

Arbeitsbericht NAB 21-20

**TBO Marthalen-1-1:
Data Report**

**Dossier VII
Hydraulic Packer Testing**

September 2021

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

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Switzerland
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**Dossier VII
Hydraulic Packer Testing**

September 2021

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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 Dossier was prepared by a project team consisting of:

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

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S. Köhler (project management, conceptualisation and review)

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The present report is based on the detailed reports about the performance and analysis of the hydraulic packer tests and fluid logging, as well as on the mobilisation reports about test equipment. These detailed reports and mobilisation reports were written by the testing companies Solexperts AG / AFRY Switzerland Ltd (R. Brauchler, H. Fisch, S. Reinhardt, U. Rösli, P. Schulte) and Solexperts AG / AFRY Switzerland Ltd / Terratec Geophysical Services GmbH & Co. KG for fluid logging (R. Brauchler, A. Maqueda, G. Mühlebach).

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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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Table of Contents

Table of Contents	I
List of Tables.....	III
List of Figures	VI
1 Introduction	1
1.1 Context.....	1
1.2 Location and specifications of the borehole	2
1.3 Documentation structure for the MAR1-1 borehole.....	6
1.4 Structure of Dossier VII.....	7
2 Strategy for the hydrogeological investigations	9
2.1 Hydrogeological objectives of the TBO boreholes.....	9
2.2 Hydrogeological investigation concept for MAR1-1	9
3 Flowmeter logging and fluid logging.....	11
3.1 Description of equipment	11
3.1.1 Borehole logging winch.....	11
3.1.2 Matrix logger	11
3.1.3 Temperature-conductivity-gamma probe with sleeve	12
3.1.4 Borehole geometry gamma probe.....	13
3.1.5 Acoustic borehole televiewer	13
3.1.6 Gamma sensors.....	14
3.1.7 Temperature-electrical conductivity meter.....	15
3.1.8 Centraliser.....	15
3.1.9 Field analysis IT structure	16
3.2 Tool application.....	16
3.2.1 Description of measurements performed.....	16
3.2.2 Analysis of pumping test data.....	19
3.2.3 Fluid logging analysis.....	20
4 Hydraulic packer tests.....	27
4.1 Test strategy.....	27
4.2 Test equipment	29
4.2.1 Downhole equipment.....	29
4.2.1.1 Heavy-duty double packer system.....	32
4.2.1.2 Packers.....	34
4.2.1.3 Downhole sensors in the quadruple sub-surface probe.....	35
4.2.1.4 Autonomous data logger in test interval	36
4.2.1.5 Zero-displacement shut-in tool	36
4.2.1.6 Test tubing	37

4.2.1.7	Slim tubing	38
4.2.1.8	Submersible pumps.....	39
4.2.1.9	Progressive cavity pump.....	40
4.2.2	Surface equipment	41
4.2.2.1	Flow board.....	41
4.2.2.2	Packer pressure control unit.....	43
4.2.2.3	Additionally recorded measurements at surface	43
4.2.2.4	Data acquisition system	44
4.2.3	GTPT equipment	45
4.2.3.1	Packers for the GTPT	47
4.2.3.2	Stainless steel lines for the GTPT.....	49
4.2.3.3	Zero-displacement shut-in tool for GTPT	49
4.2.3.4	Flow control board for GTPT	50
4.3	Test analyses.....	51
4.3.1	Workflow.....	51
4.3.2	Special effects.....	54
4.3.2.1	Borehole history	55
4.3.2.2	Interval temperature changes during testing.....	56
4.3.2.3	Mechanical effects.....	56
4.4	Test activities.....	57
4.5	Details of selected tests.....	66
4.5.1	Hydraulic packer test MAR1-1-LIA1	66
4.5.1.1	Interval characterisation.....	66
4.5.1.2	Test execution.....	67
4.5.1.3	Analysis	69
4.5.2	Hydraulic packer test MAR1-1-LIA2.....	73
4.5.2.1	Interval characterisation.....	73
4.5.2.2	Test execution.....	74
4.5.2.3	Analysis	76
4.5.3	Comparison of results.....	81
5	Summary and discussion.....	83
5.1	Flowmeter logging and fluid logging	83
5.2	Hydraulic packer test data and results	84
5.2.1	Description of tests	84
5.2.2	Overview tables and plots.....	84
5.3	Summary.....	93
6	References.....	95

Appendix A: Abbreviations, nomenclature and definitions..... A-1**Appendix B: Analysis plots of the hydraulic packer tests MAR1-1-LIA1 and MAR1-1-LIA2..... B-1****List of Tables**

Tab. 1-1:	General information about the MAR1-1 borehole.....	2
Tab. 1-2:	Core and log depth for the main lithostratigraphic boundaries in the MAR1-1 borehole	5
Tab. 1-3:	List of dossiers included in NAB 21-20	6
Tab. 3-1:	Specifications of the borehole logging winch.....	11
Tab. 3-2:	Specifications of the matrix logger.....	12
Tab. 3-3:	Specifications of the temperature-conductivity-gamma probe	12
Tab. 3-4:	Specifications of the borehole geometry gamma probe.....	13
Tab. 3-5:	Specifications of the acoustic borehole televiewer.....	14
Tab. 3-6:	Specifications of the temperature-electrical conductivity meter.....	15
Tab. 3-7:	Specifications of the centraliser.....	16
Tab. 3-8:	Specifications of the IT structure for field analysis	16
Tab. 3-9:	MAR1-1-FL1-MAL: Start and end times of the fluid logging runs performed for MAR1-1 and their associated depth range	17
Tab. 3-10:	MAR1-1-FL1-MAL: Estimated hydraulic parameters derived from pumping test analyses 1 and 2 in the framework of fluid logging in borehole MAR1-1.....	20
Tab. 3-11:	MAR1-1-FL1-MAL: Estimated hydraulic parameters resulting from the analyses of the fluid logging data	21
Tab. 4-1:	Preferred test sequence for formations with medium to high transmissivity.....	28
Tab. 4-2:	Preferred test sequence for formations with low to very low transmissivity.....	28
Tab. 4-3:	Specifications for the HDDP	32
Tab. 4-4:	Specifications for the HDDP components.....	33
Tab. 4-5:	Specifications for the HDDP packers	34
Tab. 4-6:	Specifications for the pressure transmitters mounted in the QSSP.....	35
Tab. 4-7:	Specifications for the data logger	36
Tab. 4-8:	Specifications for the zero-displacement shut-in tool.....	37
Tab. 4-9:	Specifications for the test tubing	37
Tab. 4-10:	Specifications for the slim tubing	38
Tab. 4-11:	Specifications for the submersible pumps	39
Tab. 4-12:	Specifications for the PCP	40

Tab. 4-13:	Specifications for the flowmeters	41
Tab. 4-14:	Specifications for the atmospheric pressure sensor	43
Tab. 4-15:	Specifications for the physico-chemical sensors	44
Tab. 4-16:	Specifications for the 146 mm packers for the GTPT	48
Tab. 4-17:	Specifications for the zero-displacement shut-in tool (SIT1) for the GTPT.....	50
Tab. 4-18:	Specifications for the gas flow controller / meters for the GTPT	50
Tab. 4-19:	Summary of analytical analysis methods.....	52
Tab. 4-20:	Specific periods of the pre-test borehole pressure history	56
Tab. 4-21:	Hydraulic packer testing in borehole MAR1-1: test interval and test specifications.....	59
Tab. 4-22:	Hydraulic test MAR1-1-LIA1: Information on the test interval.....	66
Tab. 4-23:	Hydraulic test MAR1-1-LIA1: Borehole pressure history	69
Tab. 4-24:	Hydraulic test MAR1-1-LIA1: Formation parameter estimation based on a radial homogeneous model considering only the borehole pressure history	70
Tab. 4-25:	Hydraulic test MAR1-1-LIA1: Formation parameter estimations based on a radial homogeneous model, taking into consideration the borehole pressure history and the observed interval temperature change.....	70
Tab. 4-26:	Hydraulic test MAR1-1-LIA1: Formation parameter estimation based on a radial homogeneous model taking into consideration the borehole pressure history and the observed interval temperature and packer pressure changes	71
Tab. 4-27:	Hydraulic test MAR1-1-LIA1: Range of formation parameter estimates based on a radial homogeneous model that considers mud density variation prior to hydraulic testing of $\pm 5\%$	71
Tab. 4-28:	Hydraulic test MAR1-1-LIA1: Range of the formation parameter estimates resulting from the sampling analysis of the test zone compressibility	72
Tab. 4-29:	Hydraulic test MAR1-1-LIA1: Formation parameter estimates for the perturbation analysis of the PW-PI associated with the lowest least squared error value.....	72
Tab. 4-30:	Hydraulic test MAR1-1-LIA1: 95% confidence intervals for the formation parameter estimates of the parameter optimisation considering a radial homogeneous model including the borehole pressure history and interval temperature change.....	72
Tab. 4-31:	Hydraulic test MAR1-1-LIA1: Best estimates of the formation parameters and associated uncertainty ranges	73
Tab. 4-32:	Hydraulic test MAR1-1-LIA1: Results for the numerical simulation of the PSR-PW-PI test sequence using a radial homogeneous model including the borehole pressure history and interval temperature changes	73
Tab. 4-33:	Hydraulic test MAR1-1-LIA2: Test interval information	74
Tab. 4-34:	Hydraulic test MAR1-1-LIA2: Borehole pressure history	76
Tab. 4-35:	Hydraulic test MAR1-1-LIA2: Formation parameter estimates based on a radial composite model considering the borehole pressure history	77

Tab. 4-36:	Hydraulic test MAR1-1-LIA2: Formation parameter estimates based on a radial composite model considering the borehole pressure history and the observed interval temperature change	78
Tab. 4-37:	Hydraulic test MAR1-1-LIA2: Formation parameter estimates derived from radial composite model that considered the borehole pressure history, interval temperature and packer pressure changes due to changes in surface temperature.....	78
Tab. 4-38:	Hydraulic test MAR1-1-LIA2: Range of the formation parameter estimates derived from a radial composite model considering a variation in the mud density prior to hydraulic testing of $\pm 5\%$	78
Tab. 4-39:	Hydraulic test MAR1-1-LIA2: Range of the inner zone parameter estimates derived from a radial composite model considering a variation in the mud density prior to hydraulic testing of $\pm 5\%$	79
Tab. 4-40:	Hydraulic test MAR1-1-LIA2: Ranges of the formation parameter estimates resulting from the sampling analysis of the test zone compressibility on PW	79
Tab. 4-41:	Hydraulic test MAR1-1-LIA2: Range of the inner zone parameter estimates resulting from the sampling analysis of the test zone compressibility on PW	79
Tab. 4-42:	Hydraulic test MAR1-1-LIA2: Parameter estimates of the perturbation analysis of the PSR-PW-PI associated with the lowest least squared error value.....	80
Tab. 4-43:	Hydraulic test MAR1-1-LIA2: Ranges of the formation parameter estimates resulting from the perturbation analysis of the PSR-PW-PI test sequence.....	80
Tab. 4-44:	Hydraulic test MAR1-1-LIA2: Range of the inner zone parameter estimates resulting from the perturbation analysis of the PSR-PW-PI test sequence.....	80
Tab. 4-45:	Hydraulic test MAR1-1-LIA2: Best estimates of the formation parameters and the associated uncertainty ranges.....	80
Tab. 4-46:	Hydraulic test MAR1-1-LIA2: Perturbation results of the formation parameter estimates and the associated uncertainty ranges based on only the pulse phases (PW, PI)	81
Tab. 5-1:	Summary of hydraulic packer testing in borehole MAR1-1: Transmissivity and hydraulic conductivity	85
Tab. 5-2:	Summary of hydraulic packer testing in borehole MAR1-1: Hydraulic head estimates.....	86
Tab. 5-3:	Summary of hydraulic packer testing in borehole MAR1-1: Permeability	87
Tab. A-1:	Lithostratigraphy abbreviations for test names in MAR1-1	A-1
Tab. A-2:	Test name definitions for hydraulic packer testing.....	A-1
Tab. A-3:	Test event abbreviations for hydraulic packer testing	A-1
Tab. A-4:	Parameter definitions	A-2
Tab. A-5:	Non-parameter abbreviations.....	A-3

List of Figures

Fig. 1-1:	Tectonic overview map with the three siting regions under investigation	1
Fig. 1-2:	Overview map of the investigation area in the Zürich Nordost siting region with the location of the MAR1-1 borehole in relation to the boreholes Benken, Schlattingen-1 and TRU1-1	3
Fig. 1-3:	Lithostratigraphic profile and casing scheme for the MAR1-1 borehole	4
Fig. 3-1:	MAR1-1-FL1-MAL: Pressure drawdown and the position in time where fluid logging runs were performed	18
Fig. 3-2:	MAR1-1-FL1-MAL: Measured pumping rates and the position in time where fluid logging runs were performed.....	18
Fig. 3-3:	MAR1-1-FL1-MAL: Measured electrical conductivity logs (Runs), calculated for a temperature of 25 °C	19
Fig. 3-4:	MAR1-1-FL1-MAL: 2 nd fluid logging analysis of fluid logging Runs 8 to 10; inflow rates, transmissivity and associated acoustic borehole televiwer images	22
Fig. 3-5:	MAR1-1-FL1-MAL: 2 nd fluid logging analysis of fluid logging Runs 8 to 10; fluid logging analysis results for Runs 9 and 10 based on the initial concentration distribution of Run 8.....	23
Fig. 3-6:	MAR1-1-FL1-MAL: 2 nd fluid logging analysis of fluid logging Runs 19 to 21; inflow rates, transmissivity and associated acoustic borehole televiwer images	24
Fig. 3-7:	MAR1-1-FL1-MAL: 2 nd fluid logging analysis of fluid logging Runs 19 to 21; fluid logging analysis results for Runs 20 and 21 based on the initial concentration distribution of Run 19.....	25
Fig. 4-1:	General configuration and specifications of the HDDP in double packer configuration.....	30
Fig. 4-2:	General configuration and specifications of the HDDP in single packer configuration.....	31
Fig. 4-3:	Schematic layout of the flow control unit.....	42
Fig. 4-4:	Schematic layout of the packer control unit	43
Fig. 4-5:	Schematic layout of the modified HDDP system and the four steps for the GTPT	47
Fig. 4-6:	Schematic layout of the flow control unit for the GTPT	51
Fig. 4-7:	Flowcharts for the on-site hydraulic packer test analysis (left) and Quick Look Analysis (QLA) (right)	53
Fig. 4-8:	Flowchart for the off-site Detailed Analysis (DA) of a hydraulic packer test	54
Fig. 4-9:	Hydraulic packer test MAR1-1-MAL1: Overview plot of pressure vs. time and date.....	61
Fig. 4-10:	Hydraulic packer test MAR1-1-BDO1: Overview plot of pressure vs. time and date.....	61

Fig. 4-11:	Hydraulic packer test MAR1-1-BDO2: Overview plot of pressure vs. time and date.....	62
Fig. 4-12:	Hydraulic packer test MAR1-1-OPA1: Overview plot of pressure vs. time and date.....	62
Fig. 4-13:	Hydraulic packer test MAR1-1-OPA2: Overview plot of pressure vs. time and date.....	63
Fig. 4-14:	Hydraulic packer test MAR1-1-OPA3: Overview plot of pressure vs. time and date.....	63
Fig. 4-15:	Hydraulic packer test MAR1-1-LIA1: Overview plot of pressure vs. time.....	64
Fig. 4-16:	Hydraulic packer test MAR1-1-LIA2: Overview plot of pressure vs. time.....	64
Fig. 4-17:	Hydraulic packer test MAR1-1-KEU1: Overview plot of pressure vs. time.....	65
Fig. 4-18:	Hydraulic packer test MAR1-1-MUK1: Overview plot of pressure vs. time and date.....	65
Fig. 4-19:	Hydraulic test MAR1-1-LIA1: Downhole equipment installation record with system layout as used in the field tests	68
Fig. 4-20:	Hydraulic test MAR1-1-LIA2: Downhole equipment installation record with system layout as used in the field tests	75
Fig. 5-1:	Summary of hydraulic testing in borehole MAR1-1: Formation transmissivity profile.....	88
Fig. 5-2:	Summary of hydraulic testing in borehole MAR1-1: Formation hydraulic conductivity profile.....	89
Fig. 5-3:	Summary of hydraulic testing in borehole MAR1-1: Static formation pressure profile.....	90
Fig. 5-4:	Summary of hydraulic testing in borehole MAR1-1: Formation hydraulic head profile (m bgl)	91
Fig. 5-5:	Summary of hydraulic testing in borehole MAR1-1: Formation hydraulic head profile (m asl).....	92
Fig. B-1:	Hydraulic test MAR1-1-LIA1: Entire record of the borehole pressure history used in the analysis	B-1
Fig. B-2:	Hydraulic test MAR1-1-LIA1: Log-log diagnostic plot of PSR, no superposition.....	B-1
Fig. B-3:	Hydraulic test MAR1-1-LIA1: Numerical simulation of the PW-PI test sequence in a Cartesian pressure plot using a radial homogeneous model considering only the borehole pressure history	B-2
Fig. B-4:	Hydraulic test MAR1-1-LIA1: Downhole temperature (T2 and T2*) and atmospheric pressure in comparison to the downhole QSSP pressure measurements	B-2
Fig. B-5:	Hydraulic test MAR1-1-LIA1: Numerical simulation of the PW-PI test sequence in a Cartesian pressure plot using a radial homogeneous model considering the borehole pressure history and interval temperature change	B-3

Fig. B-6:	Hydraulic test MAR1-1-LIA1: Manipulation of the borehole radius ($r_{w\text{ int}}$) in comparison to the surface temperature induced packer pressure changes (ΔP_{packer}), the interval volume changes (ΔV_{int}) and the sensor P2 pressure measurement.....	B-3
Fig. B-7:	Hydraulic test MAR1-1-LIA1: Numerical simulation of the PW-PI test sequence in a Cartesian pressure plot using a radial homogeneous model considering the borehole pressure history, interval temperature change and packer pressure changes.....	B-4
Fig. B-8:	Hydraulic test MAR1-1-LIA1: Numerical simulations of the PW-PI test sequence in a Cartesian pressure plot using a radial homogeneous flow model considering interval temperature changes and applying different borehole pressure history (BHPH) scenarios.....	B-4
Fig. B-9:	Hydraulic test MAR1-1-LIA1: Sampling analysis of the PW-PI sequence, c_{tz} of PW is sampled, with parameter ranges of the parameters K, S_s and P_f together with respective SSE values against c_{tz} value	B-5
Fig. B-10:	Hydraulic test MAR1-1-LIA1: Sampling analysis of the PW-PI sequence, c_{tz} of PI is sampled, with parameter ranges of the parameters K, S_s and P_f together with respective SSE values against c_{tz} value	B-6
Fig. B-11:	Hydraulic test MAR1-1-LIA1: Results of the perturbation analysis of PW-PI sequence using a radial homogeneous model considering interval temperature changes	B-7
Fig. B-12:	Hydraulic test MAR1-1-LIA1: Best simulation of the PW-PI sequence using a radial homogeneous model considering the borehole pressure history and interval temperature changes	B-8
Fig. B-13:	Hydraulic test MAR1-1-LIA1: 95% joint confidence intervals and associated correlation matrix for the PW-PI sequence using a radial homogeneous model considering the borehole pressure history and interval temperature changes	B-9
Fig. B-14:	Hydraulic test MAR1-1-LIA1: Numerical simulation of the PSR-PW-PI test sequence using a radial homogeneous model considering the borehole pressure history and interval temperature changes	B-9
Fig. B-15:	Hydraulic test MAR1-1-LIA2: Entire record of the borehole pressure history used in the analysis	B-10
Fig. B-16:	Hydraulic test MAR1-1-LIA2: Log-log diagnostic plot of PSR, no superposition.....	B-10
Fig. B-17:	Hydraulic test MAR1-1-LIA2: Log-log diagnostic plot of PW, Peres deconvolution.....	B-11
Fig. B-18:	Hydraulic test MAR1-1-LIA2: Numerical simulation of the PSR-PW-PI test sequence using a radial composite flow model considering only the borehole pressure history; comparison of the pressure residual as a function of time with the simulation considering the borehole pressure history and the interval temperature change (reference case)	B-12
Fig. B-19:	Hydraulic test MAR1-1-LIA2: Downhole temperature (T_2 and T_2^*) and atmospheric pressure in comparison to the downhole QSSP pressure measurements	B-13

- Fig. B-20: Hydraulic test MAR1-1-LIA2: Numerical simulation of the PSR-PW-PI test sequence using a radial composite flow model considering the borehole pressure history and the observed interval temperature changes B-13
- Fig. B-21: Hydraulic test MAR1-1-LIA2: Manipulation of the borehole radius ($r_{w \text{ int}}$) in comparison to the causal packer pressure changes (ΔP_{packer}), the interval volume changes (ΔV_{int}) and the pressure measurement of sensor P2 B-14
- Fig. B-22: Hydraulic test MAR1-1-LIA2: Numerical simulation of the PSR-PW-PI test sequence using a radial composite flow model considering the borehole pressure history, interval temperature changes and packer pressure changes due to surface temperature changes; comparison of the pressure residual as a function of time with the simulation considering the borehole pressure history and the interval temperature change (reference case) B-15
- Fig. B-23: Hydraulic test MAR1-1-LIA2: Numerical simulations of the PSR-PW-PI test sequence in a Cartesian pressure plot using a radial composite flow model considering interval temperature changes and applying different borehole pressure history scenarios B-16
- Fig. B-24: Hydraulic test MAR1-1-LIA2: Sampling analysis of the PSR-PW-PI sequence, c_{tz} of PW is sampled, with parameter ranges of the parameters K_{out} , $S_{S \text{ out}}$, K_{in} , $S_{S \text{ in}}$ and P_f together with respective SSE values against c_{tz} value B-17
- Fig. B-25: Hydraulic test MAR1-1-LIA2: Results of the perturbation analysis of PSR-PW-PI sequence using a radial composite model considering interval temperature changes B-18
- Fig. B-26: Hydraulic test MAR1-1-LIA2: Best simulation of the PSR-PW-PI sequence using a radial composite model considering the borehole pressure history and interval temperature changes B-19

1 Introduction

1.1 Context

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

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

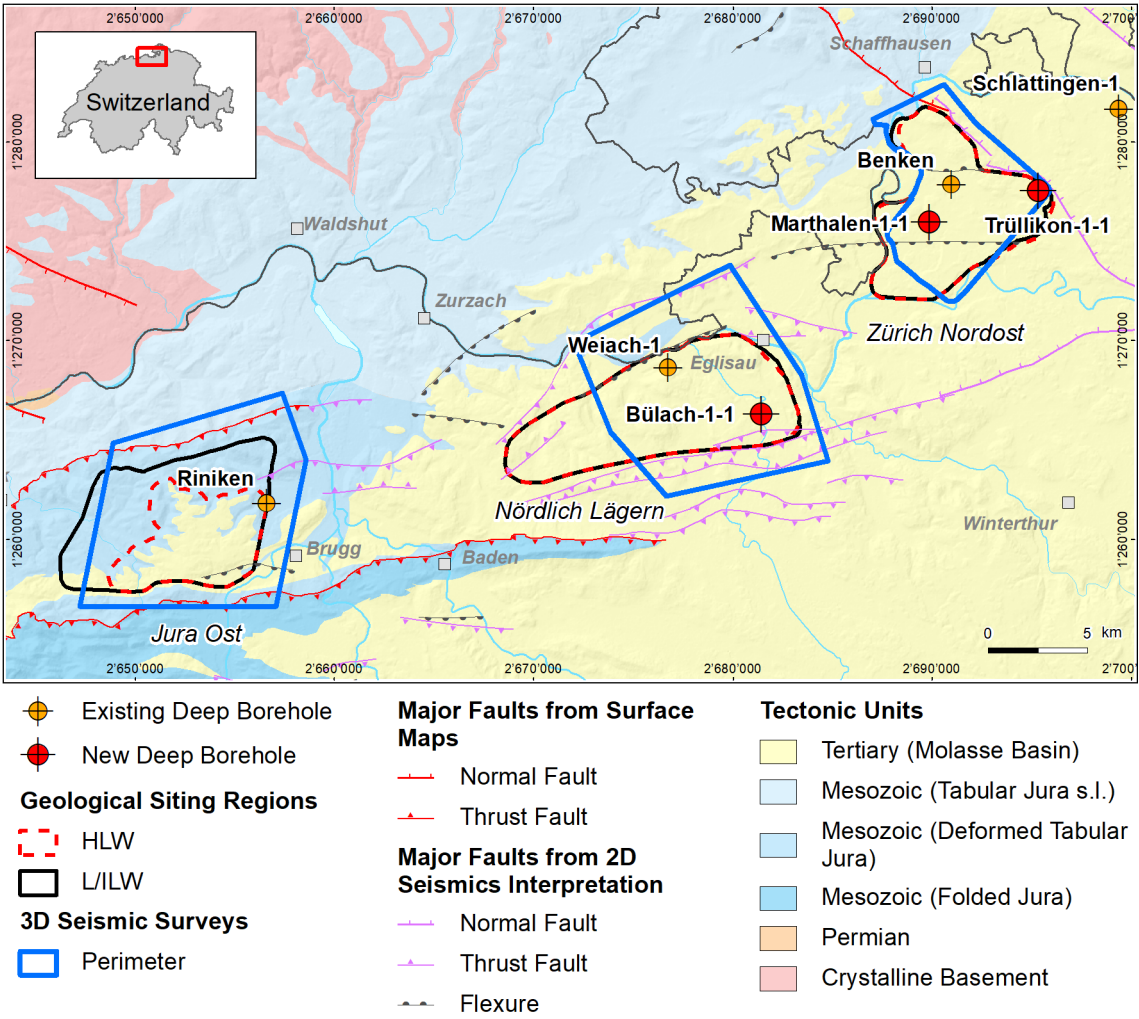


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

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

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

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

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. The comparison of the core versus log depth³ of the main lithostratigraphic boundaries in the MAR1-1 borehole is shown in Tab. 1-2.

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

² For detailed information see Dossier I.

³ Core depth refers to the depth marked on the drill cores. Log depth results from the depth observed during geophysical wireline logging. Note that the petrophysical logs have not been shifted to core depth, hence log depth differs from core depth.

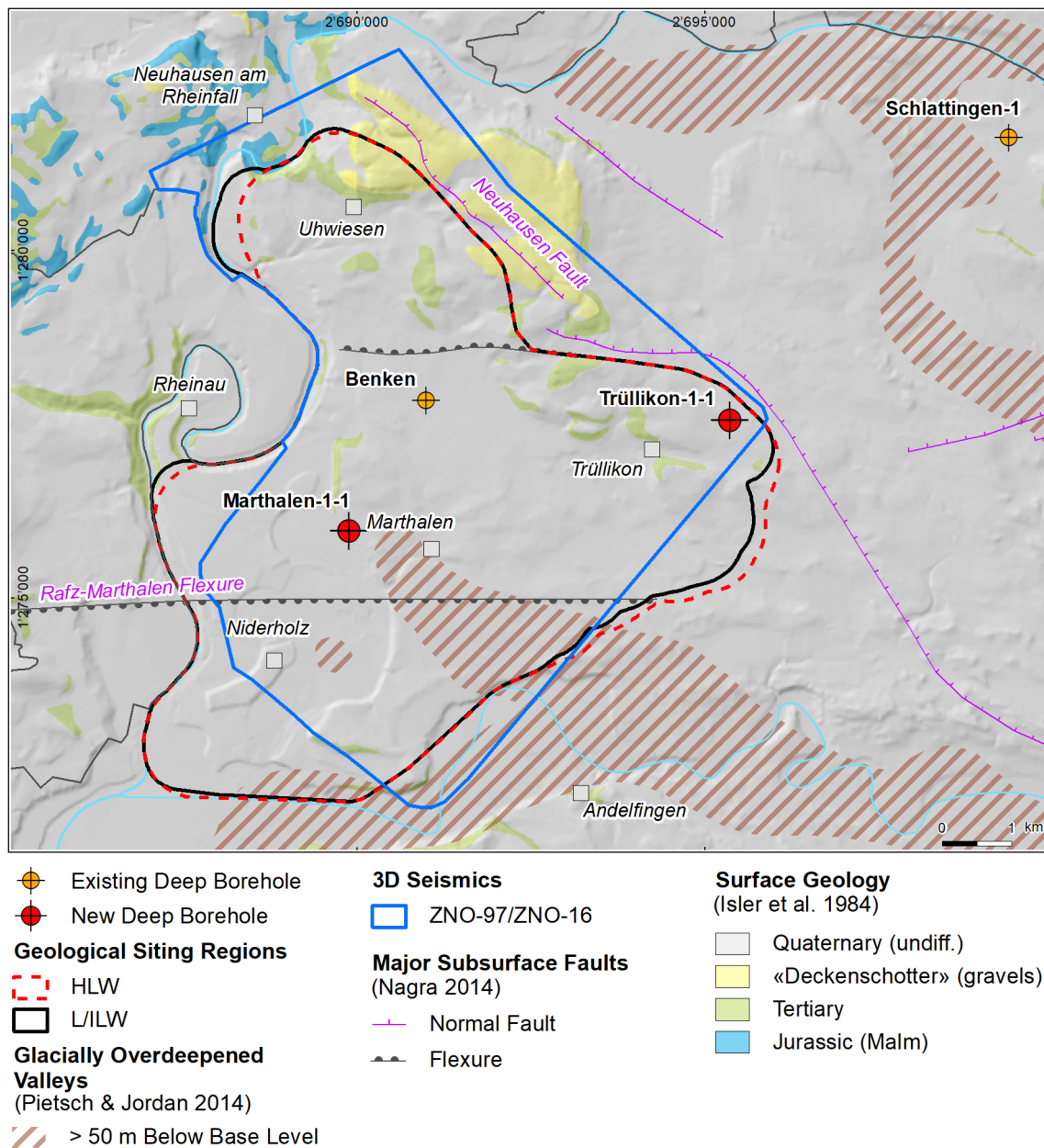


Fig. 1-2: Overview map of the investigation area in the Zürich Nordost siting region with the location of the MAR1-1 borehole in relation to the boreholes Benken, Schlattigen-1 and TRU1-1

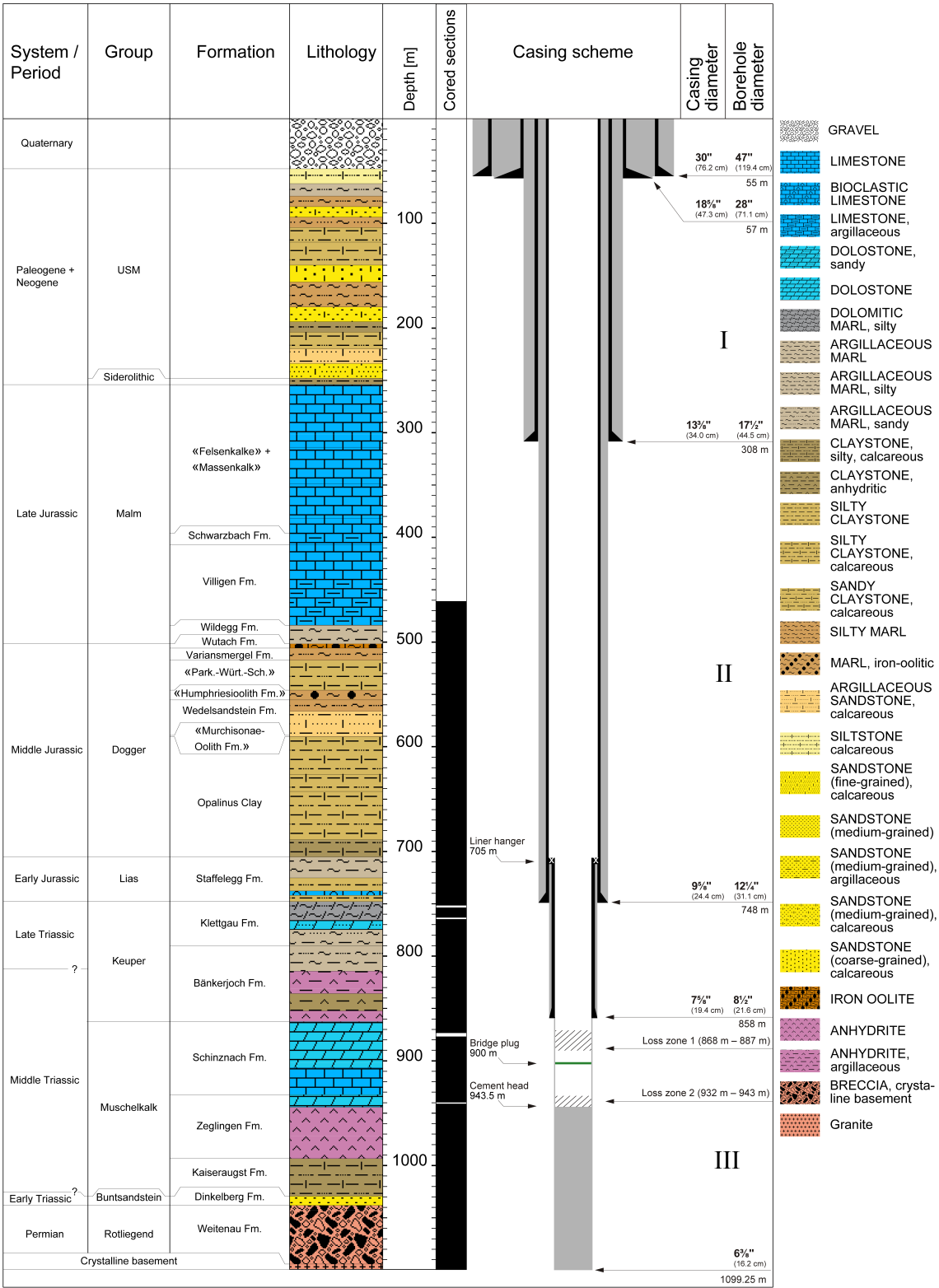


Fig. 1-3: Lithostratigraphic profile and casing scheme for the MAR1-1 borehole⁴

⁴ For detailed information see Dossier I and III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the MAR1-1 borehole⁵

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

⁵ For details regarding lithostratigraphic boundaries see Dossier III and IV; for details about depth shifts (core gonio-metry) see Dossier V.

1.3 Documentation structure for the MAR1-1 borehole

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

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

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

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

Black indicates the dossier at hand.

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

1.4 Structure of Dossier VII

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 MAR1-1 was the first 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 MAR1-1 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 MAR1-1.
- 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, and test activities in borehole MAR1-1. Selected tests and analyses are presented in detail.
- Chapter 5 summarises and discusses the data and results, mainly for the hydraulic packer tests. The results are summarised in tables and plots, and some assessments are made.
- 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 MAR1-1

The hydrogeological investigations for MAR1-1 comprised:

- Fluid logging
- Hydraulic packer testing

Given sufficiently high transmissivity, fluid logging was performed. Water inflows into the borehole were identified with a series of temperature – 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 MAR1-1:

- 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) was conducted in the MAR1-1 borehole and a hydraulic long-term monitoring system will be installed.

The detailed groundwater sampling, subsequent hydrochemical and isotope analyses (including results) are documented in Lorenz et al. (2021). 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

The fluid logging was performed with the equipment introduced below.

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, 79211 Denzlingen, Germany
Type	TT2000, Electrical, 220 V
Cable type	Rochester $\frac{3}{16}$ " 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 computer, 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 is 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 12.1 build 2388 © Advanced Logic Technology, 1995 – 2018
- Processing: WellCAD 5.2 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 is 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 Acoustic borehole televiewer

The acoustic borehole televiewer generates a continuous orientated false-colour image of the borehole wall using an ultrasonic beam. The image can be used to define different geological units to measure the orientation of geological structures or to orient existing cores using significant structures. For specifications of the acoustic borehole televiewer see Tab. 3-5.

The full circumference of the borehole is scanned with a rotating ultrasonic beam with up to 360 samples/rotation. For every "shot" the amplitude and travel time of the reflected signal is recorded. From this data a false colour image is generated for the amplitude and the travel time. Bright colours correspond to high values (i.e. high amplitude or harder reflecting surface, or longer travel time = larger diameter) and dark colours correspond to low values (i.e. low amplitude or signal attenuation, or shorter travel time = smaller diameter).

These data are displayed in an unrolled image of the borehole wall. The image is oriented to magnetic north using the orientation module that is integrated in the probe. The left and right border of the image correspond to north, the middle of the image corresponds to south.

As the deviation of the borehole from the vertical increases, the deviation from the north decreases. The image can then be oriented to the high side, using the gravity as a reference. The left and right border of the unrolled image are the high side, the middle of the image is the low side of the borehole.

In case of the presence of magnetic anomalies in the borehole that prevent proper use of the magnetic image orientation, it is possible to record high side-oriented images if the borehole is inclined. The data can then be rotated to the actual orientation in the rock using borehole survey data measured with e.g. a gyro probe.

Tab. 3-5: Specifications of the acoustic borehole televiewer

Manufacturer	LIM Logging, L-4801 Rodange, Luxembourg
Type	BHTV42
Length	2.10 m
Weight	8.0 kg
Tool diameter	42 mm
Operational temperature range	0 – 70 °C (up to 80 °C for a limited time)
Max. pressure	20 MPa
Borehole diameter range	60 – 300 mm
Image resolution	Horizontal: 90, 120, 180 or 260 pixel Vertical: defined by logging speed, typically 2 mm / pixel
Signal frequency	1.5 MHz
Gamma detector	NaI 50 mm × 25 mm crystal
Accessories	Centraliser

3.1.6 Gamma sensors

All probes described above (temperature-conductivity-gamma probe, borehole geometry gamma probe and acoustic borehole televiewer) are equipped with similar gamma-ray detectors. The detectors are of the scintillation type, set up for total count measurements. They consist of an 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 so is not 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.

