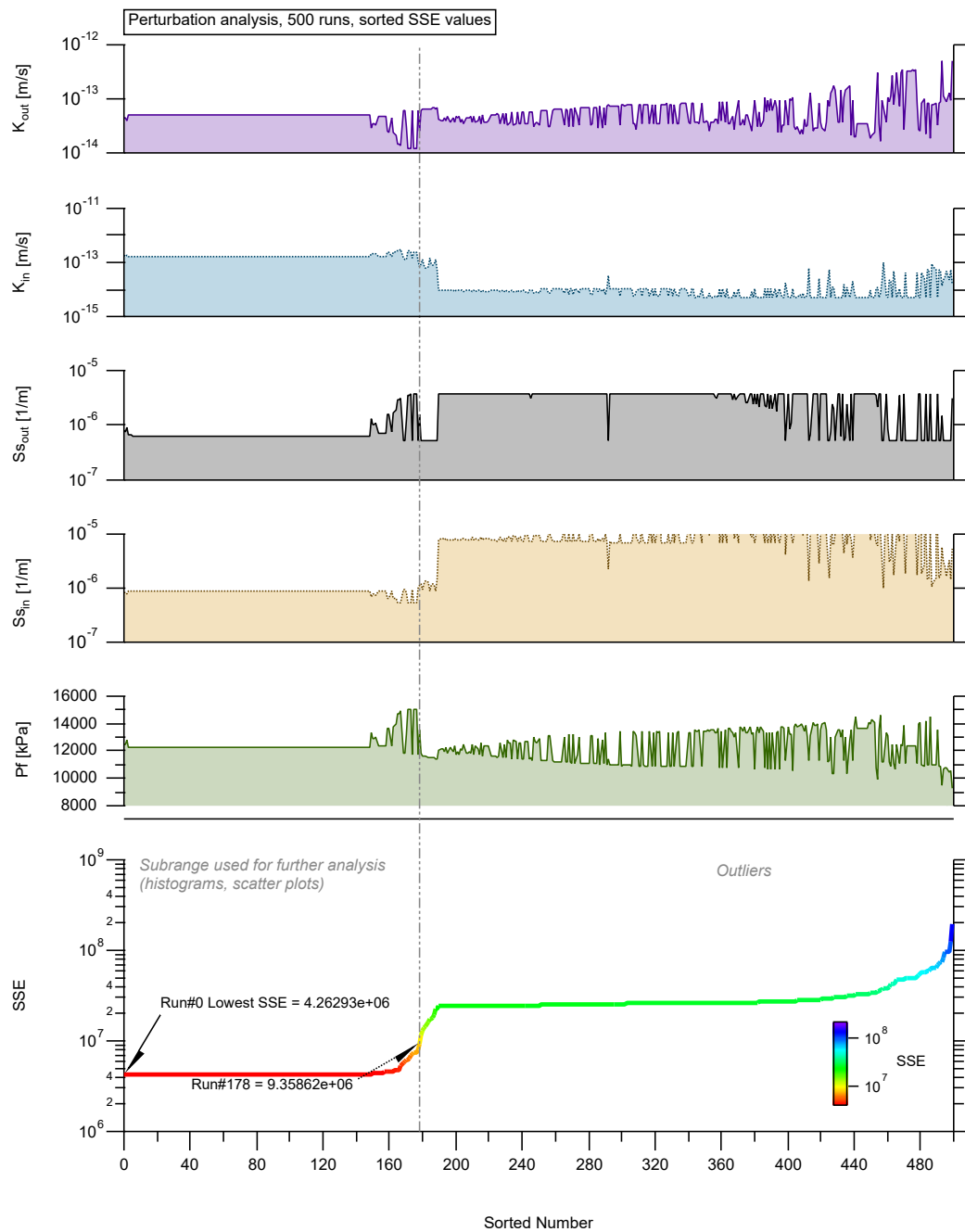


Fig. B-24: Hydraulic test STA3-1-OPA1: Resulting parameter sets of the perturbation analysis sorted by their SSE values used for the selection of the corresponding uncertainty range (exclusion of outliers)

