

Arbeitsbericht NAB 21-21

**TBO Bözberg-1-1:
Data Report**

**Dossier VII
Hydraulic Packer Testing**

February 2022

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

Hardstrasse 73
P.O. Box 280
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11

www.nagra.ch

Arbeitsbericht NAB 21-21

**TB0 Bözberg-1-1:
Data Report**

**Dossier VII
Hydraulic Packer Testing**

February 2022

R. Schwarz¹, R. Beauheim², S.M.L. Hardie³,
M. Voß¹ & A. Pechstein⁴

¹CSD Ingenieure AG

²INTERA Incorporated

³Schwarz Hara Consult

⁴Nagra

Keywords:

BOZ1-1, Jura Ost, TB0, deep drilling campaign, hydrogeology,
hydraulic packer tests, hydraulic conductivity, hydraulic head,
fluid logging, gas threshold pressure test equipment

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

Hardstrasse 73
P.O. Box 280
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11

www.nagra.ch

Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

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

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

This Dossier was prepared by a project team consisting of:

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

R. Beauheim (performance and analysis of the hydraulic packer tests)

S.M.L. Hardie (writing)

M. Voß (writing)

A. Pechstein (project management, conceptualisation and review)

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 INTERA Inc. for the hydraulic packer tests (R. Beauheim, R. Roberts (HydroResolutions LLC), A. Dausse, T. Cavallera, J. Croisé, A. Färber, M. Fort (HydroResolutions LLC) and B. Paris) and Solexperts AG / Terratec Geophysical Services GmbH & Co. KG (U. Rösli, G. Mühlebach, A. Maqueda (AFRY) and R. Brauchler (AFRY)).

Editorial work: P. Blaser and M. Unger

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

"Copyright © 2022 by Nagra, Wettingen (Switzerland) / All rights reserved.

All parts of this work are protected by copyright. Any utilisation outwith the remit of the copyright law is unlawful and liable to prosecution. This applies in particular to translations, storage and processing in electronic systems and programs, microfilms, reproductions, etc."

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 BOZ1-1 borehole	6
1.4 Structure and objectives of this dossier	7
2 Strategy for the hydrogeological investigations	9
2.1 Hydrogeological objectives of the TBO boreholes.....	9
2.2 Hydrogeological investigation concept for BOZ1-1	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 Flowmeter-temperature-conductivity-gamma probe	12
3.1.4 Temperature-conductivity-gamma probe	13
3.1.5 High-resolution flowmeter-gamma probe	14
3.1.6 Gamma sensors.....	15
3.1.7 Temperature-electrical conductivity meter.....	16
3.1.8 Centraliser.....	16
3.1.9 Field analysis IT structure	16
3.2 Performance and analysis	17
3.2.1 Description of measurements performed.....	17
3.2.2 Analysis of pumping test data.....	21
3.2.3 Fluid logging analysis.....	21
3.3 Summary and discussion of fluid logging results.....	26
4 Hydraulic packer test	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
4.2.1.10	Piston pulse generator.....	41
4.2.2	Surface equipment	41
4.2.2.1	Flow board.....	42
4.2.2.2	Packer pressure-maintenance system.....	43
4.2.2.3	Additional 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	48
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.....	68
4.5.1	Hydraulic packer test BOZ1-1-PWF1	68
4.5.1.1	Interval characterisation.....	68
4.5.1.2	Test execution.....	68
4.5.1.3	Analysis	71
4.5.2	Hydraulic packer test BOZ1-1-KEU1	75
4.5.2.1	Interval characterisation.....	75
4.5.2.2	Test execution.....	76
4.5.2.3	Analysis	78
4.6	Summary and discussion of hydraulic tests.....	83
4.6.1	Summary tables and plots.....	83
4.6.2	Discussion of data and test results	93
5	Summary	95
6	References.....	97
Appendix A: Abbreviations, nomenclature and definitions		A-1
Appendix B: Analysis plots of the hydraulic packer tests BOZ1-1-PWF1 and BOZ1-1-KEU1		B-1

List of Tables

Tab. 1-1:	General information about the BOZ1-1 borehole.....	2
Tab. 1-2:	Core and log depth for the main lithostratigraphic boundaries in the BOZ1-1 borehole	5
Tab. 1-3:	List of dossiers included in NAB 21-21	6
Tab. 3-1:	Specifications of borehole logging winch	11
Tab. 3-2:	Specifications of matrix logger.....	12
Tab. 3-3:	Specifications of the flowmeter-temperature-conductivity-gamma probe	13
Tab. 3-4:	Specifications of the temperature-conductivity-gamma probe	14
Tab. 3-5:	Specifications of the high-resolution flowmeter-gamma probe.....	15
Tab. 3-6:	Specifications of the temperature-electrical conductivity meter.....	16
Tab. 3-7:	Specifications of the centraliser.....	16
Tab. 3-8:	Specifications of the IT structure for field analysis	17
Tab. 3-9:	Fluid logging BOZ1-1-FL1-MAL: Information on the test interval	17
Tab. 3-10:	Logging activities of BOZ1-1-FL1-MAL.....	18
Tab. 3-11:	Inflow zones detected qualitatively by BOZ1-1-FL1-MAL.....	21
Tab. 3-12:	BOZ1-1-FL1-MAL: Estimated hydraulic parameters derived from pumping test analyses 1, 2 and 3 in the framework of fluid logging in borehole BOZ1-1	21
Tab. 3-13:	BOZ1-1-FL1-MAL: Estimated hydraulic parameters resulting from the analyses of the fluid logging data	22
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 PC pump	40
Tab. 4-13:	Specifications for the PPG.....	41
Tab. 4-14:	Specifications for the flowmeters	42
Tab. 4-15:	Specifications for the atmospheric pressure sensor	44

Tab. 4-16:	Specifications for the physico-chemical sensors	44
Tab. 4-17:	Specifications for the 146 mm packers for the GTPT	48
Tab. 4-18:	Specifications for the zero-displacement shut-in tool (SIT1) for the GTPT	50
Tab. 4-19:	Specifications for the gas flow controller / meters for the GTPT	50
Tab. 4-20:	Summary of analytical analysis methods.....	52
Tab. 4-21:	Specific periods of the pre-test borehole pressure history	56
Tab. 4-22:	Hydraulic packer testing in borehole BOZ1-1: test interval and test specifications.....	59
Tab. 4-23:	Hydraulic test BOZ1-1-PWF1: Information on the test interval	68
Tab. 4-24:	Hydraulic test BOZ1-1-PWF1: Borehole pressure history	71
Tab. 4-25:	Hydraulic test BOZ1-1-PWF1: Formation parameter estimation based on the perturbation analysis of PW using a radial composite flow model considering the borehole pressure history and temperature changes inside the test interval	72
Tab. 4-26:	Hydraulic test BOZ1-1-PWF1: Formation parameter estimation based on the perturbation analysis of PI using a radial composite flow model considering the borehole pressure history and temperature changes inside the test interval	73
Tab. 4-27:	Hydraulic test BOZ1-1-PWF1: Formation parameter estimation based on the perturbation analysis of the sequence PSR-PW-PI using a radial composite flow model considering the borehole pressure history and temperature changes inside the test interval	74
Tab. 4-28:	Hydraulic test BOZ1-1-PWF1: Best estimates of the formation parameters and associated uncertainty ranges.....	75
Tab. 4-29:	Hydraulic test BOZ1-1-KEU1: Test interval information	76
Tab. 4-30:	Hydraulic test BOZ1-1-KEU1: Borehole pressure history	78
Tab. 4-31:	Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the perturbation analysis of PW1 using a radial homogenous flow model with time-dependent skin considering the borehole pressure history and temperature changes inside the test interval	79
Tab. 4-32:	Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the perturbation analysis of PW2 using a radial homogenous flow model with time-dependent skin considering the borehole pressure history and temperature changes inside the test interval	80
Tab. 4-33:	Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the perturbation analysis of PI using a radial homogenous flow model with time- dependent skin considering the borehole pressure history and temperature changes inside the test interval	81
Tab. 4-34:	Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the perturbation analysis of the sequence PW1-PW2-PI using a radial homogenous flow model with time-dependent skin considering the borehole pressure history and temperature changes inside the test interval	81

Tab. 4-35:	Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the analysis of the sequence PW1-PW2-PI using a radial homogenous flow model with time-dependent skin considering the borehole pressure history, temperature changes inside the test interval and different assumptions on the hydraulic conductivity during the history	82
Tab. 4-36:	Hydraulic test BOZ1-1-KEU1: Best estimates of the formation parameters and associated uncertainty ranges.....	83
Tab. 4-37:	Summary of hydraulic packer testing in borehole BOZ1-1: Transmissivity and hydraulic conductivity	84
Tab. 4-38:	Summary of hydraulic packer testing in borehole BOZ1-1: Hydraulic head estimates	85
Tab. 4-39:	Summary of hydraulic packer testing in borehole BOZ1-1: Permeability	87
Tab. A-1:	Lithostratigraphy abbreviations for test names in BOZ1-1	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 Jura Ost siting region with the location of the BOZ1-1 borehole in relation to the boreholes Riniken and BOZ2-1	3
Fig. 1-3:	Lithostratigraphic profile and casing scheme for the BOZ1-1 borehole	4
Fig. 3-1:	BOZ1-1-FL1-MAL: Pressure drawdown and the position in time where fluid logging runs were performed	19
Fig. 3-2:	BOZ1-1-FL1-MAL: Measured pumping rates and the position in time where fluid logging runs were performed.....	19
Fig. 3-3:	BOZ1-1-FL1-MAL: Measured electrical conductivity logs (runs), calculated for a temperature of 25 °C	20
Fig. 3-4:	BOZ1-1-FL1-MAL: Measured flow rates recorded during Runs 4, 5, 6, 9 and 10	23
Fig. 3-5:	BOZ1-1-FL1-MAL: 1 st fluid logging analysis of fluid logging Runs 6, 9 and 10; fluid logging analysis results for Runs 9 and 10 are based on the initial concentration distribution of Run 6.....	24
Fig. 3-6:	BOZ1-1-FL1-MAL: 3 rd fluid logging analysis of fluid logging Runs 6, 9 and 10; fluid logging analysis results for Runs 9 and 10 are based on the initial concentration distribution of Run 6.....	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 pressure-maintenance system.....	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 BOZ1-1-MAL1: Overview plot of pressure vs. time and date.....	61
Fig. 4-10:	Hydraulic packer test BOZ1-1-PWF1: Overview plot of pressure vs. time and date.....	61
Fig. 4-11:	Hydraulic packer test BOZ1-1-PWF2: Overview plot of pressure vs. time and date.....	62
Fig. 4-12:	Hydraulic packer test BOZ1-1-OPA1: Overview plot of pressure vs. time and date.....	62

Fig. 4-13:	Hydraulic packer test BOZ1-1-OPA2: Overview plot of pressure vs. time and date.....	63
Fig. 4-14:	Hydraulic packer test BOZ1-1-OPA3: Overview plot of pressure vs. time and date.....	63
Fig. 4-15:	Hydraulic packer test BOZ1-1-OPA4: Overview plot of pressure vs. time	64
Fig. 4-16:	Hydraulic packer test BOZ1-1-LIA1: Overview plot of pressure vs. time.....	64
Fig. 4-17:	Hydraulic packer test BOZ1-1-LIA2: Overview plot of pressure vs. time.....	65
Fig. 4-18:	Hydraulic packer test BOZ1-1-KEU1: Overview plot of pressure vs. time and date.....	65
Fig. 4-19:	Hydraulic packer test BOZ1-1-MUK1: Overview plot of pressure (top) and rate (bottom) vs. time and date	66
Fig. 4-20:	Hydraulic packer test BOZ1-1-MUK2: Overview plot of pressure (top) and rate (bottom) vs. time and date	67
Fig. 4-21:	Hydraulic test BOZ1-1-PWF1: Downhole equipment installation record with system layout as used in the field test.....	70
Fig. 4-22:	Hydraulic test BOZ1-1-KEU1: Downhole equipment installation record with system layout as used in the field test.....	77
Fig. 4-23:	Summary of hydraulic testing in borehole BOZ1-1: Formation transmissivity profile.....	88
Fig. 4-24:	Summary of hydraulic testing in borehole BOZ1-1: Formation hydraulic conductivity profile.....	89
Fig. 4-25:	Summary of hydraulic testing in borehole BOZ1-1: Static formation pressure profile	90
Fig. 4-26:	Summary of hydraulic testing in borehole BOZ1-1: Formation hydraulic head profile (m bgl)	91
Fig. 4-27:	Summary of hydraulic testing in borehole BOZ1-1: Formation hydraulic head profile (m asl).....	92
Fig. B-1:	Hydraulic test BOZ1-1-PWF1: Entire record of the borehole pressure history used in the analysis	B-1
Fig. B-2:	Hydraulic test BOZ1-1-PWF1: Ramey B diagnostic plot of the PW phase	B-1
Fig. B-3:	Hydraulic test BOZ1-1-PWF1: Ramey B diagnostic plot of the PI phase	B-2
Fig. B-4:	Hydraulic test BOZ1-1-PWF1: Development of the downhole temperature, T_2^* , and pressure, P_2^* , during PW	B-2
Fig. B-5:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PW phase.....	B-3
Fig. B-6:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PW phase.....	B-3

Fig. B-7:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over S_s for the numerical simulation of the PW phase	B-4
Fig. B-8:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over r_s for the numerical simulation of the PW phase	B-4
Fig. B-9:	Hydraulic test BOZ1-1-PWF1: Cartesian horsetail plot of the perturbation simulations on PW accepting the fit discriminator	B-5
Fig. B-10:	Hydraulic test BOZ1-1-PWF1: Ramey A horsetail plot of PW (before the pressure offset) accepting the fit discriminator	B-5
Fig. B-11:	Hydraulic test BOZ1-1-PWF1: Ramey B horsetail plot of PW (before the pressure offset) accepting the fit discriminator	B-6
Fig. B-12:	Hydraulic test BOZ1-1-PWF1: Development of the downhole temperature, T_2^* , and pressure, P_2^* , during PI.....	B-7
Fig. B-13:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PI phase	B-7
Fig. B-14:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PI phase	B-8
Fig. B-15:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over S_s for the numerical simulation of the PI phase	B-8
Fig. B-16:	Hydraulic test BOZ1-1-PWF1: Cartesian horsetail plot of the perturbation simulations on PI accepting the fit discriminator	B-9
Fig. B-17:	Hydraulic test BOZ1-1-PWF1: Ramey A horsetail plot of PI accepting the fit discriminator.....	B-9
Fig. B-18:	Hydraulic test BOZ1-1-PWF1: Ramey B horsetail plot of PI accepting the fit discriminator.....	B-10
Fig. B-19:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of PSR-PW-PI.....	B-10
Fig. B-20:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of PSR-PW-PI.....	B-11
Fig. B-21:	Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over S_s for the numerical simulation of PSR-PW-PI.....	B-11
Fig. B-22:	Hydraulic test BOZ1-1-PWF1: Cartesian horsetail plot of the perturbation simulations on PSR-PW-PI accepting the fit discriminator.....	B-12
Fig. B-23:	Hydraulic test BOZ1-1-PWF1: Ramey A horsetail plot of PW (left) and PI (right) of the PSR-PW-PI simulations accepting the fit discriminator.....	B-12
Fig. B-24:	Hydraulic test BOZ1-1-PWF1: Ramey B horsetail plot of PW (left) and PI (right) of the PSR-PW-PI simulations accepting the fit discriminator.....	B-13

Fig. B-25:	Hydraulic test BOZ1-1-PWF1: Test-interval pressure (P_2^*) and temperature (T_2^*) during PW (left) and PI (right) initiation.....	B-13
Fig. B-26:	Hydraulic test BOZ1-1-PWF1: Jacobian plot of parameter sensitivity during PW.....	B-14
Fig. B-27:	Hydraulic test BOZ1-1-PWF1: Scatter plot of the perturbation results of the hydraulic conductivity versus static formation pressure for PW.....	B-14
Fig. B-28:	Hydraulic test BOZ1-1-KEU1: Entire record of the borehole pressure history used in the analysis.....	B-15
Fig. B-29:	Hydraulic test BOZ1-1-KEU1: Ramey B diagnostic plot of PW1.....	B-15
Fig. B-30:	Hydraulic test BOZ1-1-KEU1: Ramey B diagnostic plot of PW2.....	B-16
Fig. B-31:	Hydraulic test BOZ1-1-KEU1: Development of the downhole temperature, T_2^* , and pressure, P_2 , during PW1.....	B-16
Fig. B-32:	Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PW1 phase.....	B-17
Fig. B-33:	Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PW1 phase.....	B-17
Fig. B-34:	Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the perturbation simulations on PW1 accepting the fit discriminator.....	B-18
Fig. B-35:	Hydraulic test BOZ1-1-KEU1: Ramey A horsetail plot of PW1 accepting the fit discriminator.....	B-18
Fig. B-36:	Hydraulic test BOZ1-1-KEU1: Ramey B horsetail plot of PW1 accepting the fit discriminator.....	B-19
Fig. B-37:	Hydraulic test BOZ1-1-KEU1: Development of the downhole temperature, T_2^* , and pressure, P_2 , during PW2.....	B-19
Fig. B-38:	Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PW2 phase.....	B-20
Fig. B-39:	Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PW2 phase.....	B-20
Fig. B-40:	Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the perturbation simulations on PW2 accepting the fit discriminator.....	B-21
Fig. B-41:	Hydraulic test BOZ1-1-KEU1: Ramey A horsetail plot of PW2 accepting the fit discriminator.....	B-21
Fig. B-42:	Hydraulic test BOZ1-1-KEU1: Ramey B horsetail plot of PW2 accepting the fit discriminator.....	B-22
Fig. B-43:	Hydraulic test BOZ1-1-KEU1: Development of the downhole temperature, T_2^* , and pressure, P_2 , during PI.....	B-22
Fig. B-44:	Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PI phase.....	B-23

Fig. B-45:	Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PI phase	B-23
Fig. B-46:	Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the perturbation simulations on PI accepting the fit discriminator	B-24
Fig. B-47:	Hydraulic test BOZ1-1-KEU1: Ramey A horsetail plot of PI accepting the fit discriminator.....	B-24
Fig. B-48:	Hydraulic test BOZ1-1-KEU1: Ramey B horsetail plot of PI accepting the fit discriminator.....	B-25
Fig. B-49:	Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the sequence PW1-PW2-PI	B-25
Fig. B-50:	Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the sequence PW1-PW2-PI	B-26
Fig. B-51:	Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the best perturbation simulations on PW1-PW2-PI accepting the fit discriminator	B-26
Fig. B-52:	Hydraulic test BOZ1-1-KEU1: Scatter plot of the perturbation results of the hydraulic conductivity versus static formation pressure for the sequence analysis of PW1-PW2-PI.....	B-27
Fig. B-53:	Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the best perturbation simulation on PW1-PW2-PI accepting the fit discriminator for a hydraulic conductivity of the skin zone fixed to $1 \times 10^{-12} \text{ m s}^{-1}$ during the history	B-27
Fig. B-54:	Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the best perturbation simulation on PW1-PW2-PI accepting the fit discriminator for a hydraulic conductivity of the skin zone fixed to $1 \times 10^{-14} \text{ m s}^{-1}$ during the history	B-28

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 Bözberg-1-1 borehole.

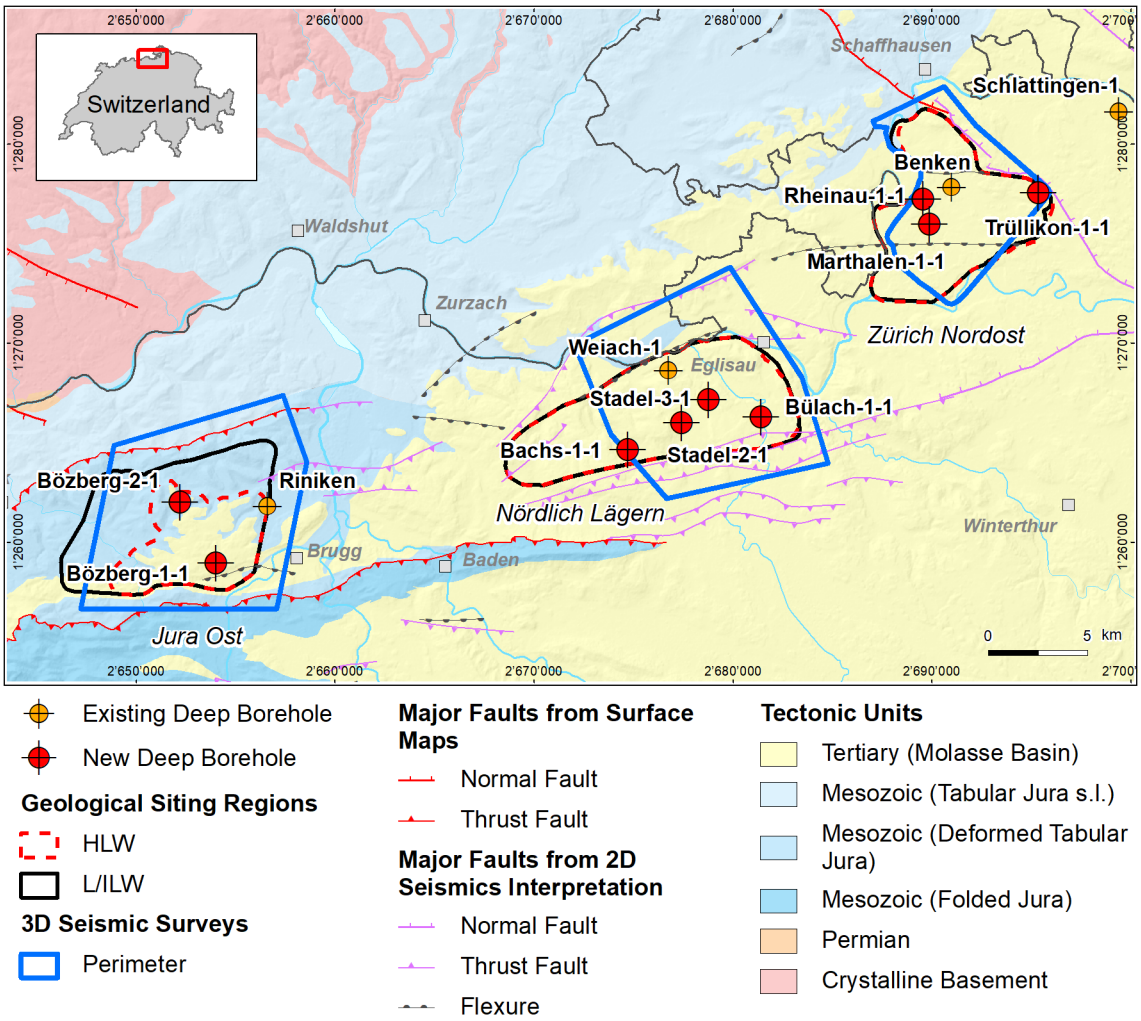


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Bözberg-1-1 (BOZ1-1) exploratory borehole is the fourth borehole drilled within the framework of the TBO project. The drill site is located in the southern part of the Jura Ost siting region (Fig. 1-2). The borehole specifications are provided in Tab. 1-1.

Due to a lost packer system, the borehole was cemented up to 682 m MD¹ (*cf.* Dossier I). Resuming coring operations, a sidetrack was initiated with a kickoff point (KOP) at 709 m MD. This sidetrack was labelled Bözberg-1-1B (BOZ1-1B). BOZ1-1B reached a final depth of 1'037.39 m MD. For easier communication and labelling, the name BOZ1-1 is generally used for this borehole, including the sidetrack, unless stated otherwise.

Tab. 1-1: General information about the BOZ1-1 borehole

Siting region	Jura Ost
Municipality	Bözberg (Canton Aargau / AG), Switzerland
Drill site	Bözberg-1 (BOZ1)
Borehole	Bözberg-1-1 (BOZ1-1) including sidetrack Bözberg-1-1B (BOZ1-1B)
Coordinates	LV95: 2'653'995.815 / 1'258'925.446
Elevation	Ground level = top of rig cellar: 513.29 m above sea level (asl)
Borehole depth	1'037.39 m measured depth (MD) below ground level (bgl) for BOZ1-1B
Drilling period	27th April 2020 – 2nd December 2020 (spud date to end of rig release)
Drilling company	PR Marriott Drilling Ltd
Drilling rig	Rig-16 Drillmec HH102
Drilling fluid	Water-based mud with various amounts of different components such as ² : 0 – 250 m: Polymers 250 – 882 m: Potassium silicate & polymers 882 – 1'037.39 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 BOZ1-1 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.

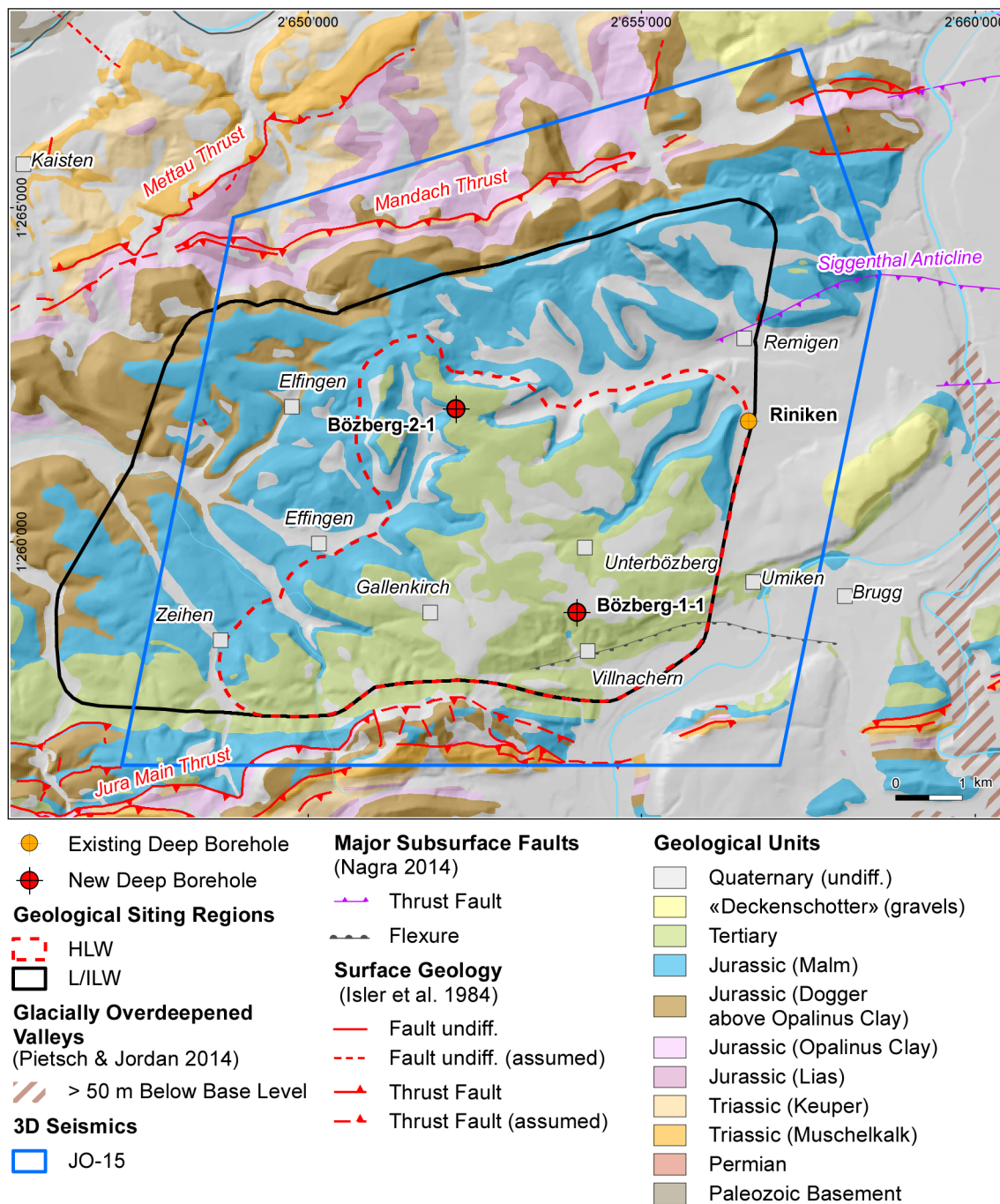
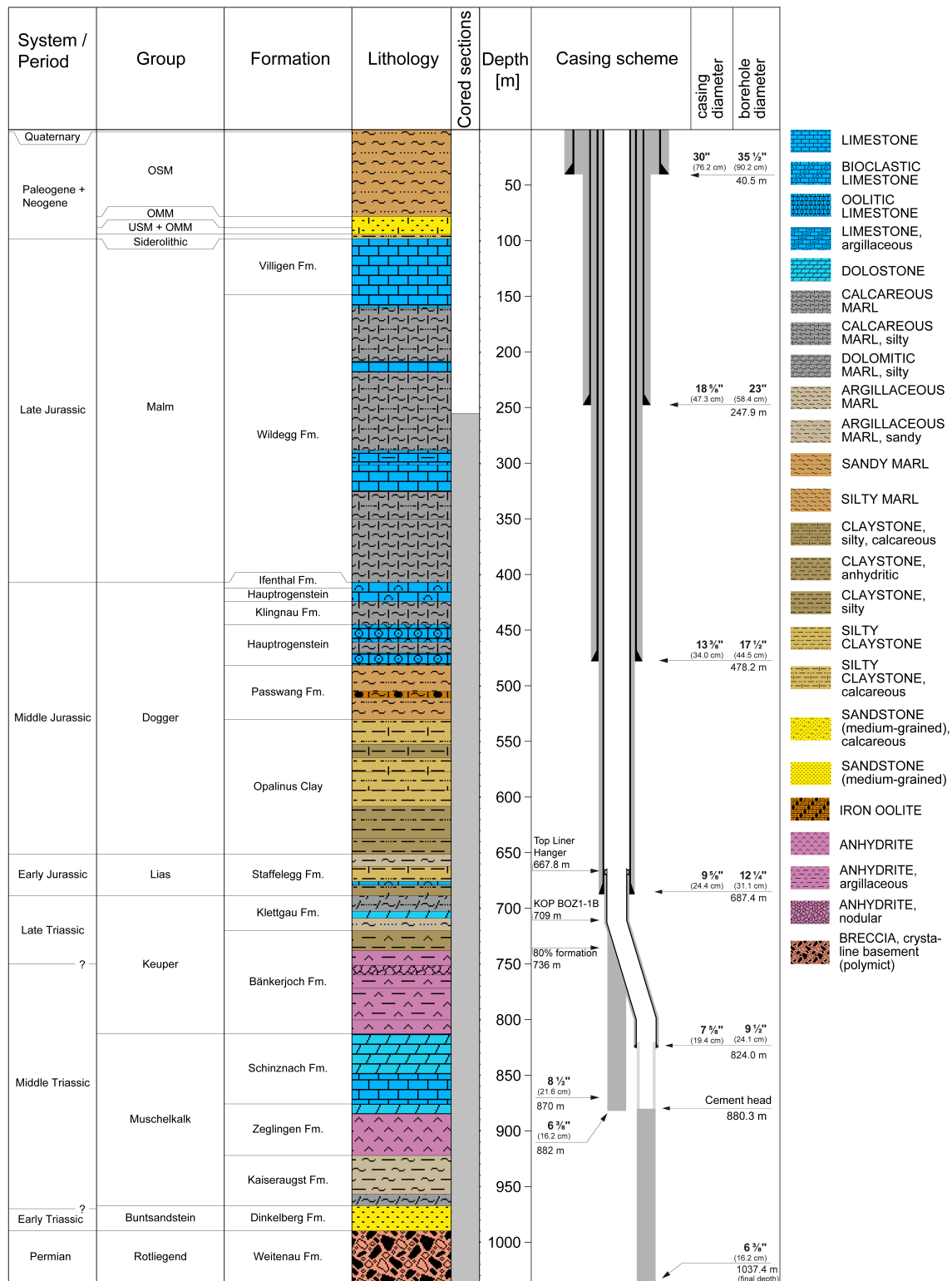


Fig. 1-2: Overview map of the investigation area in the Jura Ost siting region with the location of the BOZ1-1 borehole in relation to the boreholes Riniken and BOZ2-1

Fig. 1-3: Lithostratigraphic profile and casing scheme for the BOZ1-1 borehole⁴⁴ For detailed information see Dossier I and III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the BOZ1-1 bore-hole⁵

System / Period	Group	Formation	Core depth in m (MD)	Log
Quaternary			2	—
Paleogene + Neogene	OSM		78	—
	OMM		88	—
	USM / OMM		94	—
	Siderolithic		98	—
Jurassic	Malm	Villigen Formation	148	—
		Wildegge Formation	406.67	406.72 —
	Dogger	Ifenthal Formation	411.91	411.94 —
		Hauptrogenstein	424.11	424.13 —
		Klingnau Formation	444.85	444.93 —
		Hauptrogenstein	481.50	481.55 —
		Passwang Formation	530.28	530.32 —
		Opalinus Clay	651.39	651.46 —
	Lias	Staffellegg Formation	688.72	688.76 —
Triassic	Keuper	Klettgau Formation	720.03	720.21 —
		Bänkerjoch Formation	812.62	812.45 —
	Muschelkalk	Schinznach Formation	875.89	876.05 —
		Zeglingen Formation	922.22	922.30 —
		Kaiseraugst Formation	967.38	967.70 —
	Buntsandstein	Dinkelberg Formation	989.89	989.83 —
Permian	Rotliegend	Weitenau Formation	1037.39 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 BOZ1-1 borehole

NAB 21-21 documents the majority of the investigations carried out in the BOZ1-1 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 BOZ1-1 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 21-21

Black indicates the dossier at hand.

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

1.4 Structure and objectives of this dossier

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

Borehole BOZ1-1 was the second 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 BOZ1-1 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, fluid logging test activities, and fluid logging test results in borehole BOZ1-1.
- Chapter 4 discusses all aspects of the hydraulic packer tests including planning of test strategies, test equipment used, general concerns for the analysis of tests, test activities, and hydraulic packer test results in borehole BOZ1-1. Selected tests and analyses are presented in detail. The results are summarised in tables and plots, and some assessments are made.
- Chapter 5 summarises and discusses the data and results, mainly for the hydraulic packer tests.

Finally, this report includes a set of appendices, which present relevant general project information and further investigation details.

2 Strategy for the hydrogeological investigations

2.1 Hydrogeological objectives of the TBO boreholes

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

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

2.2 Hydrogeological investigation concept for BOZ1-1

The hydrogeological investigations for BOZ1-1 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 BOZ1-1:

- 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 BOZ1-1 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. (2022). 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, there is a manual brake and a clutch.

Tab. 3-1: Specifications of 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	Cable head is set up to form a weak joint. In the case of a stuck probe, the cable is pulled from the cable head

3.1.2 Matrix logger

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

The probe is a combination of a LIM logging / electromind temperature-electrical-conductivity-gamma probe with an Intergeo impeller flowmeter head. For this reason, the actual dimensions of the probe as mentioned below differ from the dimensions on the manufacturer's data sheet. The probe was assembled on the field contractor's request by electromind. The Intergeo flowmeter head combines a larger diameter (88 mm) with jewelled bearings for the impeller instead of ball bearings which provides improved sensitivity compared to the standard electromind impeller head. For specifications, see Tab. 3-3.

This probe measures fluid temperature, electrical fluid conductivity, vertical fluid velocity and natural gamma rays. The electrical conductivity-temperature sensor is mounted on the side of the probe. Fluid can freely flow through it while going down and up. The flowmeter is an impeller type with a cage of 88 mm and is used if relatively higher fluid flow rates are expected. If lower flow rates are anticipated that might be below the detection limit, the performance of the impeller can be improved by using a diverter disc. The diverter disc seals the annulus between the impeller cage and the borehole wall and forces most of the fluid through the sensor. This increases the fluid velocity at the sensor. Different disks are available to adjust to the borehole diameter.

The diverter disc assembly is made from a base plate that is attached to the probe, and a flexible plastic disc that can be changed depending on the borehole diameter. The base plate for the FTC60G probe is made of Nylon and its dimensions are 140 mm outer diameter, 80 mm inner diameter, 42 mm height.

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

Manufacturer	LIM logging / electromind s.a. 1 Rue de l'Industrie, 4801 Rodange, Grand Duche de Luxembourg + intergeo Haferland AG
Type	FTC60G
Length	1'710 mm
Weight	5.5 kg
Cage diameter	88 mm
Operational temperature range	0 – 70 °C (up to 80 °C for a limited time)
Max. pressure	20 MPa
Borehole diameter range	> 96 mm
Temperature sensor range	0 – 70 °C (up to 80 °C for a limited time)
Temperature sensor accuracy	0.1 °C
Temperature sensor resolution	0.001 °C
Electrical conductivity sensor linear range	0 – 3'000 µS/cm (not on data sheet, information from manufacturer)
Electrical conductivity sensor accuracy	10 µS/cm
Electrical conductivity sensor resolution	1 µS/cm
Flowmeter threshold velocity (static)	1 m/min
Flowmeter impeller sensor resolution (theoretical)	0.003 m/min
Gamma detector	NaI 50 mm × 25 mm crystal

3.1.4 Temperature-conductivity-gamma probe

The probe measures fluid temperature, electrical fluid conductivity and natural gamma rays (for specifications, see Tab. 3-4). 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 at the bottom, flows through the sensor assembly and leaves the probe through openings at the side of the probe a bit further up. This geometry is optimised for logging going down.

Tab. 3-4: 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
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

3.1.5 High-resolution flowmeter-gamma probe

This probe measures vertical fluid velocity and natural gamma rays (for specifications, see Tab. 3-5). The flowmeter is an impeller type with a cage of 45 mm. This probe is used if relatively higher fluid flow rates are expected. If lower flow rates are anticipated which might be below the detection limit, the performance of the impeller can be improved by using a diverter disk.

The diverter disc assembly is made from a base plate that is attached to the probe, and a flexible plastic disc that can be changed depending on the borehole diameter. The base plate for the probe is made of aluminium. The dimensions are: 90 mm outer diameter, 45 mm inner diameter, 11 mm height.

Tab. 3-5: Specifications of the high-resolution flowmeter-gamma probe

Manufacturer	Robertson Geologging Ltd., York Road, Deganwy, Conwy, LL31 9PX, UK
Type	HRFM
Length	1'530 mm
Weight	4.0 kg
Cage diameter	45 mm
Operational temperature range	0 – 70 °C (up to 80 °C for a limited time)
Max. pressure	20 MPa
Borehole diameter range	> 50 mm
Flowmeter threshold velocity (static)	1 m/min (not on data sheet, information from manufacturer)
Flowmeter sensor resolution (theoretical)	4 pulses per impeller revolution, the time between pulses is measured. Resolution of time measurement 20 ms (not on data sheet, information from manufacturer)
Gamma detector	NaI 50 mm × 25 mm crystal

3.1.6 Gamma sensors

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

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

Remarks on accuracy of a gamma measurement (Richards 1981): There is a 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 hand-held digital instrument to measure fluid pH, electrical conductivity and temperature (for specifications, see Tab. 3-6). This meter is used at the workshop to perform the electrical conductivity calibration of the logging tools, and on-site to check the calibration of electrical conductivity and temperature.

Tab. 3-6: 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 measurements being 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. The blades 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 Performance and analysis

Fluid logging was conducted in borehole BOZ1-1 on 27 and 28 May 2020 in the cored borehole Section II. The test is referred to as BOZ1-1-FL1-MAL and comprises the Wildegge Formation of the Malm Group, as well as the Ifenthal Formation, the Klingnau Formation and the Hauptrogenstein of the Dogger Group. The measurements were performed using the temperature-conductivity-gamma probe described in Section 3.1.4. 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 hydraulic packer test results for the interval BOZ1-1-MAL1.

3.2.1 Description of measurements performed

The drilling depth was 480 m MD and the fluid logging was performed to a depth of approximately 475 m MD after a fluid exchange from drilling fluid to tap water. Tab. 3-9 provides the information on the open borehole section. A first fluid logging measurement in borehole BOZ1-1 was performed with a temperature and conductivity probe under static conditions. The data was recorded as fluid logging Runs 1, 2 and 3. The pump was installed on 27.05.2020 at 151.33 m MD. The first production phase (RW1) started with a pumping rate of 300 l/min and ended with a pumping rate of 189 l/min. During this period, the water pressure dropped from 1'458.19 kPa to 259.11 kPa (Fig. 3-1).

Tab. 3-9: Fluid logging BOZ1-1-FL1-MAL: Information on the test interval

Test	Depth		Length [m]	Configuration	Hydraulic testing		
	from [m MD]	to [m MD]			Start date	End date	Duration [h]
BOZ1-1-FL1-MAL	252.00	480.00	228.00	Open borehole	27.05.2020	28.05.2020	13.90

The second phase of the test consisted of the recovery phase (RWR1) after the initial pumping. During this period the water pressure increased from 259.11 kPa to 273.31 kPa (Fig. 3-1).

The third phase of the test consisted of a production phase which was divided into RW2a and RW2, with a maximum pumping rate of 10.5 l/min at the beginning of RW2a (Fig. 3-2). The

reason for the subdivision of the third phase was that the RW2a phase was treated as a prescribed pressure sequence for the pumping test analysis. During phase RW2a the flow rate decreased from 10.5 l/min to 0.4 l/min within 4 hours, and the water pressure dropped from 273.31 kPa to 219.03 kPa. Steady-state conditions were not reached (Fig. 3-1 and Fig. 3-2). During RW2, the pumping rate decreased only slightly from 0.4 l/min to 0.3 l/min over 6 hours (Fig. 3-2) with a pressure decrease from 219.03 kPa to 204.85 kPa. The conditions of RW2 were considered as constant inflow into the borehole.

The fourth and final phase of the test was a recovery phase (RWR2). During this period, the water pressure increased from 204.85 kPa to 214.49 kPa within 18 min.

In total ten fluid-logging runs of electrical conductivity and temperature were carried out. The first 3 logs (Runs 1 to 3) provide the initial profile before pumping. Runs 4 and 5 were performed during a period of varying inflow into the borehole. Due to technical problems, Run 6 was complemented with the data from Runs 7 and 8, which were not provided separately. Only Runs 6 (including Runs 7 and 8), 9 and 10 were conducted under stabilised formation flowrate conditions and therefore selected for quantitative analysis. Tab. 3-10 presents an overview.

The following data was recorded and considered for the analysis:

- Six complete runs of electrical conductivity (corrected to 25 °C equivalent conductivity)⁶
- Pumping test data (pressure and flow rate)

By visual inspection of the electrical conductivity for Runs 4, 5, 6, 9 and 10 (Fig. 3-3), which were carried out during pumping, two hydraulic active features were identified (Tab. 3-11). It should be noted that the identification by visual inspection is precise at the metre scale, due to the relatively diffuse shape of the conductivity curves.

Tab. 3-10: Logging activities of BOZ1-1-FL1-MAL

¹ Due to technical difficulties, Runs 7 and 8 were included in Run 6

Logging run	Hydraulic test sequence	Date	Start time	Start depth [m MD]	End time	End depth [m MD]
1	History	27.05.2020	11:33	257.97	12:24	358.19
2				355.81		412.97
3				410.05		473.27
4	RWR1 + RW2a	27.05.2020	18:36	259.39	19:13	474.68
5	RW2a	27.05.2020	21:12	259.83	21:47	474.66
6 ¹	RW2a + RW2	27.05.2020	22:04	259.93	22:35	474.66
9	RW2	28.05.2020	01:28	272.16	01:58	474.82
10		28.05.2020	04:08	260.58	04:36	430.10

⁶ Due to technical problems which led to a discontinuation in the measurements, the data for Runs 7 and 8 were not provided separately, but instead were included as a part of Run 6. Additionally, Runs 1 to 3 were combined to form the initial profile.