3.1.7 Temperature-electrical conductivity meter

The WTW (Wissenschaftlich-technische Werkstätten GmbH) instrument pH/Cond 340i is a handheld digital instrument to measure fluid pH, electrical conductivity and temperature (for specifications, see Tab. 3-6). It 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. 3-6: 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

3.1.8 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 that the measurements are influenced by any debris that might be scraped off the borehole wall. For specifications, see Tab. 3-7.

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. They are fixed to the probe by grub screws.

Tab. 3-7: 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

3.1.9 Field analysis IT structure

Logging is performed directly into a WellCAD document to display previous and current measurements. For specifications of the IT structure, see Tab. 3-8.

Tab. 3-8: Specifications of the IT structure for field analysis

Processing software	WellCAD 5.2 build 1925 © Advanced Logic Technology, 1993 – 2018
Logging software	Matrix Logger: V 12.1 build 2388 © Advanced Logic Technology, 1995 – 2018
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 Tool application

Fluid logging was conducted in borehole MAR1-1 on the 27 and 28 February 2020 in the cored borehole Section II. The test is referred to as MAR1-1-FL1-MAL. 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 detailed analysis of the hydraulic packer test results for the interval MAR1-1-MAL1.

3.2.1 Description of measurements performed

The drilling depth was 460 m MD and the fluid logging was performed to a depth of 453 m MD. A first measurement was performed before the start of pumping, lowering the probe with a velocity of ~ 4.5 m/min between depths of 290 and 453 m MD. A second measurement under static conditions was performed by lowering the probe with a velocity of ~ 5.7 m/min from a depth of 305 m MD to a depth of 453 m MD. These two measurements were followed by a sequence of 4 pumping (rate withdrawal) phases (RW1, RW2, RW3 and RW4) during which the pumping rates varied, and the water pressure dropped accordingly. The first pumping phase (RW1) was performed with pumping rates of between 30 and 25 L/min to get beyond the wellbore

storage effect in reasonable time. During the second pumping phase (RW2) the flow rate was stabilised at approximately 1.7 L/min. To lower the water level in the borehole, a third pumping phase was performed (RW3) with pumping rates of 16 – 14 L/min, followed by a final pumping phase (RW4) where the pumping rate was stabilised at approximately 3.7 L/min.

The following data was recorded and considered for the analysis:

- 21 Runs of electrical conductivity (corrected to 25 °C equivalent conductivity)
- Pumping test data (pressure and flow rate)

Tab. 3-9 provides the start and end times of the logs (Runs). The corresponding pressure draw-down and pumping rates are shown in Fig. 3-1 and Fig. 3-2, respectively. Fig. 3-3 shows the recorded electrical conductivity logs.

Tab. 3-9: MAR1-1-FL1-MAL: Start and end times of the fluid logging runs performed for MAR1-1 and their associated depth range

Logging run	Hydraulic test sequence	Date	Start time	Start depth [m MD]	End time	End depth [m MD]
1	Pre-test	27.02.2020	06:05	289.68	06:41	452.93
2		27.02.2020	11:16	305.09	11:42	452.99
3	RW1	27.02.2020	12:14	305.86	12:43	452.96
4		27.02.2020	13:25	315.68	13:48	453.03
5		27.02.2020	14:31	314.89	14:54	452.99
6		27.02.2020	15:09	313.36	15:31	453.15
8	RW2	27.02.2020	16:16	313.70	16:38	453.00
9		27.02.2020	17:10	313.30	17:34	453.00
10		27.02.2020	18:10	309.61	18:38	452.96
11	RW3	27.02.2020	19:40	313.50	20:04	452.96
12		27.02.2020	20:14	313.24	20:38	453.03
13		27.02.2020	21:17	312.94	21:41	452.99
14		27.02.2020	22:13	312.96	22:36	452.90
15	RW4	27.02.2020	22:56	313.14	23:19	452.98
16		27.02.2020	23:49	312.96	00:13	452.96
17		28.02.2020	00:41	312.95	01:20	452.95
18		28.02.2020	01:31	312.92	01:56	452.92
19		28.02.2020	02:21	313.03	02:44	452.93
20		28.02.2020	03:11	312.95	03:34	452.95
21		28.02.2020	04:03	312.97	04:28	452.97

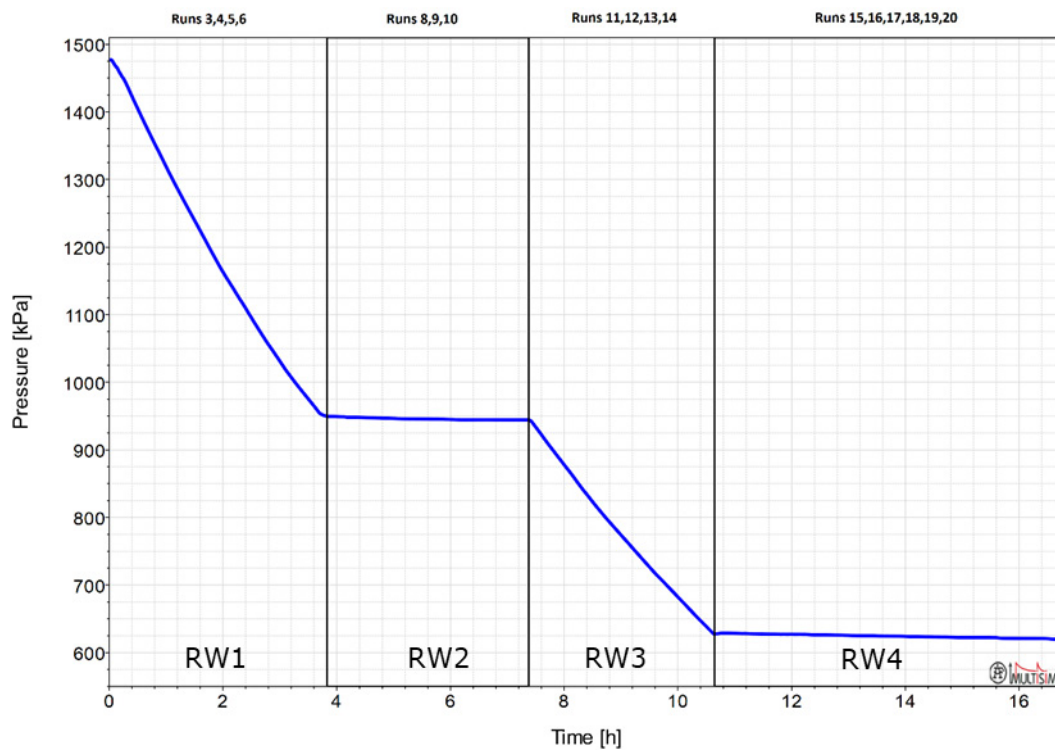


Fig. 3-1: MAR1-1-FL1-MAL: Pressure drawdown and the position in time where fluid logging runs were performed

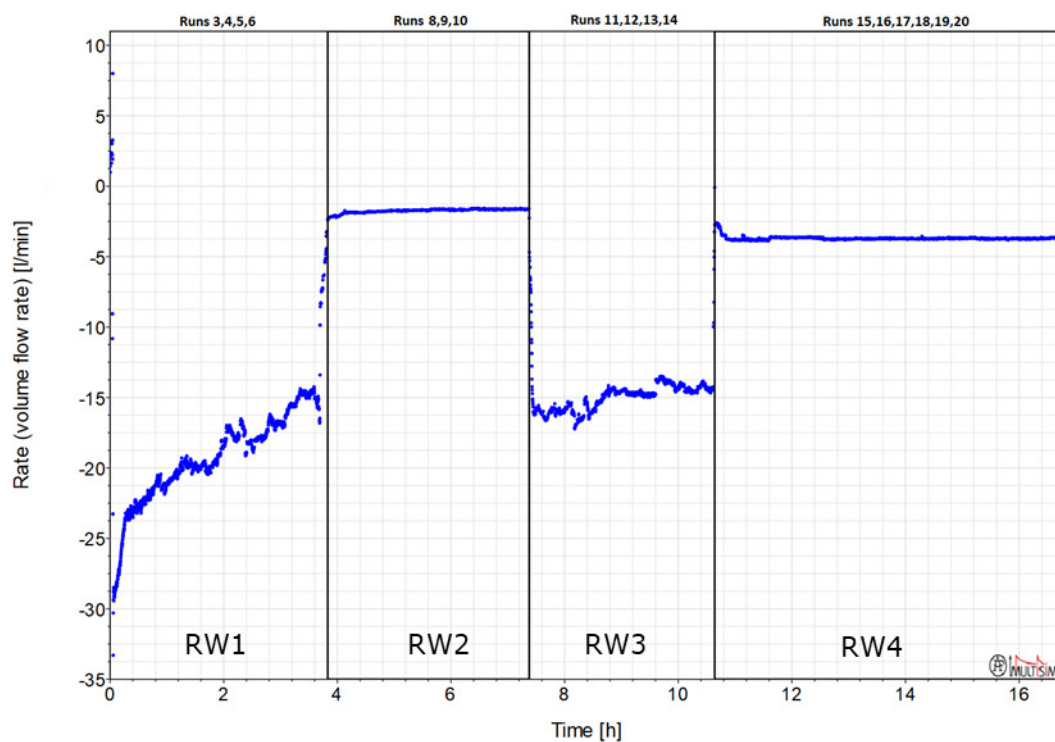


Fig. 3-2: MAR1-1-FL1-MAL: Measured pumping rates and the position in time where fluid logging runs were performed

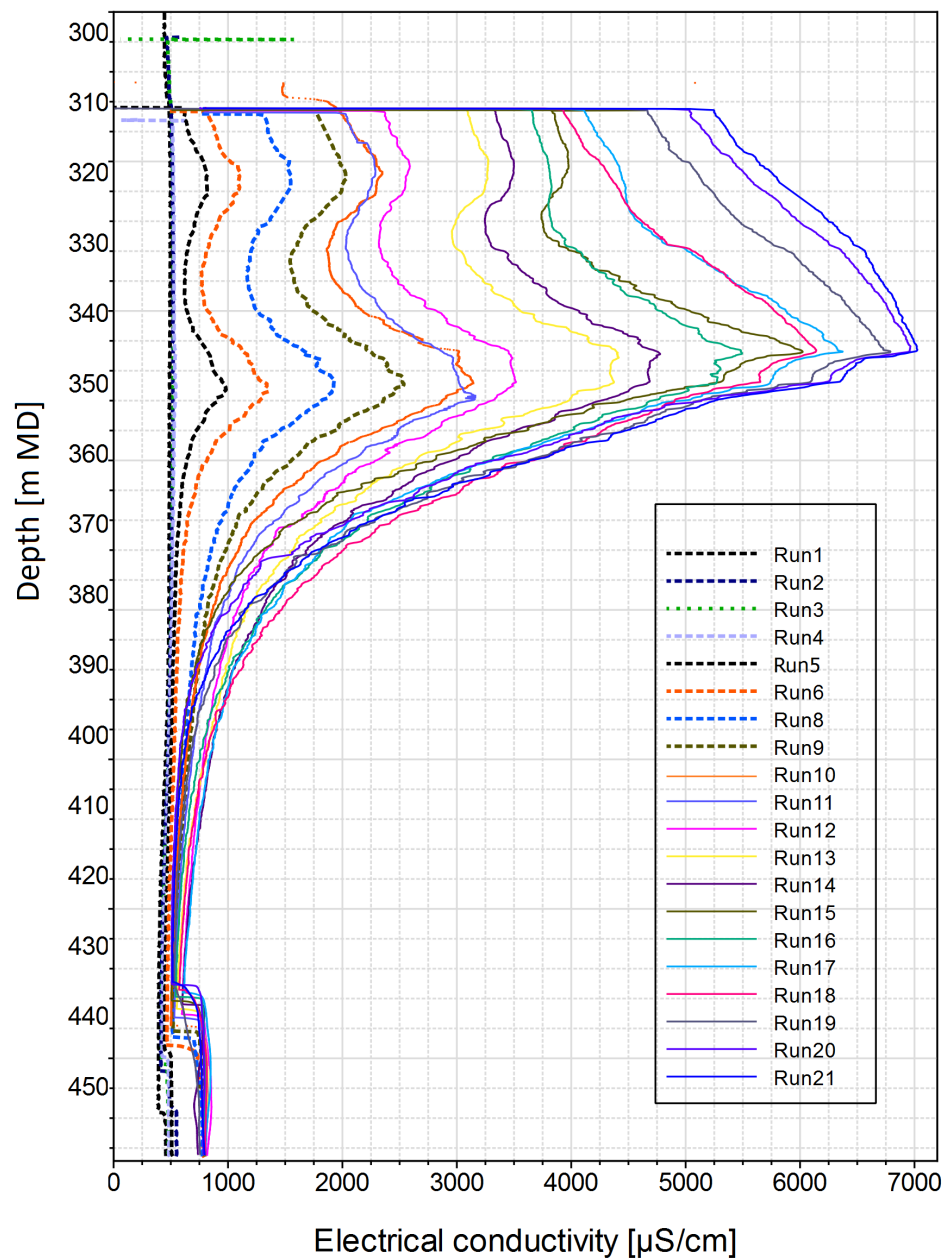


Fig. 3-3: MAR1-1-FL1-MAL: Measured electrical conductivity logs (Runs), calculated for a temperature of 25 °C

3.2.2 Analysis of pumping test data

First, the pumping test was 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.

Second, the recorded concentration profiles were analysed numerically by the contractor using a 1D numerical transport model. The inflow rates and the corresponding concentration of one fluid log are used as the initial concentration profile. Starting from this, the concentration distributions

of the following fluid logs are computed. Based on fitting the concentration profiles recorded inside the borehole, the inflow zones are determined qualitatively and quantitatively, and the transmissivities of the inflow zones are determined using the solution of Cooper & Jacob (1946).

Two analyses were performed with the borehole simulator Multisim and showed that a radial homogeneous model was best suited to match or fit the pressure and flow data. Analysis 1 comprised all production phases (RW1 to RW4), while analysis 2 was based only on the final production phase RW4.

The results of the two pumping test analyses are provided in Tab. 3-10. The transmissivity ranged between $4 \times 10^{-7} \text{ m}^2/\text{s}$ and $6 \times 10^{-7} \text{ m}^2/\text{s}$.

Tab. 3-10: MAR1-1-FL1-MAL: Estimated hydraulic parameters derived from pumping test analyses 1 and 2 in the framework of fluid logging in borehole MAR1-1

The fitted parameters are shown in bold.

Parameter	Analysis 1	Analysis 2
Pumping phases, considered	RW1 – RW4	RW4
Flow model	Radial homogeneous model	
Length of test interval [m]	148	
Hydraulic conductivity (K) [m/s]	2.77×10^{-9}	4.0×10^{-9}
Total transmissivity (T) [m^2/s]	4.09×10^{-7}	5.91×10^{-7}
Specific storage (S_s) [1/m]	6.79×10^{-7}	6.79×10^{-7}

3.2.3 Fluid logging analysis

Two prerequisites have to be fulfilled in order to analyse the concentration distribution as a function of time inside the borehole by means of a 1D transport model:

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

These conditions were expected to be fulfilled for the fluid logging runs during pumping phases RW2 and RW4 where the pumping rate caused a minimal lowering of the water level in the borehole.

Accordingly, Runs 8 to 10 were analysed considering the pumping rate during pumping phase RW2. Runs 15 to 21 were analysed considering the higher pumping rate during pumping phase RW4. The fits were performed with different dispersion coefficients between $0.01 \text{ m}^2/\text{s}$ and $7 \times 10^{-9} \text{ m}^2/\text{s}$ (considering only hydraulic diffusion). The results are summarised in Tab. 3-11.

Tab. 3-11: MAR1-1-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 [lLmin]	Transmissivity [m ² /s]
1 st fluid logging analysis of Runs 8 to 10, dispersion coefficient 0.01 m ² /s						
1	320.00	326.00	6.00	3.3	0.63	1.90×10^{-7}
2	349.00	351.50	2.50	3.3	1.02	3.30×10^{-7}
2 nd fluid logging analysis of Runs 8 to 10, dispersion coefficient 0.008 m ² /s						
1	318.00	328.50	10.50	3.5	0.61	1.76×10^{-7}
2	347.50	352.50	5.00	3.5	0.95	2.91×10^{-7}
3	360.00	370.00	10.00	3.5	0.09	2.61×10^{-8}
1 st fluid logging analysis of Runs 18 to 21, dispersion coefficient 3.5×10^{-4} m ² /s						
1	345.30	346.20	0.90	3.7	1.80	3.61×10^{-7}
2	346.40	348.00	1.60	3.7	0.40	6.17×10^{-8}
3	348.00	350.50	2.50	3.5	0.50	7.97×10^{-8}
4	350.50	351.00	0.50	3.5	0.06	1.06×10^{-8}
2 nd fluid logging analysis of Runs 19 to 21, dispersion coefficient 7×10^{-9} m ² /s						
1	316.00	324.00	8.00	2.46	1.60	2.99×10^{-7}
2	345.50	346.20	0.70	3.97	1.37	2.97×10^{-7}
3	346.40	348.00	1.60	3.51	0.40	8.40×10^{-8}
4	348.00	350.10	2.10	3.49	0.28	5.77×10^{-8}
5	350.10	351.00	0.90	3.49	0.05	1.08×10^{-8}

The position of the inflow zones, the inflow rates and the associated transmissivities for the 2nd fluid logging analysis of Runs 8 to 10 are illustrated in Fig. 3-4. The reliability and significance of the fluid logging analysis are supported by the acoustic borehole televiewer image, which shows fractures and voids associated with the defined inflow zones (they are also obvious on the FMI and acoustic images acquired later during petrophysical logging; see Dossier VI). The simulated Runs corresponding to the 2nd fluid logging analysis of Runs 8 to 10 are provided in Fig. 3-5.

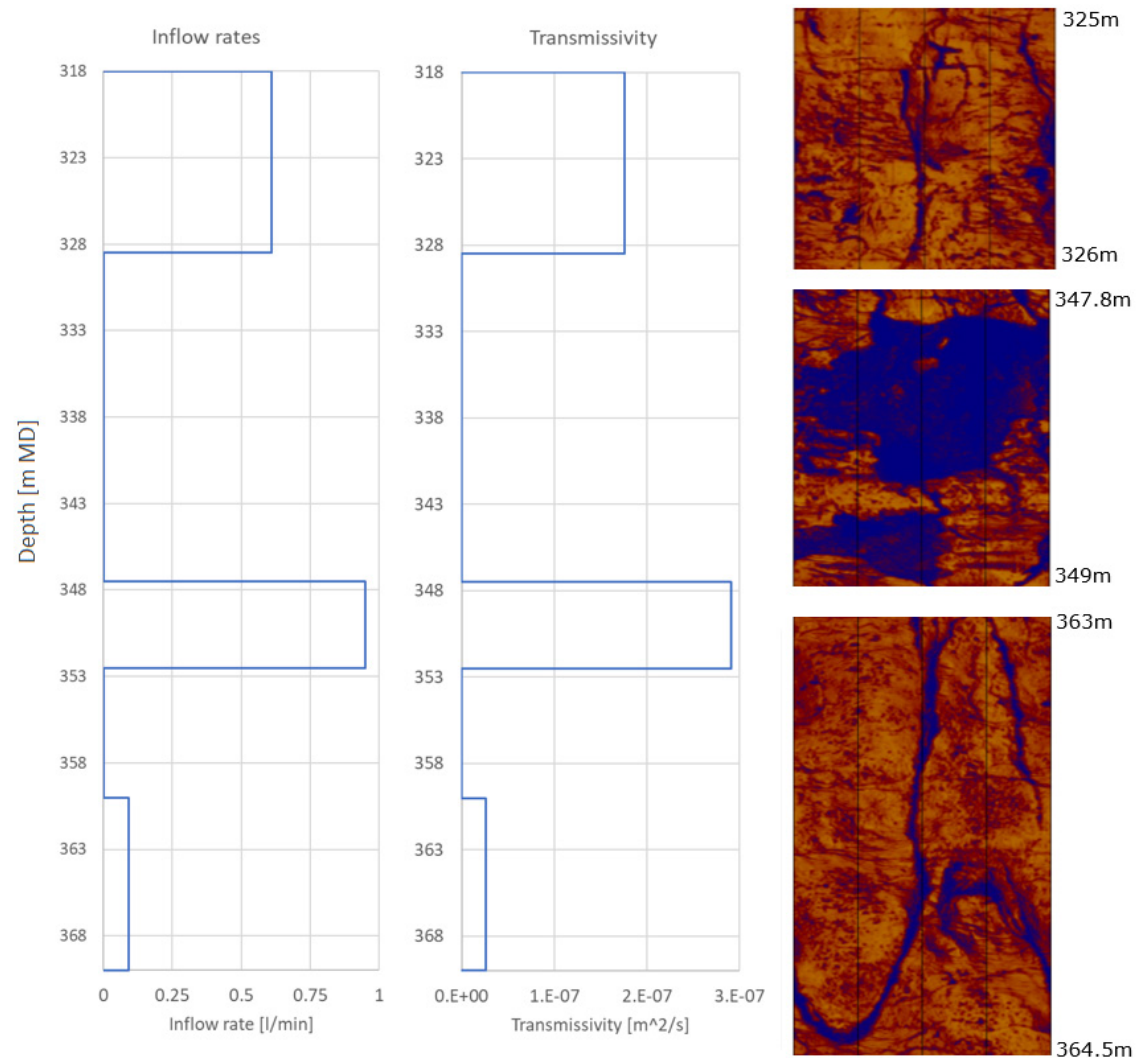


Fig. 3-4: MAR1-1-FL1-MAL: 2nd fluid logging analysis of fluid logging Runs 8 to 10; inflow rates, transmissivity and associated acoustic borehole televiewer images

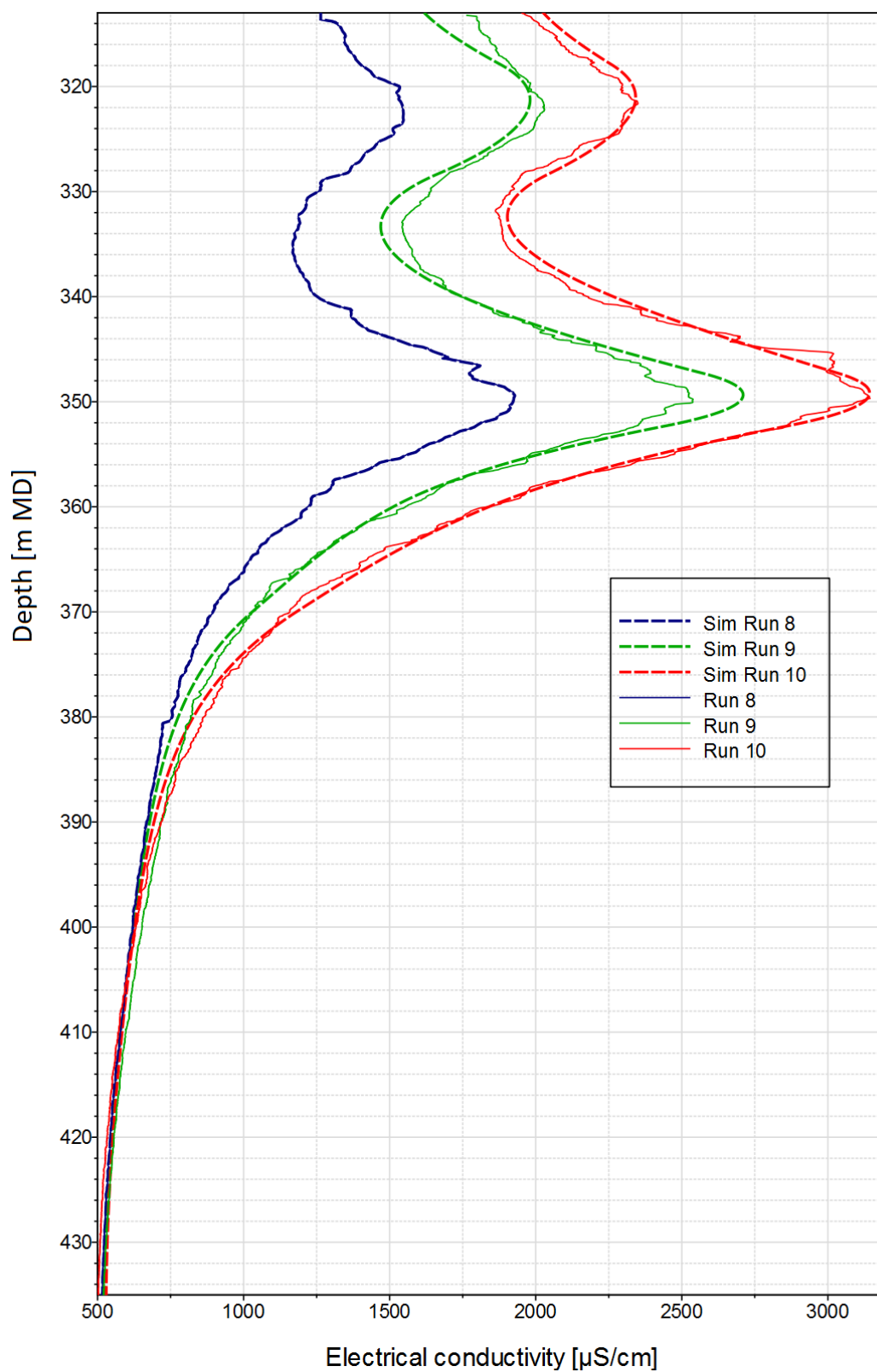


Fig. 3-5: MAR1-1-FL1-MAL: 2nd fluid logging analysis of fluid logging Runs 8 to 10; fluid logging analysis results for Runs 9 and 10 based on the initial concentration distribution of Run 8

The position of the inflow zones, the inflow rates and the associated transmissivities of the 2nd fluid logging analysis based on Runs 19 to 21 during the pumping phase RW4 are shown in Fig. 3-6, with the simulated concentration distribution being shown in Fig. 3-7.

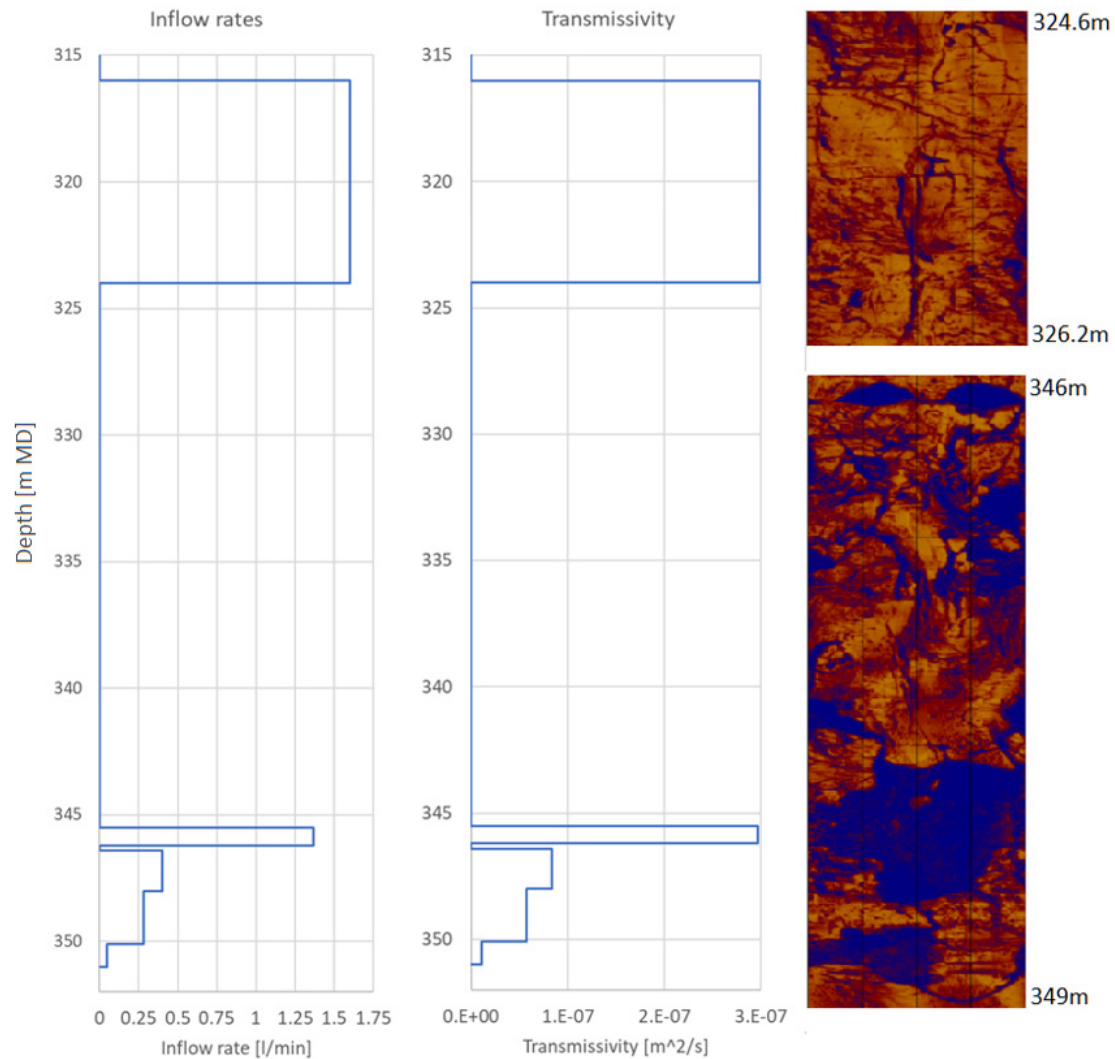


Fig. 3-6: MAR1-1-FL1-MAL: 2nd fluid logging analysis of fluid logging Runs 19 to 21; inflow rates, transmissivity and associated acoustic borehole televiewer images

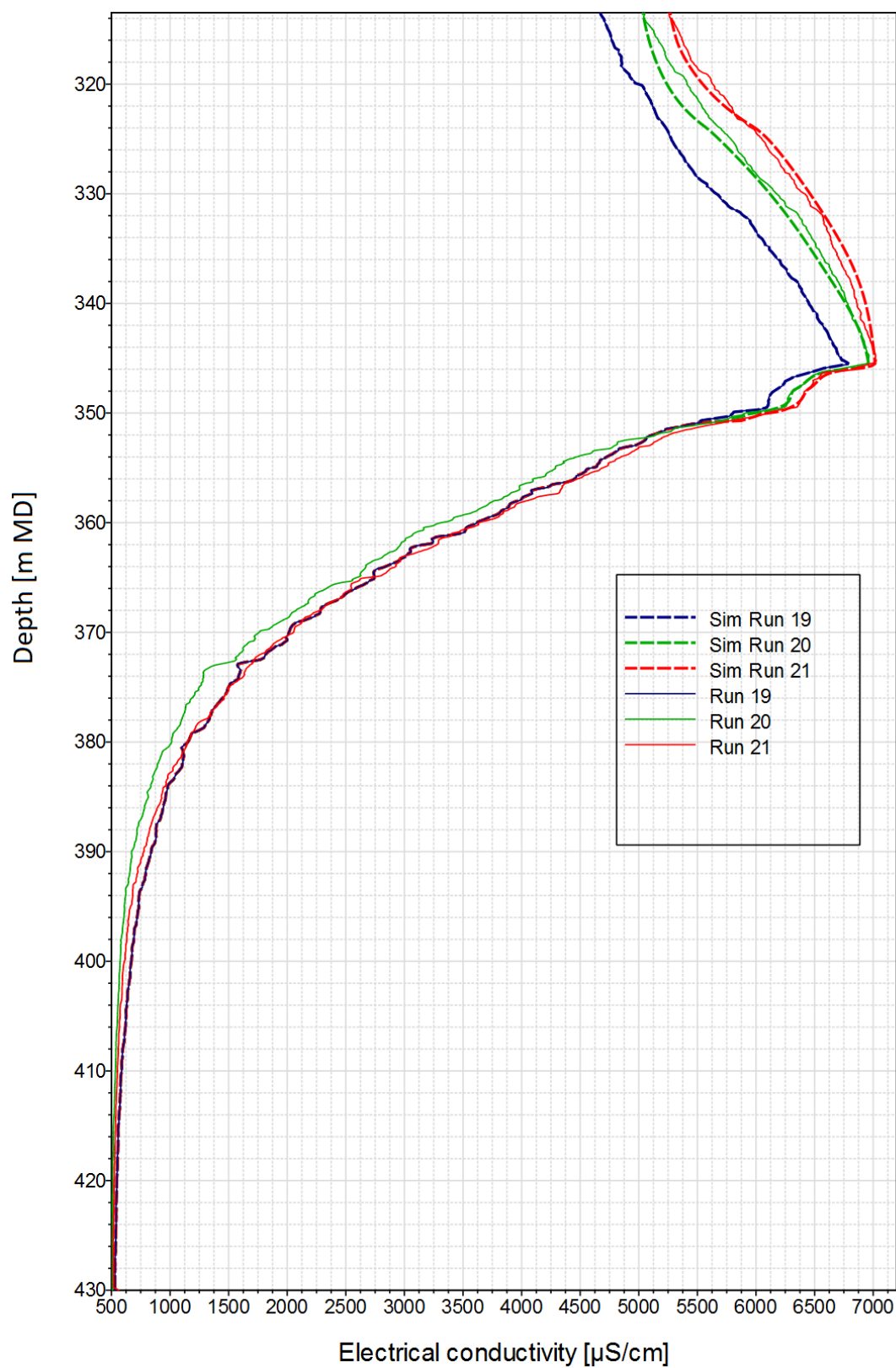


Fig. 3-7: MAR1-1-FL1-MAL: 2nd fluid logging analysis of fluid logging Runs 19 to 21; fluid logging analysis results for Runs 20 and 21 based on the initial concentration distribution of Run 19

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 like the Malm and the Muschelkalk are expected to have relatively high transmissivities.

Nagra has long-established hydraulic testing strategies (e.g. Nagra 1997) to extract the maximum information about the hydraulic characteristics of the various geological formations. Two testing strategies are preferred (Tabs. 4-1 and 4-2). 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 withdrawal (PW) or pulse injection (PI) test 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 encountered specific test conditions and results obtained while testing. This may lead to the omission of certain test phases, e.g. the diagnostic phase.

The main difference in 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 case of formations with low to very low transmissivity, the test types and their duration is different. For the determination of hydraulic head, the borehole pressure history and test duration are an important issue. 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 the 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 MAR1-1 borehole, except for the gas threshold pressure test (GTPT). The main reason was borehole stability. The model implementation as a skin in the test analysis is assumed to address the issues linked with the drilling fluid properties at the borehole wall adequately. The interval MAR1-1-MAL1 was drilled using bentonite-polymer based drilling mud. This was first exchanged with tap water for the execution of the fluid logging operation. Following this, a second fluid exchange using potassium silicate to a total drilling depth of 460 m MD was performed before the hydraulic packer test MAR1-1-MAL1 was started. Hence, during all hydraulic tests, potassium silicate was used as an additive in the drilling fluid (*cf.* Dossier I).

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

¹ For explanation of 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; creates 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 the 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 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; creates 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 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 MAR1-1) 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 2 $\frac{7}{8}$ inch (") 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 $\frac{7}{8}$ " EU API CT5 L80). A progressive cavity pump (PCP) or Moyno® type pump or a pump housing with a 4" submersible pump, integrated in the test tubing, can 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 using 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 2 $\frac{7}{8}$ " tubing at the bottom of the prolongation.