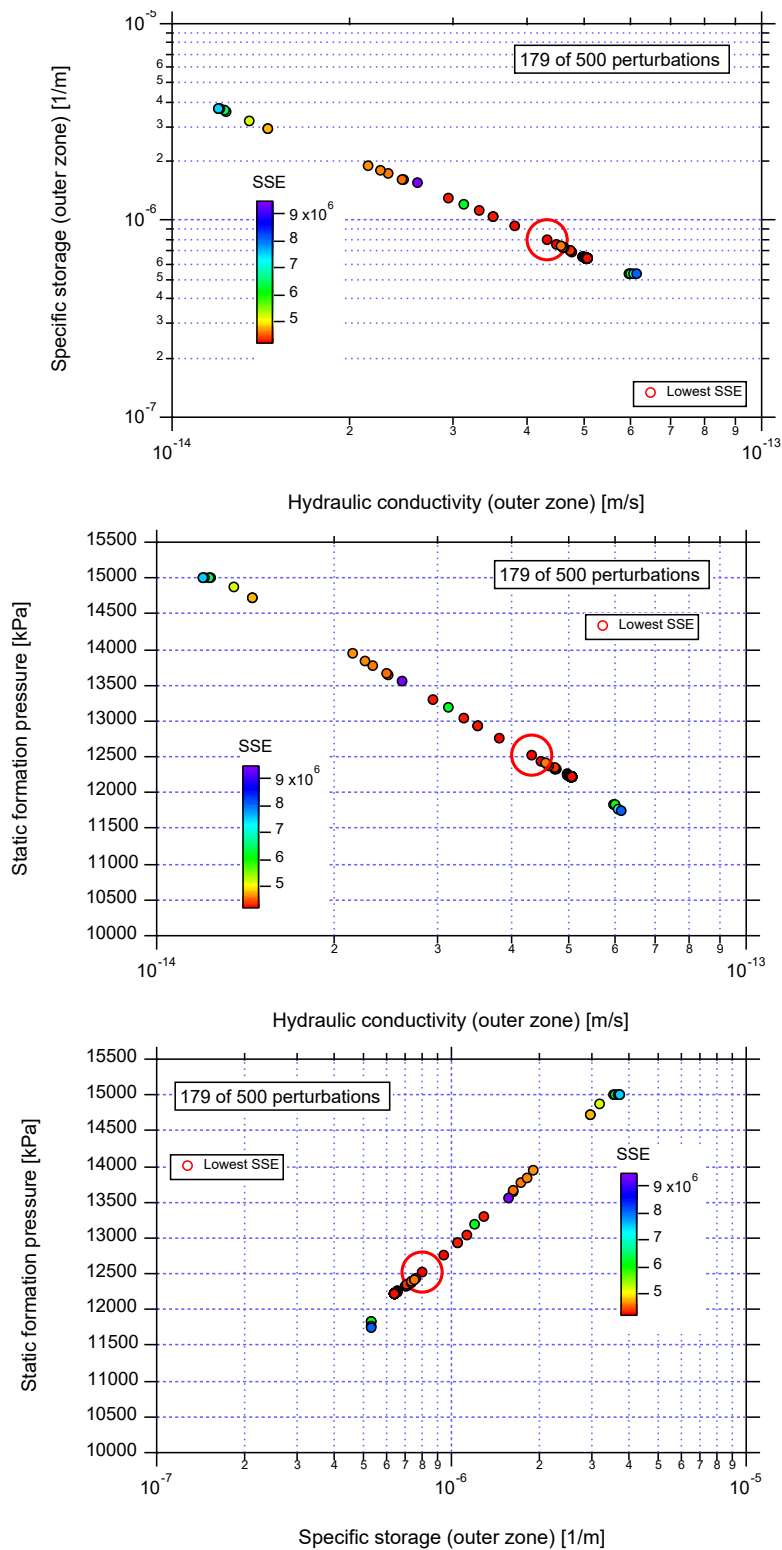


Fig. B-25: Hydraulic test STA3-1-OPA1: Scatter plots of the perturbation parameter sets for the formation parameters associated with their SSE values; $S_{S out}$ versus K_{out} (top), P_f versus K_{out} (middle) and P_f versus $S_{S out}$

The red circles mark parameter sets for the simulation with the lowest SSE.