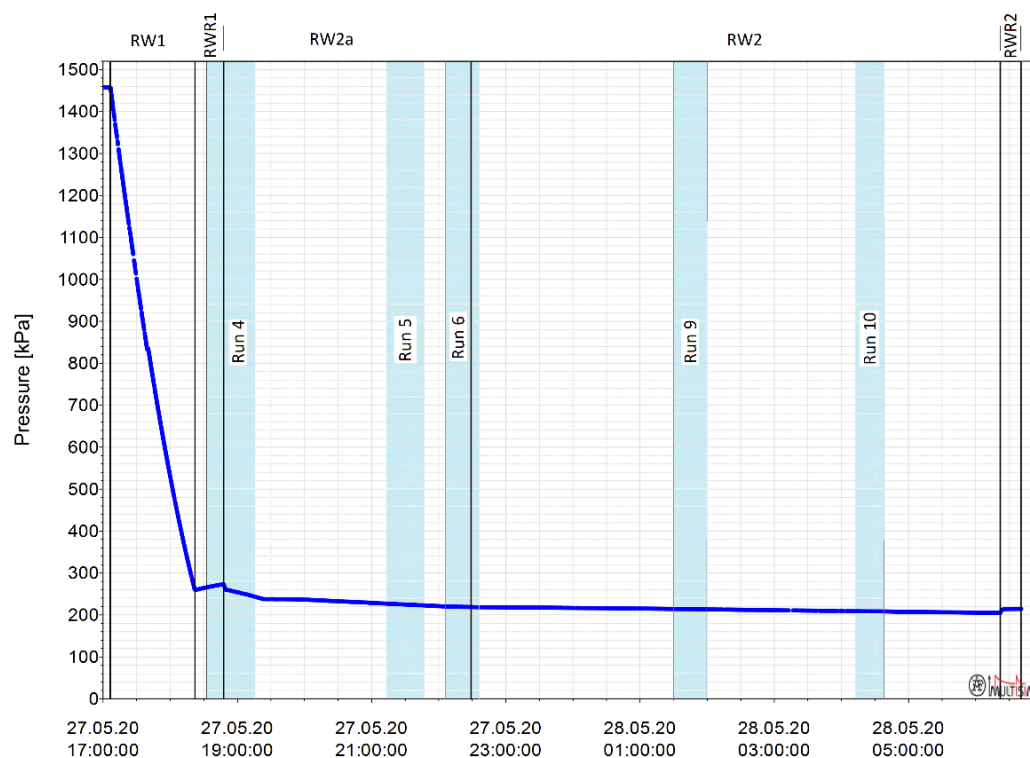


Fig. 3-1: BOZ1-1-FL1-MAL: Pressure drawdown and the position in time where fluid logging runs were performed

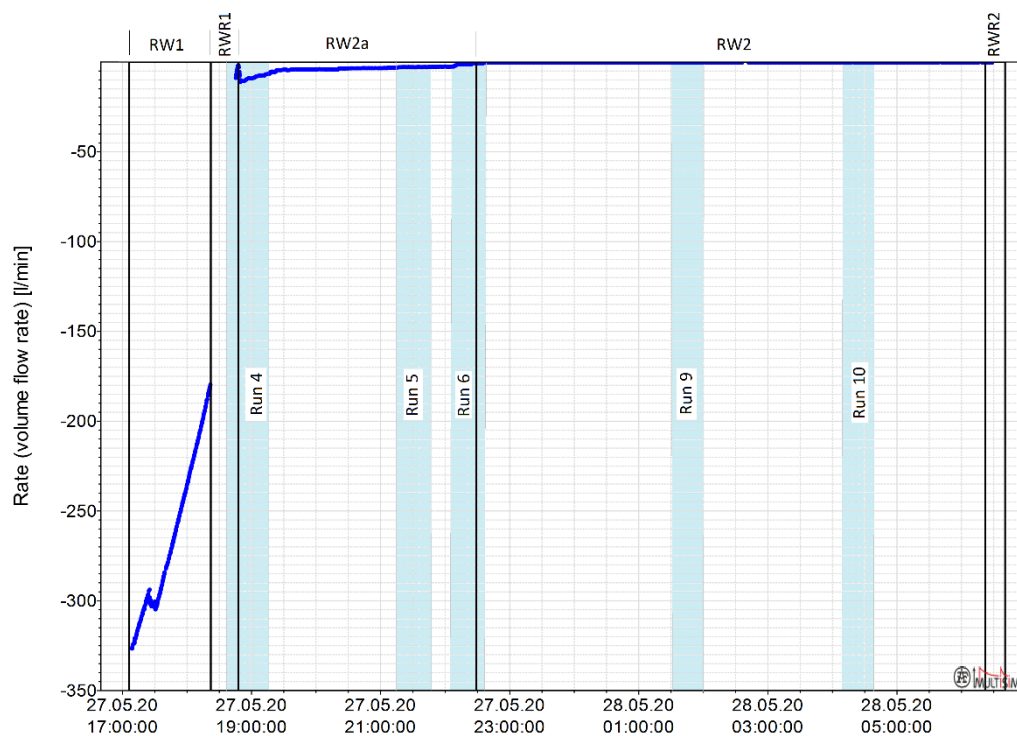


Fig. 3-2: BOZ1-1-FL1-MAL: Measured pumping rates and the position in time where fluid logging runs were performed

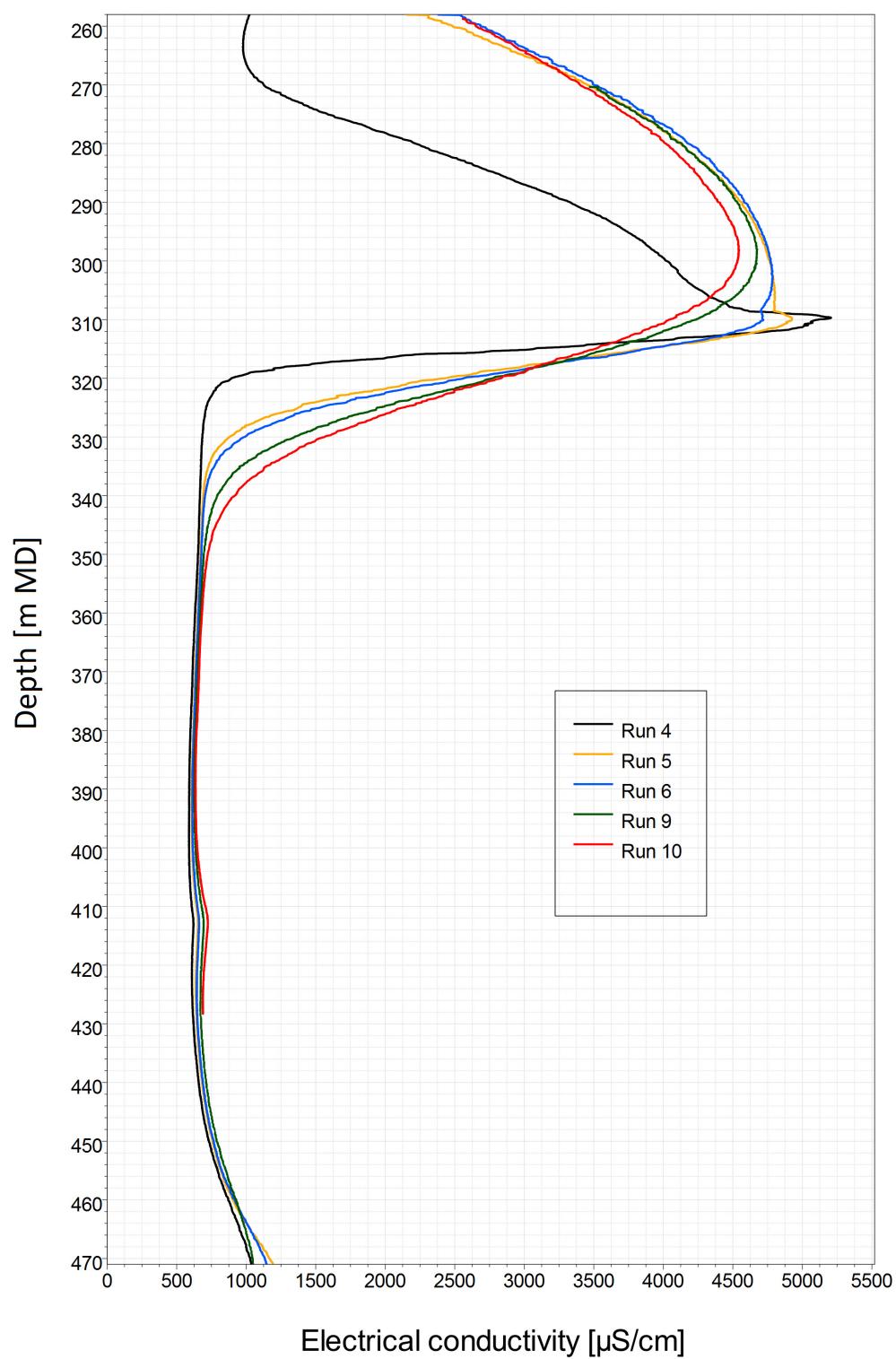


Fig. 3-3: BOZ1-1-FL1-MAL: Measured electrical conductivity logs (runs), calculated for a temperature of 25 °C

Note that the first 3 runs were not included in the visual inspection as they were performed prior to pumping.

Tab. 3-11: Inflow zones detected qualitatively by BOZ1-1-FL1-MAL

Depth [m MD]	Remark
308.00 – 310.00	Indicated by electrical conductivity
412.00 – 414.00	Indicated by electrical conductivity

3.2.2 Analysis of pumping test data

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.

Three analyses were performed and showed that a radial homogeneous model fits the pressure and flow data reasonably well. Analysis 1 comprised only the production phase RW1, analysis 2 the recovery phase RWR1 and analysis 3 was based on production phase RW2 by considering all previous phases as prescribed in the pressure history.

The results of the three pumping test analyses are summarised in Tab. 3-12. The analyses provide a transmissivity of the open borehole section between $2.2 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ and $1.4 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$.

Tab. 3-12: BOZ1-1-FL1-MAL: Estimated hydraulic parameters derived from pumping test analyses 1, 2 and 3 in the framework of fluid logging in borehole BOZ1-1

The fitted parameters are shown in bold.

Parameter	Analysis 1	Analysis 2	Analysis 3
Pumping test phases, considered	RW1	RWR1	RW2
Flow model	Radial homogeneous model	Radial homogeneous model	Radial homogeneous model
Length of test interval [m]	228		
Hydraulic conductivity (K) [m s^{-1}]	6.15×10^{-9}	2.19×10^{-9}	9.57×10^{-11}
Total transmissivity (T) [$\text{m}^2 \text{ s}^{-1}$]	1.40×10^{-6}	4.99×10^{-7}	2.18×10^{-8}
Specific storage (S_s) [m^{-1}]	1.00×10^{-6}	1.00×10^{-6}	1.00×10^{-6}

3.2.3 Fluid logging analysis

The recorded concentration profiles were analysed numerically by the contractor using a 1D numerical transport model and the simulator Multisim. The inflow rates and the concentration of a single fluid log were used as the initial conditions. From this, the concentration distributions of the following fluid logs were computed. Based on fits of the concentration profiles recorded inside the borehole, the inflow zones were determined qualitatively and quantitatively, followed by determination of the transmissivities for the inflow zones using the solution of Cooper & Jacob (1946).

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

Runs 1 – 3 measured the initial distribution of temperature and electrical conductivity before pumping. During Runs 4 and 5, the conditions of constant inflow rate and concentration were not met due to the non-static hydraulic conditions in the borehole. Thus, these runs were not considered for further analysis.

Flow rates within each of the assumed inflow zones were considered to be constant with time (i.e. steady state flow) for fluid logging Runs 6, 9 and 10 during pumping phase RW2, in which the pumping rate caused a minimal decrease of pressure in the borehole (Fig. 3-1). Fluid logging Runs 6, 9 and 10 were analysed considering the pumping rate during pumping phase RW2.

Fig. 3-4 illustrates in more detail, the measured flow rates recorded during pumping phases RW2a and RW2, or Runs 6, 9 and 10, respectively. It can clearly be seen that the flow rates were almost stable, varying only between 0.4 and 0.3 l/min. Therefore, the prerequisite of constant flow into the borehole was considered as partially fulfilled for Runs 6, 9 and 10.

Two analyses were performed with different dispersion coefficients between $0.002 \text{ m}^2 \text{ s}^{-1}$ and $0.0025 \text{ m}^2 \text{ s}^{-1}$ (considering its uncertainty) and different numbers of inflow zones. Additionally, a 3rd simulation was carried out to assess the assumption that the observed concentration development inside the borehole was possible even without a significant inflow. The results are summarised in Tab. 3-13.

Tab. 3-13: BOZ1-1-FL1-MAL: Estimated hydraulic parameters resulting from the analyses of the fluid logging data

Inflow zones	Top [m MD]	Bottom [m MD]	Inflow thickness [m]	Concentration [kg m ⁻³]	Flow rate [l min ⁻¹]	Transmissivity [m ² s ⁻¹]
1 st fluid logging analysis of Runs 6, 9 and 10, dispersion coefficient $2.5 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$						
1	307.00	309.00	2.00	2.5	0.28	3.64×10^{-8}
2	407.00	419.00	12.00	2.4	0.02	2.22×10^{-9}
2 nd fluid logging analysis of Runs 6, 9 and 10, dispersion coefficient $2.0 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$						
1	310.00	312.00	2.00	2.6	0.20	2.67×10^{-8}
2	321.00	324.00	3.00	2.7	0.06	7.55×10^{-9}
3	333.00	335.00	2.00	2.5	0.01	1.95×10^{-9}
4	407.00	419.00	12.00	2.2	0.02	2.22×10^{-9}
3 rd fluid logging analysis of Runs 6, 9 and 10, dispersion coefficient $2.4 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$						
1	252	480	228	0.0	0.00	0

Fig. 3-5 presents the first fluid logging analysis result of Runs 9 and 10. The fluid logging measurements are presented by solid lines, while the simulated concentration distributions are presented by dashed lines. As an initial boundary condition, the concentration distribution of Run 6 was selected and the concentration distribution of Runs 9 and 10 were fitted by applying a fixed

inflow concentration of approximately 2.5 kg m^{-3} and 2.4 kg m^{-3} respectively, for the lower inflow zone. As a result of a previous moment analysis, it was observed that the inflow concentration varied between 2 and 15 kg m^{-3} .

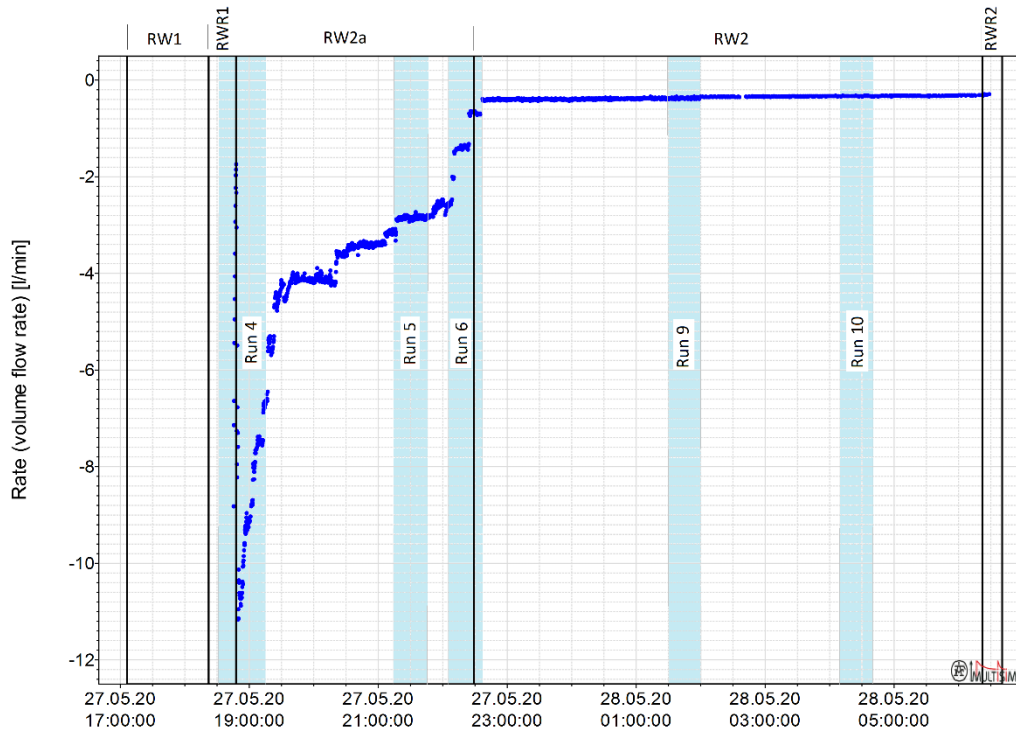


Fig. 3-4: BOZ1-1-FL1-MAL: Measured flow rates recorded during Runs 4, 5, 6, 9 and 10

The first fit was done with two inflow zones and an equivalent constant diffusion coefficient of $0.0025 \text{ m}^2 \text{ s}^{-1}$. The quality of the fits was judged as good, considering only two inflow zones were required to achieve the resulting concentration distribution. The selected diffusion coefficient allowed a good fit for the highest values of electrical conductivity, albeit the fit was not optimal above 290 m MD. Tab. 3-13 provides the parameter estimates for the inflow zones as well as the resulting hydraulic transmissivities.

The second fluid logging analysis was performed considering four inflow zones (three inflow zones for the borehole section around 310 m MD instead of one as in the first analysis) and a diffusion coefficient of $0.002 \text{ m}^2 \text{ s}^{-1}$ which was slightly lower than the value used for the first simulation. This was to be expected because the introduction of additional inflow zones leads to a reduction in dispersion. The fit quality of the concentration peaks for the second simulation was similar to that of the first. Again, Tab. 3-13 provides the estimated parameters of the inflow zones and the resulting hydraulic transmissivities.

The third fluid logging analysis was done considering no inflow zones at all. This means that the evolution of electrical conductivity is driven only by the equivalent diffusion coefficient, which was constant and had a value of $0.0024 \text{ m}^2 \text{ s}^{-1}$. For depths between 270 and 350 m MD the fit of the third analysis was better than for the previous analyses 1 and 2. However, for the lower inflow zone at $\sim 410 \text{ m MD}$ this third analysis provided a lower fit quality. Fig. 3-6 shows the simulation results, Tab. 3-13 the analysis results.

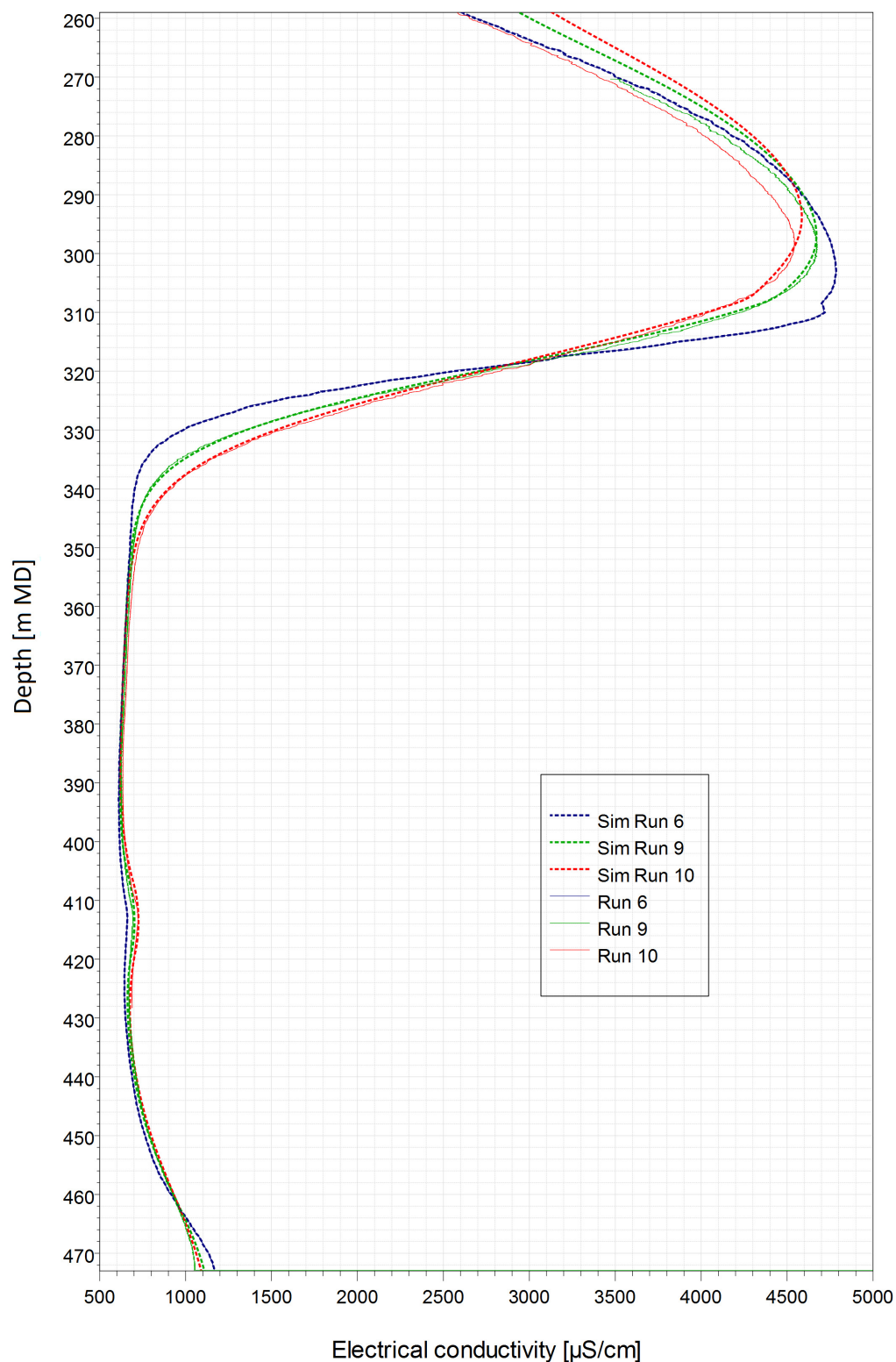


Fig. 3-5: BOZ1-1-FL1-MAL: 1st fluid logging analysis of fluid logging Runs 6, 9 and 10; fluid logging analysis results for Runs 9 and 10 are based on the initial concentration distribution of Run 6

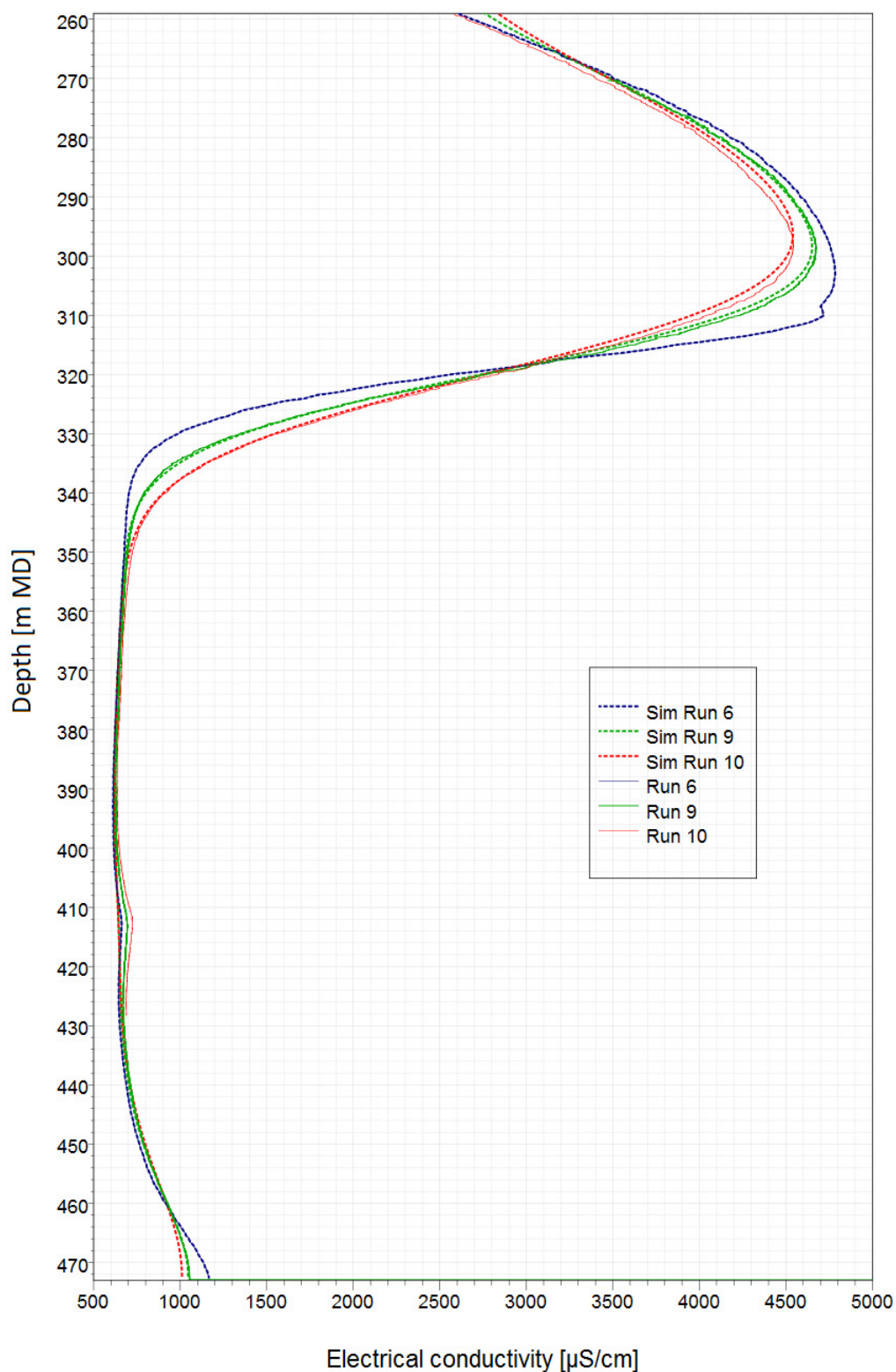


Fig. 3-6: BOZ1-1-FL1-MAL: 3rd fluid logging analysis of fluid logging Runs 6, 9 and 10; fluid logging analysis results for Runs 9 and 10 are based on the initial concentration distribution of Run 6

3.3 Summary and discussion of fluid logging results

In total, three fluid logging analyses were performed, which were based on the evaluation of the electric conductivity profiles from Runs 6, 9 and 10 during the pumping phase RW2. The first analysis considered two inflow zones, the second analysis four inflow zones and the third simulation considered no inflow zone. In general, two processes control the evolution of the electrical conductivity in the borehole: (i) inflow of formation water with a specific concentration that mixes with borehole water, and (ii) mass transport along the borehole (advective and diffusive).

The first analysis with two inflow zones led to a good fit quality between the measured and simulated electric conductivity profiles also reproducing the peak concentrations for both inflow zones with good quality. The sum of transmissivities for both inflow zones was $3.86 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$, which is in good agreement with the transmissivity value derived from pumping test analysis considering the RW2 phase ($2.18 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$).

The second simulation with four inflow zones also led to a good quality of the fit. The comparison of the analyses based on two and four inflow zones showed that increasing the number of inflow zones leads to a "reduction" in diffusion due to the two general processes controlling the evolution of the electrical conductivity. However, the increased number of inflow zones still results in a realistic value for the hydraulic diffusion coefficient due to the uncertainty of the parameter itself. The peak concentrations for inflow zones could be fitted with high quality. The sum of transmissivities for open borehole section was $3.8 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$, which is again in good agreement with the transmissivity value derived from pumping test analysis considering the RW2 phase ($2.2 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$).

The third analysis did not include any inflow to the borehole. The relatively good fit of measured and simulated electric conductivity profiles implies that diffusive mass transport along the borehole was the dominant process driving the evolution of the electrical conductivity within the borehole. However, from the measured concentration prior to pumping, it is obvious that flow from the formation into the borehole had occurred even if a quantitative analysis for these profiles was not possible.

In summary, the fluid logging analyses allowed mapping of the major inflow zone at a depth of around 310 m MD (i.e., in the Effingen Member of the Wildegg Formation), which is characterised by the largest transmissivity value of approximately $3 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ and a second inflow zone at a depth of 410 m MD characterised by a transmissivity value of approximately $2 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$. These major inflow zones may be "accompanied" by several smaller inflow zones between 321 and 335 m MD. However, the interpretation shows that these inflow zones have a minor impact on the evolution of the electrical conductivity profiles.

The analysis of the RW2 pumping test and fluid logging data provides consistent and reliable transmissivity values for the two main inflow zones at depths of around 310 m and 410 m MD. The total estimated transmissivities calculated from the fluid logging varied over a small range between $3.84 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ and $3.86 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$. This result corresponds well to the hydraulic transmissivity estimated later during the double packer test BOZ1-1-MAL1 ($3 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$), performed between 300.92 m and 328.24 m MD. Based on the results of the hydraulic test BOZ1-1-MAL1, the total uncertainty for this major inflow zone around 310 m MD ranges between $1 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ and $7 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$.

4 Hydraulic packer test

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 formations are expected to have relatively high transmissivities.

Nagra has long established hydraulic testing strategies (e.g. Nagra 1997) to extract the maximum information in relation to the hydraulic characteristics of the various geological formations. Two testing strategies are preferred (Tabs. 4-1 and 4-2) depending on the transmissivity of the formation (low to very low or medium to high). A typical test sequence is divided into different test phases: test preparation, diagnostic and main phase. The test sequence may be concluded with a pulse test (PW/PI) to check if the total test interval compressibility changed during the test. Modifications to the strategies are made according to the preliminarily available information, the encountered specific test conditions and obtained results 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 the case of formations with low to very low transmissivity, the test types and their duration are different. For the determination of hydraulic head, the borehole pressure history and test duration are important issues. Depending on the pressure difference between the static formation conditions and the pressure induced in the borehole during the pre-test pressure history, the estimates of hydraulic head can be strongly affected due to non-static pressure conditions in the surrounding borehole area.

A further aspect of the testing strategy is the use of drilling fluid as a test fluid (see Tab. 1-1). In contrast to previous exploration boreholes drilled by Nagra (e.g. Benken), no exchange of drilling fluid in the test interval was performed in the BOZ1-1 borehole during hydraulic testing. The main reason was borehole stability. The model implementation as a skin in the test analysis is assumed to adequately address the issues linked with drilling fluid properties at the borehole wall. Potassium silicate and polymers were used as drilling fluid additives during all hydraulic tests (*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; create pressure conditions for the initiation of the first test, first estimate of formation pressure; recognition of temperature and pressure trends
Diagnostic phase	PW	First estimates of hydraulic conductivity, which are used to plan the following test sequence
Diagnostic / main phase	SW	Estimation of hydraulic conductivity, which is used to plan the following test sequence, especially the pumping rate and drawdown of the RW phase
	SWS	Estimation of an accurate flow model and hydraulic parameters; hydrostatic pressure for subsequent pumping phase
Main phase	RW	Defined signal with a larger radius of influence; allows a representative groundwater sample of the formation to be taken as well as the detection of boundary conditions
	RWS	Estimation of an accurate flow model and hydraulic parameters as well as boundary conditions
Optional	PW/PI	Estimation of the total test interval compressibility at the end of the test

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

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

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

4.2 Test equipment

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

4.2.1 Downhole equipment

The packer system referred to as the heavy-duty double packer system (HDDP) was used for all hydraulic packer tests in open borehole sections. It consists of a top and bottom inflatable packer (non-inflated outer diameter 114 mm for borehole BOZ1-1) 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 $\frac{7}{8}$ " tubing above the bottom packer.

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

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

A hydraulically controlled non-displacement downhole shut-in tool (SIT) placed above the probe carrier shell was used to isolate the test zone from the test tubing (2 $\frac{7}{8}$ " EUE API CT5 L80). A progressive cavity (PC) pump 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.

Additionally, a piston pulse generator (PPG) can be mounted in the test interval. It introduces a unique and proven technology to reduce the uncertainty associated with determining the test zone compressibility for conducting pulse tests in formations with a low transmissivity.

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

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

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

BOZ1-1 Double-Packer Test Tool			max. OD (mm)	min. ID (mm)	Length (m)
Tubing (2-7/8 inch)			93.2	62.0	indiv.
Crossover			93.2	62.0	1.188
Downhole Shut-in Valve		0.805			
Compensation Packer		0.570	106	24.0	1.558
Coupling		0.183			
Crown Joint		0.146	100	40.0	0.331
Connector		0.185			
Piston Pulse Generator		0.078	60		0.460
Crossover		0.022	114.3	25.4	
Crown Joint				97.2	2.456
Connector				40.0	
Cable Base				40.0	0.373
Probe Carrier with Quadruple Sub-Surface Probe (QSSP) and Sensor Positions		Cable head and Cable Plug PRV	105	24.0	1.133
Crown Joint			105	40.0	1.753
Crossover			100	40.0	0.313
Safety joint			70	41.0	0.207
Pup Joint			98	62.0	0.559
Connector+side-entry sub			93		0.911
Mandrel			59		
Top Packer (114 mm)			114		0.255
Below Side Entry Sub			118	49.0	1.200
Crossover			114		0.260
Tubing (2 7/8 inch)			59		0.243
Filter (Screen length 0.97 m)			93		0.280
Crossover			93.2 (73.0)	62.0	indiv.
P1 Seal Sub			94		
Mandrel			90	62.0	1.645
Bottom Packer (114 mm)			80		
Bottom Cap			95		0.150

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

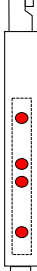
BOZ1-1 Single-Packer Test Tool		max. OD (mm)	min. ID (mm)	Length (m)
Tubing (2-7/8 inch) --				
Coupling		93.2	62.0	indiv.
		93.2	62.0	0.134
PCP Stator (1.7 - 5.5 L/min)		78.6	34.0	1.309
Stop pin		0.4	93.2	
			78.6	62.0
				0.460
Tubing (2-7/8 inch)		93.2	62.0	indiv.
Crossover		93.2	62.0	1.192
Downhole Shut-in Valve		0.805		
Compensation Packer		0.570	106	24.0
				1.558
Coupling		0.183		
		0.146		
Crown Shaft		0.185	100	40.0
				0.331
Connector			40.0	0.127
Cable Base		Cable head and Cable Plug PRV	105	24.0
				1.129
Probe Carrier with Quadruple Sub-Surface Probe (QSSP) and Sensor Positions		P3 P4 P2/T2 P1	105	40.0
				1.621
Crown Shaft			100	40.0
				0.321
Crossover			70	41.0
				0.160
Safety joint			100	62.0
				0.255
Crossover		0.15	93	
Connector		0.214		0.468
Mandril		0.104	59	
				0.260
Top Packer (114 mm)		Packer seals 0.08 m above uninflated position	114	49.0
				1.200
			114	49.0
				0.260
Below Side Entry Sub			59	
				0.234
Crossover			93	
				0.088
Tubing (2-7/8 inch)			93.2 (73.0)	62.0
				indiv.
Filter (Screen length 0.97 m)		P2* 0.97	94	
			90	62.0
			80	
				1.350
Crossover			95	
				0.200
Bottom Cap			95	
				0.160

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

4.2.1.1 Heavy-duty double packer system

The technical data of the Heavy-duty double packer system (HDDP) are provided in Tab. 4-3. A summary of the downhole equipment with the most important 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]
Quadruple flat-pack	3 each ¼" OD × 0.035" WT 316L 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	
Tubing	2⅞" EUE API CT5 L80	62
Pup joints	2⅞" EUE API CT5 L80/N80	62
Shut-in tool (SIT)	Duplex 1.4462	24
Pressure release valve (PRV)	Duplex 1.4462	24
Cable base	Duplex 1.4462	
Quadruple sub-surface probe (QSSP)	Duplex 1.4462 4 pressure sensors P1, P2, P3 and P4	3 × Ø19
Coarse thread safety joint	3 ²¹ / ₃₂ " OD, with 2 ⁷ / ₁₆ " bore with 2⅞" EUE box × pin connections	62
Packers for large borehole diameter	IPI 5¾" (146 mm), steel wire reinforced, duplex, natural rubber Packer 1 Packer 2	49 49
Packers for normal borehole diameter	IPI 4½" (114 mm), steel wire reinforced, duplex, natural rubber Packer 1 Packer 2	49 49
Filter	HP well screen: sand free filter screen mounted on 2⅞" tubing L 80 Length: 0.50 m Length: 1.00 m	73 73

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. Anti-freeze was added to the water. Both packer pressure lines were connected to the packer control board at the winch and equipped with pressure sensors (pressure range 0 – 30'000 kPa) for packer pressure monitoring. The packer pressure sensors were connected to the data acquisition system (DAS) for continuous recording. To keep packer pressures constant, the packers were connected to a pressure-maintenance system (see Section 4.2.2.2).

Tab. 4-5: Specifications for the HDDP packers

Manufacturer	Inflatable Packers International, Perth, Australia	
Packer types	IPI 4½" (114 mm)	IPI 5¾" (146 mm)
Material and type	Duplex, 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, not inflated	114 mm max.	146 mm max.
Inner diameter	49 mm min.	49 mm min.
Overall length: Bottom packer Top packer	1.93 m 2.08 m	1.92 m 1.92 m
Rubber sleeve length	1.20 m	1.20 m
Thread connections	2⅞" 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 ± 3 kPa at atmospheric pressure conditions.

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

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

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

¹ FS = full scale

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 (FS ¹)	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

¹ FS = full scale

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

4.2.1.6 Test tubing

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

Tab. 4-9: Specifications for the test tubing

Test tubing type	Seamless steel tubing and pup joints: 2 $\frac{7}{8}$ " 6.5 ppf L80 B*P EUE R2 API 5CT
Manufacturer	Normec, Celle, Germany
Steel grade	L80
Inner diameter	62.00 mm
Outer diameter	73.02 mm
Coupling outer diameter	93.20 mm
Thread	API 2 $\frac{7}{8}$ " EUE
Weight per meter	9.68 kg
Volume per meter	3.02 l
Individual tubing length	Range 2, ~ 9.5 m
Number of individual tubing lengths	162
Total length of test tubing	Ca. 1'500 m
Lengths of pup joints	Length, quantity 0.5 m, 2 1.0 m, 2 2.0 m, 2 3.0 m, 4 4.5 m, 4

4.2.1.7 Slim tubing

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

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

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

Tab. 4-10: Specifications for the slim tubing

Slim tubing	Manufactured by Solexperts		
Types	Polyethylene tube	Stainless steel tube	Legris Polyamide Calibre tube
Inner diameter	12 mm	6 mm	4 mm
Outer diameter	16 mm	8 mm	6 mm
Length	300 m	300 m	700 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 PA-23SY, 0 – 5'000 kPa, accuracy 0.25% FS ¹		
Pressure sensor (P-slim)	Keller PA-27XW, 0 – 3'000 kPa, accuracy < 0.07% FS, linearity 0.2% FS		
Installation procedure	Wireline system of the drill rig		

¹ FS = full scale

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	Pumping tests, fluid logging

4.2.1.9 Progressive cavity pump

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

Tab. 4-12: Specifications for the PC pump

PC 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

4.2.1.10 Piston pulse generator

The piston pulse generator (PPG) is an optional downhole tool. It brings a unique and proven technology for conducting pulse tests to the more traditional low-permeability hydraulic testing realm. In an effort to reduce the uncertainty associated with determining the test zone compressibility, a hydraulic piston (i.e. the PPG) of known volume is incorporated into the hydraulic test tool (HTT). This PPG resides within the test zone but not conventionally in between the packers. The PPG is contained within a housing that is located above the top packer and below the downhole SIT.

When deployed in a borehole, the packers are inflated, the piston is put into the appropriate position (fully extended or fully retracted), the SIT is closed, thereby isolating the test zone from the rest of the borehole, and the test zone is allowed to equilibrate for a period of time.

When it has been decided to initiate a pulse with the PPG, fluid from the pressurised fluid reservoir is routed to the appropriate hydraulic line (piston extend or piston retract) through the hydraulic control panel, thereby changing the position of the piston and changing the test zone volume by a known amount during a few minutes. The resulting test zone pressure change is measured and can be used for the calculation of the interval storage / test zone compressibility. The specifications are listed in Tab. 4-13.

It should be noted that only one piston can be deployed at a time and the piston must be either fully extended or fully retracted. Therefore, only displacement volumes of 50 ml, 250 ml or 500 ml can be achieved once the HTT is deployed.

Tab. 4-13: Specifications for the PPG

PPG type	INTERA-PPG-1
Manufacturer	HydroResolutions
Dimensions	OD: 0.1143 m Length: max. 2.54 m
Weight	Max. 79.38 kg
Material	Steel

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
- PC pump 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 two flowmeters of type Yokogawa AXF were available. The flowmeters covered a flow rate range between 0.01 and 100 l/min (Tab. 4-14). The schematic layout of the flow control unit is displayed in Fig. 4-3.

Tab. 4-14: Specifications for the flowmeters

	Measuring range and accuracy			
	Lower limit		Upper limit	
	[l/min]	[% FS]	[l/min]	[% FS]
AXF 010	0.1	1	11.78	0.35
AXF 025	1.0	1	100	0.35

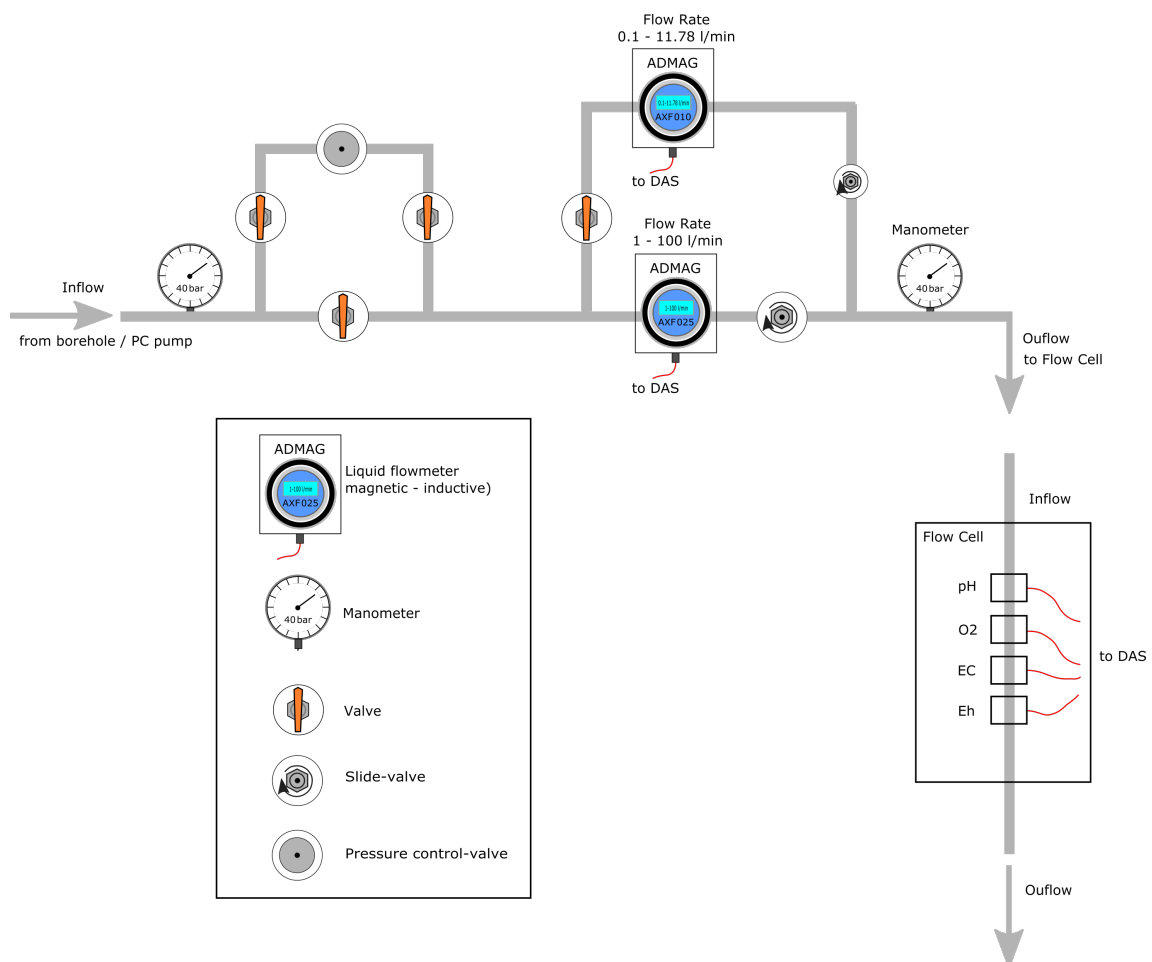


Fig. 4-3: Schematic layout of the flow control unit

4.2.2.2 Packer pressure-maintenance system

The packer pressure-maintenance system has four principal components: a pressurised nitrogen source (bottle) with pressure regulator, an Alicat pressure controller, a high-pressure hydraulic accumulator containing pressurised nitrogen over packer-inflation fluid, and a Mettler digital scale to monitor changes in the fluid volume in the reservoir. The Alicat flow controller is connected to the nitrogen bottle and to the reservoir. The desired packer-inflation pressure ("set" point) is entered into the controller, which has its own pressure sensor, and the controller then adds nitrogen to the reservoir if the pressure drops below the set point or vents nitrogen from the reservoir if the pressure rises above the set point. The digital scale can be read manually in addition to being connected to the DAS. The packer pressure-maintenance system is installed in the mobile trailer. Fig. 4-4 illustrates a schematic layout of the packer pressure-maintenance system. Additionally, two transducers (type Keller PA-23SY, 30'000 kPa) mounted on the surface inflation control panel were used to monitor the packer inflation pressures.

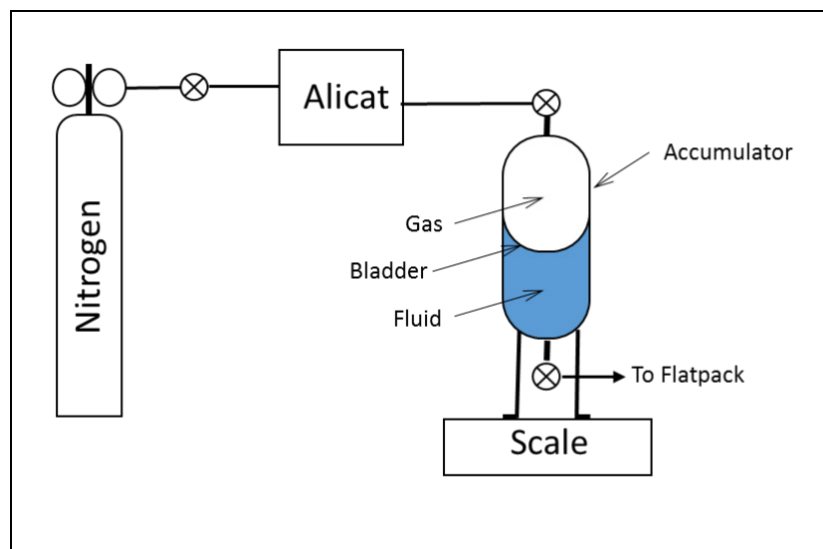


Fig. 4-4: Schematic layout of the packer pressure-maintenance system

4.2.2.3 Additional recorded measurements at surface

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

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

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

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

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

Sensor type	EC	pH	Eh	O ₂	Temp
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 °C – 100 °C	0 °C – 60 °C	0 °C – 60 °C	-5 °C – 50 °C	-50 °C – 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 continuously for 'online' analysis and data back-up. An uninterruptible power supply was utilised to protect the system from short power interruptions.

4.2.3 GTPT equipment

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

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

- 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 additional surface equipment encompasses the following components:

- Standard hydrotest equipment
- 1 gas flow controller 0 – 5 l/min (injection line to interval) (l = litre normal)
- 2 gas flowmeters 0 – 150 l/min (one connected to back flow line from exchange chamber and one to injection line for NaOH displacement)
- A flow control board for one gas flow controller and two gas flowmeters with valves and manometers
- 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 provided by the field test contractor.

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

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 SIT2⁷ closed

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

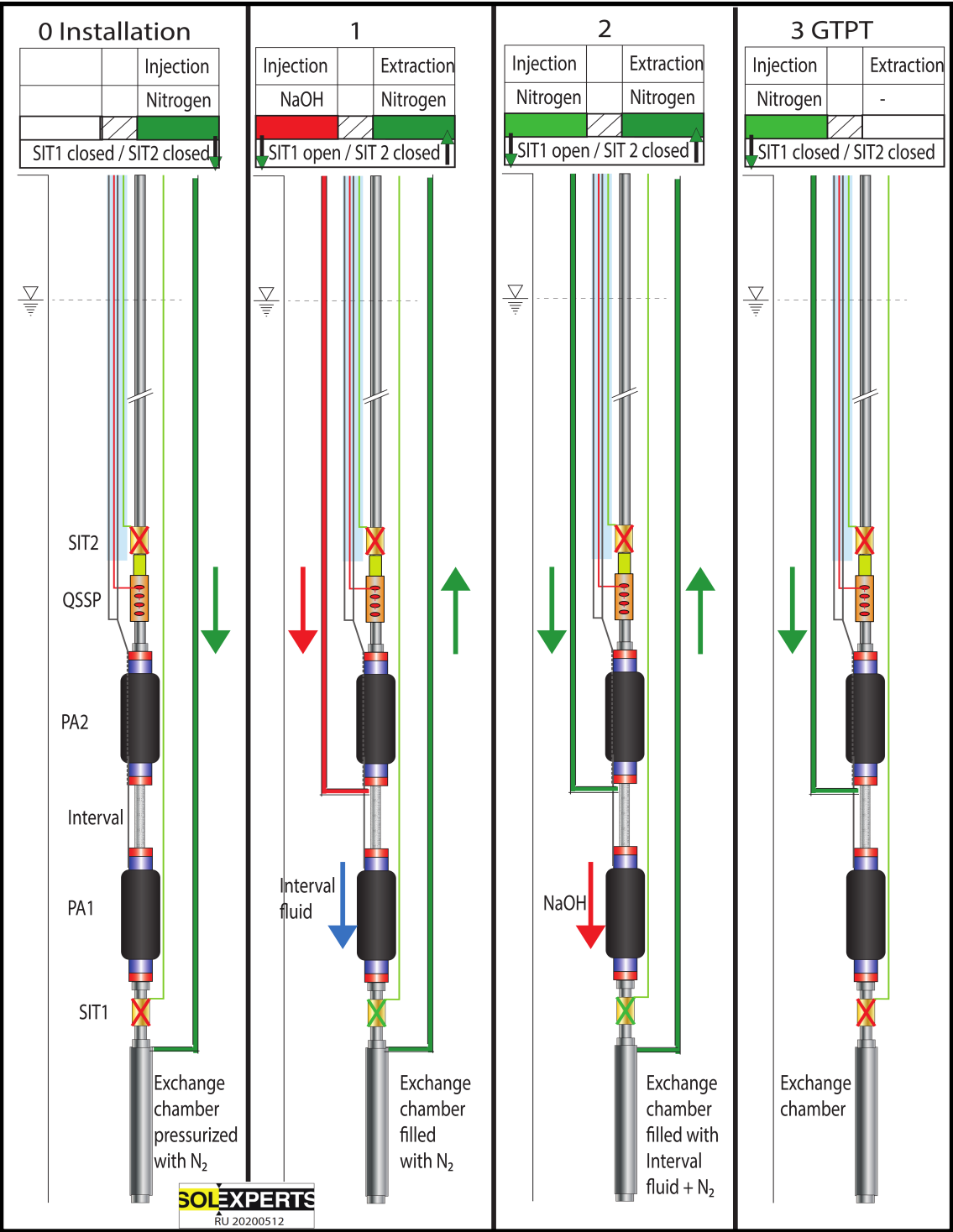


Fig. 4-5: Schematic layout of the modified HDDP system and the four steps for the GTPT

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 ¼" 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. 4-17. Before installation, the packers with the corresponding lines were saturated with water and anti-freeze.