The quadruple flat-pack consists of three hydraulic steel pipes of $\frac{1}{4}$ " outer diameter (OD) and one electrical conductor coated in a thermoplastic protective cover. Two steel pipes were used for packer inflation, one for the control of the SIT and one for 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]	Tensile Strength [tons]	Weight [kg]
Tubing (2 7/8 inch)		x		93.2 (73.0)	62.0	indiv.	45	
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		0.185		
X Over			x					
Hydraulic Shut In Tool			x	106.0	24.0	1.41		69
Coupling								
Crown Shaft			x	100.0	40.0	0.378		
Cable Base								
Cable Head and Cable Plug 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	0.525 0.652 0.795 0.892 1.707		132
Crown Shaft			x	100.0	40.0			
X-Over								
Safety Joint			x	93.0	62.0		90	14 (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						
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								
P1 Seal Sub			x	95.0	...	0.431		
			x					
						0.215		
Bottom Packer (146 mm)				146.0	49.0	1.20		98
						0.225		
						0.164		
Bottom Cap				95.0	...	0.16		

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	Stub ACME	max. OD [mm]	min. ID [mm]	Length [m]	Tensile Strength [tons]	Weight [kg]
Tubing (2 7/8 inch)		x		93.2 (73.0)	62.0	indiv.	45	
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		0.185		
X Over			x					
Hydraulic Shut In Tool			x	106.0	24.0	1.41		69
Coupling								
Crown Shaft			x	100.0	40.0	0.378		
Cable Base								
Cable Head and Cable Plug 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						0.525		
P4						0.652		
P2 / T2						0.795		
P1						0.992		
Crown Shaft			x	100.0	40.0	0.27		
X-Over						0.128		
Safety Joint			x	93.0	62.0		90	14 (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			0.08		
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		
Bottom Cap						0.314		6

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 HDDP are provided in Tab. 4-3. A summary of the downhole equipment with the most important 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	Maximum tensile force [t]
Quadruple flat-pack	3 each ¼" OD × 0.035" WT316L stainless steel welded and cold drawn annealed tubes 153'339 kPa nominal burst pressure 49'139 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	n/a
Tubing	2⅞" EU API CT5 N80	62	9.68 kg/m	45.3
Pup joints	2⅞" EU API CT5 L80/N80	62	9.68 kg/m	45.3
Shut-in tool (SIT)	Duplex 1.4462	24	69 kg	16
Pressure release valve (PRV)	Duplex 1.4462	24	132 kg	16
Cable base	Duplex 1.4462			16
Quadruple sub-surface probe (QSSP)	Duplex 1.4462 4 pressure sensors P1, P2, P3 and P4			16
Coarse thread safety joint	3 ²¹ / ₃₂ " OD, with 2 ⁷ / ₁₆ " bore with 2⅞" EUE box × pin connections	62	26 kg	90
Packers for large borehole diameter	IPI 5¾" (146 mm), steel wire reinforced, duplex, natural rubber			16
	Packer 1	49	98 kg	
	Packer 2	49	106 kg	
Packers for normal borehole diameter	IPI 4½" (114 mm), steel wire reinforced, duplex, natural rubber			16
	Packer 1	49	78 kg	
	Packer 2	49	67 kg	
Filter	HP well screen: sand free filter screen mounted on 2⅞" tubing L80			16
	Length: 0.50 m	73	13 kg	
	Length: 1.00 m	73	19 kg	
Total system weight	At 1'400 m depth including PCP, quadruple flat-pack cable and centralisers		ca. 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 line was integrated in the quadruple flat-pack using a booster pump. Depending on the environmental temperatures, an 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 – 60'000 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 vessel via the packer control board for the entire test time. The pressure vessel was placed in a water bath to keep its temperature as constant as possible.

Tab. 4-5: Specifications for the HDDP packers

Manufacturer	Inflatable Packers International (IPI), Perth, Australia	
Packer types	IPI 4½" (114 mm)	IPI 5¾" (146 mm)
Material and type	Duplex, natural rubber, sliding end	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 (OD), not inflated	114 mm max.	146 mm max.
Inner diameter (ID)	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" EUE pin × 2⅞" EUE box	2⅞" EUE pin × 2⅞" EUE 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 showed ± 0 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

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

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

Data logger type	DataCan Memory Pressure Gauge 1.25" Welded Piezo III
Manufacturer	Data Can, Red Deer, Canada
Pressure range (full scale, FS)	0 – 20'684 kPa (absolute)
Pressure accuracy	0.03% FS
Resolution	0.0003% FS
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 booster 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-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 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
Maximum applicable tensile force	16 tonnes

4.2.1.6 Test tubing

American Petroleum Institute (API) specification 5 CT-05 2⅞" 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 and pipes: API 5CT-05 (PSL1), 8 th edition End of pipes: EUE, Tubing&Coupling API 5CT-05 (PSL1), 8th edition
Manufacturer	Interpipe Nikopolsky Normec, Celle, Germany
Steel grade	N80 (tubing), N80/L80 (pup joints)
Inner diameter	62.00 mm
Outer diameter	73.02 mm
Coupling outer diameter	93.20 mm
Thread	API 2⅞" EUE
Weight per metre	9.68 kg
Volume per metre	3.02 L
Individual tubing length	Range 2, ~ 9.5 m
Number of individual tubings	174
Total length of test tubing	Ca. 1'500 m
Lengths of pup joints	Length, quantity 1.00 m, 2 1.03 m, 1 1.50 m, 2 1.55 m, 1 1.75 m, 1 1.83 m, 1 3.00 m, 3
Maximum applicable tensile force	45.3 tonnes

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 defines the wellbore storage of the test system during the slug. To improve the resolution of the pressure change, slim tubing was used to reduce the diameter of the test tubing for slug tests in formations with low transmissivity.

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 seals the annulus between the 2⅞" 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 top of the slim tubing packer, referred to as P4-slim. The 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 2⅞" test tubing for a slug withdrawal test to the specified depth, the slim tubing was installed in the test 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 pipe. The use of a stiff tube for the slim tubing ensured a constant inner diameter independent of the pressure (fluid level).

Tab. 4-10: Specifications for the slim tubing

Slim tubing	Manufactured by Solexperts AG	
Types	PE (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 (full scale, FS), accuracy 0.1% FS	
Pressure sensor (P-slim)	Keller DCX-22, 0 – 5'000 kPa (full scale, FS), accuracy < 0.05% FS, resolution 0.0025% FS	
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, e.g. for fluid logging. 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, Schweiz	
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	Injection tests, fluid logging

4.2.1.9 Progressive cavity pump

For constant rate or constant head 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 the 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

Pump type	Progressive cavity pump
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 to 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 to 70 °C 1 for pump rates 1.7 – 5.5 L/min, Temp. 10 °C to 70 °C
Available rotors	3 for pump rates 10.4 – 60 L/min, Temp. 10 °C to 30 °C, 30 °C to 50 °C, 50 °C to 70 °C 3 for pump rates 1.7 – 5.5 L/min, Temp. 10 °C to 30 °C, 30 °C to 50 °C, 50 °C to 70 °C

4.2.2 Surface equipment

The surface equipment consisted of the following equipment:

- Winch for quadruple flat-pack cable
- Flow control system
- Pressure vessel for packer pressure stabilisation
- 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 type Yokogawa AXF/ADMAG were used. 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

	Measuring range and accuracy			
	Lower limit		Upper limit	
	[L/min]	[% FS]	[L/min]	[% FS]
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

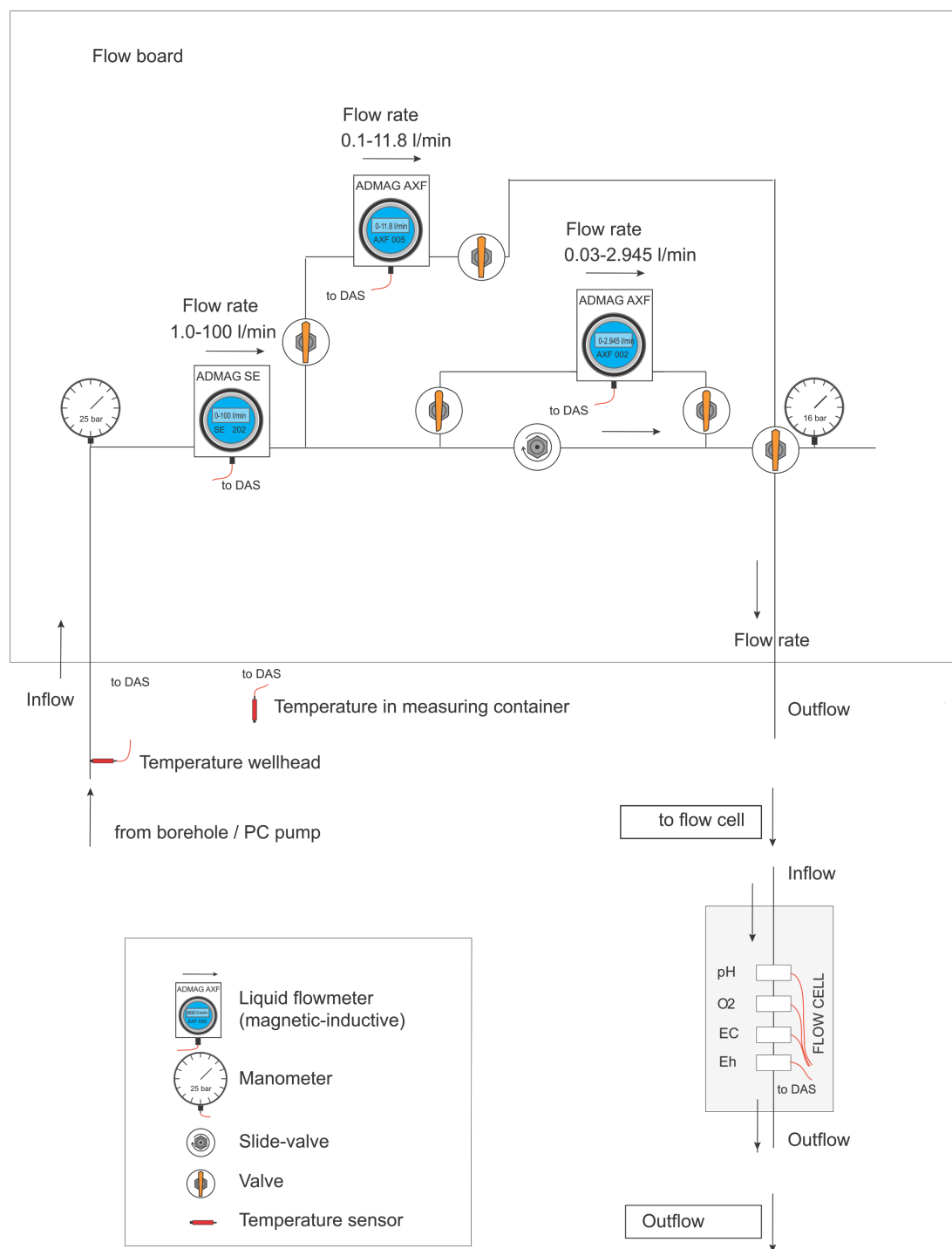


Fig. 4-3: Schematic layout of the flow control unit

4.2.2.2 Packer pressure control unit

Two transducers (type Keller PA-23SY, 60'000 kPa) mounted on the surface inflation control panel were used to monitor the packer inflation pressures (Fig. 4-4).

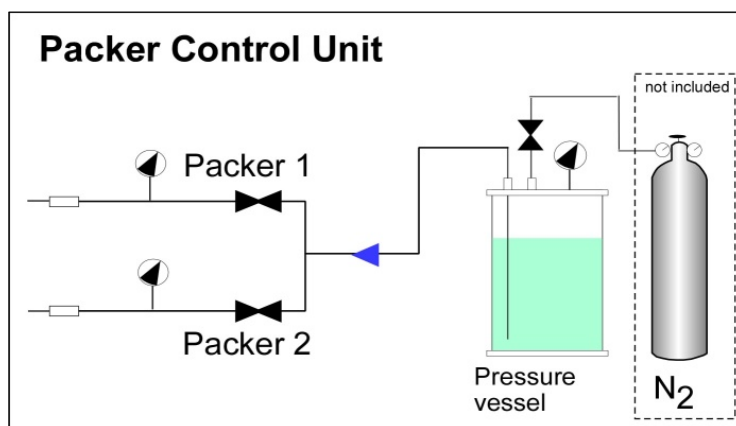


Fig. 4-4: Schematic layout of the packer control unit

4.2.2.3 Additionally recorded measurements at surface

A single pressure transducer (type Keller PAA-33X, 80 – 120 kPa absolute) was mounted in the monitoring trailer and used to monitor barometric pressure (Tab. 4-14).

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. 4-15. The specifications of the temperature sensor are also given in Tab. 4-15. The sensors were calibrated on-site before each use.

Tab. 4-14: Specifications for the atmospheric pressure sensor

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

Tab. 4-15: Specifications for the physico-chemical sensors

Sensor type	Electrical conductivity (EC)	Potential of hydrogen (pH)	Oxidation / reduction potential (Eh)	Oxygen (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)	1.5 × 10 ⁻³ °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 industrial PCs, screens and 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 an interface 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 every 20 s 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 to be used together with the HDDP system. The individual parts were assembled on-site, together with the HDDP system.

The system parts for the downhole equipment were the following:

- Second shut-in tool below the bottom packer with crown shaft
- X-over 2 $\frac{7}{8}$ " to 4 $\frac{1}{2}$ "
- 4 $\frac{1}{2}$ " exchange chamber below the lower SIT1 for the collection of exchanged NaOH and test water (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)
- Lifting device for the 4 $\frac{1}{2}$ " tubing installation: X-over 4 $\frac{1}{2}$ " tubing pin and 2 $\frac{7}{8}$ " tubing box to use the existing 2 $\frac{7}{8}$ " tubing lifting heads. Suitable slip plate for securing the 4 $\frac{1}{2}$ " tubing during installation is provided by the drilling company
- Bottom cap / bull nose 4 $\frac{1}{2}$ "
- Dip tube (OD 21.3 mm, wall thickness 2.6 mm) stainless steel with threads and couplings, 15 pieces of 3 m length, 1 piece of 2 m length, 1 piece of 1 m length, 1 piece of 0.5 m length, inside the exchange chamber, with swivel connection and installation tools
- 3 additional $\frac{1}{4}$ " stainless steel lines (OD 6.35 mm, inner diameter 4.55 mm) besides the standard quadruple flat-pack (SIT1 line, backflow line from exchange chamber, injection line in interval equipped with check valve)
- 2 pressure sensors Keller PA-23SY to measure the pressure at the injection and backflow lines
- 2 146 mm inflatable packers with a double mandrel including five through-going pieces of $\frac{1}{4}$ " stainless steel lines and fittings
- 1 memory gauge Keller DCX-22 for the P1 measurement
- Steel bands to tighten the third $\frac{1}{4}$ " stainless steel line to the 2 $\frac{7}{8}$ " tubing. The other 2 additional $\frac{1}{4}$ " stainless steel lines can be integrated in the notches of the existing centralisers / cable protectors.

The surface equipment encompasses the following components:

- Standard hydrotest equipment
- 1 gas flow controller 0 – 5 ln/min (injection line to interval) (ln = litre normal)
- 2 gas flowmeters 0 – 150 ln/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
- A closed 200 L tank for NaOH solution injection via the (gas-) injection line; injection of artificial formation water was skipped
- An additional high-pressure injection pump instead of a booster to obtain a higher injection rate and to save time
- 3 coils for the additional $\frac{1}{4}$ " stainless steel lines, two lines equipped with an additional pressure sensor

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 chapters.

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

1. Repeatedly pressurising the (empty) exchange chamber with nitrogen (N_2) to avoid any damage during installation
2. Injection of sodium hydroxide (NaOH) through the injection line to push the interval fluid to the exchange chamber and 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 NaOH 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 SIT2⁶ closed

⁶ 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 is positioned above SIT1, which controls the fluid connection between the exchange chamber and the test interval during a GTPT.

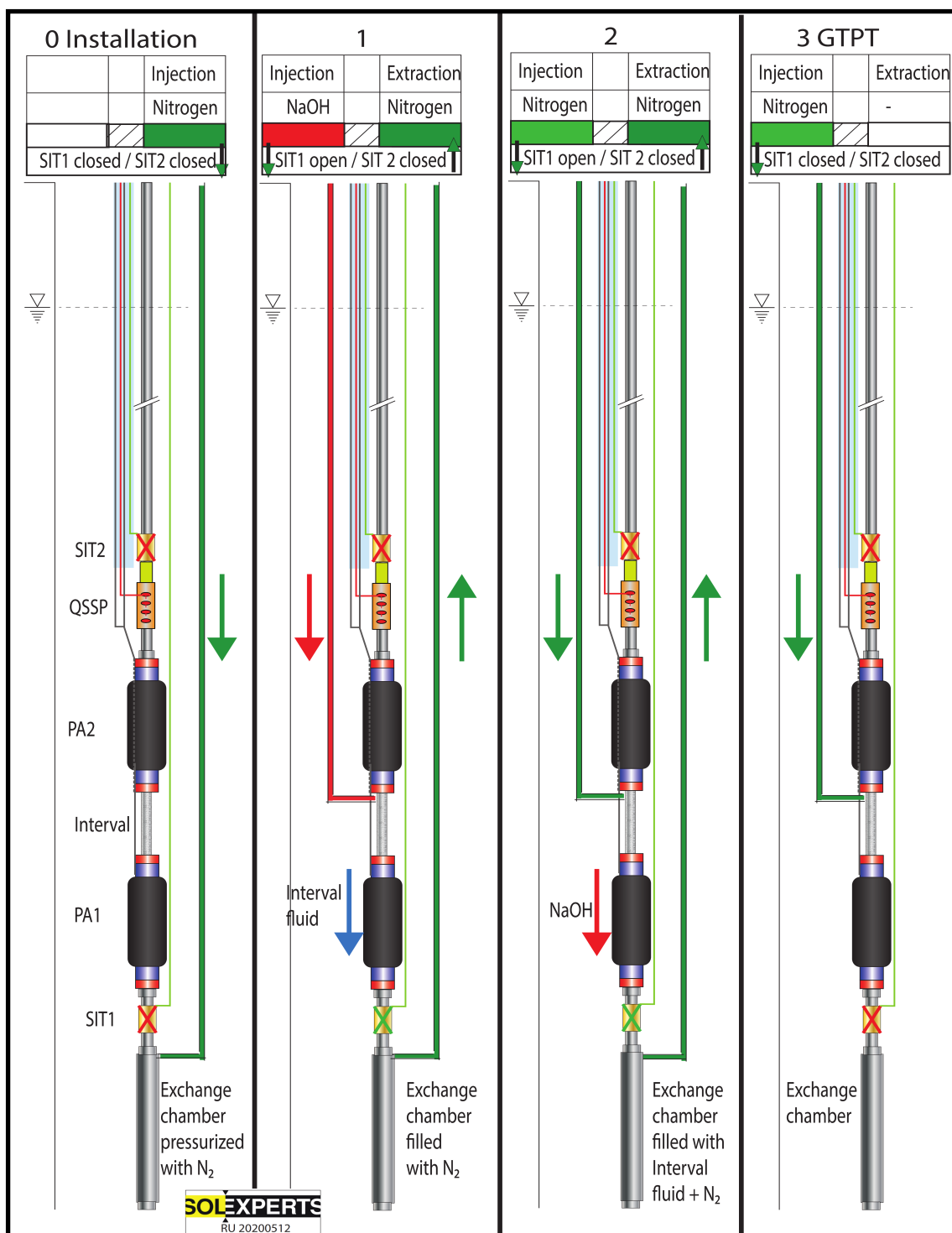


Fig. 4-5: Schematic layout of the modified HDDP system and the four steps for the GTPT

4.2.3.1 Packers for the GTPT

The system comprises two new packers with a diameter of 146 mm which have a double mandrel including five pieces of 1/4" stainless steel lines and the corresponding fittings.

A detailed description of packers and the use of the ¼" stainless steel lines is given in Tab. 4-16. Because of the different design compared to the standard packers, the P1 pressure below the bottom packer could not be measured with the QSSP probe during the GTPT. Therefore, an autonomous data logger was connected to one of the ¼" stainless steel lines through the mandrel of the bottom packer. A Keller DCX-22 logger, 0 – 12'500 kPa, (accuracy 0.05% FS, resolution 0.0025% FS) was used. Before installation, the packers with the corresponding lines were saturated with water and anti-freeze (if necessary).

Tab. 4-16: 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. Line with memory gauge for P1 2. SIT1 line 3. Not used 4. Backflow line 5. Not used Packer 2 (upper packer) 1. Inflation line packer 1 2. SIT1 line 3. Injection line 4. Backflow line 5. Not used Note: The final allocation of the line ports is 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" EUE pin × 2⅞" EUE 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 injection in 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 are coiled up on the corresponding coils. Each stainless steel line is 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 is equipped with a check valve which enables flow into the test interval but no backflow from the test interval into the injection line. The check valve opens at 4 bar injection pressure.

4.2.3.3 Zero-displacement shut-in tool for GTPT

The new SIT1 is similar to the SIT2 (the HTTP SIT used for hydraulic packer testing) which controls 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 is hydraulically operated over a 1/4" stainless steel line using the booster pump. The opening and closing are performed via an axially moveable valve piston. The valve piston is moved via the hydraulic (closure)-line by application of pressure and the valve is closed. The valve piston is reset at pressure release through a pre-stressed spring, and the valve is opened (pressure-free open).

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 proper functioning of the valve, also at deep groundwater levels. The specifications are given in Tab. 4-17.

Tab. 4-17: 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 to 10 L/min	± 0 kPa
Closing pressure	9000 – 10'500 kPa
Maximum applicable tensile force	16 tonnes

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 has a measuring range of 0.1 – 5 ln/min. The two flowmeters for the flow rate measurements during the displacement of NaOH with gas and during backflow have a measuring range of 3 – 150 ln/min (Tab. 4-18). A schematic drawing of the flow board is included in Fig. 4-6.

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

Tab. 4-18: Specifications for the gas flow controller / meters for the GTPT

	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 ln/min	3 – 150 ln/min	3 – 150 ln/min
Accuracy (incl. linearity)	$\pm 0.5\%$ Rd (reading), $\pm 0.1\%$ FS	$\pm 0.5\%$ Rd (reading), $\pm 0.1\%$ FS	$\pm 0.5\%$ Rd (reading), $\pm 0.1\%$ FS
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

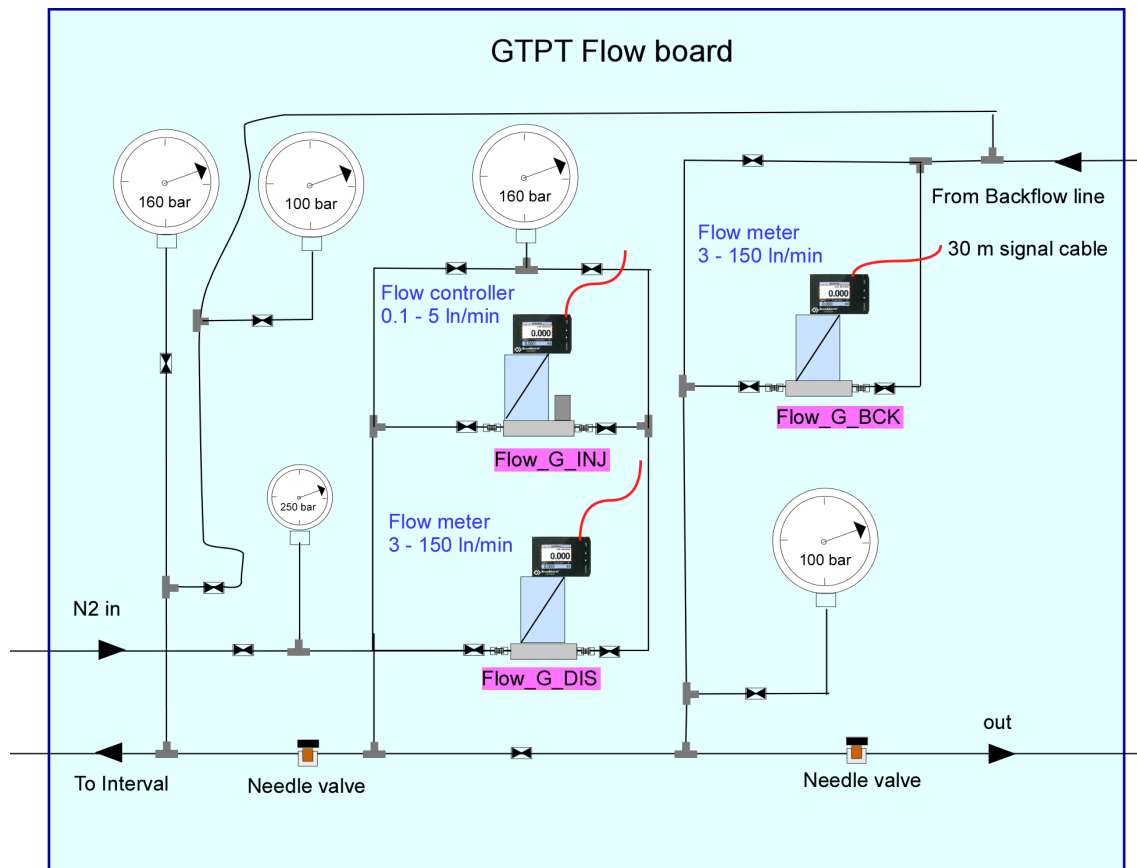


Fig. 4-6: Schematic layout of the flow control unit for the GTPT

4.3 Test analyses

4.3.1 Workflow

For MAR1-1, the general on-site analysis approach involved mainly numerical techniques considering the whole borehole pressure history. Analytical solutions were used mainly 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, particularly the representation of the borehole history period and the starting input parameters were defined.

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

- Identification of the 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 limited perturbation analysis was used to assess the suitability of the numerical solution

- Numerical simulation of the entire test sequence in Cartesian coordinates using the optimised parameter set obtained from the analysis of the individual phases
This final step was used to check the consistency of the model to the entire data set
- Consistency check of the test analysis as well as estimated parameters by the technical supervisor

The results were used to continuously 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.

Two programmes were used for the analytical and numerical interpretation: Hugo TM (Solexperts AG) 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. 4-19.

Tab. 4-19: Summary of analytical analysis methods

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

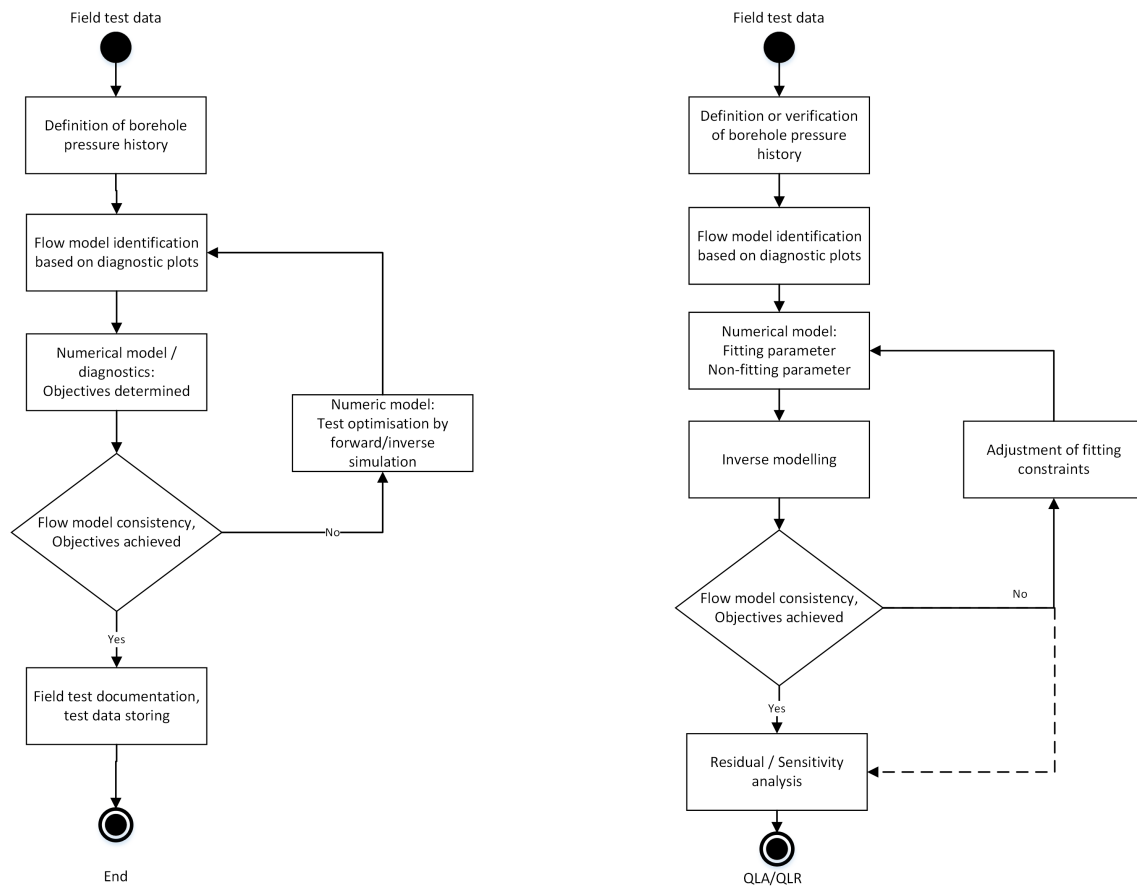


Fig. 4-7: Flowcharts for the on-site hydraulic packer test analysis (left) and Quick Look Analysis (QLA) (right)

The Detailed Analysis (DA) was performed off-site after the test was 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) programme. 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, 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.

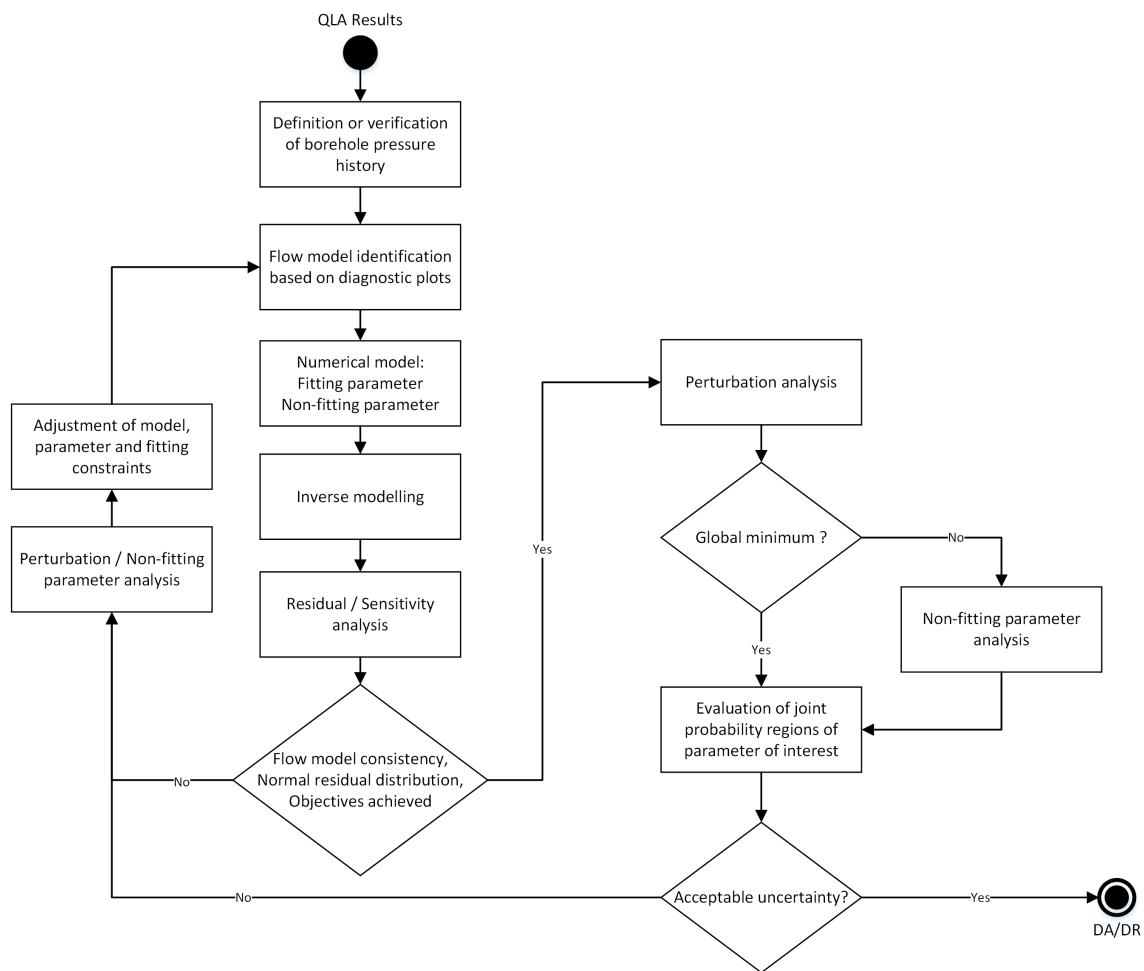


Fig. 4-8: Flowchart for the off-site Detailed Analysis (DA) of a hydraulic packer test

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). They 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 by the diffusion equation. Disturbances are of short duration in formations with medium to high transmissivity. In formations with low transmissivity, disturbances of 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 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. The hydraulic packer tests were performed without exchange of drilling fluid with testing fluid with the aim to reduce potential pressure and temperature disturbances. In addition to this preventive 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 had already 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 testing
- Pressure records of preceding hydraulic testing

The drilling fluid densities were measured four times per day and documented in the drill mud report by the drill mud engineer from AKROS Oilfield Services GmbH. In addition, continuous recordings were available from the mud logging company GEODATA, 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 (hydraulic potential), which in turn depends on the transmissivity of the formation. In formations with low transmissivity, like Opalinus Clay, the determination of the static formation pressure can be impossible in a reasonable time due to the long duration of the pressure history. This was proven by the measurements of the Benken long-term monitoring system, which demonstrated that the static formation pressures of 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 MAR1-1 are provided in Tab. 4-20.

Tab. 4-20: Specific periods of the pre-test borehole pressure history

Pre-test 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.

Test name	Drilling through midpoint: date and time	Start hydraulic testing: date and time	Borehole history duration [h]
MAR1-1-MAL1	23.02.2020 16:55	29.02.2020 18:04	145.14
MAR1-1-BDO2	08.03.2020 19:17	14.04.2020 18:26	887.15
MAR1-1-BDO1	10.03.2020 08:41	11.04.2020 19:47	779.11
MAR1-1-OPA1	11.03.2020 15:43	02.04.2020 11:03	523.33
MAR1-1-OPA3	12.03.2020 15:06	21.04.2020 09:13	954.13
MAR1-1-OPA2	16.03.2020 07:46	07.04.2020 21:36	541.83
MAR1-1-LIA2	18.03.2020 14:04	30.03.2020 14:43	288.65
MAR1-1-LIA1	19.03.2020 07:05	27.03.2020 00:31	185.44
MAR1-1-KEU1	20.05.2020 10:19	22.05.2020 20:42	58.38
MAR1-1-MUK1	28.05.2020 12:48	31.05.2020 20:07	79.32

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 (pre-version 3), 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 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 media (Detournay & Cheng 1988). The Opalinus Clay has shown a time-dependent deformation during tunnel excavation in Mont Terri (see Lisjak et al. 2015 for a sum-up 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 MAR1-1 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 of 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

A total of ten test intervals were investigated in borehole MAR1-1 using the HDDP in single and double packer configuration. The most important test specifications are summarised in Tab. 4-21. The initial plan called for eight test intervals. The hydraulic packer tests were performed in the following geological formations (*cf.* Dossier III):

- Malm Group with a focus on some inflow zones detected with fluid logging in the «Felsenkalke» + «Massenkalk» (MAR1-1-MAL1)
- Dogger Group («Brauner Dogger») including the Variansmergel Formation, the «Parkinsoni-Württembergica-Schichten» and the «Humphriesioolith Formation» (MAR1-1-BDO2) as well as the «Humphriesioolith Formation», the Wedelsandstein Formation and the «Murchisonae-Oolith Formation» (MAR1-1-BDO1)
- Dogger Group with a focus on Opalinus Clay (MAR1-1-OPA1, MAR1-1-OPA3 and MAR1-1-OPA2)
- Lias Group with a focus on Staffelegg Formation including Gross Wolf, Rietheim, Breitenmatt / Rickenbach, Grünschoholz and Frick Members (MAR1-1-LIA2) resp. including Breitenmatt / Rickenbach, Grünschoholz, Frick, Beggingen and Schambelen Members (MAR1-1-LIA1)
- Keuper Group with a focus on Klettgau Formation including Gruhalde, Seebi, Gansingen and Ergolz Members (MAR1-1-KEU1)
- Loss zones in the Muschelkalk Group resp. in the Schinznach Formation (MAR1-1-MUK1)

All hydraulic tests (except the GTPT) were performed in the cored borehole section with a borehole diameter of 6⅜", with 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 density and viscosity of the drilling fluid were reported by the mud engineer in daily mud reports. The tubing was typically filled with traced tap water (sodium-naphthionate, at a concentration of approximately 10 ppm); for the hydraulic test within the shales 1.5-naphthalene disulfonate acid (NDSA, 10 ppm) was used as the tracer. 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. It was possible to create flow from the formation into the borehole by means of slug and pumping tests only during the following tests: MAR1-1-MAL1, MAR1-1-BDO2, MAR1-1-BDO1, MAR1-1-OPA3, MAR1-1-OPA2, MAR1-1-KEU1 and MAR1-1-MUK1.

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 stator of the PC pump in the test string was optimised. 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).

For tests MAR1-1-KEU1 and MAR1-1-MUK1 drilling was stopped for hydraulic testing, especially for MAR1-1-MUK1 after significant mud losses. For the other tests, a longer section was drilled and then the hydraulic tests were performed. The curves of measured pressures (measured by the downhole sensors in the QSSP and the autonomous data logger in the interval) and pumping rates (measured by the flow board at the surface) for all tests conducted in borehole MAR1-1 are provided in Figs. 4-9 to 4-18. The figures are taken directly from the detailed reports (DR) of the field test contractor.

The temperature increase was included in the analysis for formations without a pumping period (low 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 0.05 °C to 5.1 °C for all tests.