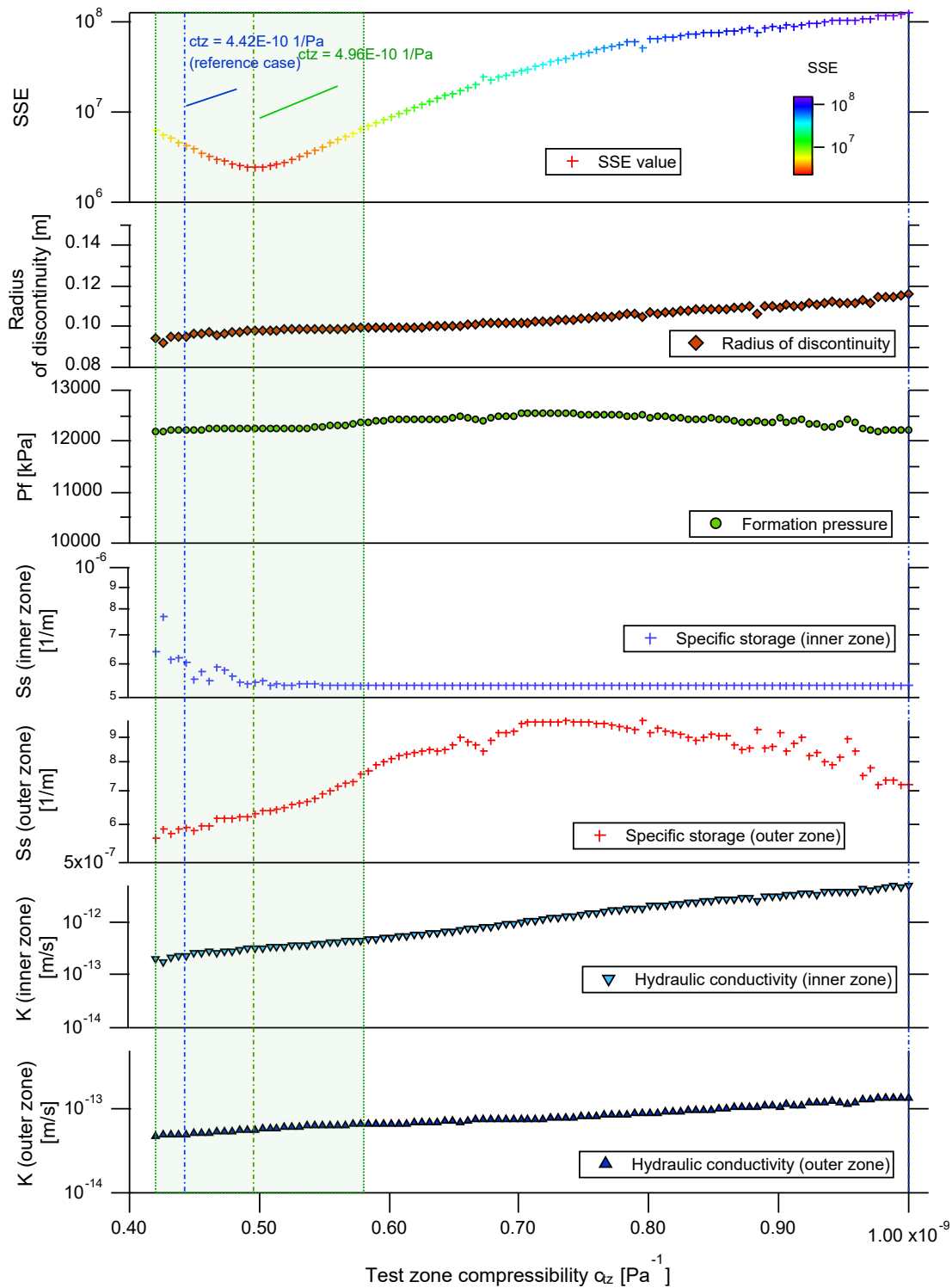


Fig. B-26: Hydraulic test STA3-1-OPA1: Resulting parameter sets of the sampling analysis as a function of the test zone compressibility (c_{tz}); the blue dashed line indicates the c_{tz} value used in the entire analysis fit (except the sampling analysis), the green dashed line indicates the parameters associated with the lowest SSE and the green dotted lines indicate the uncertainty range limits