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

Manufacturer	Inflatable Packers International (IPI), Perth, Australia
Packer types	IPI 5¼" (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. SIT1 line 2. Not used 3. Backflow line 4. Not used 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

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 were coiled up on the corresponding coils. Each stainless steel line was connected to a valve and a 250 bar manometer. Two coils (injection and backflow lines) were additionally equipped with pressure sensors of the type Keller PA-23SY, 0 – 300 bar.

The outlet port for the injection line at the lower end of the top packer was equipped with a check valve which 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 HDDP 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. 4-18.

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

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

4.2.3.4 Flow control board for GTPT

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

In addition to the flow controller and flowmeters, the flow board 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. 4-19: 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 l/min	3 – 150 l/min	3 – 150 l/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

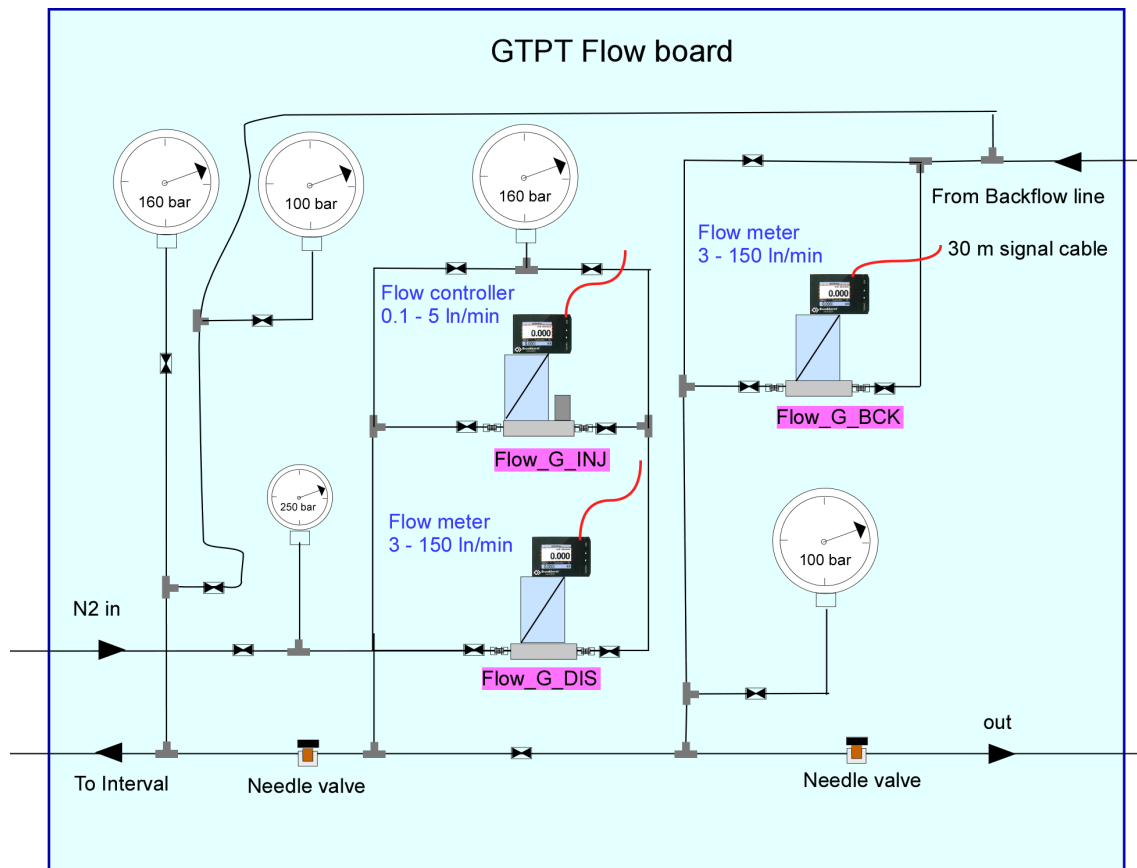


Fig. 4-6: Schematic layout of the flow control unit for the GTPT

4.3 Test analyses

4.3.1 Workflow

For BOZ1-1, the general on-site analysis approach involved mainly numerical techniques considering the entire 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 most appropriate flow model, e.g. by log-log diagnostic plots (Bourdet et al. 1989)
- Numerical simulation of individual test sequences in Cartesian coordinates
- Confirmation of the applied flow model suitability via diagnostic representations of the recorded and simulated pressure data

- Assessment of the suitability of the numerical solution and associated uncertainties through limited perturbation analyses
- Numerical simulation of the entire test sequence in Cartesian coordinates using the optimised parameter set obtained from individual phase analysis
- Confirmation of the consistency of the model applied to the entire data set
- Consistency check of the test analysis and the 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.

The test data were analysed numerically using the nSIGHTS software (Geofirma Engineering Ltd. & INTERA 2011). For slug and pulse tests, the consistency check typically involved one or more of the semi-log and log-log plots developed by Ramey et al. (1975). Recovery tests were presented according to Horner (1951). A summary of the applied test analysis methods is presented in Tab. 4-20.

Tab. 4-20: Summary of analytical analysis methods

Test phase	Analysis method	Reference
Pulse test	Semi-log and log-log representations of the transient pressure change and derivative versus time	Ramey et al. (1975)
Slug test (flow phase SW)	Semi-log and log-log representations of the transient pressure change and derivative versus time	Ramey et al. (1975)
Slug test recovery (pressure recovery after slug flow phase, SWS)	Semi-log and log-log representations of the transient pressure change and derivative versus time Diagnostics: Semi-log representations of the transient pressure change	Bourdet et al. (1989) Horner (1951)
Constant rate test	Log-log representations of the transient pressure change and derivative versus time Diagnostics: Analysis on transient pressure data	Bourdet et al. (1989) Horne (1995)
Pressure recovery after constant rate tests	Log-log representations of the transient pressure change and derivative versus 'superposition time' Diagnostics: Log-log stabilisation of the derivative Diagnostics: Semi-log representations of the transient pressure change	Bourdet et al. (1989) Horne (1995) Horner (1951)

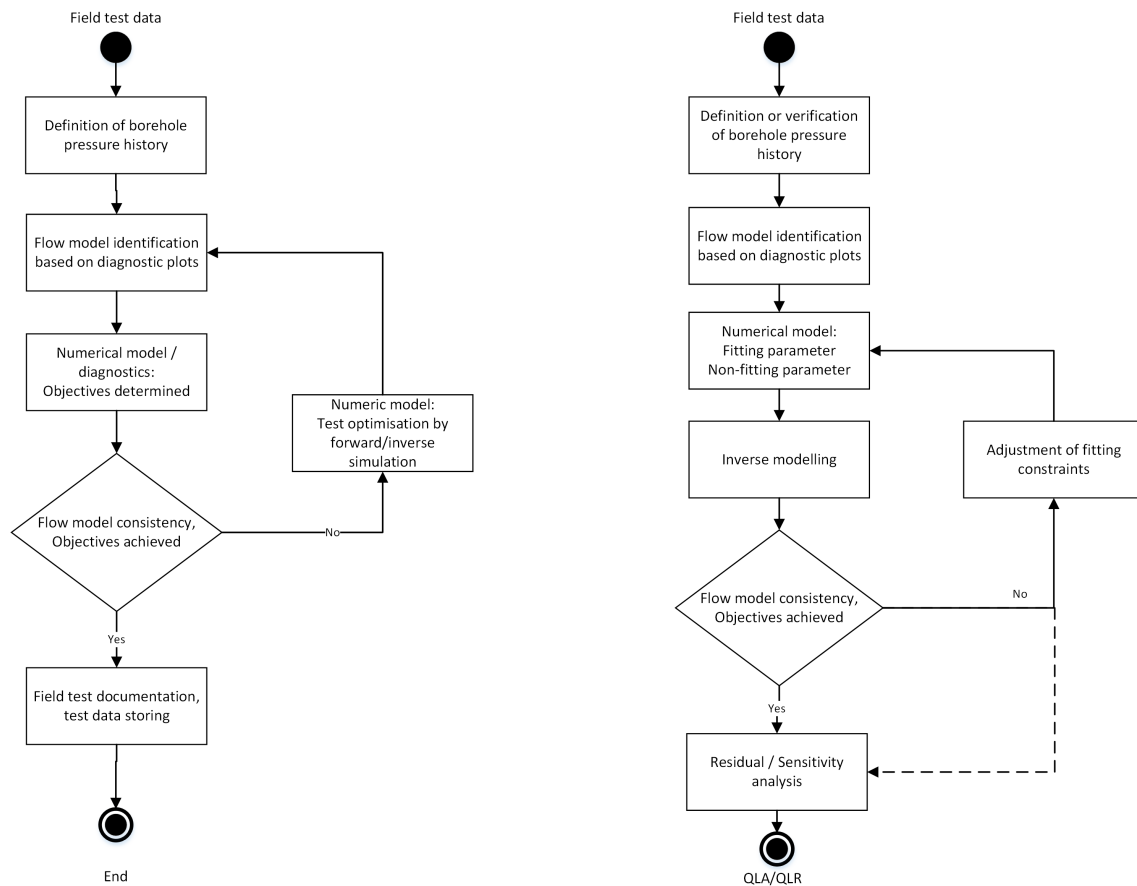


Fig. 4-7: Flowcharts for the on-site hydraulic packer test analysis (left) and Quick Look Analysis (QLA) (right)

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.

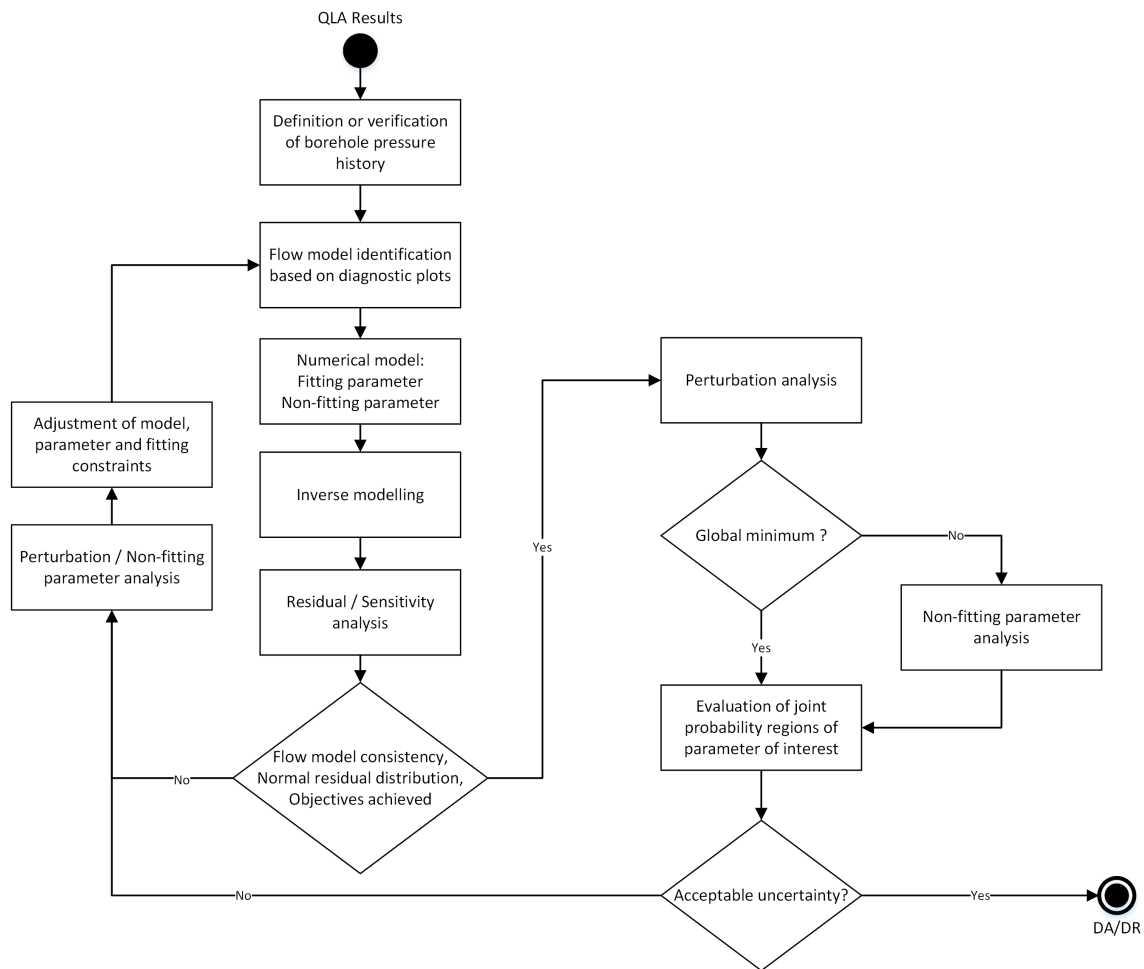


Fig. 4-8: Flowchart for the off-site Detailed Analysis (DA) of a hydraulic packer test

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). These are referred to as disturbances because they are not considered in the analysis. However, it is possible to describe the development of temperature and pressure signals using the diffusion equation. Disturbances are of short duration in formations with medium to high transmissivity. In formations with low transmissivity, disturbances in the pressure or temperature field can have a significant influence on the pressure signal measured during the test in the test interval (e.g. Nagra 1997, Grauls 1999, Nagra 2001).

Any disturbances of the pressure field during the time before the hydraulic test is started, are summarised under the name 'borehole pressure history'. Disturbances in the pressure and temperature fields can be caused by drilling and other activities before testing. In addition, disturbances

can occur even during testing, e.g. mechanical effects 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 of reducing potential pressure or temperature disturbances. In addition to this preventative measure, the numerical analysis tool can estimate the effect of these influences, so that plausibility ranges for the parameter estimations can be defined. In the following, possible individual special effects that have previously been identified, e.g. for the Benken borehole (Nagra 2001), are discussed in more detail.

4.3.2.1 Borehole history

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

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

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

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

The specific periods of the borehole pressure history taken into account for the analysis of the hydraulic packer tests in borehole BOZ1-1 are provided in Tab. 4-21.

Tab. 4-21: 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]
BOZ1-1-MAL1	14.05.2020 13:35	30.05.2020 19:55	390.33
BOZ1-1-PWF2	29.06.2020 15:04	17.07.2020 19:46	436.70
BOZ1-1-PWF1	30.06.2020 10:27	13.07.2020 23:31	325.07
BOZ1-1-OPA2	02.07.2020 01:40	07.07.2020 15:03	133.38
BOZ1-1-OPA3	02.07.2020 01:40	10.07.2020 07:48	198.13
BOZ1-1-OPA1	02.07.2020 09:56	03.07.2020 19:25	33.48
BOZ1-1-OPA4	23.07.2020 18:09	08.08.2020 21:38	387.48
BOZ1-1-LIA2	27.07.2020 05:36	03.08.2020 22:52	185.27
BOZ1-1-LIA1	28.07.2020 03:47	30.07.2020 23:40	67.88
BOZ1-1-KEU1	02.09.2020 10:22	13.09.2020 07:59	261.62
BOZ1-1-MUK1	18.09.2020 09:10	20.09.2020 05:31	44.35
BOZ1-1-MUK2	19.09.2020 03:37	26.09.2020 06:31	170.90

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 medium (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 summary of the observations and for a numerical interpretation of the data). Opalinus Clay time-dependent behaviour is most likely due to the undrained and drained excavation response, rather than mechanical creep phenomena. In formations with low transmissivity, time-dependent deformations can have an influence on the pressure signal observed in the test interval.

However, there are no data on mechanical deformations available for the tests in borehole BOZ1-1 that would allow the characterisation of mechanical effects on the tests in formations with low transmissivity. Deformations of the borehole wall can be included in the analysis by all the numerical software packages used by the means of an appropriate parameterisation during the analysis in the same way as for temperature changes inside the interval. The resulting pressure change is caused by volume changes, which can be either linear or quadratic. The proportionality factor between the volume change and the pressure change is the interval compressibility.

4.4 Test activities

A total of twelve test intervals were investigated in borehole BOZ1-1 using the HDDP in single and double packer configuration. The most important test specifications are summarised in Tab. 4-22. The hydraulic packer tests were performed in the following geological formations (*cf.* Dossier III):

- Malm Group with a focus on the Effingen Member of the Wildegg Formation (BOZ1-1-MAL1) following the realisation of a fluid logging
- Dogger Group («Brauner Dogger») with a focus on the Passwang Formation including the Rothenfluh, Waldenburg and Bruggli Members, the "Humphriesi-Schichten" and the "Cond. Equivalents of the Sissach, Hauenstein and Hirnichopf Members" (BOZ1-1-PWF1, BOZ1-1-PWF2)
- Dogger Group with a focus on Opalinus Clay (BOZ1-1-OPA1, BOZ1-1-OPA2, BOZ1-1-OPA3 and BOZ1-1-OPA4)
- Lias Group with a focus on Staffelegg Formation including Gross Wolf, Rietheim, Breitenmatt / Rickenbach, Grünschholz and Frick Members (BOZ1-1-LIA2) resp. including Frick, Beggingen and Schambelen Members (BOZ1-1-LIA1)
- Keuper Group with a focus on Klettgau Formation including Gruhalde, Gansingen and Ergolz Members (BOZ1-1-KEU1)
- Muschelkalk Group with a focus on the Schinznach Formation including Stamberg, Liederts-wil, Leutschenberg and Kienberg Members (BOZ1-1-MUK1) resp. additionally including the "Dolomitzone" in the Zeglingen Formation (BOZ1-1-MUK2)

All hydraulic tests (except the GTPT) were performed in the cored borehole section with a borehole diameter of 6¾", 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 or 1.5-naphthalene disulfonate acid (for the hydraulic test within the shales) were used as tracers at concentrations of approximately 10 ppm. The SIT was closed during the entire time the HDDP was lowered to the test depth and also during installation. Therefore, in test intervals with low transmissivity, the interval fluid density was not affected by traced water in the test tubing as mainly withdrawal tests were performed and no or only very little fluid flow occurred. If a pressure increase of more than 100 kPa was observed in the test interval during inflation of the top packer, the SIT was opened and the COM phase started. Due to the higher density of the mud in the test interval, for formations with low transmissivity, it was assumed that no flow occurred from the test tubing into the test interval during the COM phase. Flow from the formation into the borehole by means of slug and pumping tests was created during the following tests: BOZ1-1-MAL1, BOZ1-1-PWF2, BOZ1-1-OPA1, BOZ1-1-OPA2, BOZ1-1-OPA3, BOZ1-1-OPA4, BOZ1-1-MUK1 and BOZ1-1-MUK2.

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 up to the limit of the allowable pumping head. If two tests were performed sequentially without pulling the HDDP out of the borehole between tests, a stator was already installed for the first test (usually the deeper test).

For the tests BOZ1-1-OPA1, BOZ1-1-LIA1, BOZ1-1-MUK1 and BOZ1-1-MUK2 drilling was stopped for hydraulic testing. For the other tests, a longer section was drilled and then the hydraulic tests were performed. The measured pressures (measured by the downhole sensors in the QSSP) and pumping rates (measured by the flow board at the surface) for all tests conducted in borehole BOZ1-1 are provided in Figs. 4-9 to 4-20. 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 0.04 °C to 4.96 °C for all tests.

Due to technical problems during test BOZ1-1-OPA1, the hydraulic tests BOZ1-1-OPA2 and BOZ1-1-OPA3 investigate the same interval at a similar depth as test BOZ1-1-OPA1.

Tab. 4-22: Hydraulic packer testing in borehole BOZ1-1: 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 ()]
BOZ1-1-MAL1	300.92 – 328.24	314.58	Double	INF1, INF2, PSR, PW, SW1, SWS1, SW2, SWS2, SW3, SWS3, DEF	30.05. – 02.06.2020 (67.1 h)	Malm Group: calcareous marlstone to limestone of the Effingen Member of the Wildegg Formation. The test was designed to investigate inflow zones detected by the fluid logging.	T, h _{ss} , (FM), WS
BOZ1-1-PWF2	492.05 – 511.05	501.55	Double	INF1, INF2, COM, PSR, SW, SWS, SWS2, PI, PW, DEF	17.07 – 20.07.2020 (69.1 h)	Dogger Group («Brauner Dogger»): marls and limestones interspersed with iron-oolite of the Passwang Formation. The hydraulic test was designed as an overview test and targeted the upper part of the Passwang Formation.	T, h _{ss} , FM
BOZ1-1-PWF1	511.15 – 530.14	520.65	Double	INF1, INF2, COM, PSR, PW, PI, DEF	13.07. – 16.07.2020 (55.4 h)	Dogger Group («Brauner Dogger»): marls and limestones interspersed with iron-oolite of the Passwang Formation. The hydraulic test was designed as an overview test and targeted the lower part of the Passwang Formation.	T, h _{ss} , FM
BOZ1-1-OPA2	538.00 – 557.00	547.50	Double	INF1, INF2, COM, PSR, SW1, SWS1, SW2, SWS2, DEF	07.07. – 09.07.2020 (41.3 h)	Dogger Group, test interval entirely within Opalinus Clay. Test BOZ1-1-OPA2 was designed to test the upper part of the Opalinus Clay where silty calcareous beds are present.	T, h _{ss} , FM
BOZ1-1-OPA3	538.00 – 557.00	547.50	Double	INF1, INF2, COM, PSR1, SW1, PSR2, SW2, SWS2, PW, PI, DEF	10.07. – 13.07.2020 (84.2 h)	Dogger Group: test interval entirely within Opalinus Clay. Test BOZ1-1-OPA3 was designed to test the upper part of the Opalinus Clay where silty calcareous beds are present.	T, h _{ss} , FM
BOZ1-1-OPA1	544.00 – 564.00	554.00	Single	INF, COM, PSR, PW, SW, SWS, DEF	03.07. – 06.07.2020 (53.5 h)	Dogger Group: test interval entirely within Opalinus Clay. Test BOZ1-1-OPA1 was designed to test the upper part of the Opalinus Clay where silty calcareous beds are present.	T, h _{ss} , FM
BOZ1-1-OPA4 (GTPT interval)	602.35 – 608.10	605.23	Double	INF1, INF2, COM, PSR, PW, SW, SWS, GTPT, DEF	08.08. – 15.08.2020 (162.7 h)	Dogger Group: test interval entirely within Opalinus Clay. Test BOZ1-1-OPA4 was designed to test a zone with fractures between appr. 604 and 607 m MD. It preceded the realisation of a GTPT.	T, h _{ss} , FM, (WS)
BOZ1-1-LIA2	651.00 – 674.14	662.57	Double	INF1, INF2, COM, PSR, PW1, PI, PW2, DEF	03.08. – 06.08.2020 (57.7 h)	Approximately 0.4 m of Opalinus Clay at the top of the interval, the rest is contained entirely within the Lias Group, Staffelegg Formation (approx. 3.4 m of Gross Wolf Member, approx. 4.4 m of Rietheim Member, approx. 3.1 m of Grünscholz, Breitenmatt and Rickenbach Members, and approx. 11.9 m of Frick Member) mainly consisting of silty claystones, limestones and marls. This overview test was designed to investigate mainly the marly facies of the Staffelegg Formation.	T, h _{ss} , (FM)

Tab. 4-22: continued

Test name ¹	Interval depth [m MD]	Interval midpoint [m MD]	Packer configuratio n	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 ()]
BOZ1-1-LIA1	674.00 – 690.00	682.00	Single	INF, COM, PSR, PW, PI, DEF	30.07. – 02.08.2020 (64.3 h)	Lias Group with approx. 14.72 m of Staffelegg Formation (approx. 1.71 m of Frick Member, 3.4 m of Beggingen Member and approx. 9.6 m of Schambelen Member) and Keuper Group with approx. 1.3 m of Klettgau Formation, Gruhalde Member. Rocks within the test interval mainly consist of silty claystones, limestones and marls. This overview 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), WS
BOZ1-1-KEU1	702.10 – 720.59	711.35	Double	INF1, INF2, PSR1, PW1, PSR2, PW2, PI, DEF	13.09. – 15.09.2020 (61.5 h)	Keuper Group with approx. 17.9 m of Klettgau Formation (approx. 0.5 m of Gruhalde Member, approx. 6.2 m of Gansingen Member and approx. 11.2 m of Ergolz Member) and approx. 0.6 m of Bänkerjoch Formation. Rocks within the test interval mainly consist of marls, sandstones and claystones. The aim of this test was to target possibly transmissive zones of the Klettgau Formation.	(T), h _s , (FM), WS
BOZ1-1-MUK1	845.69 – 867.00	856.35	Single	INF1, COM1, PSR1, SW, SWS, DEF1, INF2, COM2, PSR2, RW, RWS, DEF2	20.09. – 23.09.2020 (82.4 h)	Muschelkalk Group: test interval entirely within Schinznach Formation with approx. 3.3 m of Stamberg Member, approx. 8.4 m of Liedertswil Member and approx. 9.6 m of Leutschenberg and Kienberg Members consisting mainly of dolostones and limestones interspersed with anhydrites. The test was conducted after considerable mud losses in the Schinznach Formation.	T, h _s , (FM), WS
BOZ1-1-MUK2	845.78 – 882.00	863.89	Single	INF, PSR, SW, SWS, RW, RWS, DEF	26.09. – 30.09.2020 (99.0 h)	Muschelkalk Group: approx. 30.1 m of Schinznach Formation (approx. 3.2 m of Stamberg Member, approx. 8.4 m of Liedertswil Member and approx. 18.4 m of Leutschenberg and Kienberg Members) and approx. 6.1 m of Zeglingen Formation, "Dolomitzone". Rocks within the test interval mainly consist of dolostones and limestones interspersed with anhydrites. The test was conducted after considerable mud losses in the Schinznach Formation when drilling resumed after test BOZ1-1-MUK1.	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 (striethrough if the target was not reached).

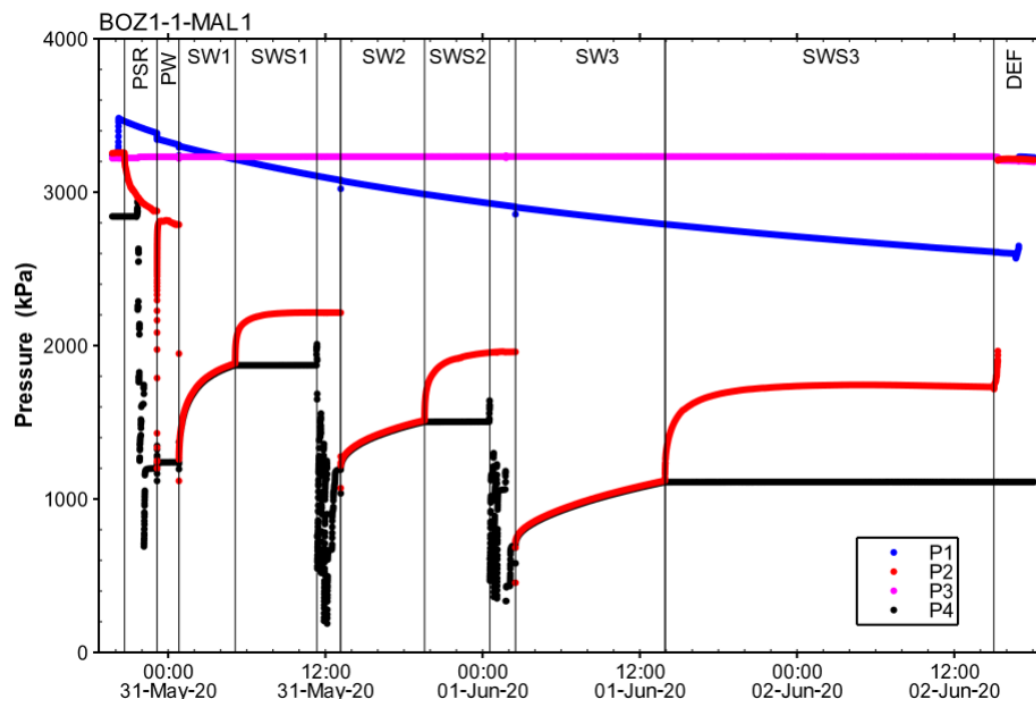


Fig. 4-9: Hydraulic packer test BOZ1-1-MAL1: Overview plot of pressure vs. time and date

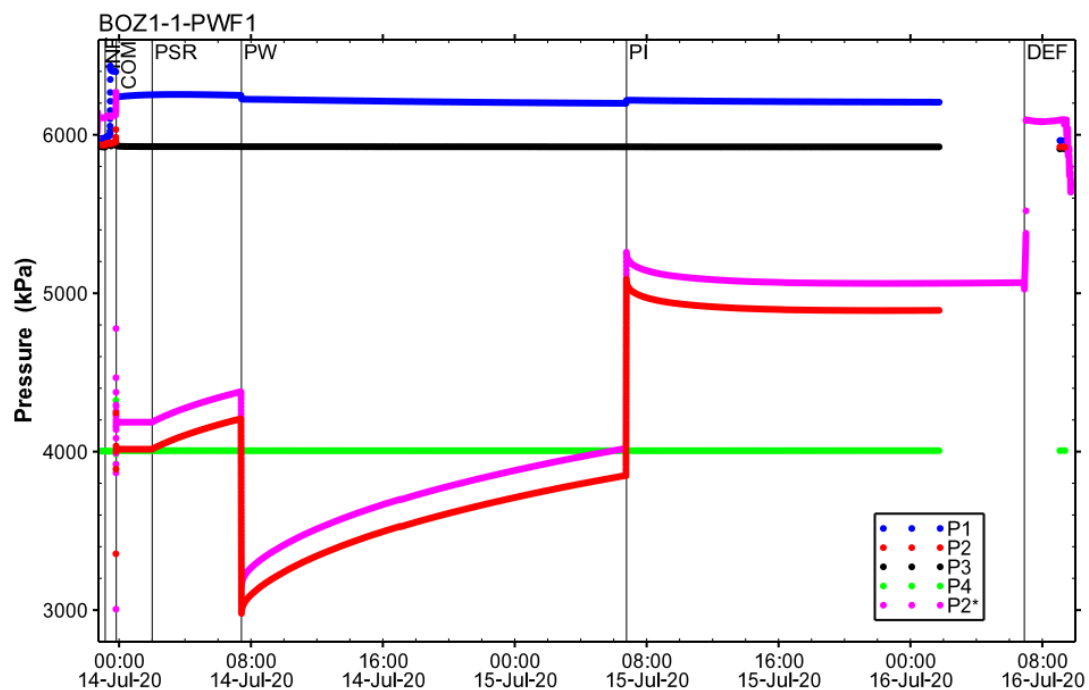


Fig. 4-10: Hydraulic packer test BOZ1-1-PWF1: Overview plot of pressure vs. time and date

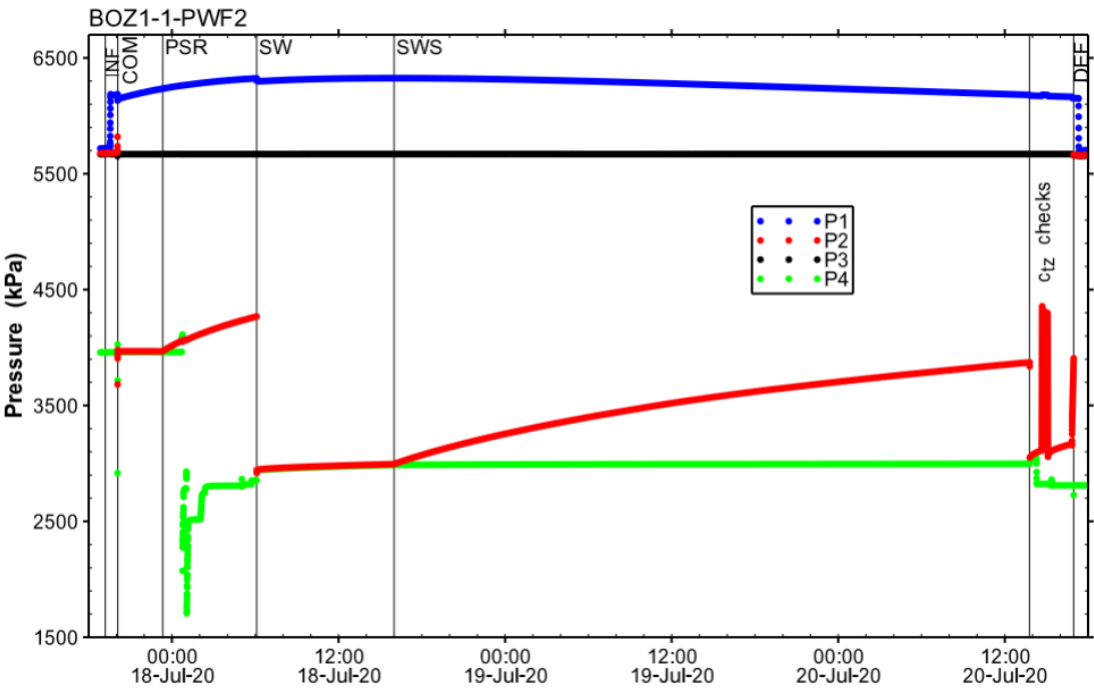


Fig. 4-11: Hydraulic packer test BOZ1-1-PWF2: Overview plot of pressure vs. time and date

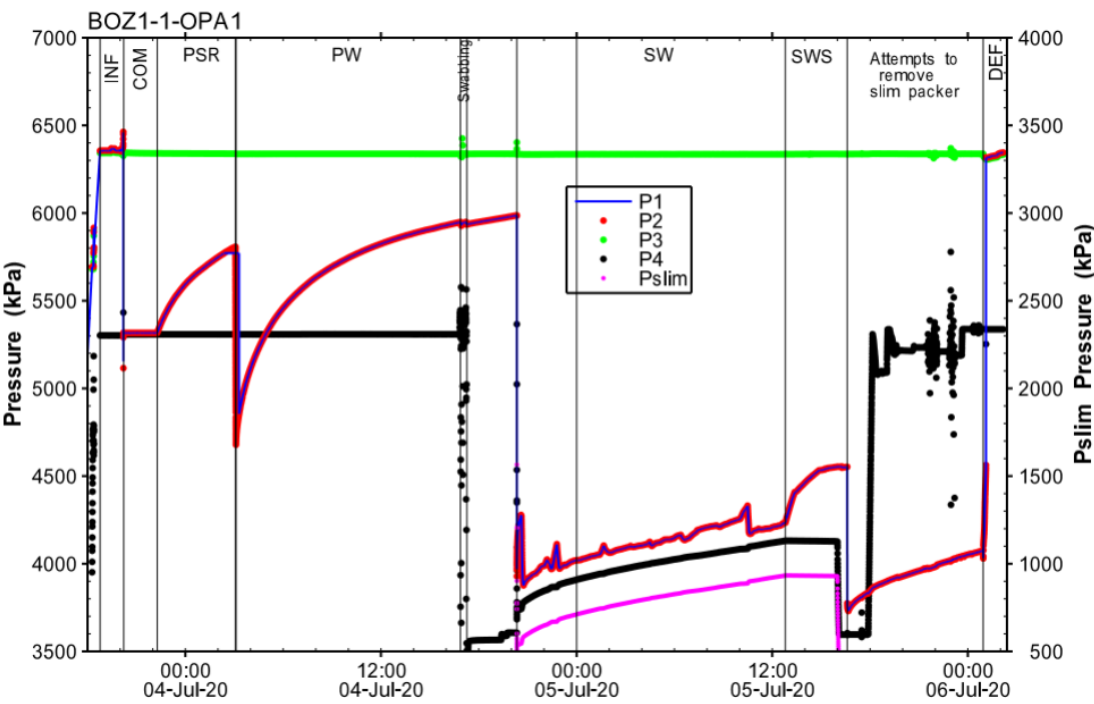


Fig. 4-12: Hydraulic packer test BOZ1-1-OPA1: Overview plot of pressure vs. time and date

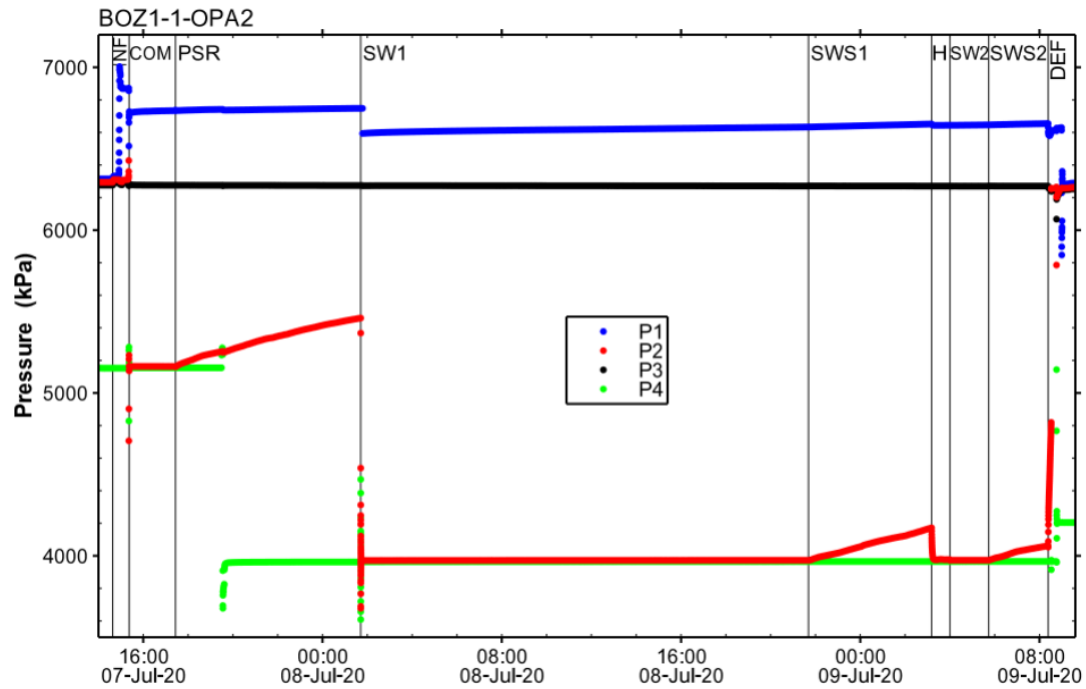


Fig. 4-13: Hydraulic packer test BOZ1-1-OPA2: Overview plot of pressure vs. time and date

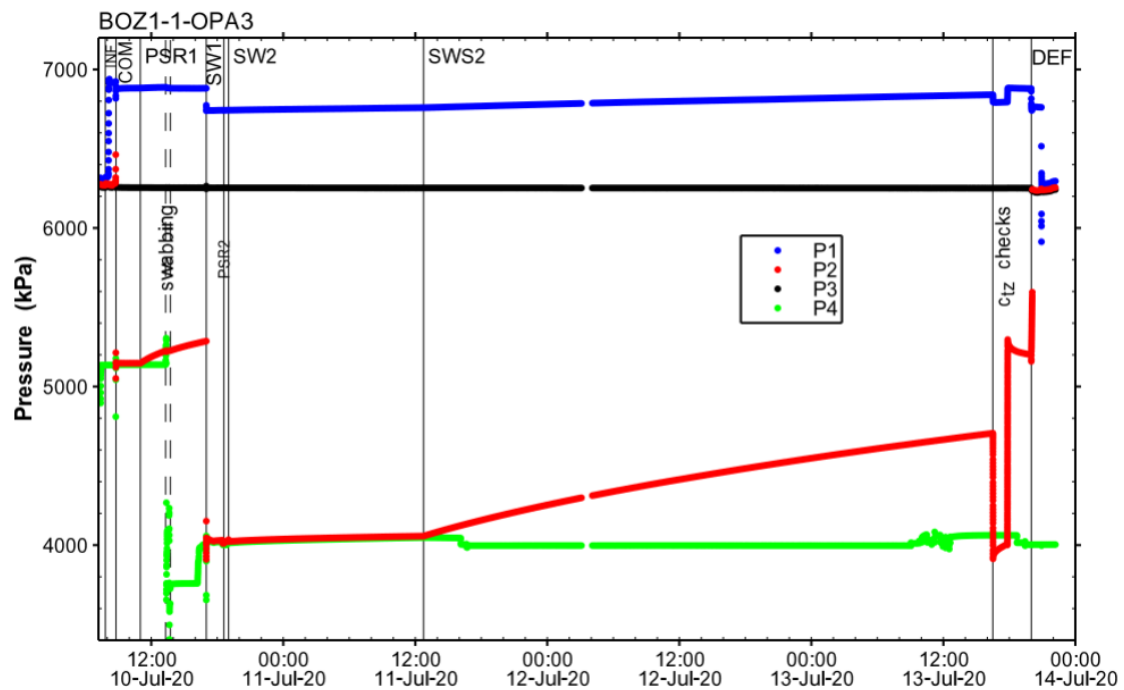


Fig. 4-14: Hydraulic packer test BOZ1-1-OPA3: Overview plot of pressure vs. time and date

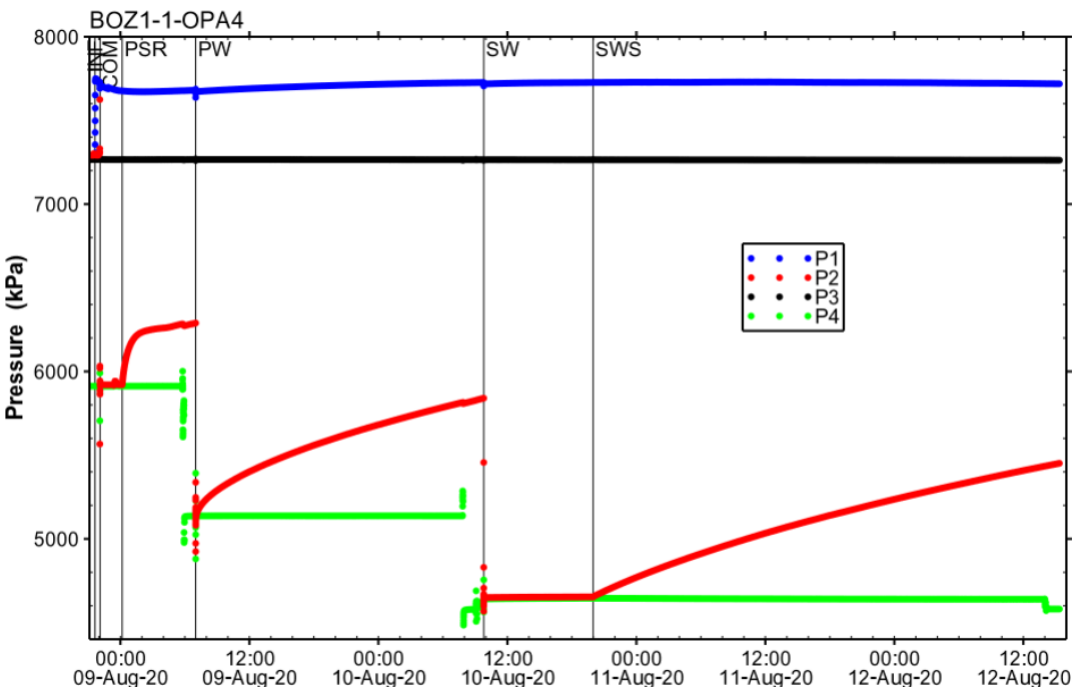


Fig. 4-15: Hydraulic packer test BOZ1-1-OPA4: Overview plot of pressure vs. time

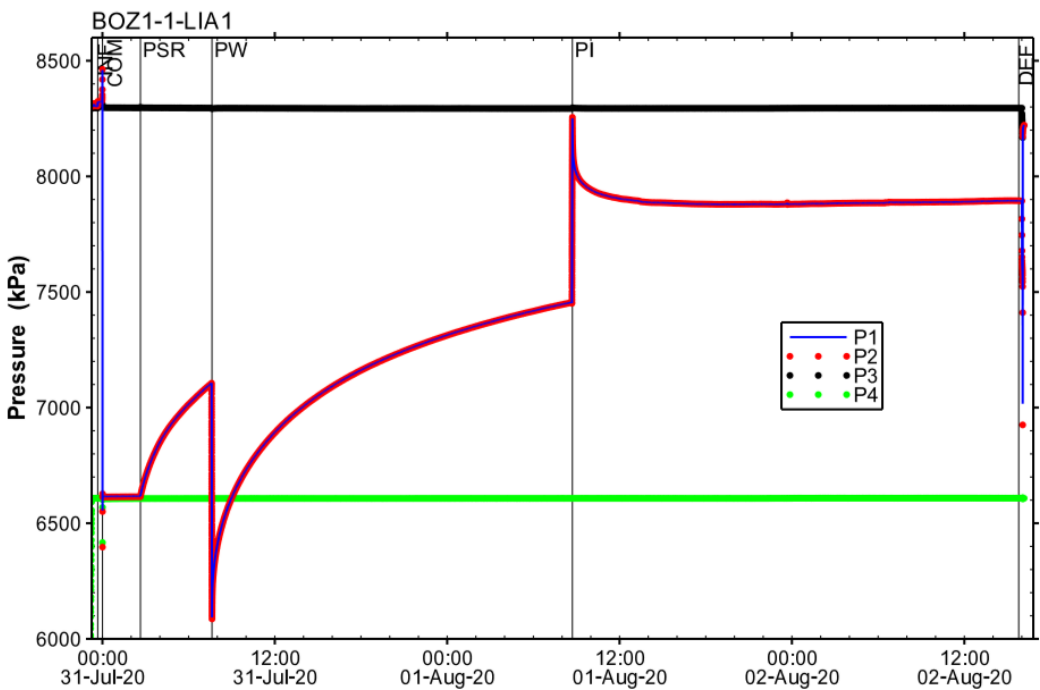


Fig. 4-16: Hydraulic packer test BOZ1-1-LIA1: Overview plot of pressure vs. time

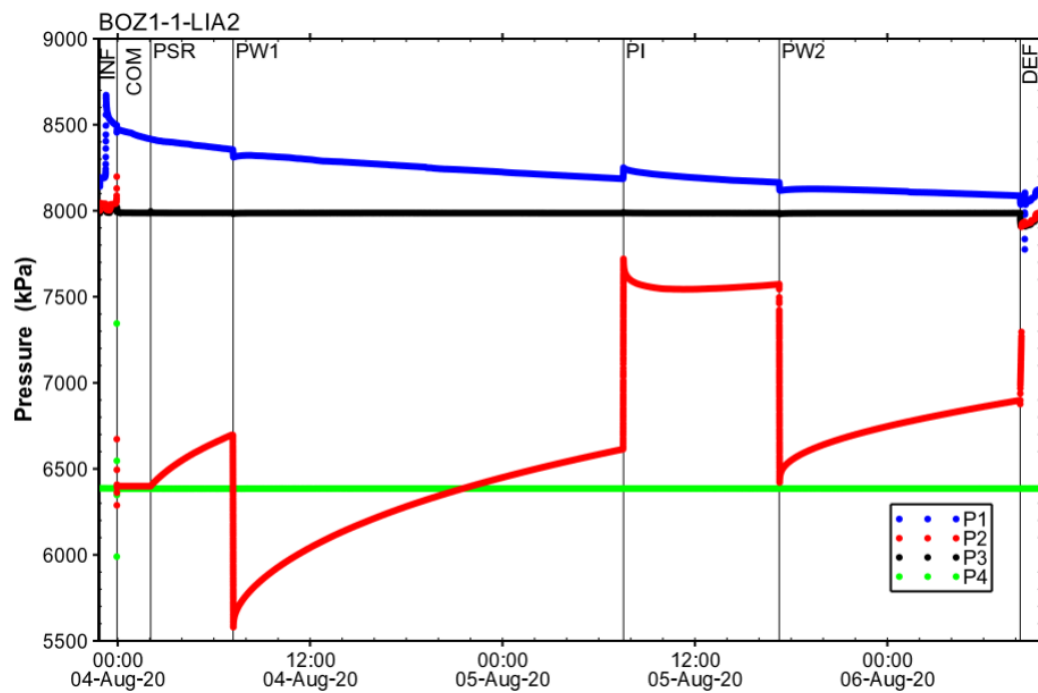


Fig. 4-17: Hydraulic packer test BOZ1-1-LIA2: Overview plot of pressure vs. time

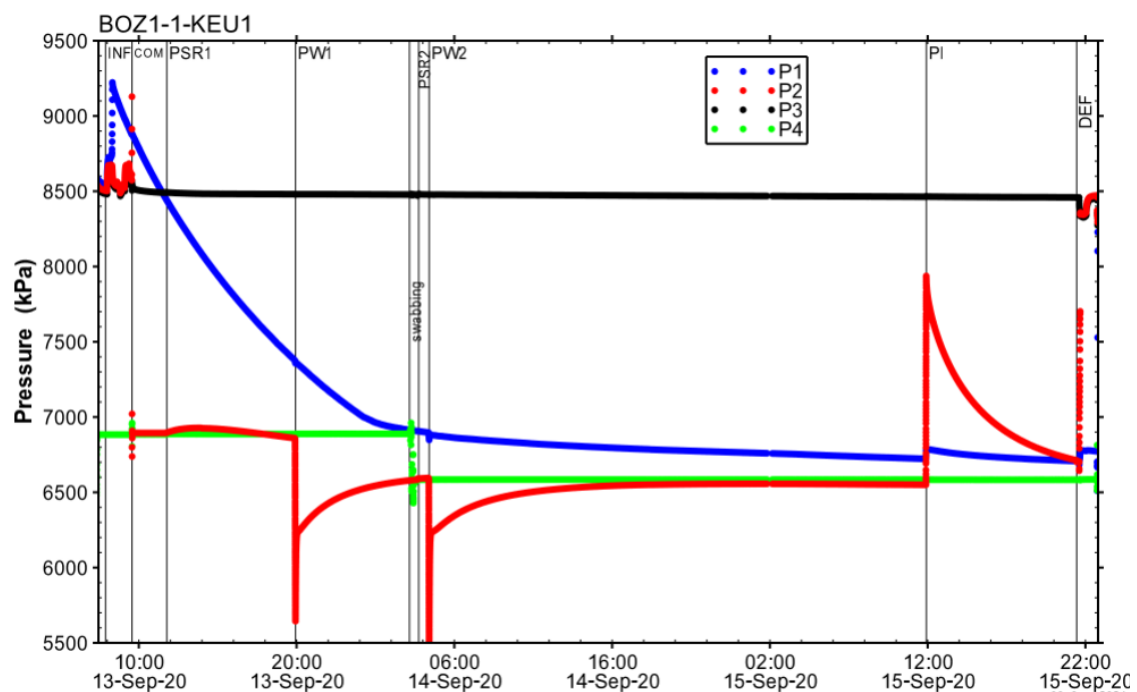


Fig. 4-18: Hydraulic packer test BOZ1-1-KEU1: Overview plot of pressure vs. time and date