Tab. 4-21: Hydraulic packer testing in borehole MAR1-1: test interval and test specifications

Test name ¹	Interval depth [m MD]	Interval midpoint [m MD]	Packer configuration	Test phases ¹	Testing period (duration)	Geological information [depth and length values rounded; groups and formations usually named from top down; for details see Dossier III]	Objectives ² [secondary aims in brackets ()]
MAR1-1-MAL1	335.63 – 352.62	344.13	Double	INF1, INF2, COM, PSR, PW, SW, SWS, RW1, RW2, RW3, RW4, RW5, MRS, DEF	29.02. – 04.03.2020 (82.8 h)	Malm Group with a focus on some inflow zones detected with the fluid logging in the «Felsenkalke» + «Massenkalk» (<i>cf.</i> Section 3.2).	T, h _s , (FM), WS
MAR1-1-BDO2	510.30 – 549.77	530.04	Double	INF, INF2, COM, PSR, PW, SW, SWS, PW2, DEF	14.04 – 18.04.2020 (84.1 h)	Dogger Group («Brauner Dogger»): mostly marls and clay- stones of the Variansmergel Formation (approx. 7.1 m), and of the «Parkinsoni-Württembergica-Schichten» (approx. 28.5 m); the approx. 3.8 m of «Humphriesioolith Formation» in the lowest section of the test interval consisted of a hetero- geneous iron-oolitic succession with marls and limestones. The hydraulic test was designed as an overview test.	T, h _s , FM
MAR1-1-BDO1	551.00 – 590.47	570.74	Double	INF1, INF2, COM, PSR, PW, SW, SWS, PW2, DEF	11.04. – 14.04.2020 (69.6 h)	Dogger Group («Brauner Dogger»): the approx. 4.2 m of «Humphriesioolith Formation» in the top section of the test interval consisted of a heterogeneous iron-oolitic succession with marls and limestones, followed by approx. 33.9 m of mostly argillaceous sandstones and siltstones of the Wedelsandstein Formation and approx. 1.3 m of «Murchisonae-Oolith Formation» with calcareous lithoclasts, iron-oids and abundant fossils. Designed as an overview test, hydraulic test MAR1-1-BDO1 includes a fault zone at a depth of 556 m.	T, h _s , FM
MAR1-1-OPA1	590.00 – 609.99	600.00	Double	INF1, INF2, COM, PSR, PW, PW2, PI, DEF	02.04. – 06.04.2020 (94.6 h)	Dogger Group with approx. 0.4 m of «Murchisonae-Oolith Formation» and approx. 19.6 m of Opalinus Clay. The test was designed to investigate a section with a variable clay content at the top of the Opalinus Clay as well as a fault zone at a depth of approx. 606 m depth.	T, h _s , FM
MAR1-1-OPA3 (GTPT interval)	617.00 – 622.30	619.65	Double	INF1, INF2, COM, PSR, PW, SW, SWS, DEF	21.04. – 25.04.2020 (93.2 h)	Dogger Group, test interval entirely within Opalinus Clay with a focus on a fault zone between approx. 620 and 621 m.	T, h _s , FM
MAR1-1-OPA2	666.50 – 705.97	686.24	Double	INF1, INF2, COM, PSR, SW, SWS, PW, DEF	07.04. – 11.04.2020 (91.2 h)	Dogger Group with approx. 38.9 m of Opalinus Clay and Lias Group with approx. 0.6 m of Staffelegg Formation. The test was designed to investigate the basal clay rich facies of the Opalinus Clay as well as a set of tectonic features between approx. 667 and 681 m depth.	T, h _s , FM

Tab. 4-21: continued

MAR1-1-LIA2	707.20 – 727.19	717.20	Double	INF1, INF2, COM, PSR, PW, PI, DEF	30.03. – 02.04.2020 (66.7 h)	Lias Group, test interval entirely within Staffelegg Formation (approx. 4.9 m of Gross Wolf Member, approx. 9.4 m of Rietheim Member, approx. 2.6 m of Breitenmatt and Rickenbach Members, approx. 1.1 m of Grünschholz Member and approx. 2.1 m of Frick Member) mainly consisting of marls, claystones, bituminous shales and limestones. The test was designed to investigate mainly the marly facies of the Staffelegg Fm.	T, h _s , FM
MAR1-1-LIA1	723.00 – 742.99	733.00	Double	INF1, INF2, COM, PSR, PW, PI, DEF	27.03. – 30.03.2020 (84.3 h)	Lias Group, test interval entirely within Staffelegg Formation (approx. 1.1 m of Breitenmatt and Rickenbach Members, approx. 1.1 m of Grünschholz Member, approx. 12.6 m of Frick Member, approx. 4.2 m of Beggingen Member and approx. 1.0 m of Schambelen Member) mainly consisting of silty claystones, limestones and marls. The test was designed to investigate the clay rich part of the Staffelegg Formation as well as the carbonate-rich rocks of the Beggingen Member.	T, h _s , (FM)
MAR1-1-KEU1	755.15 – 789.13	772.14	Double	PRE0, INF2, INF1, COM, PSR, PW, SW, SWS, SW2, SWS2, PW2, DEF	22.05. – 24.05.2020 (47.5 h)	Keuper Group, test interval entirely within Klettgau Formation (approx. 18.4 m of Gruhalde Member, approx. 9.0 m of Seebi Member, approx. 1.6 m of Gansingen Member and approx. 5.1 m of Ergolz Member) to target possibly transmissive zones. Rocks within the test interval mainly consist of argillaceous and dolomitic marls, dolostones and some dolomitic breccias and sandstones as well as (especially towards to lower section of the test interval) anhydrites.	T, h _s , (FM)
MAR1-1-MUK1	821.20 – 877.00	849.10	Single	INF, COM, MR1, MR2, MRS, DEF	31.05. – 04.06.2020 (85.7 h)	Keuper Group with approx. 41.3 m of Bänkerjoch Formation (mainly consisting of anhydrites, claystones and marls) and in Muschelkalk Group with approx. 14.5 m of Schinznach Formation including approx. 5.1 m of Asp Member (mainly consisting of dolostones and bituminous shales) and approx. 9.4 m of Stamberg Member (mainly consisting of dolostones) with pronounced loss zones. The test was conducted after important mud losses were detected in the Schinznach Formation. The upper packer was installed in the Bänkerjoch Formation to ensure the tightness of the test interval.	(T), h _s , (FM), WS

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

² FM = flow model, T = transmissivity, h_s = static hydraulic head, WS = water sample (strikethrough if the target was not reached).

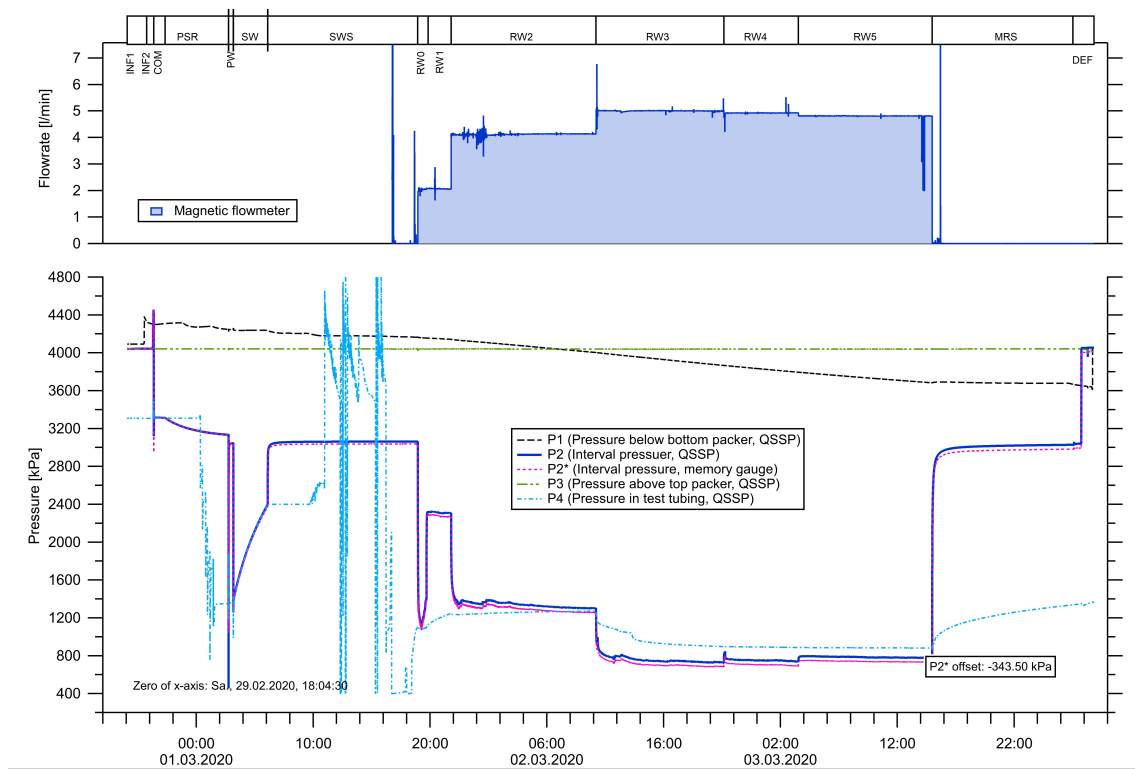


Fig. 4-9: Hydraulic packer test MAR1-1-MAL1: Overview plot of pressure vs. time and date

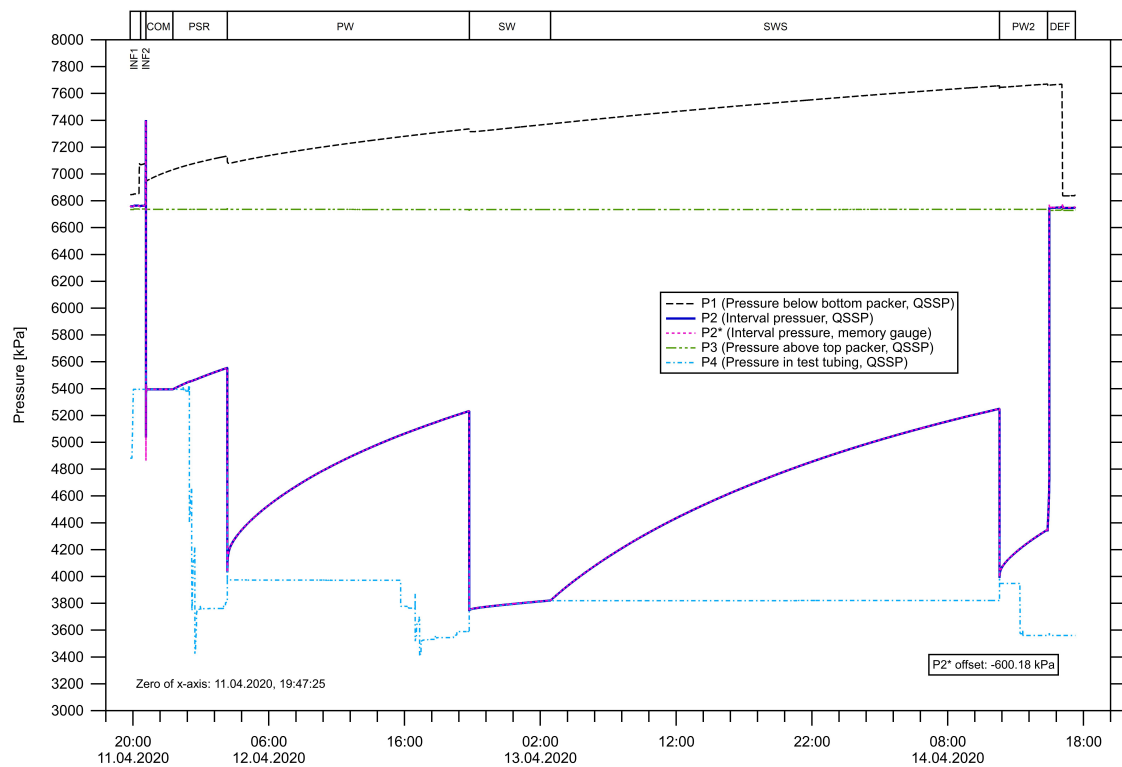


Fig. 4-10: Hydraulic packer test MAR1-1-BDO1: Overview plot of pressure vs. time and date

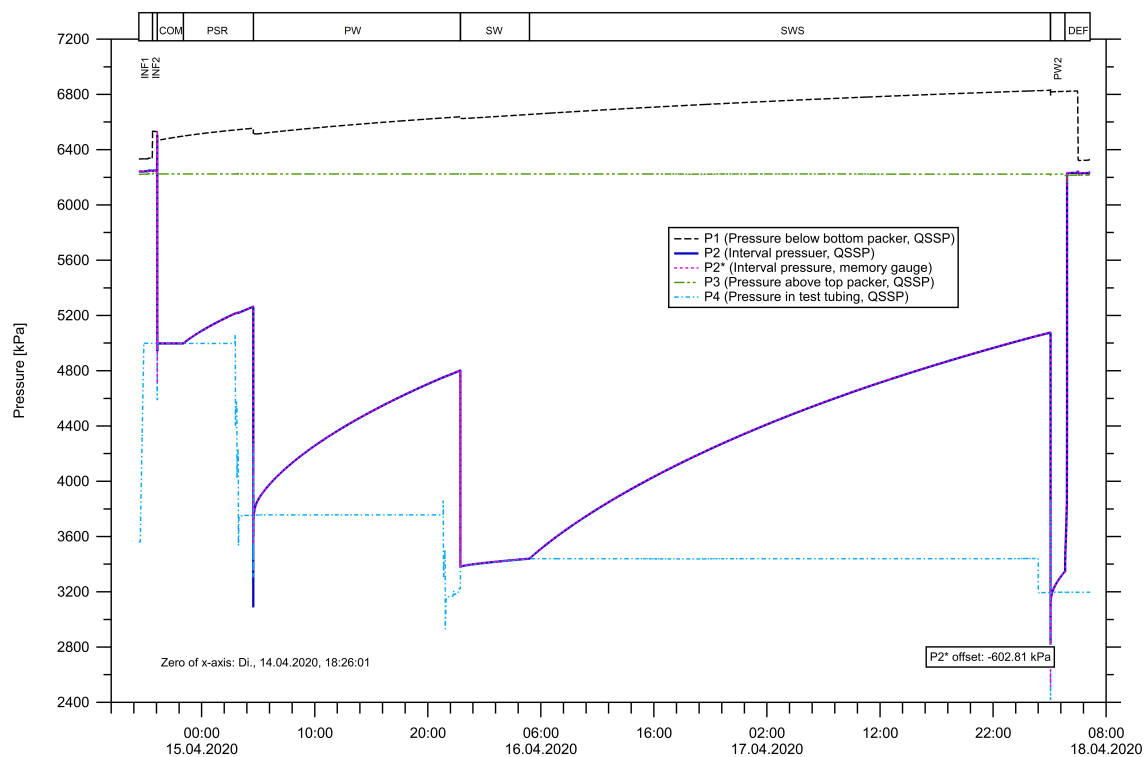


Fig. 4-11: Hydraulic packer test MAR1-1-BDO2: Overview plot of pressure vs. time and date

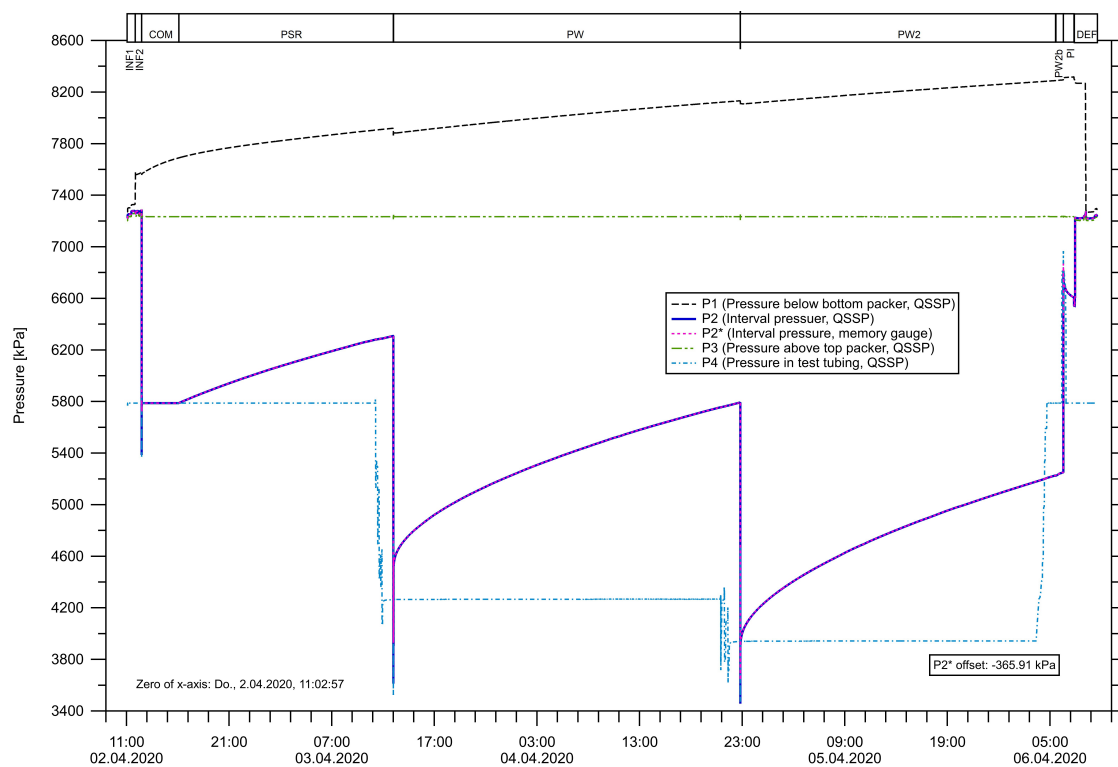


Fig. 4-12: Hydraulic packer test MAR1-1-OPA1: Overview plot of pressure vs. time and date

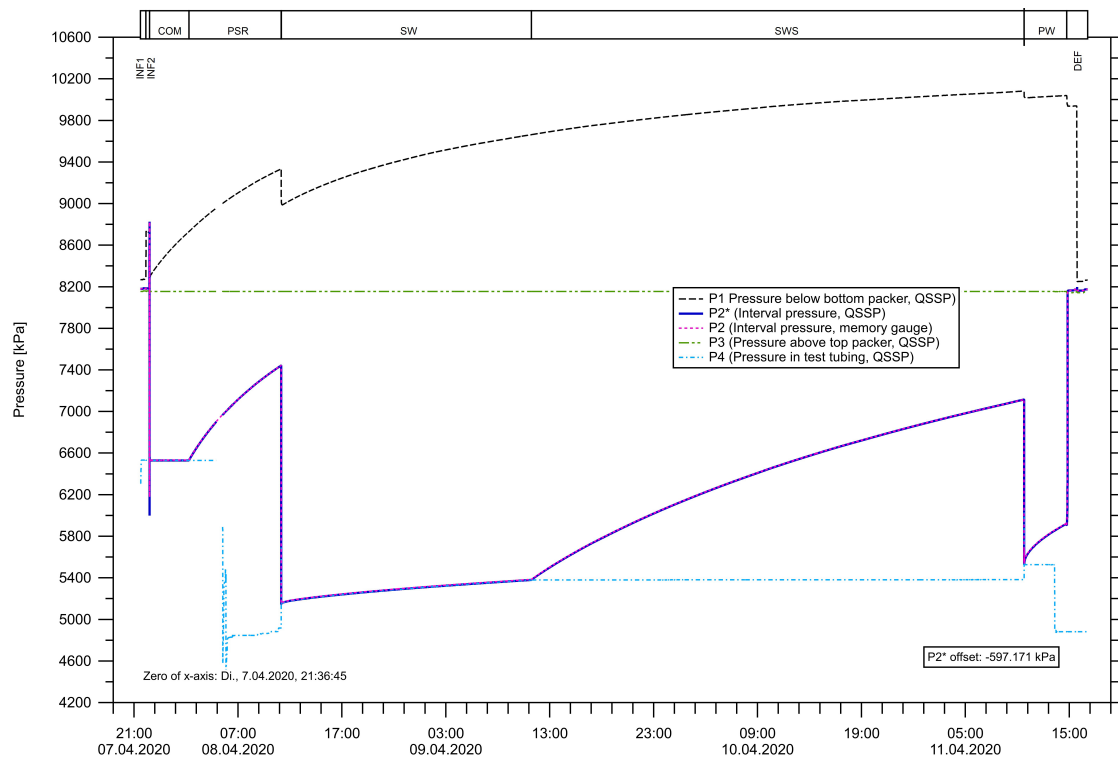


Fig. 4-13: Hydraulic packer test MAR1-1-OPA2: Overview plot of pressure vs. time and date

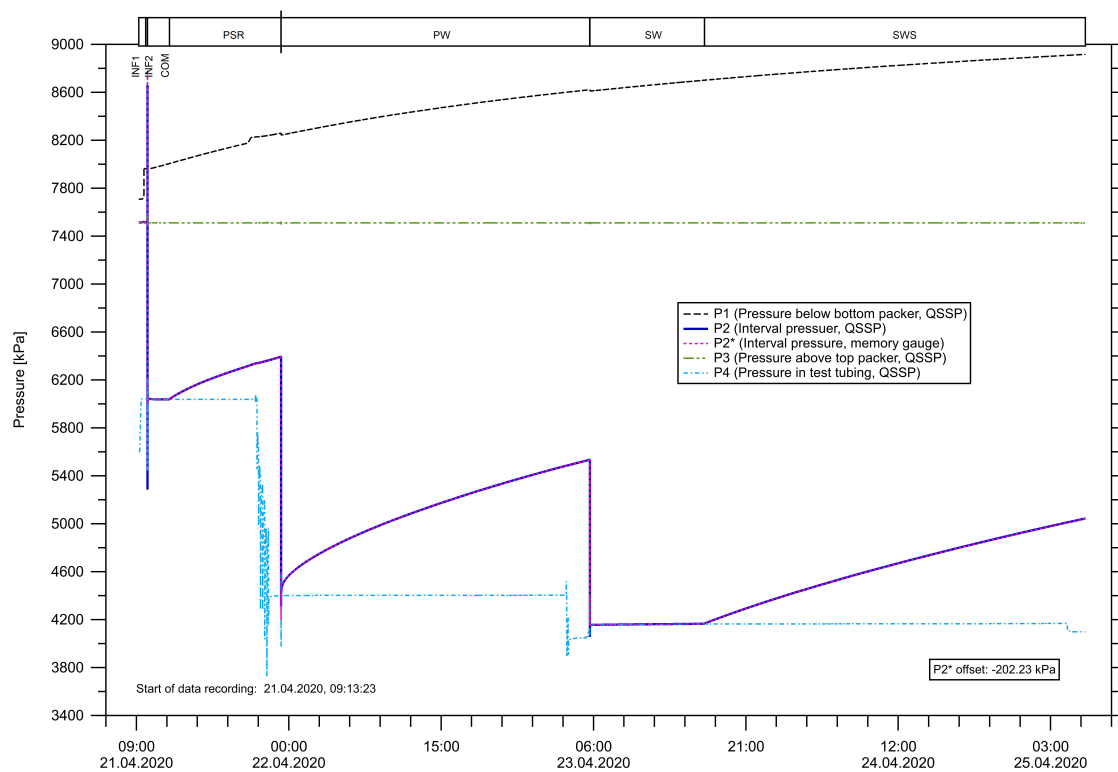


Fig. 4-14: Hydraulic packer test MAR1-1-OPA3: Overview plot of pressure vs. time and date

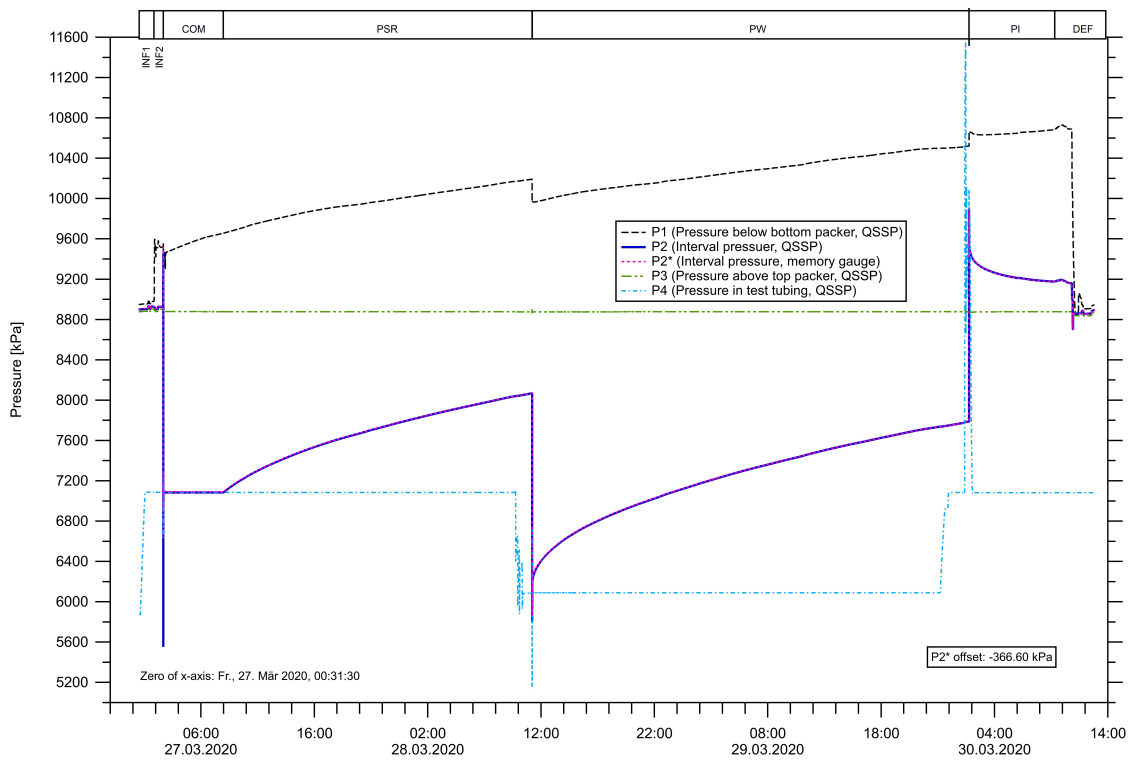


Fig. 4-15: Hydraulic packer test MAR1-1-LIA1: Overview plot of pressure vs. time

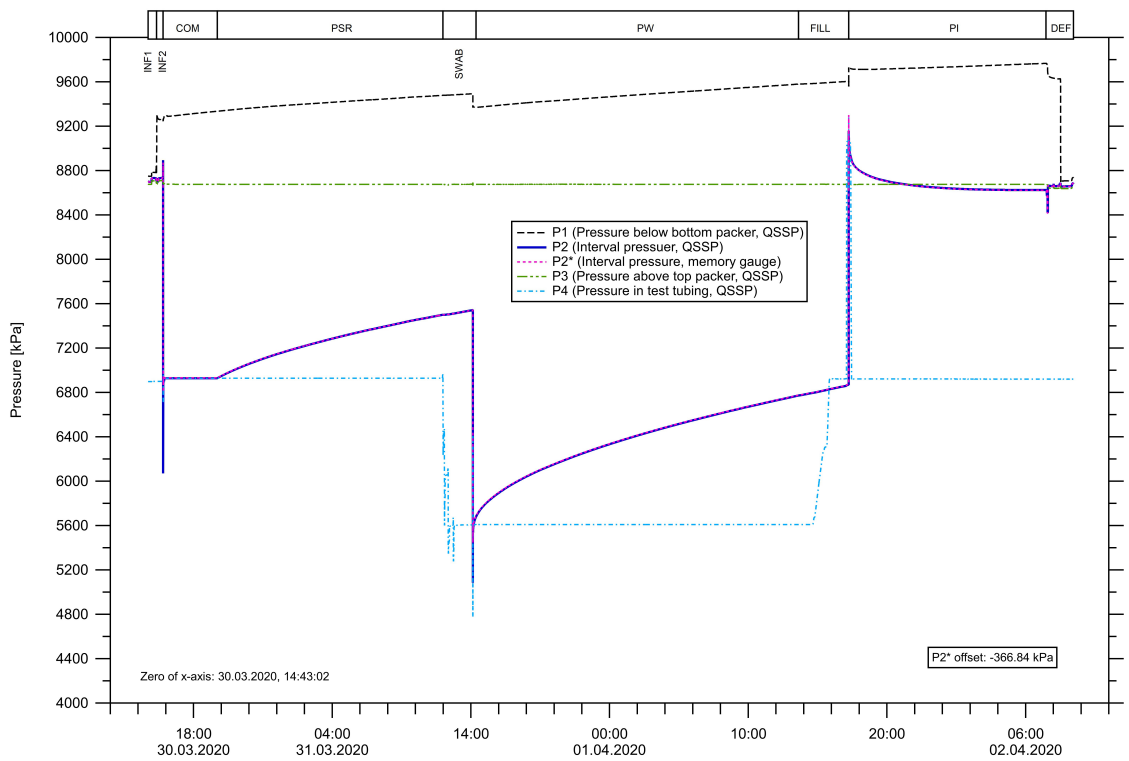


Fig. 4-16: Hydraulic packer test MAR1-1-LIA2: Overview plot of pressure vs. time

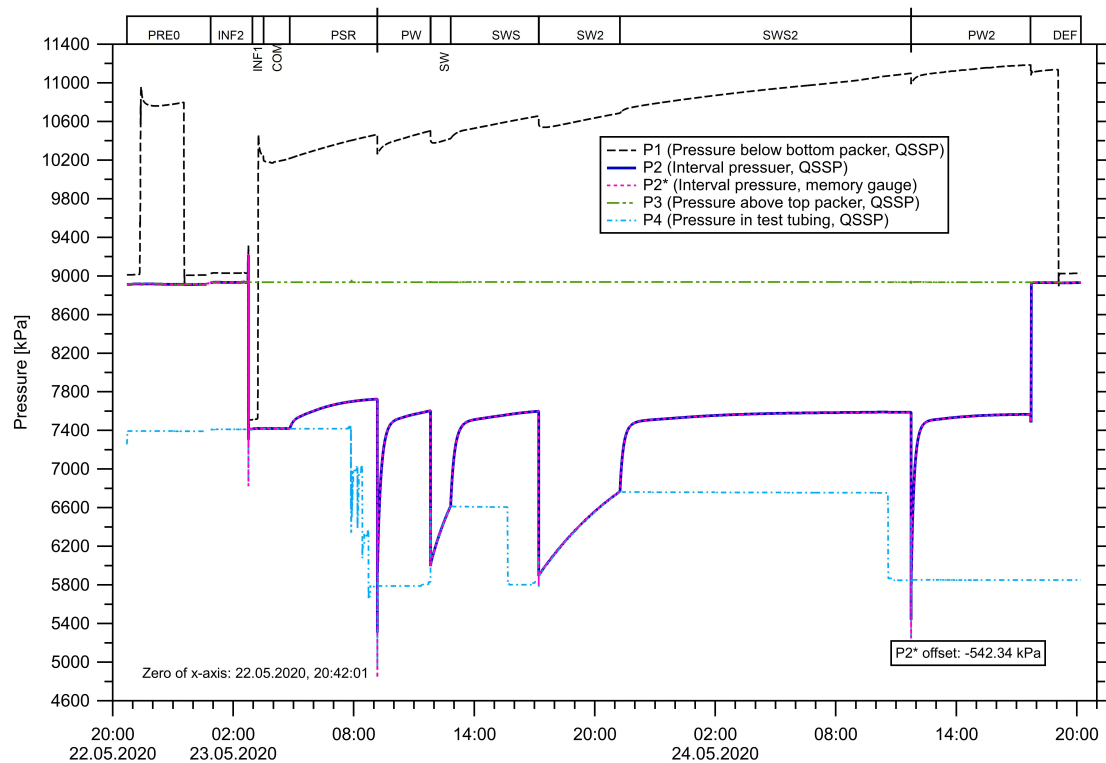


Fig. 4-17: Hydraulic packer test MAR1-1-KEU1: Overview plot of pressure vs. time

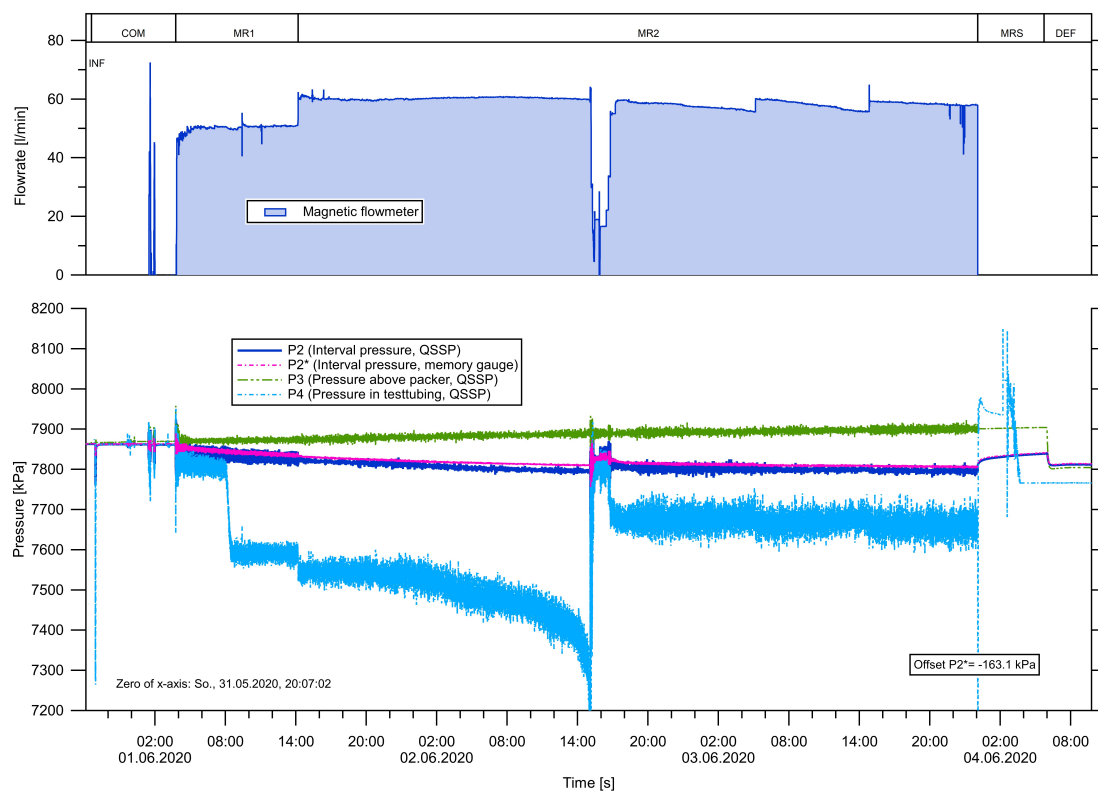


Fig. 4-18: Hydraulic packer test MAR1-1-MUK1: Overview plot of pressure vs. time and date

4.5 Details of selected tests

Two of the hydraulic packer tests are presented below in more detail: MAR1-1-LIA1 and MAR1-1-LIA2. Both hydraulic packer tests were focused on the estimation of formation parameters of the Lias, the Staffelegg Formation, under undisturbed conditions. The main differences between the two tests are the duration of the pressure history period prior to the hydraulic test (LIA1: 167 h; LIA2: 270 h) and the duration of the test execution (LIA1: 84 h; LIA2: 67 h). The main phase of both tests was a pulse phase focussing on the low transmissivity of the undisturbed Staffelegg Formation.

The selected examples examine the potential impact of the hydraulic test duration and pressure history duration on the estimation of formation parameters, i.e. the uncertainty associated with these two influencing factors. They show the applied analysis strategy and how the influence of different effects on, e.g. packer pressure changes due to surface temperature changes, interval temperature changes during testing and borehole pressure history are handled. The results of the two test analyses are provided in the summary chapter (Chapter 5) together with the results of all other tests performed.

4.5.1 Hydraulic packer test MAR1-1-LIA1

The hydraulic packer test MAR1-1-LIA1 represents an example of testing formations with low transmissivity with a moderate pressure history duration and a standard hydraulic test execution duration.

4.5.1.1 Interval characterisation

The hydraulic test MAR1-1-LIA1 was performed in a double packer configuration. The entire interval is located in the Staffelegg Formation of the Lias Group. The test interval was selected because it is located in the undisturbed layer of the Staffelegg Formation. The test interval covers part of the Breitenmatt and Rickenbach Members (721.48 – 724.08 m MD), the Grünschholz Member (724.08 – 725.13 m MD), the Frick Member (725.13 – 737.74 m MD), the Beggingen Member (737.74 – 741.98 m MD) and parts of the Schambelen Member (741.98 – 747.83 m MD). The primary test objectives were to obtain reliable estimates of T (and K) for the formation, the freshwater hydraulic head and if possible, to also take a water sample. Details of the interval and test duration are provided in Tab. 4-22.

Tab. 4-22: Hydraulic test MAR1-1-LIA1: Information on the test interval

Test	Depth		Length [m]	Packer confi- guration	Hydraulic testing		
	from [m MD]	to [m MD]			Start date	End date	Duration [h]
MAR1-1-LIA1	723.00	742.99	19.99	Double	27.03.2020	30.03.2020	84.3

4.5.1.2 Test execution

Fig. 4-19 shows the system installation record as provided by the field test contractor. The equipment components are those described above.

After installation, the first three tubing joints were filled with traced freshwater (10 ppm of 1.5-NDSA solution), and the packer system was pulled back as much as possible from the rig floor. After the shut-in tool (SIT) was opened to release the air, the HDDP was lowered to the test interval position, with regular checks every 10 tubing joints so that the tubing could be filled with traced freshwater and a communications' check between the gauges and the DAS could be performed. The test was started by inflating the bottom packer (INF1) followed by the inflation of the top packer (INF2) using a 2:1 mixture of anti-freeze water. The SIT was opened when the top packer began to isolate the interval volume. The COM phase lasted 5.3 h before the SIT was again closed to initiate the PSR phase. The PSR phase lasted 27.3 h. After the PSR phase, a pulse withdrawal (PW) was initiated. The PW phase lasted for 38.5 h. The PW test was terminated by initiation of a pulse injection test (PI), duration 7.6 h. Due to packer pressure instabilities during the entire test, a test sequence was started with stepwise packer inflation and deflation to establish a basis for estimating the effect of the packer pressure changes on the measurement in the interval. The subsequent deflation (DEF) of the packers was carried out with the SIT closed. In the following, the SIT remained closed for the relocation of the HDDP to the subsequent test interval MAR1-1-LIA2.

