



ARBEITSBERICHT NAB 23-40 Rev. 1

GAST – Gas Flow Test
Preliminary Interpretation

October 2024

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

Hardstrasse 73 | 5430 Wettingen | Switzerland
+41 56 437 11 11 | info@nagra.ch | nagra.ch



ARBEITSBERICHT

NAB 23-40 Rev. 1

GAST – Gas Flow Test
Preliminary Interpretation

October 2024

KEYWORDS

Grimsel Test Site, GAST, Gas Flow Test, sand/bentonite

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

Hardstrasse 73 | 5430 Wettingen | Switzerland
+41 56 437 11 11 | info@nagra.ch | 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 report was prepared by Bill [G.W.] Lanyon (Fracture Systems Ltd.), Jocelyn Gisiger (Solexperts AG), Ursula Rösli (Solexperts AG), Emiliano Stopelli (Nagra) and Thomas Spillmann (Nagra). The figures were prepared by Bill Lanyon with exception of the GAST section layouts which were prepared by Reto Flückiger (Nagra).

Stratis Vomvoris, Olivier Leupin and Ingo Blechschmidt (all Nagra) are acknowledged for their detailed review of the report and valuable comments.

NAB 23-40, May 2025: Corrigendum

This report was revised in May 2025. The corrections include a revision of headspace volumes in Tab. 2-1 and adjustment of gas volumes in Tab. 8-2.

The beginning of Phase 9 was corrected to 01.09.2023 11:00. A number of editorial corrections were necessary throughout the text to provide full consistency with other cited reports.

To maintain consistency with the documents submitted for the general licence applications, the original publication date is retained.

Abstract

Gas-permeable seal sections can provide an engineering solution for limiting gas overpressures by gas release along the backfilled structures of a deep geological repository for low- and intermediate level waste. The Gas-permeable Seal Test (GAST) is a large-scale experiment at the Grimsel Test Site (GTS) to demonstrate the effective functioning of gas-permeable seals at repository scale. For that purpose, a seal made of a mixture of 80% sand and 20% bentonite was constructed in 2011 – 2012 and saturated over about a decade prior to performing a series of gas tests.

This report documents the main results obtained from the long-term multi-phase Gas Flow Test (GFT) that was carried out May 2022 – November 2023. The test successfully demonstrated end-to-end gas flow along a flow path within the highly saturated sand/bentonite seal. The path developed very quickly (within a week) and at a small gas overpressure, as indicated by early time responses of pore pressure sensors. The end-to-end gas flow path along the 8-m-long seal section was fully established about one month later and was kept at near constant pressure for six months. The gas injection rates increased during this period, indicating a significant reduction in flow resistance over time. The highest sustained gas injection rate achieved during the various test phases of the GFT was 1,380 mL/min, equivalent to 725 m³N/yr. Almost all injected gas was recovered from the extraction point. The injected helium tracer was also largely recovered at the extraction point, and detected both within the sand/bentonite and at the sand/bentonite granular bentonite interface.

Mid-term shut-in and tracer-flushing phases were followed by the injection of a further gas tracer mix using conservative gas tracers (helium, argon, xenon) with differences in solubility and diffusivity. Tracer breakthroughs and recovery were similar to those for helium in the first gas tracer phase. Final tracer-flushing and characterisation phases concluded the GFT with an overall gas tracer test duration of 16 months.

Interpretation of the observed flow and pressure, tracer and other sensor data indicates:

- The speed of gas flow development points to a localised discrete flow path that is likely to have exploited heterogeneity in porosity and bentonite content within the seal section.
- The gas flow path is interpreted as being of low volume with limited desaturation of the bulk of the sand/bentonite although the resistance to gas flow significantly decreases over time.
- The GFT demonstrated the ability of the sand/bentonite to transport large volumes of gas at repository-relevant flowrates across an 8-m-long sand/bentonite seal at low entry pressure and relatively small gradients, from initially saturated conditions in the sand/bentonite.
- Injected tracer gases were unambiguously detected within the sand/bentonite.
- The GFT dataset is of high quality and suitable for the development of detailed two-phase flow models of the test.

In conclusion, the key objectives of the GAST and specifically of the GFT were achieved and the enhanced gas permeability of a large-scale sand/bentonite seal was successfully demonstrated. Water permeability before and after the gas tests remained low. Detailed aspects of the observed responses could benefit from further interpretation and modelling.

Table of Contents

Abstract	I
Table of Contents	III
List of Tables.....	VIII
List of Figures	XI
List of Acronyms and Sensor Abbreviations	XVII
1 Introduction	1
1.1 The Gas-permeable Seal Test	1
1.2 Objectives	2
1.3 GAST layout.....	2
1.4 Gas Flow Test timeline	3
1.5 Conventions	5
1.5.1 GAST local reference coordinate system	5
1.5.2 GAST instrumentation.....	5
1.6 Report structure	6
2 Conditions prior to the GFT	9
2.1 GAST layout and materials	9
2.2 GAST instrumentation.....	9
2.2.1 Sensor status	10
2.2.2 Physical state	12
2.2.3 Water injection and pressure evolution	13
2.2.4 Saturation state (01.05.22).....	17
2.2.5 Stress state (01.05.22).....	22
2.2.6 Temperature.....	25
2.3 Porewater	25
2.3.1 Sand filters.....	25
2.3.2 Sand/bentonite porewater dissolved gases.....	25
3 Water-gas exchange and start of injection Phases 2 – 3 and gas breakthrough to S14 (02.05. – 12.05.22)	27
3.1 Injection and extraction boundary conditions.....	27
3.2 Pressure response.....	29
3.3 Stress response.....	37
3.4 Saturation response (TDR, Index tests).....	39
3.5 Gas tracers and sampling.....	40
3.6 Interpretation summary of the W-GX and gas breakthrough to S14.....	40
3.6.1 Location of S02 – S14 gas flow path.....	40
3.6.2 Gas entry into the sand/bentonite	43

4	Phases 4 and 5 – Gas Mix #1 stable gas path with sampling (12.05.22 – 01.12.22)	45
4.1	Injection and extraction boundary conditions	45
4.2	Pressure response	47
4.3	Stress response	53
4.4	Saturation response (index tests, TDR)	55
4.5	Gas tracers and sampling	55
4.6	Response to events during Phases 4 and 5 (analysis of shut-ins, pulses)	57
4.6.1	Drainage of S14 filter	57
4.6.2	Response to shut-in on 30.07.22	59
4.7	Interpretation summary	59
4.7.1	Gas flow path characteristics	59
4.7.2	Gas flow path summary data	60
5	Phases 6 and 7 – N₂ flush and switch to rate control (01.12.22 – 18.04.23)	63
5.1	Injection and extraction boundary conditions	63
5.2	Pressure response	64
5.3	Stress response	68
5.4	Saturation response (TDR, index tests)	69
5.5	Gas tracers and sampling	70
5.6	Response to events during Phases 5 and 6	71
5.6.1	Shut-in 30.12.22 – 10.01.23	71
5.6.2	Rate changes on 22.03.23 and 23.03.23	72
5.7	Interpretation summary	75
5.7.1	Gas flow path characteristics	75
5.7.2	Gas flow path summary data	76
6	Phases 8 and 9: gas Mix #2 and N₂ flush (18.04.23 – 01.09.23)	77
6.1	Injection and extraction boundary conditions	77
6.2	Pressure response	77
6.3	Stress response	82
6.4	Saturation response (index tests, TDR)	83
6.5	Gas tracers and sampling	84
6.6	Response to events during Phases 8 and 9 (analysis of shut-ins, pulses)	85
6.7	Interpretation summary	85
6.7.1	Gas flow path characteristics	85
6.7.2	Gas flow path data summary	85
7	Phases 10 and 11: flow path diagnostics and gas removal (01.09.23 – 01.01.24)	87
7.1	Injection and extraction boundary conditions	87
7.1.1	Phase 10 flow path diagnostics	87
7.1.2	Phase 11 gas extraction	88
7.2	Pressure response	91

7.3	Stress response.....	95
7.4	Saturation response (TDR, index tests)	95
7.5	Gas tracers and sampling.....	96
7.6	Response to events during Phases 10 and 11 (analysis of shut-ins, pulses).....	96
7.6.1	Step-rate tests.....	96
7.6.2	RW tests in selected PPEs	98
7.6.3	S02 slug withdrawal test.....	98
7.6.4	Gas and water injection into the S14 filter	99
7.6.5	Gas-water exchange (G-WX) in S02.....	103
7.7	Interpretation summary.....	103
7.7.1	Gas flow path characteristics	103
7.7.2	Gas flow path summary data	103
7.8	State of the in-situ experiment post-Gas Flow Test.....	105
7.8.1	Residual free gas.....	105
7.8.2	Gas in solution	105
8	Summary preliminary interpretation	107
8.1	Conditions at the start of the GFT	107
8.2	Gas path key findings	108
8.2.1	Gas path localisation.....	108
8.2.2	Gas path development and effective properties.....	114
8.2.3	Gas entry pressure into the sand/bentonite	115
8.2.4	Gas flow in the GBM.....	116
8.2.5	Gas flow in the geosphere.....	117
8.3	Comparison with GPT1	117
8.4	GFT gas volumes and recovery	120
9	Concluding remarks	123
9.1	Gas transport in the GAST seal	123
9.2	GFT outcomes	123
10	References.....	125
App. A	Instrumentation layouts	A-1
A.1	Section S01	A-2
A.2	Section S02.....	A-2
A.3	Section S03	A-3
A.4	Section S04	A-3
A.5	Section S06	A-4
A.6	Section S07	A-4
A.7	Section S08	A-5
A.8	Section S09	A-5
A.9	Section S10	A-6
A.10	Section S11	A-6
A.11	Section S12	A-7

A.12	Section S14.....	A-7
A.13	Section S15.....	A-8
A.14	Section S16.....	A-8
A.15	Section S17.....	A-9
A.16	Boreholes.....	A-10
A.17	Piezometer and hydraulic lines.....	A-10
A.17.1	Piezometer emplacement.....	A-10
App. B	Flow data treatment	B-1
B.1	Background.....	B-1
B.2	Relevant datasets	B-2
B.2.1	Mass balance dataset.....	B-2
B.3	Measurement of gas injection into S02.....	B-3
B.3.1	Measurement of water and gas extraction from S14	B-3
B.3.2	Conversion of gas flow rate between ml/min and mlN/min.....	B-4
B.3.3	Summary.....	B-5
App. C	Estimation of gas volumes in filters.....	C-1
C.1	Background.....	C-1
C.1.1	Filter compressibility and gas volume.....	C-2
C.1.2	Idealised filter and sand/bentonite geometry	C-3
C.2	S02 gas volume and “water level”	C-6
C.2.1	S02 filter pulse tests.....	C-6
C.2.2	Sinusoidal rate gas-injection tests in S02	C-6
C.2.3	Responses in other piezometers.....	C-8
C.2.4	Differential pressure across S02 and water level.....	C-9
C.3	S14 gas volume and “water level”	C-13
C.3.1	S14 filter pulse tests.....	C-13
C.3.2	Sinusoidal volumetric extraction S14.....	C-14
C.4	Summary.....	C-14
C.4.1	S02 gas and water volume	C-14
C.4.2	S14 gas and water volumes.....	C-16
App. D	Hydraulic index testing (PPEs).....	D-1
D.1	Results of PPE index testing.....	D-1
D.2	Interpretation of PPE index testing.....	D-4
App. E	Gas tracers.....	E-1
E.1	Results from gas tracer injection and sampling.....	E-1
E.1.1	Dipole test and baseline dissolved gas content.....	E-1
E.2	Gas tracer measurements	E-4
E.2.1	Injected gas mix samples.....	E-4
E.2.2	S14 extraction samples	E-5
E.2.3	PPE samples	E-10
E.3	Interpretation of gas tracer data	E-15
E.3.1	Methane and PPE_S03_L6L-1	E-17

App. F	TDR data	F-1
F.1	Introduction	F-1
F.1.1	Potential mechanisms for water content change around TDRs	F-6
F.1.2	Time periods for gas and water injections.....	F-6
F.1.3	Adjustment of TDR traces for drift/shift over time	F-8
F.1.4	Travel time calculation	F-8
F.2	TDR stability prior to the GFT	F-9
F.2.1	Assessment of stability/reliability.....	F-9
F.3	TDP responses during the GFT	F-14
F.3.1	TDP sensors showing instability during gas injection.....	F-15
F.3.2	TDP sensors showing changes during gas injection.....	F-17
F.4	TDL sensor responses during gas injection	F-23
F.5	TDR responses during the water injection phase (Phase 11).....	F-29
F.5.1	TDP sensors showing changes during water injection (Phase 11)	F-29
F.5.2	TDL sensor responses during water injection (Phase 11).....	F-31
F.6	Summary.....	F-37
App. G	Geosphere and drainage data	G-1
G.1	Geosphere pressure.....	G-1
G.2	Geosphere drainage	G-4
App. H	Effective properties for sand/bentonite and gas path.....	H-1
H.1	Hydraulic conductivity/permeability	H-1
H.2	Gas path effective properties	H-2
H.2.1	Instantaneous gas recovery	H-2
H.2.2	Effective permeability×area.....	H-2

List of Tables

Tab. 1-1:	GFT phase start dates, durations and gas mixes	4
Tab. 1-2:	GFT compositions for gas mix and nitrogen injections.....	5
Tab. 2-1:	GAST construction materials pore volumes and water required for full saturation	9
Tab. 2-2:	Sensor counts and abbreviations of the GAST engineered barrier system (EBS)	10
Tab. 2-3:	GAST instrumentation status as of 01.05.22	11
Tab. 2-4:	Saturation indicators prior to GFT (01.05.22) for seal section sand/ bentonite and GBM.....	21
Tab. 2-5:	Total pressure (kPa) values on 01.05.22.....	22
Tab. 2-6:	Estimated effective stress (kPa) on 01.05.22.....	23
Tab. 2-7:	Pore pressure (kPa abs) values on 01.05.22.....	24
Tab. 2-8:	Baseline estimate of dissolved gas in sand/bentonite porewater	25
Tab. 3-1:	Pore pressure (kPa abs) values on 06.05.22 at 00:00.....	35
Tab. 3-2:	Pore pressure change (kPa) from 01.05.22 00:00 to 06.05.22 00:00.....	35
Tab. 3-3:	Pore pressure (kPa abs) values on 12.05.22 at 00:00.....	36
Tab. 3-4:	Pore pressure change (kPa) from 12.05.22 00:00 to 06.05.22 00:00.....	36
Tab. 3-5:	Total pressure (kPa) values on 06.05.22 at 00:00.....	38
Tab. 3-6:	Total pressure (kPa) change from 01.05.22 00:00 to 06.05.22 00:00.....	38
Tab. 3-7:	Total pressure (kPa) values on 12.05.22 at 00:00.....	39
Tab. 3-8:	Total pressure (kPa) change from 01.05.22 00:00 to 12.05.22 00:00.....	39
Tab. 4-1:	Pore pressure (kPa abs) values on 01.12.22 at 00:00.....	50
Tab. 4-2:	Pore pressure change (kPa) from 01.05.22 00:00 to 01.12.22 00:00.....	50
Tab. 4-3:	Total pressure (kPa) values on 01.12.22 at 00:00.....	54
Tab. 4-4:	Total pressure (kPa) change from 01.05.22 00:00 to 01.12.22 00:00.....	54
Tab. 4-5:	Gas path summary GFT Phases 3 – 5 (Gas Mix #1 06.05.22 – 01.12.22).....	60
Tab. 4-6:	Estimates of unrecovered free gas mass	62
Tab. 4-7:	Estimates of unrecovered dissolved gas mass	62
Tab. 5-1:	Pore pressure (kPa abs) values on 18.04.23 at 00:00.....	67
Tab. 5-2:	Pore pressure change (kPa) from 01.05.22 00:00 to 18.04.23 00:00.....	67
Tab. 5-3:	Total pressure (kPa) values on 18.04.23 at 00:00.....	69
Tab. 5-4:	Total pressure (kPa) change from 01.05.22 00:00 to 18.04.23 00:00.....	69
Tab. 5-5:	Flow rate changes at end of Phase 7	73
Tab. 5-6:	Gas path summary GFT Phases 6 and 7 (N ₂ Flush #1 01.12.22 – 18.04.23).....	76
Tab. 6-1:	Pore pressure (kPa abs) values on 01.09.23 at 00:00.....	81