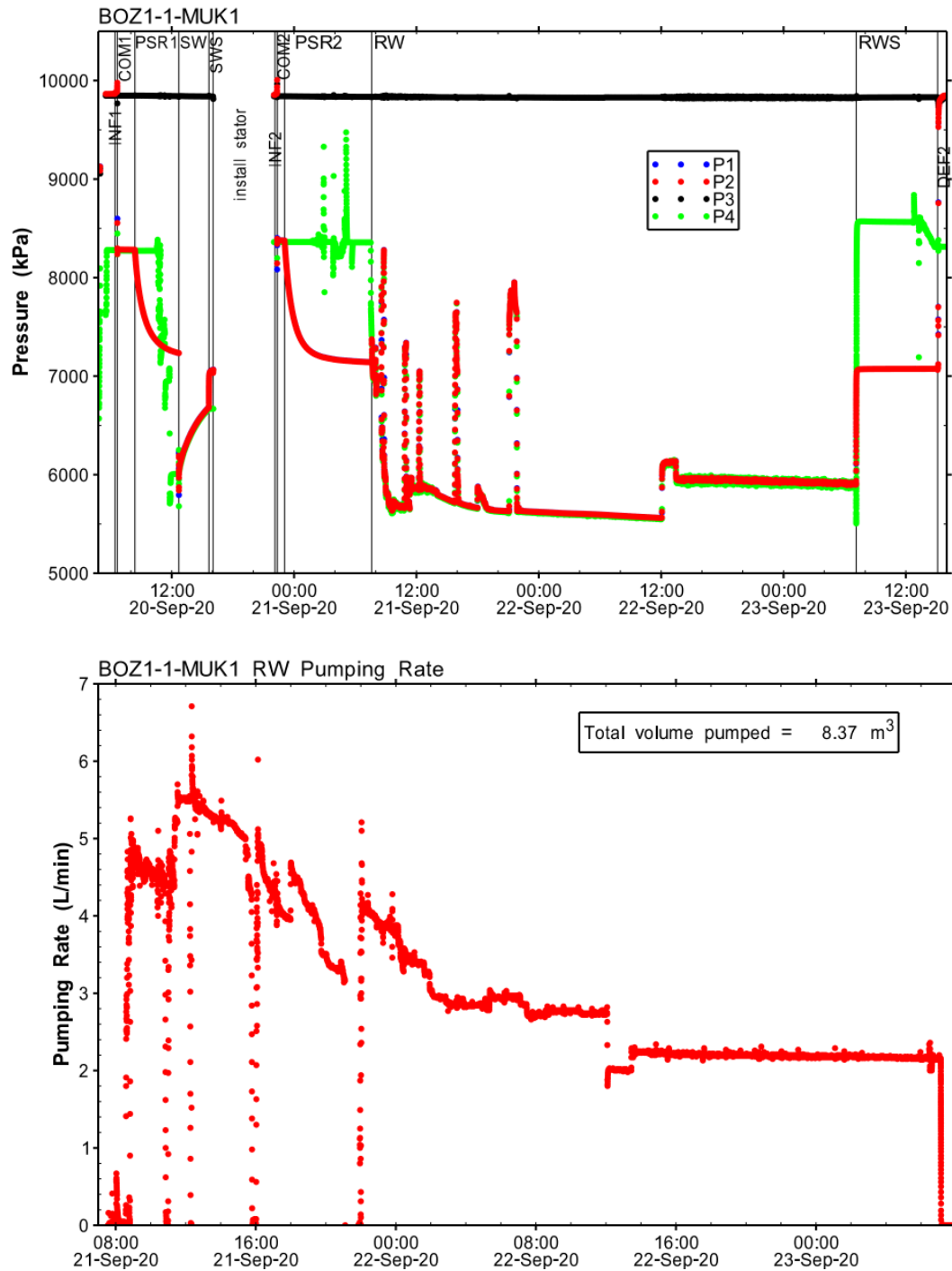


Fig. 4-19: Hydraulic packer test BOZ1-1-MUK1: Overview plot of pressure (top) and rate (bottom) vs. time and date

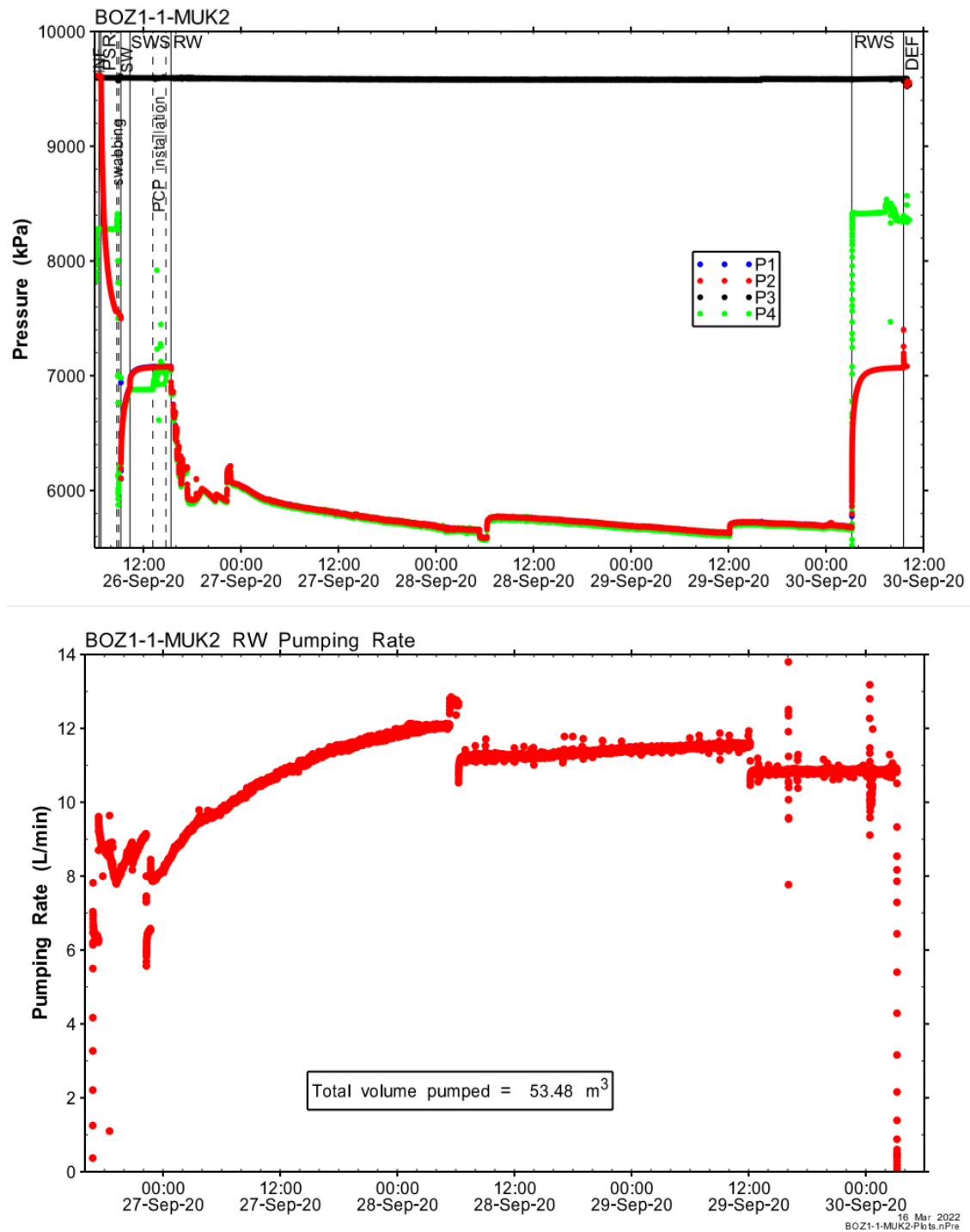


Fig. 4-20: Hydraulic packer test BOZ1-1-MUK2: Overview plot of pressure (top) and rate (bottom) vs. time and date

4.5 Details of selected tests

Two of the hydraulic packer tests are presented below in more detail: BOZ1-1-PWF1 and BOZ1-1-KEU1. Both hydraulic tests were performed in a combination of a pulse withdrawal and a pulse injection test phase. This approach is preferred by the hydraulic test field contractor when the apparent static formation pressure indicated by the initial pulse withdrawal is near or higher than the pressure at the end of this phase, and also due to the use of the piston pulse generator that allows determination of the wellbore storage with a high degree of accuracy.

The two test examples show the application of the approach, which used two pulse phases (withdrawal and injection pulse phase) to provide estimates of the formation parameters including the associated ranges of uncertainty. In both tests the observed borehole conditions did not differ between withdrawal and injection conditions, as is indicated by the estimated test zone compressibility values presented in the following subsections. The results of the two test analyses are provided in Section 4.6 together with the results of all other tests performed.

4.5.1 Hydraulic packer test BOZ1-1-PWF1

The hydraulic packer test BOZ1-1-PWF1 represents an example of testing formations with low transmissivity using both an intermediate pressure history duration and a short hydraulic test execution duration. For the analysis, the measurements of the P2* gauge (512.99 m MD) inside the test interval were used. Note that the measurement of P2* (memory gauge in the interval) is an absolute pressure measurement in contrast to the measurements of all sensors in the quadruple sub-surface probe. Therefore, Fig. 4-10 additionally presents the measurements of P2*.

4.5.1.1 Interval characterisation

The hydraulic test BOZ1-1-PWF1 was performed in a double packer configuration. The entire interval is located in the Passwang Formation of the Dogger Group and was designed to target the lower part of the formation. As test interval, a rather homogeneous part of the Passwang Formation with no visible major features was selected. The test interval covered part of the Waldenburg and the lower part of the Bruggli Member (511.15 – 529.89 m MD) and the "Cond. Equivalents of the Sissach, Hauenstein and Hirnichopf Members" (529.89 – 530.14 m MD). The primary test objectives were to obtain reliable estimates of T (and K) for the formation, the freshwater hydraulic head and a determination of the flow model. Details of the interval and test duration are provided in Tab. 4-23.

Tab. 4-23: Hydraulic test BOZ1-1-PWF1: Information on the test interval

Test	Depth		Length [m]	Packer configuration	Hydraulic testing		
	from [m MD]	to [m MD]			Start date	End date	Duration [h]
BOZ1-1-PWF1	511.15	530.14	18.99	Double	13.07.2020	16.07.2020	55.38

4.5.1.2 Test execution

Fig. 4-21 shows the system installation record as provided by the field test contractor. The equipment components are described in Section 4.2.

The hydraulic test tool (HTT) including the heavy-duty double packer system (HDDP) and the piston pulse generator (PPG) was installed in borehole BOZ1-1 on 07.07.2020. After testing in the Opalinus Clay formation the HTT was repositioned in the borehole for the hydraulic test BOZ1-1-PWF1. 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 shut-in tool (SIT) was opened when the top packer began to isolate the interval volume. The COM phase lasted 2 hours and 10 minutes which allowed some of the pressure and temperature transients caused by tool installation and packer inflation to dissipate before the SIT was again closed to initiate the PSR phase. The PSR phase lasted 5 hours and 22 minutes in order to allow the test interval pressure to establish a recovery trend after being isolated. After execution of the PSR phase, a pulse withdrawal phase (PW) was initiated, lasted for a period of 23 hours and 18 minutes. The PW test was terminated by initiation of a pulse injection test (PI), with a duration of 24 hours and 8 minutes. The subsequent deflation (DEF) of the packers was carried out with the SIT closed. The SIT remained closed for relocation of the HTT to the subsequent test interval BOZ1-1-PWF2.

BOZ1-1-PWF1 Double-Packer HTT Buildup 13.07.2020			max. OD (mm)	min. ID (mm)	Tensile strength (tonnes)	Weight (kg)	Length (m)	Cumulative length from top of tubing (m)	Cumulative depth (m bgl)
Tubing (2-7/8 inch) --									
54 jts+stretch			93.2	62.0	45	4895	505.17	505.17	499.14
Crossover			93.2	62.0			1.192	506.36	500.33
Downhole Shut-in Valve			0.805						
Compensation Packer			0.570	106	16	69	1.558		
Coupling			0.183					507.917	501.890
Crown Shaft			0.146						
Connector			0.185	100	40.0		0.331	508.248	502.221
Piston Pulse Generator			0.078	60			0.460	508.708	502.681
Crossover									
Crown Shaft									
Connector									
Cable Base									
Cable head and Cable Plug PRV			105	24.0			1.129	512.977	506.950
Probe Carrier with Quadruple Sub-Surface Probe (QSSP) and Sensor Positions									
Crown Shaft									
Crossover									
Safety joint									
Crossover									
Side entry sub									
Mandril									
Top Packer (114 mm)									
Below Side Entry Sub									
Crossover									
Filter (Screen length 0.97 m)									
Tubing (2-7/8 inch) --									
1 jt+2 pups									
Crossover									
P1 Seal Sub									
Mandril									
Bottom Packer (114 mm)									
Mandril									
Bottom Cap									

Fig. 4-21: Hydraulic test BOZ1-1-PWF1: Downhole equipment installation record with system layout as used in the field test

4.5.1.3 Analysis

Borehole pressure history

The borehole pressure history used for the analysis of the BOZ1-1-PWF1 tests is shown in Fig. B-1 (see Appendix B) and summarised in Tab. 4-24. The calculation of the mean interval fluid density using the measurement of the P2 pressure sensor (prior to packer inflation) gives a density of $1'187 \text{ kg m}^{-3}$. This value corresponds to the documented density of the drill mud during drilling ($1'190 \text{ kg m}^{-3}$; see Dossier I). For periods without a level measurement, the mud level was assumed to be at the level of the drain pipe of 3.4 m above ground level, because for periods with no active mud circulation, the drillers generally kept the borehole full to the level of the drain pipe. Therefore, the measured pressure value of the P2* gauge was used for the history periods once the HTT had reached the test depth and the borehole was filled with drill mud. This pressure value was also used for the BOZ1-1-OPA1, -OPA2, and -OPA3 testing periods when changes in the annulus fluid pressure were insignificant. During periods of coring, Geodata monitored the mud circulation pressures using a pressure gauge mounted 1.6 m above the rig floor. These pressures were extrapolated to the depth of the P2* transducer. During the petrophysical logging and other activities in the borehole, no additional mud level measurements were documented. Hence, it was assumed that the mud level was at the level of the drain pipe. Once the HTT was at test depth and data acquisition began, the P2* gauge measured pressure directly.

Tab. 4-24: Hydraulic test BOZ1-1-PWF1: Borehole pressure history

- ¹ Interval pressure (absolute) at P2* sensor level (512.99 m MD) calculated from the history information, e.g. fluid level and density.
- ² Drilling through interval midpoint (520.65 m MD).
- ³ Pressure measured when the borehole is filled with mud (e.g. when P2* at test depth before inflation of packer).

Description	Start date and time	Duration [h] Total: 325.07	Pressure ¹ [kPa]	
			Start	End
Drilling ²	30.06.2020 10:27	60.47	8'543	6'114 ³
Pull out of hole (POOH) of coring string	02.07.2020 22:55	5.08	6'114 ³	6'114 ³
Run in hole (RIH) of HTT in single packer configuration	03.07.2020 04:00	15.42	6'114 ³	6'114 ³
BOZ1-1-OPA1	03.07.2020 19:25	53.52	6'114 ³	6'114 ³
POOH of HTT	06.07.2020 00:56	10.07	6'114 ³	6'114 ³
Logging	06.07.2020 11:00	6.75	6'114 ³	6'114 ³
Installation and RIH of HTT in double packer configuration	06.07.2020 17:45	21.30	6'114 ³	6'114 ³
BOZ1-1-OPA2	07.07.2020 15:03	41.33	6'114 ³	6'114 ³
POOH / RIH of HTT	09.07.2020 08:23	23.42	6'114 ³	6'114 ³
BOZ1-1-OPA3	10.07.2020 07:48	84.18	6'114 ³	6'114 ³
Replacement of HTT	13.07.2020 19:59	3.53	6'114 ³	6'114 ³
Start testing BOZ1-1-PWF1	13.07.2020 23:31	-	6'114 ³	-

Flow model evaluation

The hydraulic test sequence was analysed using a radial composite flow model. This model approach was based on the analysis of the Ramey B diagnostic plots for the PW and PI phases. Figs. B-2 and B-3 show the diagnostic plots of the PW and the PI phases, respectively, with pressures normalised to an assumed static formation pressure of 5'900 kPa for the PW and to 5'030 kPa for the PI. The slight offset to the right of the derivative data after approximately 0.001 elapsed days on both plots is suggestive of decreasing hydraulic conductivity, as might be caused by a negative skin. No traditional skin model was applied using a step change of the hydraulic conductivity in a given distance. For the analysis, a radial composite system was used in which the logarithm of the hydraulic conductivity transitioned linearly with distance from the skin value (K_s) at the borehole wall to another optimised value of the formation hydraulic conductivity (K) at some distance (r_s) from the borehole.

Analysis of the pulse withdrawal phase (PW)

In the analysis, the temperature changes during test phases were considered inside the test interval. Fig. B-4 shows the development of the downhole temperature and pressure as measured by the memory gauge.

The initiation of the PW was done by retraction of a 250 ml piston using the piston pulse generator installed in the HTT (Fig. 4-21). The corresponding pressure change of 1'228 kPa leads to a calculated test zone compressibility of $5.2 \times 10^{-10} \text{ Pa}^{-1}$. Using this value for the test zone compressibility and after some initial fitting, a perturbation with 500 optimisations was performed. Unfortunately, during these simulations the PW phase had to be broken in two parts because of a 3 kPa offset observed in the middle of the test phase. Fig. B-5 shows the distribution of the normalised objective function value (normalised fit value) over the results for the estimation of the hydraulic conductivity. A fit discriminant value of 1.4 for the normalised objective function was chosen to determine the uncertainty range of the parameter value. Figs. B-6 to B-8 present the distribution of the normalised objective function value over the matched formation parameters (static formation pressure at depth of P2* P_f , specific storage S_s and radial extension of the skin zone r_s). Tab. 4-25 shows the best estimates and the resulting uncertainty ranges.

Tab. 4-25: Hydraulic test BOZ1-1-PWF1: Formation parameter estimation based on the perturbation analysis of PW using a radial composite flow model considering the borehole pressure history and temperature changes inside the test interval

¹ Static formation pressure at depth of P2* gauge (512.99 m MD).

PW results	K [m s ⁻¹]	S_s [m ⁻¹]	P_f ¹ [kPa]
Best estimate	5.3×10^{-14}	1.8×10^{-6}	5'699
Uncertainty range	$3.8 \times 10^{-14} - 9.2 \times 10^{-14}$	$2.3 \times 10^{-7} - 3.0 \times 10^{-6}$	5'200 – 5'993

Fig. B-9 shows the 193 simulations of the 500 optimisations that are chosen as representative for the measurement (Cartesian horsetail plot). The provided uncertainty ranges are determined from these simulations that provide lower normalised objective function values as defined by the fit discriminator. Figs. B-10 and Fig. B-11 show the Ramey A and Ramey B horsetail plots, respectively, of the PW phase before the offset was observed.

Analysis of the pulse injection phase (PI)

In this analysis, the temperature changes during test phases were considered inside the test interval. Fig. B-12 shows the development of the downhole temperature and pressure as measured by the memory gauge.

The initiation of the PI was done with an extension of a 250 ml piston using the piston pulse generator installed in the HTT (Fig. 4-21). The corresponding pressure change of 1'240 kPa leads also to a calculated test zone compressibility of $5.2 \times 10^{-10} \text{ Pa}^{-1}$. Using this value of the test zone compressibility and after some initial fitting, a perturbation using 1'000 optimisations was performed. A fit discriminant value of 1.02 was defined to isolate the parameter global minima and to determine the uncertainty range and 321 perturbation optimisations were accepted as providing reasonable fits to the data. Figs. B-13 to B-15 present the distribution of the normalised objective function value over the matched formation parameters. Tab. 4-26 shows the best estimates and the resulting uncertainty ranges.

Tab. 4-26: Hydraulic test BOZ1-1-PWF1: Formation parameter estimation based on the perturbation analysis of PI using a radial composite flow model considering the borehole pressure history and temperature changes inside the test interval

¹ Static formation pressure at depth of P2* gauge (512.99 m MD).

² Limit of optimisation range.

PI results	K [m s ⁻¹]	Ss [m ⁻¹]	P _f ¹ [kPa]
Best estimate	1.4×10^{-13}	3.4×10^{-8}	5'031
Uncertainty range	$1.0 \times 10^{-13} - 1.5 \times 10^{-13}$	$1.0 \times 10^{-8} {}^2 - 2.3 \times 10^{-7}$	5'027 – 5'050

Fig. B-16 shows the 321 simulations of 1'000 optimisations that were used as the basis for the determination of the uncertainty ranges due to the selection of all simulations providing lower normalised objective function values as defined by the fit discriminator. Figs. B-17 and B-18 show the Ramey A and Ramey B horsetail plots, respectively, of the PI phase.

Analysis of the test sequence (PSR-PW-PI)

In the analysis, the temperature changes during all test phases were considered inside the test interval. The weighting of the PI phase was increased during the optimisation process in order to achieve an equal result for all test phases. After some initial fitting, a perturbation using 500 optimisations was performed. A fit discriminator of 1.079 was used to eliminate outliers and build the base of the uncertainty range estimation. 328 perturbation optimisations were accepted as providing reasonable fits to the data. Figs. B-19 to B-21 present the distribution of the normalised objective function value over the matched formation parameters. Tab. 4-27 shows the best estimates and the resulting uncertainty ranges.

Tab. 4-27: Hydraulic test BOZ1-1-PWF1: Formation parameter estimation based on the perturbation analysis of the sequence PSR-PW-PI using a radial composite flow model considering the borehole pressure history and temperature changes inside the test interval

¹ Static formation pressure at depth of P2* gauge (512.99 m MD).

² Limit of optimisation range.

PW-PI results	K [m s ⁻¹]	S _s [m ⁻¹]	P _r ¹ [kPa]
Best estimate	1.5×10^{-13}	1.0×10^{-8} ²	5'039
Uncertainty range	$1.4 \times 10^{-13} - 1.5 \times 10^{-13}$	$1.0 \times 10^{-8} - 5.8 \times 10^{-8}$	5'028 – 5'050

However, it has to be considered that the best fits were obtained when S_s was at the minimum value set for the optimisation range, in this case $1 \times 10^{-8} \text{ m}^{-1}$ (Fig. B-21). This caused asymmetric minima for the other fitting parameters in addition to unrealistically low estimates of S_s . Fig. B-22 shows the 328 simulations used as the basis for the determination of the uncertainty ranges. All selected simulations provided lower normalised objective function values as defined by the fit discriminator. Figs. B-23 and B-24 show the Ramey A and Ramey B horsetail plots, of the PW (before the offset was observed) and PI respectively, for these 328 simulations.

Estimates of values and uncertainty ranges of the formation parameters

Further analyses to assess the uncertainty of the results were not considered to be necessary due to prior analysis results in TBO boreholes. Thus, the influence of the borehole pressure history was always included as described previously (see Tab. 4-24). Variations were not simulated due to the use of existing measurements during coring. Previous analyses results (in both the BUL1-1 and MAR1-1 boreholes) had also shown that there was no significant influence of slight changes in mud density. The test zone compressibility was determined by a pressure change measured with the memory gauge sensor P2* (Fig. B-25) and the QSSP sensor P2 that indicated no significant difference in the estimated pressure change. The associated volume change was clearly defined by the piston volume using the PPG. Therefore, a sampling analysis to take into account inaccuracies in the determination of the wellbore storage was not necessary.

According to the field test contractor, skin and storage properties were not reliably defined by the analyses due to the fact that the optimisation process uses these parameters (skin and storage properties) to match the effects on the pressure development at early-times due to non-hydraulic processes. Additionally, storage properties cannot be reliably determined from a single-borehole test. However, the chosen parameter will affect the estimation of the hydraulic conductivity and hydraulic head, as the estimates of these parameters are correlated due to the model used. Hence, this effect has to be considered in the correct choice of perturbation parameter ranges.

In particular, the head estimation of the PW analysis seems to be poorly constrained with a wide range of uncertainty (Tab. 4-25). The Jacobian plot for the PW phase (Fig. B-26) shows that the sensitivity to P_s was still rising at the end of the test phase indicating that the duration of the test phase was too short. This will affect the estimation of the hydraulic conductivity as seen in the scatter plot of the hydraulic conductivity versus static formation pressure showing a negative correlation (Fig. B-27). Due to the negative correlation, this resulted in higher values for the hydraulic conductivity due to lower static formation pressure values.

The most reliable or best estimate for the hydraulic conductivity was derived from the analysis of the sequence PSR-PW-PI due to the fact that these estimates were constrained by the entire test sequence. The provided uncertainty ranges were based on all presented analysis results. The best estimate and the uncertainty range of the static formation pressure, the hydraulic head respectively, was derived from the analysis of PI and PSR-PW-PI. This estimation of the static formation pressure was assumed to be highly uncertain as described previously. For the storage value of the formation, no best estimate or confidence range are provided, for the reasons described previously. However, it should be noted that the unrealistically low values for specific storage (Tabs. 4-26 and 4-27) could influence the results of the formation parameters and the perturbation analyses carried out take this into account. Tab. 4-28 presents the results of the analysis of the formation parameters for BOZ1-1-PWF1. The best estimate and the bandwidth of the hydraulic conductivity take into account the high uncertainty in the value of the specific storage coefficient.

Tab. 4-28: Hydraulic test BOZ1-1-PWF1: Best estimates of the formation parameters and associated uncertainty ranges

¹ Static formation pressure at midpoint of test interval (520.65 m MD).

Results	K [m s ⁻¹]	P_s ¹ [kPa]
Best estimate	1×10^{-13}	5'022
Uncertainty range	$4 \times 10^{-14} - 2 \times 10^{-13}$	5'014 – 5'037

4.5.2 Hydraulic packer test BOZ1-1-KEU1

The hydraulic packer test BOZ1-1-KEU1 represents an example of testing in formations with medium transmissivity, a moderate pressure history duration and a moderate hydraulic test duration. For the analysis, the measurements of the P2 sensor (698.69 m MD) of the QSSP were used.

4.5.2.1 Interval characterisation

The hydraulic test BOZ1-1-KEU1 was performed in a double packer configuration. The entire interval is located in the Klettgau Formation of the Keuper Group. The test interval covers the layers of main interest of the Klettgau Formation, believed to be potentially conductive. The test interval covered part of the Gruhalde Member (702.10 – 702.59 m MD), the Gansingen Member (702.59 – 708.79 m MD), the Ergolz Members (708.79 – 720.03 m MD) and a small part of the Bänkerjoch Formation (720.03 – 720.59 m MD). The primary test objectives were to obtain reliable estimates of T (and K) for the formation, the associated flow model, the freshwater hydraulic head and the collection of a water sample if possible. Details of the interval and test duration are provided in Tab. 4-29.

Tab. 4-29: Hydraulic test BOZ1-1-KEU1: Test interval information

Test	Depth		Length [m]	Packer configuration	Hydraulic testing		
	from [m MD]	to [m MD]			Start date	End date	Duration [h]
BOZ1-1-KEU1	702.10	720.59	18.49	Double	13.09.2020	15.09.2020	61.68

4.5.2.2 Test execution

Fig. 4-22 shows the system installation record as provided by the field test contractor. The equipment components are those described above. The test in interval BOZ1-1-KEU1 was performed after the following procedures were completed:

- A period of continued coring starting with coring through the midpoint of the test interval
- Caliper logging
- Installation of the HTT

The shut-in tool (SIT) remained closed during the installation. 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 2 hours and 6 minutes, after which the SIT was again closed to initiate the PSR phase. The PSR phase lasted 8 hours and 7 minutes. After the PSR phase, a pulse withdrawal (PW1) was initiated with the piston pulse generator (PPG) and this phase lasted for 7 hours and 44 minutes. A second pulse withdrawal test phase (PW2) was initiated after a short second PSR2 phase (to extend the piston again) of 37 minutes by again retracting the 250 ml piston. PW2 lasted for 31 hours and 29 minutes and was terminated by an extension of the piston to initiate a pulse injection (PI). The PI phase lasted for 9 hours and 31 minutes. 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 removed from the borehole with a closed SIT.

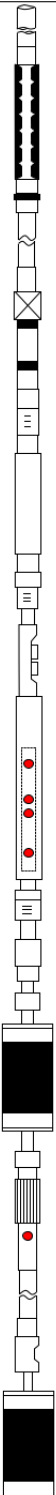
BOZ1-1-KEU1 Double-Packer HTT Buildup 12.09.2020			max. OD (mm)	min. ID (mm)	Tensile strength (tonnes)	Weight (kg)	Length (m)	Cumulative length from top of tubing (m)	Cumulative depth (m bgl)
Tubing (2-7/8 inch) -- 31 jts+2 pups			93.2	62.0	45	2875	296.60	296.60	290.65
Coupling			93.2	62.0			0.134	296.734	290.784
PCP Stator (1.7- 5.5 L/min)			78.6	34.0			1.309		
Stop pin		0.405	93.2 78.6	62.0			0.460	298.043 298.503	292.093 292.553
Tubing (2-7/8 inch) -- 42 jts + stretch			93.2	62.0	45	3853	397.53	696.038	690.088
Crossover			93.2	62.0			1.192	697.230	691.280
Downhole Shut-in Valve		0.805							
Compensation Packer		0.570	106	24.0	16	69	1.558		
Coupling		0.183						698.788	692.838
Crown Shaft		0.146	100	40.0			0.331	699.119	693.169
Connector		0.185	60				0.460	699.579	693.629
Piston Pulse Generator		0.078		25.4					
			114.3	97.2	30.5	65	2.455		
Crossover		0.022		40.0			0.237	702.034 702.271	696.084 696.321
Crown Shaft			100	40.0			0.321	702.592	696.642
Connector				40.0			0.127	702.719	696.769
Cable Base		Cable head and Cable Plug PRV	105	24.0			1.129	703.848	697.898
Probe Carrier with Quadruple Sub-Surface Probe (QSSP) and Sensor Positions		P3 0.525 P4 0.652 P2/T2 0.795 P1 0.992	105	40.0	16	132	1.621	705.469	699.519
Crown Shaft			100	40.0			0.321	705.790	699.840
Crossover			70	41.0			0.160	705.950	700.000
Safety joint			100	62.0	90	7.5	0.255	706.205	700.255
Crossover		0.15	93						
Side entry sub		0.214					0.468	706.673	700.723
Mandril		0.104	59				0.260	706.933	700.983
Top Packer (114 mm)		Packer seals 0.08 m above uninflated position	114	49.0			1.200	708.133	702.183
Below Side Entry Sub			49	49.0			0.260	708.393	702.443
Crossover			59				0.234	708.627	702.677
Filter (Screen length 0.97 m)			93				0.162	708.789	702.839
		0.97	90	62.0					
		P2* 0.247	80						
Tubing (2-7/8 inch) -- 1 jt+2 pups			93.2 (73.0)	62.0	45	150	15.520	710.139	704.189
Crossover		0.15	95					725.659	719.709
P1 Seal Sub		0.315	95			4	0.569		
Mandril		0.104	60					726.228	720.278
			114	49.0			0.260	726.488	720.538
Bottom Packer (114 mm)		Packer seals 0.05 m below uninflated position	114	49.0	16	80	1.200	727.688	721.738
			114	49.0			0.260	727.948	721.998
Mandril			59				0.105	728.053	722.103
Bottom Cap			95			6	0.160	728.213	722.263

Fig. 4-22: Hydraulic test BOZ1-1-KEU1: Downhole equipment installation record with system layout as used in the field test

4.5.2.3 Analysis

Borehole pressure history

The borehole history used for the analysis of the BOZ1-1-KEU1 tests is shown in Fig. B-28 and summarised in Tab. 4-30. The calculation of the mean interval fluid density using the P2 pressure sensor measurement (prior to packer inflation) resulted in a density of $1'234 \text{ kg m}^{-3}$. This value corresponds to the documented density of the drill mud during drilling ($1'240 \text{ kg m}^{-3}$; see Dossier I) and to the measurement prior to the packer inflation of the hydraulic test BOZ1-1-KEU1. For periods without a level measurement, the mud level was assumed to be at the level of the drain pipe of 3.4 m above ground level, because for periods with no active mud circulation, the drillers generally kept the borehole full to the level of the drain pipe. During periods of coring, Geodata monitored the mud circulation pressures using a pressure gauge mounted 1.6 m above the rig floor. These pressures were extrapolated to the depth of the P2 transducer. Once the HTT was at test depth and data acquisition began for the hydraulic test BOZ1-1-KEU1, the P2 gauge measured pressure directly.

Tab. 4-30: Hydraulic test BOZ1-1-KEU1: Borehole pressure history

- ¹ Interval pressure at P2 sensor level (698.69 m MD) measured or calculated from the history information, e.g. fluid level and density.
- ² Drilling through interval midpoint (711.35 m MD).
- ³ Pressure measured when the borehole was filled with mud (e.g. when P2 first at test depth).

Description	Start date and time	Duration [h] Total: 261.55	Pressure ¹ [kPa]	
			Start	End
Drilling ²	02.09.2020 10:22	220.85	11'217	8'554 ³
Pull out of hole (POOH) of coring string	11.09.2020 15:13	8.28	8'554 ³	8'554 ³
Caliper logging	11.09.2020 23:30	4.25	8'554 ³	8'554 ³
Installation and run in hole (RIH) of HTT in double packer configuration	12.09.2020 03:45	28.17	8'554 ³	8'554 ³
Start testing BOZ1-1-KEU1	13.09.2020 07:55	-	8'554 ³	-

Flow model evaluation

The evaluation of the flow model approach was based on the PW1 and PW2 phases. Fig. B-29 and Fig. B-30 show the Ramey B diagnostic plots of PW1 and PW2, respectively, with pressures normalised to assumed P_s values of 6'357 and 6'359 kPa, respectively. The anomalous early-time behaviour created a number of inflections in both the normalised pressure and derivative data suggestive of a transition from higher to lower K with distance and/or time. No further conclusions could be drawn about an appropriate flow model to use for test interpretation. Hence, a homogeneous flow model with a time-dependent skin was used for the analysis. In order to reduce the number of free parameters during the optimisation process, the hydraulic conductivity of the skin zone during the history, K_s (pre-PW1), was fixed to $1 \times 10^{-13} \text{ m s}^{-1}$. The influence of this assumption was studied as presented later in this Section. For the same reason, the specific storage of the formation S_s was fixed to $2 \times 10^{-6} \text{ m}^{-1}$.

Analysis of the pulse withdrawal phases (PW1)

In the analysis, the temperature change during test phases was considered inside the test interval. Fig. B-31 shows the development of the downhole temperature as measured by the memory gauge and pressure of the P2 probe on the QSSP.

The initiation of the PW was done with a retraction of a 250 ml piston using the piston pulse generator installed in the HTT (Fig. 4-22). The corresponding pressure change of 1'212 kPa leads to a calculated test zone compressibility of $5.4 \times 10^{-10} \text{ Pa}^{-1}$. Using this value of the test zone compressibility and after some initial fitting, a perturbation of 1'000 optimisations was performed. The best estimate for the skin specific storage is at a very low value of $1 \times 10^{-8} \text{ m}^{-1}$. Figs. B-32 and B-33 show the distribution of the normalised objective function value of the optimisation results as a function of the matched formation parameters (hydraulic conductivity and static formation pressure). The resulting estimates were influenced by the limitation of the specific storage of the skin zone and most of them are one-sided in the resulting parameter space of the perturbation. A fit discriminant value of 1.15 for the normalised objective function was chosen to determine the uncertainty range of the parameter values. Tab. 4-31 shows the resulting formation parameter ranges.

Tab. 4-31: Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the perturbation analysis of PW1 using a radial homogenous flow model with time-dependent skin considering the borehole pressure history and temperature changes inside the test interval

¹ Fixed in order to reduce the number of correlated fitting parameters.

² Static formation pressure at depth of the P2 gauge (698.69 m MD).

PW1 results	K [m s ⁻¹]	S _s ¹ [m ⁻¹]	P _f ² [kPa]
Best estimate	2.9×10^{-12}	2×10^{-6}	6'468
Uncertainty range	$2.1 \times 10^{-12} - 5.2 \times 10^{-12}$	-	6'459 – 6'500

Fig. B-34 shows the 308 simulations used as base for the determination of the uncertainty ranges due to the selection of all simulations providing lower normalised objective function values as defined by the fit discriminator. Figs. B-35 and B-36 show the Ramey A and Ramey B horsetail plots, respectively, of the PW1 phase.

Analysis of the pulse withdrawal phases (PW2)

In the analysis, the temperature changes during test phases were considered inside the test interval. Fig. B-37 shows the development of the downhole temperature as measured by the memory gauge and pressure on the P2 probe of the QSSP.

The initiation of the PW was done with a retraction of a 250 ml piston using the piston pulse generator installed in the HTT (Fig. 4-22). The corresponding pressure change of 1'122 kPa leads to a calculated test zone compressibility of $5.8 \times 10^{-10} \text{ Pa}^{-1}$. Using this value of the test zone compressibility and after some initial fitting, a perturbation of 1'000 optimisations was performed. Figs. B-38 and B-39 show the distribution of the normalised objective function value of the optimisation results as a function of the matched formation parameters (hydraulic conductivity and static formation pressure). A fit discriminant value of 1.065 for the normalised objective function was chosen to determine the uncertainty ranges of the parameters. Tab. 4-32 shows the resulting formation parameter ranges.

Tab. 4-32: Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the perturbation analysis of PW2 using a radial homogenous flow model with time-dependent skin considering the borehole pressure history and temperature changes inside the test interval

¹ Fixed in order to reduce the number of correlated fitting parameters.

² Static formation pressure at depth of P2 gauge (698.69 m MD).

PW2 results	K [m s ⁻¹]	S_s ¹ [m ⁻¹]	P_f ² [kPa]
Best estimate	2.4×10^{-12}	2×10^{-6}	6'382
Uncertainty range	$1.5 \times 10^{-12} - 4.1 \times 10^{-12}$	-	6'338 – 6'409

Fig. B-40 shows the 649 simulations used as base for the determination of the uncertainty ranges due to the selection of all simulations providing lower normalised objective function values as defined by the fit discriminator. Figs. B-41 and B-42 show the Ramey A and Ramey B horsetail plots, respectively, of the PW2 phase.

Analysis of the pulse withdrawal phases (PI)

In the analysis, the temperature change during test phases were considered inside the test interval. Fig. B-43 shows the development of the downhole measured temperature and pressure.

The initiation of the PI was done by an extension of a 250 ml piston using the piston pulse generator installed in the HTT (Fig. 4-22). The corresponding pressure change of 1'386 kPa leads also to a calculated test zone compressibility of $4.7 \times 10^{-10} \text{ Pa}^{-1}$. Using this value for the test zone compressibility and after some initial fitting, a perturbation of 1'000 optimisations was performed. A fit discriminant of 1.1 was defined to isolate the parameter global minima and to determine the uncertainty ranges. 567 perturbation optimisations were accepted as providing reasonable fits to the data. Figs. B-44 and B-45 present the distribution of the objective function value over the matched formation parameters. Tab. 4-33 shows the best estimates and the resulting uncertainty ranges.

Tab. 4-33: Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the perturbation analysis of PI using a radial homogenous flow model with time-dependent skin considering the borehole pressure history and temperature changes inside the test interval

¹ Fixed in order to reduce the number of correlated fitting parameters.

² Static formation pressure at depth of P2 gauge (698.69 m MD).

PI results	K [m s ⁻¹]	S_s ¹ [m ⁻¹]	P_f ² [kPa]
Best estimate	3.8×10^{-12}	2×10^{-6}	6'150
Uncertainty range	$3.5 \times 10^{-12} - 4.2 \times 10^{-12}$	-	5'944 – 6'250

Fig. B-46 shows the 567 simulations used as base for the determination of the uncertainty ranges due to the selection of all simulations providing lower normalised objective function values as defined by the fit discriminator. Figs. B-47 and B-48 show the Ramey A and Ramey B horsetail plots, respectively, of the PI phase.

Analysis of the full test sequence (PW1-PW2-PI)

Similar to the PI analysis, a total of 10 fitting parameters were used: formation hydraulic conductivity K, skin hydraulic conductivity K_s (PW1, PW2, and PI), static formation pressure P_f, skin specific storage S_{ss} (pre-PW1, PW1, PW2, and PI), and the thickness of the skin zone t_s. After some initial fitting, a perturbation with 1'000 parameter optimisations was used to determine the best estimates and the uncertainty ranges of the fitting parameter. In the analysis, the temperature changes during test phases were considered inside the test interval. A value for the test zone compressibility of $5.3 \times 10^{-10} \text{ Pa}^{-1}$ was used for all test phases. A fit discriminant of 1.06 was defined to isolate the parameter global minima and to determine the uncertainty ranges. 797 perturbation optimisations were accepted as providing reasonable fits to the data. Figs. B-49 and B-50 present the distribution of the objective function value over the matched formation parameters (hydraulic conductivity and static formation pressure). Tab. 4-34 shows the best estimates and the resulting uncertainty ranges.

Tab. 4-34: Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the perturbation analysis of the sequence PW1-PW2-PI using a radial homogenous flow model with time-dependent skin considering the borehole pressure history and temperature changes inside the test interval

¹ Fixed in order to reduce the number of correlated fitting parameters.

² Static formation pressure at depth of P2 gauge (698.69 m MD).

PW1-PW2-PI results	K [m s ⁻¹]	S_s ¹ [m ⁻¹]	P_f ² [kPa]
Best estimate	5.3×10^{-12}	2×10^{-6}	6'336
Uncertainty range	$5.1 \times 10^{-12} - 5.5 \times 10^{-12}$	-	6'301 – 6'357

Fig. B-51 shows the 797 simulations used as a base for the determination of the uncertainty ranges due to the selection of all simulations providing lower normalised objective function values as defined by the fit discriminator. Fig. B-52 shows the scatter plot of the optimisation results indicating a positive correlation between the static formation pressure and the hydraulic conductivity of the formation. The diagnostic representations of all three test phases are of the same quality as shown for the single-phase analyses.

Estimation of the influence to the formation parameter estimates due to the assumptions on the history period

At the beginning of the analysis, the hydraulic conductivity was fixed for the skin zone during the history, K_s (pre-PW1), in order to reduce the number of free parameters in the optimisation process. To evaluate the effect of this assumption on the formation parameter estimates, two sets of perturbations using the entire available data set (PW1-PW2-PI) were performed using an upper and lower estimate for the hydraulic conductivity of the skin during the history times. A range of two orders of magnitude were studied (K_s (pre-PW1): $1 \times 10^{-14} - 1 \times 10^{-12} \text{ m s}^{-1}$). Tab. 4-35 shows the resulting estimates for the formation parameters.

Tab. 4-35: Hydraulic test BOZ1-1-KEU1: Formation parameter estimation based on the analysis of the sequence PW1-PW2-PI using a radial homogenous flow model with time-dependent skin considering the borehole pressure history, temperature changes inside the test interval and different assumptions on the hydraulic conductivity during the history

¹ Fixed in order to reduce the number of correlated fitting parameters.

² Static formation pressure at depth of P2 gauge (698.69 m MD).

PW1-PW2-PI results	K [m s ⁻¹]	S_s ¹ [m ⁻¹]	P_f ² [kPa]
K_s (pre-PW1) = $1 \times 10^{-12} \text{ m s}^{-1}$	2.2×10^{-12}	2×10^{-6}	5'851
K_s (pre-PW1) = $1 \times 10^{-13} \text{ m s}^{-1}$	5.3×10^{-12}	2×10^{-6}	6'336
K_s (pre-PW1) = $1 \times 10^{-14} \text{ m s}^{-1}$	5.5×10^{-12}	2×10^{-6}	6'329

Fig. B-53 and Fig. B-54 show the best simulation of all the perturbation simulations performed, with a fixed hydraulic conductivity of the skin zone during the history of $1 \times 10^{-12} \text{ m s}^{-1}$, and $1 \times 10^{-14} \text{ m s}^{-1}$ respectively.

Estimates of the formation parameter values and uncertainty ranges

The influence of the borehole history was always included in the analyses of all tests. Variations in the borehole history were not simulated due to the use of existing measurements during coring. Previous analyses results (in the BUL1-1 and MAR1-1 boreholes) had also shown that there was no significant influence of slight changes in mud density.

The test zone compressibility was determined by a pressure change measured with both the QSSP sensor P2 and the memory gauge sensor P2*. These sensors indicated no significant difference in pressure change. The associated volume change was clearly defined by the piston volume using the PPG. Therefore, a sampling analysis to account for inaccuracies in the determination of the wellbore storage was not necessary.

According to the field test contractor, skin and storage properties were not reliably defined by the analyses due to the fact that the optimisation process used these parameters (skin and storage properties) to match the effects on the pressure development at early-times due to non-hydraulic processes. Additionally, storage properties cannot be reliably determined from a single-borehole test. However, the chosen parameter will affect the estimation of the hydraulic conductivity and hydraulic head, as the estimates of these parameters are correlated due to the model used. Hence, this effect is considered in the correct choice of perturbation parameter ranges.

The best estimates of hydraulic properties represent the geometric mean for the formation hydraulic conductivity and arithmetic mean for the static formation pressure of the best estimates from analyses of all BOZ1-1-KEU1 test phases. Tab. 4-36 shows the results. The uncertainty ranges represent the overall ranges from the analysis of all BOZ1-1-KEU1 test phases. The studied effect of the chosen hydraulic conductivity of the skin zone during the history was less than the uncertainty due to the analysis of the different test phases and the entire test sequence.