Installation Record - Double Packer + Moyno Pump

SOLEXPERTS

HDDP Packertests				Location	Marthalen	Date	25.03.2020	Engineer	AK
Borehole	MAR1-1	Direction	vertical	Reference point (= GL)	399.48 m asl	Interval	LIA1	JOB Nr.	2666
Borehole Depth	750.0 m	Casing Depth	308 m bgl	Interval length	19.99 m	Test depth (UPLS)	723.00 m bgl	System	HDDP 114 ▼
Borehole Diameter	161.93 mm	Stickup b. Rig floor	-2.45 m	Water depth	m bgl	Test file	MAR1_1_LIA1	Quadro Probe	QSSP 3 ▼

Note: All depths shown are not correct for borehole deviation

		Qty	L unit	L total	Depth	OD	ID	Wgt	Str	Comments:
		-	m	m	m	mm	mm	kg	t	
Rig floor										
Wellhead, Wellhead equipment (not shown)										
Stickup										
Ground level (GL)										
Tubing 2"7/8 EU										
Tubing extension										
Moyno-Pump										
Stator										
Stop Pin										
Tubing 2"7/8 EU										
2 x Siphon + X-Over										
SIT 2"7/8 DAS										
SIT										
DAP										
Cable Base incl. Coupling + Crown Shaft										
QSSP P3										
QSSP P4										
QSSP P2										
QSSP P1										
Crown Shaft incl. 1 X-Over										
Safety Joint incl. X-Over										
Packer Stick Up / Above Side Entry Sub										
UPUS										
Upper Packer										
UPLS										
Packer Stick Down										
Packer Stick Up / Above Side Entry Sub										
X-Over										
Tubing 2"7/8 EU (Tally list 1)										
X-Over										
X-Over										
Filter										
Screen										
X-Over										
P1-Seal Sub										
Inkl. 2 X-Over for Tubing 2"7/8 u. Filter										
Packer Stick Up										
LPUS										
Lower Packer										
LPLS										
Packer Stick Down										
Bottom Cap										
End of Borehole (m bgl):										
Total Weight (kg):										

Fig. 4-19: Hydraulic test MAR1-1-LIA1: Downhole equipment installation record with system layout as used in the field tests

4.5.1.3 Analysis

Borehole pressure history

The borehole history used for the analysis of the MAR1-1-LIA1 tests is shown in Fig. B-1 (see Appendix B) and summarised in Tab. 4-23. The calculation of the mean interval fluid density using the measurement of the P2 pressure sensor (prior to packer inflation) gives a density of 1'257.9 kg/m³. This value corresponds to the documented density of the drill mud during drilling (1'250 kg/m³, see Dossier I) and was used as the drill mud density to calculate the pre-test borehole pressure history. For periods without a water table measurement, the water level was assumed to be at the level of the drain pipe of -1.95 m MD, because for periods with no active mud circulation, the drillers generally kept the borehole full to the level of the drain pipe. Unfortunately, during the petrophysical loggings, micro-hydraulic fracturing (MHF) tests and the blow out preventer (BOP) test, no additional water level measurements were documented. Once the HDDP was at test depth and data acquisition began, the P2 gauge measured pressure directly.

Tab. 4-23: Hydraulic test MAR1-1-LIA1: Borehole pressure history

¹ Interval pressure at P2 sensor level (719.22 m MD) calculated from the history information, e.g. fluid level and density

² Drilling through interval midpoint (733.00 m MD)

Description	Start date and time	Duration [h] Total: 167.3	Pressure ¹ [kPa]	
			Start	End
Drilling	19.03.2020 07:05 ²	17.9	8'903	8'903
Petrophysical logging	20.03.2020 12:30	43.5	8'903	8'903
Micro-hydraulic fracturing (MHF) tests	22.03.2020 08:00	63.2	8'903	8'903
Petrophysical logging	24.03.2020 23:15	5.8	8'903	8'903
Pull out of hole (POOH) auxiliary casing	25.03.2020 05:00	11.5	8'903	8'903
Blow out preventer (BOP) test	25.03.2020 16:30	14.5	8'903	8'903
Run in hole (RIH) HDDP	26.03.2020 13:39	10.9	8'903	8'901
Start testing MAR1-1-LIA1	27.03.2020 00:31	-	8'901	

Flow model evaluation

The hydraulic test sequence was analysed using a radial homogeneous flow model. This model approach was based on the flow model analysis of the PSR phase. The PSR phase of MAR1-1-LIA1 was the only test phase used for a flow model diagnostics. Fig. B-2 shows a log-log diagnostic graph (Bourdet et al. 1989) of the PSR phase. The diagnostic graph shows a long-lasting period of almost four log cycles dominated by wellbore storage. After three to four log cycles, the pressure curve and derivative slowly start to flatten, indicating the beginning of the transition phase towards a formation response. However, a clear indication of an infinite acting radial flow region (IARF) and the flow model could not be established. Hence, a radial homogeneous flow model as well as a radial composite flow model will be used. Due to the short duration of single

test phases, the analysis focused on a radial homogeneous flow model. A radial composite model, that could incorporate a potential skin zone around the borehole, was investigated once, without confirming the necessity for this model (including the skin zone).

Analysis of the pulse phases (PW-PI)

The analysis of the pulse phases was based on a parameter optimisation using a radial homogeneous flow model. Tab. 4-24 presents the resulting formation parameter estimates (hydraulic conductivity K , specific storage S_s and static formation pressure P_f). Fig. B-3 presents the resulting simulation considering only the borehole pressure history.

Tab. 4-24: Hydraulic test MAR1-1-LIA1: Formation parameter estimation based on a radial homogeneous model considering only the borehole pressure history

PW-PI results	K [m/s]	S_s [1/m]	P_f [kPa]
Radial homogeneous model considering only the borehole pressure history	9.7×10^{-14}	2.2×10^{-6}	9'932

Consideration of possible influences on the formation parameter estimates

The following factors can possibly influence the estimation of the formation parameters and were taken into consideration:

1. Influence of interval temperature changes during the test phases
2. Influence of packer pressure changes due to surface temperature changes
3. Influence of the borehole pressure history
4. Influence of uncertain estimations of the wellbore storage

The influence of interval temperature changes was studied via a parameter optimisation taking into consideration the measured temperature changes inside the test interval. The measured temperature range recorded by the memory gauge sensor T2* was between 42.8 °C and 43.1 °C. Fig. B-4 shows the measurement in comparison with the pressure measurement during MAR1-1-LIA1. Tab. 4-25 shows the resulting formation parameter estimates. Fig. B-5 presents the resulting simulation with the borehole pressure history and the interval temperature change observed.

Tab. 4-25: Hydraulic test MAR1-1-LIA1: Formation parameter estimations based on a radial homogeneous model, taking into consideration the borehole pressure history and the observed interval temperature change

PW-PI results	K [m/s]	S_s [1/m]	P_f [kPa]
Radial homogeneous model considering the borehole pressure history and interval temperature change	7.8×10^{-14}	2.8×10^{-6}	10'085

The influence of packer pressure changes on the interval volume were studied by a sequence of stepwise packer inflation and deflation at the end of the hydraulic test MAR1-1-LIA1. The resulting interval volume changes due to changes in surface temperature were considered in the numerical simulation by a variation of the borehole radius. Fig. B-6 shows the manipulation of the borehole radius in comparison to the interval volume changes (caused by the surface temperature induced packer pressure changes) and the sensor P2 pressure measurement. Tab. 4-26 presents the results of the formation parameter estimates. Fig. B-7 shows the resulting simulations considering the borehole pressure history, interval temperature and observed packer pressure changes.

Tab. 4-26: Hydraulic test MAR1-1-LIA1: Formation parameter estimation based on a radial homogeneous model taking into consideration the borehole pressure history and the observed interval temperature and packer pressure changes

PW-PI results	K [m/s]	Ss [1/m]	P _r [kPa]
Radial homogeneous model considering the borehole pressure history, interval temperature and packer pressure changes	8.8×10^{-14}	2.4×10^{-6}	9'991

The influence of the borehole pressure history was studied by using a set of parameter optimisations based on different assumptions for the mud density value prior to the hydraulic test MAR1-1-LIA1. The mud density was varied within a range of $\pm 5\%$ ($1'195 \text{ kg/m}^3 - 1'321 \text{ kg/m}^3$). The resulting ranges of the formation parameter estimates are provided in Tab. 4-27.

Tab. 4-27: Hydraulic test MAR1-1-LIA1: Range of formation parameter estimates based on a radial homogeneous model that considers mud density variation prior to hydraulic testing of $\pm 5\%$

PW-PI results	K [m/s]	Ss [1/m]	P _r [kPa]
Estimate range	$7.7 \times 10^{-14} - 7.9 \times 10^{-14}$	$2.7 \times 10^{-6} - 2.8 \times 10^{-6}$	9'863 – 10'304

A negative correlation exists between the mud density and all formation parameter estimates. A graph of the simulations representation in Cartesian coordinates is presented in Fig. B-8.

The influence of uncertainties in the wellbore storage estimates was studied by a sampling analysis of the non-fitting parameter of the test zone compressibility (c_{tz}). The lower and upper bound for the sampling analysis of the c_{tz} value was defined to $4.3 \times 10^{-10} \text{ 1/Pa}$ and $9.3 \times 10^{-10} \text{ 1/Pa}$. This corresponds to a significant extension of the range given by the estimated test zone compressibility at the beginning of the PW and PI phase of MAR1-1-LIA1. The resulting ranges for the formation parameter estimates are provided in Tab. 4-28. The best estimate for the test zone compressibility of the PW phase was $7.8 \times 10^{-10} \text{ 1/Pa}$ (associated with the lowest sum of squared errors, SSE) with an uncertainty range from $5.8 \times 10^{-10} \text{ 1/Pa}$ to $8.3 \times 10^{-10} \text{ 1/Pa}$. Fig. B-9 presents the results of the sampling analysis of the PW phase. For the PI phase the best estimate was $4.9 \times 10^{-10} \text{ 1/Pa}$ (associated with the lowest SSE) with an uncertainty range from $4.6 \times 10^{-10} \text{ 1/Pa}$ to $6.2 \times 10^{-10} \text{ 1/Pa}$. Fig. B-10 presents the results of the sampling analysis of the PI phase.

Tab. 4-28: Hydraulic test MAR1-1-LIA1: Range of the formation parameter estimates resulting from the sampling analysis of the test zone compressibility

Results	K [m/s]	S _s [1/m]	P _f [kPa]
Estimate range for PW	$6.2 \times 10^{-14} - 8.8 \times 10^{-14}$	$2.2 \times 10^{-6} - 4.0 \times 10^{-6}$	9'790 – 11'000
Estimate range for PI	$5.0 \times 10^{-14} - 8.8 \times 10^{-14}$	$2.4 \times 10^{-6} - 4.0 \times 10^{-6}$	9'950 – 11'000

Estimates of values and uncertainty ranges of the formation parameters

Finally, a perturbation analysis of 500 runs was performed to investigate the characteristics of the formation parameter estimates, i.e. to verify that the solution corresponds to a global minimum in the parameter space (formation hydraulic conductivity, storage and the static formation pressure). 483 runs were selected as appropriate to provide the resulting range of estimates by a least squared error threshold value of 1.27×10^{10} . Fig. B-11 shows the resulting formation parameter estimates in comparison to their associated least squared error, sorted by the least squared error values of the single parameter optimisation results. Tab. 4-29 presents the resulting formation parameter estimates associated with the lowest least squared error. The values correspond to the previous results derived using the radial homogeneous flow model that included borehole pressure history, interval temperature and packer pressure changes (see Tab. 4-26). The associated simulation results are shown in Fig. B-12.

Tab. 4-29: Hydraulic test MAR1-1-LIA1: Formation parameter estimates for the perturbation analysis of the PW-PI associated with the lowest least squared error value

PW-PI results	K [m/s]	S _s [1/m]	P _f [kPa]
Radial homogeneous model considering the borehole pressure history and interval temperature	7.8×10^{-14}	2.8×10^{-6}	10'085

The ranges for the formation parameter estimates resulting from the perturbation analysis are smaller than the 95% confidence intervals of the parameter optimisation provided in Tab. 4-30. The correlations and the confidence interval are presented in Fig. B-13.

Tab. 4-30: Hydraulic test MAR1-1-LIA1: 95% confidence intervals for the formation parameter estimates of the parameter optimisation considering a radial homogeneous model including the borehole pressure history and interval temperature change

Results	K [m/s]	S _s [1/m]	P _f [kPa]
95% confidence intervals	$7.6 \times 10^{-14} - 8.0 \times 10^{-14}$	$2.6 \times 10^{-6} - 2.9 \times 10^{-6}$	10'059 – 10'111

Based on the analyses performed, the values for the formation parameter estimates and their uncertainties are summarised in Tab. 4-31.

Tab. 4-31: Hydraulic test MAR1-1-LIA1: Best estimates of the formation parameters and associated uncertainty ranges

Results	K [m/s]	S _s [1/m]	P _f [kPa]
Best estimate	7.8×10^{-14}	2.8×10^{-6}	10'085
Uncertainty range	$5.0 \times 10^{-14} - 8.8 \times 10^{-14}$	$2.2 \times 10^{-6} - 4.0 \times 10^{-6}$	9'790 – 11'000

Confirmation simulation of the flow model

One parameter optimisation including the PSR phase was conducted to confirm the result of the estimate of the PW-PI phase. The resulting formation parameter estimates are in good agreement with the parameter set calculated for the PW-PI phase (Tab. 4-32). Fig. B-14 shows the simulation results that were judged as good for the PSR and PW phases and reasonable for the PI phase.

Tab. 4-32: Hydraulic test MAR1-1-LIA1: Results for the numerical simulation of the PSR-PW-PI test sequence using a radial homogeneous model including the borehole pressure history and interval temperature changes

PSR-PW-PI results	K [m/s]	S _s [1/m]	P _f [kPa]
Radial homogeneous model considering the borehole pressure history and interval temperature	7.8×10^{-14}	2.9×10^{-6}	10'122

4.5.2 Hydraulic packer test MAR1-1-LIA2

The hydraulic packer test MAR1-1-LIA2 represents an example of testing in formations with low transmissivity, a moderate pressure history duration and a short hydraulic test duration.

4.5.2.1 Interval characterisation

The hydraulic test MAR1-1-LIA2 was performed in a double packer configuration. The entire interval is located in the Staffelegg Formation of the Lias Group. The test interval was selected because it is located in an undisturbed layer of the Staffelegg Formation. The test interval covers part of the Gross Wolf Member (705.40 – 712.10 m MD), the Rietheim Member (712.10 – 721.48 m MD), the Breitenmatt and Rickenbach Members (721.48 – 724.08 m MD), the Grünschholz Member (724.08 – 725.13 m MD) and parts of the Frick Member (725.13 – 737.74 m MD). The primary test objectives were to obtain reliable estimates of T (and K) for the formation, the associated flow model, and the freshwater hydraulic head. Details of the interval and test duration are provided in Tab. 4-33.

Tab. 4-33: Hydraulic test MAR1-1-LIA2: Test interval information

Test	Depth		Length [m]	Packer confi- guration	Hydraulic testing		
	from [m MD]	to [m MD]			Start date	End date	Duration [h]
MAR1-1-LIA2	707.20	727.19	19.99	Double	30.03.2020	02.04.2020	66.7

4.5.2.2 Test execution

Fig. 4-20 shows the system installation record as provided by the field test contractor. The equipment components are those described above.

The test in interval MAR1-1-LIA2 was performed after the completion of the test MAR1-1-LIA1. After the final DEF event of MAR1-1-LIA1, the system was moved upwards by 15.80 m to the position of MAR1-1-LIA2. The shut-in tool (SIT) remained closed during relocation. The test was started by inflating the bottom packer (INF1) followed by inflation of the top packer (INF2) using a 2:1 mixture of anti-freeze:water. The SIT was opened when the top packer began to isolate the interval volume. The COM phase lasted 3.9 h, after which the SIT was again closed to initiate the PSR phase. The PSR phase lasted 18.4 h. After the PSR phase, a pulse withdrawal (PW) was initiated and the phase lasted for 26.9 h. The PW test was terminated by initiation of a pulse injection test (PI) that lasted for 14.2 h. The subsequent deflation (DEF) of the packers was carried out with the SIT closed. After sufficient backflow of the packer fluid, the test system was relocated to the subsequent test interval MAR1-1-OPA1.

Installation Record - Double Packer + Moyno Pump				SOLEXPERTS			
				Seite 1 / 4			
HDDP Packertests				Location	Marthalen	Date	30.03.2020
				Reference point (= GL)	399.48 m asl	Interval	LIA2
Borehole	MAR1-1	Direction	vertical	Interval length	19.99 m	Test depth (UPLS)	707.20 m bgl
Borehole Depth	750.0 m	Casing Depth	308 m bgl	Water depth	1.07 m bgl	Testfile	MAR1_1_LIA2
Borehole Diameter	161.93 mm	Stickup b. Rig floor	-2.18 m			Quadro Probe	QSSP 3
Job Nr.				MaW			
System				HDDP 114			
Note: All depths shown are not correct for borehole deviation							
Qty	L unit	L total	Depth	OD	ID	Wgt	Str
		m	m	mm	mm	kg	t
Rig floor	-2.84						
Wellhead, Wellhead equipment (not shown)							
Stickup	-5.02 m bgl						
Ground level (GL)			0.00	93.2	62.0	0	
Tubing 2"7/8 EU	Tally list 3						
	Tubing extension			93.2	62.0		
Moyno-Pump	Stator	0	702.90	78.6 (93.2)	0.0	0	45
	Stop Pin	0	0.00	-5.02	78.6	62.0	
Tubing 2"7/8 EU	Tally list 2	77	702.90	697.88	93.2	62.0	6953
	2 x Siphon + X-Over	1	1.80	698.36	93.2		
SIT 2"7/8 DAS	SIT	1	0.66	106.0	24.0	69	
	DAP	1	1.17				
Cable Base incl. Coupling + Crown Shaft		1	1.31	105.0	24.0		
Probe Carrier with Quadruple Probe	QSSP P3		0.53	703.15			16.0
	QSSP P4		0.13	703.27			
	QSSP P2		0.14	703.42			
	QSSP P1		0.63	703.61			
Crown Shaft incl. 1 X-Over		1	0.40	100.0	40.0		
Safety Joint incl. X-Over			0.79	93.0	62.0		90.0
Packer Stick Up / Above Side Entry Sub			0.37				
	UPUS		0.20	706.00			
Up. Packer	Upper Packer	1	1.20	114.0	32.0	67	
	UPLS		0.26	707.20			
Packer Stick Down			0.05				
Packer Stick Up / Above Side Entry Sub			0.20	66.0	32.0		
X-Over		1	0.08	80.0	60.0	3	
Tubing 2"7/8 EU (Tally list 1)		4	16.93	93.2	62.0	164	
X-Over		1	0.05	93.5	512	3	
X-Over		1	0.25				
Filter	Screen	1	1.00	89.0	50.0	19	
X-Over		1	0.05				
P1-Seal Sub	Incl. 2 X-Over für Tubing 2"7/8 u. Fil		0.32	78	--		
Packer Stick Up			0.11				
	LPUS		0.26	727.19			
Lower Packer Seal	Lower Packer	1	1.20	114.0	32.0	78	
	LPLS		0.26	728.39			
Packer Stick Down			0.11	728.91			
Bottom Cap			0.16	95.0	--		
End of Borehole (m bgl):				750.00	Total Weight (kg): 7491		

Fig. 4-20: Hydraulic test MAR1-1-LIA2: Downhole equipment installation record with system layout as used in the field tests

4.5.2.3 Analysis

Borehole pressure history

The borehole history used for the analysis of the MAR1-1-LIA2 tests is shown in Fig. B-15 and summarised in Tab. 4-34. The calculation of the mean interval fluid density using the P2 pressure sensor measurement (prior to packer inflation) gives a density of 1'257.6 kg/m³. This value corresponds to the documented density of the drill mud during drilling (1'250 kg/m³, see Dossier I) and to the measurement prior to the packer inflation of the hydraulic test MAR1-1-LIA1. It was used as drill mud density to calculate the pre-test borehole pressure history. For periods without a water table measurement, the water level was assumed to be at the level of the drain pipe of -1.95 m MD, because for periods with no active mud circulation, the drillers generally kept the borehole full up to the level of the drain pipe. Unfortunately, during the petrophysical loggings MHF tests and the BOP test, no additional water level measurements were documented. Once the HDDP was at test depth and data acquisition began first for the hydraulic test MAR1-1-LIA1 and after the relocation of the HDDP, the P2 gauge measured pressure directly. The pressure measurements of the annulus during MAR1-1-LIA1 (P3) were corrected to the depth of P2 (MAR1-1-LIA2).

Tab. 4-34: Hydraulic test MAR1-1-LIA2: Borehole pressure history

- ¹ Interval pressure at P2 sensor level (703.42 m MD) calculated from the history information, e.g. fluid level and density
² Drilling through interval midpoint (717.20 m MD)
³ Including the time of relocation of HTTP between MAR1-1-LIA1 and MAR1-1-LIA2

Description	Start date and time	Duration [h] Total: 270.5	Pressure ¹ [kPa]	
			Start	End
Drilling	18.03.2020 14:04 ²	34.9	8'706	8'706
Petrophysical logging	20.03.2020 12:30	43.5	8'706	8'706
MHF tests	22.03.2020 08:00	63.2	8'706	8'706
Petrophysical logging	24.03.2020 23:15	5.8	8'706	8'706
POOH auxiliary casing	25.03.2020 05:00	11.5	8'706	8'706
BOP test	25.03.2020 16:30	14.5	8'706	8'706
RIH HDDP	26.03.2020 13:39	10.9	8'706	8'706
Start testing MAR1-1-LIA1	27.03.2020 00:31	86.2 ³	8'705	8'691
Start testing MAR1-1-LIA2	30.03.2020 14:43	-	8'700	

Flow model evaluation

The evaluation of the flow model approach was based on the PSR and PW phase. The PSR und PW phases of MAR1-1-LIA2 were the only test phase used for a flow model diagnostics. Fig. B-16 shows a log-log diagnostic graph (Bourdet et al. 1989) for the PSR phase. Fig. B-17 gives the deconvolved log-log diagnostic graph of the PW test using the deconvolution approach (Peres et al. 1989). These two diagnostic graphs show a long-lasting period of almost two log

cycles dominated by wellbore storage. After this period, the pressure curve and derivative slowly start to flatten, indicating the beginning of the transition phase towards a formation response. However, a clear indication of an infinite acting radial flow region (IARF) and the flow model could not be established for both phases. Hence, a flow model which deviates from the radial flow assumption is unlikely, and due to the limited radial extent of the pressure disturbance by testing (radius of investigation), models including an external boundary can be excluded.

Analysis of the pulse phases including the initial pressure recovery phase (PSR-PW-PI)

The pulse phase analysis was based on a parameter optimisation using a radial composite model that could incorporate a possible skin zone around the borehole. Tab. 4-35 presents the resulting inner zone and formation parameters (inner zone hydraulic conductivity K_{in} , inner zone specific storage $S_{s\ in}$, radius of discontinuity r_d and formation hydraulic conductivity K_{out} , formation specific storage $S_{s\ out}$ and static formation pressure P_f). Fig. B-18 presents the resulting simulation considering only the borehole pressure history.

Tab. 4-35: Hydraulic test MAR1-1-LIA2: Formation parameter estimates based on a radial composite model considering the borehole pressure history

PSR-PW-PI results	K_{in} [m/s]	$S_{s\ in}$ [1/m]	r_d [m]	K_{out} [m/s]	$S_{s\ out}$ [1/m]	P_f [kPa]
Radial composite model considering the borehole pressure history	1.3×10^{-13}	2.1×10^{-6}	0.09	2.6×10^{-14}	5.0×10^{-6}	11'813

Consideration of possible influences on the formation parameter estimates

The following factors that could possibly influence the formation parameter estimates were studied:

1. Influence of interval temperature changes during the test phases
2. Influence of packer pressure changes due to surface temperature changes
3. Influence of the borehole pressure history
4. Influence of uncertain estimations of the wellbore storage

The influence of interval temperature changes was studied via a parameter optimisation that considered the measured temperature changes inside the test interval. The memory gauge sensor T2* measured a temperature range that was between 41.9 °C and 42.1 °C. Fig. B-19 shows the temperature measurement in comparison with the pressure measurement during MAR1-1-LIA2. Tab. 4-36 presents the resulting formation parameter estimates. Fig. B-20 shows the resulting simulation considering the borehole pressure history and observed interval temperature changes.

Tab. 4-36: Hydraulic test MAR1-1-LIA2: Formation parameter estimates based on a radial composite model considering the borehole pressure history and the observed interval temperature change

PSR-PW-PI results	K_{in} [m/s]	Ss_{in} [1/m]	r_d [m]	K_{out} [m/s]	Ss_{out} [1/m]	P_f [kPa]
Radial composite model considering the borehole pressure history and interval temperature changes	1.8×10^{-13}	1.8×10^{-6}	0.09	3.1×10^{-14}	3.6×10^{-6}	11'564

The influence of packer pressure changes on the interval volume were studied by a sequence of stepwise packer inflation and deflation at the end of the hydraulic test MAR1-1-LIA1. The interval of MAR1-1-LIA1 was identical to this test because the equipment was only relocated in the borehole. The resulting interval volume changes due to changes in surface temperature were considered in the numerical simulation by varying the borehole radius. Fig. B-21 shows the manipulation of the borehole radius in comparison to the interval volume changes (caused by the surface temperature induced packer pressure changes) and the sensor P2 pressure measurement. Tab. 4-37 presents the resulting formation parameter estimates. Fig. B-22 shows the resulting simulations considering the borehole pressure history, interval temperature and observed packer pressure changes.

Tab. 4-37: Hydraulic test MAR1-1-LIA2: Formation parameter estimates derived from radial composite model that considered the borehole pressure history, interval temperature and packer pressure changes due to changes in surface temperature

PSR-PW-PI results	K_{in} [m/s]	Ss_{in} [1/m]	r_d [m]	K_{out} [m/s]	Ss_{out} [1/m]	P_f [kPa]
Radial composite model considering the borehole pressure history and interval temperature changes	2.0×10^{-13}	1.7×10^{-6}	0.09	2.6×10^{-14}	4.2×10^{-6}	11'645

The influence of the borehole pressure history was studied by a set of parameter optimisations based on different approaches to the mud density prior to the hydraulic test MAR1-1-LIA2. The mud density was varied in a range of $\pm 5\%$ ($1'195 \text{ kg/m}^3 - 1'321 \text{ kg/m}^3$). The resulting formation parameter estimate ranges are provided in Tab. 4-38. The ranges of the inner zone parameters are provided in Tab. 4-39. A graphical representation in Cartesian coordinates is presented in Fig. B-23.

Tab. 4-38: Hydraulic test MAR1-1-LIA2: Range of the formation parameter estimates derived from a radial composite model considering a variation in the mud density prior to hydraulic testing of $\pm 5\%$

PSR-PW-PI results	K_{out} [m/s]	Ss_{out} [1/m]	P_f [kPa]
Estimate ranges	$2.5 \times 10^{-14} - 7.6 \times 10^{-14}$	$1.2 \times 10^{-6} - 4.9 \times 10^{-6}$	9'935 – 12'000

Tab. 4-39: Hydraulic test MAR1-1-LIA2: Range of the inner zone parameter estimates derived from a radial composite model considering a variation in the mud density prior to hydraulic testing of $\pm 5\%$

¹ Radius of discontinuity was fixed.

PSR-PW-PI results	K_{in} [m/s]	Ss_{in} [1/m]	r_d [m]
Estimate range	$1.1 \times 10^{-13} - 2.5 \times 10^{-13}$	$1.4 \times 10^{-6} - 2.6 \times 10^{-6}$	0.09 ¹

The influence of uncertainty in the wellbore storage estimates was studied by a sampling analysis of the non-fitting parameter of the test zone compressibility (c_{tz}) on the pulse withdrawal phase (PW). The lower and upper bound for the sampling analysis of the c_{tz} value was defined to 4.0×10^{-10} 1/Pa and 1.0×10^{-9} 1/Pa. This corresponds to a significant extension of the range given by the estimated test zone compressibility of MAR1-1-LIA2. The resulting ranges for the formation parameter estimate are provided in Tab. 4-40 (inner zone parameters in Tab. 4-41). The best estimate for the test zone compressibility of the PW phase was 6.8×10^{-10} 1/Pa (associated with the lowest SSE) with an uncertainty range from 5.7×10^{-10} 1/Pa to 7.7×10^{-10} 1/Pa. Fig. B-24 presents the results of the sampling analysis of the PW phase.

Tab. 4-40: Hydraulic test MAR1-1-LIA2: Ranges of the formation parameter estimates resulting from the sampling analysis of the test zone compressibility on PW

PSR-PW-PI results	K_{out} [m/s]	Ss_{out} [1/m]	P_f [kPa]
Estimate range	$2.0 \times 10^{-14} - 1.7 \times 10^{-14}$	$5.0 \times 10^{-7} - 5.0 \times 10^{-6}$	9'792 – 11'922

Tab. 4-41: Hydraulic test MAR1-1-LIA2: Range of the inner zone parameter estimates resulting from the sampling analysis of the test zone compressibility on PW

¹ Radius of discontinuity was fixed.

PSR-PW-PI results	K_{in} [m/s]	Ss_{in} [1/m]	r_d [m]
Estimate range	$7.5 \times 10^{-14} - 1.9 \times 10^{-13}$	$1.4 \times 10^{-6} - 4.7 \times 10^{-6}$	0.09 ¹

Estimates of the formation parameter values and uncertainty ranges

Finally, a perturbation analysis of 400 runs was performed to investigate the characteristics of the formation parameter estimates, i.e. to verify that the solution corresponds to a global minimum in the parameter space (formation hydraulic conductivity, storage and the static formation pressure). 365 runs were selected as appropriate to provide the resulting range of formation parameter estimates by a least squared error threshold value of 3.78×10^7 . Fig. B-25 shows the resulting formation parameter estimates in comparison to their associated least squared error sorted by the least squared error values of the single parameter optimisation results. Tab. 4-42 presents the resulting parameter estimates associated with the lowest least squared error. The associated simulation result is shown in Fig. B-26.

Tab. 4-42: Hydraulic test MAR1-1-LIA2: Parameter estimates of the perturbation analysis of the PSR-PW-PI associated with the lowest least squared error value

PSR-PW-PI results	K_{in} [m/s]	Ss_{in} [1/m]	r_d [m]	K_{out} [m/s]	Ss_{out} [1/m]	P_f [kPa]
Radial composite model considering the borehole pressure history and interval temperature changes	1.7×10^{-13}	1.9×10^{-6}	0.09	3.3×10^{-14}	3.5×10^{-6}	11'464

The ranges of the formation parameter estimates resulting from the perturbation analysis are provided in Tab. 4-43 (inner zone parameter ranges are in Tab. 4-44).

Tab. 4-43: Hydraulic test MAR1-1-LIA2: Ranges of the formation parameter estimates resulting from the perturbation analysis of the PSR-PW-PI test sequence

PSR-PW-PI results	K_{out} [m/s]	Ss_{out} [1/m]	P_f [kPa]
Estimate range	$2.3 \times 10^{-14} - 1.0 \times 10^{-13}$	$7.0 \times 10^{-7} - 5.0 \times 10^{-6}$	9'532 – 12'000

Tab. 4-44: Hydraulic test MAR1-1-LIA2: Range of the inner zone parameter estimates resulting from the perturbation analysis of the PSR-PW-PI test sequence

¹ Radius of discontinuity was fixed.

PSR-PW-PI results	K_{in} [m/s]	Ss_{in} [1/m]	r_d [m]
Estimate range	$6.8 \times 10^{-14} - 8.9 \times 10^{-12}$	$1.4 \times 10^{-6} - 1.0 \times 10^{-5}$	0.09 ¹

Based on the investigations carried out, the formation parameter values and their associated uncertainties are summarised in Tab. 4-45. It should be noted that the estimate for the specific storage is highly uncertain. The uncertainty range is defined based on the plausibility range derived by Nagra from previous field and laboratory studies for the Lias Group.

Tab. 4-45: Hydraulic test MAR1-1-LIA2: Best estimates of the formation parameters and the associated uncertainty ranges

Results	K [m/s]	Ss [1/m]	P_f [kPa]
Best estimate	3.3×10^{-14}	3.5×10^{-6}	11'464
Uncertainty range	$2.0 \times 10^{-14} - 1.7 \times 10^{-13}$	$5.0 \times 10^{-7} - 5.0 \times 10^{-6}$	9'792 – 11'922

Confirmation simulation

To validate the results presented above, an additional perturbation analysis was performed using only the pulse phases PW and PI. The perturbation analysis results for the formation parameter estimates confirm the previous results. Tab. 4-46 gives the formation parameter values associated to the simulation of the lowest sum of squared errors (SSE) and the resulting uncertainty ranges.

Tab. 4-46: Hydraulic test MAR1-1-LIA2: Perturbation results of the formation parameter estimates and the associated uncertainty ranges based on only the pulse phases (PW, PI)

Results	K [m/s]	S_s [1/m]	P_f [kPa]
Value associated to the lowest SSE	4.1×10^{-14}	2.7×10^{-6}	11'464
Uncertainty range	$2.4 \times 10^{-14} - 2.0 \times 10^{-13}$	$5.0 \times 10^{-7} - 5.0 \times 10^{-6}$	9'030 – 12'000

4.5.3 Comparison of results

Both hydraulic tests, MAR1-1-LIA1 and MAR1-1-LIA2, show good agreement in the estimation of the hydraulic conductivity of the formation (MAR1-1-LIA1: 7.8×10^{-14} m/s, MAR1-1-LIA2: 3.3×10^{-14} m/s). Due to the shorter test duration and the longer pressure history, the uncertainty interval for the MAR1-1-LIA2 is greater than for MAR1-1-LIA1. In addition, the uncertainty range is affected by the uncertainty in the estimation of the specific storage of the formation, especially for MAR1-1-LIA2 which could be ascribed to the shorter duration of single test phases. Both are within an acceptable range and the results can be considered reliable.

The main difference between the tests (besides the fact that they cover different depth ranges with an overlap of only approx. 4.2 m) is the resulting best estimate and uncertainty range for the static formation pressure / hydraulic head. The results of MAR1-1-LIA2 are more uncertain and tend towards a possible higher overestimate, e.g. due to the increasing duration of the pressure history. The reason for this will be studied in more detail in the future. In this context, Nagra will install long-term pressure monitoring systems in selected boreholes including MAR1-1.

5 Summary and discussion

5.1 Flowmeter logging and fluid logging

Fluid logging was conducted in borehole MAR1-1 during February 2020 in the partially cored Section II. The test is referred to as MAR1-1-FL1-MAL. 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 the detailed analysis of the hydraulic packer test results of the interval MAR1-1-MAL1.

In total four fluid logging analyses were performed, two of which taking into account Runs 8 to 10 during the pumping phase RW2 and the other two ones taking into account Runs 18 to 21 and 19 to 21, respectively, during the pumping phase RW4. The analyses based on Runs 8 to 10 show that Runs 9 and 10 can be simulated by only two inflow zones. The comparison of the models based on two and three inflow zones shows that the incorporation of additional inflow zones is achieved by reducing the hydraulic dispersion processes in the borehole. The sum of transmissivities for the inflow zones during the pumping phase RW2 is $5.2 \times 10^{-7} \text{ m}^2/\text{s}$ (for 2 inflow zones) and $7.3 \times 10^{-7} \text{ m}^2/\text{s}$ (for 3 inflow zones), which is in good agreement for the transmissivity values derived from the pumping test that vary between $4 \times 10^{-7} \text{ m}^2/\text{s}$ and $6 \times 10^{-7} \text{ m}^2/\text{s}$.

The investigation based on Runs 15 to 21 (pumping phase RW4) demonstrated that a constant flow rate is crucial for the analysis of fluid logs. A 1st fluid logging analysis based on Runs 18 to 21 and a 2nd fluid logging analysis based on Runs 19 to 21 were simulated by using four and five inflow zones and a negation of the hydraulic dispersion effects in the borehole (consideration of only diffusion processes).

The reliability and significance of the fluid logging analysis is supported by the FMI and the acoustic borehole images (see Section 3.2.3 as well as Dossier VI), which show fractures and voids associated with the defined inflow zones. The sum of transmissivities for all the inflow zones for the 2nd fluid logging analysis of pumping phase RW4 is $7.5 \times 10^{-7} \text{ m}^2/\text{s}$, while for the 1st fluid logging analysis it is $5.1 \times 10^{-7} \text{ m}^2/\text{s}$. These values are very similar to the value derived from the analysis of the pumping phase RW2 of Runs 8 to 10 as well as the transmissivity values derived from the pumping test that vary between $4 \times 10^{-7} \text{ m}^2/\text{s}$ and $6 \times 10^{-7} \text{ m}^2/\text{s}$. Based on the results of pumping phases RW2 and RW4, it may be excluded that a longer pumping period or an increased pumping rate could "activate" new fractures leading to higher transmissivity values.