Tab. 6-2:	Pore pressure change (kPa) from 01.05.22 00:00 to 18.04.23 00:00	81
Tab. 6-3:	Total pressure (kPa) values on 18.04.23 at 00:00	83
Tab. 6-4:	Total pressure (kPa) change from 01.05.22 00:00 to 18.04.23 00:00	83
Tab. 6-5:	Gas path summary GFT Phases 8 and 9 (Gas Mix #2 and N ₂ Flush #2 18.04.23 – 01.09.23)	86
Tab. 7-1:	Phase 10 flow steps	87
Tab. 7-2:	Phase 11 flow steps	89
Tab. 7-3:	Pressure difference across seal at end of Phase 10 step tests	97
Tab. 7-4:	RW tests in selected PPEs (27.10.23)	98
Tab. 7-5:	Gas path summary GFT Phase 10 (N ₂ step-rate injection tests 01.09. – 22.09.23)	104
Tab. 7-6:	Gas path summary GFT Phase 11 reverse flow step	104
Tab. 7-7:	Residual gas volumes	105
Tab. 8-1:	Comparison of GPT1 and the GFT	119
Tab. 8-2:	Gas and water volumes and recovery at the end of Phase 10	121
Tab. A-1:	Port lines, piezometers and differential pressure gauges	A-12
Tab. B-1:	Injected gas composition from laboratory sampling of gas bundles	B-1
Tab. B-2:	Mass balance workbooks	B-2
Tab. B-3:	Summary of flow measurement uncertainty	B-5
Tab. C-1:	Gas volume estimation methods	C-2
Tab. C-2:	Filter pulse tests	C-5
Tab. C-3:	Volume calculation during W-GX (Phase 2) between 02.05.22 and 06.05.22 11:22	C-7
Tab. C-4:	Gauge offsets and elevation for PPE_S02_L1 and PL_S02_L6L-1	C-10
Tab. C-5:	S02 fluid flow during G-WX	C-15
Tab. C-6:	Estimated gas volume in S14 during the GFT	C-17
Tab. D-1:	Hydraulic index test campaigns, prior to, during and after the GFT	D-1
Tab. E-1:	Water sources for saturation of the GAST seal section	E-2
Tab. E-2:	Dipole test dissolved gas content and baseline estimate	E-3
Tab. E-3:	Specified GFT gas mix volume fractions	E-4
Tab. E-4:	Definition of GFT gas mixes used in this interpretation study based on laboratory analyses results	E-4
Tab. E-5:	Initial selection of PPEs for sampling during the GFT (June 2022)	E-10
Tab. E-6:	PPEs sampled during the GFT	E-12
Tab. E-7:	Summary of PPE gas sampling during Gas Mix #1 and Gas Mix #2 injection	E-15
Tab. F-1:	Position and length of the TDL and TDP sensors	F-5

Tab. F-2:	Possible mechanisms for water content change during the GFT	F-6
Tab. F-3:	Summary of the stability/reliability of TDPs and TDLs.....	F-13
Tab. F-4:	Summary of TDP sensors showing changes during the GFT	F-21
Tab. G-1:	Borehole interval mid-points around GAST.....	G-2
Tab. H-1:	Effective hydraulic properties of the sand/bentonite (GAST in-situ experiment).....	H-1
Tab. H-2:	Cross-section area of sand/bentonite	H-3

List of Figures

Fig. 1-1:	3D view of the Grimsel Test Site showing the location of GAST in the WT drift	1
Fig. 1-2:	Vertical sections of the “as-built” GAST in situ experiment.....	3
Fig. 1-3:	Timeline of GFT phases, injected gases, and relationship to the chapters (Ch) in this report	4
Fig. 1-4:	Plotting colour and coordinate system conventions used in this report.....	7
Fig. 2-1:	Timing of last useful recorded data from RH sensors at L6 and in GBM (L7, L8).....	11
Fig. 2-2:	Estimated pore volume in sand filters above a level	13
Fig. 2-3:	Flow and pressure history of the GAST in-situ experiment from 01.07.12 to 01.05.22, prior to the GFT	14
Fig. 2-4:	Flow and pressure history of GAST during equilibration period (01.12.12 to 01.05.22), prior to the start of the GFT	15
Fig. 2-5:	Pressure profile along GAST prior to the GFT (01.05.22).....	16
Fig. 2-6:	Pressure distribution prior to the GFT (01.05.22)	17
Fig. 2-7:	Cumulative water injection and pressure history from 01.07.12 to 01.05.22	18
Fig. 2-8:	RH measurements in GBM headspace (11.07.12 to 01.05.22).....	20
Fig. 2-9:	Summary of pre-GFT saturation state	20
Fig. 3-1:	W-GX in S02 – volumes and rates	27
Fig. 3-2:	S14 extraction and S02 injection with selected pressure measurements during the W-GX	28
Fig. 3-3:	Pressure profile along GAST on 01.05.22 (hollow symbols) and 06.05.22 (solid symbols).....	29
Fig. 3-4:	Profile of pressure change between 01.05.22 and 06.05.22 along GAST	30
Fig. 3-5:	Pore pressure during GFT Phases 2 and 3	31
Fig. 3-6:	Change in pressure during GFT Phases 2 and 3	32
Fig. 3-7:	Pore pressure distribution on a) 01.05.22, b) 06.05.22 and c)15.05.22	33
Fig. 3-8:	Change in total pressure during GFT Phases 2 and 3	37
Fig. 3-9:	Change in pore pressure from 01.05.22 at L6.....	41
Fig. 3-10:	Change in pore pressure from 01.05.22 at L4.....	41
Fig. 3-11:	Comparison of change in pore pressure from 01.05.22 for PPEs and TPW at L4	42
Fig. 3-12:	Schematic vertical section showing pore pressure changes related to gas flow path from 03.05. to 08.05.22	42
Fig. 3-13:	Schematic vertical section showing pore pressure change from 01.05.22 to 03.05.22 13:00	43

Fig. 3-14:	Schematic vertical section showing total pressure change from 01.05.22 to 03.05.22 13:00	43
Fig. 3-15:	Schematic vertical section showing measured pore pressure at 02.05.22 21:00	44
Fig. 3-16:	Schematic vertical section showing pressure difference relative to S02 at 02.05.22 21:00	44
Fig. 4-1:	S02 injection and S14 extraction rates during GFT Phases 4 and 5	46
Fig. 4-2:	Average volumetric flow rates and filter pressure during GFT Phases 4 and 5.....	46
Fig. 4-3:	Pressure profile along GAST ON 01.05.22 and 01.12.22	48
Fig. 4-4:	Profile of change in pressure between 01.05.22 and 01.12.22 along GAST.....	48
Fig. 4-5:	Pressure profile on 01.12.22 and simple 1D flow model profiles	49
Fig. 4-6:	Pore pressure during GFT Phases 2 – 5	51
Fig. 4-7:	Change in pressure during GFT Phases 2 – 5	52
Fig. 4-8:	Change in total pressure during GFT Phases 4 and 5	53
Fig. 4-9:	S14 (PL_S14_L1) and PPE traced gas fractions during Phases 2 – 5	56
Fig. 4-10:	S02 injection and S14 extraction rates during the early part of GFT Phase 4 (up to 12.06.22)	57
Fig. 4-11:	Smoothed S13 TDL travel time from start of the GFT to 12.06.22.....	58
Fig. 4-12:	S14 water level (left) evolution from TDL and (right) sketch of gas accumulation when the gas breakthrough took place on 08.06.22	58
Fig. 4-13:	Flow and filter pressure shut-in and restart (30.07.22 12:35 – 03.08.22 07:34).....	59
Fig. 5-1:	Filter pressure, flow rates and S14 water fraction during Phases 6 and 7	63
Fig. 5-2:	Pressure profile across seal section during Phases 6 and 7.....	64
Fig. 5-3:	Pore pressure during Phases 6 and 7.....	65
Fig. 5-4:	Change in pore pressure during Phases 6 and 7 from the start of the GFT (01.01.22)	66
Fig. 5-5:	Change in total pressure from start of the GFT during Phases 6 and 7	68
Fig. 5-6:	S14 (PL_S14_L1) and PPE traced gas fractions during Phases 6 and 7	70
Fig. 5-7:	Filter pressure and flow rates during shut-in and resumption of flow	71
Fig. 5-8:	Filter pressure and flow rates following the rate change on 22.03.2023	72
Fig. 5-9:	Pressure change following the rate change on 22.02.2023	74
Fig. 6-1:	Filter pressure and injection and extraction flow rates during Phases 8 and 9	77
Fig. 6-2:	Pressure distribution across seal sections during Phases 8 and 9	78
Fig. 6-3:	PPE_S08_L4 change in response due to sampling.....	78

Fig. 6-4:	Pore pressure during Phases 8 and 9.....	79
Fig. 6-5:	Pore pressure change from start of the GFT (01.01.22) during Phases 8 and 9	80
Fig. 6-6:	Total pressure change from 01.05.22 during Phases 8 and 9.....	82
Fig. 6-7:	S14 (PL_S14_L1) and PPE traced gas fractions during Phases 8 and 9	84
Fig. 7-1:	S02 and S14 filter boundary conditions during Phase 10	88
Fig. 7-2:	S02 and S14 filter boundary conditions during Phase 11	90
Fig. 7-3:	Gas extraction from PPE_S03_L6L-1 and PPE_S06_L6H-2.....	91
Fig. 7-4:	Pressure distribution across seal prior to and during Phase 10 flow Step #1	91
Fig. 7-5:	Pressure distribution across seal during reverse flow period (Phase 11).....	92
Fig. 7-6:	Pore pressure during Phases 10 and 11.....	93
Fig. 7-7:	Change in pore pressure since the start of the GFT during Phases 10 and 11	94
Fig. 7-8:	Change in total pressure since the start of the GFT (01.05.22) during Phases 10 and 11.....	95
Fig. 7-9:	Pressure across seal section (PPE_S02_L1-PPE_S14_L1) during Phase 10 step tests	96
Fig. 7-10:	Pressure, flow and estimated effective gas permeability×area during step-rate tests	98
Fig. 7-11:	S02 and S14 filter boundary conditions during the GFT Phase 11 reverse flow period	99
Fig. 7-12:	Pressure across seal section (PPE_S02_L1-PPE_S14_L1) during Phase 11 reverse flow period.....	100
Fig. 7-13:	Pore pressure in seal section at L4 during Phase 11 reverse flow period.....	101
Fig. 7-14:	Pore pressure in seal section at L6 during Phase 11 reverse flow period.....	101
Fig. 7-15:	Evolution of water level in S14 sand filter as interpreted from TDL data.....	102
Fig. 7-16:	Situation in S14 filter on 11.11.23 at 06:00 as interpreted from TDL data.....	102
Fig. 8-1:	Pressure change (from 01.05.22) during the S02 W-GX and early gas injection for the L4 and L6 piezometers.....	110
Fig. 8-2:	Total pressure measurements since 01.05.22.....	111
Fig. 8-3:	Summary of S13 TDL responses to drainage and resaturation.....	112
Fig. 8-4:	Schematic vertical section showing sensor observations during the GFT related to gas path location.....	113
Fig. 8-5:	Vertical section illustrating the concept for the GFT gas path	114
Fig. 8-6:	Flow rates (centre) and pressures (bottom) up to the end of GFT Phase 10, together with effective permeability × area and instantaneous recovery (top)	115

Fig. 8-7:	Schematic vertical section showing pressure profile and breakthrough pressures on 02.05.22 at 21:00	116
Fig. 8-8:	RH and temperature from operating RH sensors during the GFT	117
Fig. A-1:	Overview of GAST sections	A-1
Fig. A-2:	Photographs of selected piezometers upon emplacement in a) L4 and b) L6	A-11
Fig. C-1:	S02 estimated gas volume and injection rate.....	C-1
Fig. C-2:	Idealised sand filter and sand/bentonite cross-section	C-3
Fig. C-3:	S02 estimated gas volume and injection rate.....	C-7
Fig. C-4:	FFT analysis of gas injection flow and selected piezometers in S03	C-8
Fig. C-5:	Differential pressure measurements in S02. Figure shows the “idealised” water level.....	C-9
Fig. C-6:	Differential pressure in S02 from DP-4 and calculated pressure difference	C-11
Fig. C-7:	Estimated pore volume in sand filter above a level. Assumes uniform porosity and as-built geometry	C-12
Fig. C-8:	Calculated water level from S02 pressure difference	C-13
Fig. C-9:	Estimated gas volumes for S02 and S14 during the GFT	C-15
Fig. C-10:	S14 extraction gas/water fraction, gas, water and total extraction rate and cumulative volumes	C-16
Fig. D-1:	Timeline of index testing during GFT phases	D-2
Fig. D-2:	Time histories of PPE compressibility from index testing for L2, L3, L4 and L6.....	D-2
Fig. D-3:	Time histories of PPE compressibility from index testing for L2, L3, L4 and L6.....	D-3
Fig. D-4:	Time histories for selected PPEs of compressibility and pore pressure	D-4
Fig. D-5:	Spatial pattern of PPE compressibility from index testing a) prior to the GFT and b) at the end of the GFT on 30.11.23.....	D-5
Fig. D-6:	Evolution of spatial pattern of PPE compressibility from index testing for all campaigns.....	D-9
Fig. E-1:	WT drift and location of the ADUS 96.001 borehole (BOADUS).....	E-2
Fig. E-2:	Dipole test layout.....	E-3
Fig. E-3:	Water and gas extracted from S14.....	E-6
Fig. E-4:	Tracer gas fraction in S14 samples and from the miniRUEDI membrane module	E-7
Fig. E-5:	Tracer gas fractions in S14 samples for the breakthrough and tailing of Gas Mix #1	E-8
Fig. E-6:	Tracer gas fractions in S14 samples for the breakthrough and tailing of Gas Mix #2	E-9
Fig. E-7:	PPE_S10_L4 sampling	E-11

Fig. E-8:	Tracer gas fractions for samples from S14 and PPEs: a) Gas Mix #1, b) Gas Mix #2	E-13
Fig. E-9:	Normalised tracer gas fractions for samples from S14, PPE_S06_L6H_2 and PPE_S10_L4.....	E-14
Fig. E-10:	Location and types of gas sampling during the GFT.....	E-16
Fig. E-11:	Sample methane gas fraction during the GFT (only samples above the limit of detection).....	E-17
Fig. F-1:	TDR sensors. Left) TDLs at S13, right) TDP.....	F-1
Fig. F-2:	Cross-sectional view of the TDL sensor positions at S13	F-2
Fig. F-3:	Plan view of TDP positions in layers L2, L3, L4 and L5	F-3
Fig. F-4:	Side view of the positions of the TDLs and TDPs	F-4
Fig. F-5:	Dates for TDR traces analysed	F-7
Fig. F-6:	Adjustment of drift/shift in the traces with time.....	F-8
Fig. F-7:	Resaturation and equilibration phases prior to the GFT phases	F-9
Fig. F-8:	Stability assessment for TDP_S10_L5	F-10
Fig. F-9:	Stability assessment for TDP_S11_L5	F-10
Fig. F-10:	Summary of TDP stability/reliability: a) L5, b) L4, c) L3, d) L2.....	F-12
Fig. F-11:	Example of travel time plot for the GFT phases.....	F-14
Fig. F-12:	TDR sensor showing instability during the GFT phases (TDP_S06_L5)	F-15
Fig. F-13:	TDR sensor showing instability during the GFT phases (TDP_S09_L5)	F-16
Fig. F-14:	TDR sensor showing changes during the GFT phases (TDP_S03_L2)	F-17
Fig. F-15:	TDR sensor showing changes during the GFT phases (TDP_S06_L3)	F-18
Fig. F-16:	TDR sensor showing changes during the GFT phases (TDP_S09_L3)	F-18
Fig. F-17:	TDR sensor showing changes during the GFT phases (TDP_S10_L3)	F-19
Fig. F-18:	TDR sensor showing changes during the GFT phases (TDP_S11_L3)	F-20
Fig. F-19:	TDR sensor showing changes during the GFT phases (TDP_S10_L5)	F-20
Fig. F-20:	3D map of the TDPs that showed some changes during gas injection.....	F-23
Fig. F-21:	TDL sensor responses during the GFT phases (TDL_S13_L5-1)	F-23
Fig. F-22:	TDL sensor responses during the GFT phases (TDL_S13_L5-2)	F-24
Fig. F-23:	TDL sensor responses during the GFT phases (TDL_S13_L4-2)	F-25
Fig. F-24:	TDL sensor responses during the GFT phases (TDL_S13_L4-1)	F-25
Fig. F-25:	TDL sensor responses during the GFT phases (TDL_S13_L3-2)	F-26
Fig. F-26:	TDL sensor responses during the GFT phases (TDL_S13_L2-1)	F-27
Fig. F-27:	TDL sensor responses during the GFT phases (TDL_S13_L2-2)	F-27
Fig. F-28:	Map of gas accumulation during Phases 2, 3 and 4.....	F-28
Fig. F-29:	3D image of gas accumulation when the gas breakthrough took place on 08.06.22	F-29