Tab. 4-36: Hydraulic test BOZ1-1-KEU1: Best estimates of the formation parameters and associated uncertainty ranges

¹ Static formation pressure at midpoint of test interval (711.35 m MD).

Results	K [m s ⁻¹]	P _f ¹ [kPa]
Best estimate	3.4×10^{-12}	6'488
Uncertainty range	$1.5 \times 10^{-12} - 5.5 \times 10^{-12}$	6'098 – 6'654

4.6 Summary and discussion of hydraulic tests

4.6.1 Summary tables and plots

The results of the transmissivity and hydraulic conductivity estimations for all tested intervals are summarised in Tab. 4-37. The estimated freshwater hydraulic heads and static formation pressures are documented in Tab. 4-38. Both tables present the best estimates along with confidence ranges as determined by the field test contractor and documented in the corresponding Detailed Reports.

The permeabilities for all tested intervals are summarised in Tab. 4-39 and were calculated based on the hydraulic conductivities provided in Tab. 4-37. An assumed density of 1'000 kg m⁻³ and dynamic viscosity of 1×10^{-3} Pa s were used for the calculation of the hydraulic permeability values.

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

Tab. 4-37: Summary of hydraulic packer testing in borehole BOZ1-1: 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 ¹		Lowest estimate ¹		Highest estimate ¹	
	From [m MD]	To [m MD]	From [m asl]	To [m asl]			T [m ² s ⁻¹]	K [m s ⁻¹]	T _{min} [m ² s ⁻¹]	K _{min} [m s ⁻¹]	T _{max} [m ² s ⁻¹]	K _{max} [m s ⁻¹]
BOZ1-1-MAL1	300.92	328.24	212.37	185.05	27.32	homogeneous, discrete time-dependent skin	3 × 10 ⁻⁰⁸	1 × 10 ⁻⁰⁹	2 × 10 ⁻⁰⁸	7 × 10 ⁻¹⁰	7 × 10 ⁻⁰⁸	2 × 10 ⁻⁰⁹
BOZ1-1-PWF2	492.05	511.05	21.24	2.24	19.00	2-zone radial composite	1 × 10 ⁻¹²	6 × 10 ⁻¹⁴	3 × 10 ⁻¹³	2 × 10 ⁻¹⁴	3 × 10 ⁻¹²	2 × 10 ⁻¹³
BOZ1-1-PWF1	511.15	530.14	2.14	-16.85	18.99	2-zone radial composite	3 × 10 ⁻¹²	1 × 10 ⁻¹³	7 × 10 ⁻¹³	4 × 10 ⁻¹⁴	3 × 10 ⁻¹²	2 × 10 ⁻¹³
BOZ1-1-OPA2 ²	538.00	557.00	-24.71	-43.71	19.00	homogeneous, discrete skin	1 × 10 ⁻¹²	6 × 10 ⁻¹⁴	4 × 10 ⁻¹³	2 × 10 ⁻¹⁴	2 × 10 ⁻¹²	1 × 10 ⁻¹³
BOZ1-1-OPA3 ²	538.00	557.00	-24.71	-43.71	19.00	homogeneous, discrete time-dependent skin	1 × 10 ⁻¹²	6 × 10 ⁻¹⁴	4 × 10 ⁻¹³	2 × 10 ⁻¹⁴	2 × 10 ⁻¹²	1 × 10 ⁻¹³
BOZ1-1-OPA1 ³	544.00	564.00	-30.71	-50.71	20.00	2-zone radial composite	-	-	-	-	-	-
BOZ1-1-OPA4	602.35	608.10	-89.06	-94.81	5.75	homogeneous, discrete time-dependent skin	2 × 10 ⁻¹³	4 × 10 ⁻¹⁴	6 × 10 ⁻¹⁴	1 × 10 ⁻¹⁴	2 × 10 ⁻¹²	3 × 10 ⁻¹³
BOZ1-1-LIA2	651.00	674.14	-137.71	-160.85	23.14	homogeneous, discrete time-dependent skin	8 × 10 ⁻¹³	3 × 10 ⁻¹⁴	1 × 10 ⁻¹³	5 × 10 ⁻¹⁵	3 × 10 ⁻¹²	1 × 10 ⁻¹³
BOZ1-1-LIA1	674.00	690.00	-160.71	-176.71	16.00	homogeneous, discrete time-dependent skin	3 × 10 ⁻¹¹	2 × 10 ⁻¹²	8 × 10 ⁻¹²	5 × 10 ⁻¹³	1 × 10 ⁻¹⁰	7 × 10 ⁻¹²
BOZ1-1-KEU1	702.10	720.59	-188.81	-207.30	18.49	homogeneous, discrete time-dependent skin	6 × 10 ⁻¹¹	3 × 10 ⁻¹²	3 × 10 ⁻¹¹	2 × 10 ⁻¹²	1 × 10 ⁻¹⁰	6 × 10 ⁻¹²
BOZ1-1-MUK1	845.69	867.00	-332.40	-353.71	21.31	2-zone radial composite, time-dependent skin	5 × 10 ⁻⁰⁵	2 × 10 ⁻⁰⁶	2 × 10 ⁻⁰⁵	7 × 10 ⁻⁰⁷	2 × 10 ⁻⁰⁴	7 × 10 ⁻⁰⁶
BOZ1-1-MUK2	845.78	882.00	-332.49	-368.71	36.22	homogeneous, time-dependent skin	9 × 10 ⁻⁰⁶	3 × 10 ⁻⁰⁷	3 × 10 ⁻⁰⁶	8 × 10 ⁻⁰⁸	3 × 10 ⁻⁰⁵	8 × 10 ⁻⁰⁷

¹ Based on the results presented by the field test contractor in the corresponding DR.² Test results from BOZ1-1-OPA2 and BOZ1-1-OPA3 refer to a similar test interval.³ Operational problems affected the pressure signal and prevented the estimation of hydraulic parameters.

Tab. 4-38: Summary of hydraulic packer testing in borehole BOZ1-1: Hydraulic head estimates

Test interval details and hydraulic model							Hydraulic head [m bgl]			Hydraulic head [m asl]			Formation pressure		
Test name	Interval depth				Interval length [m]	Hydraulic model	Best ¹ h	Lowest ¹ h _{min}	Highest ¹ h _{max}	Best ¹ h	Lowest ¹ h _{min}	Highest ¹ h _{max}	Best ¹ P _s	Lowest ¹ P _{s min}	Highest ¹ P _{s max}
	From [m MD]	To [m MD]	From [m asl]	To [m asl]			[m bgl]	[m bgl]	[m bgl]	[m asl]	[m asl]	[m asl]	[kPa]	[kPa]	[kPa]
BOZ1-1-MAL1	300.92	328.24	212.37	185.05	27.32	homogeneous, discrete time- dependent skin	149	162	135	364	352	378	1'620	1'501	1'757
BOZ1-1-PWF2	492.05	511.05	21.24	2.24	19.00	2-zone radial composite	-43	-19	-78	556	532	592	5'344	5'107	5'689
BOZ1-1-PWF1 ⁴	511.15	530.14	2.14	-16.85	18.99	2-zone radial composite	9	9	7	505	504	506	5'022	5'014	5'037
BOZ1-1-OPA2 ²	538.00	557.00	-24.71	-43.71	19.00	homogeneous, discrete skin	-113	-83	-163	626	596	677	6'481	6'181	6'973
BOZ1-1-OPA3 ²	538.00	557.00	-24.71	-43.71	19.00	homogeneous, discrete time- dependent skin	-113	-83	-163	626	596	677	6'481	6'181	6'973
BOZ1-1-OPA1 ³	544.00	564.00	-30.71	-50.71	20.00	2-zone radial composite	-	-	-	-	-	-	-	-	-
BOZ1-1-OPA4	602.35	608.10	-89.06	-94.81	5.75	homogeneous, discrete time- dependent skin	-147	-65	-194	660	578	707	7'375	6'574	7'841
BOZ1-1-LIA2	651.00	674.14	-137.71	-160.85	23.14	homogeneous, discrete time- dependent skin	-318	-197	-486	831	710	999	9'617	8'432	11'268
BOZ1-1-LIA1	674.00	690.00	-160.71	-176.71	16.00	homogeneous, discrete time- dependent skin	-130	-114	-145	643	628	658	7'966	7'813	8'112

¹ Based on the results presented by the field test contractor in the corresponding DR.² Test results from BOZ1-1-OPA2 and BOZ1-1-OPA3 refer to a similar test interval.³ Operational problems affected the pressure signal and prevented the estimation of hydraulic parameters.⁴ Narrow range of the hydraulic head, test BOZ1-1-PWF2 provides a more realistic uncertainty of the hydraulic head.

Tab. 4-38: continued

Test interval details and hydraulic model							Hydraulic head [m bgl]			Hydraulic head [m asl]			Formation pressure		
Test name	Interval depth				Interval length [m]	Hydraulic model	Best [†] h	Lowest [†] h _{min}	Highest [†] h _{max}	Best [†] h	Lowest [†] h _{min}	Highest [†] h _{max}	Best [†] P _s	Lowest [†] P _{s min}	Highest [†] P _{s max}
	From [m MD]	To [m MD]	From [m asl]	To [m asl]			[m bgl]	[m bgl]	[m bgl]	[m asl]	[m asl]	[m asl]	[kPa]	[kPa]	[kPa]
BOZ1-1-KEU1	702.10	720.59	-188.81	-207.30	18.49	homogeneous, discrete time- dependent skin	50	90	33	463	424	480	6'488	6'098	6'654
BOZ1-1-MUK1	845.69	867.00	-332.40	-353.71	21.31	2-zone radial composite, time- dependent skin	120	121	119	393	392	394	7'220	7'210	7'230
BOZ1-1-MUK2	845.78	882.00	-332.49	-368.71	36.22	homogeneous, time-dependent skin	116	120	114	397	394	399	7'335	7'300	7'358

[†] Based on the results presented by the field test contractor in the corresponding DR.

Tab. 4-39: Summary of hydraulic packer testing in borehole BOZ1-1: 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]				
BOZ1-1-MAL1	300.92	328.24	212.37	185.05	27.32	1×10^{-16}	7×10^{-17}	2×10^{-16}
BOZ1-1-PWF2	492.05	511.05	21.24	2.24	19	6×10^{-21}	2×10^{-21}	2×10^{-20}
BOZ1-1-PWF1	511.15	530.14	2.14	-16.85	18.99	2×10^{-20}	4×10^{-21}	2×10^{-20}
BOZ1-1-OPA2	538	557	-24.71	-43.71	19	6×10^{-21}	2×10^{-21}	1×10^{-20}
BOZ1-1-OPA3	538	557	-24.71	-43.71	19	6×10^{-21}	2×10^{-21}	1×10^{-20}
BOZ1-1-OPA1 ³	544	564	-30.71	-50.71	20	-	-	-
BOZ1-1-OPA4	602.35	608.1	-89.06	-94.81	5.75	4×10^{-21}	1×10^{-21}	3×10^{-20}
BOZ1-1-LIA2	651	674.14	-137.71	-160.85	23.14	3×10^{-21}	5×10^{-22}	1×10^{-20}
BOZ1-1-LIA1	674	690	-160.71	-176.71	16	2×10^{-19}	5×10^{-20}	7×10^{-19}
BOZ1-1-KEU1	702.1	720.59	-188.81	-207.3	18.49	3×10^{-19}	2×10^{-19}	6×10^{-19}
BOZ1-1-MUK1	845.69	867	-332.4	-353.71	21.31	2×10^{-13}	7×10^{-14}	7×10^{-13}
BOZ1-1-MUK2	845.78	882	-332.49	-368.71	36.22	3×10^{-14}	8×10^{-15}	8×10^{-14}

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

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

³ The possibility that the pressure signal was affected during the test cannot be ruled out.

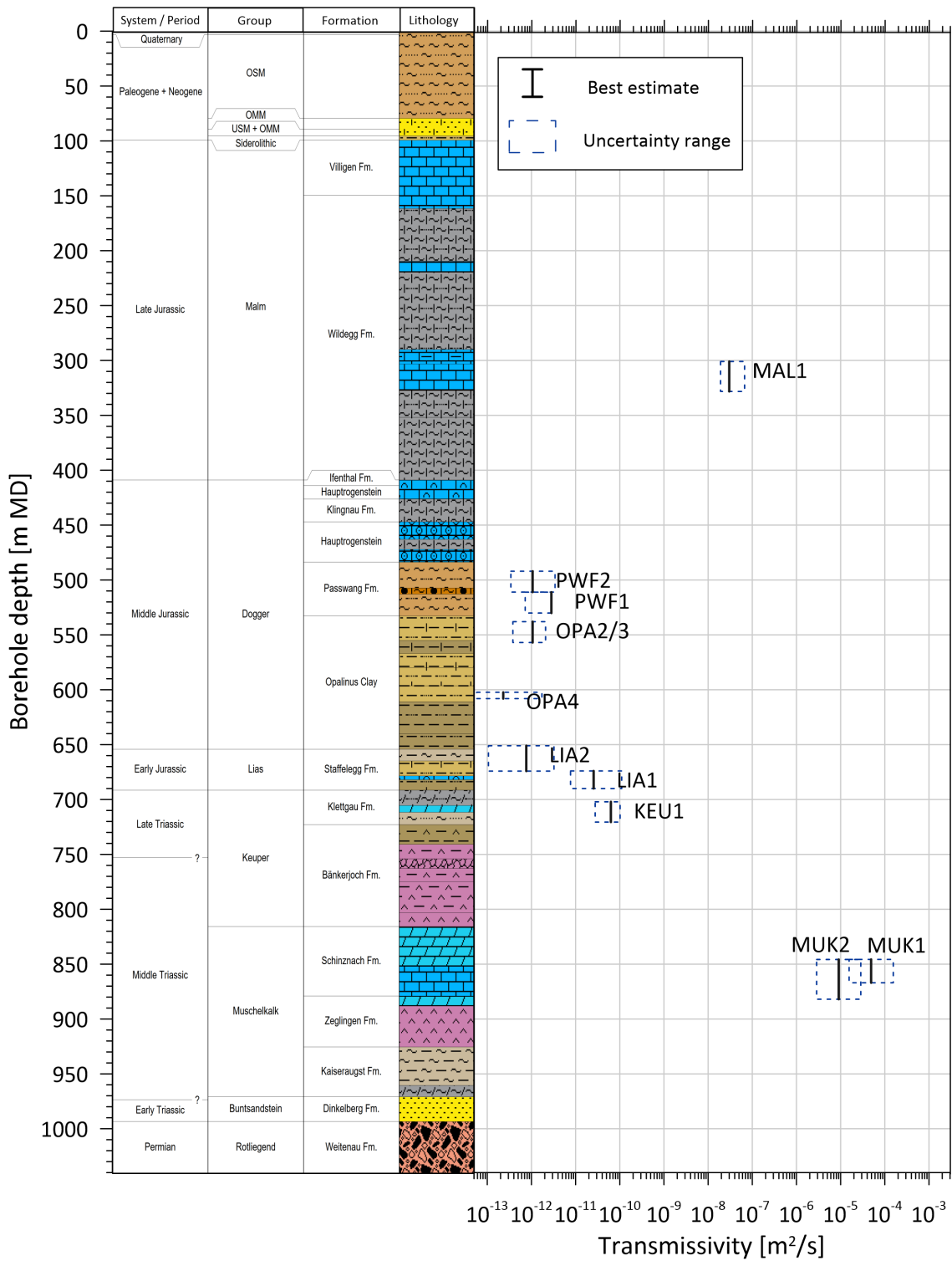


Fig. 4-23: Summary of hydraulic testing in borehole BOZ1-1: Formation transmissivity profile

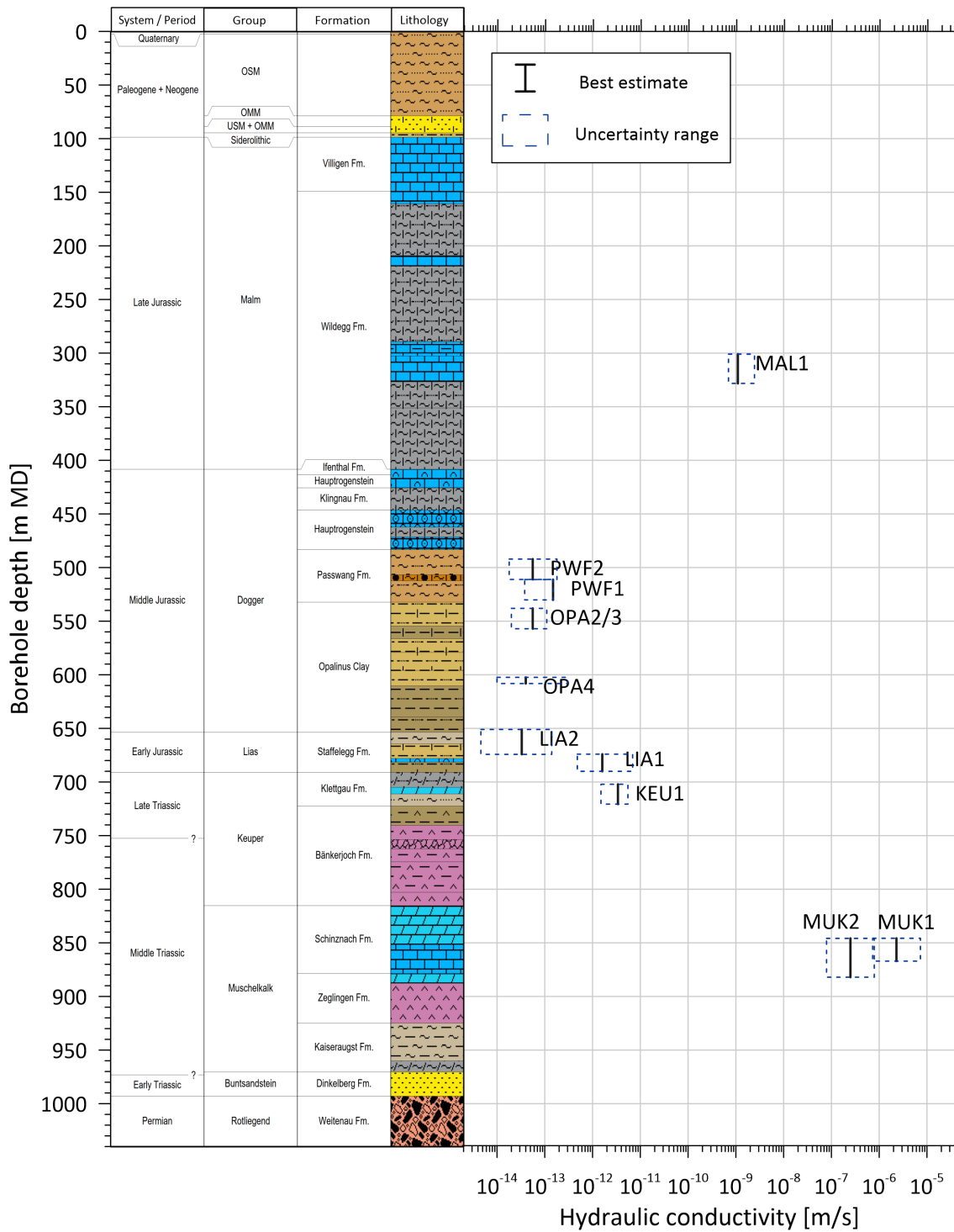


Fig. 4-24: Summary of hydraulic testing in borehole BOZ1-1: Formation hydraulic conductivity profile

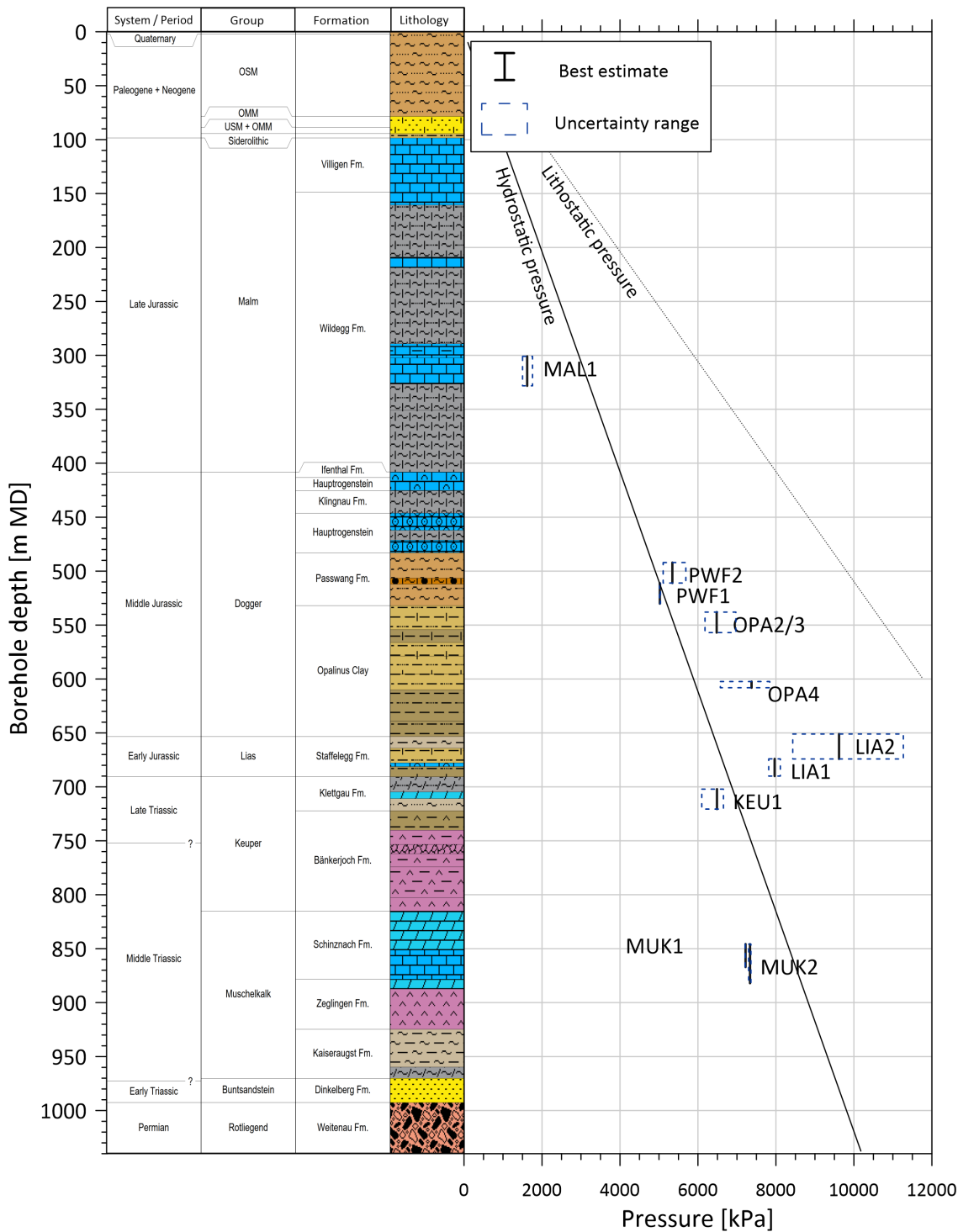


Fig. 4-25: Summary of hydraulic testing in borehole BOZ1-1: Static formation pressure profile
The lithostatic pressure is based on the assumption of a mean density of 2'000 kg m⁻³.

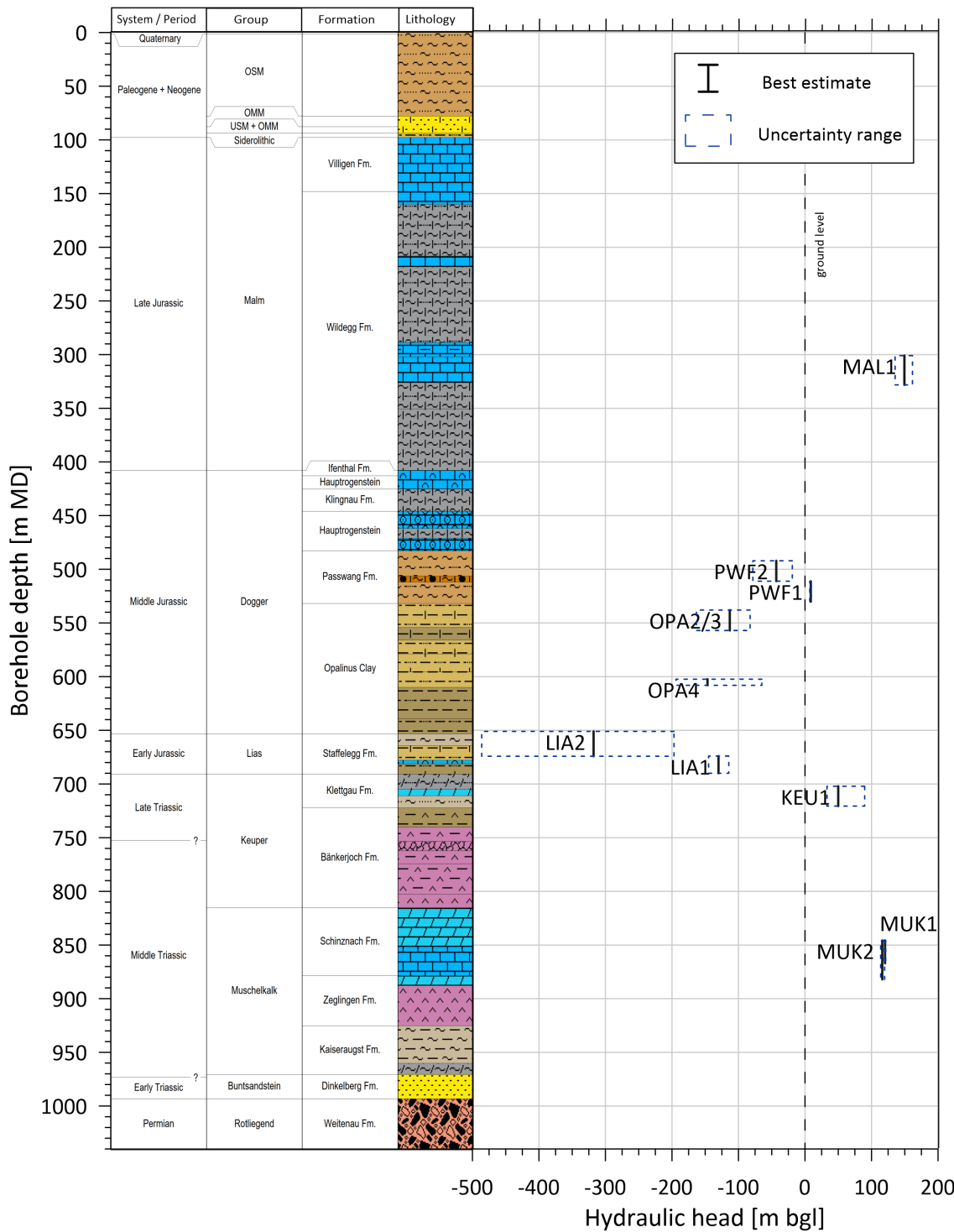


Fig. 4-26: Summary of hydraulic testing in borehole BOZ1-1: Formation hydraulic head profile (m bgl)

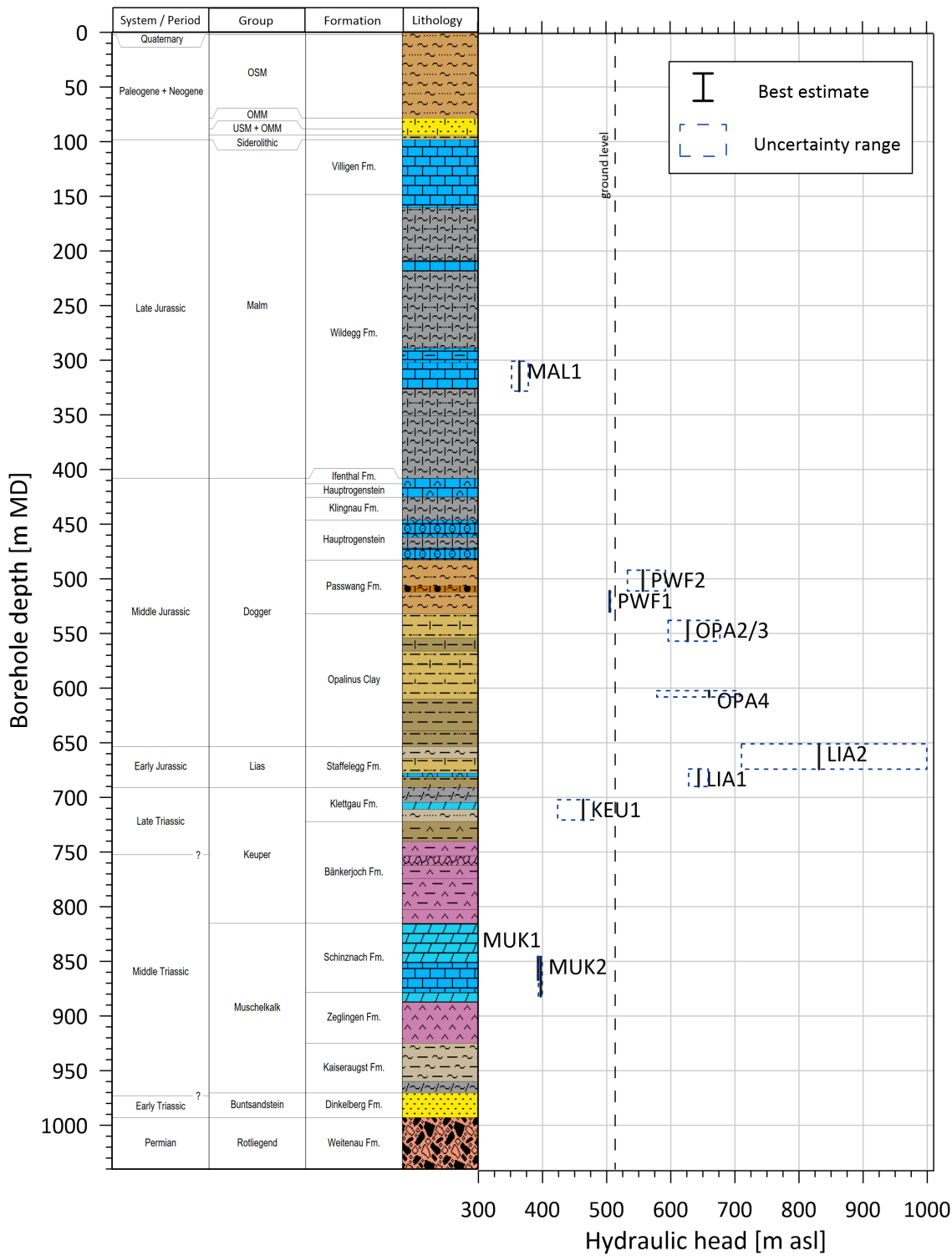


Fig. 4-27: Summary of hydraulic testing in borehole BOZ1-1: Formation hydraulic head profile (m asl)

4.6.2 Discussion of data and test results

One hydraulic test in BOZ1-1 focused on the Wildegge Formation as part of the Malm Group and took place after the fluid logging campaign (discussed in Chapter 3 above). As a result of the fluid logging campaign, the packer test interval was chosen to test the main inflow zone (at around 310 m MD) of the open borehole section between 252 m MD and 480 m MD. The resulting best estimate of the hydraulic transmissivity of the hydraulic test BOZ1-1-MAL1 ($3.0 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$) indicates that the main inflow was captured by the hydraulic packer test and compares well to the result of the analysis of the associated pump phase during fluid logging (total hydraulic transmissivity of approx. $3.8 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$).

The Passwang Formation of the Dogger Group was studied through two hydraulic tests carried out during a series of hydraulic tests that began with BOZ1-1-OPA1. The test BOZ1-1-PWF1 was performed after the test BOZ1-1-OPA3 and followed by test BOZ1-1-PWF2. An analysis of BOZ1-1-PWF1 is presented in more detail in Section 4.5.1. The measurement results for both test intervals in the Passwang Formation were analysed using 2-zone radial composite flow models as there were no indications that a more complex model was required. The best estimates of the hydraulic conductivity differ only by a factor of 3 and by a value of approximately 50 m for the hydraulic head. The uncertainties were mainly due to the limiting conditions of testing (e.g. duration of history and testing). The best estimates of the formation parameters for both tests were based on the analysis of the main test sequences, PW-PI including the PSR for BOZ1-1-PWF1, and SW-SWS for BOZ1-1-PWF2. However, the narrow range in the determination of the hydraulic head in test BOZ1-1-PWF1 seems unrealistic due to the existing uncertainties and the differences between the two tests (BOZ1-1-PWF1, BOZ1-1-PWF2). A bandwidth of 60 m seems more realistic, as determined in the evaluation of the test BOZ1-1-PWF2.

The Opalinus Clay was tested within borehole BOZ1-1 using a total of 4 hydraulic tests. The series of tests was started by test BOZ1-1-OPA1. The initial pulse phase of BOZ1-1-OPA1 was somewhat flat and after inspection of the recorded pressure signal, small disturbances were detected during the PSR phase. During the following slug and slug recovery phases it became clear that the SIT did malfunction which already affected the previous PSR and pulse events, leading to the pressure disturbances described above. Test BOZ1-1-OPA1 had therefore to be excluded from the evaluation due to technical problems. The following tests BOZ1-1-OPA2 and BOZ1-1-OPA3 were performed at the same interval position, which differed only slightly from the location of the BOZ1-1-OPA1 test interval, but technical problems continued. A slug test phase in BOZ1-1-OPA2 and a slug test phase followed by a pressure recovery phase for BOZ1-1-OPA3 could be analysed from these two hydraulic tests. Since the two tests were performed over the same interval, they were interpreted together to reduce the uncertainty on the results of the formation parameters for this particular interval. The most reliable results were obtained from the test sequence of BOZ1-1-OPA3, and the results of the hydraulic test BOZ1-1-OPA2 were incorporated into the determination of the parameter ranges for the tested interval. The hydraulic test BOZ1-1-OPA4 was executed as the final test of the following test series which commenced with BOZ1-1-LIA1 followed by BOZ1-1-LIA2. Test BOZ1-1-OPA4 was extended by the execution of a GTPT which is not part of this documentation. For BOZ1-1-OPA4, the test duration was around a quarter of the very long pressure history. The best estimates for the hydraulic conductivity and transmissivity, respectively, of the analyses of the single phases and the test sequence differ only by a factor of about 3. However, the uncertainty in the hydraulic head estimation was high due to the very long pressure history phase. The estimates of the hydraulic head are not considered realistic due to physical processes that cannot be captured by the hydraulic modelling software used, e.g. poroelastic effects.

The Staffelegg Formation of the Lias Group was studied using two hydraulic tests, namely BOZ1-1-LIA1 and BOZ1-1-LIA2. The analysis of both intervals was based on a homogeneous flow model with a discrete time-dependent skin value, as no indication of a more complex flow model could be observed. The best estimates of the hydraulic transmissivity and conductivity represent the geometric means of the best estimates from the different analyses performed for each test, namely the analyses of the individual test phases and the analysis of the entire test sequences. Comparably, the best estimates for the hydraulic head represent the arithmetic mean. The best estimate of the hydraulic conductivity for the BOZ1-1-LIA1 is significantly higher than the best estimate for the BOZ1-1-LIA2 with no overlap of their uncertainty ranges. It is noted that the test interval BOZ1-1-LIA1 included limestone layers of the Beggingen Member of the Staffelegg Formation and the Gruhalde Member of the Klettgau Formation, also limestone (see Tab. 4-22). As with the Opalinus Clay, the estimated hydraulic heads are not considered realistic, most probably due to physical processes not captured by the hydraulic analysis model.

The Klettgau Formation of the Keuper Group was tested via hydraulic test BOZ1-1-KEU1. For the analysis of this test, a homogeneous flow model with skin was used due to the fact that no other appropriate flow model could be clearly identified. The behaviour of the test fluid (potassium silicate) during the pressure history was implemented in the model using a separate skin value. In addition, the skin value during testing was separately handled for each test phase (PW1, PW2 and PI). The best estimates of the hydraulic conductivity for the interpretation of each of the single test phases and for the sequence analysis ranged by only a factor of 2. For the static formation pressure the best estimates were in a range of approx. 30 m. However, the resulting uncertainty ranges for the formation parameters are higher, reflecting the uncertainty in the history period and the flow model.

Two hydraulic test sequences were performed in the Schinznach Formation of the Muschelkalk Group. Both tests were performed using a single packer configuration, but it should be noted that mud losses were observed before testing commenced. The test sequence BOZ1-1-MUK1 was terminated after it became clear that a groundwater sample of a good quality could not be taken within a reasonable amount of time. Subsequently, coring of the borehole was continued for an additional 15 m depth. Again, significant mud losses were observed before installation of the equipment for test sequence BOZ1-1-MUK2. The BOZ1-1-MUK2 test interval was about 15 m longer than the BOZ1-1-MUK1 test interval and hence, the analysis of BOZ1-1-MUK2 had to account for a more complex pressure field around the borehole. Both tests indicated an inner (near borehole) zone of changing hydraulic conductivity over time, which was likely due to clean-up effects during pumping. Additionally, test diagnostics did indicate no infinite acting radial flow regime during late testing times (no IARF) but point to vertical flow components. This behaviour can be analysed by changes of the flow dimension, time-dependent changes of the hydraulic conductivity or a change of the hydraulic conductivity as a function of the distance from the borehole. For the test analyses, homogeneous and 2-zone radial composite flow models with time dependent skin properties were used. The uncertainty in the flow model is mainly reflected in the uncertainty of the estimated hydraulic conductivity. Moreover, the effective thickness of the contributing formation / inflow zone could not be determined exactly due to a very likely existing dominant inflow area of unknown thickness within the open hole section. The uncertainty ranges for the hydraulic transmissivity overlap for both tests but an unambiguous best estimate for the hydraulic conductivity of the formation could not be determined. However, the hydraulic head was estimated within a small range of uncertainty for both tests. It is noted that the focus of both tests was the collection of a groundwater sample and the pressure recovery phases carried out after the pumping phase were rather short and differ in their duration (as well as the radius of investigation).

5 Summary

Borehole Bözberg-1-1 (BOZ1-1) is the first exploratory borehole drilled in the TBO project in the siting region Jura Ost.

A total of 12 hydraulic packer test sequences and one fluid logging campaign were performed in borehole BOZ1-1 between April 2020 and December 2020. All hydraulic packer tests were performed in the cored borehole section using an HDDP packer system in single packer or double packer configuration (*cf.* Tab. 4-22). The activities were performed in the following geological formations (*cf.* Dossier III):

- Malm Group including Wildegg Formation and Dogger Group including Ifenthal Formation, Klingnau Formation and Hauptrogenstein (BOZ1-1-FL1-MAL)
- Malm Group with a focus on the Effingen Member of the Wildegg Formation (BOZ1-1-MAL1)
- Dogger Group («Brauner Dogger») with a focus on the Passwang Formation including the Rothenfluh, Waldenburg and Brügglı Members, the "Humphriesi-Schichten" and the "Cond. Equivalents of the Sissach, Hauenstein and Hirnichopf Members" (BOZ1-1-PWF1, BOZ1-1-PWF2)
- Dogger Group with a focus on Opalinus Clay (BOZ1-1-OPA1, BOZ1-1-OPA2, BOZ1-1-OPA3 and BOZ1-1-OPA4)
- Lias Group with a focus on Staffelegg Formation including Gross Wolf, Rietheim, Breitenmatt / Rickenbach, Grünschholz and Frick Members (BOZ1-1-LIA2) resp. including Frick, Beggingen and Schambelen Members (BOZ1-1-LIA1)
- Keuper Group with a focus on Klettgau Formation including Gruhalde, Gansingen and Ergolz Members (BOZ1-1-KEU1)
- Muschelkalk Group with a focus on Schinznach Formation including Stamberg, Liedertswil, Leutschenberg and Kienberg Members (BOZ1-1-MUK1) resp. additionally including the "Dolomitzone" in the Zeglingen Formation (BOZ1-1-MUK2)

All hydraulic tests were supported by an on-site field analysis to optimise the test procedure. The pressures and rates measured during all tests are illustrated in Figs. 4-9 to 4-20. The main results and best estimates of hydraulic formation parameters are presented in Tabs. 4-37 to 4-39 and Figs. 4-23 to 4-27. Operational problems during test BOZ1-1-OPA1 did not allow for generating a data set of sufficient quality to estimate formation parameters. Tests BOZ1-1-OPA2 and -OPA3 were performed at similar depths as test BOZ1-1-OPA1 and provided conclusive formation parameters. The performance of rate withdrawal tests was limited to the hydraulic tests in the Muschelkalk Group (BOZ1-1-MUK1 and -MUK2).

The fluid logging analysis (BOZ1-1-FL1-MAL; *cf.* Section 3.2) and two hydraulic test analyses (BOZ1-1-PWF1 and BOZ1-1-KEU1; *cf.* Sections 4.5.1 and 4.5.2) were selected for a detailed description in this report.

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 investigated 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 Opalinus Clay

and the Lias Group. Due to inevitable, short-term borehole test conditions, the hydraulic heads estimated for BOZ1-1-OPA2, BOZ1-1-OPA3, BOZ1-1-OPA4, BOZ1-1-LIA1 and BOZ1-1-LIA2 appear to be affected by a large overestimation. They are considered as 'apparent' hydraulic heads.

General investigations concerning the physical explanation for the overestimation of the hydraulic head are continuing. The presented analysis considers the temperature effects in the test interval and the pressure induced effects resulting from the high-density drill mud during the entire time since drilling through the interval midpoint. Nagra will install long-term pressure monitoring systems in BOZ1-1 and other selected boreholes to study these and further findings in detail.

6 References

- Barker, J.A. (1988): A generalized radial flow model for hydraulic tests in fractured rock. *Water Resour. Res.* 24/10, 1796-1804.
- Black, J., Holmes, D., Brightman, M. (1987): Crosshole investigations – Hydrogeological results and interpretations. Nagra Technical Report NTB 87-37.
- Bourdet, D., Ayoub, J.A. & Pirard, Y.M. (1989): Use of pressure derivative in well-test interpretation. *Society of Petroleum Engineers, SPE Formation Evaluation*, 293-302.
- Cooper, H.H. & Jacob, C.E. (1946): A generalized graphical method for evaluating formation constants and summarizing well field history. *Am. Geophys. Union Trans.* 27, 526-534.
- Detournay, E. & Cheng, A.H.-D. (1988): Poroelastic response of a borehole in a non-hydrostatic stress field. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 25/3, 171-182.
- Geofirma Engineering Ltd. & INTERA Inc. (2011): nSIGHTS Version 2.50 User Manual. INTERA Inc., Austin, TX, USA.
- Grauls, D. (1999): Overpressures: Causal mechanisms, conventional and hydromechanical approaches. *Oil & Gas Science and Technology – Rev. IFP* 54, 667-678.
- Horne, R.N. (1995): *Modern Well Test Analysis: A Computer-Aided Approach*. 2nd Edition. Petroway Inc., Palo Alto, CA, USA.
- Horner, D.R. (1951): Pressure Buildup in Wells. *Proceedings Third World Petroleum Congress* 2, 503-523, The Hague, Netherlands. Reprinted 1967. *Pressure Analysis Methods*, AIME Reprint Series 9,45-50. SPE.
- Isler, A., Pasquier, F. & Huber, M. (1984): Geologische Karte der zentralen Nordschweiz 1:100'000. Herausgegeben von der Nagra und der Schweiz. *Geol. Komm.*
- Jäggi, K. & Vogt, T. (2020): OPA: Sondierbohrung Benken, Langzeitbeobachtung 2019, Dokumentation der Messdaten. Nagra Arbeitsbericht NAB 20-05.
- Lisjak, A., Garitte, B., Grasselli, G., Müller, H.R. & Vietor, T. (2015): The excavation of a circular tunnel in a bedded argillaceous rock (Opalinus Clay): Short-term rock mass response and FDEM numerical analysis. *Tunnelling and Underground Space Technology* 45, 227-248.
- Lorenz, G.D., Pechstein, A. & Stopelli, E. (2022): Borehole BOZ1-1 (Bözberg-1-1): Fluid sampling and analytical hydrochemical data report. Nagra Arbeitsbericht NAB 22-21.
- Luo, J., Monningkoff, B. & Becker, J.K. (2014): Hydrogeological model Jura Ost. Nagra Arbeitsbericht NAB 13-26.
- Marschall, P., Croisé, J., Schlickenrieder, L., Boisson, J.Y., Vogel, P. & Yamamoto, S. (2003): Synthesis of hydrogeological investigations at the Mont Terri site (Phases 1 – 5). Mont Terri Technical Report TR 01-02. Mont Terri Project, Switzerland.

- Nagra (1997): Hydrological investigations at Wellenberg: Hydraulic packer testing in boreholes SB4a/v and SB4a/s. Methods and field results. Nagra Technischer Bericht NTB 95-02.
- Nagra (2001): Sondierbohrung Benken – Untersuchungsbericht. Nagra Technischer Bericht NTB 00-01.
- Nagra (2008): Vorschlag geologischer Standortgebiet für das SMA- und das HAA-Lager – Geologische Grundlagen. Nagra Technischer Bericht. NTB 08-04.
- Nagra (2014a): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage. Geologische Grundlagen. Dossier II: Sedimentologische und tektonische Verhältnisse. Nagra Technischer Bericht NTB 14-02.
- Nagra (2014b): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage. Geologische Grundlagen. Dossier VI: Barriereneigenschaften der Wirt- und Rahmengesteine. Nagra Technischer Bericht NTB 14-02.
- Pickens, J.F., Grisak, G.E., Avis, J.D., Belanger, D.W., Thury, M. (1987): Analysis and interpretation of borehole hydraulic tests in deep boreholes: Principles, model development, and application. *Water Resour. Res.* 23/7, 1341-1375.
- Pietsch, J. & Jordan, P. (2014): Digitales Höhenmodell Basis Quartär der Nordschweiz – Version 2013 (SGT E2) und ausgewählte Auswertungen. Nagra Arbeitsbericht NAB 14-02.
- Ramey, H.J., Jr., Agarwal, R.G. & Martin, I. (1975): Analysis of 'Slug Test' or DST Flow Period Data. *Journal of Canadian Petroleum Technology* 14/3, 37-47.
- Richards, D.J. (1981): Technical Manual on Radiometrics – Geophysical Field Manual for Technicians No. 2. South African Geophysical Association.