The comparison of the results derived from Runs 8 to 10 (pumping phase RW2) and Runs 19 to 21 (pumping phase RW4) provides the following insights:

- Two significant inflow zones exist at around 320 m MD and 348 m MD
- The main inflow zones are around 350 m MD.
- Another less significant inflow zone was detected in the analysis of Runs 8 to 10 at a depth between 360 m MD and 370 m MD. However, it could not be validated by the analysis of Runs 19 to 21. For this reason, the existence of this inflow zone is deemed uncertain.

The fluid logging analysis allowed mapping of the major inflow zones. The estimated transmissivity values are considered reliable and robust with a range of total transmissivity between 5.1×10^{-7} and $7.5 \times 10^{-7} \text{ m}^2/\text{s}$. The range of estimated transmissivities is very close to the transmissivity determined in the analysis of the associated pumping test that ranged between 4×10^{-7} and $6 \times 10^{-7} \text{ m}^2/\text{s}$. Also, the total transmissivity of the inflow zones is in very good agreement

with the transmissivity values obtained from the packer test MAR1-1-MAL1 interval 335.6 – 352.6 m MD using a radial composite flow model. However, the final analysis led to an estimate of lower hydraulic transmissivity (between 1×10^{-8} and 3×10^{-7} m²/s).

5.2 Hydraulic packer test data and results

5.2.1 Description of tests

Ten hydraulic packer test sequences were performed within ten test intervals in the borehole MAR1-1 between February 2020 and June 2020. All tests were performed in the cored borehole section using an HDDP packer system in single packer or double packer configuration (*cf.* Tab. 4-21).

- One hydraulic packer test investigated the partially fractured and porous limestones of the Malm Group («Felsenkalk» + «Massenkalk»): MAR1-1-MAL1.
- Two hydraulic packer tests in the Dogger Group including the Variansmergel Formation, the «Parkinsoni-Württembergica-Schichten» and the «Humphriesoolith Formation»: MAR1-1-BDO2, respectively the «Humphriesoolith Formation», the Wedelsandstein Formation and the «Murchisonae-Oolith Formation»: MAR1-1-BDO1.
- Three hydraulic packer tests in the Dogger Group focused on the Opalinus Clay: MAR1-1-OPA1, MAR1-1-OPA3 and MAR1-1-OPA2.
- Two hydraulic packer tests focused on the Lias Group: with a focus on the Staffelegg Formation including the Gross Wolf, Rietheim, Breitenmatt / Rickenbach, Grünschholz and Frick Members: MAR1-1-LIA2, respectively including the Breitenmatt / Rickenbach, Grünschholz, Frick, Beggingen and Schambelen Members: MAR1-1-LIA1.
- One hydraulic packer test was performed in the heterogeneous sequence of mainly sandstone, argillaceous marl, claystone and anhydrite of the Keuper Group (Klettgau Formation including Gruhalde, Seebi, Gansingen and Ergolz Members): MAR1-1-KEU1.
- The final hydraulic packer test investigated loss zones in the Muschelkalk Group resp. in the Schinznach Formation: MAR1-1-MUK1.

5.2.2 Overview tables and plots

The results of the transmissivity and hydraulic conductivity estimations for all tested intervals are summarised in Tab. 5-1. The estimated freshwater hydraulic heads and static formation pressures are documented in Tab. 5-2. Both tables present the best estimates along with confidence ranges as determined by the field test contractor in the corresponding DR.

The permeabilities for all tested intervals are summarised in Tab. 5-3. They were calculated based on the hydraulic conductivities provided in Section 4.5 and Tab. 5-1 and assumed a density of 1'000 kg/m³ and dynamic viscosity of 1×10^{-3} Pa s.

The hydraulic parameters T, K, P_f and h_s (in terms of m MD and m asl) are illustrated with respect to the borehole depth and the geological profile in Figs. 5-1 to 5-5. The best estimates are indicated by vertical lines in the corresponding interval position. The confidence ranges are shown as dashed rectangles, delimited vertically by the corresponding interval extent and laterally by the minimum and maximum values.

Tab. 5-1: Summary of hydraulic packer testing in borehole MAR1-1: Transmissivity and hydraulic conductivity

Test interval details and hydraulic model						Transmissivity and hydraulic conductivity						
Test name	Interval depth				Interval length [m]	Hydraulic model	Best estimate		Lowest estimate		Highest estimate	
	From [m MD]	To [m MD]	From [m asl]	To [m asl]			T [m ² /s]	K [m/s]	T _{min} [m ² /s]	K _{min} [m/s]	T _{max} [m ² /s]	K _{max} [m/s]
MAR1-1-MAL1	335.63	352.62	63.85	46.86	16.99	radial composite	2×10^{-07}	1×10^{-08}	1×10^{-08}	8×10^{-10}	3×10^{-07}	2×10^{-08}
MAR1-1-BDO2	510.30	549.77	-110.82	-150.29	39.47	radial homogeneous	5×10^{-12}	1×10^{-13}	3×10^{-12}	6×10^{-14}	5×10^{-12}	1×10^{-13}
MAR1-1-BDO1	551.00	590.47	-151.52	-190.99	39.47	radial composite (skin)	8×10^{-12}	2×10^{-13}	5×10^{-12}	1×10^{-13}	3×10^{-11}	8×10^{-13}
MAR1-1-OPA1	590.00	609.99	-190.52	-210.51	19.99	radial homogeneous	1×10^{-12}	6×10^{-14}	6×10^{-13}	3×10^{-14}	2×10^{-12}	9×10^{-14}
MAR1-1-OPA3	617.00	622.30	-217.52	-222.82	5.30	radial homogeneous	3×10^{-13}	5×10^{-14}	1×10^{-13}	2×10^{-14}	3×10^{-13}	7×10^{-14}
MAR1-1-OPA2	666.50	705.97	-267.02	-306.49	39.47	radial homogeneous	2×10^{-12}	4×10^{-14}	1×10^{-12}	3×10^{-14}	3×10^{-12}	9×10^{-14}
MAR1-1-LIA2	707.20	727.19	-307.72	-327.71	19.99	radial composite (skin)	7×10^{-13}	3×10^{-14}	4×10^{-13}	2×10^{-14}	3×10^{-12}	2×10^{-13}
MAR1-1-LIA1	723.00	742.99	-323.52	-343.51	19.99	radial homogeneous	2×10^{-12}	8×10^{-14}	1×10^{-12}	5×10^{-14}	5×10^{-12}	2×10^{-13}
MAR1-1-KEU1	755.15	789.13	-355.67	-389.65	33.98	radial composite (skin, constant head boundary)	1×10^{-08}	3×10^{-10}	4×10^{-09}	1×10^{-10}	2×10^{-08}	5×10^{-10}
MAR1-1-MUK1	821.20	877.00	-421.72	-477.52	55.80	radial composite + constant head boundary	8×10^{-05}	1×10^{-06}	7×10^{-05}	1×10^{-06}	2×10^{-04}	3×10^{-06}

Tab. 5-2: Summary of hydraulic packer testing in borehole MAR1-1: Hydraulic head estimates

Test interval details and hydraulic model							Hydraulic head [m MD]			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 MD]	[m MD]	[m MD]	[m asl]	[m asl]	[m asl]	[kPa]	[kPa]	[kPa]
MAR1-1-MAL1	335.63	352.62	63.85	46.86	16.99	radial composite	24	30	19	376	370	381	3'146	3'086	3'193
MAR1-1-BDO2	510.30	549.77	-110.82	-150.29	39.47	radial homogeneous	-291	-264	-405	690	663	804	8'057	7'789	9'172
MAR1-1-BDO1	551.00	590.47	-151.52	-190.99	39.47	radial composite (skin)	-141	-70	-226	540	470	625	6'985	6'289	7'814
MAR1-1-OPA1	590.00	609.99	-190.52	-210.51	19.99	radial homogeneous	-298	-210	-457	697	609	856	8'811	7'949	10'369
MAR1-1-OPA3	617.00	622.30	-217.52	-222.82	5.30	radial homogeneous	-439	-216	-611	838	616	1'010	10'385	8'199	12'073
MAR1-1-OPA2	666.50	705.97	-267.02	-306.49	39.47	radial homogeneous	-517	-384	-592	916	783	992	11'818	10'515	12'558
MAR1-1-LIA2	707.20	727.19	-307.72	-327.71	19.99	radial composite (skin)	-468	-298	-515	868	697	915	11'634	9'962	12'092
MAR1-1-LIA1	723.00	742.99	-323.52	-343.51	19.99	radial homogeneous	-312	-222	-405	712	621	805	10'255	9'370	11'170
MAR1-1-KEU1	755.15	789.13	-355.67	-389.65	33.98	radial composite (skin, constant head boundary)	-26	-25	-28	426	424	427	7'832	7'818	7'848
MAR1-1-MUK1	821.20	877.00	-421.72	-477.52	55.80	radial composite + constant head boundary	16	17	15	383	382	384	8'170	8'158	8'180

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

Tab. 5-3: Summary of hydraulic packer testing in borehole MAR1-1: Permeability

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]				
MAR1-1-MAL1	335.63	352.62	63.85	46.86	16.99	1×10^{-15}	8×10^{-17}	2×10^{-15}
MAR1-1-BDO2	510.30	549.77	-110.82	-150.29	39.47	1×10^{-20}	6×10^{-21}	1×10^{-20}
MAR1-1-BDO1	551.00	590.47	-151.52	-190.99	39.47	2×10^{-20}	1×10^{-20}	8×10^{-20}
MAR1-1-OPA1	590.00	609.99	-190.52	-210.51	19.99	6×10^{-21}	3×10^{-21}	9×10^{-21}
MAR1-1-OPA3	617.00	622.30	-217.52	-222.82	5.30	5×10^{-21}	2×10^{-21}	7×10^{-21}
MAR1-1-OPA2	666.50	705.97	-267.02	-306.49	39.47	4×10^{-21}	3×10^{-21}	9×10^{-21}
MAR1-1-LIA2	707.20	727.19	-307.72	-327.71	19.99	3×10^{-21}	2×10^{-21}	2×10^{-20}
MAR1-1-LIA1	723.00	742.99	-323.52	-343.51	19.99	8×10^{-21}	5×10^{-21}	2×10^{-20}
MAR1-1-KEU1	755.15	789.13	-355.67	-389.65	33.98	3×10^{-17}	1×10^{-17}	5×10^{-17}
MAR1-1-MUK1	821.20	877.00	-421.72	-477.52	55.80	2×10^{-13}	1×10^{-13}	3×10^{-13}

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/m³, dynamic viscosity: 1×10^{-3} Pa s).

² Based on the results presented by the field test contractor in the corresponding DR.

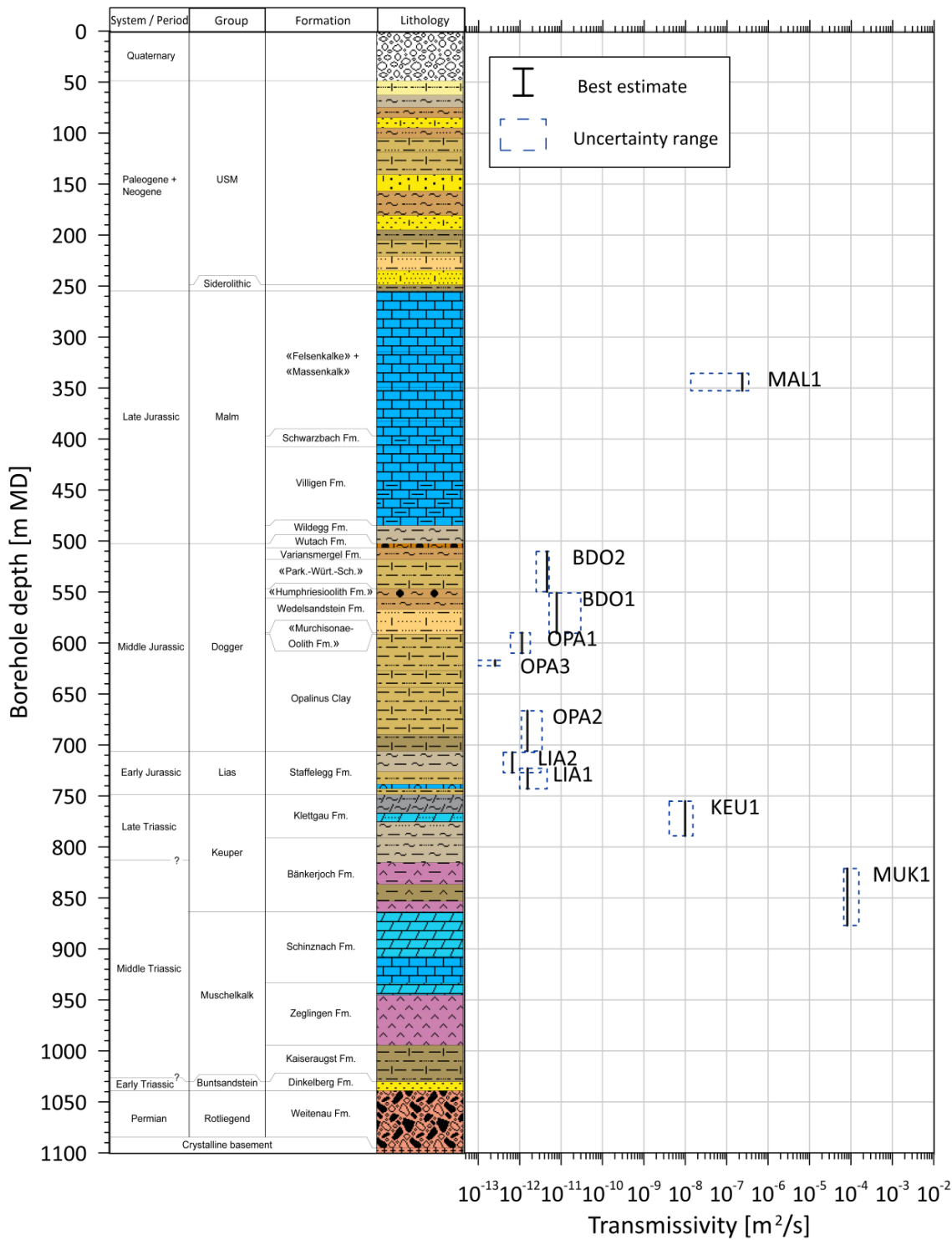


Fig. 5-1: Summary of hydraulic testing in borehole MAR1-1: Formation transmissivity profile

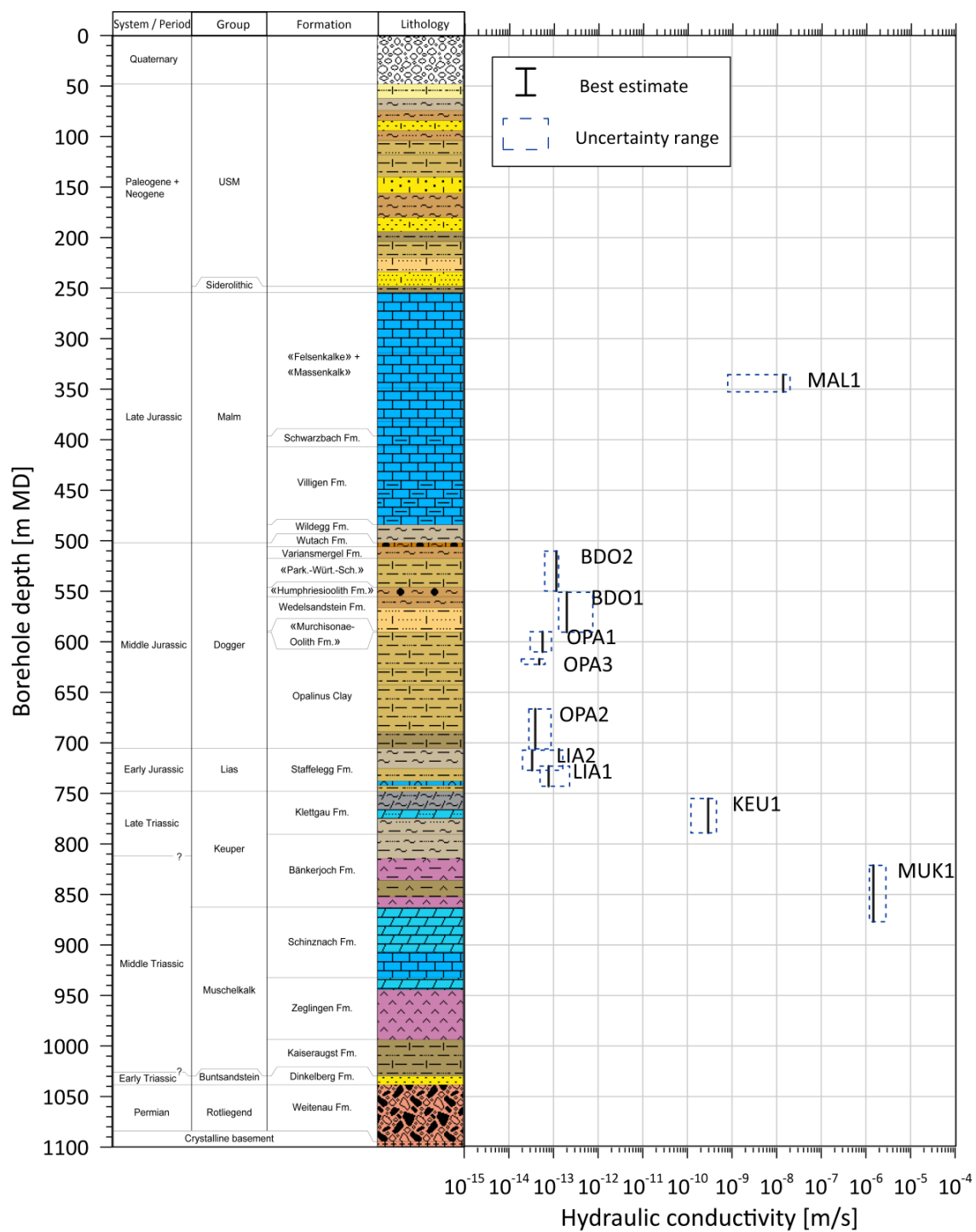


Fig. 5-2: Summary of hydraulic testing in borehole MAR1-1: Formation hydraulic conductivity profile

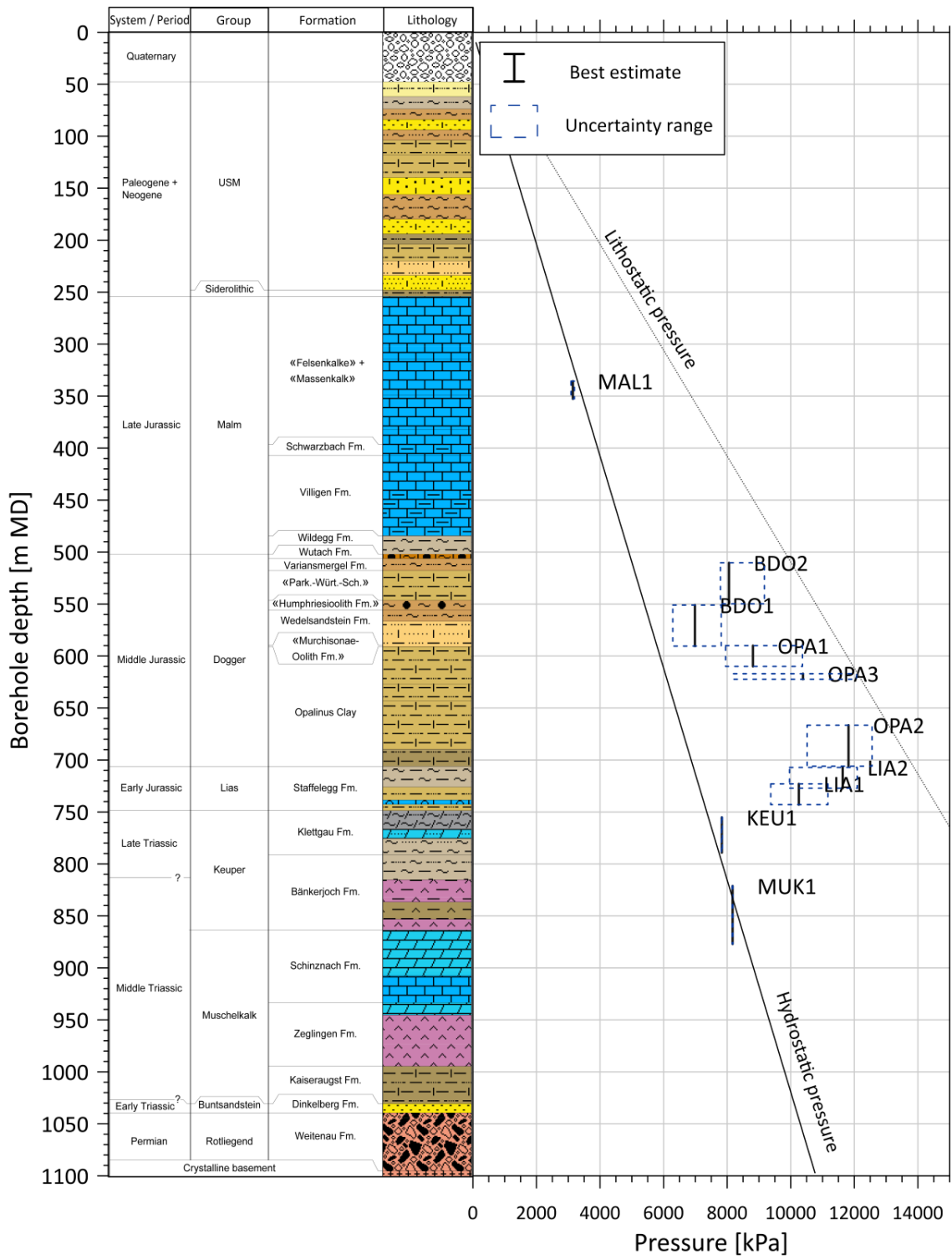


Fig. 5-3: Summary of hydraulic testing in borehole MAR1-1: Static formation pressure profile
The lithostatic pressure is based on the assumption of a mean density of 2'000 kg/m³.

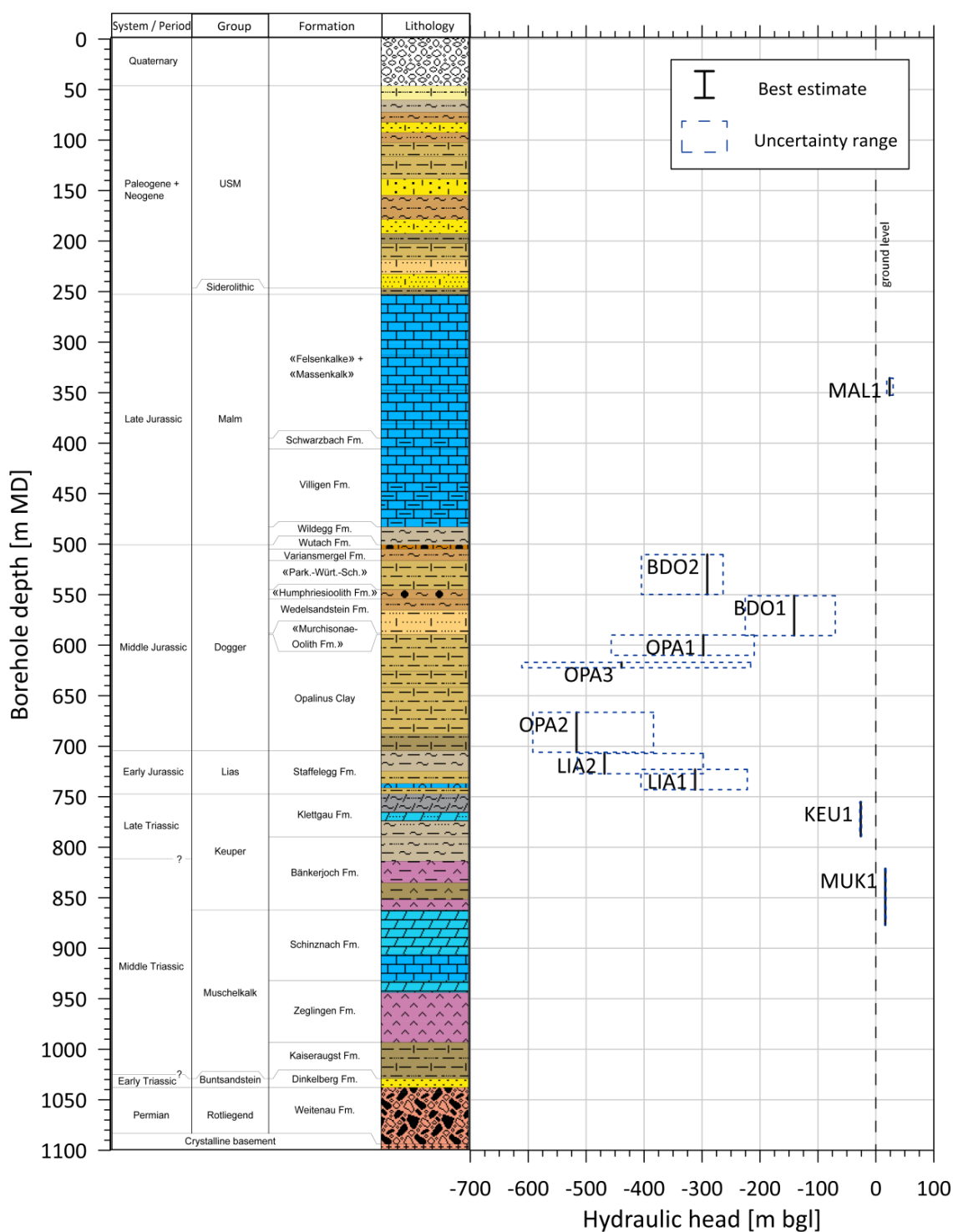


Fig. 5-4: Summary of hydraulic testing in borehole MAR1-1: Formation hydraulic head profile (m bgl)

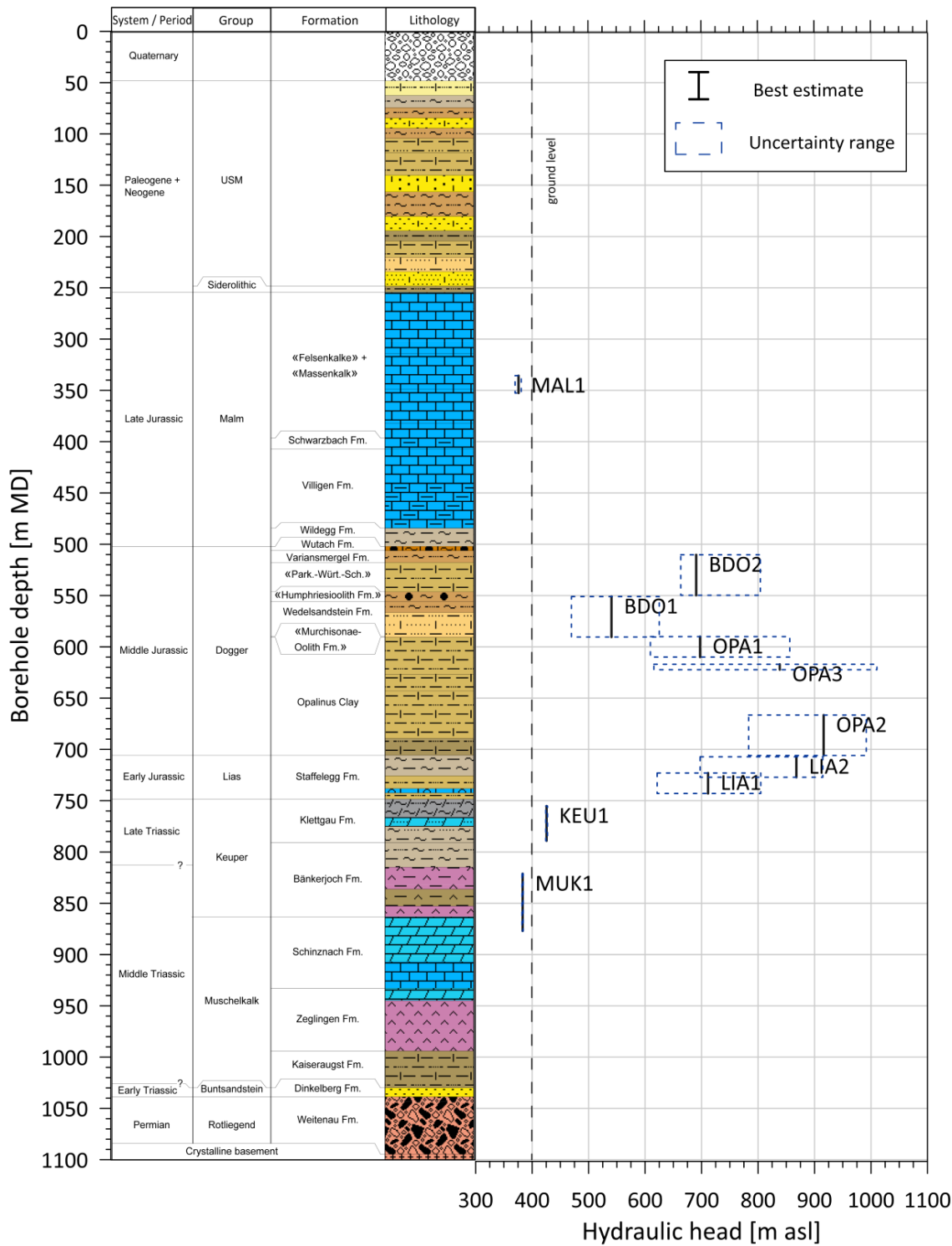


Fig. 5-5: Summary of hydraulic testing in borehole MAR1-1: Formation hydraulic head profile (m asl)

5.3 Summary

Borehole Marthalen-1-1 (MAR1-1) was the second TBO borehole drilled in the siting region Zürich Nordost (ZNO).

A total of ten test intervals were investigated in this borehole by means of hydraulic packer tests. The hydrogeological investigations focused on the properties of Opalinus Clay (MAR1-1-OPA1, MAR1-1-OPA3 and MAR1-1-OPA2) as well as the confining units above (MAR1-1-BDO1, MAR1-1-BDO2) and below (MAR1-1-LIA2, MAR1-1-LIA1). In addition, the regional aquifers of the Malm Group (MAR1-1-MAL1) and the Muschelkalk Group (MAR1-1-MUK1) as well as the potential aquifer of the Keuper Group (MAR1-1-KEU1) were investigated. Fluid logging was conducted in borehole Section II resp. the Malm Group (MAR1-1-FL1-MAL) that could be analysed quantitatively and qualitatively. A formation fluid sample could be taken from MAR1-1-MAL1 and MAR1-1-MUK1.

All hydraulic tests were supported by an on-site field analysis to optimise the test procedure.

Two hydraulic test analyses (MAR1-1-LIA1 and MAR1-1-LIA2; *cf.* Sections 4.5.1 and 4.5.2) were selected for this report to present the general analysis procedure as well as the influence on the analysis results of the duration of the pressure history period prior to the hydraulic test and the duration of the individual test phases.

The pressures and rates measured during all tests are illustrated in Figs. 4-9 to 4-18. The main results are presented in Tabs. 5-1 to 5-3 and Figs. 5-1 to 5.5.

The best estimates and the uncertainty of the hydraulic conductivities and transmissivities lie within a reasonable range within the expected spectrum of values for the evaluated formations (e.g. Nagra 2008, Nagra 2014a and b). Similarly, the extrapolated hydraulic heads are within an expected range (Luo et al. 2014), except for the hydraulic tests performed in the Dogger and the Lias Group. Due to inevitable, short-term borehole test conditions, the hydraulic heads estimated for MAR1-1-BDO1, MAR1-1-BDO2, MAR1-1-OPA1, MAR1-1-OPA2, MAR1-1-OPA3, MAR1-1-LIA1 and MAR1-1-LIA2 appear to be affected by a large overestimation. They have to be considered as 'apparent'.

General investigations concerning the physical explanation for the overestimation of the hydraulic head are continuing. The current analysis considers only the temperature effects in the test interval and the pressure induced effects resulting from the high-density drilling mud during the entire time since drilling through the interval midpoint. Nagra will install long-term pressure monitoring systems in MAR1-1 and other selected boreholes to study these and further findings in detail.