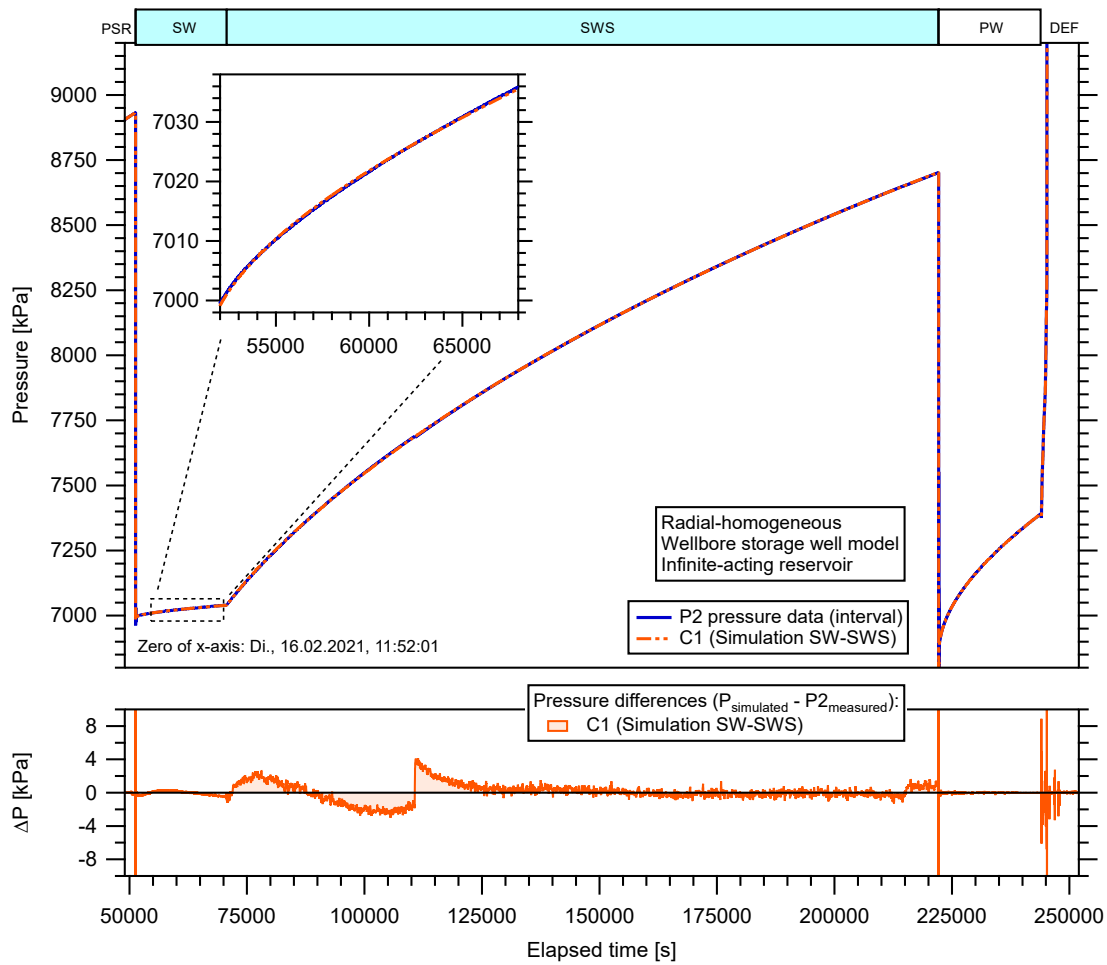


Fig. B-27: Hydraulic test STA3-1-OPA1: Cartesian plot of the simulation using the best parameter estimates resulting from a parameter optimisation of the sequence SW-SWS with a radial composite flow model (top) and their corresponding pressure residuals (bottom)