Fig. F-30:	TDR sensor showing changes during the GFT phases (TDP_S10_L3)	F-30
Fig. F-31:	TDR sensor showing changes during the GFT phases (TDP_S10_L5)	F-30
Fig. F-32:	TDL sensor responses during the GFT phases (TDL_S13_L2-2)	F-31
Fig. F-33:	TDL sensor responses during the GFT phases (TDL_S13_L2-1)	F-32
Fig. F-34:	TDL sensor responses during the GFT phases (TDL_S13_L3-2)	F-32
Fig. F-35:	TDL sensor responses during the GFT phases (TDL_S13_L4-1)	F-33
Fig. F-36:	TDL sensor responses during the GFT phases (TDL_S13_L4-2)	F-33
Fig. F-37:	TDL sensor responses during the GFT phases (TDL_S13_L5-2)	F-34
Fig. F-38:	TDL sensor responses during the GFT phases (TDL_S13_L5-1)	F-35
Fig. F-39:	Map of water accumulation during Phase 11.....	F-36
Fig. F-40:	3D image of water accumulation at the end of gas displacement by water injection into S14 on 12.11.23	F-36
Fig. G-1:	Location of boreholes surrounding GAST.....	G-1
Fig. G-2:	Interval pressure from the short boreholes surrounding GAST	G-2
Fig. G-3:	Interval pressure from SB 80.003 intervals (i1,i2,i3 close to GAST).....	G-3
Fig. G-4:	Interval pressure from the SB 80.003 borehole intervals during Phases 10 and 11 of the GFT	G-4
Fig. G-5:	GAST drainage line flow, temperature and electrical conductivity during the GFT. The S02 and S14 filter pressures are shown for comparison purposes	G-5
Fig. H-1:	Sand/bentonite hydraulic conductivity from laboratory tests, in-situ estimates and small-scale PPE tests.....	H-1

List of Acronyms and Sensor Abbreviations

DAS	Data acquisition system
EBS	Engineered barrier system
EC	Electrical conductivity
GAST	Gas-permeable Seal Test
GBM	Granular bentonite Material
GFT	Gas Flow Test
GPT	Gas Property Test
GTS	Grimsel Test Site
G-WX	Gas-water exchange
L/ILW	Low-/intermediate-level waste
NAB	Nagra Work Report (<i>Nagra Arbeitsbericht</i>)
NTB	Nagra Technical Report (<i>Nagra Technischer Bericht</i>)
PL	Port line
PPE	Piezometer
RH	Relative humidity
STP	Standard temperature and pressure
TDR	Time domain reflectometer
TDL	Longitudinal TDR
TDP	Point TDR
TPB	Total pressure cell at L6 interface
TPW	Total pressure cell on tunnel wall
W-GX	Water-gas exchange
WT	Wärmetest ¹

¹ The Wärmetest was a heater test performed at GTS between 1980 and 1990. The WT drift is where GAST is performed.

1 Introduction

1.1 The Gas-permeable Seal Test

The Gas-permeable Seal Test (GAST) is an international partner project² to demonstrate the feasibility and functionality of a gas-permeable seal at realistic scale and under realistic boundary conditions. The seal was constructed of dynamically compacted 80/20 sand/bentonite (S/B) mixture and emplaced from 2011 to 2012 in the WT drift at the Grimsel Test Site (GTS; Fig. 1-1). Saturation of the seal section started in September 2012 but was interrupted by a leakage event in 2014. Saturation was restarted in August 2015 after the repairs were successfully implemented. Following almost a decade of seal saturation and pressurisation with water, the long-term Gas Flow Test (GFT) was initiated in 2022. Preparations included baseline characterisation, installation of state-of-the-art equipment to perform the gas tests and to enable quantitative hydrochemical analyses, and the establishment of a pore pressure gradient along the seal section. The GFT was planned and performed as an “end-to-end” gas flow test across the 8-m-long sand/bentonite seal section (Fig. 1-2) with gas injection into the S02 sand filter and gas extraction from the S14 sand filter. The GFT design was also based on experience from the Gas Property Test (GPT), a preliminary gas injection test focusing on the first few metres of the sand/bentonite seal (see Lanyon & Herbert 2021).

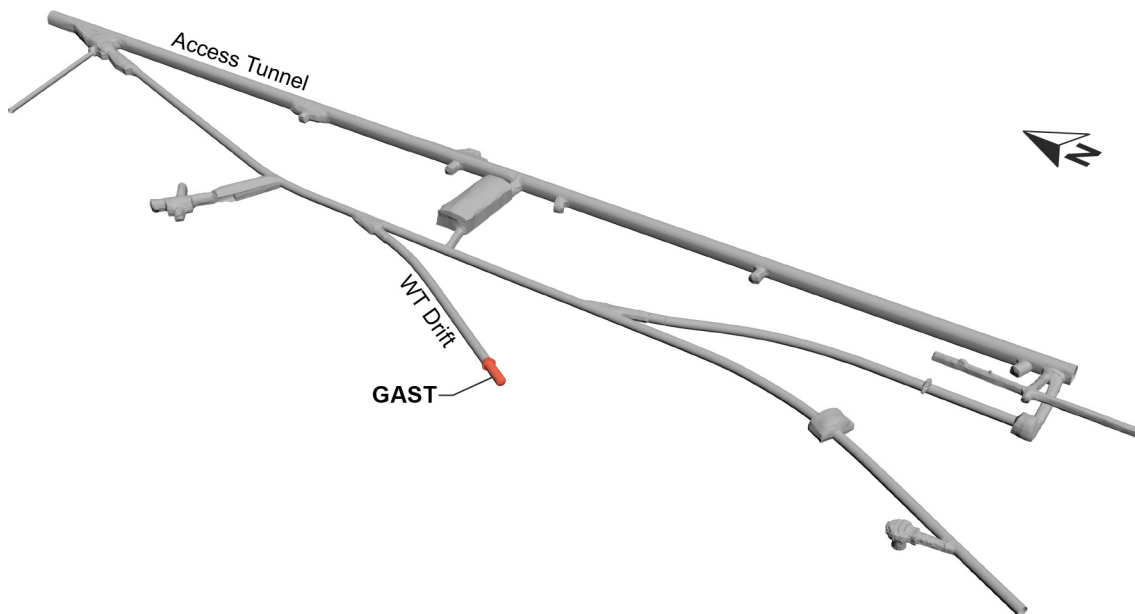


Fig. 1-1: 3D view of the Grimsel Test Site showing the location of GAST in the WT drift

² The partner organisations participating in GAST include l'Agence Nationale pour la gestion des Déchets Radioactifs (ANDRA, France), Korea Radioactive Waste Agency (KORAD, Korea), Nuclear Waste Management Organization (NWMO, Canada), and Nuclear Waste Service (NWS, UK).

1.2 Objectives

This report provides a first interpretation of the GFT. The main objectives of this interpretation are to deliver:

- a description of the main phases of the GFT,
- a first integration of the different datasets acquired during the GFT,
- a description of the creation and evolution of the gas flow path,
- a preliminary evaluation of gas transport properties.

More detailed interpretations of specific aspects of the GFT (e.g. gas tracer transport) are planned together with a wider synthesis of the project. A detailed description of the test and associated activities is given in the “GAST Gas Flow Test Data” report (Rösli et al. 2025).

1.3 GAST layout

The as-built status of the GAST in-situ experiment is fully documented in Rüedi et al. (2012).

Fig. 1-2 shows the “as-built” geometry of the main components of the GAST system:

- 8-m-long 80/20 sand/bentonite (S/B) section providing a gas-permeable seal. The sand/bentonite was emplaced and then compacted into 10-cm-thick horizontal layers,
- granular bentonite material (GBM) surrounding the sand/bentonite in a 25-cm-thick ring space and a 95-cm-thick (at its maximum height) headspace,
- sand filters (S02 and S14) at each end of the seal section for water and gas injection,
- concrete plug confining the seal section with two upper instrumentation ducts,
- bentonite block walls sealing the ends of the filters from the concrete wall at the end of the tunnel and the concrete plug,
- instrument risers at sections along the sand/bentonite carrying lines and cables from sensors in the sand/bentonite and granular bentonite into the main duct,
- main duct carrying lines and cables from the instrumentation beneath the plug in a square-section slot cut into the rock, and
- wellhead (installed in 2015) providing a pressure seal for the main duct with access to lines and cables.

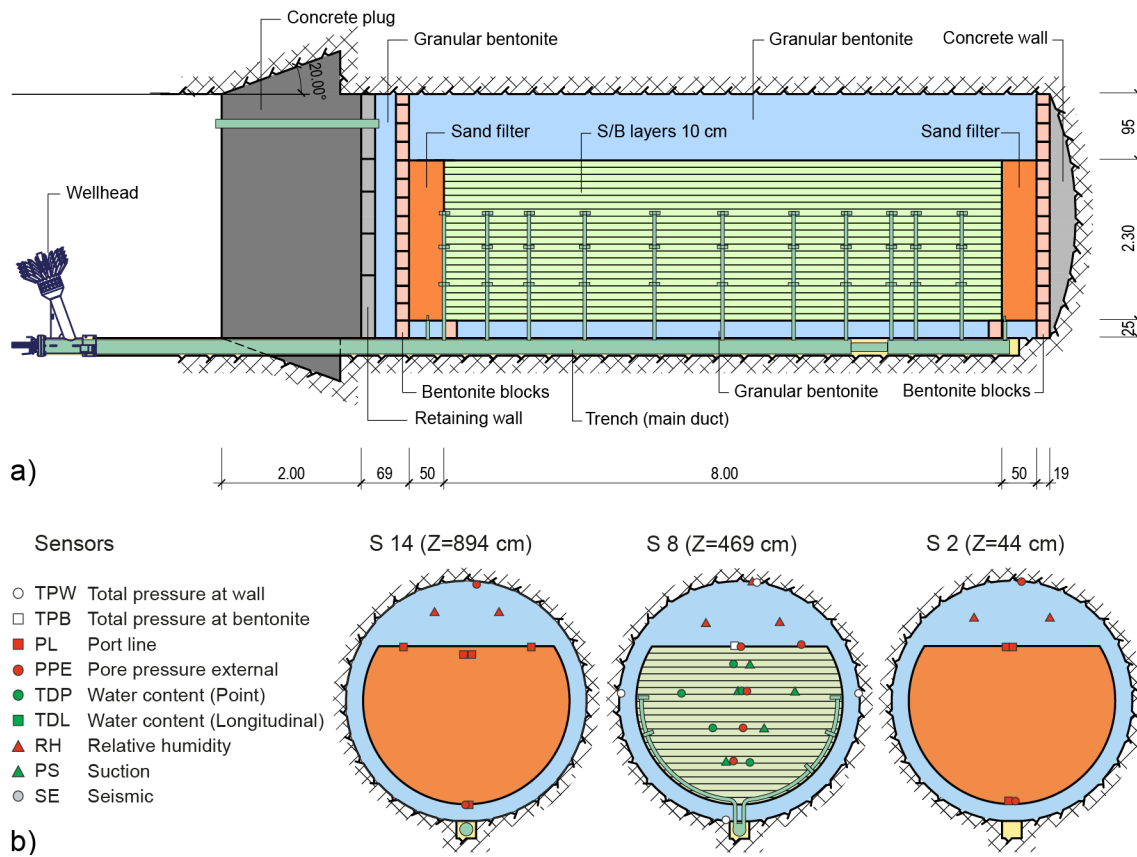


Fig. 1-2: Vertical sections of the “as-built” GAST in situ experiment

a) axial section; b) cross-sections of the sand filters (S14 and S02) and instrumentation section S08.

Diagrams of all the instrumentation sections (S01 to S17) are provided in App. A.

1.4 Gas Flow Test timeline

For the GFT, a set of test phases was defined to facilitate its documentation and interpretation. The phase listing in Tab. 1-1 includes a preparatory test (Phase 1), gas injection (Phases 2 – 10), and a reverse flow test (Phase 11) before the start of resaturation. Effective gas testing ran for over 624 days from the start of gas injection on 02.05.22³, to the start of resaturation on 16.01.24. Most phases represent distinct changes in the boundary conditions applied to the test (e.g. changes of gas tracer or injection conditions). The relatively short Phases 2 and 3 reflect periods of intense operational work involving reactions and decisions on a day-to-day basis. Once gas flow stabilised (Phase 4), regular weekly field team meetings were considered appropriate, and the phase durations were extended.

This report is organised around the phases listed in Tab. 1-1 and shown in Fig. 1-3.

³ The GFT started with the water-gas exchange (W-GX) in the S02 sand filter.

Tab. 1-1: GFT phase start dates, durations and gas mixes

Start	Name	Day of GFT	Duration [days]	Injection	Focus
15.03.22 13:39	Phase 1: Filter water exchange / pulse testing		47.8	H ₂ O	Preparation
02.05.22 08:00	Phase 2: Water-gas exchange (Gas Mix #1)	0	4.1	Gas Mix #1	Demonstration of gas transport through S/B
06.05.22 11:22	Phase 3: Stepwise gas pressure increase	4.1	6.1		
12.05.22 12:50	Phase 4: Stabilisation of gas flow	10.2	33.8		
15.06.22 08:34	Phase 5: Sampling in stable gas flow path	44.0	168.9		
01.12.22 07:05	Phase 6: Flush flow path with N ₂	213.0	83.3	N ₂	Removal of tracer
22.02.23 13:21	Phase 7: Pressure gradient adjustment	296.2	54.7	N ₂	Reduction of flow
18.04.23 07:20	Phase 8: Gas Mix #2	351.0	72.2	Gas Mix #2	
29.06.23 12:16	Phase 9: N ₂ Flush	423.2	64.0	N ₂	
01.09.23 11:00	Phase 10: Shut-in and step-rate tests	487.2	60.9	N ₂	Path diagnostics
01.11.23 10:00	Phase 11: Reverse flow, S02 G-WX, gas extraction	548.1	76.1	N ₂	Removal of gas
16.01.24 12:04	Resaturation (S02 injection)	624.2		H ₂ O	Resaturation

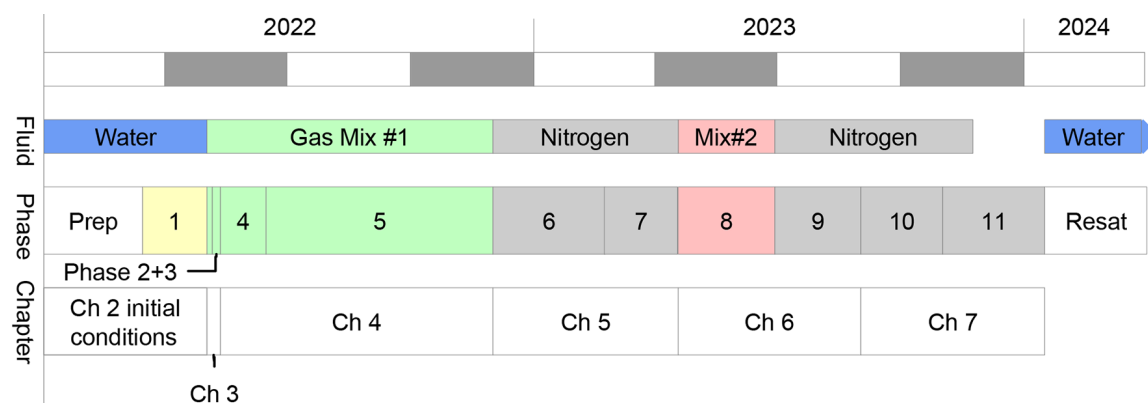


Fig. 1-3: Timeline of GFT phases, injected gases, and relationship to the chapters (Ch) in this report

The GFT can also be considered in terms of the different gas tracer injections (this approach is taken in Rösli et al. 2025). The compositions of the injected gases / gas tracer mixes are listed in Tab. 1-2 showing the volume fractions of the component gases (see App. E for details). The use of gas tracers in the GFT was an important aspect of the demonstration of gas transport through the seal section. Previously, a preliminary gas injection test (GPT1) had been performed using only nitrogen injection (see Lanyon & Herbert 2021), thereby maintaining the natural background of tracer concentration. Furthermore, GPT1 focused on the area near the sand filter (S02) and was not an end-to-end test.