6 References

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Appendix A: Abbreviations, nomenclature and definitions

Tab. A-1: Lithostratigraphy abbreviations for test names in MAR1-1

Lithostratigraphy	Abbreviation
Malm Group	MAL
«Brauner Dogger» (Dogger parts above OPA in regions Nördlich Lägern (NL) and ZNO)	BDO
Opalinus Clay	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	MAR1-1-MUK1: First test interval in Muschelkalk aquifer in borehole MAR1-1

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	1/Pa
g	Acceleration due to gravity (9.81)	$m\ s^{-2}$
h_s	Static hydraulic head (freshwater head) $h_s = z_{ref} - z_{int} + \left[\frac{P_f + \rho_{int} g (z_{int} - z_2) - P_{atm} - P_{offset}}{\rho_w g} \right]$	m asl
k	Intrinsic permeability	m^2
K	Hydraulic conductivity	m/s
K_{in}	Inner-zone hydraulic conductivity	m/s
K_{out}	Outer-zone hydraulic conductivity	m/s
K_s	Hydraulic conductivity of skin zone	m/s
n	Fractal 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^*	Pressure in test interval (memory gauge)	Pa, kPa
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)	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	m^3/s
Q, Q_{tot}	Cumulative flow volume	m^3
r_d	Radius of discontinuity	m
$r_{w\ int}$	Borehole radius of the test interval	mm
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	1/m
$S_{s\ in}$	Inner-zone specific storage	1/m

Abbreviation / symbol	Description	Unit
$S_{s\ out}$	Outer-zone specific storage	1/m
S_{ss}	Specific storage of skin zone	1/m
T	Transmissivity	m ² /s
t, dt	Time, elapsed time	s
T_{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)	°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	
BP	Bredehoeft-Papadopulos type-curves	
BHPH	Borehole pressure history	
BOP	Blow out preventer	
CBP	Cooper-Bredehoeft-Papadopulos type-curves	
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	

Abbreviation	Description	Unit
GmbH	Gesellschaft mit beschränkter Haftung (company with limited liability)	
GTPT	Gas threshold pressure test	
HDDP	Heavy-duty double packer system	
HLW	High level waste	
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	
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	
PC, PCP	Progressive cavity pump	
POOH	Pull out of hole	
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
TRU1-1	Trüllikon-1 drill site, borehole 1	
WS	Water sample	

Abbreviation	Description	Unit
WT	Water table	
WTW	Wissenschaftlich-technische Werkstätten GmbH	
ZH	Zürich	
ZNO	Siting region Zürich Nordost	

Appendix B: Analysis plots of the hydraulic packer tests MAR1-1-LIA1 and MAR1-1-LIA2

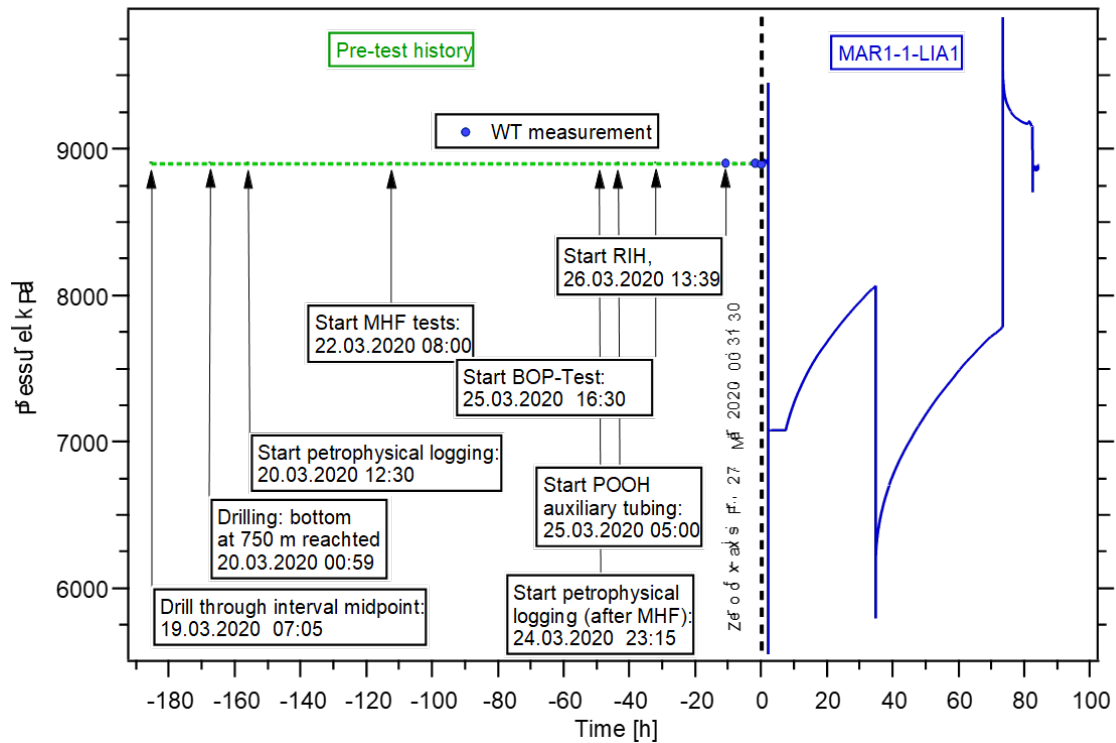


Fig. B-1: Hydraulic test MAR1-1-LIA1: Entire record of the borehole pressure history used in the analysis

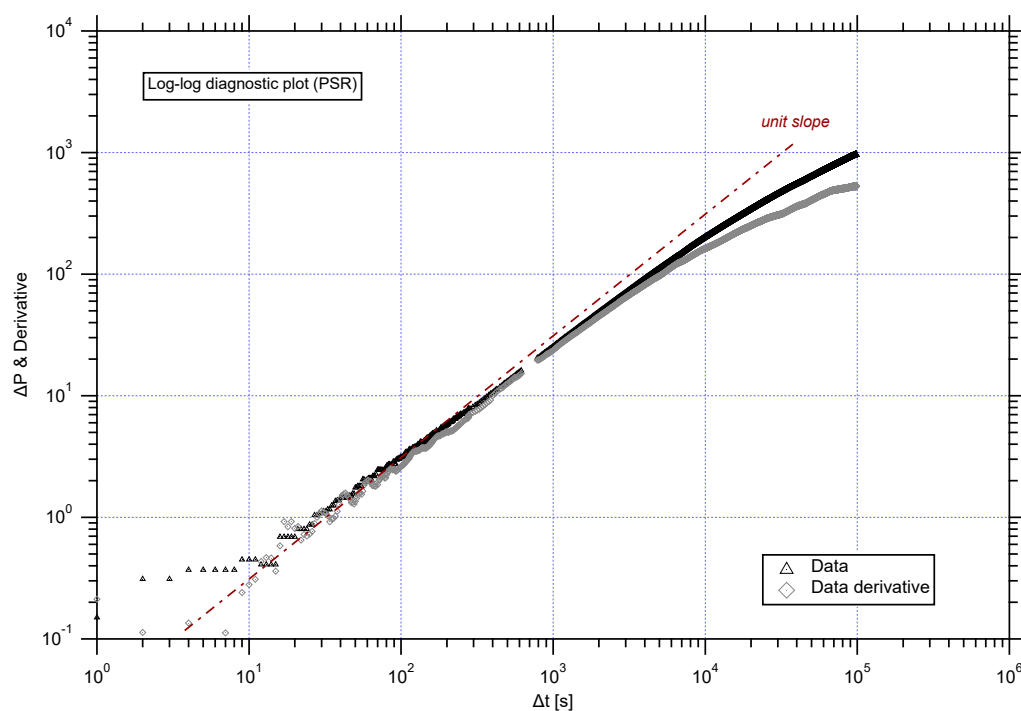


Fig. B-2: Hydraulic test MAR1-1-LIA1: Log-log diagnostic plot of PSR, no superposition

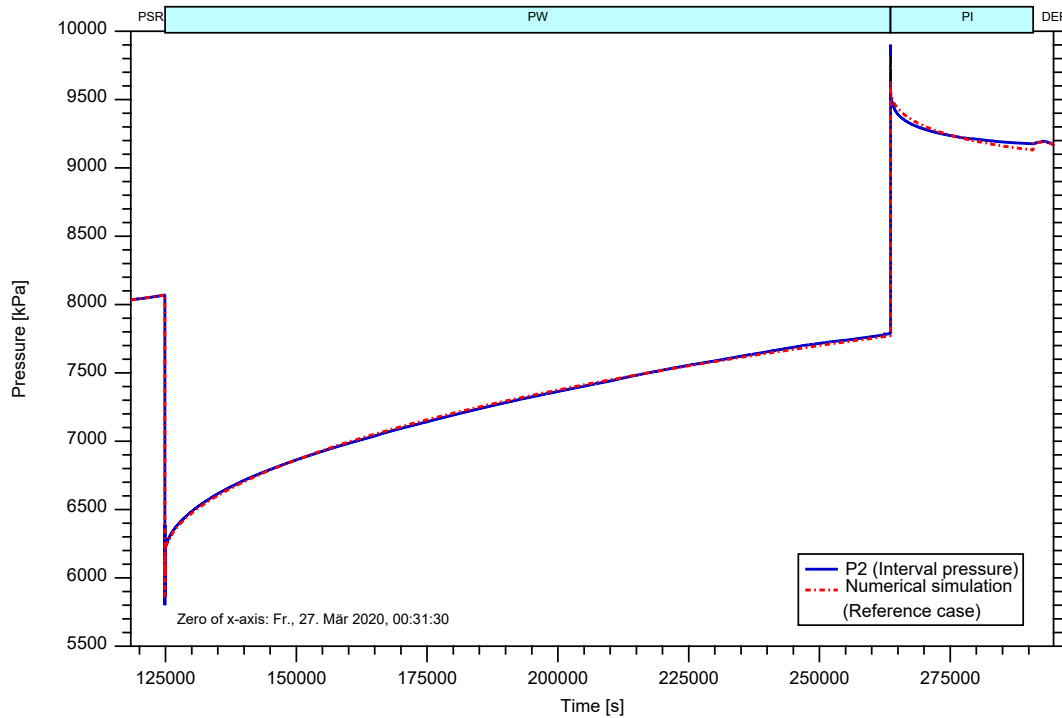


Fig. B-3: Hydraulic test MAR1-1-LIA1: Numerical simulation of the PW-PI test sequence in a Cartesian pressure plot using a radial homogeneous model considering only the borehole pressure history

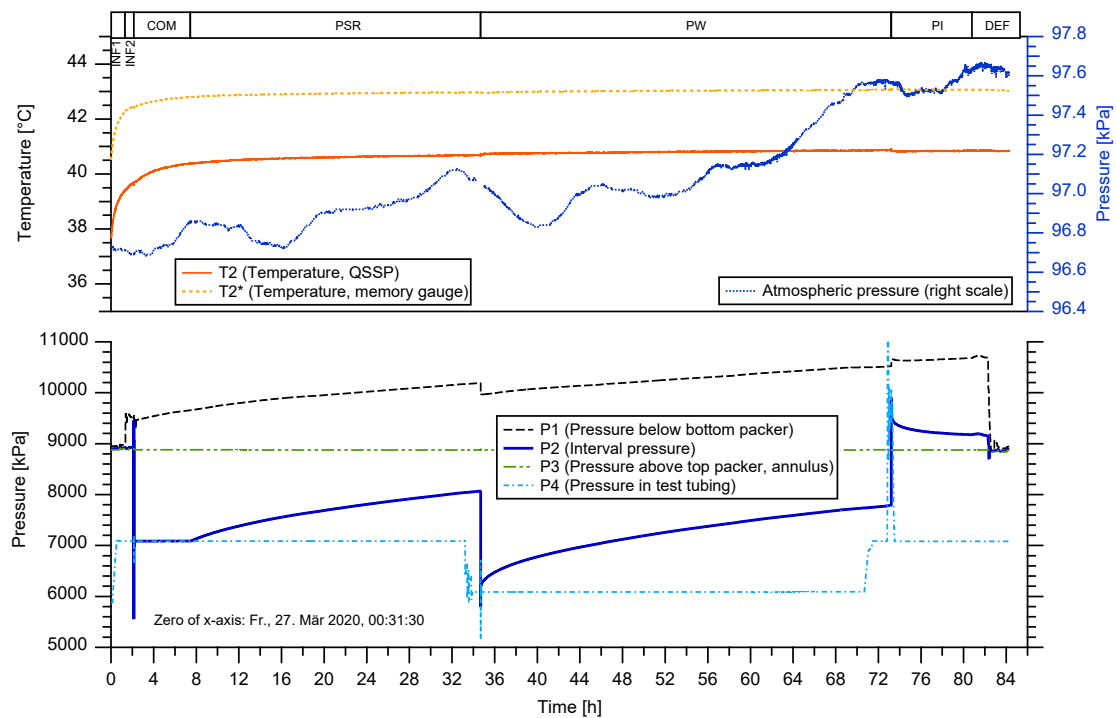


Fig. B-4: Hydraulic test MAR1-1-LIA1: Downhole temperature (T2 and T2*) and atmospheric pressure in comparison to the downhole QSSP pressure measurements

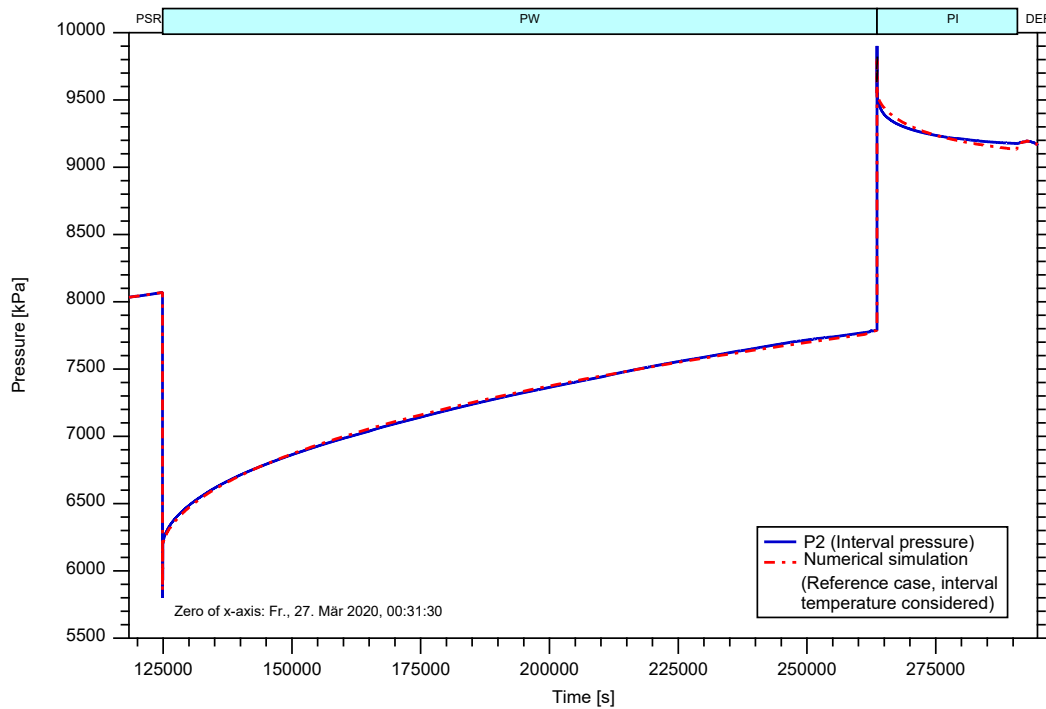


Fig. B-5: Hydraulic test MAR1-1-LIA1: Numerical simulation of the PW-PI test sequence in a Cartesian pressure plot using a radial homogeneous model considering the borehole pressure history and interval temperature change

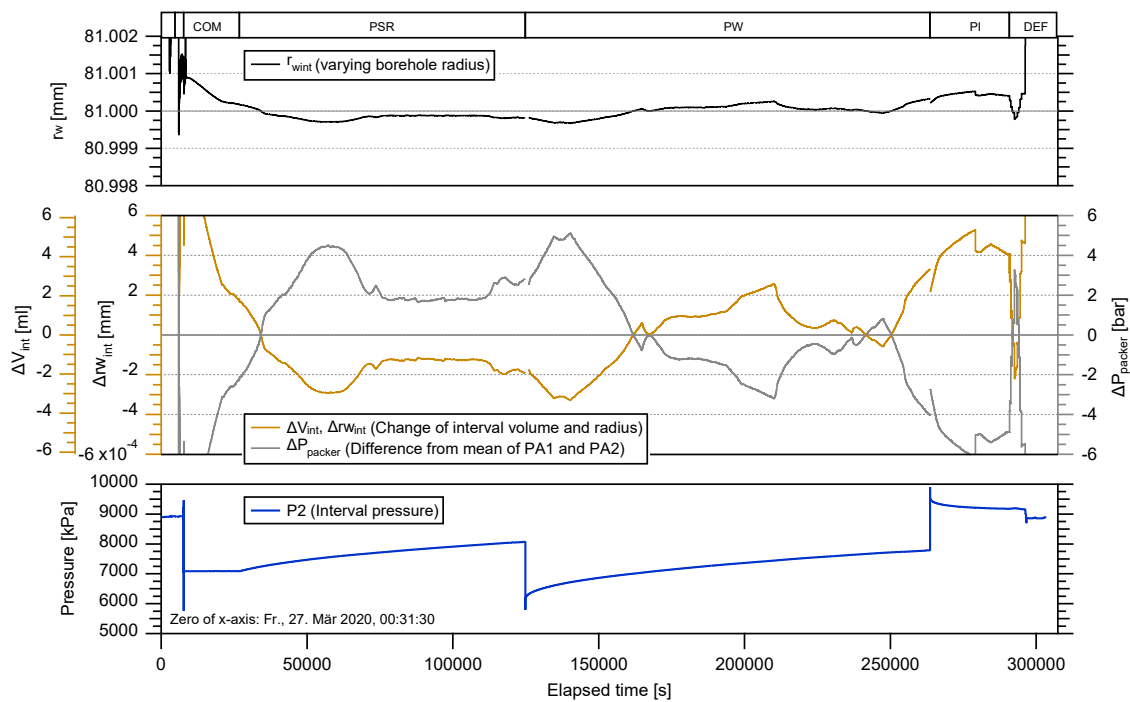


Fig. B-6: Hydraulic test MAR1-1-LIA1: Manipulation of the borehole radius ($r_{w \text{ int}}$) in comparison to the surface temperature induced packer pressure changes (ΔP_{packer}), the interval volume changes (ΔV_{int}) and the sensor P2 pressure measurement

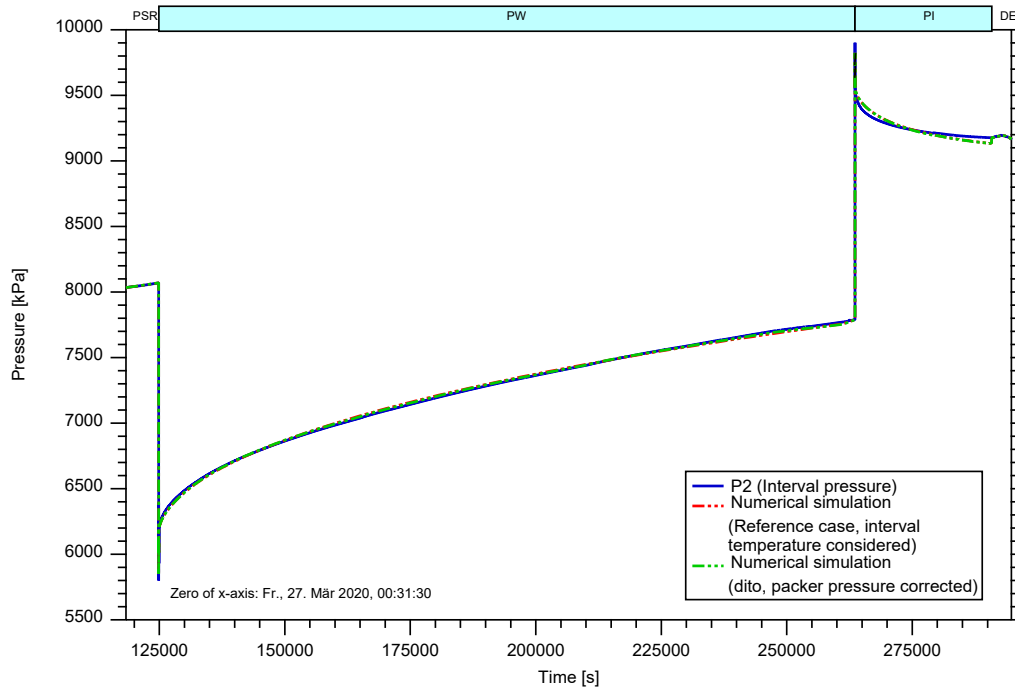


Fig. B-7: Hydraulic test MAR1-1-LIA1: Numerical simulation of the PW-PI test sequence in a Cartesian pressure plot using a radial homogeneous model considering the borehole pressure history, interval temperature change and packer pressure changes

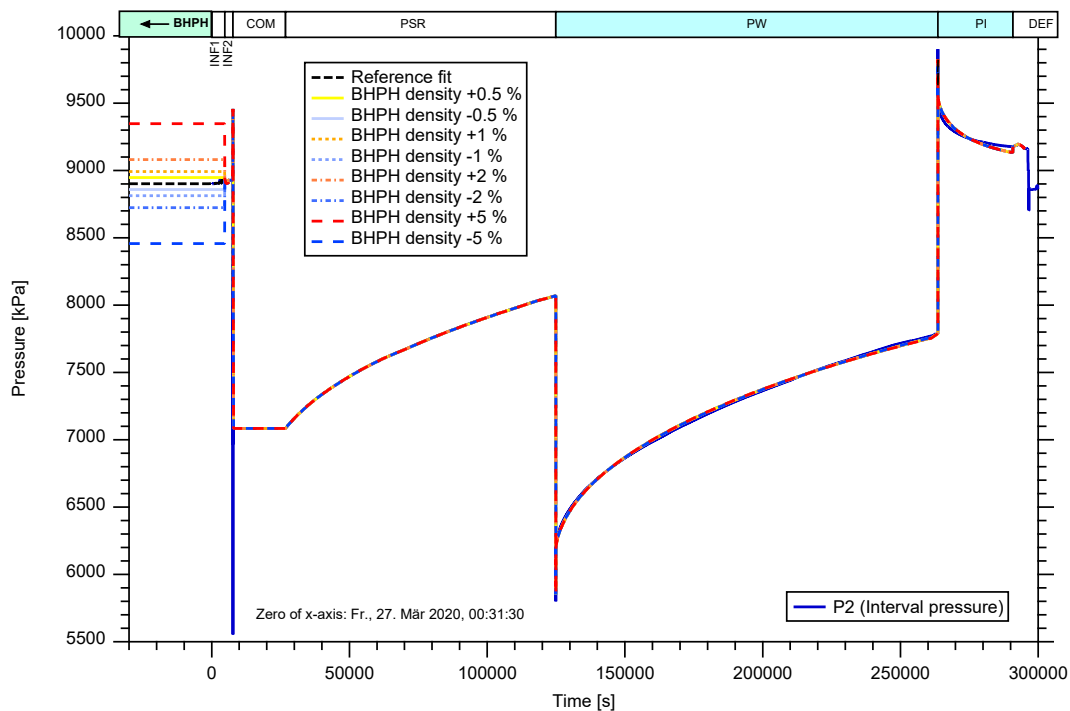


Fig. B-8: Hydraulic test MAR1-1-LIA1: Numerical simulations of the PW-PI test sequence in a Cartesian pressure plot using a radial homogeneous flow model considering interval temperature changes and applying different borehole pressure history (BHPH) scenarios

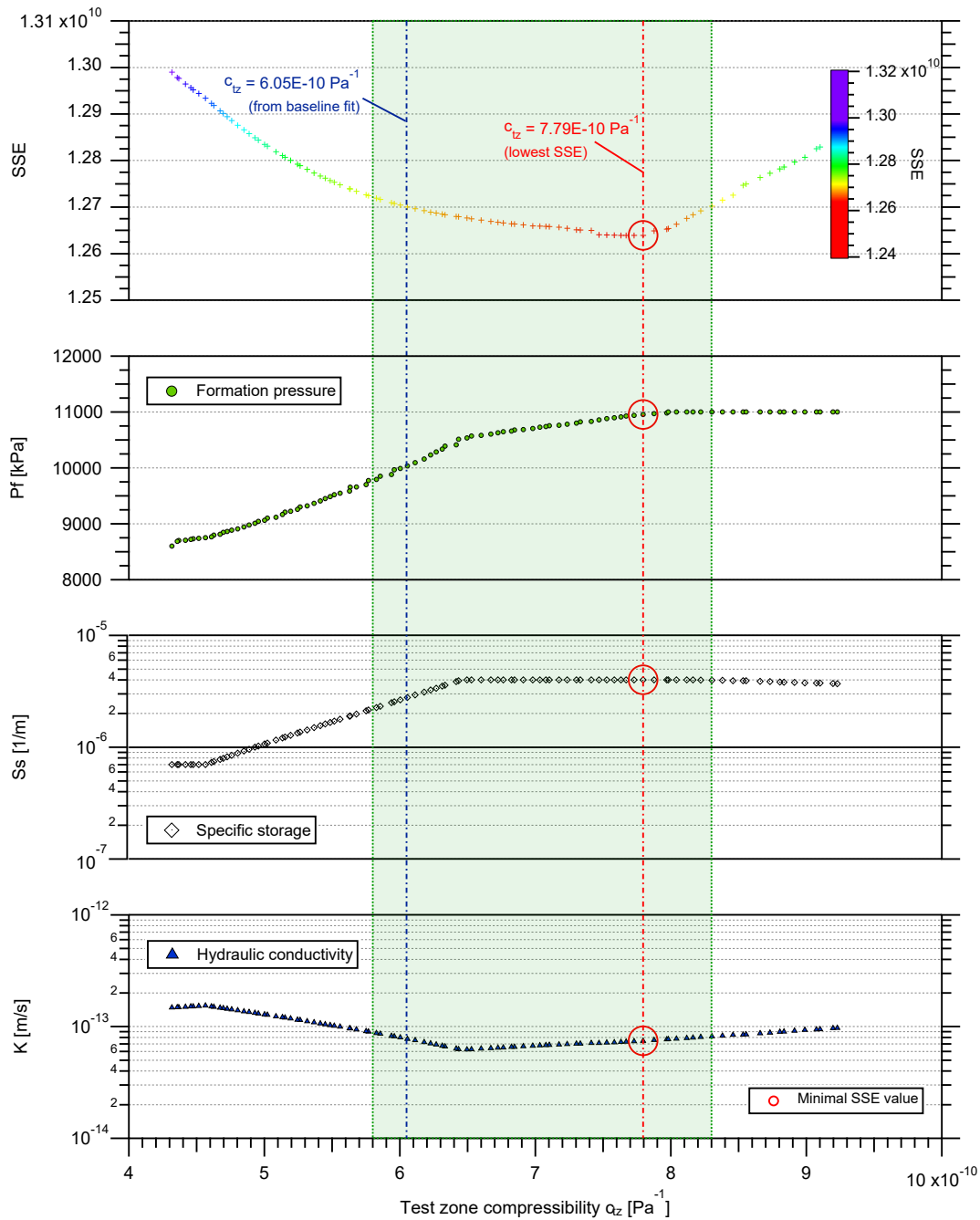


Fig. B-9: Hydraulic test MAR1-1-LIA1: Sampling analysis of the PW-PI sequence, c_{tz} of PW is sampled, with parameter ranges of the parameters K , S_s and P_f together with respective SSE values against c_{tz} value

Red circle/line shows lowest SSE, blue line shows c_{tz} value used for other simulations, green area shows fits with comparable low SSE values defined as uncertainty range.

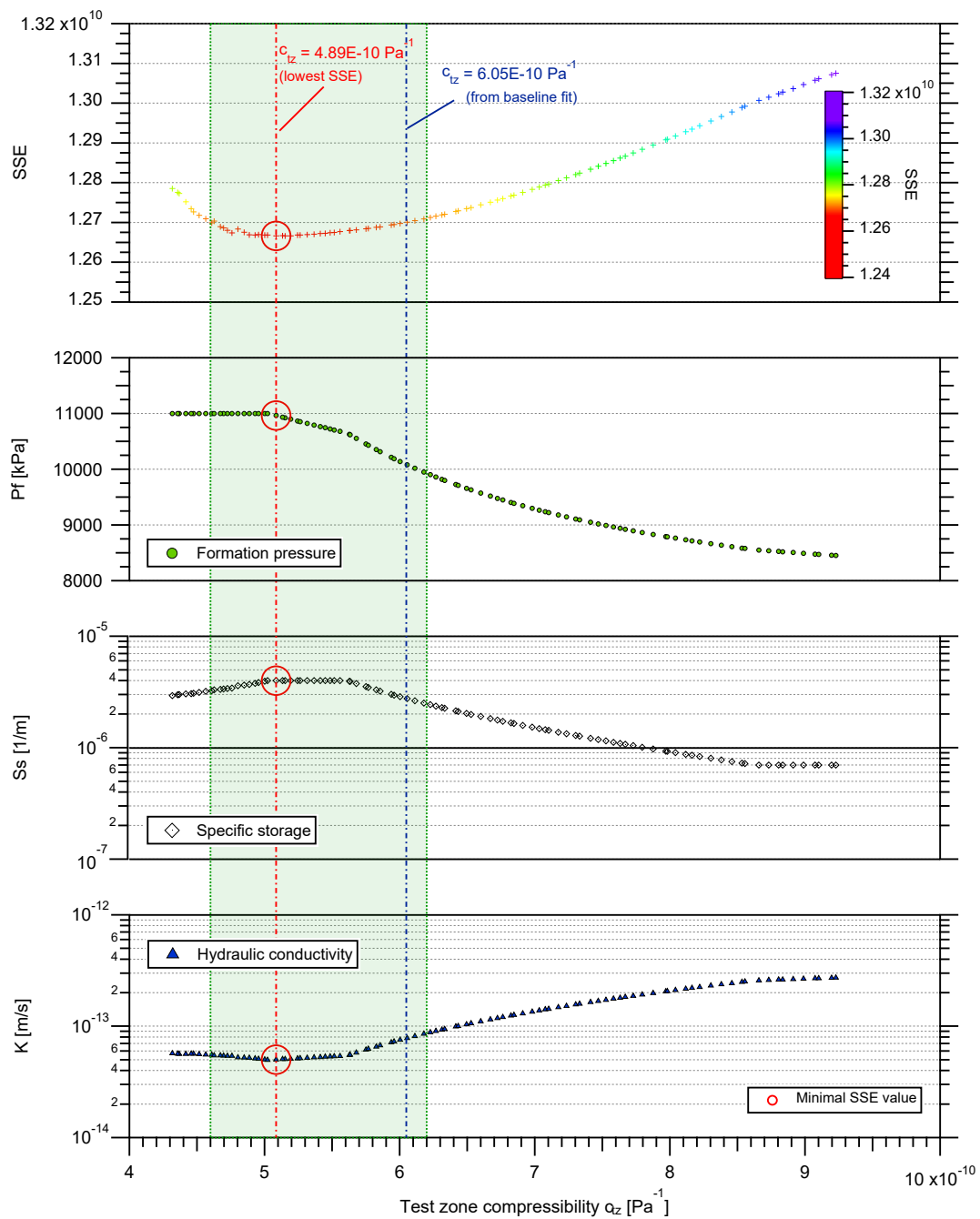


Fig. B-10: Hydraulic test MAR1-1-LIA1: Sampling analysis of the PW-PI sequence, c_{tz} of PI is sampled, with parameter ranges of the parameters K , S_s and P_f together with respective SSE values against c_{tz} value

Red circle/line shows lowest SSE, blue line shows c_{tz} value used for other simulations, green area shows fits with comparable low SSE values defined as uncertainty range.

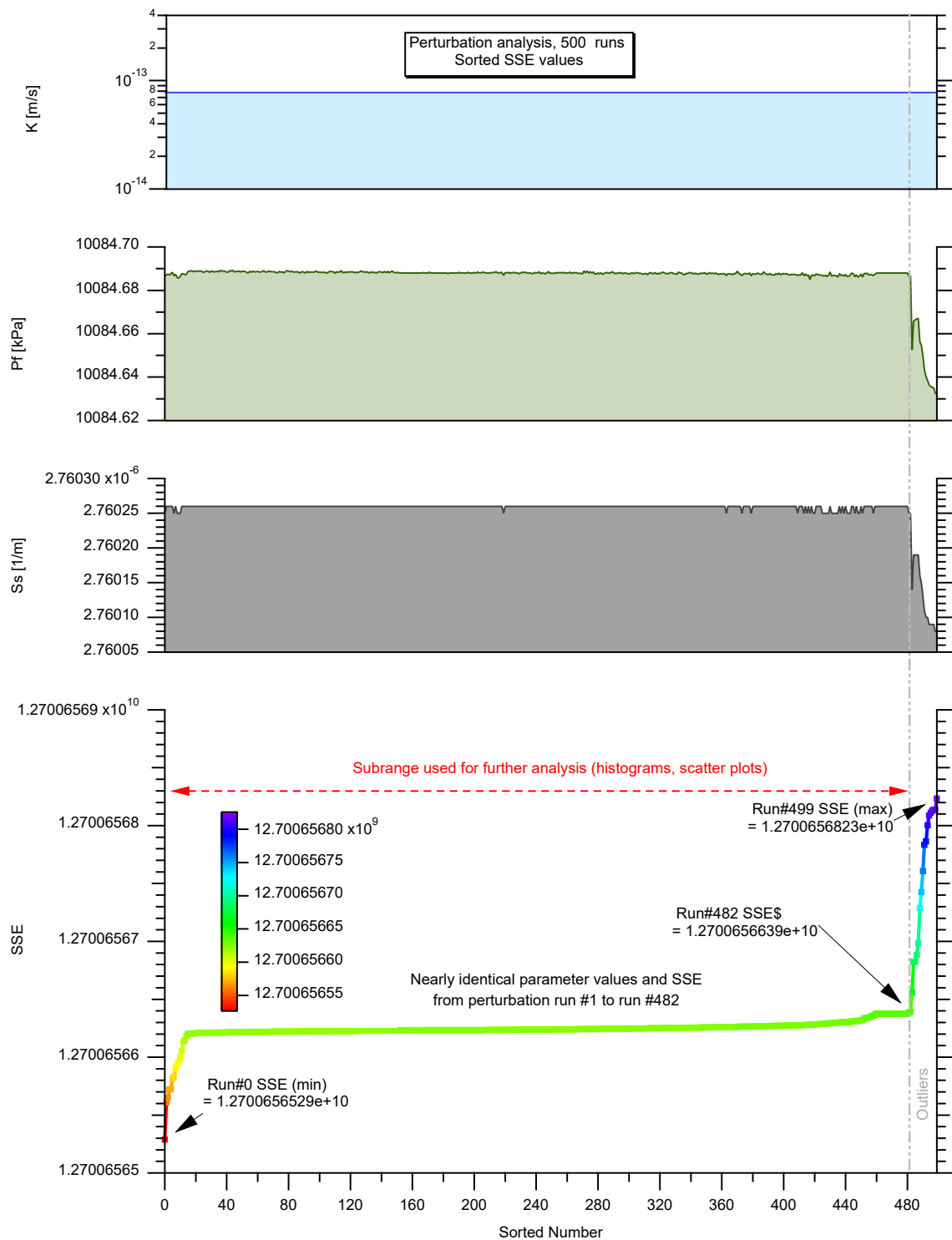


Fig. B-11: Hydraulic test MAR1-1-LIA1: Results of the perturbation analysis of PW-PI sequence using a radial homogeneous model considering interval temperature changes

Sorted by the least squared error of the simulations in combination with the associated parameter estimates. The subrange used for the interpretation of the parameter ranges is indicated by the red dashed line with arrows.

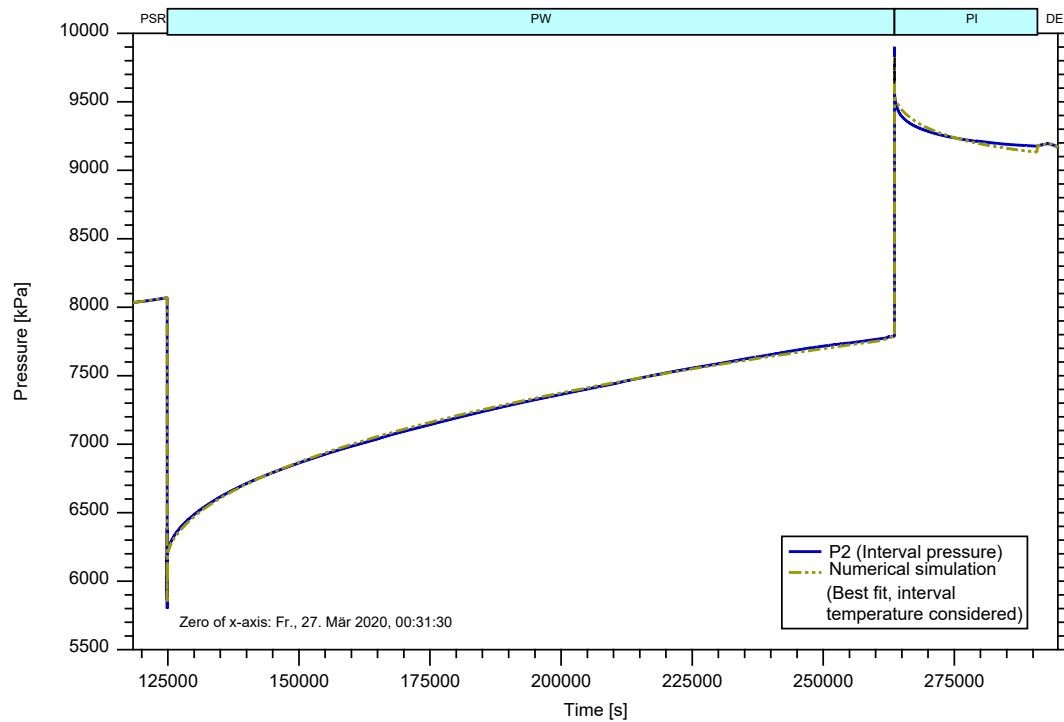


Fig. B-12: Hydraulic test MAR1-1-LIA1: Best simulation of the PW-PI sequence using a radial homogeneous model considering the borehole pressure history and interval temperature changes

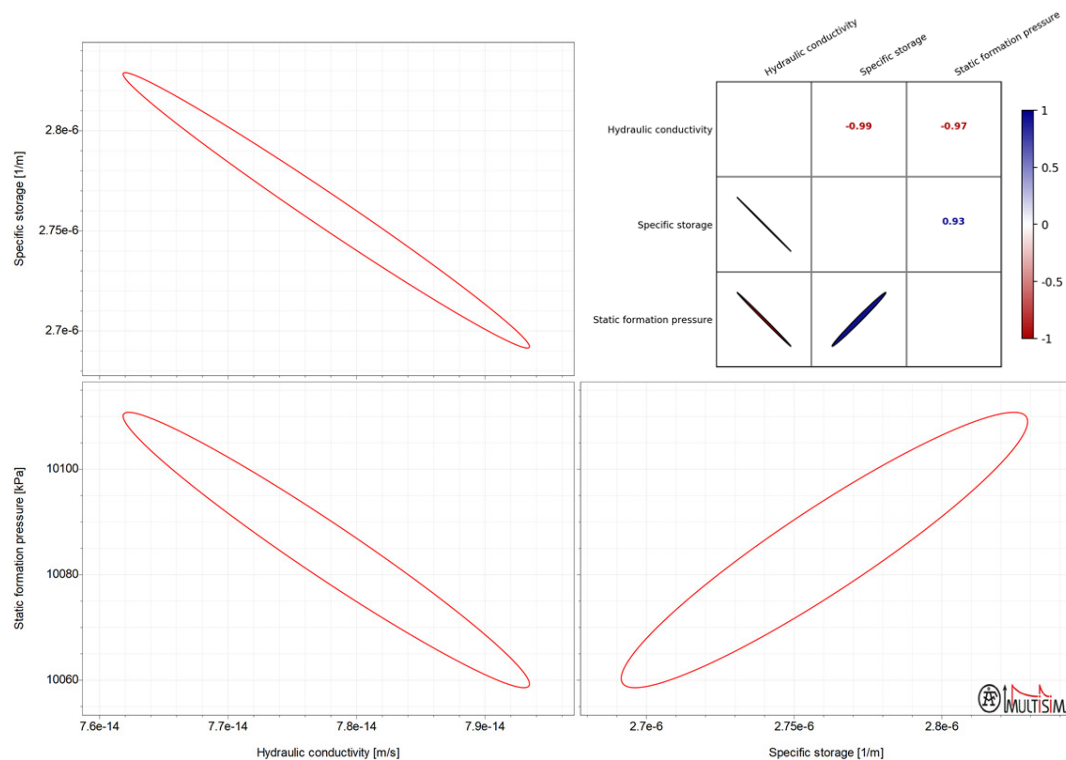


Fig. B-13: Hydraulic test MAR1-1-LIA1: 95% joint confidence intervals and associated correlation matrix for the PW-PI sequence using a radial homogeneous model considering the borehole pressure history and interval temperature changes

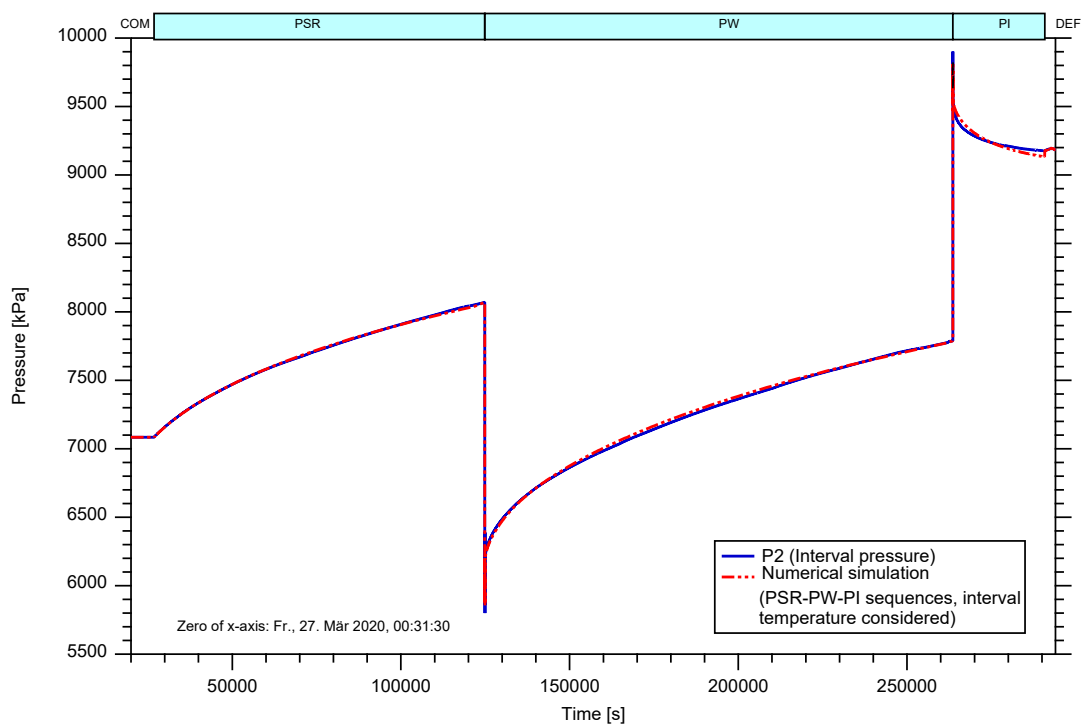


Fig. B-14: Hydraulic test MAR1-1-LIA1: Numerical simulation of the PSR-PW-PI test sequence using a radial homogeneous model considering the borehole pressure history and interval temperature changes