Appendix A: Abbreviations, nomenclature and definitions

Tab. A-1: Lithostratigraphy abbreviations for test names in BOZ1-1

Lithostratigraphy	Abbreviation
Malm Group	MAL
Passwang Formation (Dogger)	PWF
Opalinus Clay (Dogger)	OPA
Lias Group	LIA
Keuper Group	KEU
Muschelkalk Group	MUK

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

Abbreviation	Example
Drill site abbreviation – lithostratigraphy abbreviation ¹ + number of test	BOZ1-1-MUK1: First test interval in Muschelkalk aquifer in borehole BOZ1-1

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	$m\ s^{-1}$
K_{in}	Inner-zone hydraulic conductivity	$m\ s^{-1}$
K_{out}	Outer-zone hydraulic conductivity	$m\ s^{-1}$
K_s	Hydraulic conductivity of skin zone	$m\ s^{-1}$
n	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, respectively P_2^* level)	Pa, kPa
P_{int}	Pressure at midpoint of test interval	Pa, kPa
P_{offset}	Offset of a pressure probe at atmospheric pressure	Pa, kPa
P_s	Static formation pressure (at midpoint of test interval if not specified otherwise)	Pa, kPa
ΔP_{packer}	Interval packer pressure changes	bar
q	Flow rate	$m^3\ s^{-1}$
Q, Q_{tot}	Cumulative flow volume	m^3
r_d	Radius of discontinuity	m
r_s	Radius of the skin zone extension	m
$r_{w\ int}$	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	-

Abbreviation / symbol	Description	Unit
S_s	Specific storage	1/m
$S_{s \text{ in}}$	Inner-zone specific storage	1/m
$S_{s \text{ out}}$	Outer-zone specific storage	1/m
S_{ss}	Specific storage of skin zone	1/m
t_s	Thickness of the skin zone extension	m
T	Transmissivity	$\text{m}^2 \text{s}^{-1}$
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	
BHPH	Borehole pressure history	
BOP	Blow out preventer	
BOZ1-1	Bözberg-1 drill site, borehole 1	
cps	Counts per second	
CU	Copper	
DA	Detailed analysis	
DAS	Data acquisition system	
DR	Detailed report	
EU	External upset coupling	
EUE	External upset end	

Abbreviation	Description	Unit
FM	Flow model	
FS	Full scale	
GmbH	Gesellschaft mit beschränkter Haftung (company with limited liability)	
GTPT	Gas threshold pressure test	
HDDP	Heavy-duty double packer system	
HLW	High level waste	
HTT	Hydraulic test tool	
IARF	Infinite acting radial flow region	
ID	Inner diameter	
IPI	Inflatable Packers International, Perth, Australia	
IT	Information technology	
L/ILW	Low and intermediate level waste	
ln	Litre normal	ln
MAR1-1	Marthalen-1 drill site, borehole 1	
MD	Measured depth	m
MHF	Micro-hydraulic fracturing	
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	
PPG	Piston pulse generator	
PRV	Pressure release valve	
QC	Quality control	
QLA	Quick look analysis	
QLR	Quick look report	
QSSP	Quadruple sub-surface probe	
Rd	Reading	
RIH	Run in hole	
SIT	Shut-in tool	
SSE	Sum of squared errors	

Abbreviation	Description	Unit
TBO	Tiefbohrung(en) (German for deep borehole(s))	
TVD	True vertical depth	m
WS	Water sample	
WT	Water table	
WTW	Wissenschaftlich-technische Werkstätten GmbH	
ZH	Zürich	
ZNO	Siting region Zürich Nordost	

Appendix B: Analysis plots of the hydraulic packer tests BOZ1-1-PWF1 and BOZ1-1-KEU1

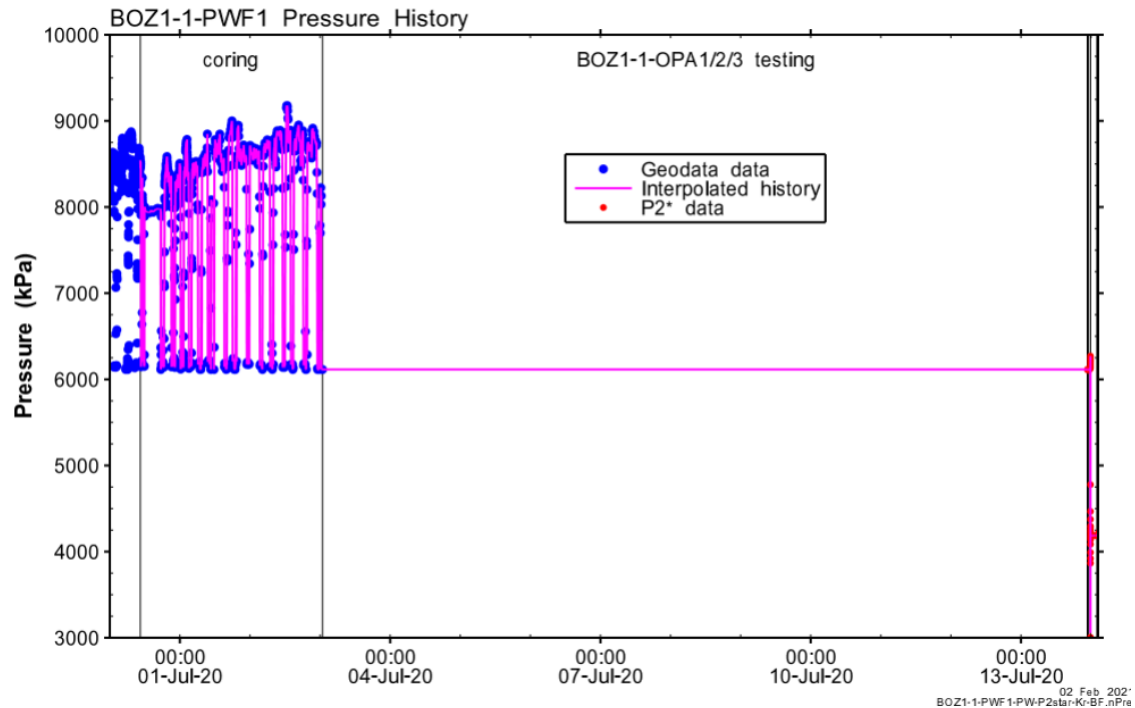


Fig. B-1: Hydraulic test BOZ1-1-PWF1: Entire record of the borehole pressure history used in the analysis

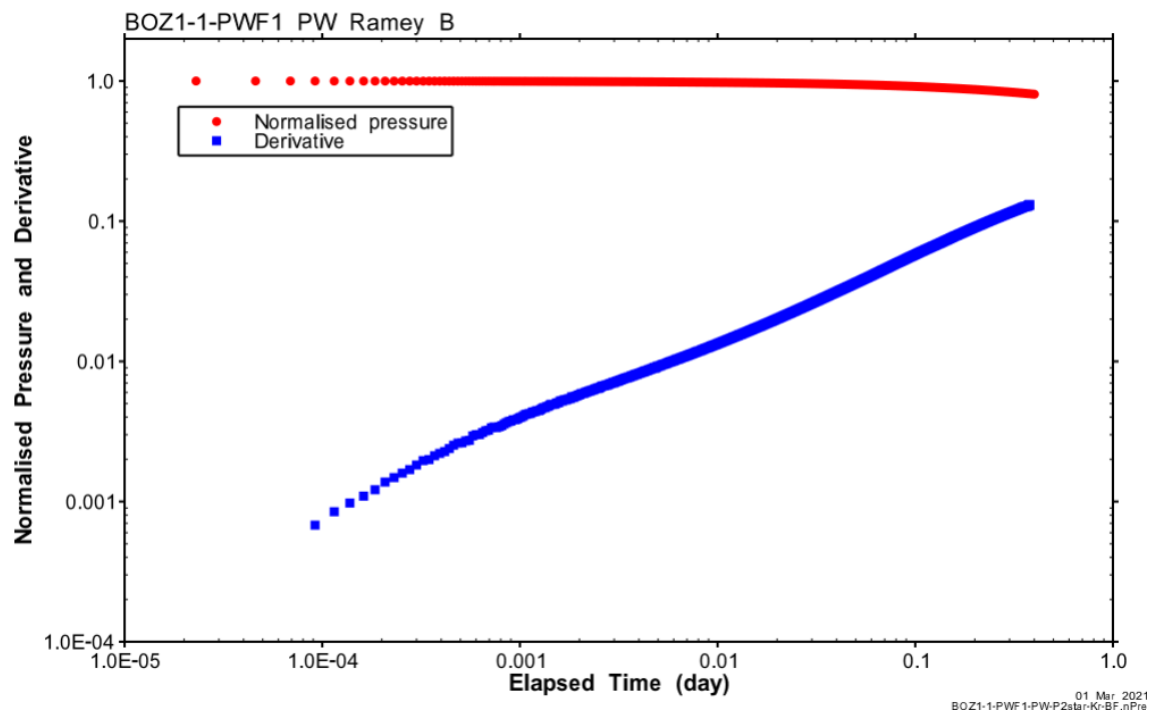


Fig. B-2: Hydraulic test BOZ1-1-PWF1: Ramey B diagnostic plot of the PW phase

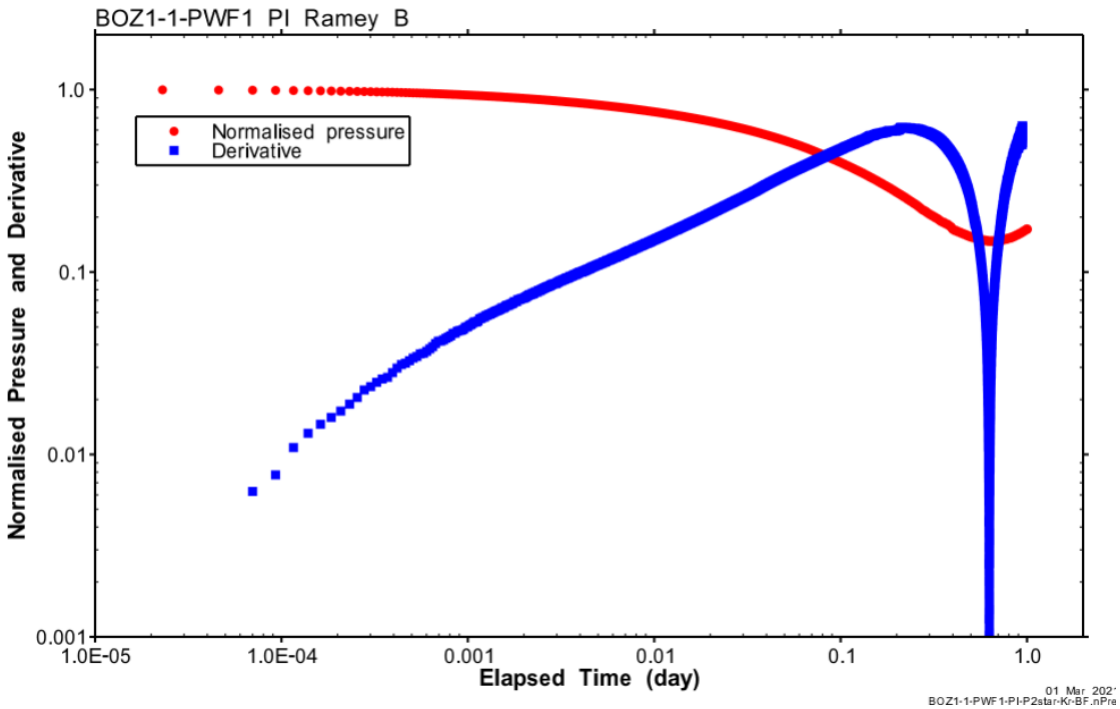


Fig. B-3: Hydraulic test BOZ1-1-PWF1: Ramey B diagnostic plot of the PI phase

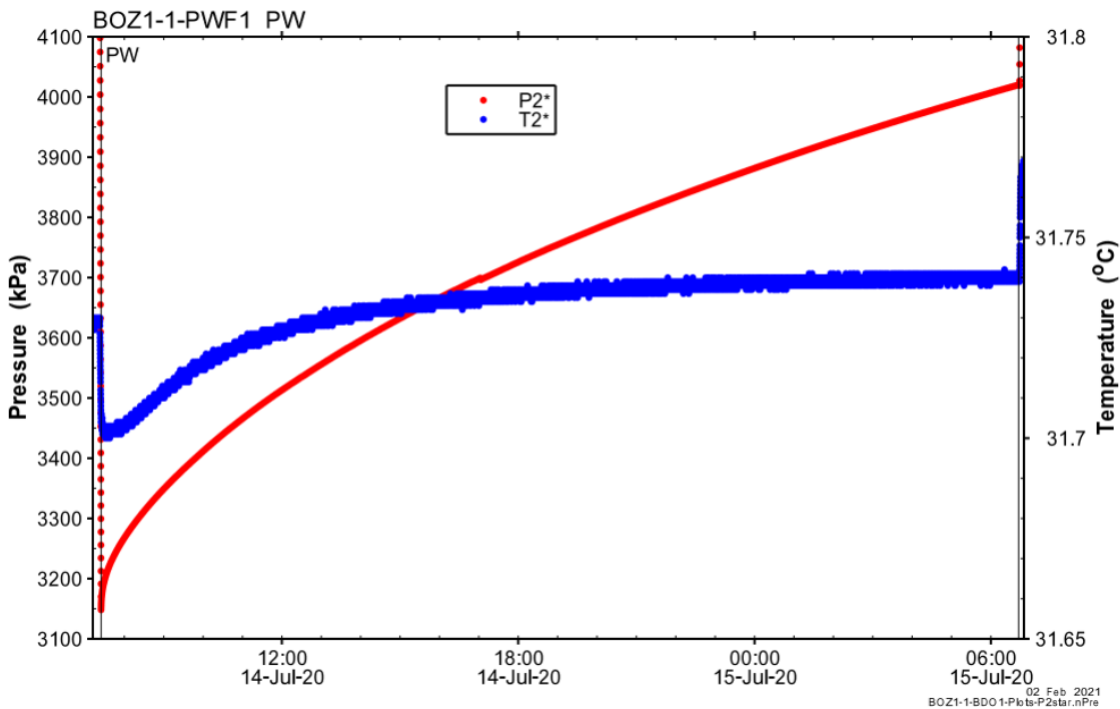


Fig. B-4: Hydraulic test BOZ1-1-PWF1: Development of the downhole temperature, T2*, and pressure, P2*, during PW

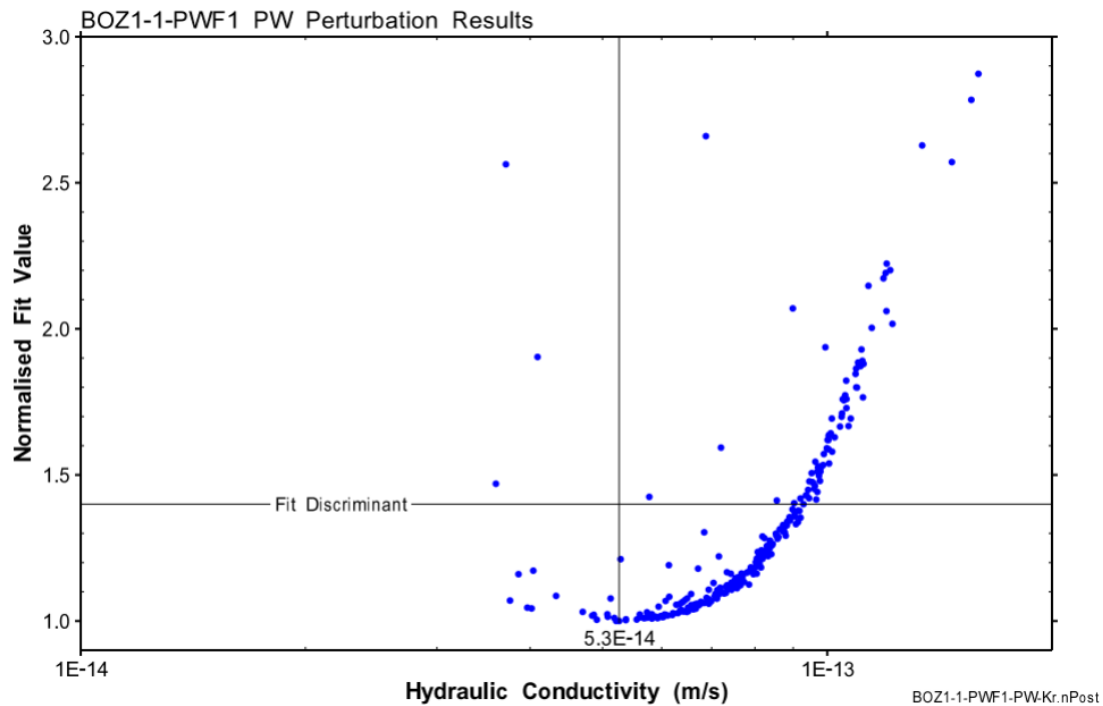


Fig. B-5: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PW phase
272 / 500 results with a normalised objective function value less than 3.

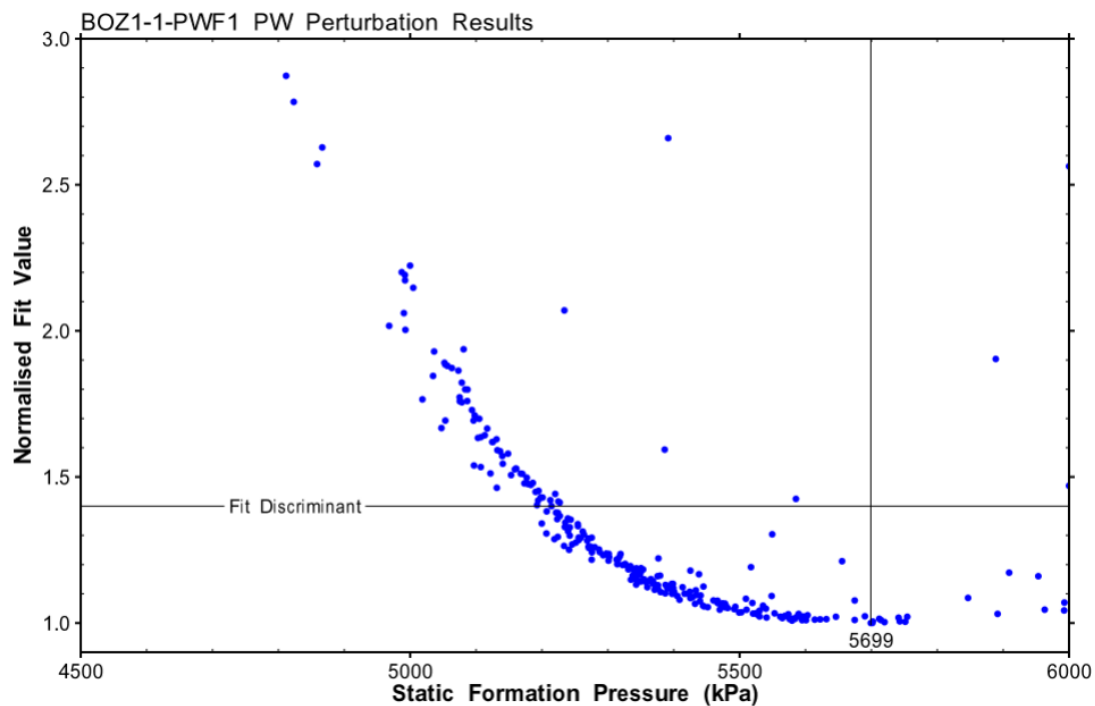


Fig. B-6: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PW phase
272 / 500 results with a normalised objective function value less than 3.

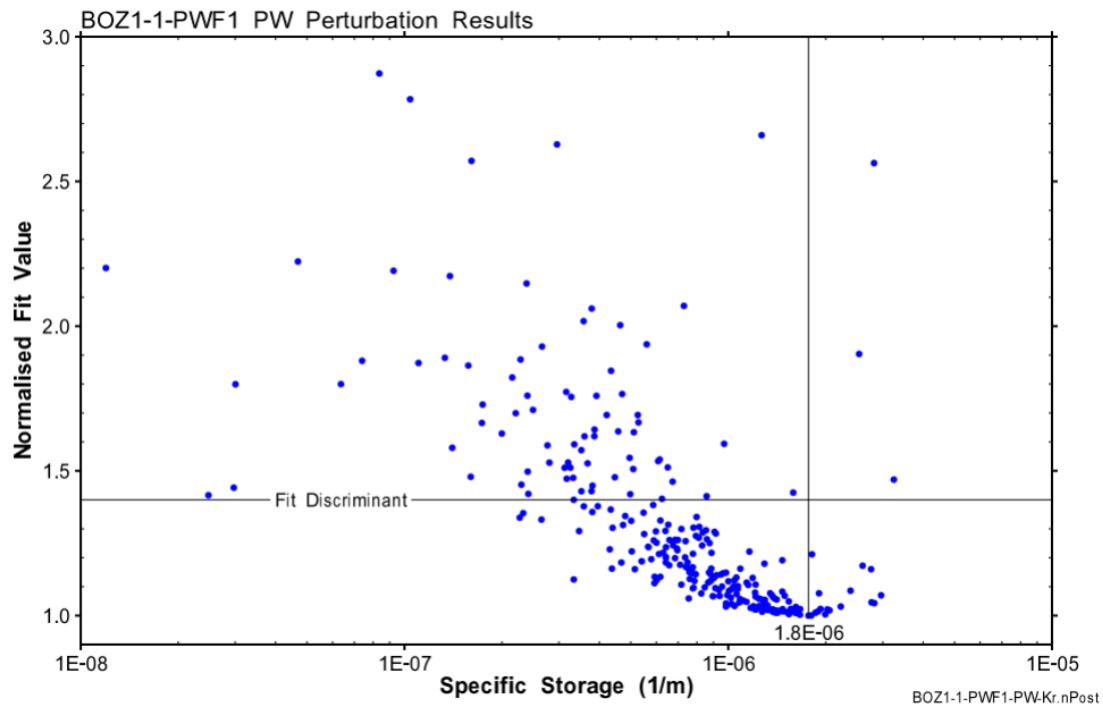


Fig. B-7: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over S_s for the numerical simulation of the PW phase
272 / 500 results with a normalised objective function value less than 3.

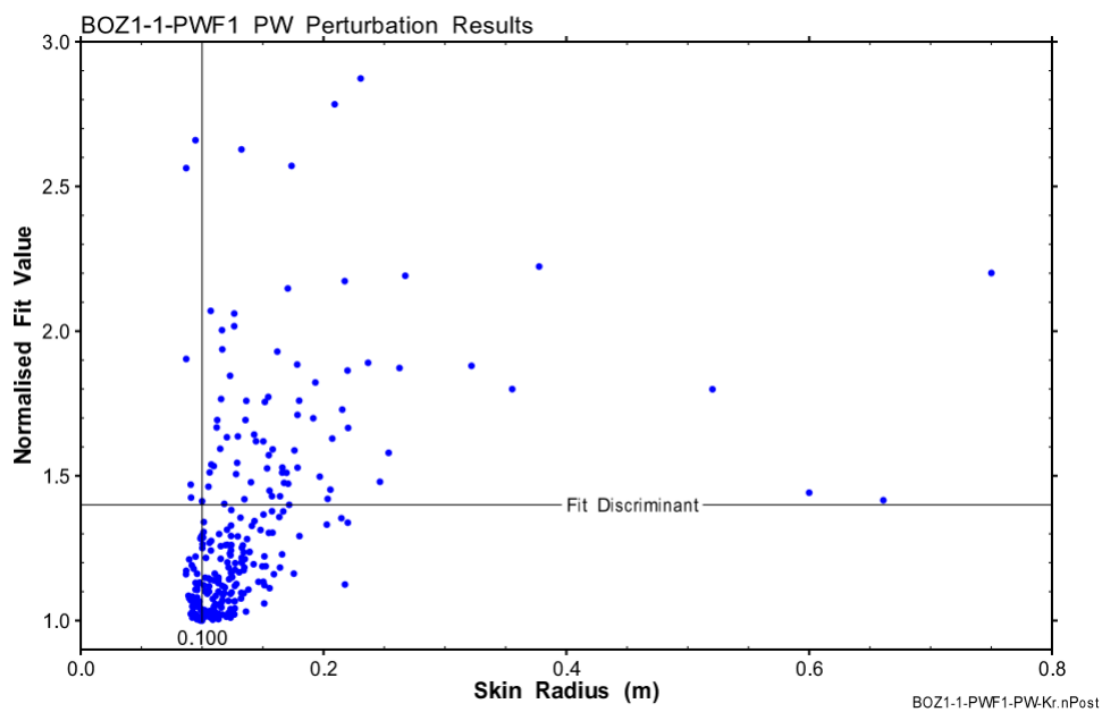


Fig. B-8: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over r_s for the numerical simulation of the PW phase
272 / 500 results with a normalised objective function value less than 3.

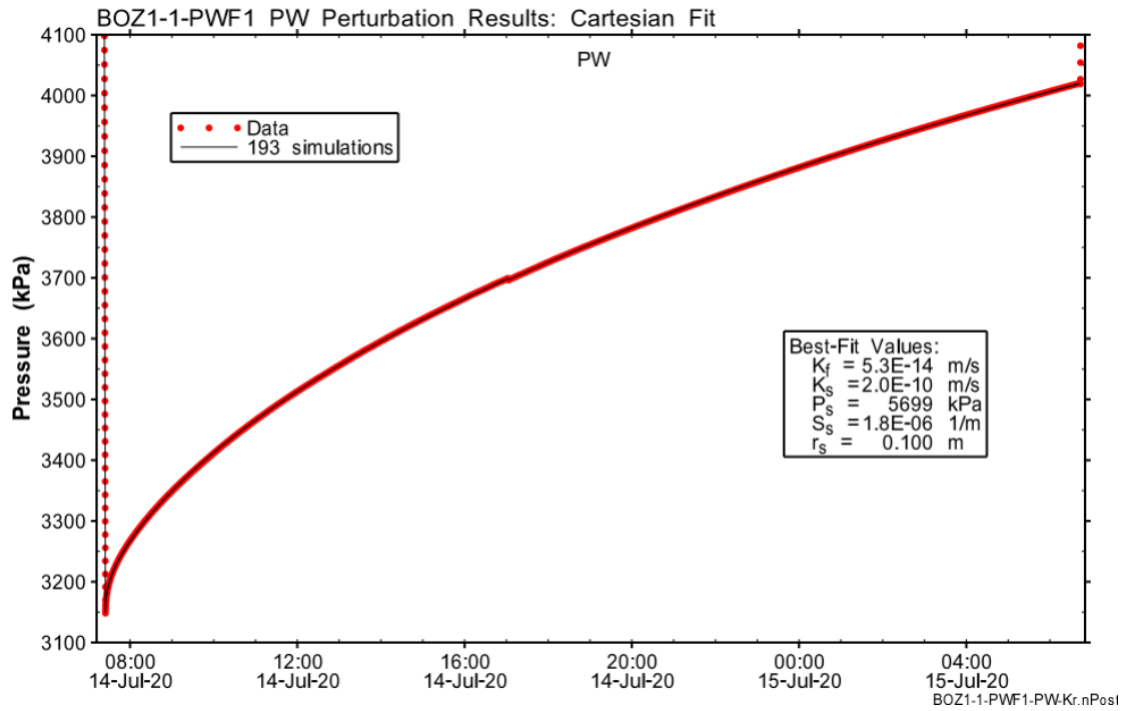


Fig. B-9: Hydraulic test BOZ1-1-PWF1: Cartesian horsetail plot of the perturbation simulations on PW accepting the fit discriminator

193 / 500 results with a normalised objective function value less than 1.4.

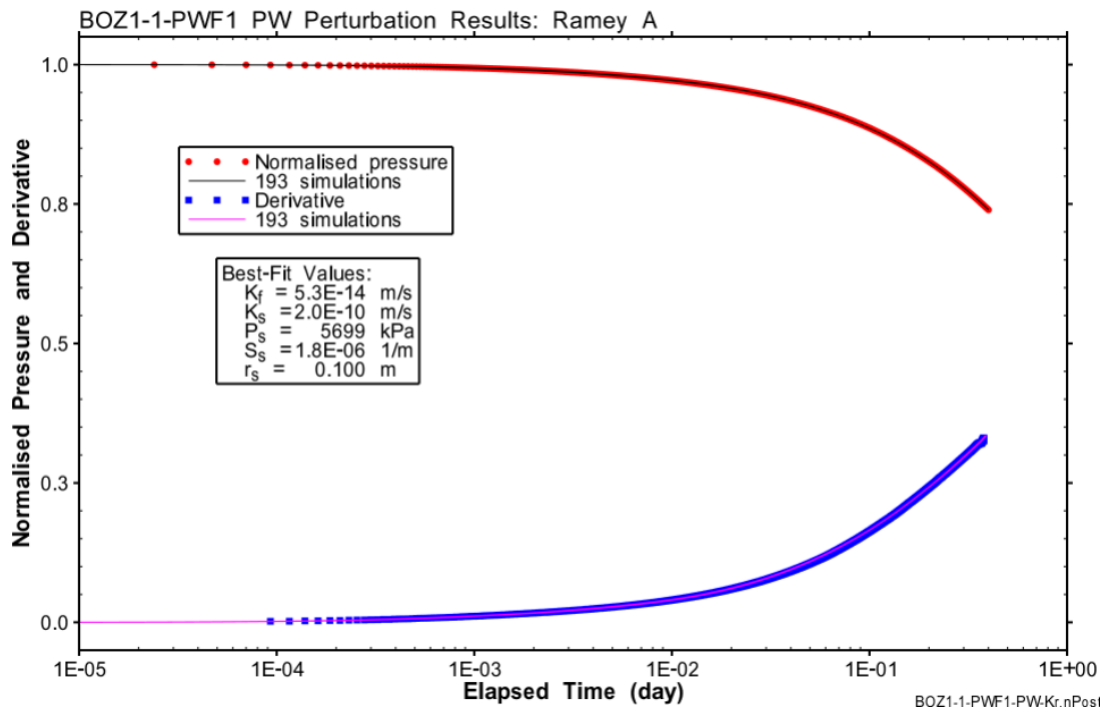


Fig. B-10: Hydraulic test BOZ1-1-PWF1: Ramey A horsetail plot of PW (before the pressure offset) accepting the fit discriminator

193 / 500 results with a normalised objective function value less than 1.4.

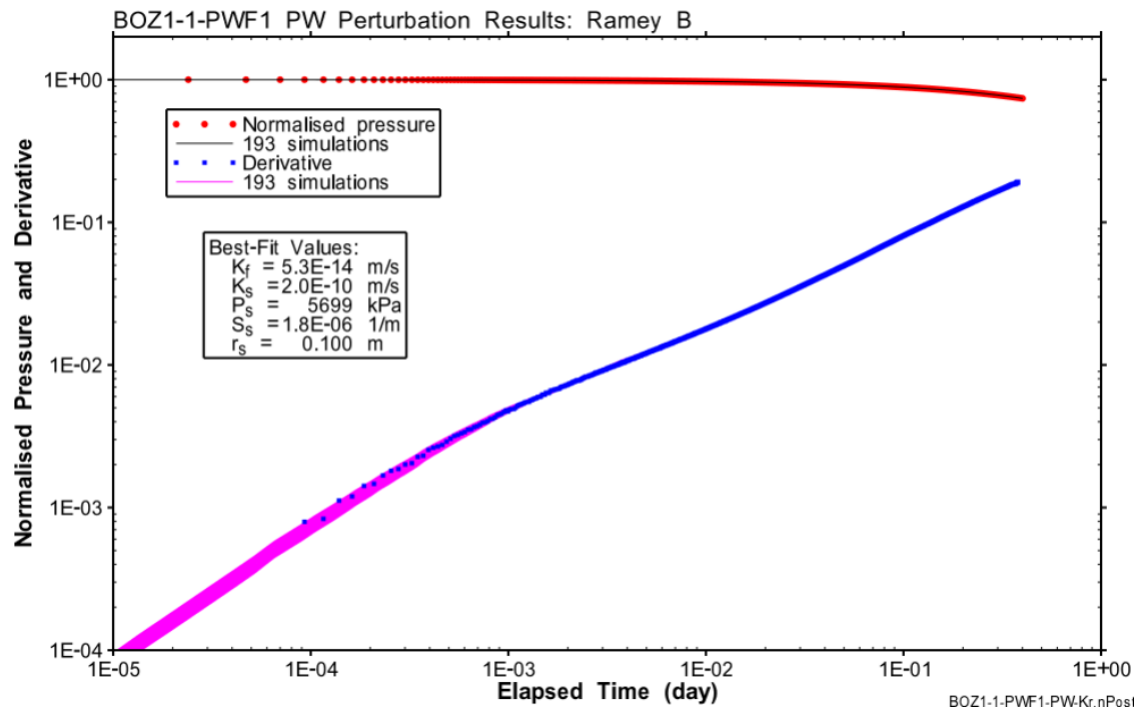


Fig. B-11: Hydraulic test BOZ1-1-PWF1: Ramey B horsetail plot of PW (before the pressure offset) accepting the fit discriminator

193 / 500 results with a normalised objective function value less than 1.4.

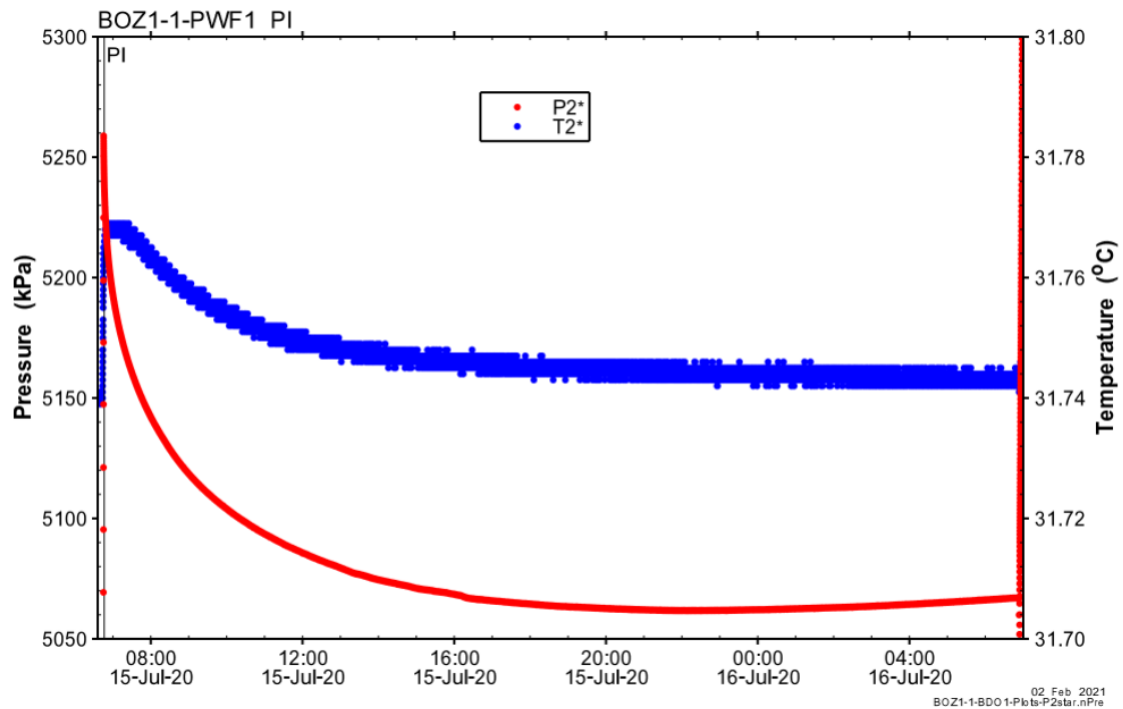


Fig. B-12: Hydraulic test BOZ1-1-PWF1: Development of the downhole temperature, $T2^*$, and pressure, $P2^*$, during PI

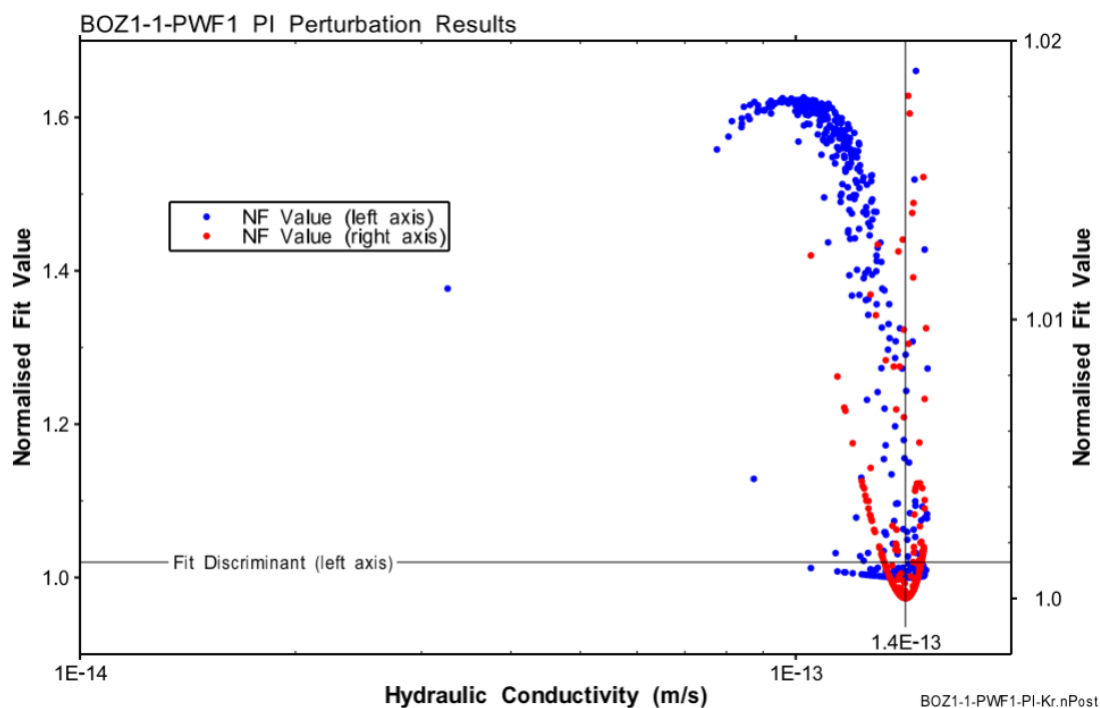


Fig. B-13: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PI phase
657 / 1000 results with a normalised objective function value less than 1.7.

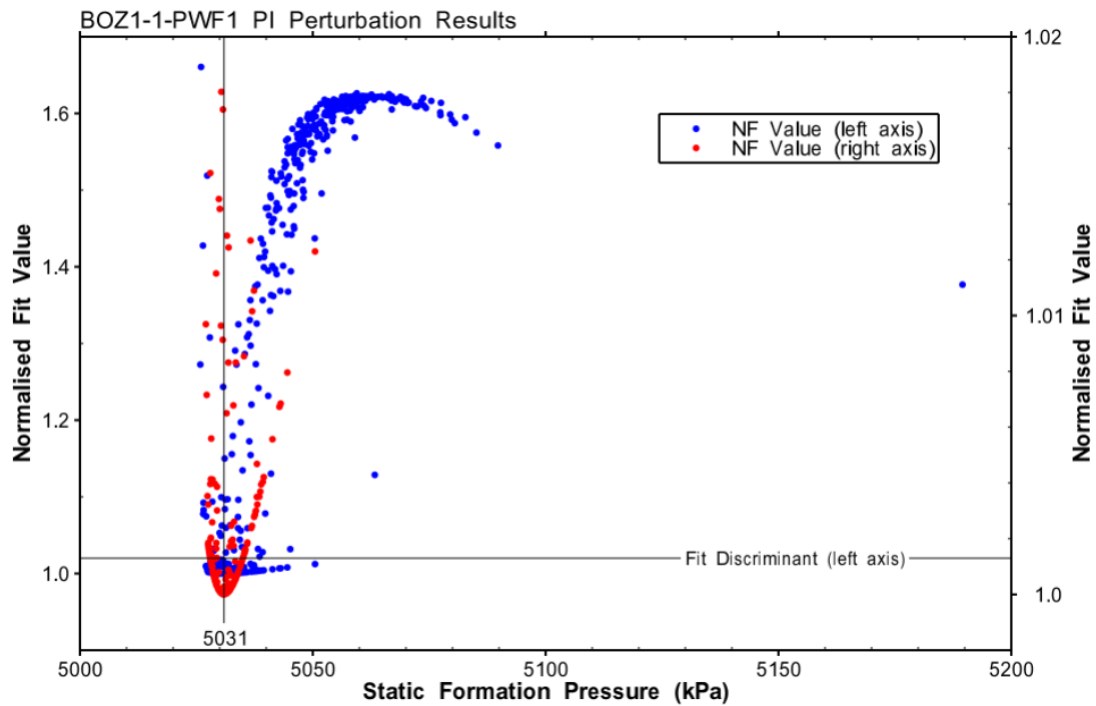


Fig. B-14: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PI phase
657 / 1000 results with a normalised objective function value less than 1.7.

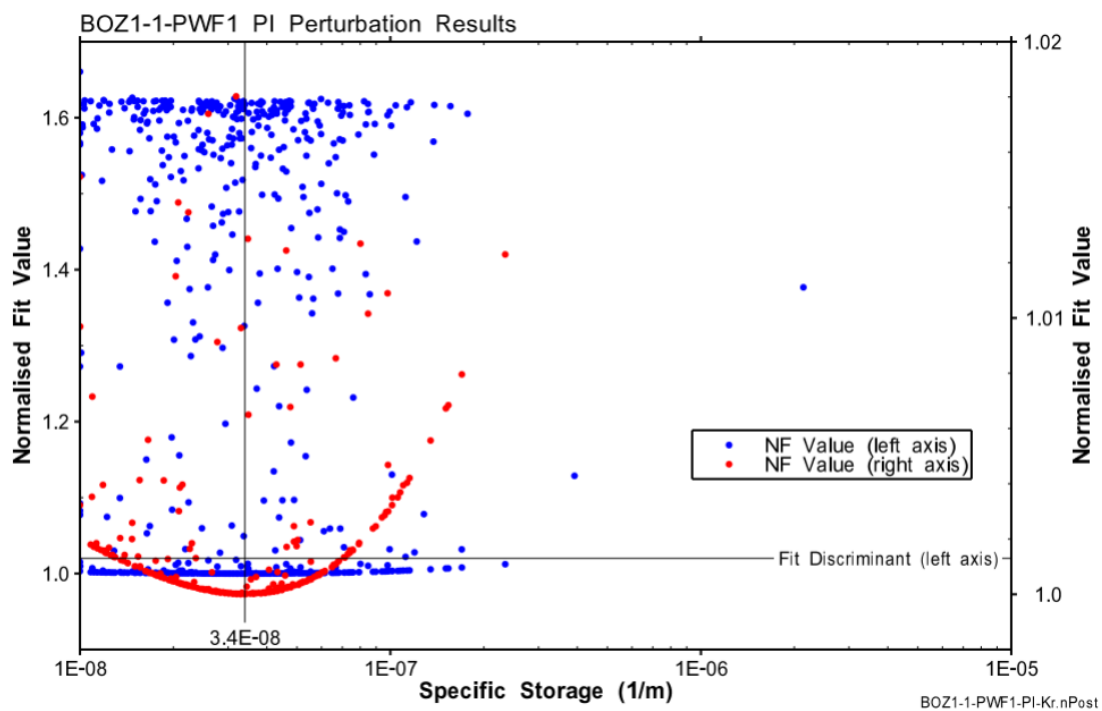


Fig. B-15: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over S_s for the numerical simulation of the PI phase
657 / 1000 results with a normalised objective function value less than 1.7.

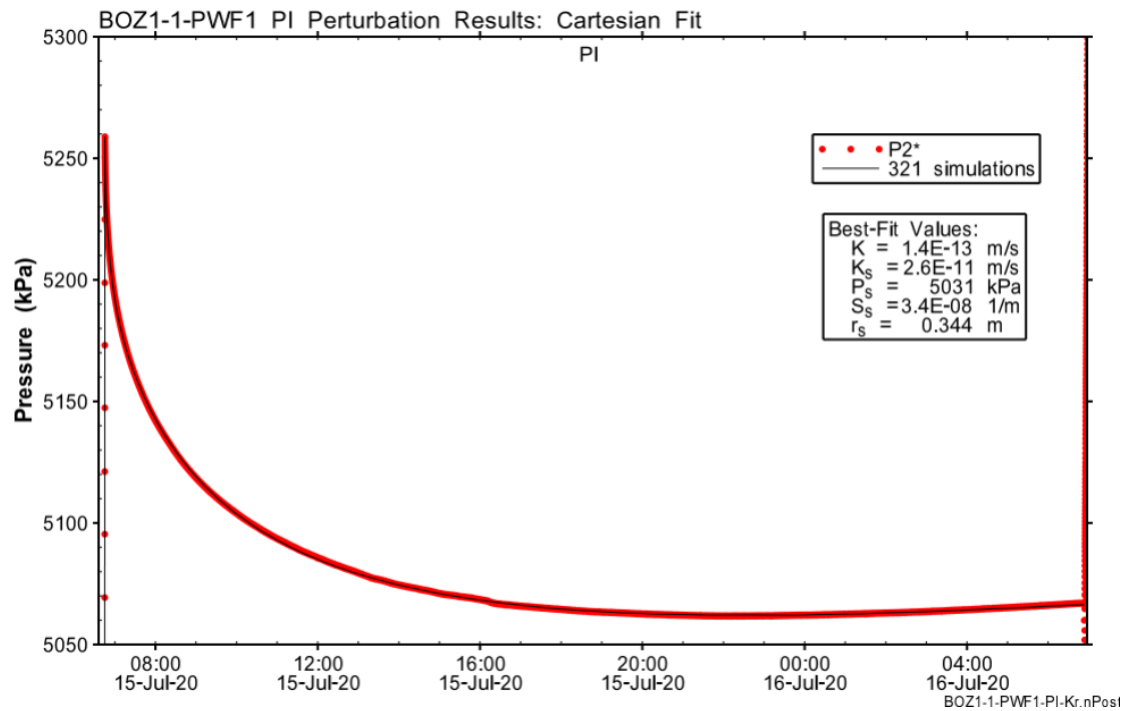


Fig. B-16: Hydraulic test BOZ1-1-PWF1: Cartesian horsetail plot of the perturbation simulations on PI accepting the fit discriminator

321 / 1000 results with a normalised objective function value less than 1.4.

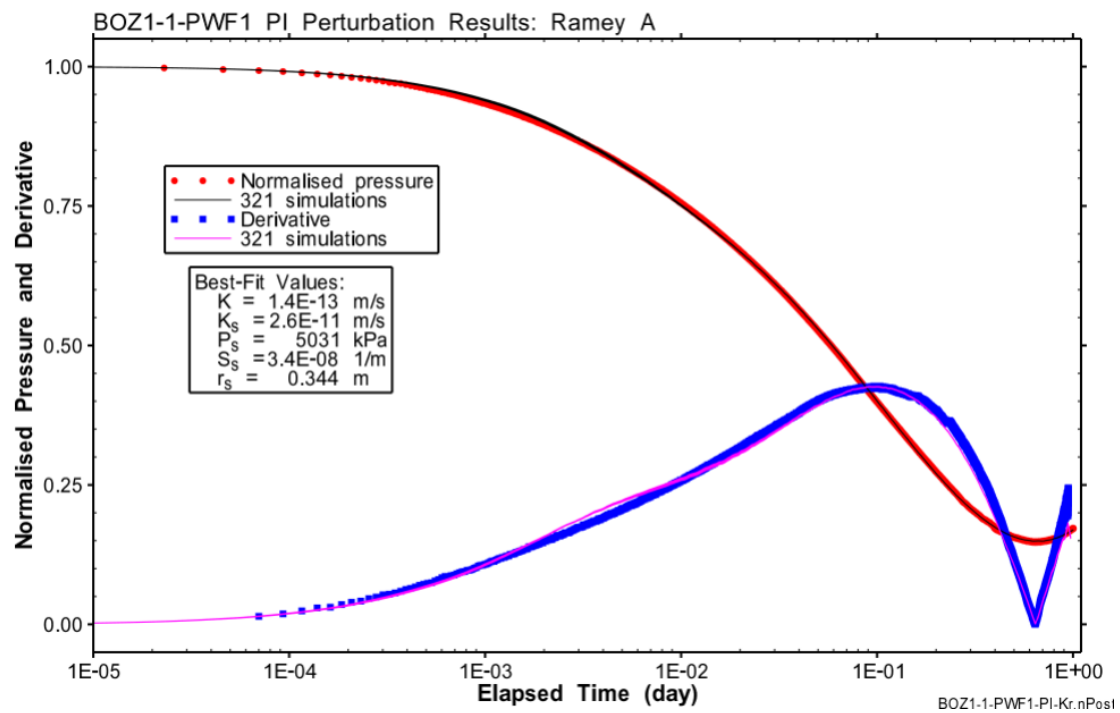


Fig. B-17: Hydraulic test BOZ1-1-PWF1: Ramey A horsetail plot of PI accepting the fit discriminator

321 / 1000 results with a normalised objective function value less than 1.02.