The GFT phases and gas mixes injected are shown in Fig. 1-3.

Tab. 1-2: GFT compositions for gas mix and nitrogen injections

Gas	Start of injection	N ₂ [vol.%]	He [vol.%]	Ar [vol.%]	Xe [vol.%]
Gas Mix #1	02/05/2022 08:00	97.9%	2.07%	0.0%	0.00%
N ₂ #1	01/12/2022 07:05	99.9%	0.00%	0.1%	0.00%
Gas Mix #2	18/04/2023 07:20	73.2%	10.1%	16.7%	0.09%
N ₂ #2	29/06/2023 12:16	99.9%	0.02%	0.1%	0.00%

1.5 Conventions

1.5.1 GAST local reference coordinate system

A local reference coordinate system was established for GAST with its origin at floor level at the rear of the tunnel (see Fig. 1-4 for graphical representation). The axes were defined as:

- “horizontal cross” (X_{GAST}): horizontal distance from the tunnel axis to a point in the tunnel (-1.75 to +1.75 m),
- “vertical distance” (Y_{GAST}): distance (elevation) from the tunnel floor to a point in the tunnel (0.00 to + 3.50 m),
- “longitudinal” (Z_{GAST}): distance from the end of the S/B section to a point in the tunnel (0.00 to +10.00 m), Z_{GAST} points 30.6° east of north.

The relationship to Swiss grid coordinates was established using two survey points in the floor of the WT drift.

1.5.2 GAST instrumentation

Sensors and sampling points in the experiment are arranged at instrument vertical sections (typically corresponding to the instrument risers shown in Fig. 1-4) and levels defined during the experiment design (Rüedi et al. 2011). Within this report, most figures follow the colour conventions shown in Fig. 1-4. Where data from a single level are plotted, sensor data are coloured using the convention shown in Fig. 1-4a. Where data from a single section are plotted, sensor data are coloured using the convention shown in Fig. 1-4b.

Most sections in the sand/bentonite contain piezometers, time domain reflectometers (TDRs), relative humidity sensors (in GBM) and psychrometers (see Section 2.2). Two sections in the sand/bentonite are instrumented differently. Section S05 contains a seismic array that is no longer operating. Section S13 (the contact of the sand/bentonite and the geotextile containing the S14 sand filter) is equipped with longitudinal TDRs (TDLs) to monitor filter saturation.

1.6 Report structure

The rest of this report is organised as follows:

- Chapter 2 describes the state of the in-situ test at the start of the GFT (i.e. the initial conditions),
- Chapter 3 covers GFT Phases 2 and 3: W-GX and the start of injection of Gas Mix #1,
- Chapter 4 covers Phases 4 and 5: injection of Gas Mix #1 in a stable gas path with sampling,
- Chapter 5 covers Phases 6 and 7: first N₂ flush and switch to a controlled injection rate,
- Chapter 6 covers Phases 8 and 9: injection of Gas Mix #2 and second N₂ flush,
- Chapter 7 covers Phase 10 and 11: flow path diagnostics and degassing,
- Chapter 8 is a summary of the overall interpretation,
- Chapter 9 provides conclusions and recommendations.

A series of appendices provide summary descriptions of particular datasets.

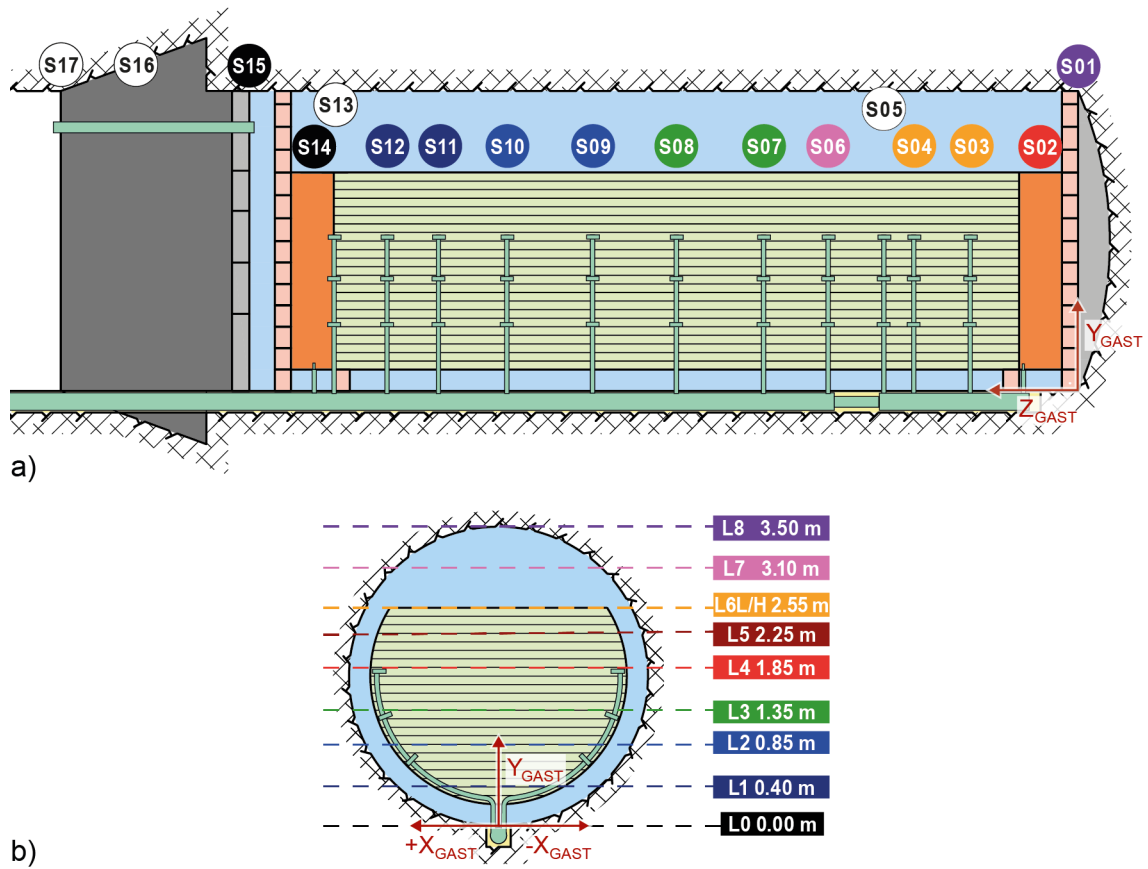


Fig. 1-4: Plotting colour and coordinate system conventions used in this report

a) colour by instrument section, b) colour by instrument level

2 Conditions prior to the GFT

2.1 GAST layout and materials

The main construction components of the GAST system (Fig. 1-2) are listed in Tab. 2-1 together with their estimated volume, porosity, initial saturation and water needed for full saturation. Some S/B material parameter are derived from bulk averages from construction quality control measurements (dry density: $1.65 - 1.73 \text{ g/cm}^3$, water content: 10.3 – 11.7%; Rüedi et al. 2012). Additional uncertainties on the volumes, porosity and initial saturation, as set out in Appendix B of Lanyon & Senger (2015), are not considered in the results for this report.

Tab. 2-1: GAST construction materials pore volumes and water required for full saturation
Bottom of Layer 1 is ~0.25 m above Level L0 (Fig. 1-4).

Material	Component	Volume [m ³]	Porosity [%]	Pore volume [m ³]	Initial saturation [%]	Water needed [m ³]
Sand/ gravel	Filter	5.74	39	2.25 ⁴	0.03	2.25
Bentonite blocks	Walls	3.66	37	1.36	68	0.44
Granular bentonite	Wall	2.89	46	1.32	31	0.91
	Ring space	15.90	46	7.28	31	5.04
	Headspace	19.00	46	8.80	30	6.15
	Total	37.79		17.40		12.11
Sand/ bentonite	Layer 1 – Layer 28	45.89	35 – 38	16.01 – 17.45	45 – 51	7.82 – 9.65

2.2 GAST instrumentation

GAST was instrumented with many sensors to monitor the sealing behaviour during water saturation and gas transport in the subsequent gas injection phase. Additional sensors monitor the hydraulic effects in the host rock and the curing and deformation of the concrete plug. Sensors in the seal section are connected to the data acquisition system (DAS) via instrumentation risers located at instrumentation sections S03 to S13. Additional instrumentation sections are located in

⁴ The filter pore volume given here is the total for the two filters at emplacement. Initial saturation of S14 required ~1,100 l of water showing good agreement with this estimate. Experience from GPT1 (Lanyon & Herbert 2021) suggests that the gas-accessible porosity in S02 is ~50% of that given here, due to compaction of the filters and invasion by the adjacent walls of highly compacted bentonite (see Section 2.22.2.2).

the sand filters, at the end of the tunnel (S01) and plugs (S15, S16, S17) as Fig. 1-4 shown in Fig. 1-4. Tab. 2-2 lists the sensors and the abbreviations used. All sensors are named according to type, section (position along tunnel) and level (elevation). The naming convention is:

TTT_Sss_Ll-n, where *TTT* is the type, *ss* is the section number (01 – 17), *l* is the level number 0 – 8 and *n* is the number when there is more than one sensor at the same section and level.

For example, TPW_S08_L4-2 is the second ($n=2$) total pressure cell on tunnel wall (TPW) in instrumentation Section *S08* at Level *L4*. App. A provides a compilation of instrumentation layouts along vertical cross-sections S01 – S17.

Tab. 2-2: Sensor counts and abbreviations of the GAST engineered barrier system (EBS)

Sensor	Type/abbreviation	Quantity
Pore pressure external (transducers linked by hydraulic lines to filters in the EBS)	PPE	39
Port lines	PL	10
Total pressure cells on tunnel wall	TPW	20
Total pressure cells at L6 interface	TPB	3
Volumetric water content probes (time domain reflectometer)	TDP/TDL	38
Seismic sensor housing	SE	34
Psychrometers	PS	30
Relative humidity sensors	RH	20
Temperature sensors	PT1000	3
Displacement sensors	DI	4
Flowmeters	FRW	3
Pressure sensors	PRE	3
Pressure sensor	Water column	1

2.2.1 Sensor status

As the construction and instrumentation of the field test was completed in 2012, some sensors had been in situ for over 10 years since the start of the GFT and were no longer operational. The sensor status as of 01.05.22 is summarised in Tab. 2-3. The majority of piezometers and total pressure cells were operational at the beginning of the GFT, while many TDRs and RH sensors stopped providing useful data. Fig. 2-1 shows the timing of last reliable data from RH sensors in the GBM head space.

Tab. 2-3: GAST instrumentation status as of 01.05.22

Sensor	Status	Comment
Piezometers and port lines	All operating (44 with transducers)	Hydraulic line saturation was assessed with index tests in March 2022 Total: 10 PL lines and 39 PPE lines.
Psychrometers	Inoperative	Lines were cut and clamped/sealed in wellhead as part of post-leak sealing operations in 2015/16
Total pressure cells	19/23 operating	Connection to the 3 TPB cells at L6 failed during post leak sealing. One TPW cell at L4 in S10 failed.
TDRs	Sensor by sensor evaluation	Some damage observed due to water invasion (see App. F).
RH sensors	2 of 20 still operating	Typically became out of range and stopped providing data as they approached 100% ⁵ RH. Two remaining sensors RH > 95%.
Seismic array (S05)	Inoperative	Disconnected after leak and subsequent sealing.

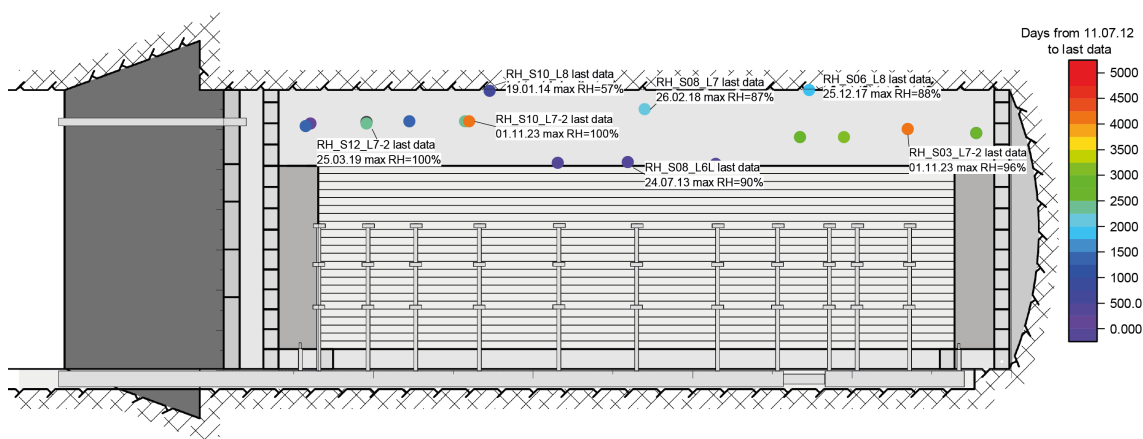


Fig. 2-1: Timing of last useful recorded data from RH sensors at L6 and in GBM (L7, L8)

Pressure measurements

Pore pressure is measured by gauges located in the WT drift connected by hydraulic lines to the piezometer filter tips within the sand/bentonite and GBM (see Appendix A.17.1). Within the tunnel the gauges were located at 1.43 to 1.9 m above the tunnel floor. At the start of GFT pulse water injection test were performed in the PPEs (see App. D) so that the hydraulic lines are expected to have been water-filled. Later during the test some hydraulic lines were desaturated during gas sampling of selected PPEs.

⁵ These RH sensors have an operating range from 0 to 95% and are known to go into “failure” mode as they approach full saturation.

Within this report, pressure is reported in kPa absolute pressure without correction for gauge height⁶. The atmospheric pressure measured in the WT drift varied between 80 and 84 kPa during the GFT.

GAST documentation

The history of the GAST in-situ experiment is documented in a series of reports covering the “as-built” state (Ruedi et al. 2012) and interpretation of the different phases (Lanyon & Senger 2015, Lanyon & Herbert 2021, Lanyon et al. 2022). A brief summary is given in Section 2.2.4. Detailed descriptions of the field activities and instrumentation are provided in a series of maintenance reports (Rösli et al. 2018a, 2018b, 2019, 2020).

2.2.2 Physical state

The bulk of the emplaced materials is expected to have remained in place during saturation, and the geometry is expected to broadly resemble the as-built layout shown in Fig. 1-2. However, the long-term saturation is likely to have resulted in some deviations from the as-built geometry and conditions listed in Tab. 2-1.

It should be noted that the 2014 leakage event (see Lanyon & Senger 2015) resulted in flushing of 30 – 40 kg of solids (primarily sand) from the seal section. Although the source of the material remained uncertain, it is believed that this material was flushed from around the S14 filter when it rapidly depressurised, likely creating locally more permeable features around the base of the S14 filter (the piezometers at L2 in S12 show a higher connectivity to the filter than those in L3 or L4, Lanyon & Senger 2015). Remediation works (van Meir et al. 2017) reestablished the overall integrity of the GAST system boundary such that it was able to withstand the required test pressures.

Changes due to saturation

The highly compacted bentonite blocks used for the sealing walls at the outer side of the two sand filters (see Fig. 1-2) are expected to have undergone significant swelling. The as-compacted block dry density of 1.69 Mg/m³ would result in swelling pressure of 8 – 10 MPa under constant volume conditions. It is therefore likely that the two sand filters will have been compacted to some extent. In addition, fine material and bentonite gel could have penetrated the geotextile surrounding the filters and filled some of the porosity. Water extraction from the S02 filter during a filter dipole test in 2017 and later during the water-gas-exchange prior to GPT1 showed suspended solids (Rösli et al. 2019) that caused problems with filter clogging. It is therefore likely that fine material is present in suspended form within the porewater and could have built up at the base of the two sand filters. Water column measurements performed during GPT1 to establish the “gas level” within the filter suggested that the gas-accessible pore volume was approximately half that expected from the porosity estimated based on the as-built data. This reduction in gas-accessible porosity is probably due to a combination of compaction and clogging of the sand filter. It is likely that the S14 filter will have undergone a similar reduction in porosity. Fig. 2-2 shows the estimated pore volume above a given level in the sand filter. Assuming 50% of the as-built porosity is accessible, there are 340 l of pore space above L3 and 558 l above L1. Deformation of the sand filter is likely to have changed both the porosity and geometry, but Fig. 2-2 provides an approximate guide to the relationship between water level in the filters and gas volume. The water levels in the two filters are important boundary conditions for gas transport. Estimates of the gas volumes in the two sand filters during the GFT are given in App. C.