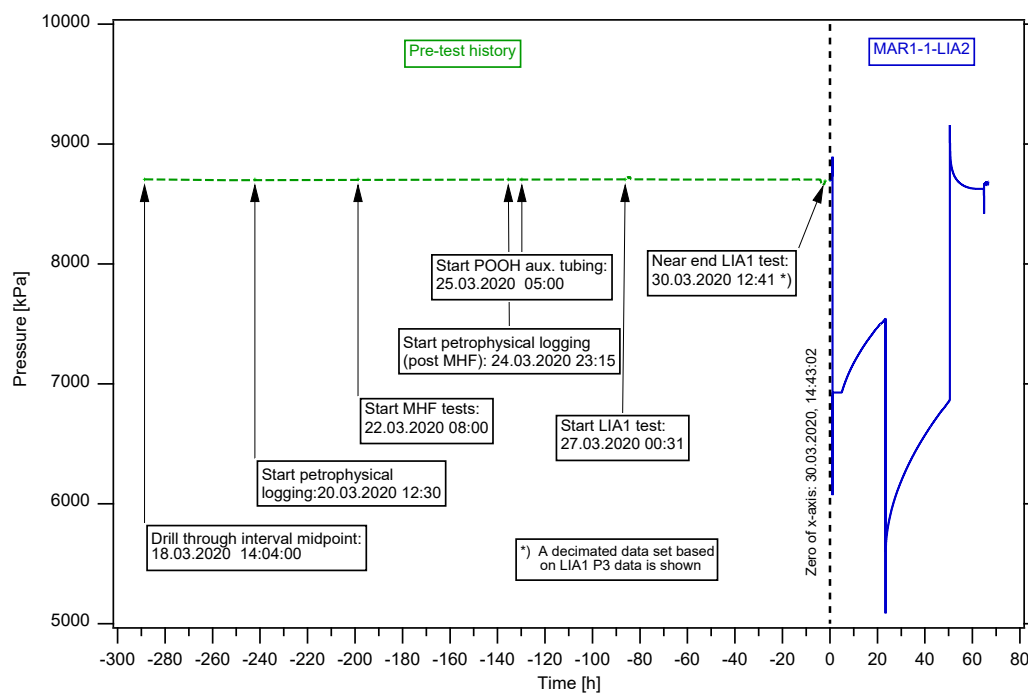


Fig. B-15: Hydraulic test MAR1-1-LIA2: Entire record of the borehole pressure history used in the analysis

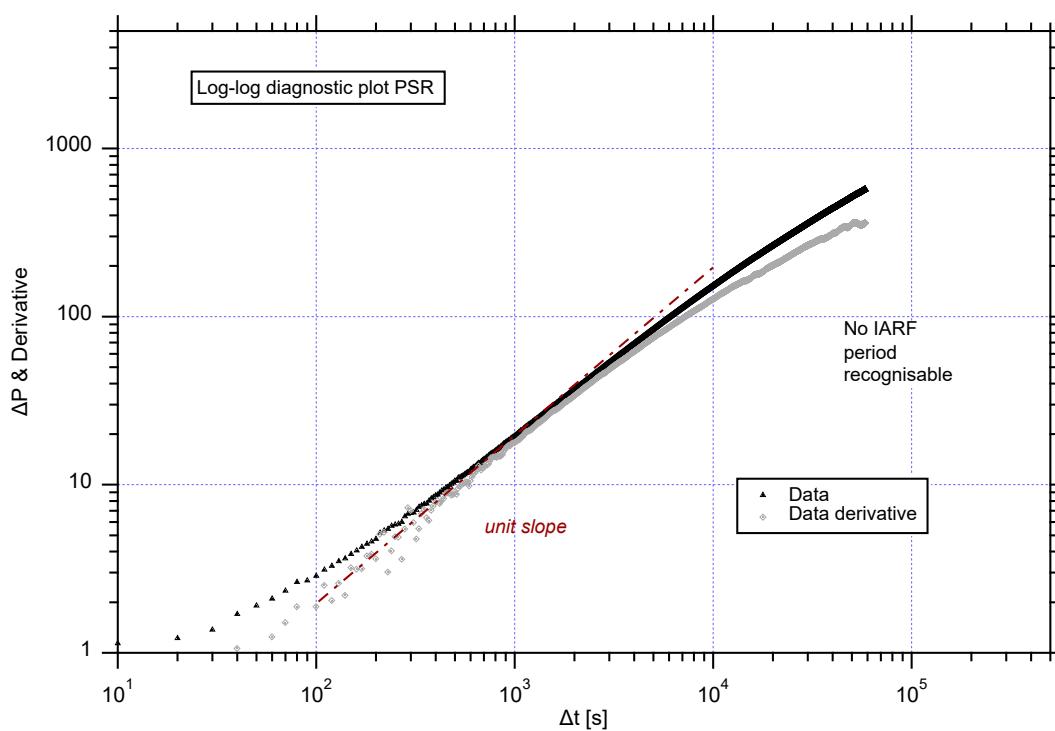


Fig. B-16: Hydraulic test MAR1-1-LIA2: Log-log diagnostic plot of PSR, no superposition

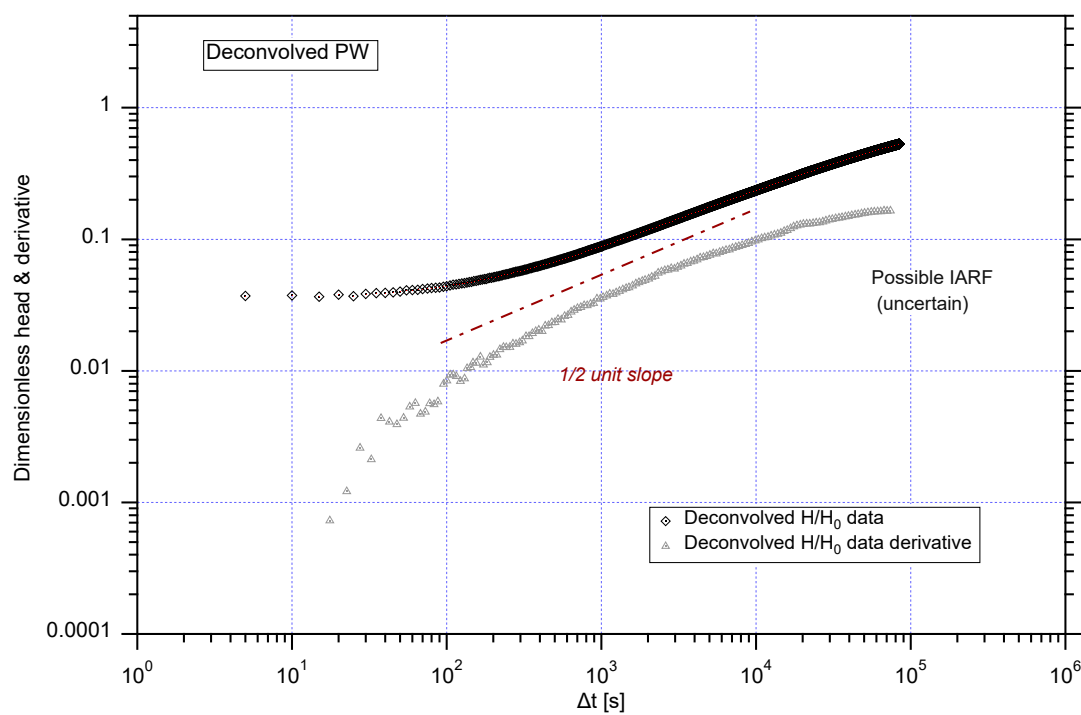


Fig. B-17: Hydraulic test MAR1-1-LIA2: Log-log diagnostic plot of PW, Peres deconvolution

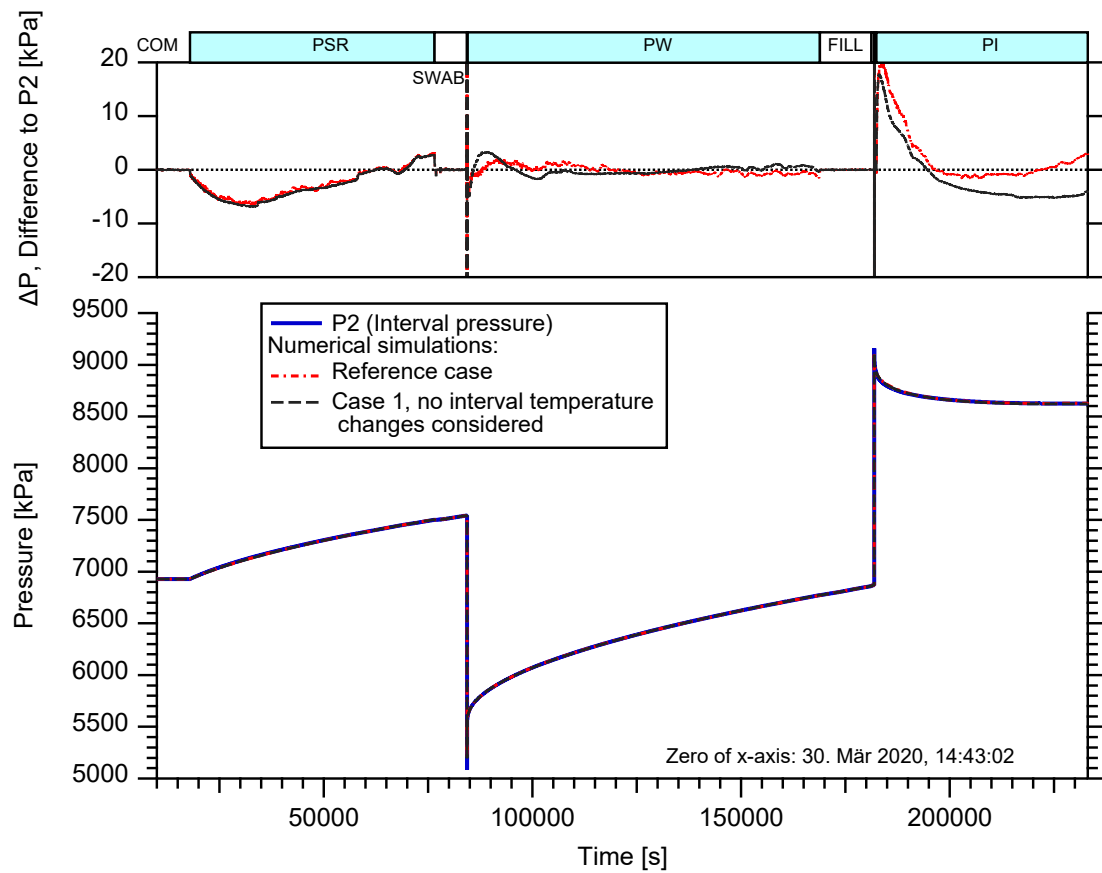


Fig. B-18: Hydraulic test MAR1-1-LIA2: Numerical simulation of the PSR-PW-PI test sequence using a radial composite flow model considering only the borehole pressure history; comparison of the pressure residual as a function of time with the simulation considering the borehole pressure history and the interval temperature change (reference case)

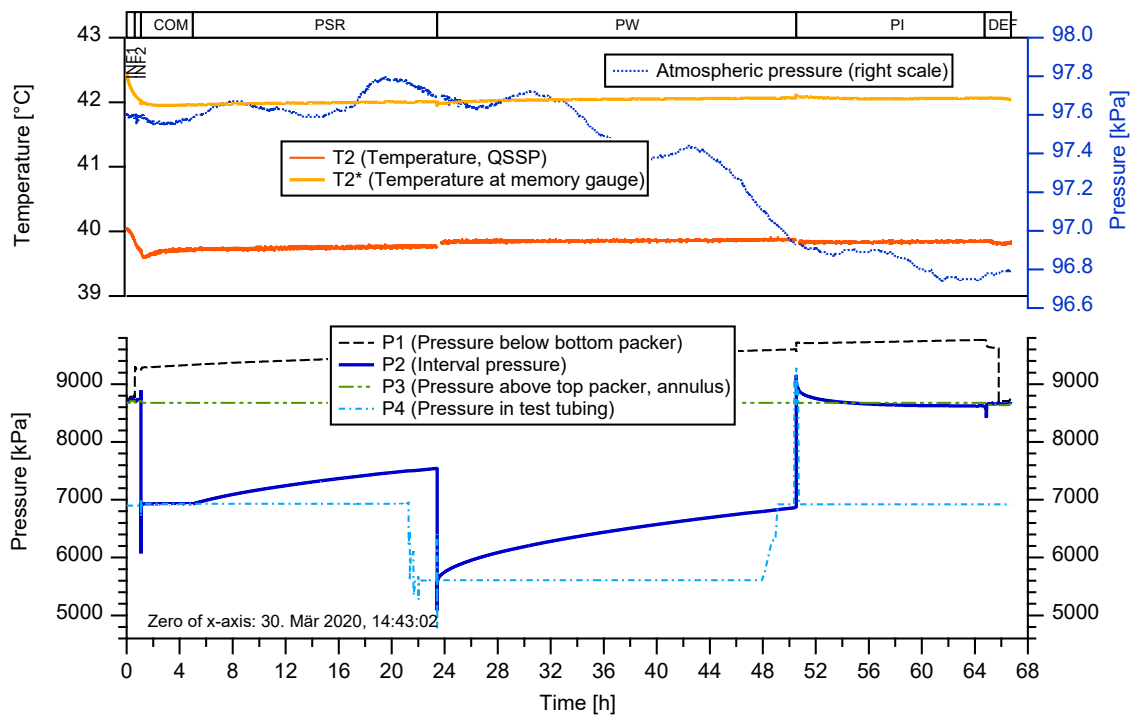


Fig. B-19: Hydraulic test MAR1-1-LIA2: Downhole temperature (T2 and T2*) and atmospheric pressure in comparison to the downhole QSSP pressure measurements

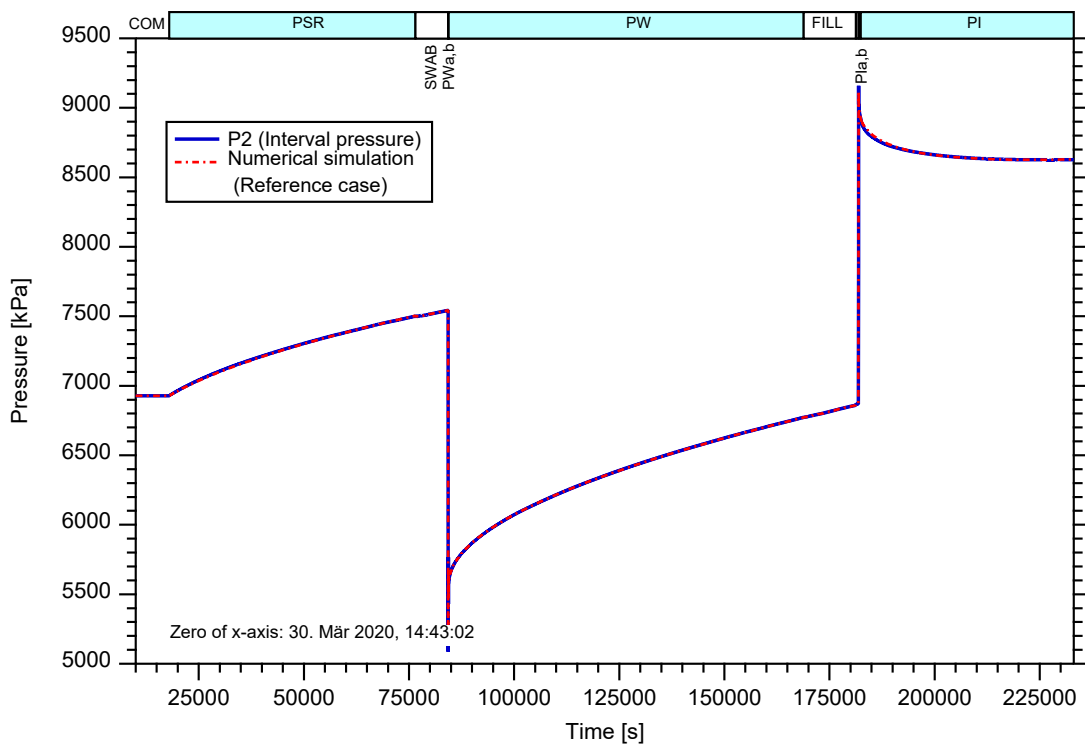


Fig. B-20: Hydraulic test MAR1-1-LIA2: Numerical simulation of the PSR-PW-PI test sequence using a radial composite flow model considering the borehole pressure history and the observed interval temperature changes

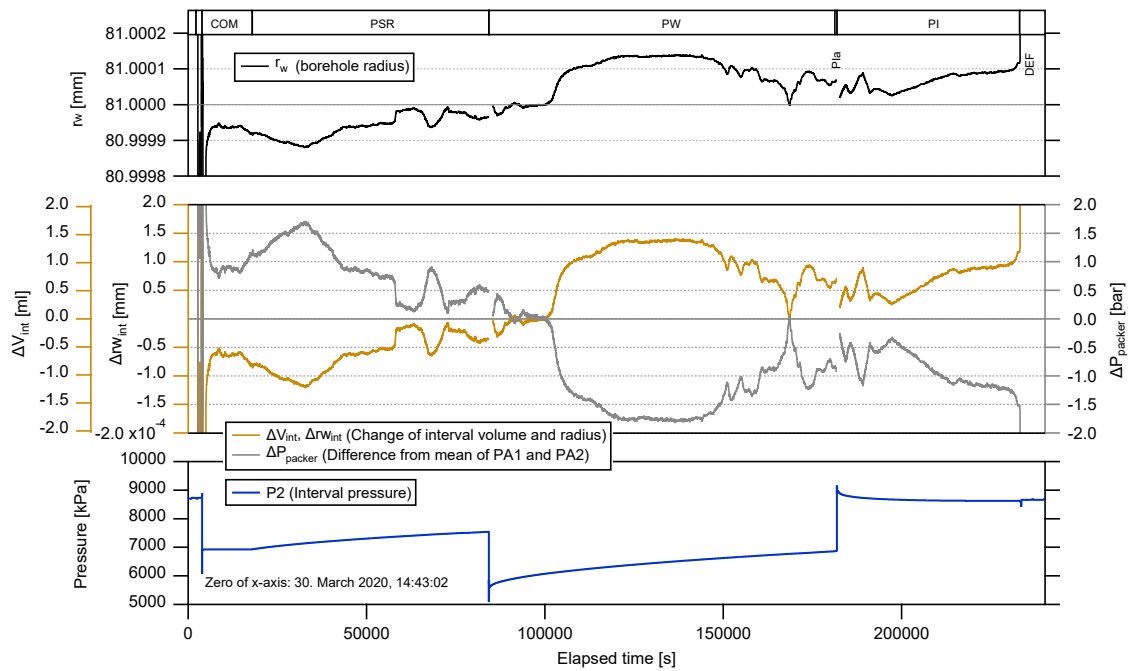


Fig. B-21: Hydraulic test MAR1-1-LIA2: Manipulation of the borehole radius ($r_{w,int}$) in comparison to the causal packer pressure changes (ΔP_{packer}), the interval volume changes (ΔV_{int}) and the pressure measurement of sensor P2

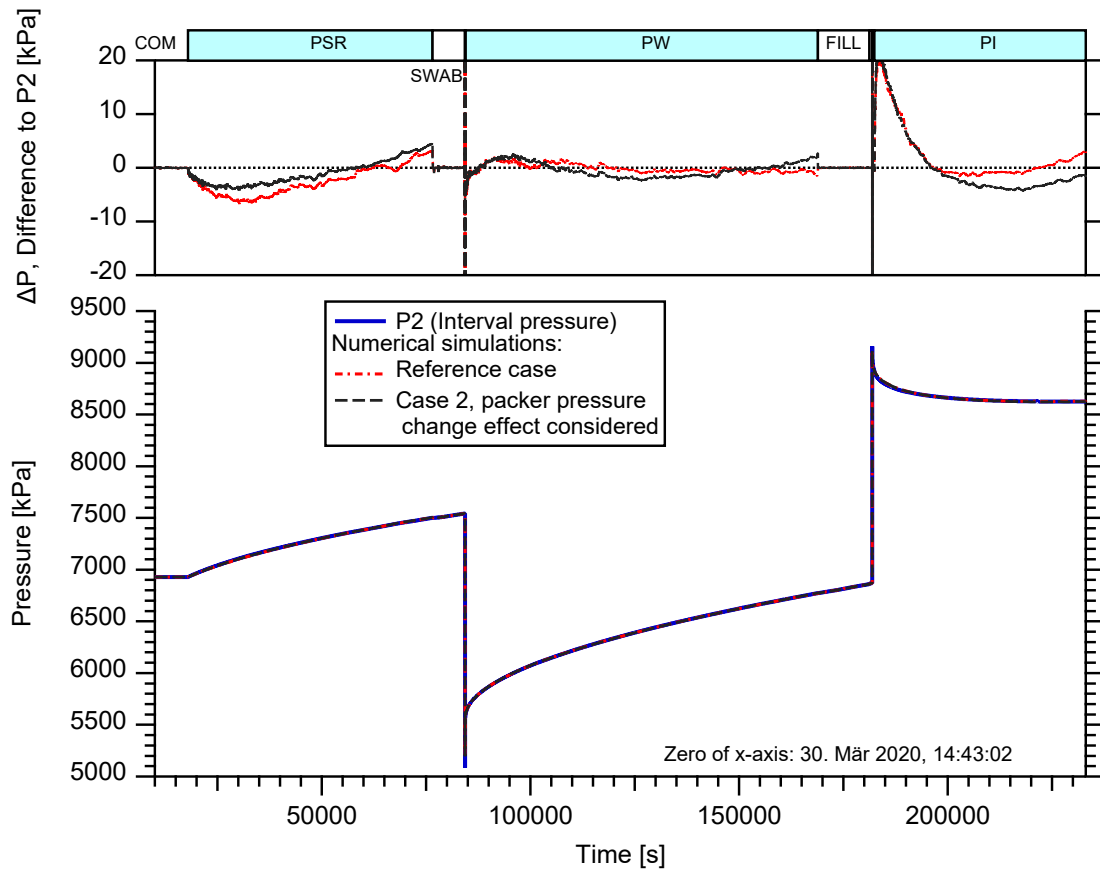


Fig. B-22: Hydraulic test MAR1-1-LIA2: Numerical simulation of the PSR-PW-PI test sequence using a radial composite flow model considering the borehole pressure history, interval temperature changes and packer pressure changes due to surface temperature changes; comparison of the pressure residual as a function of time with the simulation considering the borehole pressure history and the interval temperature change (reference case)

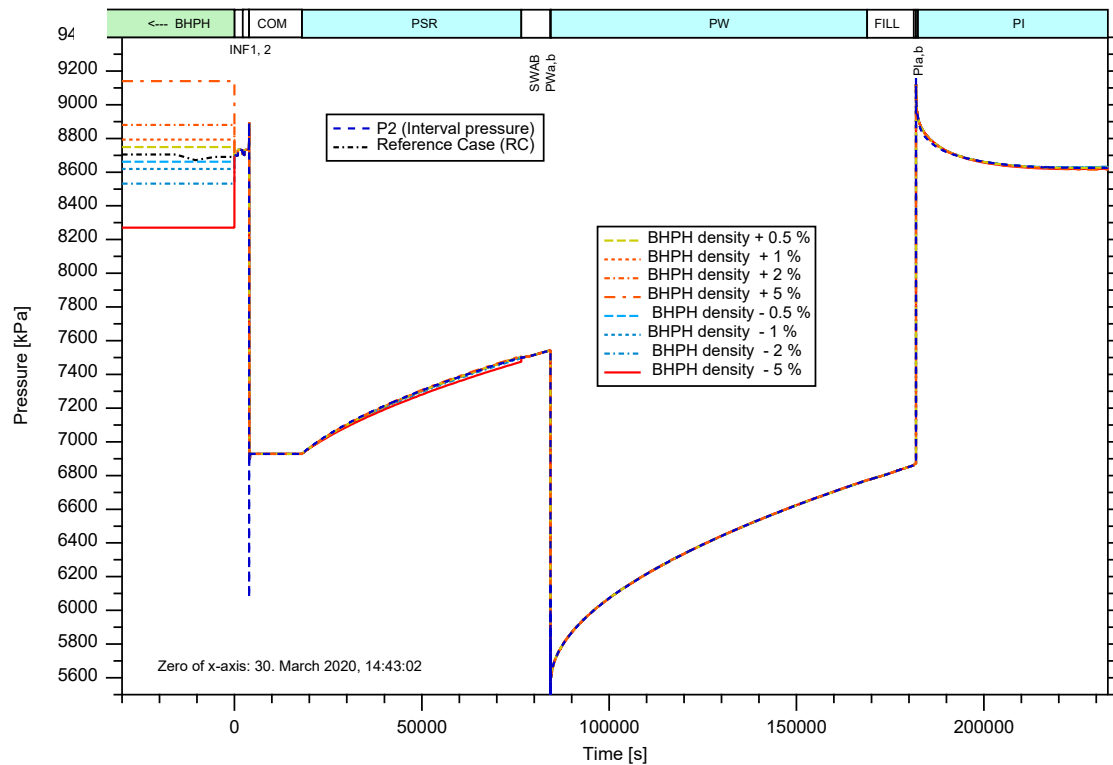


Fig. B-23: Hydraulic test MAR1-1-LIA2: Numerical simulations of the PSR-PW-PI test sequence in a Cartesian pressure plot using a radial composite flow model considering interval temperature changes and applying different borehole pressure history scenarios

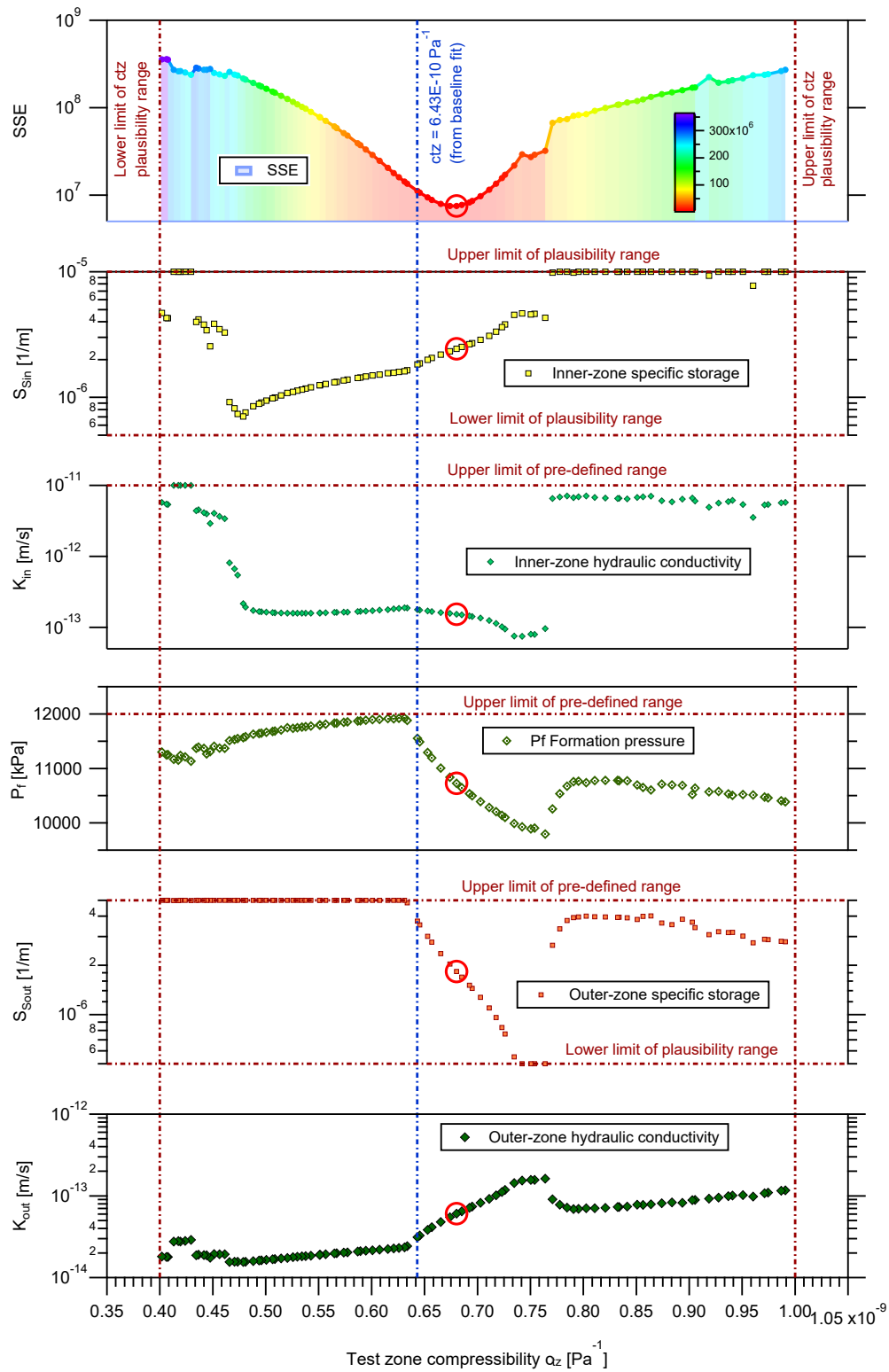


Fig. B-24: Hydraulic test MAR1-1-LIA2: Sampling analysis of the PSR-PW-PI sequence, c_{tz} of PW is sampled, with parameter ranges of the parameters K_{out} , S_{Sout} , K_{in} , S_{Sin} and P_f together with respective SSE values against c_{tz} value

Red circle shows lowest SSE, blue line shows c_{tz} value used for other simulations.

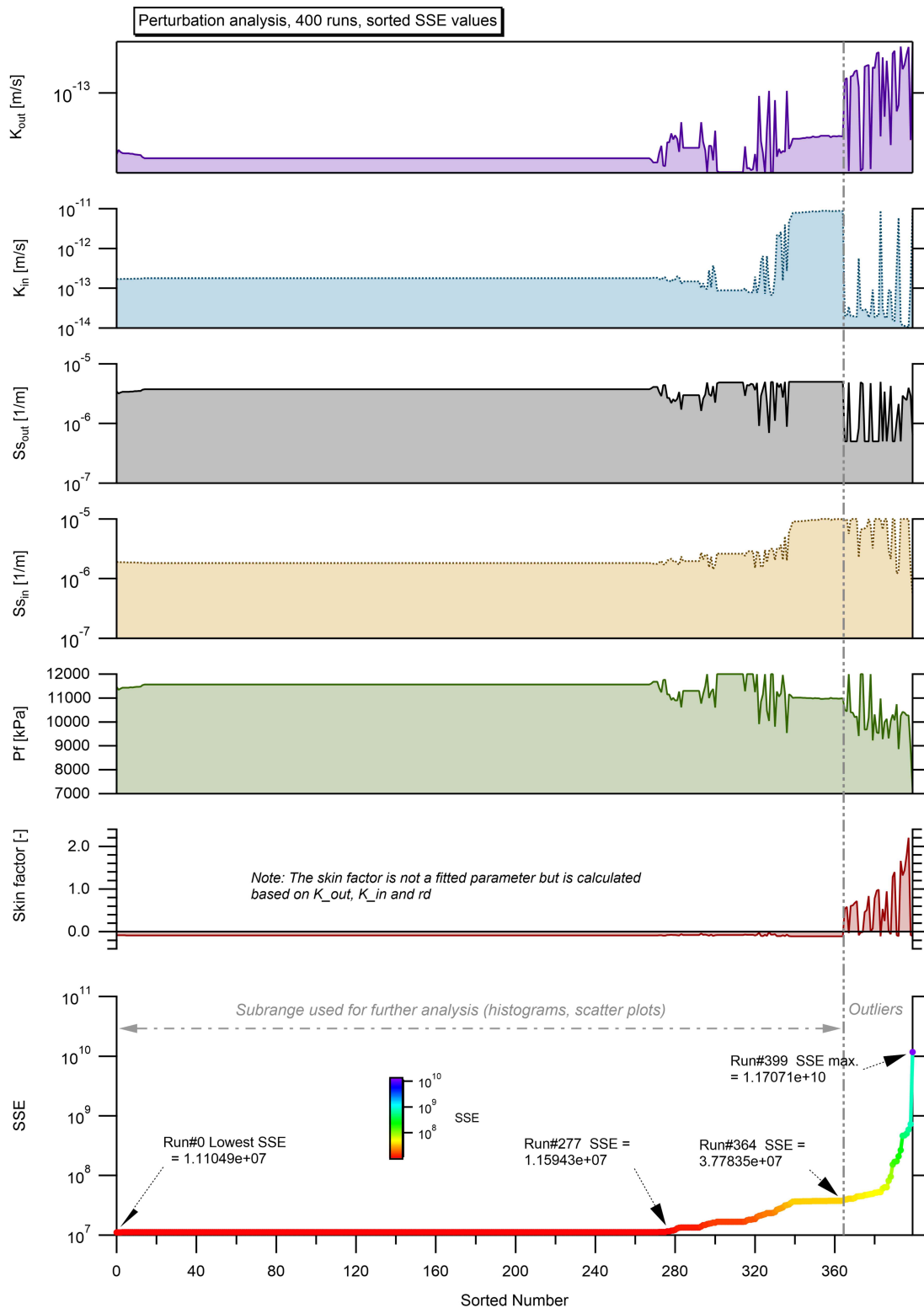


Fig. B-25: Hydraulic test MAR1-1-LIA2: Results of the perturbation analysis of PSR-PW-PI sequence using a radial composite model considering interval temperature changes

Sorted by the least squared error of the simulations in combination with the associated parameter estimates; the subrange used for the interpretation of the parameter ranges is indicated by the grey dashed line with arrows

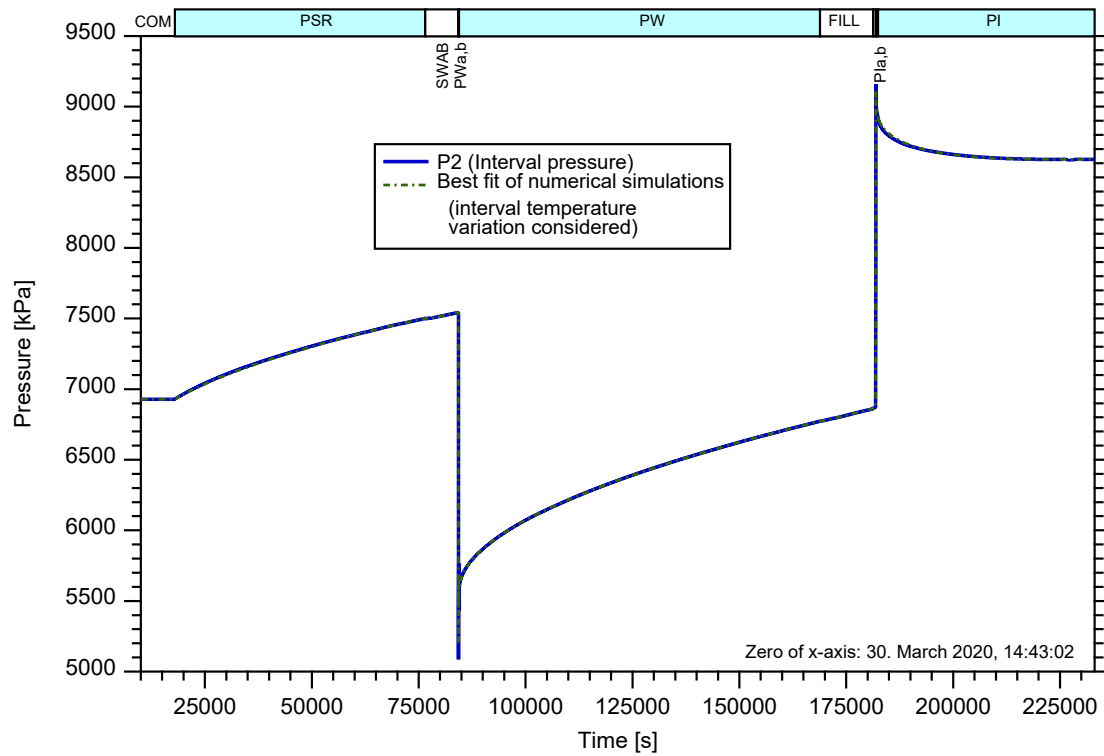


Fig. B-26: Hydraulic test MAR1-1-LIA2: Best simulation of the PSR-PW-PI sequence using a radial composite model considering the borehole pressure history and interval temperature changes