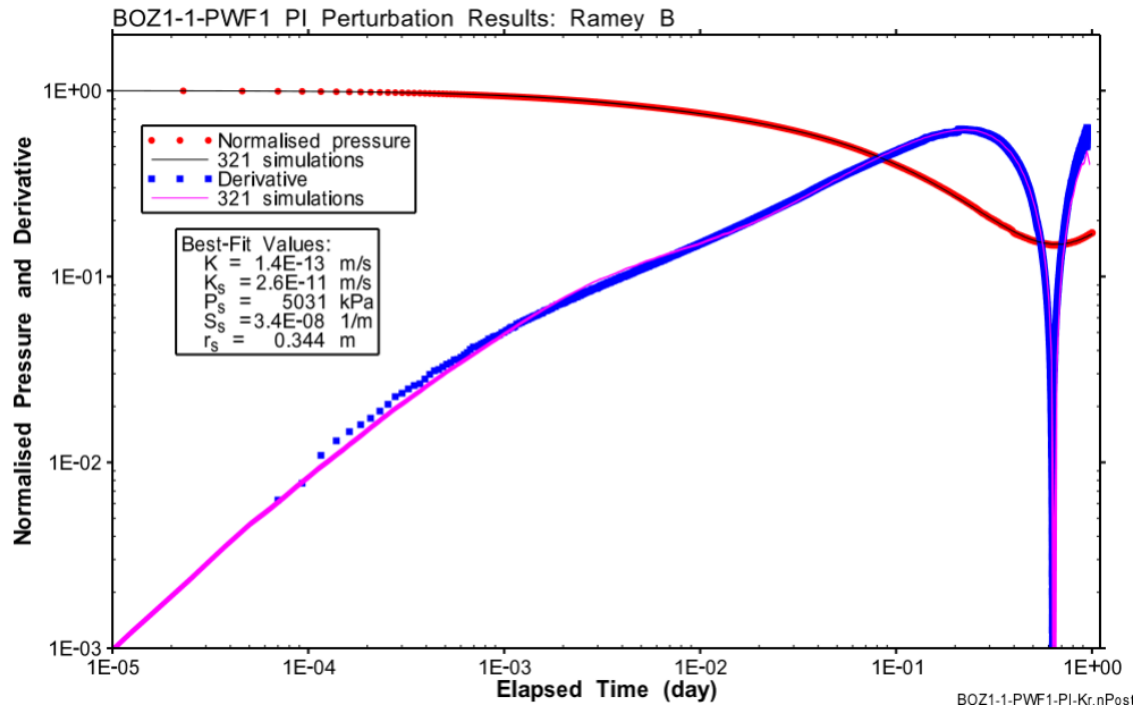


Fig. B-18: Hydraulic test BOZ1-1-PWF1: Ramey B horsetail plot of PI accepting the fit discriminator

321 / 1000 results with a normalised objective function value less than 1.02.

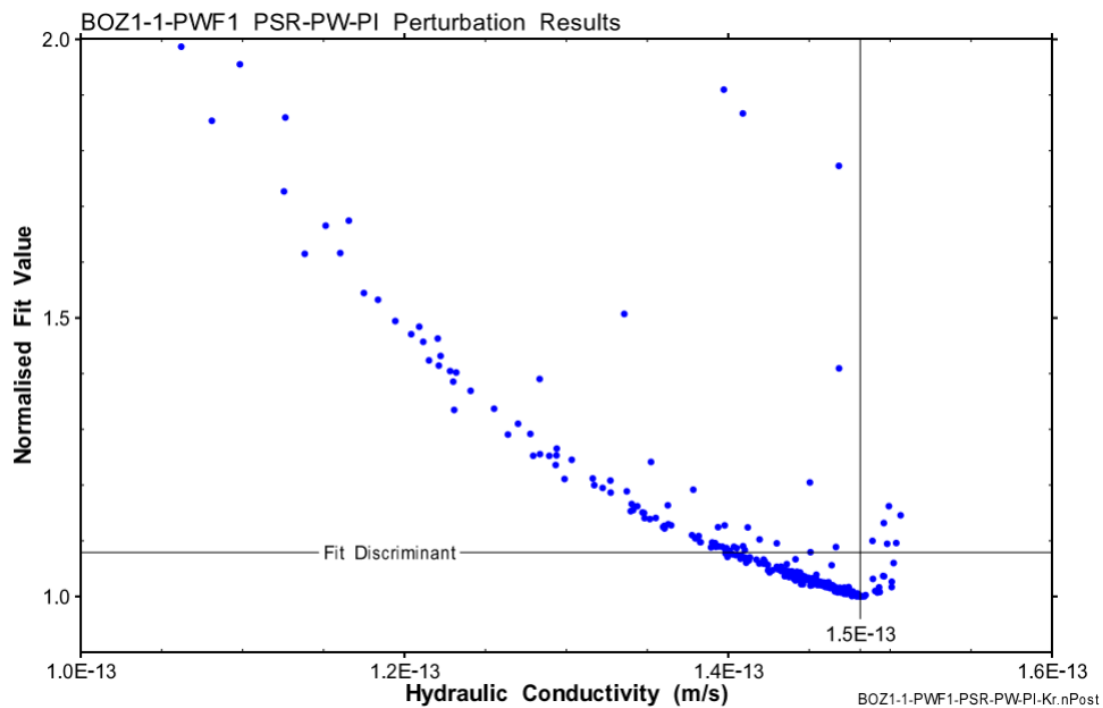


Fig. B-19: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of PSR-PW-PI

426 / 500 results with a normalised objective function value less than 2.

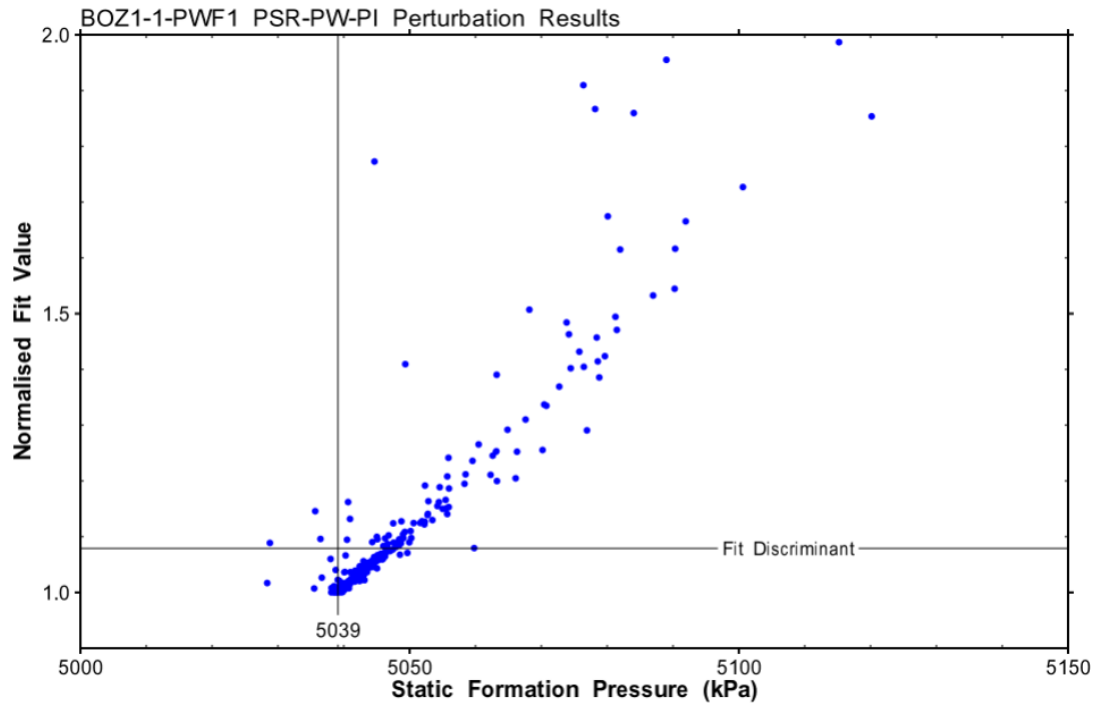


Fig. B-20: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of PSR-PW-PI
426 / 500 results with a normalised objective function value less than 2.

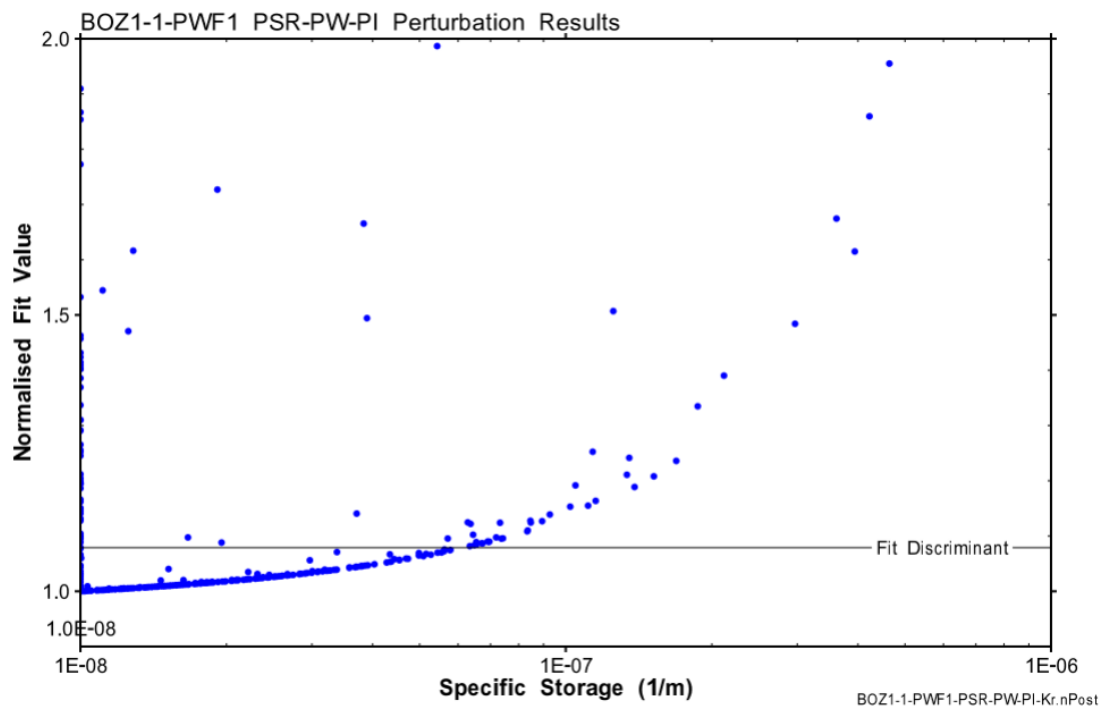


Fig. B-21: Hydraulic test BOZ1-1-PWF1: Distribution of the normalised objective function value (normalised fit value) over S_s for the numerical simulation of PSR-PW-PI
426 / 500 results with a normalised objective function value less than 2.

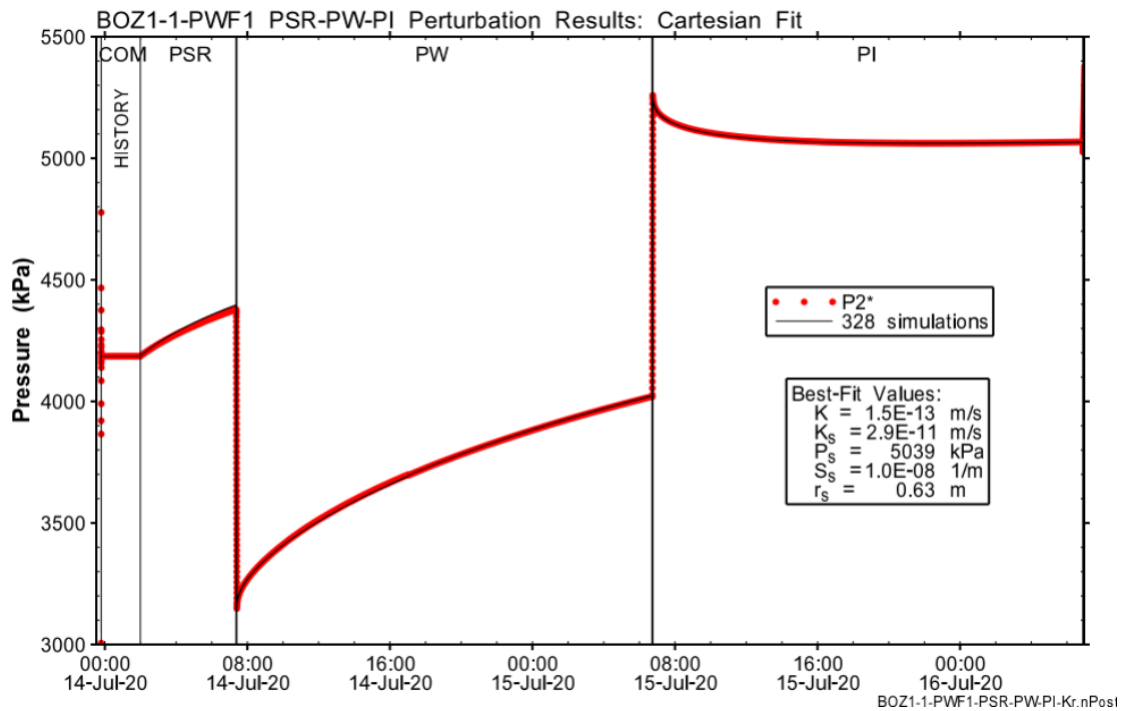


Fig. B-22: Hydraulic test BOZ1-1-PWF1: Cartesian horsetail plot of the perturbation simulations on PSR-PW-PI accepting the fit discriminator

328 / 500 results with a normalised objective function value less than 1.079.

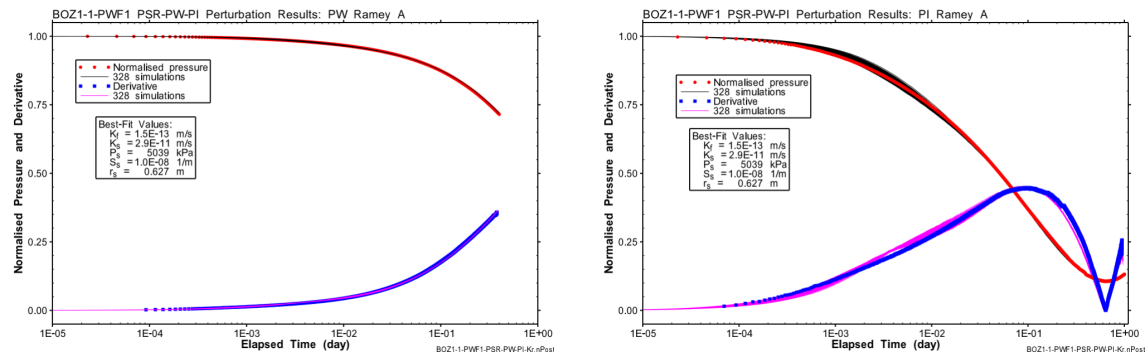


Fig. B-23: Hydraulic test BOZ1-1-PWF1: Ramey A horsetail plot of PW (left) and PI (right) of the PSR-PW-PI simulations accepting the fit discriminator

328 / 500 results with a normalised objective function value less than 1.079.

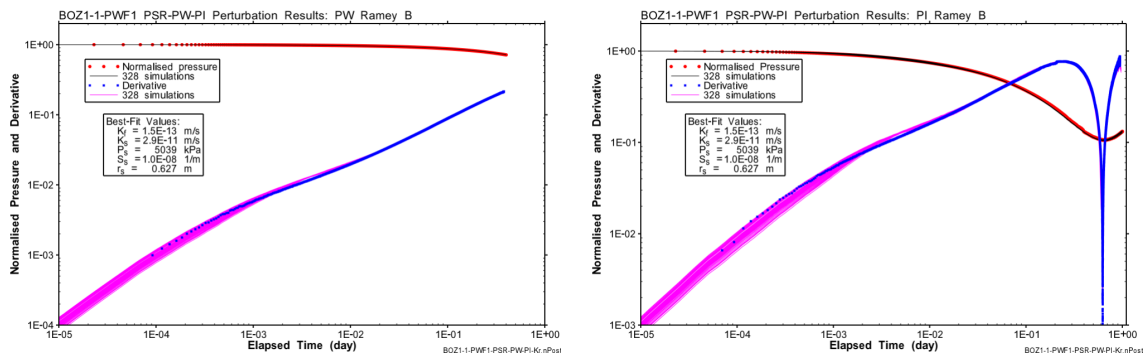


Fig. B-24: Hydraulic test BOZ1-1-PWF1: Ramey B horsetail plot of PW (left) and PI (right) of the PSR-PW-PI simulations accepting the fit discriminator

328 / 500 results with a normalised objective function value less than 1.079.

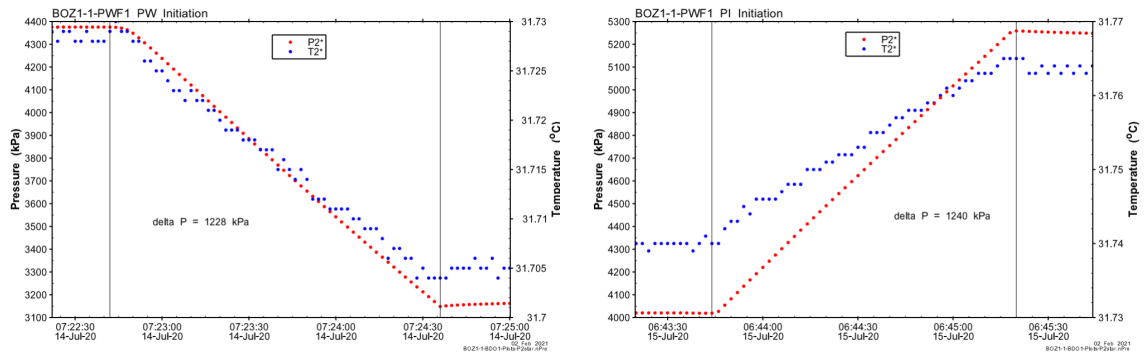


Fig. B-25: Hydraulic test BOZ1-1-PWF1: Test-interval pressure (P2*) and temperature (T2*) during PW (left) and PI (right) initiation

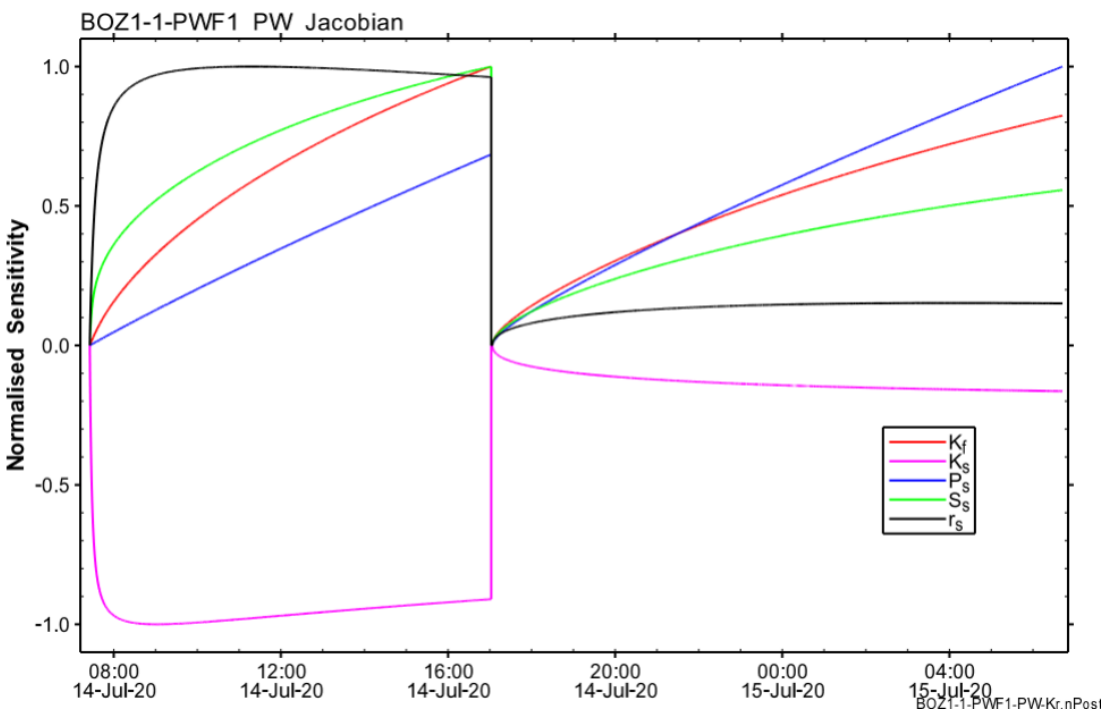


Fig. B-26: Hydraulic test BOZ1-1-PWF1: Jacobian plot of parameter sensitivity during PW

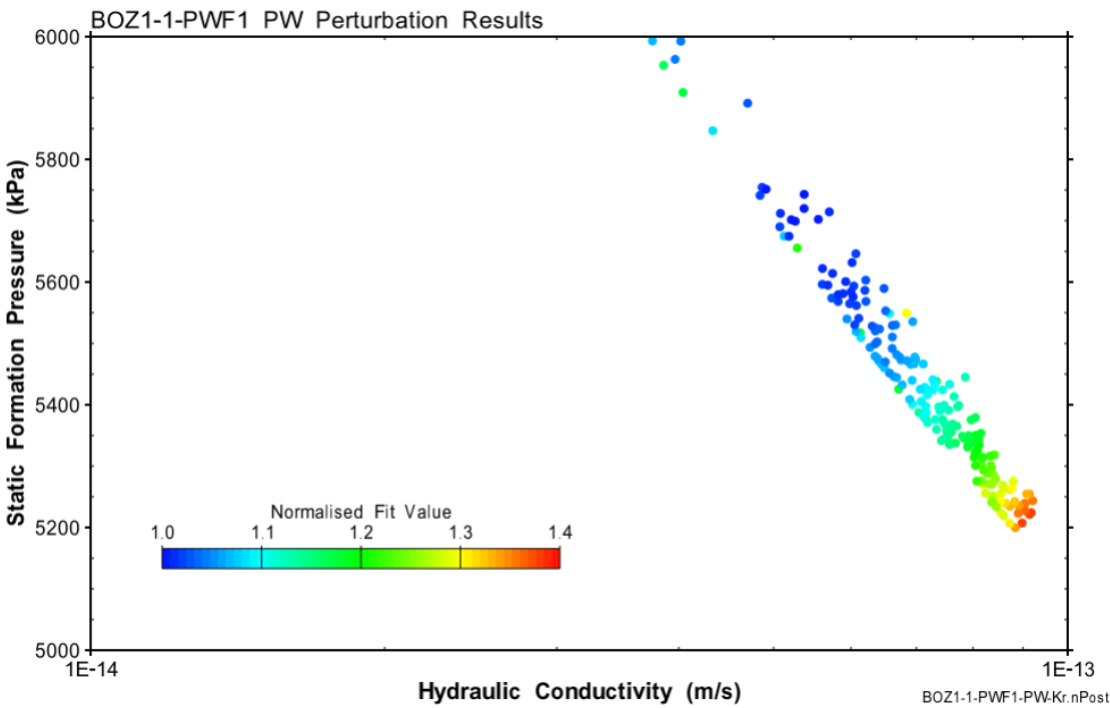


Fig. B-27: Hydraulic test BOZ1-1-PWF1: Scatter plot of the perturbation results of the hydraulic conductivity versus static formation pressure for PW

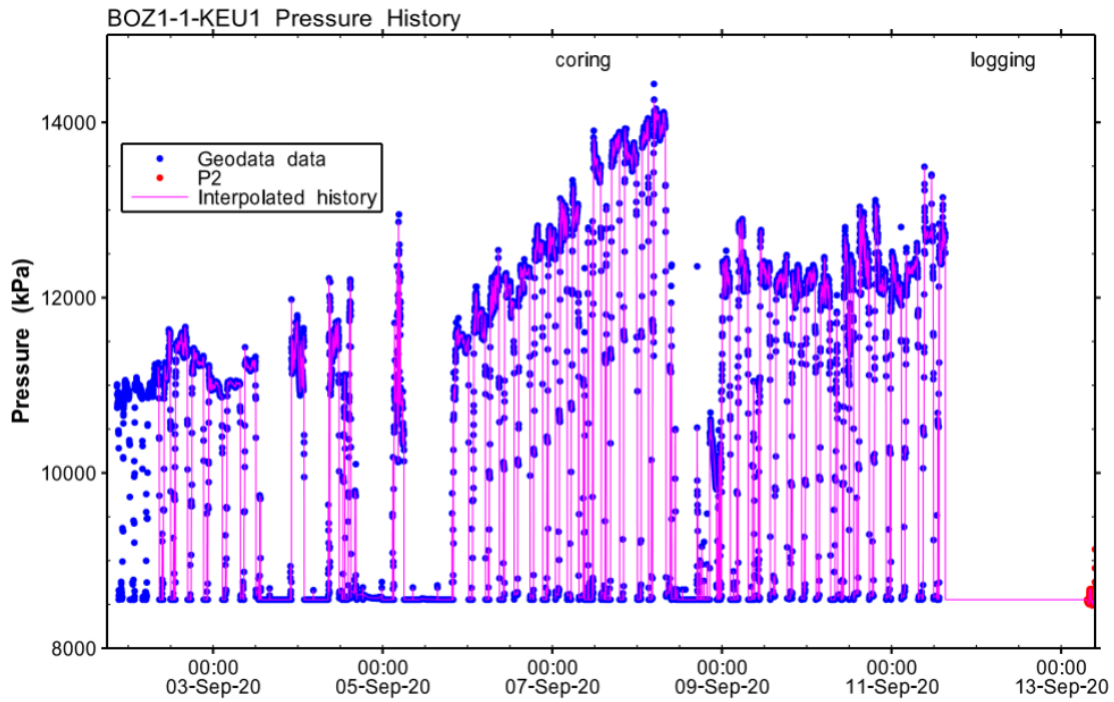


Fig. B-28: Hydraulic test BOZ1-1-KEU1: Entire record of the borehole pressure history used in the analysis

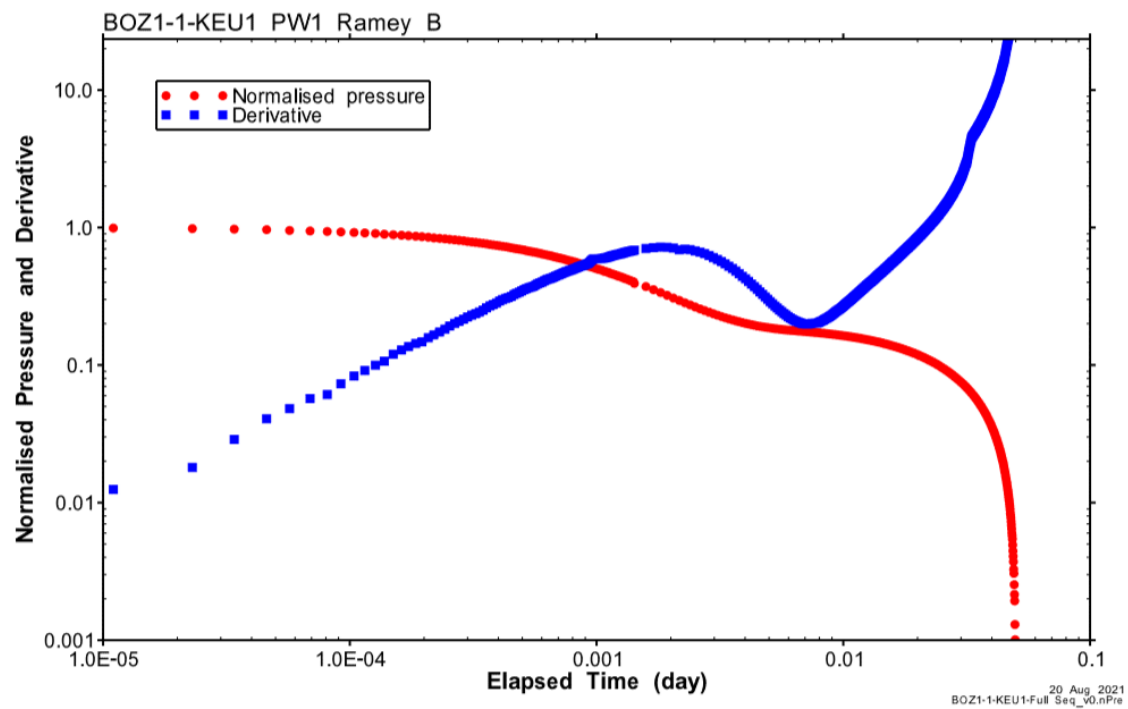


Fig. B-29: Hydraulic test BOZ1-1-KEU1: Ramey B diagnostic plot of PW1

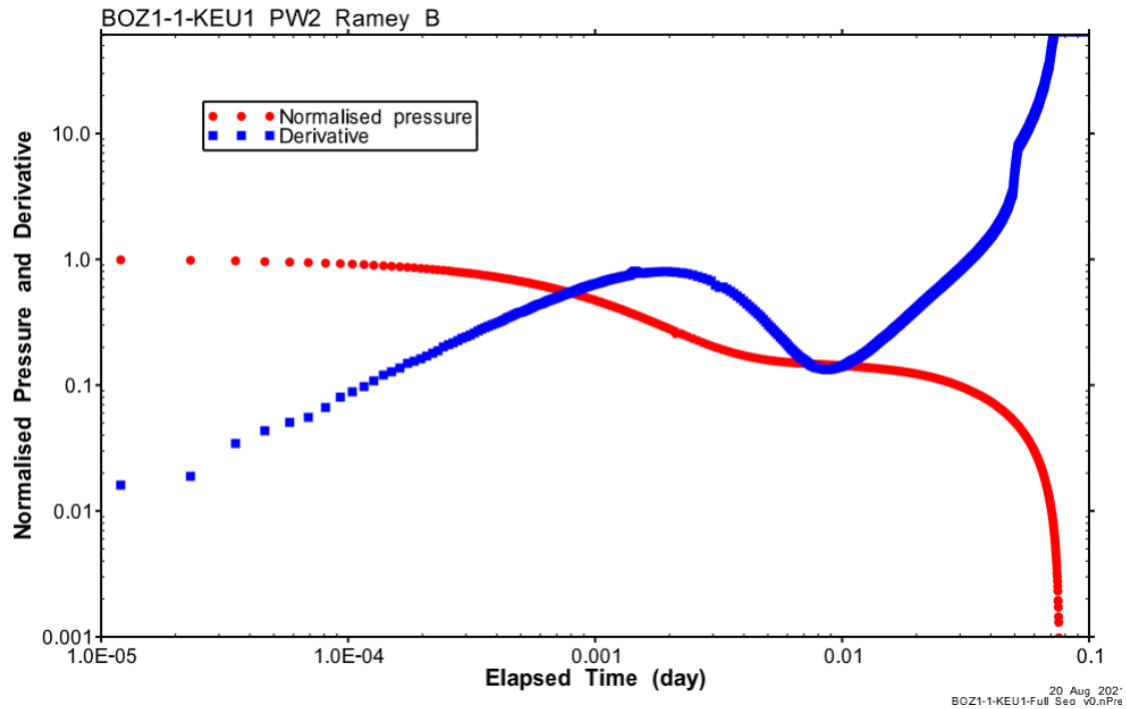


Fig. B-30: Hydraulic test BOZ1-1-KEU1: Ramey B diagnostic plot of PW2

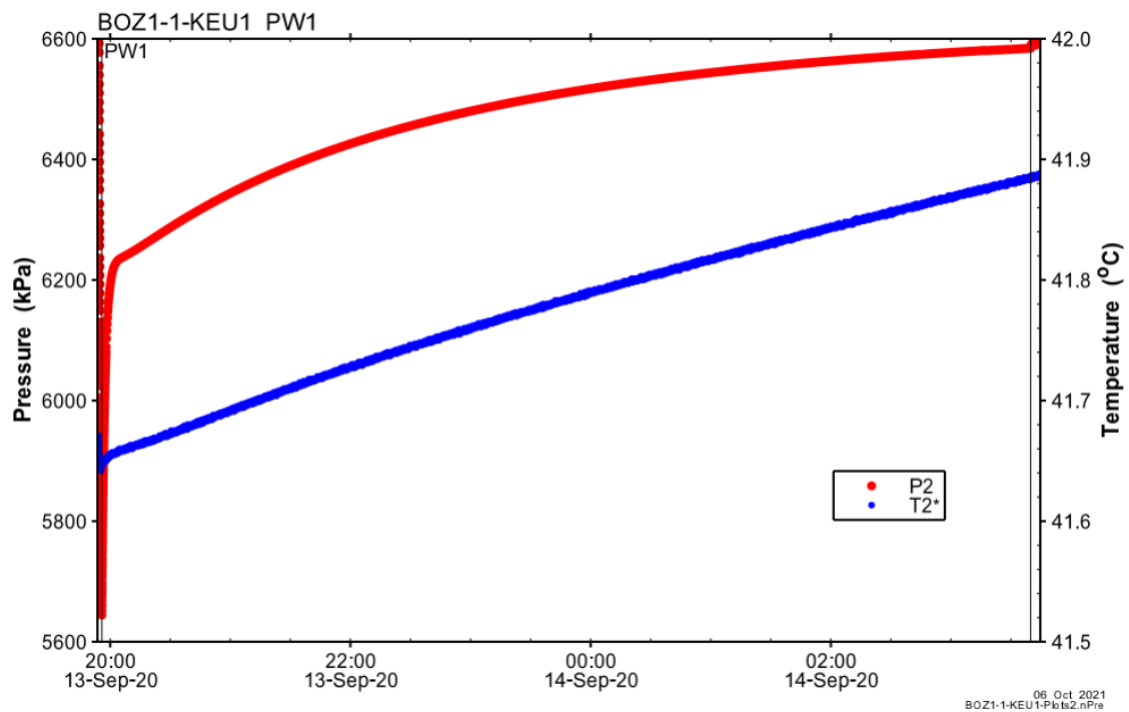


Fig. B-31: Hydraulic test BOZ1-1-KEU1: Development of the downhole temperature, T2*, and pressure, P2, during PW1

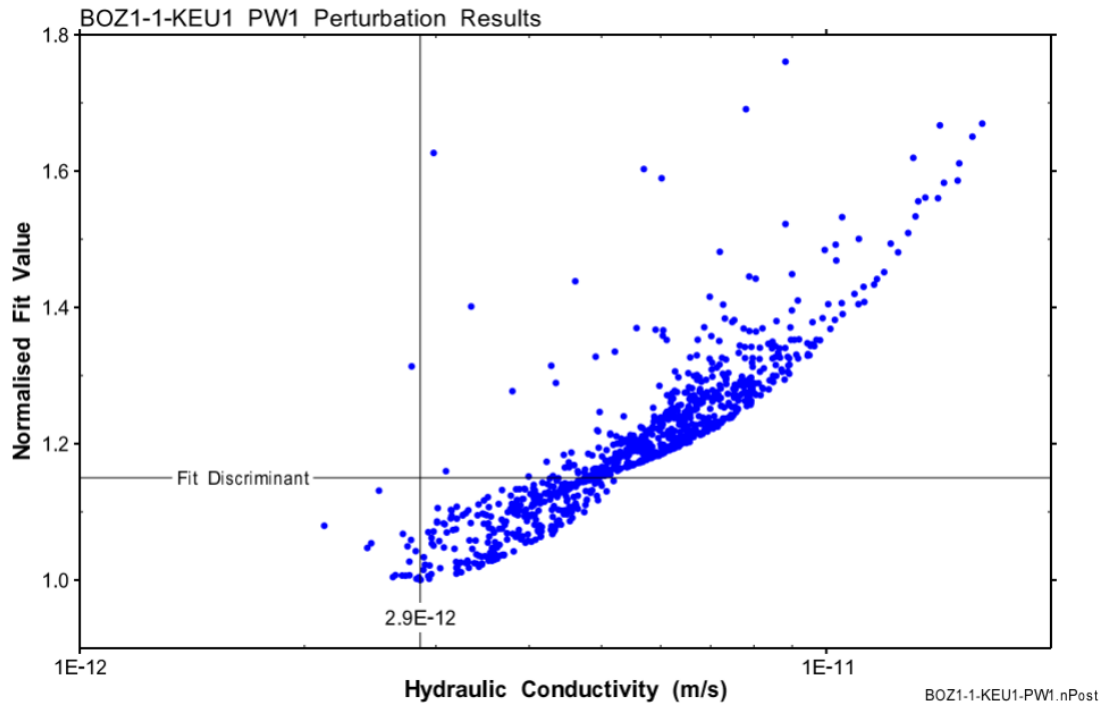


Fig. B-32: Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PW1 phase
951 / 1000 results with a normalised objective function value less than 1.8.

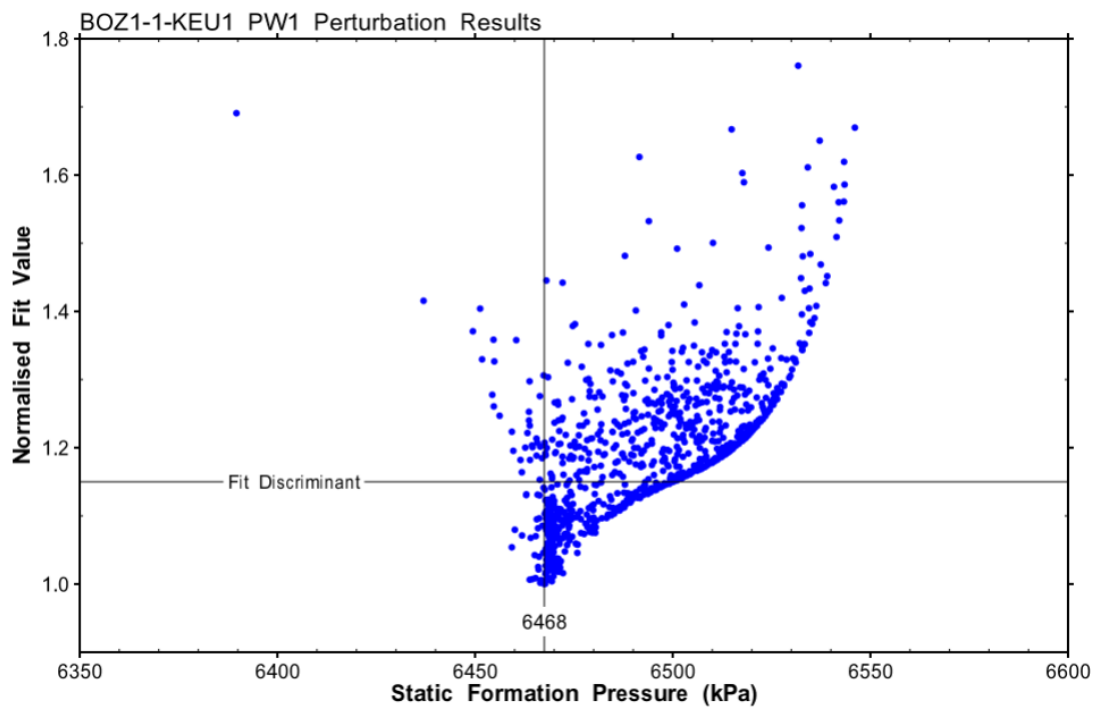


Fig. B-33: Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PW1 phase
951 / 1000 results with a normalised objective function value less than 1.8.

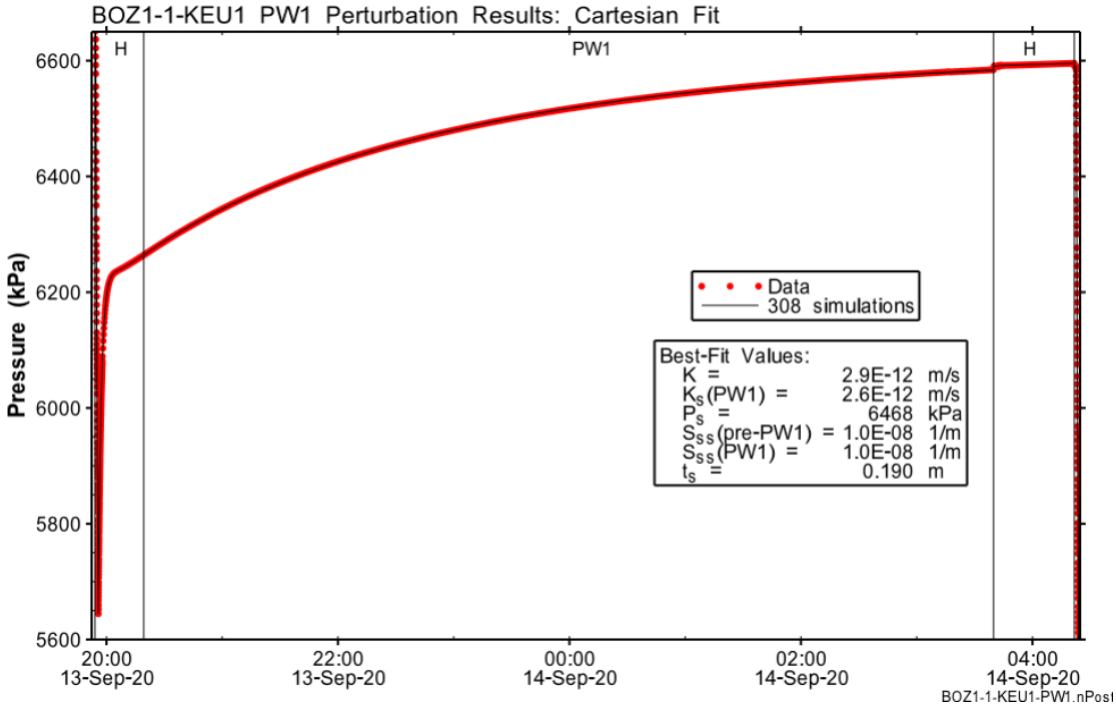


Fig. B-34: Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the perturbation simulations on PW1 accepting the fit discriminator

308 / 1000 results with a normalised objective function value less than 1.15.

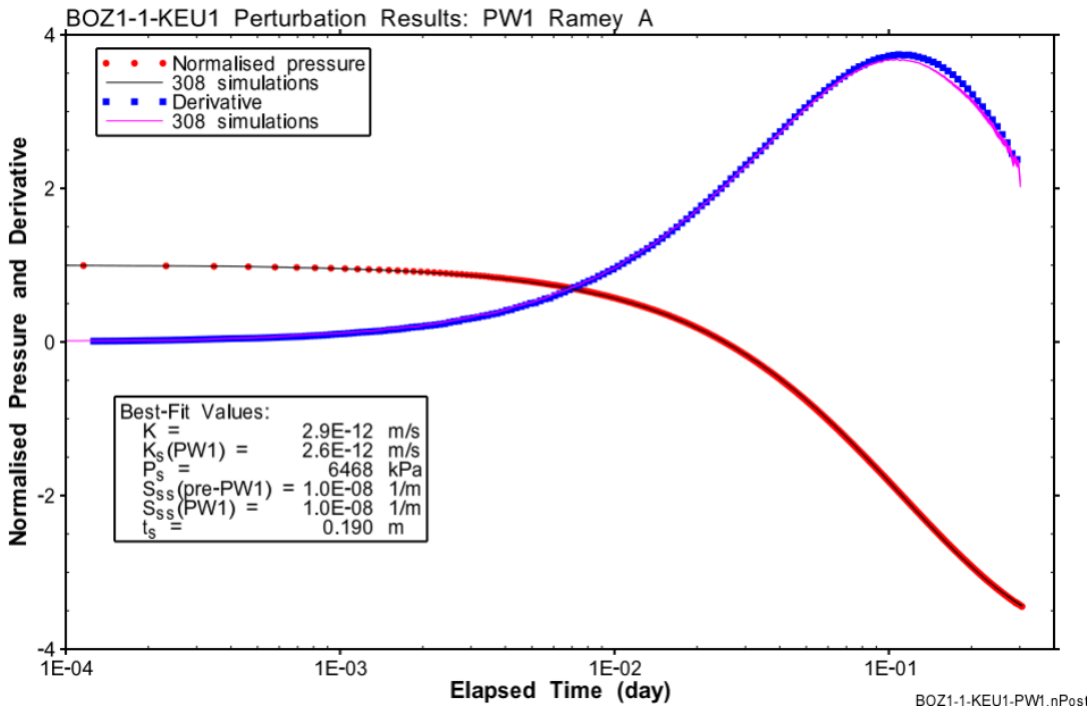


Fig. B-35: Hydraulic test BOZ1-1-KEU1: Ramey A horsetail plot of PW1 accepting the fit discriminator

308 / 1000 results with a normalised objective function value less than 1.15.

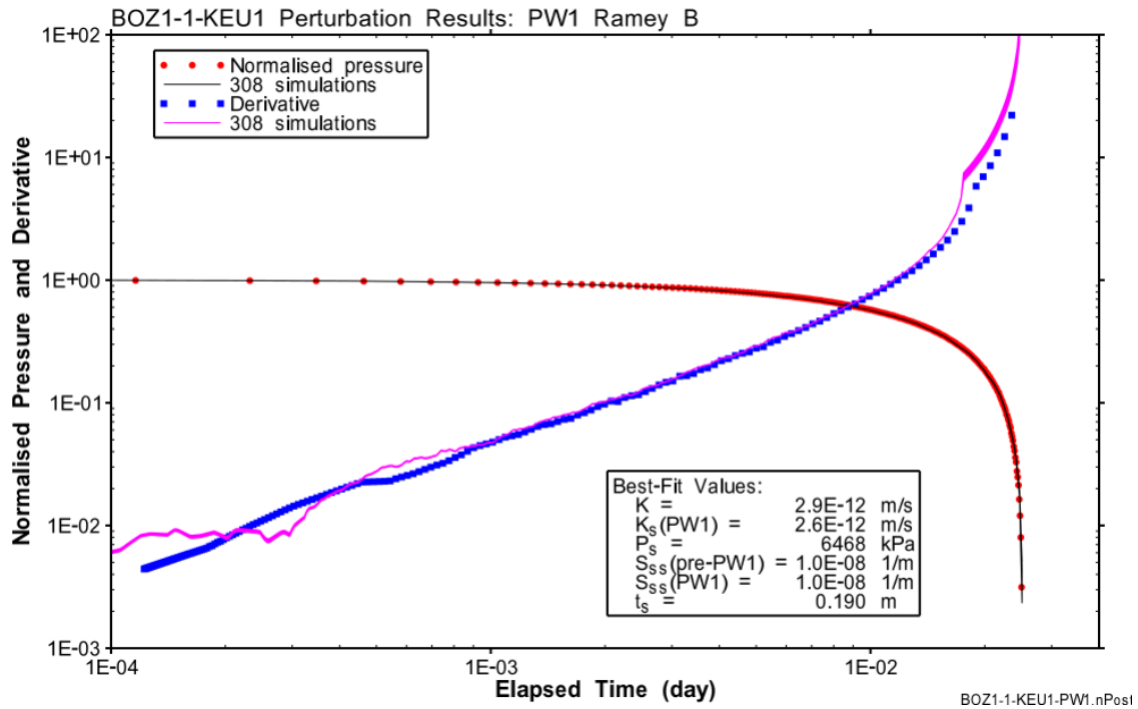


Fig. B-36: Hydraulic test BOZ1-1-KEU1: Ramey B horsetail plot of PW1 accepting the fit discriminator

308 / 1000 results with a normalised objective function value less than 1.15.