⁶ Gauges installed in horizontal arrangement along the WT drift with negligible variations in height.

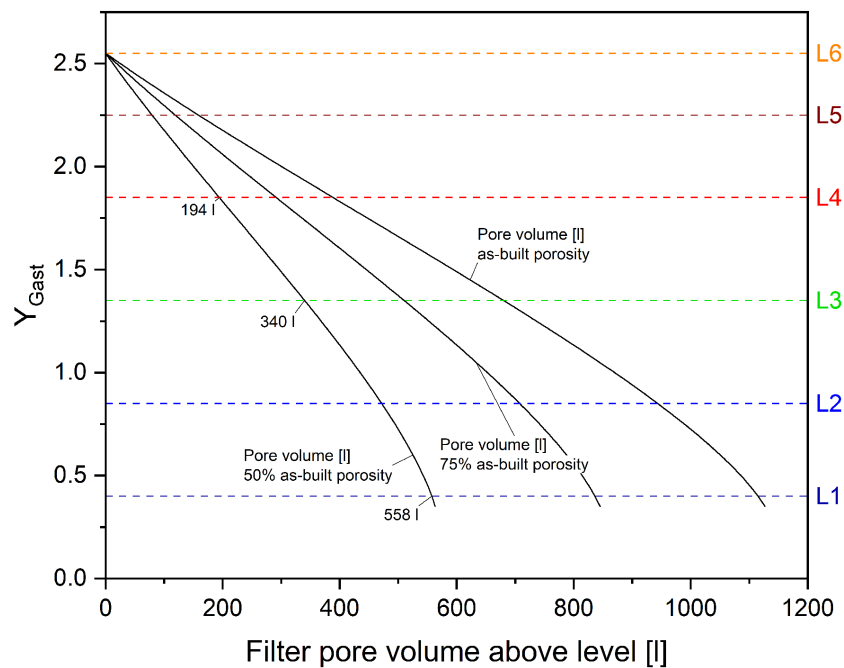


Fig. 2-2: Estimated pore volume in sand filters above a level
Assumes uniform porosity and as-built geometry.

Negligible effects of the 2014 leakage

It is believed that the main influence of the leak event in 2014 after sealing, has been on the local properties between the S14 filter and S12, particularly around the base of the sand/bentonite and the connection to the main duct, which is believed to be the source of the leakage. Locally faster pressure responses are seen in PPE_S12_L2-2, which may relate to the leak path from the filter. The impact on GFT is however believed to be minor due to the end-to-end nature of flow from S02 to S14 and the gas path location in the upper part of the sand/bentonite.

As part of the remediation works, bentonite gel was injected into the interface between the concrete bulkhead and host rock interface, providing a gas-tight boundary against the open WT drift.

2.2.3 Water injection and pressure evolution

Fig. 2-3 shows the history of filter pressure and flowrates since the start of saturation in 2012. The main experimental phases are briefly discussed below (further details can be found in Lanyon et al. 2022).

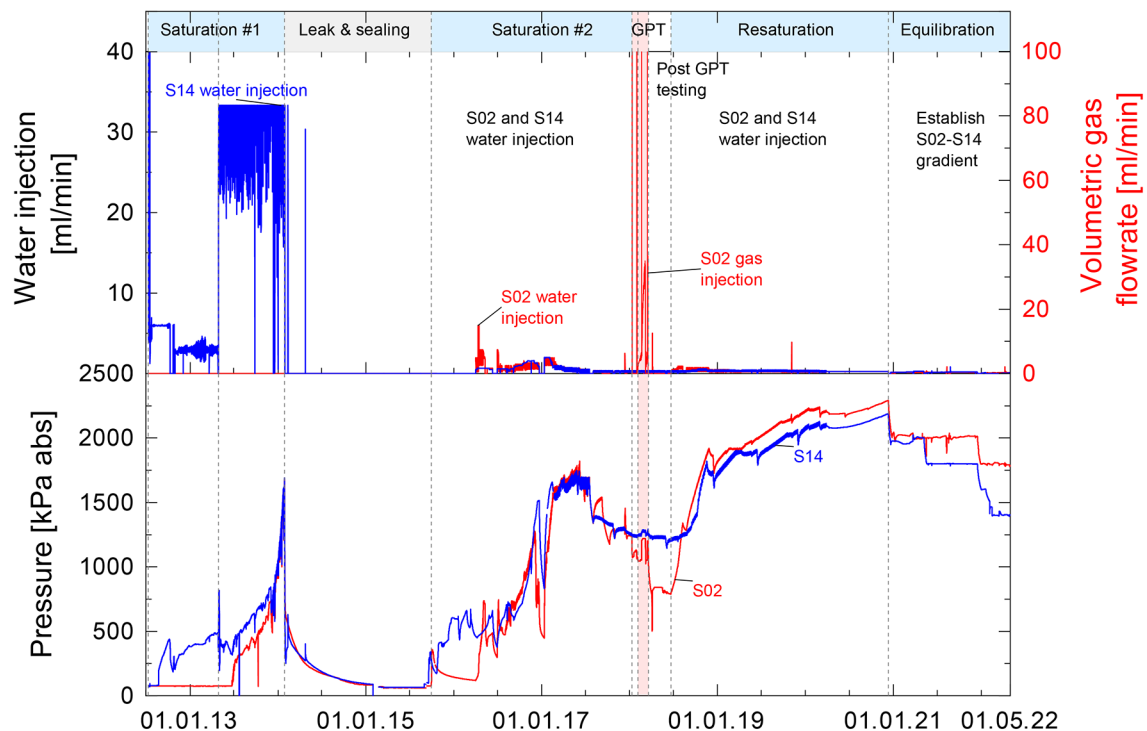


Fig. 2-3: Flow and pressure history of the GAST in-situ experiment from 01.07.12 to 01.05.22, prior to the GFT

Saturation Phase #1

Saturation Phase #1 lasted from July 2012 to the end of January 2014 and included an initial low-pressure water injection, followed by a subsequent high-pressure injection phase starting in April 2013.

Saturation Phase #1 ended on 28.01.14 when a leak of water into the WT drift occurred, resulting in a sudden drop in pressure within the sand filters and fluid outflow. Approximately 400 l of water were pumped from the sump at the end of the main duct in the WT drift. The fluid presumably originated from the S14 filter, in the vicinity of which the leak had been likely caused by a rupture of an instrumentation riser or connection element. The resulting development of a path from the filter to the rupture rapidly desaturated the S14 sand filter and depressurised the GAST materials. It was estimated that the produced water contained approximately 30 – 40 kg of suspended solids. Following investigations of the leak, a plan was developed and executed to seal the experiment by injection of bentonite gel (expansive bentonite gel) into the main duct and risers, and the installation of a wellhead to seal the main duct. Bentonite gel was also injected into the bulkhead-host rock interface.

Saturation Phase #2

Saturation Phase #2 started in September 2015 with water injection into the two sand filters. The objectives were to:

- identify any high-conductivity zones that might have been created during saturation and the leakage event,

- determine and characterise the EBS (including saturation state),
- achieve a controlled saturation of the buffer prior to gas injection.

Saturation Phase #2 continued until December 2017 with water injection rates below 2 ml/min with pressure in both filters reaching 1,600 kPa by the end of 2017. At this point, it was decided that a gas injection could be safely performed at pressures between 1,000 and 1,400 kPa. Water injection into S02 continued at a constant 0.2 ml/min. Water injection into S14 used a sinusoidal rate with a mean of 0.26 ml/min until late 2017 (Fig. 2-3).

GPT1 and recovery

The Gas Property Test (GPT1) was performed between December 2017 and June 2018. The test included an initial water-gas exchange (W-GX) in the S02 filter, followed by a series of rate- and pressure-controlled nitrogen gas injections between 04.02.18 and 18.03.18. Following the short preliminary GPT1, the injection filter was resaturated and the water injection pressure (into the S02 and S14 filters) increased over the period from June 2018 to the end of 2021 (Fig. 2-3). Pressure in the two filters exceeded 2 MPa for a considerable period.

At the end of 2021, during the equilibration period, pressure in the filters was reduced in a series of steps to establish a hydraulic gradient from S02 (1,800 kPa) towards S14 (1,400 kPa). Fig. 2-4 shows the S02 and S14 filter pressures and injection rates from December 2021 to the start of the GFT. From mid-February 2022 onwards, the filter pressures were maintained at 1,800 kPa (S02) and 1,400 kPa (S14) by means of low flow injection rates (~ 0.1 ml/min).

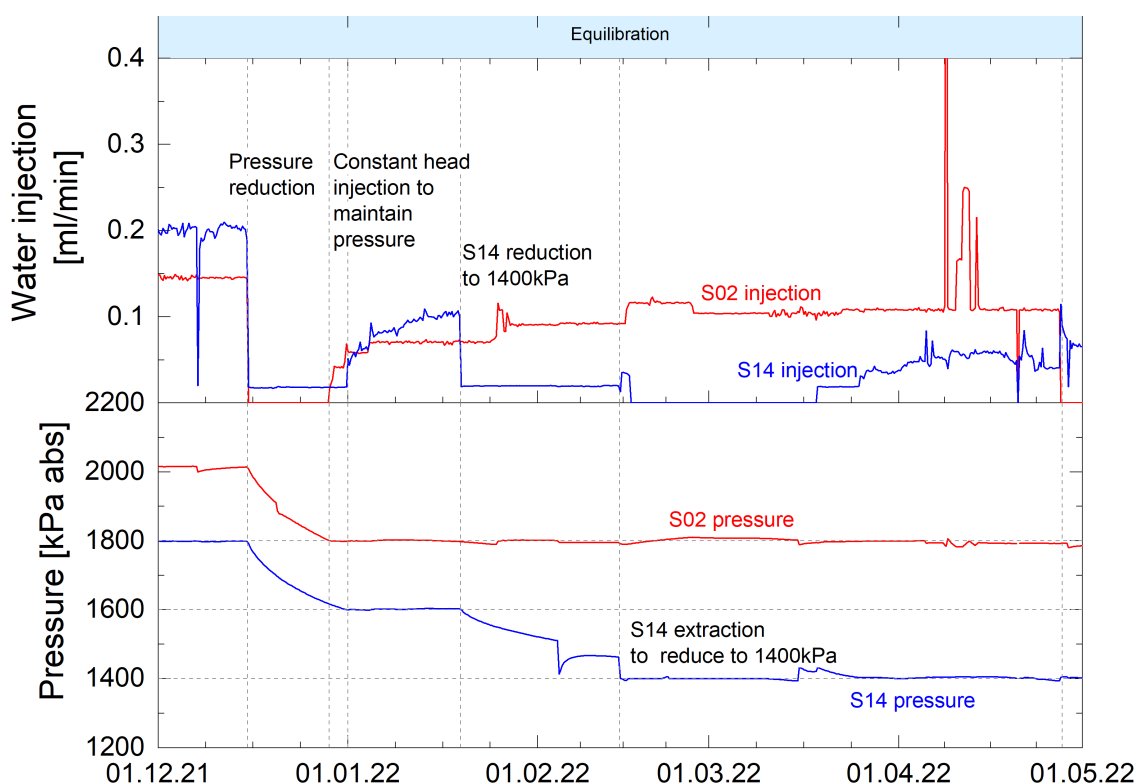


Fig. 2-4: Flow and pressure history of GAST during equilibration period (01.12.12 to 01.05.22), prior to the start of the GFT

Conditions prior to the GFT

Prior to the start of the GFT, the injection flow rate into the S02 filter was set to 0.1 ml/min on 12.04.22 and maintained at this rate until the S02 W-GX. During April 2022, the average injection rate was 0.11 ml/min and the water injection rate into S14 needed to maintain filter pressure of 1,400 kPa was <0.1 ml/min with an average injection rate of ~0.06 ml/min. Injection into S14 halted during the W-GX on 03.05.22 at 07:22.

The pressure profile along the experiment prior to the GFT (01.05.22) is shown in Fig. 2-5 and Fig. 2-6. At instrumentation levels L2, L3 and L4, a steep gradient occurs from S02 to about S08 after which the gradient becomes shallower as it approaches S14. Pressure in L4 is typically ~100 kPa lower than in L2 and L3.

Pressure in L6 is heterogeneous with no clear gradient. The pressure at the sand/bentonite-granular bentonite interfaces at L6 is highest close to the sand filters (PPE_S03_L6H-2 and PPE_S12_L6H_2), but even these sensors show a significantly lower pressure than seen in L4 at the same sections. The piezometers at L6 were emplaced differently to those in the sand/bentonite (see Section A.17.1 in App. A) and could have been subject to local variations in the GBM density, potentially resulting in pressure differences.

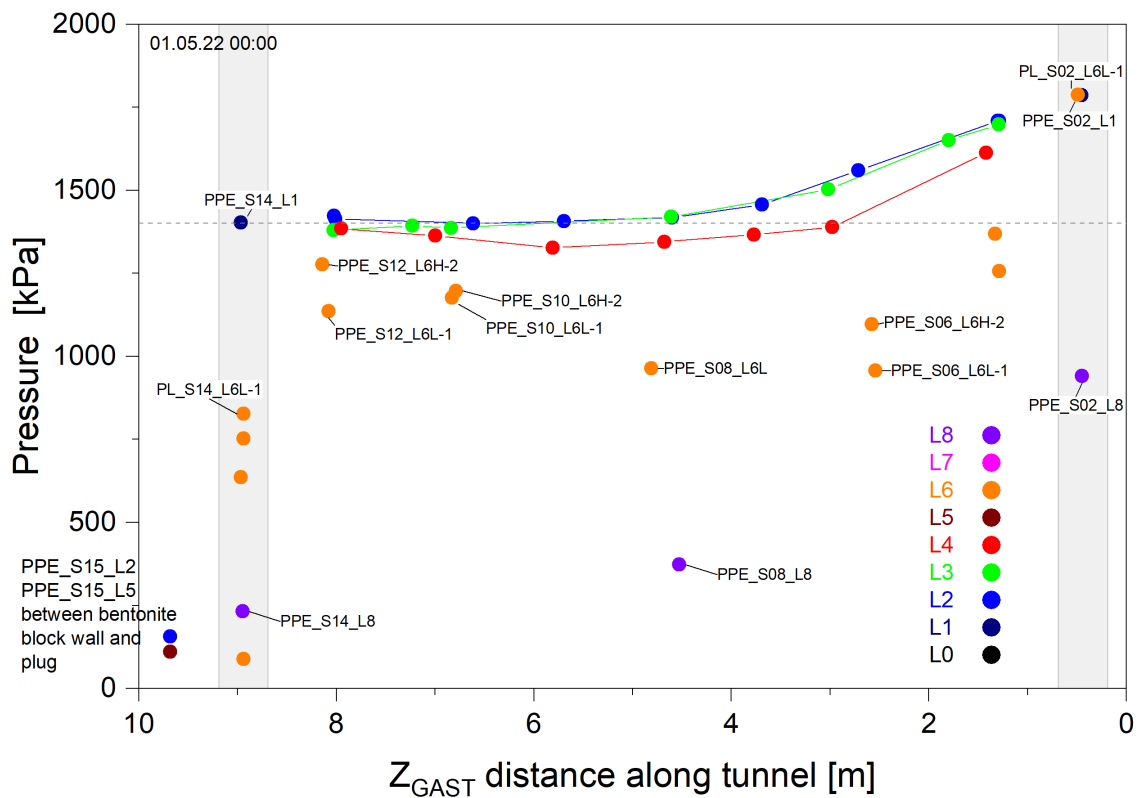


Fig. 2-5: Pressure profile along GAST prior to the GFT (01.05.22)

Data coloured by instrumentation level (L1 – L8), grey bars indicate sand filters.

Piezometers at S06 and S08 in L6 show a lower pressure of ~1,000 kPa. The piezometers in the granular bentonite at L8 (the crown of the tunnel) also show low pressure. This is attributed to the slow ongoing saturation of the granular bentonite and the influence of the pressure in the geosphere (see App. G). Pressure in the rock around the tunnel is likely to be particularly low around the plug but any flow from the sand/bentonite to the rock will be limited by the low permeability of the GBM.

A cross-section of the measured pressure on 01.05.22 is shown in Fig. 2-6. The overall pattern is shown with a pressure gradient across the sand/bentonite from S02 to S14 and from L3 upwards into L4 and L6. Low pressures are seen in the bentonite. The low pressures measured at the top of the S14 sand filter (L6) relate to sensors in the GBM located outside the filter.

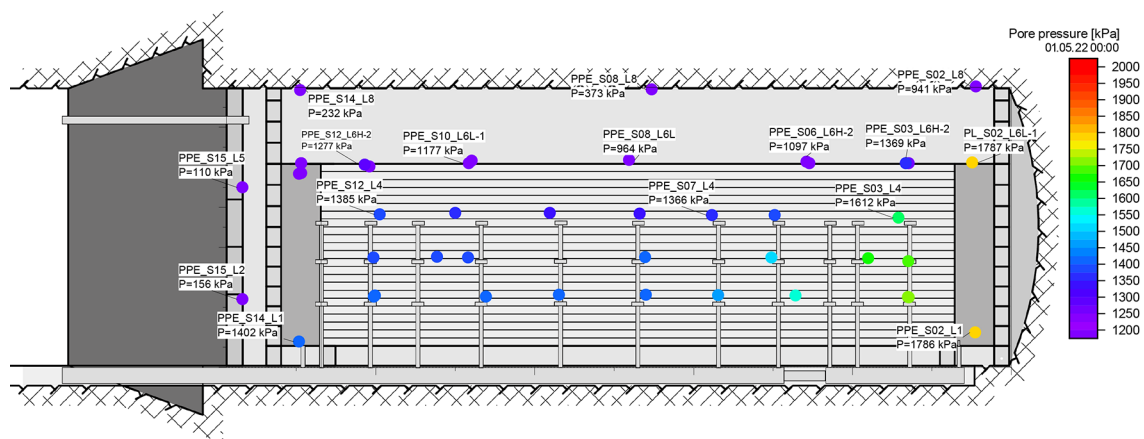


Fig. 2-6: Pressure distribution prior to the GFT (01.05.22)

2.2.4 Saturation state (01.05.22)

Sand filters

In June 2018 following GPT1, a gas volume of 50 l was estimated to be left above the PL_S02_L6L-2 extraction line. Since then, the gas will have been compressed and dissolved in the S02 filter porewater. A pre-GFT filter pulse test suggested a compressibility of 5 ml/kPa (App. C) comparable to that of S14, the saturation of which was unaffected by GPT1. While it is possible that there was a small volume (1 – 2 l) of trapped residual gas from GPT1, it seems likely that the filter was fully saturated.

The S14 sand filter is expected to have been fully saturated at the start of GFT. The S14 filter has been water-filled since July 2012. Its pressure exceeded 2.0 MPa from 2020 until the start of the equilibration period in December 2021. Some degassing could potentially occur if the filter pressure is significantly reduced, depending on the dissolved gas content⁷. Filter pulse tests performed in December 2021 and March 2022 suggested a compressibility of 5 – 6 ml/kPa. This is slightly higher than the S02 filter compressibility of 3.5 ml/kPa estimated prior to GPT1 and could be due to different stress conditions at the start of the GFT and possible ongoing deformation of the sand filter.

⁷ Measurements of dissolved gases (Ar, N₂) in the S14 filter water indicate oversaturation relative to atmospheric pressure but undersaturation relative to the pore pressure in the filter (~1.8 MPa).

Fig. 2-7 shows the cumulative water injection prior to the GFT. The water required to saturate the pore volume of the sand filters and the sand/bentonite (11.9 m^3 , Tab. 2-2) had been injected during Saturation Phase #1. A further 12.11 m^3 of water would be required to fully saturate all the GBM, however, less was actually injected. An uncertain quantity of water is likely to have come from the host rock.

Sand/bentonite

The sand/bentonite body (L1-L6) is thought to be highly saturated⁸, based largely on observed pore pressure (measured value and response to stress change). Direct measurements of saturation are unavailable due to the lack of a material-specific calibration for the TDRs and difficulty in interpreting the psychrometer responses (no longer operational). A qualitative evaluation of the post-GPT1 response of the TDRs (see App. F) showed that most TDRs had stabilised at a relatively high travel time (4-5 ns) during the resaturation and equilibration periods prior to the GFT. This was interpreted as to indicate highly saturated conditions.

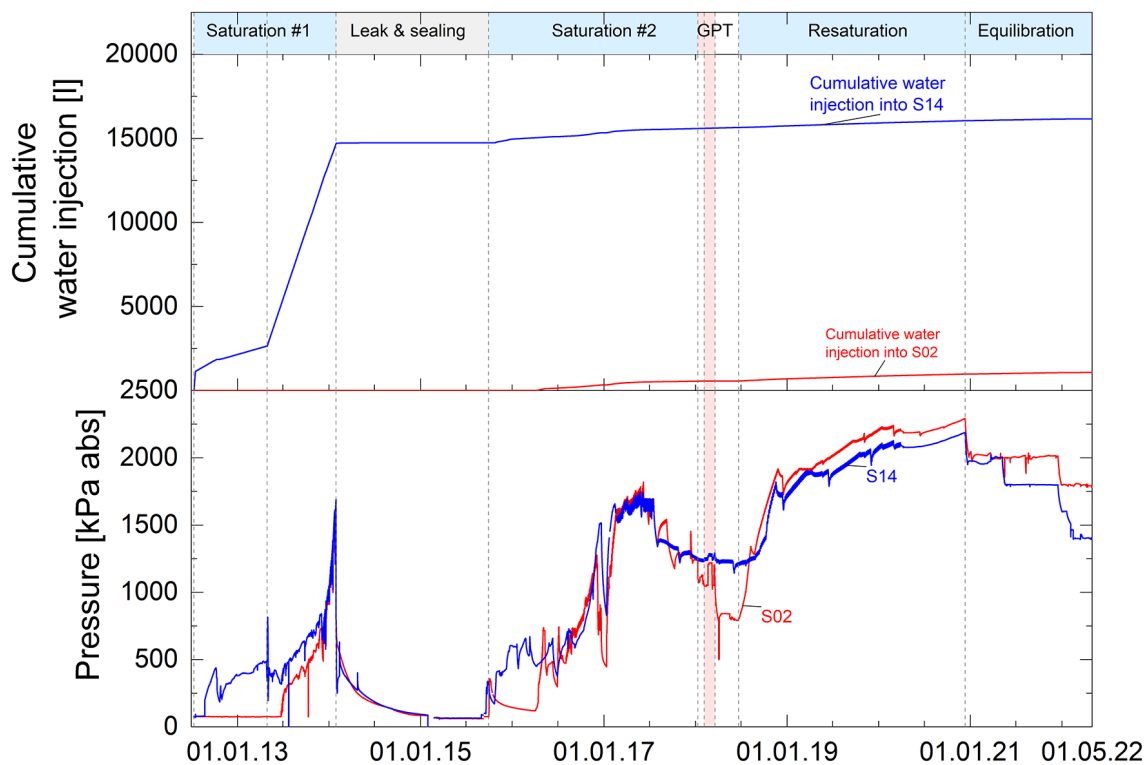


Fig. 2-7: Cumulative water injection and pressure history from 01.07.12 to 01.05.22

The measured pressures at L2 – L4 in the sand/bentonite show a well-defined hydraulic gradient between the filters. Hydraulic index tests (see App. D) in the PPEs indicated low compressibility and saturated conditions local to the PPE filter tips. There are no piezometers at L5 in the sand/bentonite, but TDRs at L5 show similar travel times and behaviours to those in L2, L3 and L4.

⁸ See discussion in Lanyon et al. (2022) for the saturation state on 01.01.21.

It is unlikely that significant degassing occurred within the sand/bentonite when pressure was reduced during the equilibration phase to produce the S02 – S14 hydraulic gradient. The dissolved gas content in the sand/bentonite porewater measured during the L2 dipole test suggested that the nitrogen partial pressure was ~100 kPa, indicating that the porewater was undersaturated with gas (see Appendix E.1).

Sand/bentonite-GBM interface at L6

The L6 sand/bentonite–granular bentonite interface is assumed to be largely saturated. The measured pressure exceeds 950 kPa but is very heterogeneous, ranging from ~970 kPa at S08 to over 1,350 kPa near the S02 sand filter. This could indicate some channelling at the interface or variation in local conditions around the filter (perhaps caused by locally higher GBM content). As previously mentioned, the L6 piezometers were emplaced differently from those within the sand/bentonite which could have resulted in greater variability in pressure measurements. All RH sensors at L6 failed in late 2013 after showing a slight reduction in RH since emplacement (perhaps due to drying by the overlying GBM).

GBM

The granular bentonite in the ring space around the sand/bentonite is likely to be saturated due to its small thickness (~25 cm) and potential for saturation of both the rock and the sand/bentonite. The high swelling pressures measured at S06, S08 and S10 also indicate significant saturation. There are no other sensors in the granular bentonite ring space.

The granular bentonite in the headspace above the sand/bentonite is 95 cm thick at the crown of the tunnel (Fig. 1-2). The two operational RH sensors in L7 measured 95% and 97%, indicating some remaining residual partial saturation (Fig. 2-8). All other RH sensors in the GBM headspace were no longer operational, falling out of range as they approached 100% relative humidity. Saturation may also be lower in the very centre of the headspace volume, with the possibility of some regions of trapped gas. Pressure at the top of the headspace (L8) in S08 was over 370 kPa and rising at the start of the GFT.

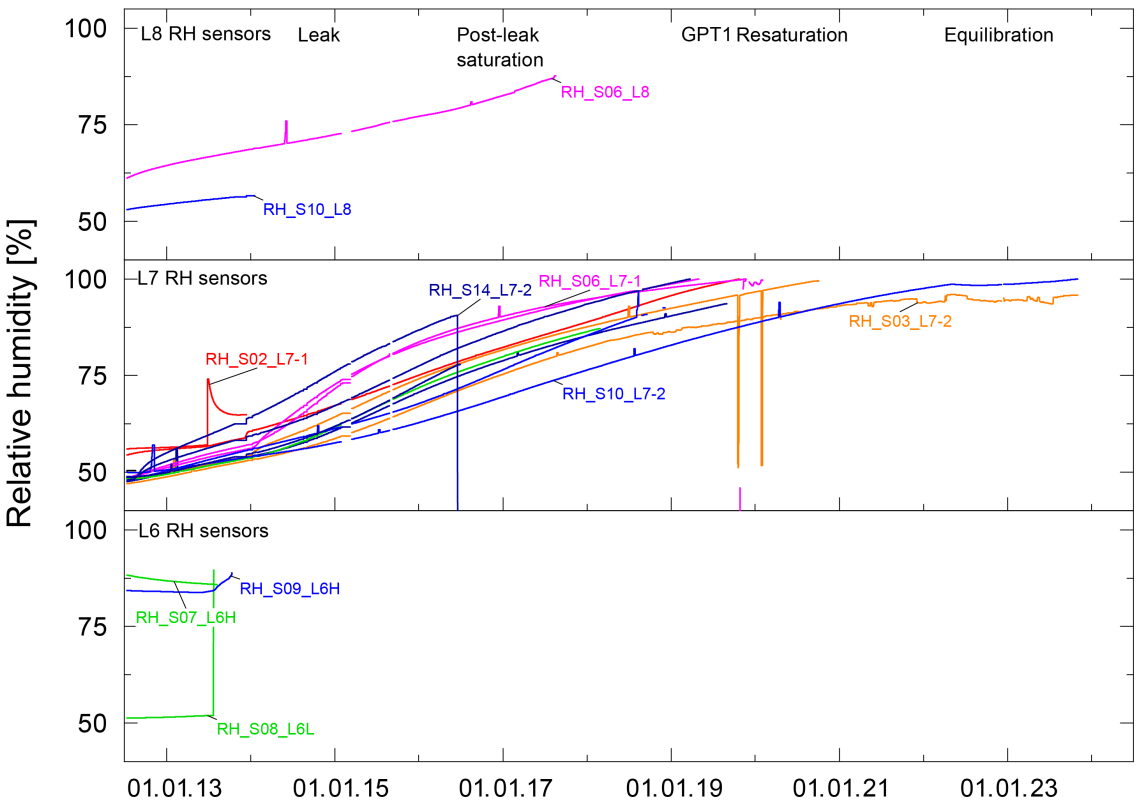


Fig. 2-8: RH measurements in GBM headspace (11.07.12 to 01.05.22)

The interpreted saturation state is summarised in Tab. 2-4 and illustrated in Fig. 2-9.

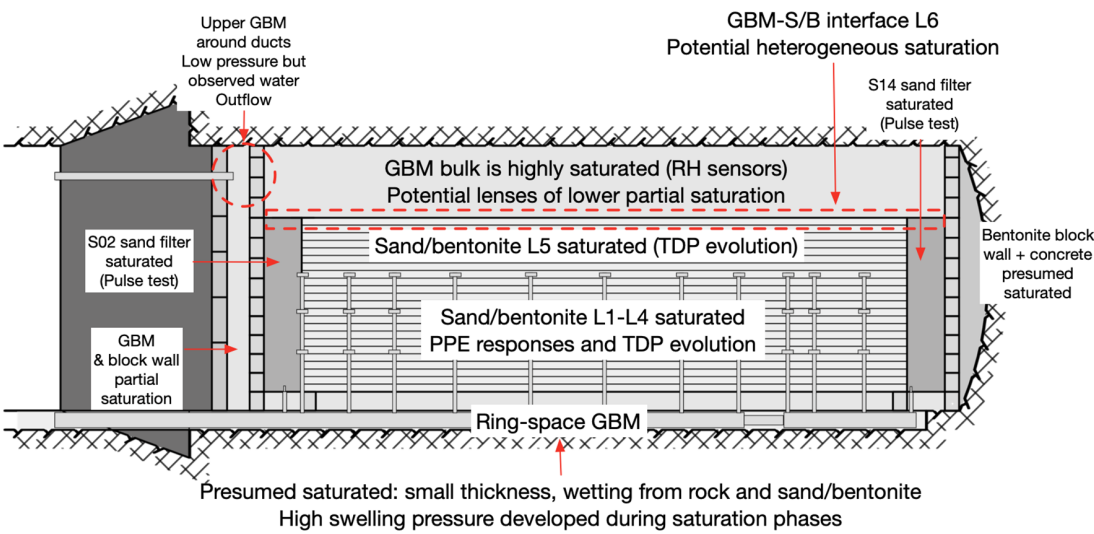


Fig. 2-9: Summary of pre-GFT saturation state

Tab. 2-4: Saturation indicators prior to GFT (01.05.22) for seal section sand/bentonite and GBM

	Pressure distribution	Hydraulic index tests (see App. D)	Response to sinusoidal pumping	Assessment of TDR stability (see App. F)	RH measurements	Saturation status
Headspace GBM	Low at L8	N/A	No response observed	N/A	Two operational sensors >95%, other sensors out of range	Mostly highly saturated. Some partially saturated lenses could still exist
L6	Variable and 200 – 300 kPa lower than L4	Higher compressibility at S06	Small	N/A	Failed early	Heterogeneous?
L5	N/A	N/A	N/A	Mostly stable travel time and trace shape for working sensors	N/A	High ~100%?
L4	Well-defined gradient between S02 (1,800 kPa) and S14 (1,400 kPa). L4 typically 100 kPa lower than L2,L3 in S03-S10	Low compressibility ~10 ⁻¹² (m ³ /Pa)	PPE response increases over time and approaches magnitude of TPW response in S06, S08, S10			
L3						
L2						
Ring space GBM	N/A	N/A	N/A	N/A	N/A	Saturated. The GBM has a small thickness and will have been wetted by inflow from rock. TPW sensors show high loads.

Bentonite block walls and GBM near plug

Both the bentonite block wall (19 cm thick) between the S02 filter and the tunnel end and the granular bentonite above the filter were likely to be highly saturated. The S02 filter has been largely water-filled since July 2013 but was used for the GPT1 gas injection in January-March 2018. The pressure in the top of the granular bentonite at S02 is over 900 kPa.

The bentonite block wall between the S14 filter and the plug is likely to be highly saturated but the granular bentonite between the wall and the plug could include some zones of partial saturation, as pressures are low and water flow through the bentonite block wall will be small. There is insufficient instrumentation to determine the saturation distribution. The total thickness at construction was 49 cm (30 cm GBM and 19 cm of bentonite blocks). The blocks were in direct contact with the S14 filter which has been water-filled since July 2012. The measured pressure is low in S15 between the bentonite wall and the plug (110 – 160 kPa) and at S14 L8 (~230 kPa). The low pressures could partly be due to leakage around the plug or via the instrumentation ducts to the open WT drift. A small amount of water leakage has been observed from the instrumentation ducts, and tracers from water injected in S14 have been observed in the instrumentation duct outflow. However, the measured total pressures on the S15 concrete wall are ~2.2 MPa or greater, indicating significant swelling.