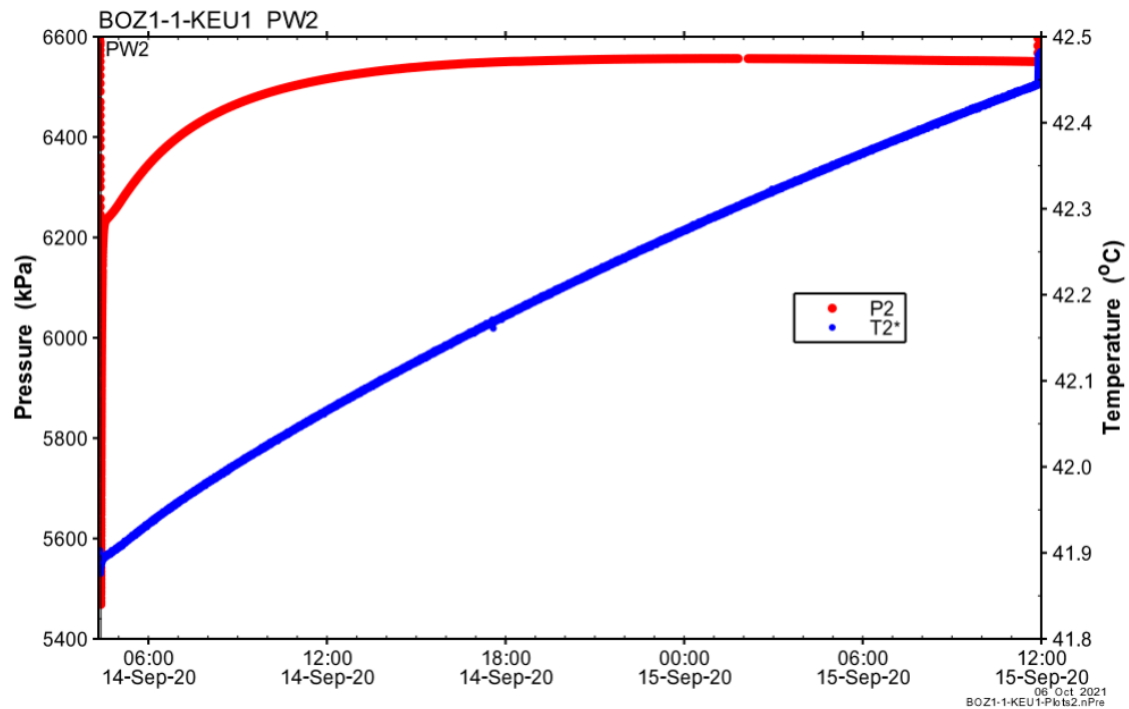


Fig. B-37: Hydraulic test BOZ1-1-KEU1: Development of the downhole temperature, T2*, and pressure, P2, during PW2

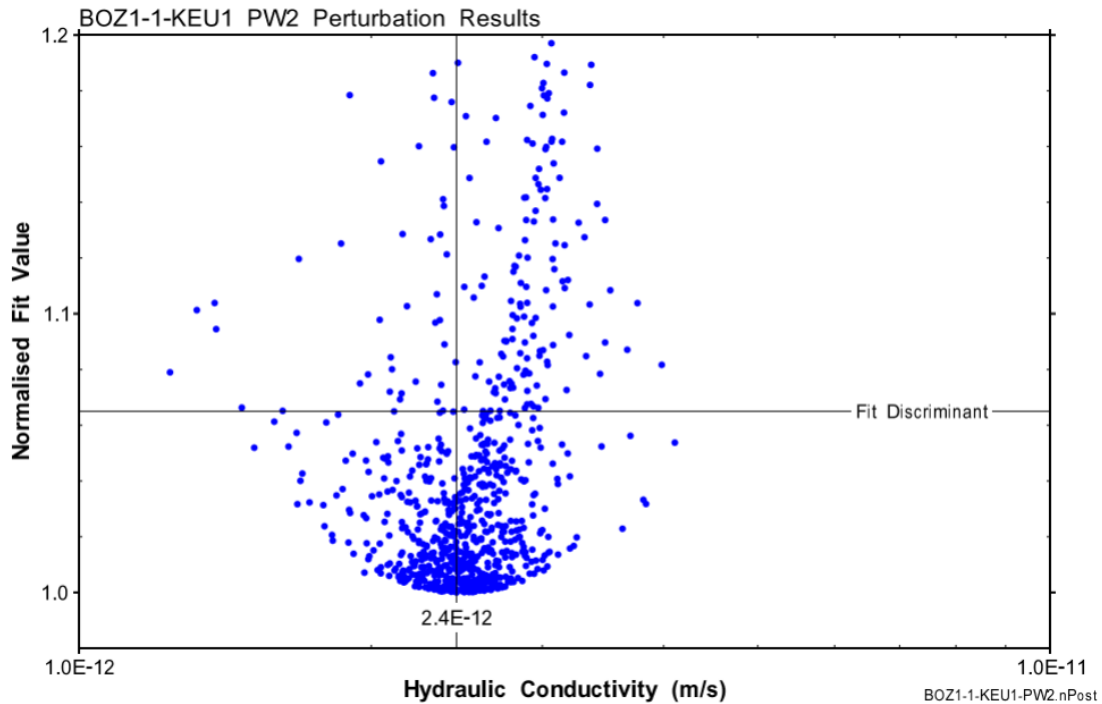


Fig. B-38: Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PW2 phase
823 / 1000 results with a normalised objective function value less than 1.2.

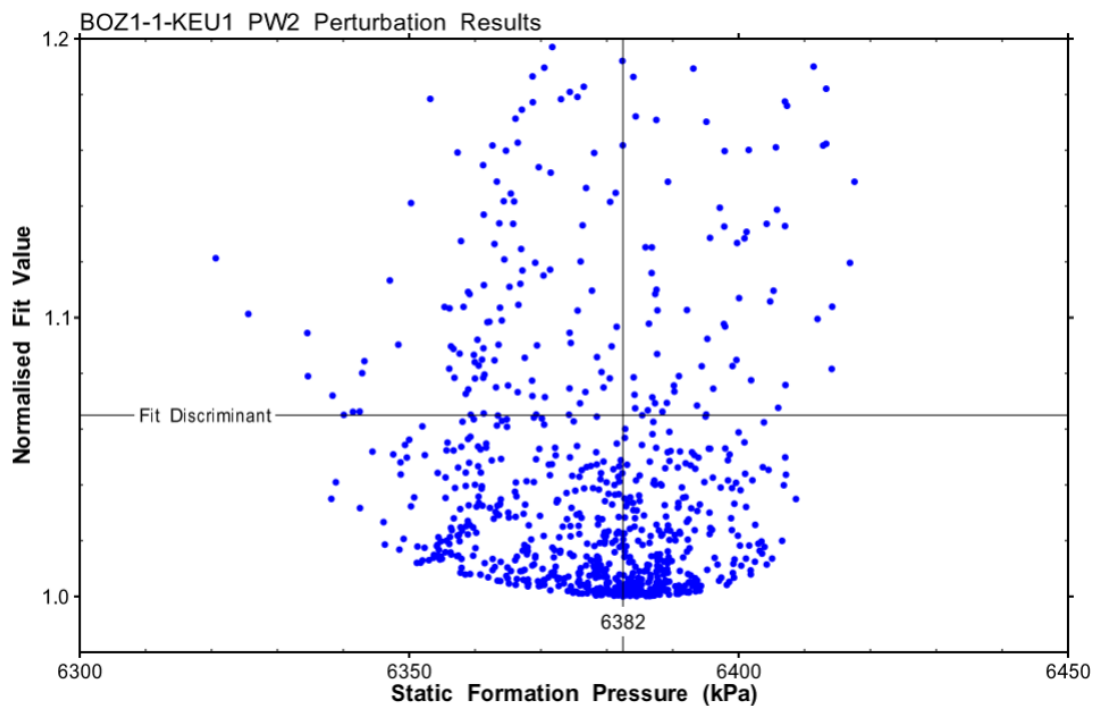


Fig. B-39: Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PW2 phase
823 / 1000 results with a normalised objective function value less than 1.2.

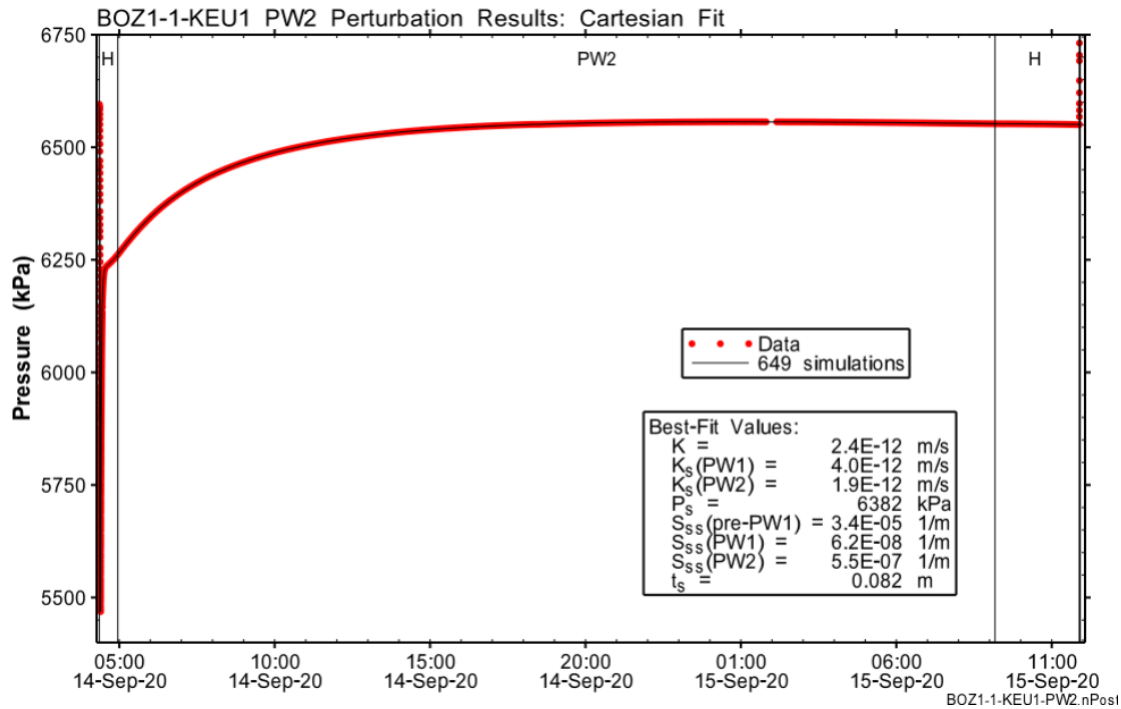


Fig. B-40: Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the perturbation simulations on PW2 accepting the fit discriminator

649 / 1000 results with a normalised objective function value less than 1.065.

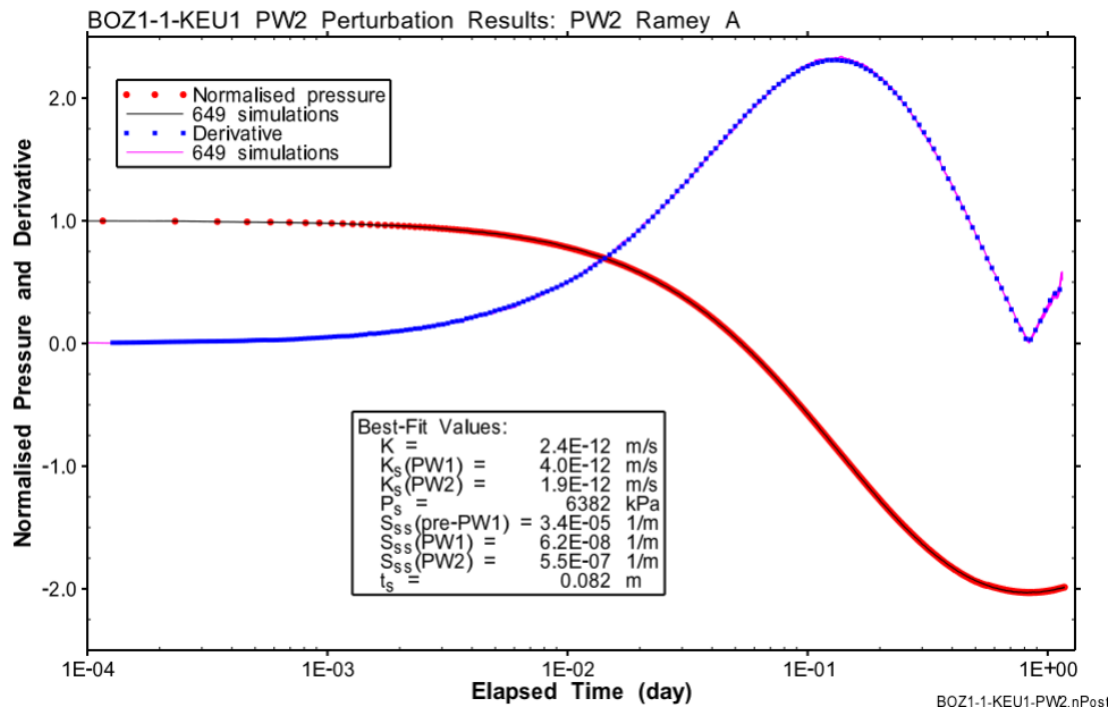


Fig. B-41: Hydraulic test BOZ1-1-KEU1: Ramey A horsetail plot of PW2 accepting the fit discriminator

649 / 1000 results with a normalised objective function value less than 1.065.

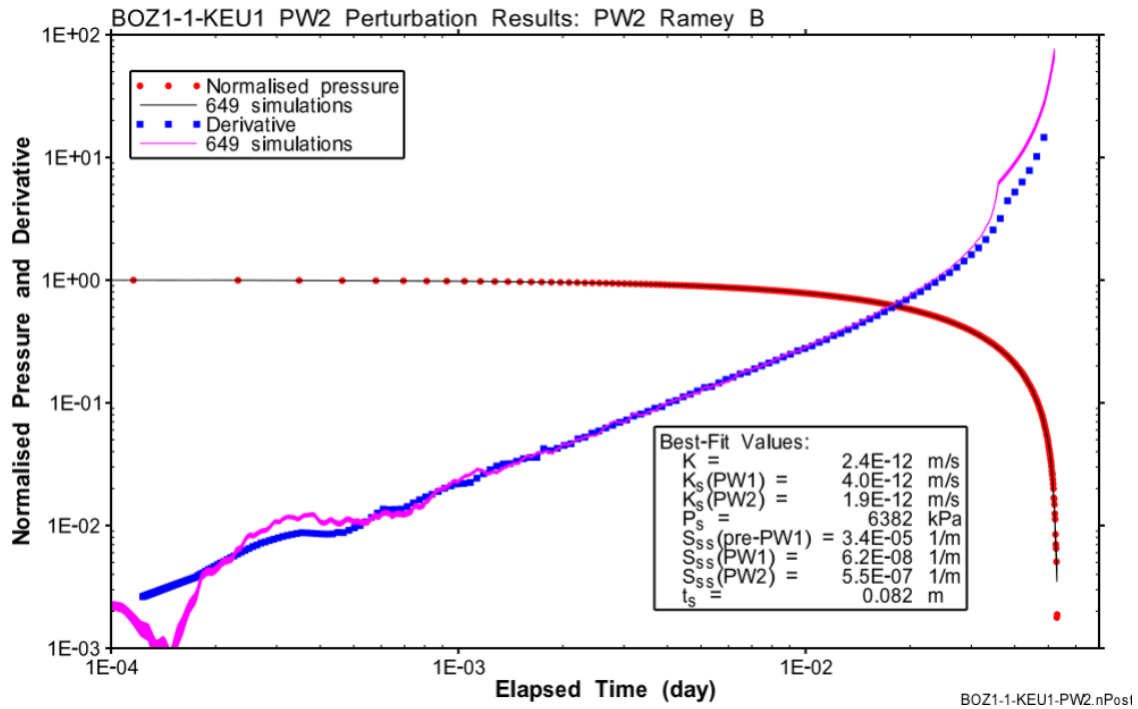


Fig. B-42: Hydraulic test BOZ1-1-KEU1: Ramey B horsetail plot of PW2 accepting the fit discriminator

649 / 1000 results with a normalised objective function value less than 1.065.

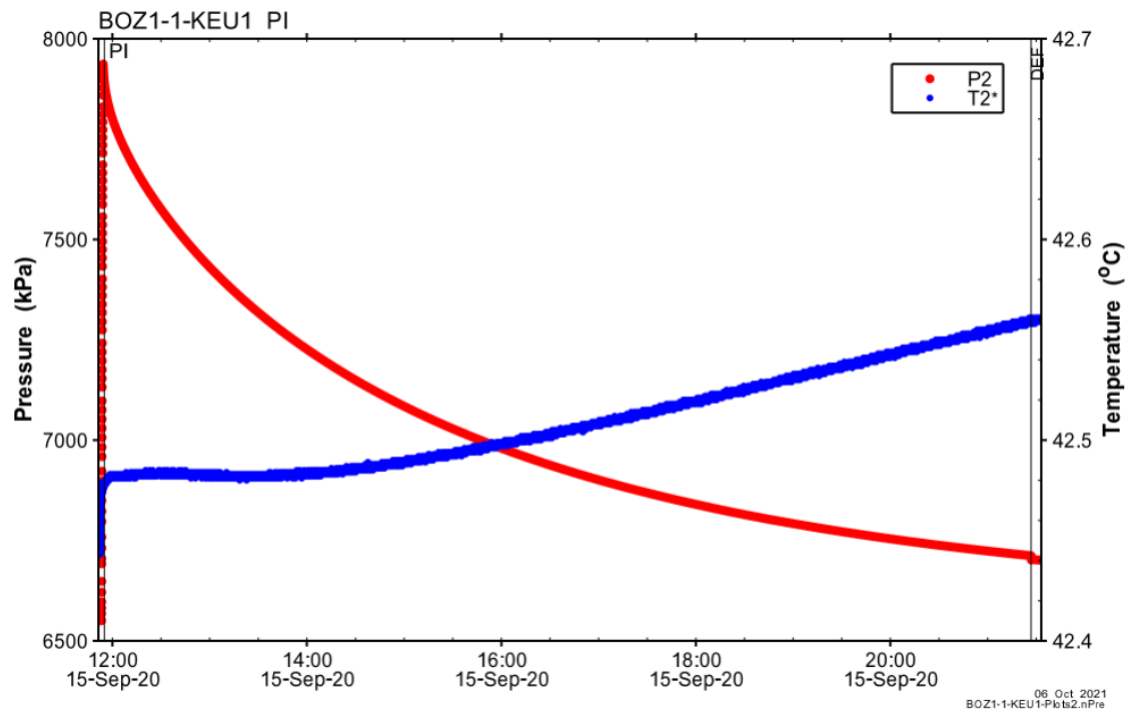


Fig. B-43: Hydraulic test BOZ1-1-KEU1: Development of the downhole temperature, $T2^*$, and pressure, $P2$, during PI

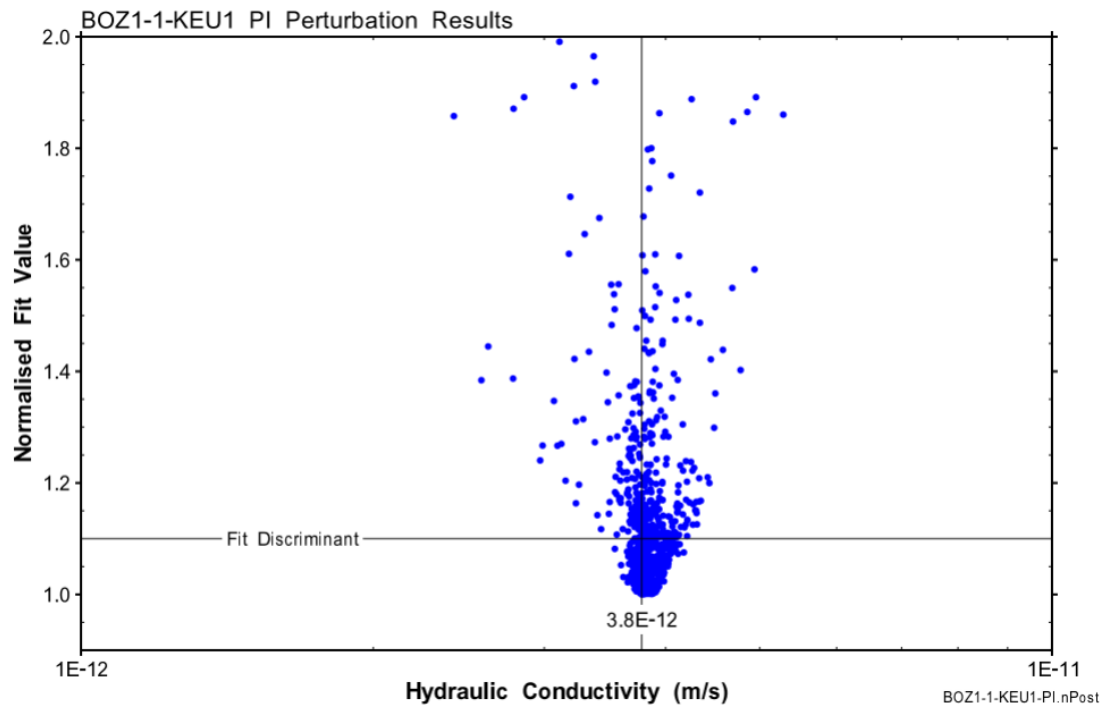


Fig. B-44: Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the PI phase
934 / 1000 results with a normalised objective function value less than 2.

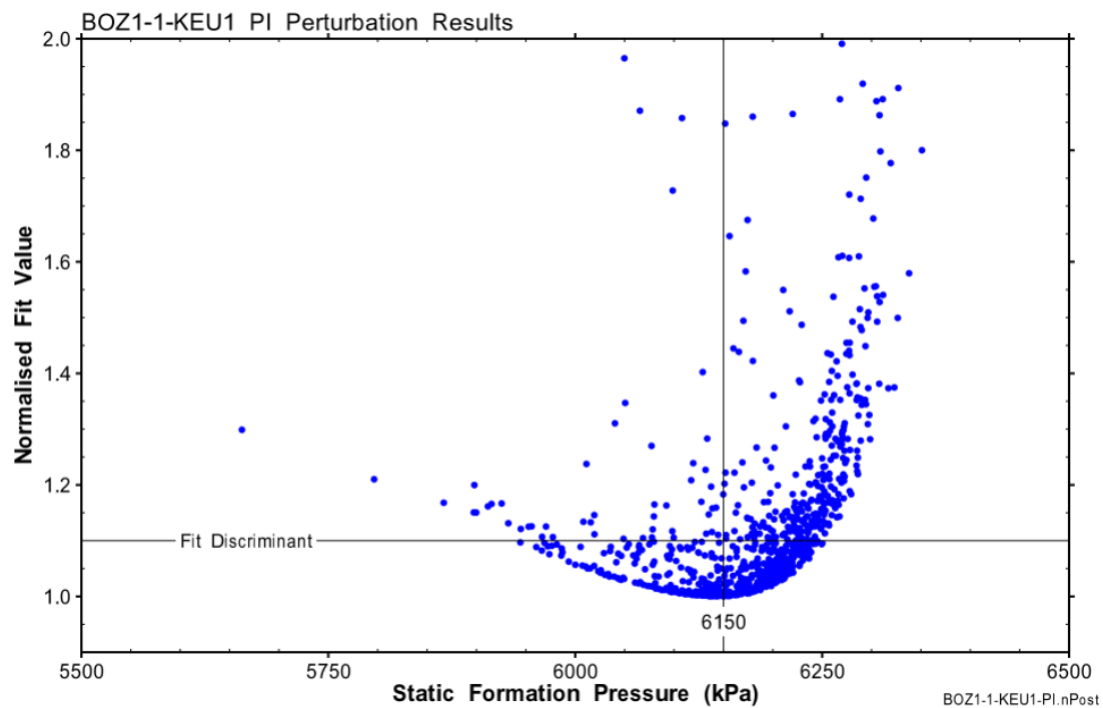


Fig. B-45: Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the PI phase
934 / 1'000 results with a normalised objective function value less than 2.

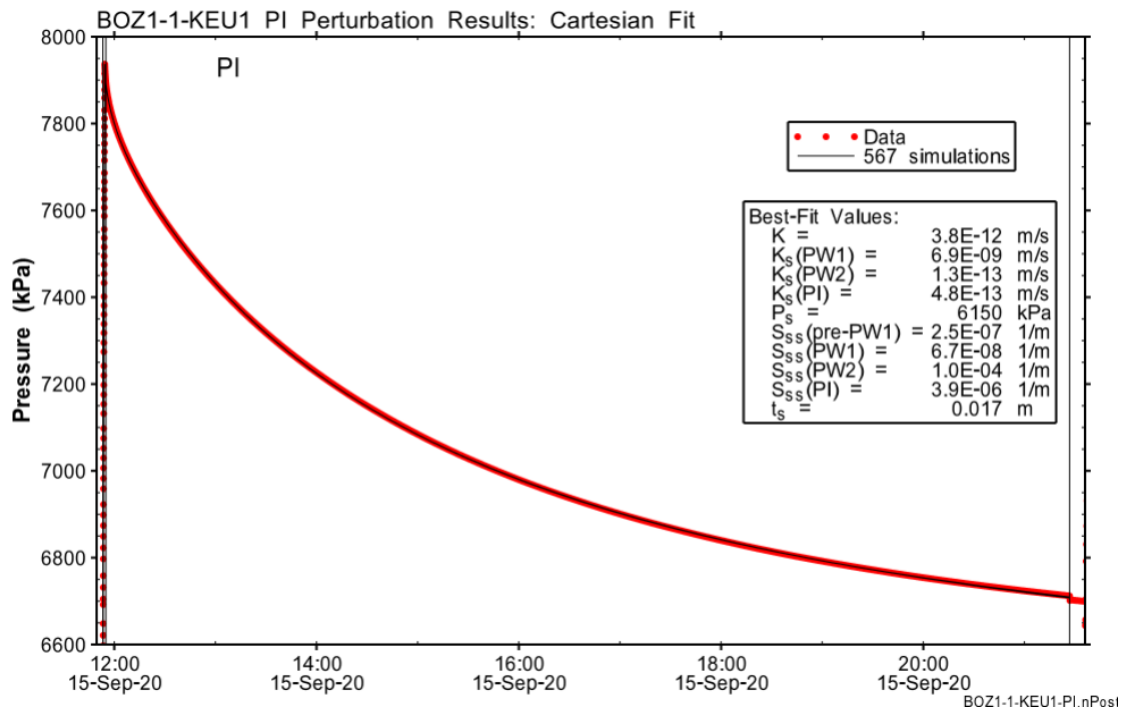


Fig. B-46: Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the perturbation simulations on PI accepting the fit discriminator

567 / 1'000 results with a normalised objective function value less than 1.1.

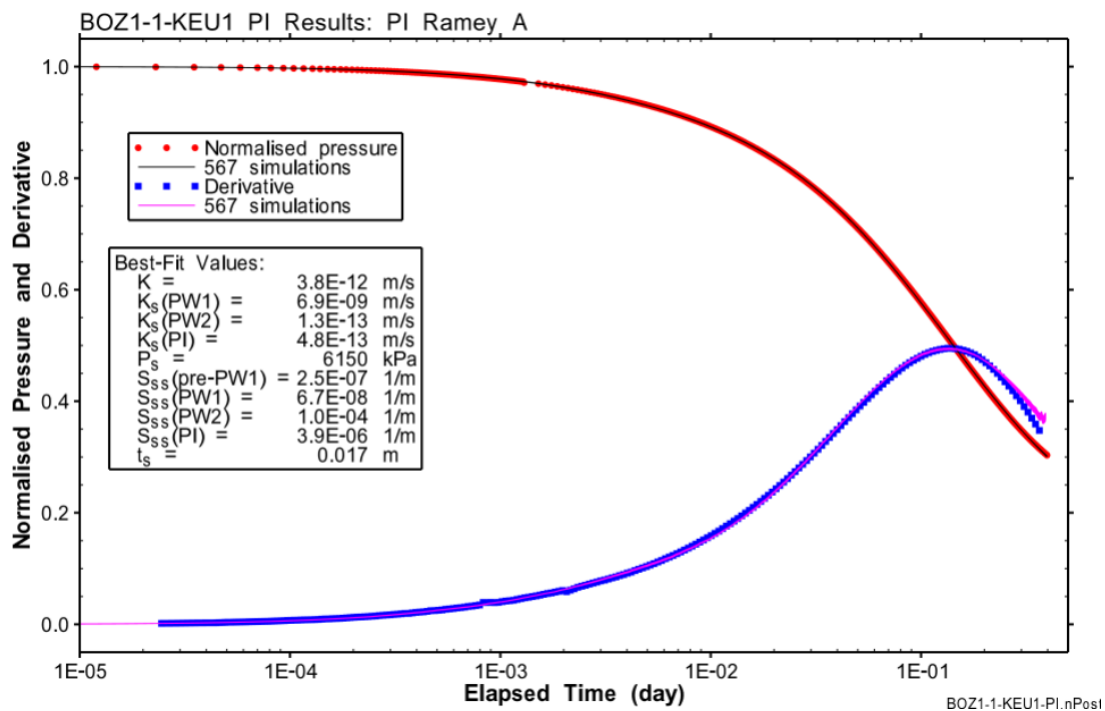


Fig. B-47: Hydraulic test BOZ1-1-KEU1: Ramey A horsetail plot of PI accepting the fit discriminator

567 / 1'000 results with a normalised objective function value less than 1.1.

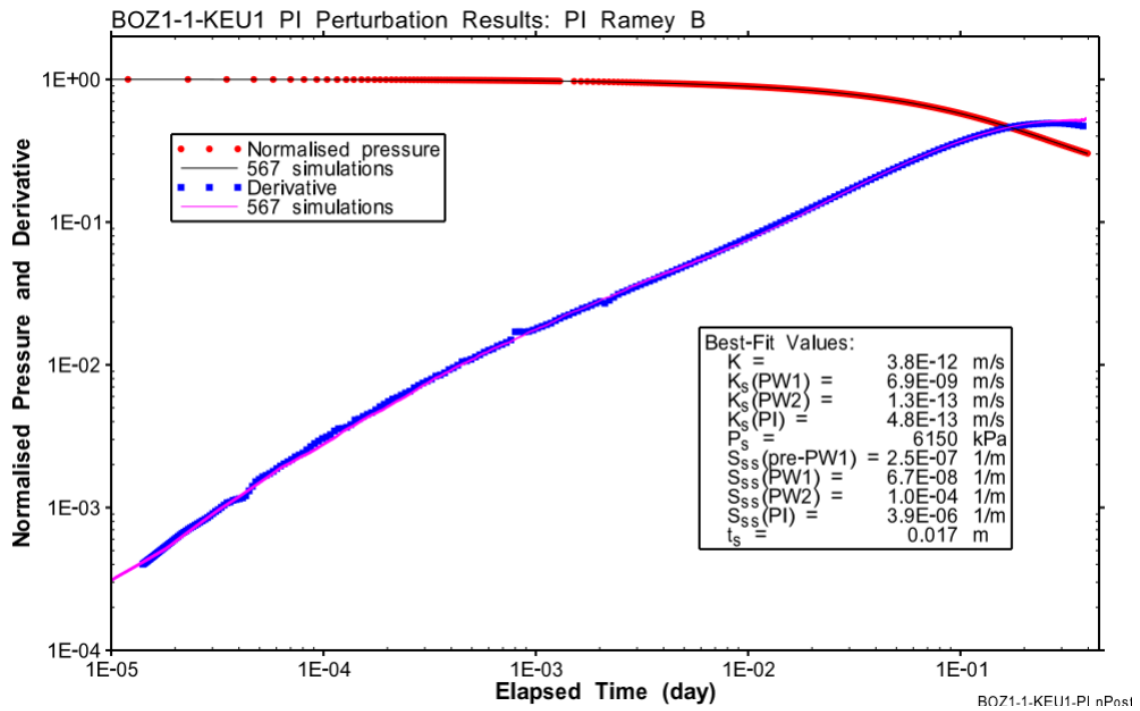


Fig. B-48: Hydraulic test BOZ1-1-KEU1: Ramey B horsetail plot of PI accepting the fit discriminator

567 / 1'000 results with a normalised objective function value less than 1.1.

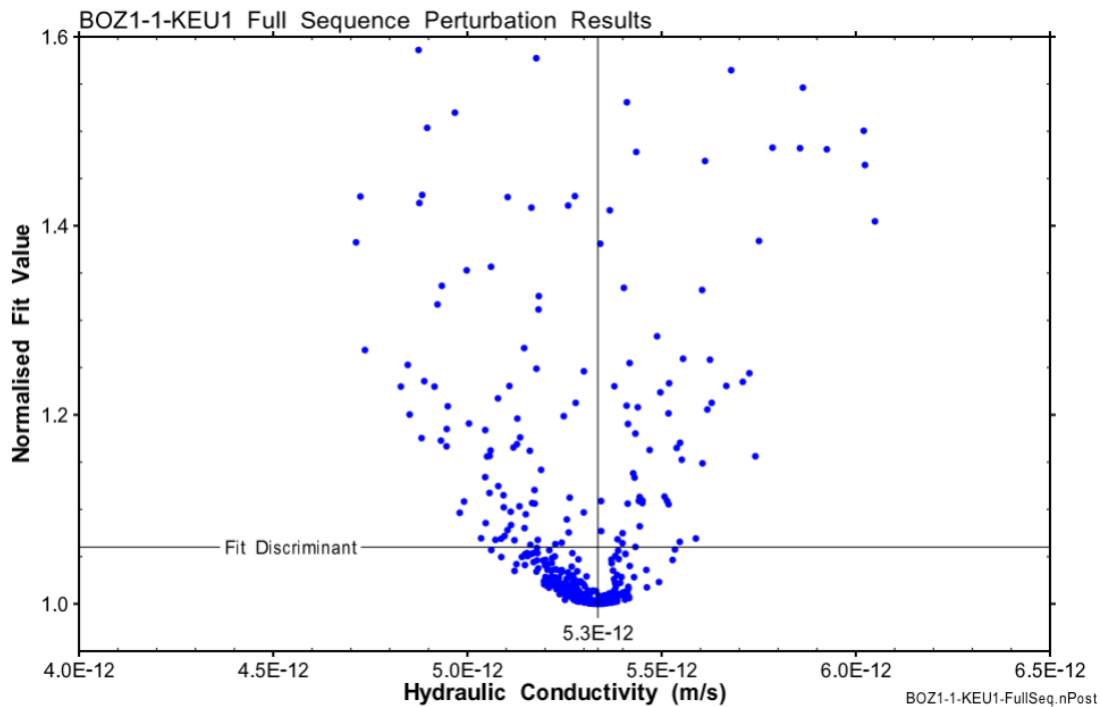


Fig. B-49: Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over K for the numerical simulation of the sequence PW1-PW2-PI

932 / 1'000 results with a normalised objective function value less than 1.6.

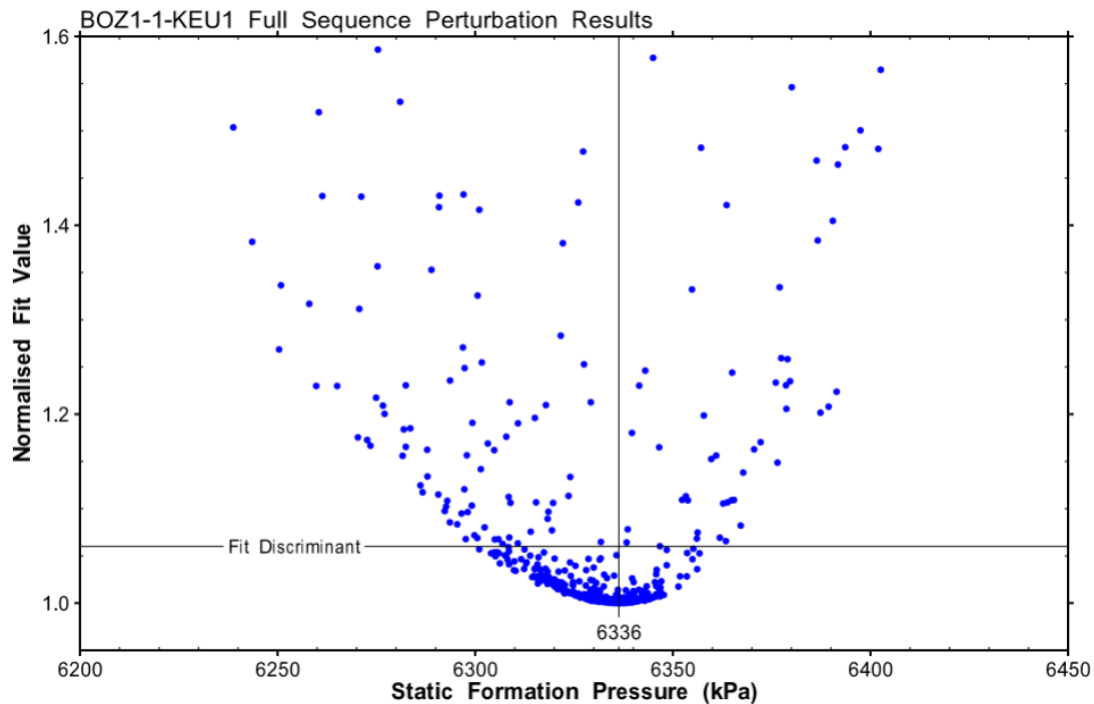


Fig. B-50: Hydraulic test BOZ1-1-KEU1: Distribution of the normalised objective function value (normalised fit value) over P_f for the numerical simulation of the sequence PW1-PW2-PI

932 / 1'000 results with a normalised objective function value less than 1.6.

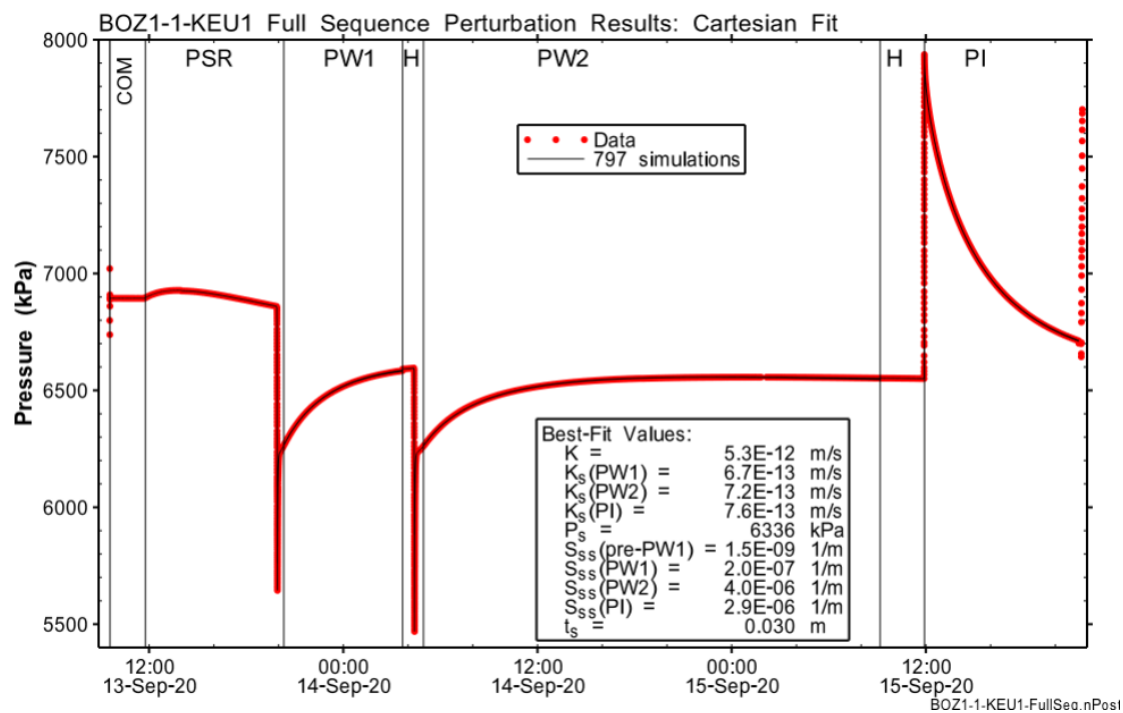


Fig. B-51: Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the best perturbation simulations on PW1-PW2-PI accepting the fit discriminator

797 / 1'000 results with a normalised objective function value less than 1.06.

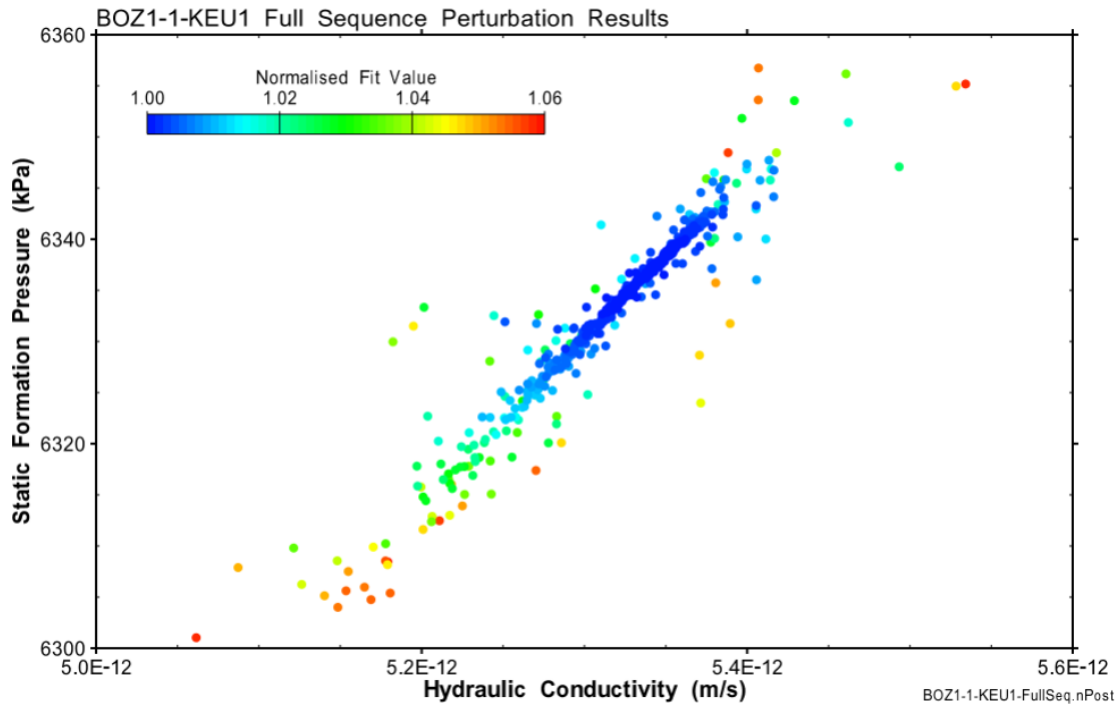


Fig. B-52: Hydraulic test BOZ1-1-KEU1: Scatter plot of the perturbation results of the hydraulic conductivity versus static formation pressure for the sequence analysis of PW1-PW2-PI

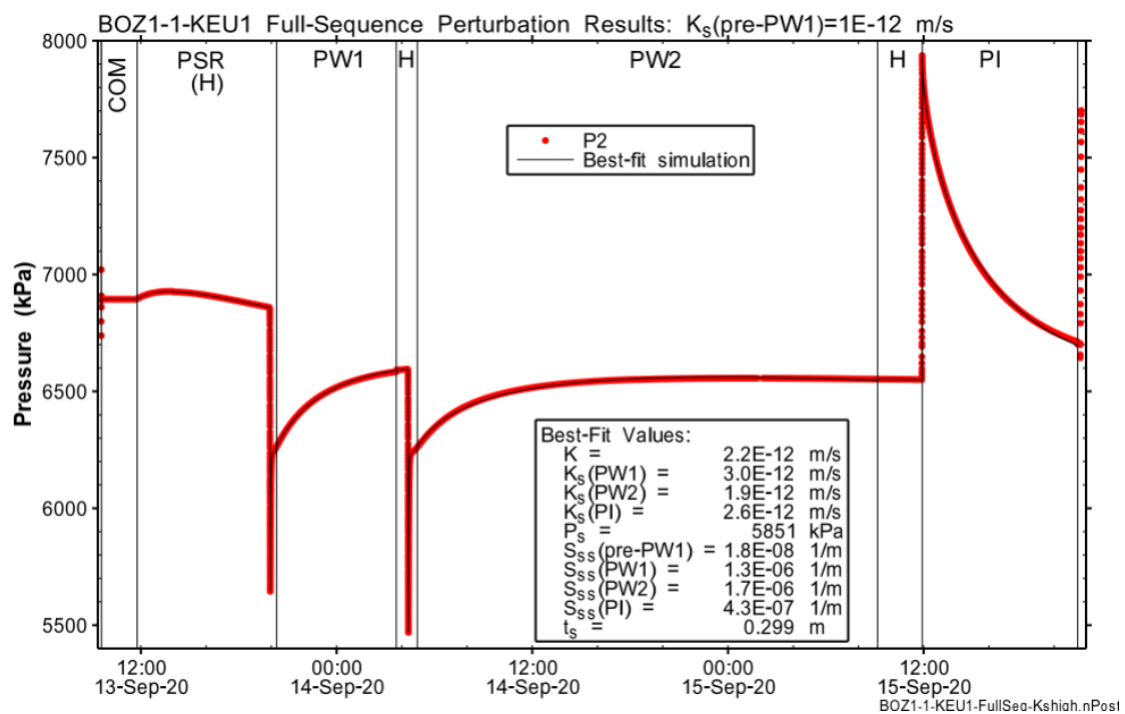


Fig. B-53: Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the best perturbation simulation on PW1-PW2-PI accepting the fit discriminator for a hydraulic conductivity of the skin zone fixed to $1 \times 10^{-12} \text{ m s}^{-1}$ during the history

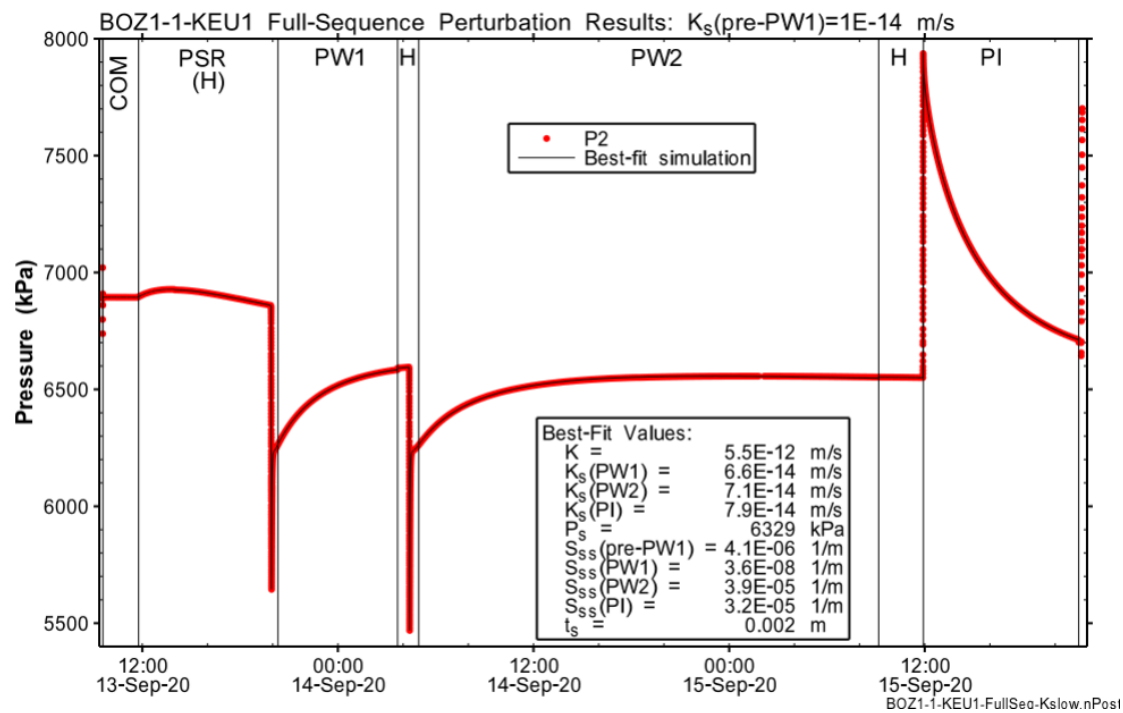


Fig. B-54: Hydraulic test BOZ1-1-KEU1: Cartesian horsetail plot of the best perturbation simulation on PW1-PW2-PI accepting the fit discriminator for a hydraulic conductivity of the skin zone fixed to $1 \times 10^{-14} \text{ m s}^{-1}$ during the history