2.2.5 Stress state (01.05.22)

Measured total stress is between 2.1 and 2.8 MPa (Tab. 2-5), with the lowest stress being measured at the top of the tunnel (L8) at S06. The total stress within the EBS is influenced by the swelling pressure developed by the bentonite and the pore pressure. Pore pressure is significantly less than 2 MPa and is lower at the top of the tunnel (Tab. 2-7). Effective stresses (Tab. 2-6) are therefore thought to be compressive and 0.5 MPa or more within the EBS, but measurements are limited.

Tab. 2-5: Total pressure (kPa) values on 01.05.22

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				2,187		2,289		2,072			
L7											
L6	2,447										2,810
L5											
L4	2,209/ 2,339			2,168		2,284/ 2,372		2,321/ 2,328			2,374/ 2,441
L3											
L2											
L1	2,428										2,588
L0				2,757		2,666		2,834			

Tab. 2-6: Estimated effective stress (kPa) on 01.05.22

Effective stress estimated from measured total and piezometers at the same level. Only the total pressure cell TPW_S08_L8 is located close to a piezometer (PPE_S08_L8).

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				2,030		1,916		975			
L7											
L6	2,336										1,024
L5											
L4	2,098/ 2,229			805		940/ 1,028		933/ 940			588/ 655
L3											
L2											
L1	2,317										802
L0				1,357		1,249		1,275			

Tab. 2-7: Pore pressure (kPa abs) values on 01.05.22

[illegible]

2.2.6 Temperature

The temperature within the seal section was monitored by the two operational RH sensors at S03 and S10 in the granular bentonite. They indicated EBS temperatures of 13.5 – 14 °C, which is typical of measurements taken over the last few years⁹ at both the GAST and other experiments at the GTS. The measured temperature of the wellhead and surface monitoring equipment was typically ~16 °C during the experiment. The temperature sensor associated with the electrical conductivity (EC) sensor for drainage flow showed a slightly higher temperature of ~17 °C. It is likely that there were local variations in temperature within the tunnel due to lighting, ventilation and equipment-related heating but for the purposes of estimating gas mass from measured volume, a fixed temperature of 16 °C has been assumed in this report.

Other climate conditions in the WT drift were not monitored but are assumed to be similar to those measured elsewhere in the GTS, reflecting ventilation with relatively dry air through the winter.

2.3 Porewater

2.3.1 Sand filters

The porewater within S02 was exchanged with a 10 ppm 1,5-NDSA (Naphthalin-1,5-disulphonsate) BOADUS water in August 2021. Produced water had an EC of 200 – 800 µS/cm, and the exchange was managed using online EC measurements to detect the arrival of “fresh” water at the extraction. The estimated injection and extraction volumes were in good agreement with 797 l injected and 793 l extracted.

It was not possible to fully exchange the water in S14 because of the lack of hydraulic lines at the top of the sand filter. However, pressure in the filter was reduced to 1,115 kPa on 25.08.21 and the 2.7-NDSA tracer was then injected into the filter. Problems with clogging were encountered during the extraction, and it was necessary to perform repeat injection/extractions to unclog the line.

2.3.2 Sand/bentonite porewater dissolved gases

Analysis of water samples taken from PPE_S07_L2 during the dipole test (see Rösli et al. 2025) provided a baseline estimate for the dissolved gas content of the sand/bentonite porewater (see Tab. 2-8 and discussion in App. E.1.1).

Tab. 2-8: Baseline estimate of dissolved gas in sand/bentonite porewater

	Dissolved gas content [cm ³ STP/kg]					Calculated dissolved gas fraction [%]			
	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
Baseline (average)		0.09		15.57	16.07		0.49		97.20

⁹ The temperature sensors associated with RH sensors show anomalous readings when close to saturation.

3 Water-gas exchange and start of injection Phases 2 – 3 and gas breakthrough to S14 (02.05. – 12.05.22)

3.1 Injection and extraction boundary conditions

The water-gas exchange (W-GX) was started on 02.05.22 at 08:00, with extraction of water from PL_S02_L1 and injection of gas in PL_S02_L6L-2. The exchange went smoothly until the first gas breakthrough at the extraction (L1) on 05.05.22 at 16:00. Subsequent further water extraction was attempted, but on 06.05.22, the extracted fluid was mostly gas, and extraction was halted, marking the end of the W-GX.

Fig. 3-1 shows the injected gas and produced water volumes and flow rates. The two cumulative volumes are in excellent agreement until gas is produced at the extraction. The gas volume is calculated from the measured pressure at the top of the sand filter (PL_S02_L6L-1). While some of the injected gas was expected to go into solution in the porewater of the filter, the data suggest that (as planned) the injected and extracted volumes match closely in the early phase of the W-GX. However, over time, produced water volumes are slightly lower than the volume of gas injected. This indicates either that gas was produced at the L1 extraction, that gas migrated into the sand/bentonite or that some minor calibration bias in the flowmeters occurred ¹⁰.

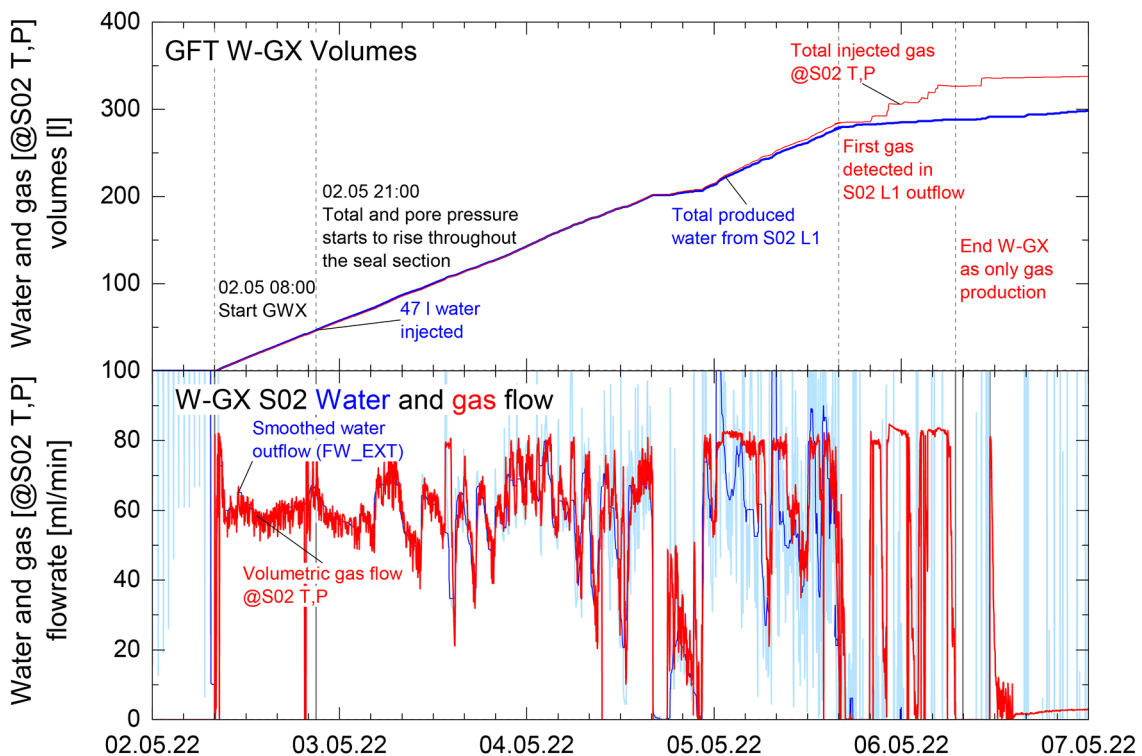


Fig. 3-1: W-GX in S02 – volumes and rates

¹⁰ Outflow during W-GX was routed to a large tank (the “mock-up tank”) equipped with a water level gauge, and the total water volume extracted was checked against the measured level.

Gas injection during the W-GX was performed with a pressure of 1,850 kPa, which was slightly above the pressure in S02 prior to the start of the GFT. This resulted in an initial small pressure response in the sand/bentonite, but from 02.05.22 21:00, a larger, approximately linear increase in pressure is observed in many of the sand/bentonite piezometers, despite a slight reduction in pressure within the S02 filter. This linear response is interpreted as indicating the first entry of gas into the sand/bentonite and displacement of water from the developing gas path.

The extraction of gas from L1 was due to a dynamic finger/cone of gas caused by the extraction. Once the extraction halted, gas migrated upwards within the S02 sand filter to establish a water level at about 1.5 m, ~15 cm above L3 (see discussion of the S02 water level in App. C.2.4). Overall, filter water was replaced with gas in a single phase without any major problems – partly because the problems encountered during GPT1 with clogging and monitoring of the exchange had been anticipated and addressed in the preparations for the GFT.

Gas breakthrough to S14

During the W-GX, pressure started to rise in S14 and water was periodically extracted from PL_S14_L1 to maintain the S14 filter pressure at 1,400 kPa. This was managed automatically using a syringe pump from 06.05.22 09:29. By 07.05.22 14:06, it was necessary to run the syringe pump continuously. Although small amounts of water will be displaced as the gas path develops, the relatively large flowrates produced from S14 (compared to those prior to GFT, see Fig. 2-4) suggest that gas was entering S14 by 08.05.22 or perhaps earlier. Later gas flow into S14 was confirmed by the TDL sensors at S13, showing reducing water content from 18.05.22 (see Section 4.6.1), and finally by gas breakthrough at the S14 L1 extraction on 08.06.22.

After the end of the W-GX, injection was switched to constant pressure mode with a set-point at 1,800 kPa (PL_S02_L6L-1) on 06.05.22 at 11:22. After ramping up the injection flowrate, the setpoint was raised to 1,900 kPa on 12.05.22 at 12:50.

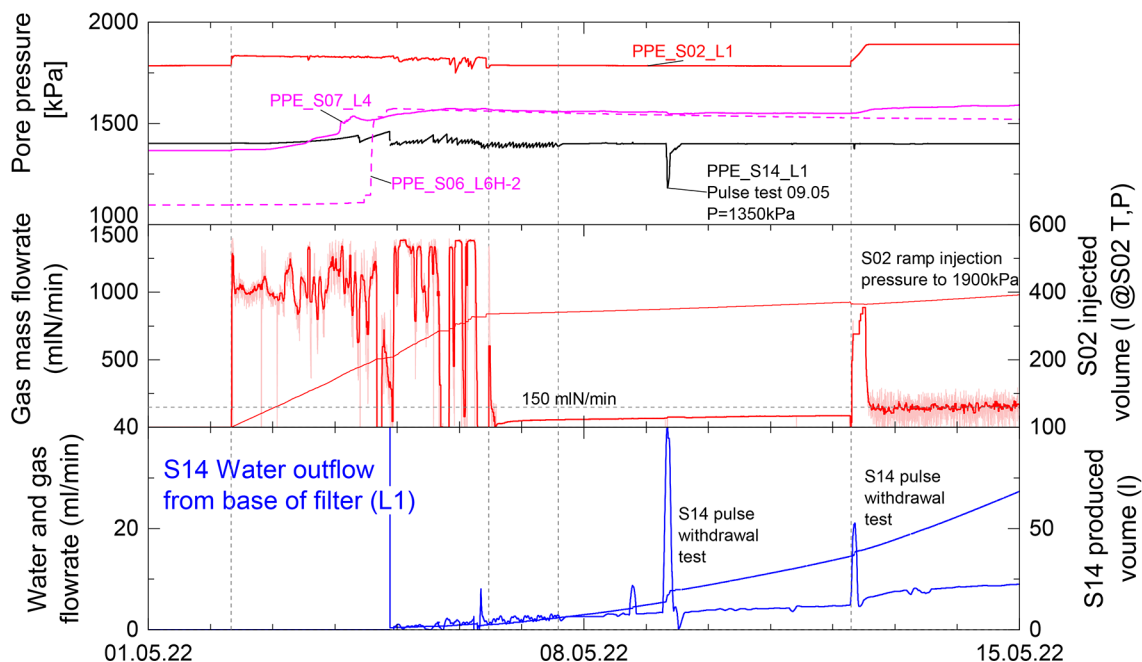


Fig. 3-2: S14 extraction and S02 injection with selected pressure measurements during the W-GX

Fig. 3-2 shows the S02 gas injection and S14 water extraction rates together with the filter pressures and selected piezometers. A pulse withdrawal test was performed in S14 on 09.05.22 when the pressure was reduced to 1,350 kPa. Gas injection rates rose to a steady 150 mlN/min after ramping up the injection pressure to 1,900 kPa. The water extraction from S14 increases with time to ~10 ml/min over the same period.

3.2 Pressure response

Fig. 3-3 shows the pressure profile along GAST at the different instrumentation levels on 01.05.22 (prior to the start of GFT) and 06.05.22. Prior to the GFT, there is a clear gradient from S02 towards S14 at levels L2, L3 and L4. Pressure in L4 is about 100 kPa below that of L2 and L3. Pressure at L6 is heterogeneous with some sensors showing very low pressure (~1,000 kPa). By 06.05.22, pressure had risen almost everywhere with L4 pressures typically slightly higher than those in L2 and L3 between S07 and S14.

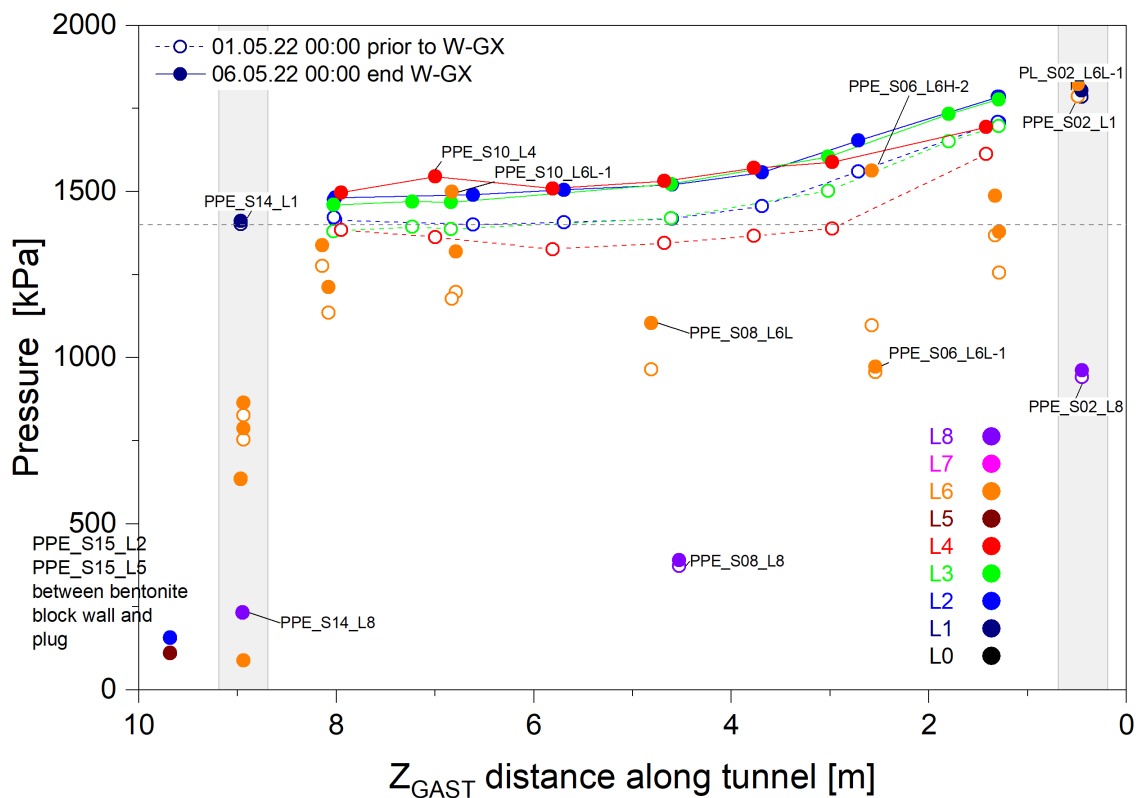


Fig. 3-3: Pressure profile along GAST on 01.05.22 (hollow symbols) and 06.05.22 (solid symbols)

Sensors coloured by instrumentation level (see Fig. 1-4).

Fig. 3-4 shows a profile of pressure change from prior to the start of the GFT (on 01.05.22). L4 shows a consistently larger pressure increase than L2 or L3. Some of the L6 piezometers that showed low pressure prior to the GFT rise significantly during the early part of the GFT, but only PPE_S10_L6L-1 is at a pressure comparable to the L4 piezometers.

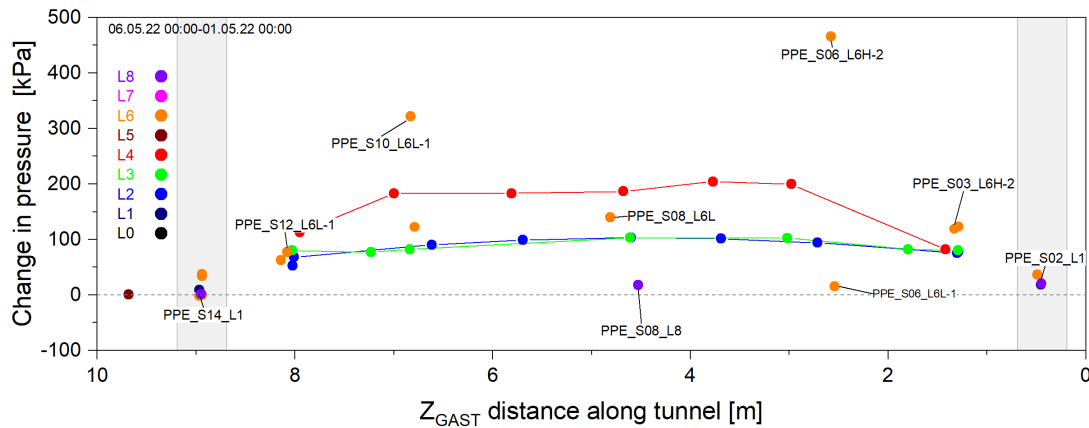


Fig. 3-4: Profile of pressure change between 01.05.22 and 06.05.22 along GAST

Fig. 3-5 shows the measured pressures during the early part of the GFT (to 15.05). Fig. 3-6 shows the change in pressure since the start of GFT (zero-point at 01.05.22). Most piezometers in the sand/bentonite show a small response to the start of the W-GX followed by a linearly increasing pressure response from 02.05.22 21:00. This increasing trend, despite the falling pressure in the S02 filter, is interpreted as a response to water being displaced by gas entry into the sand/bentonite. The gradual increase up to about 100 kPa is clearly seen in all the piezometers in L2 and L3. L4 shows typically larger pressure responses due to the initially lower pressures in that layer. At PPE_S07_L4, the trend is broken on 04.05.22 with a pressure peak at 06:58. A significant jump in pressure is subsequently seen in L6 at PPE_S6_L6H-2 with a more gradual pressure rise in PPE_S10_L6L-1. PPE_S06_L6H-2 showed a similar, very abrupt response early in GPT1 (see Lanyon & Herbert 2021). The response to the S14 pulse test on 09.05.22 is clearly seen in the piezometers in L2, L3 and L4 close to the S14 filter, with the largest response in S12. No responses to the pulse test are seen in L6.

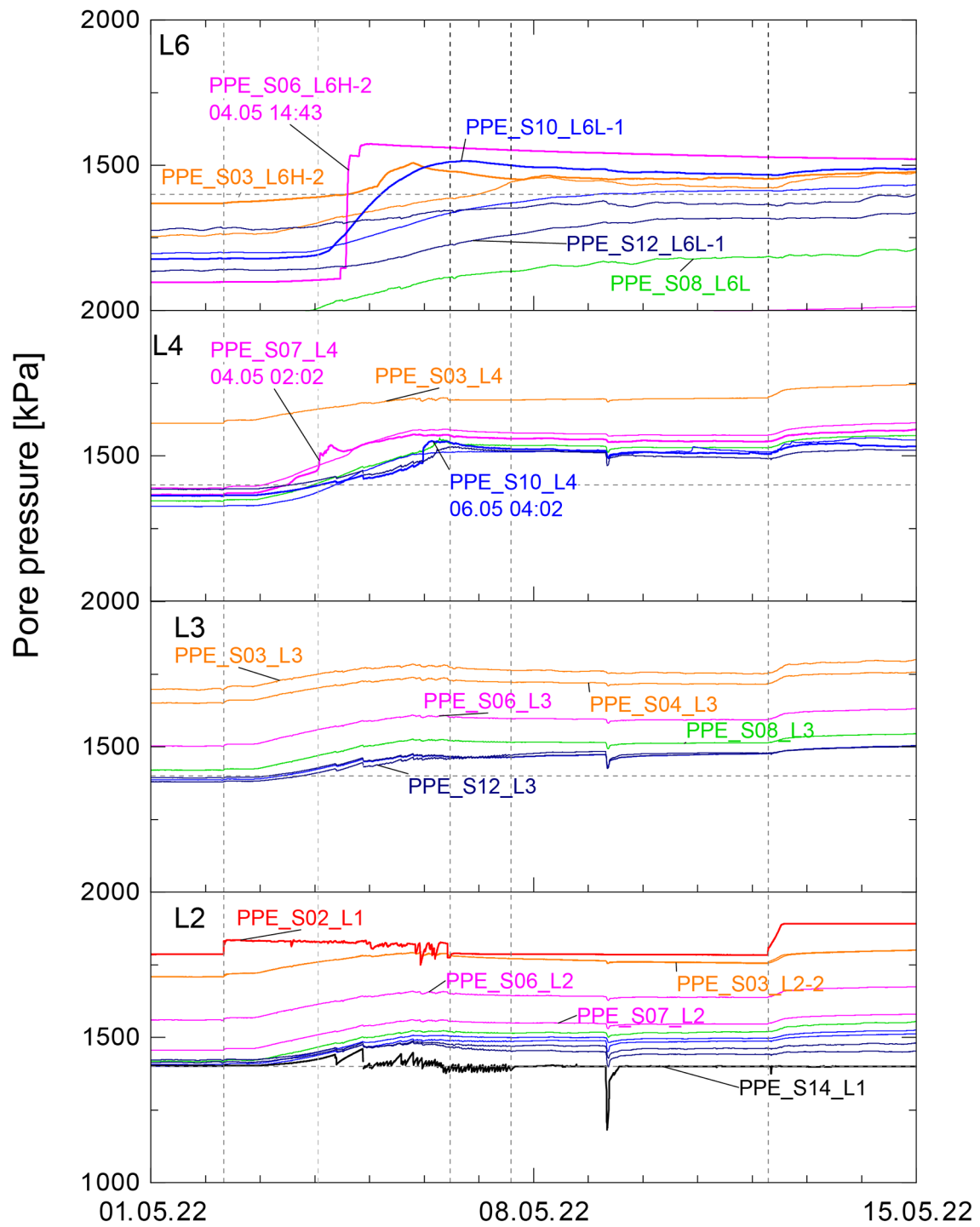


Fig. 3-5: Pore pressure during GFT Phases 2 and 3

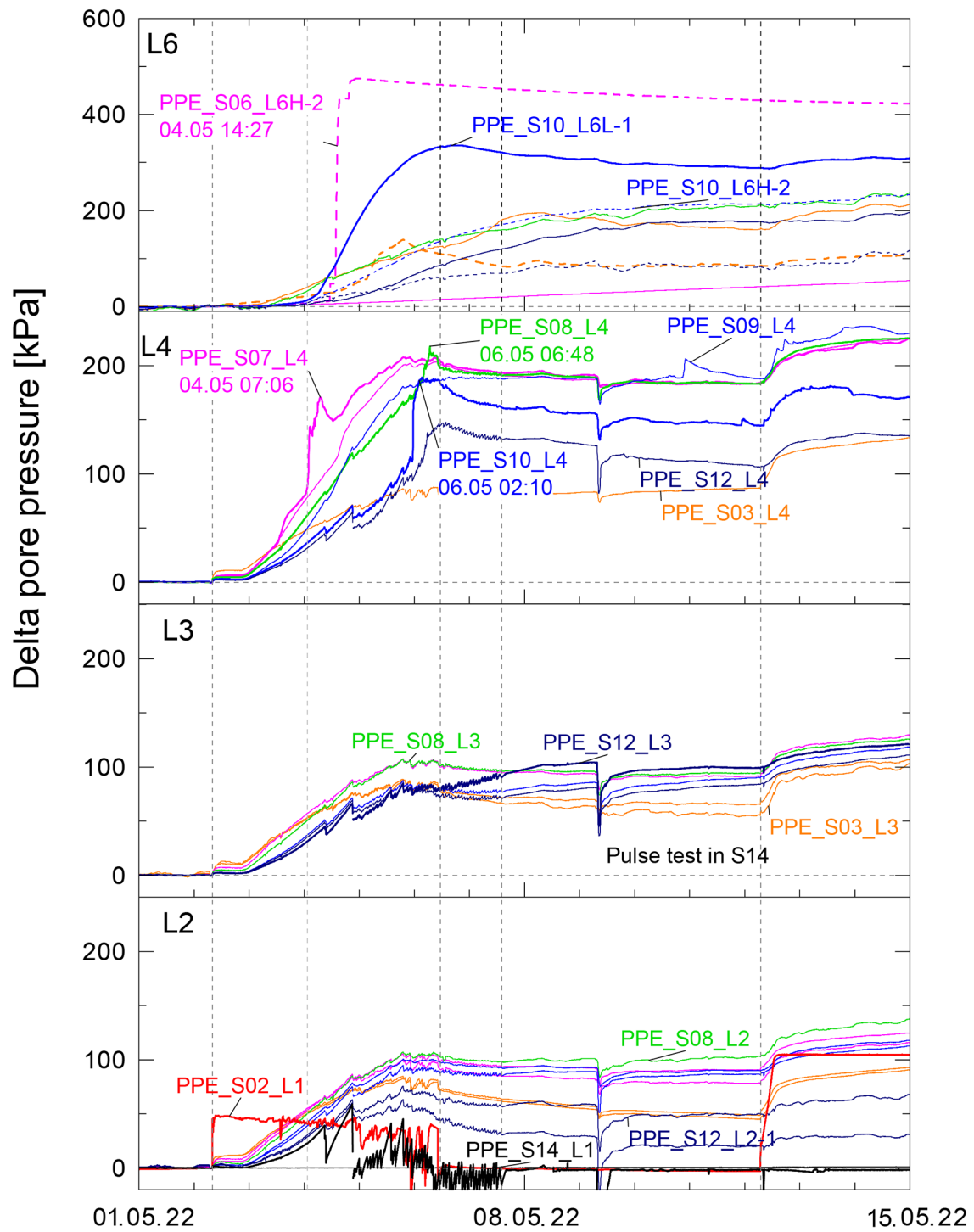


Fig. 3-6: Change in pressure during GFT Phases 2 and 3
Change in pressure (delta) calculated from 01.05.22.

PPE_S12_L3 shows a somewhat different response (Fig. 3-6) to other piezometers in L3 with a continued linear pressure rise. The noisy response is due to the episodic extraction from S14.

Fig. 3-7 shows the spatial distribution of pore pressure on 01.05.22, 06.05.22 and 15.05.22. There is a clear increase in pressure in the sand/bentonite body of ~100 kPa by 06.05.22 and some larger changes in some of the L6 sensors at the top of the sand/bentonite. Only very small pressure changes are seen in the piezometers at L8 and in S15.

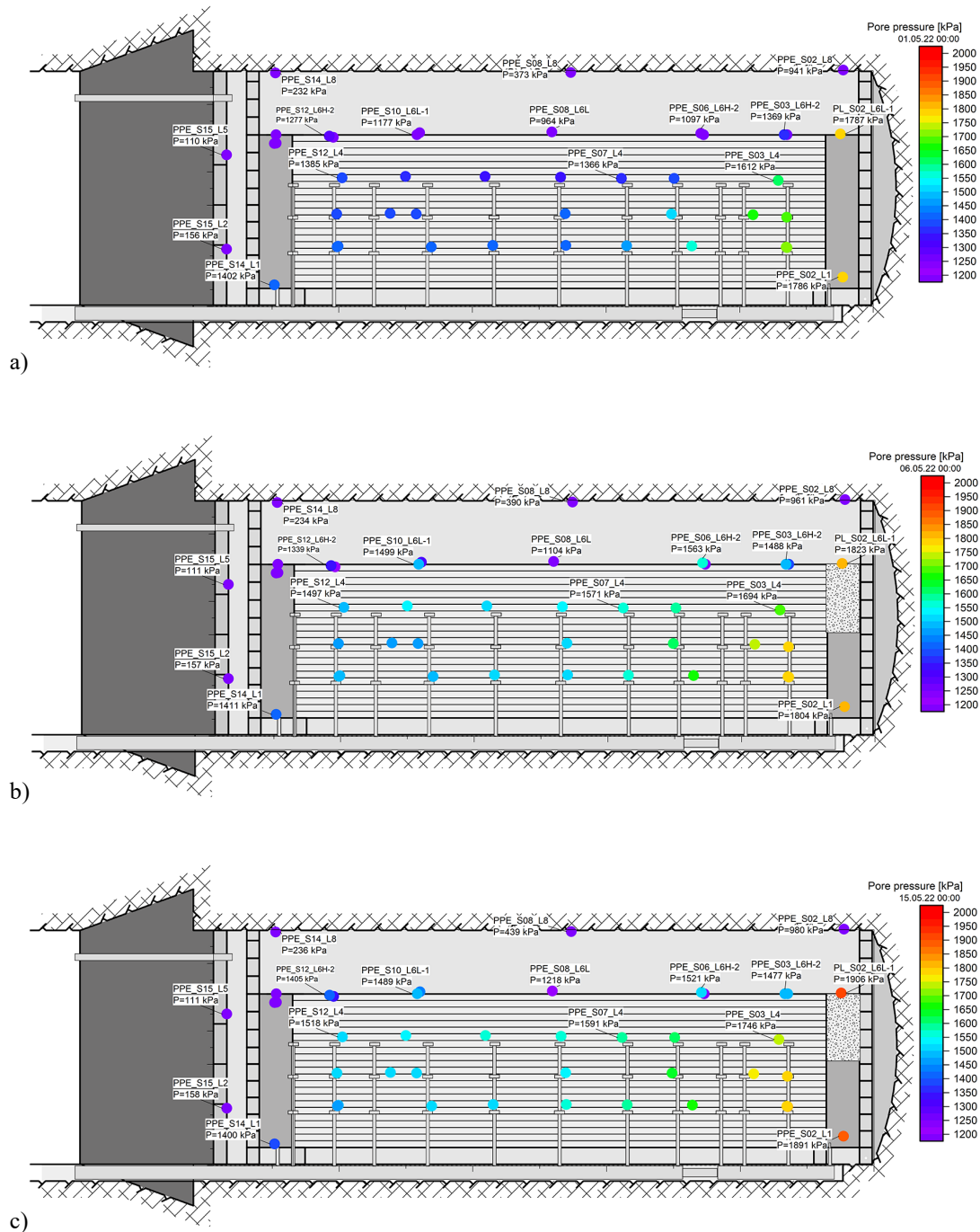


Fig. 3-7: Pore pressure distribution on a) 01.05.22, b) 06.05.22 and c) 15.05.22

Approximate location of S02 gas level shown.

Pressure values on 06.05.22, near the end of the W-GX, and the change since 01.05.22 are tabulated in Tab. 3-1 and Tab. 3-2. Pressure values on 12.05.22, at the end of Phase 3, and the change since 01.05.22 are tabulated in Tab. 3-3 and Tab. 3-4.

[illegible][illegible]

Tab. 3-3: Pore pressure (kPa abs) values on 12.05.22 at 00:00

[illegible]

Tab. 3-4: Pore pressure change (kPa) from 12.05.22 00:00 to 06.05.22 00:00

[illegible]

3.3 Stress response

Fig. 3-8 shows the change in total pressure during the period. Almost all the total pressure cells show a consistent linear rise of 100 – 150 kPa between 02.05.22 and 06.05.22. This is similar to the pressure trend seen in L2 and L3 and probably represents the bulk response to the expulsion of water from the gas path between S02 and S14. The irregular responses most clearly seen in the axial TP cells in S15 (on the plug wall, see Fig. 1-4) correspond to the episodic depressurisation of S14 prior to the start of continuous extraction. TPW_S08_L8 shows a significant drop from 06.05.22 before stabilising on 07.05.22.

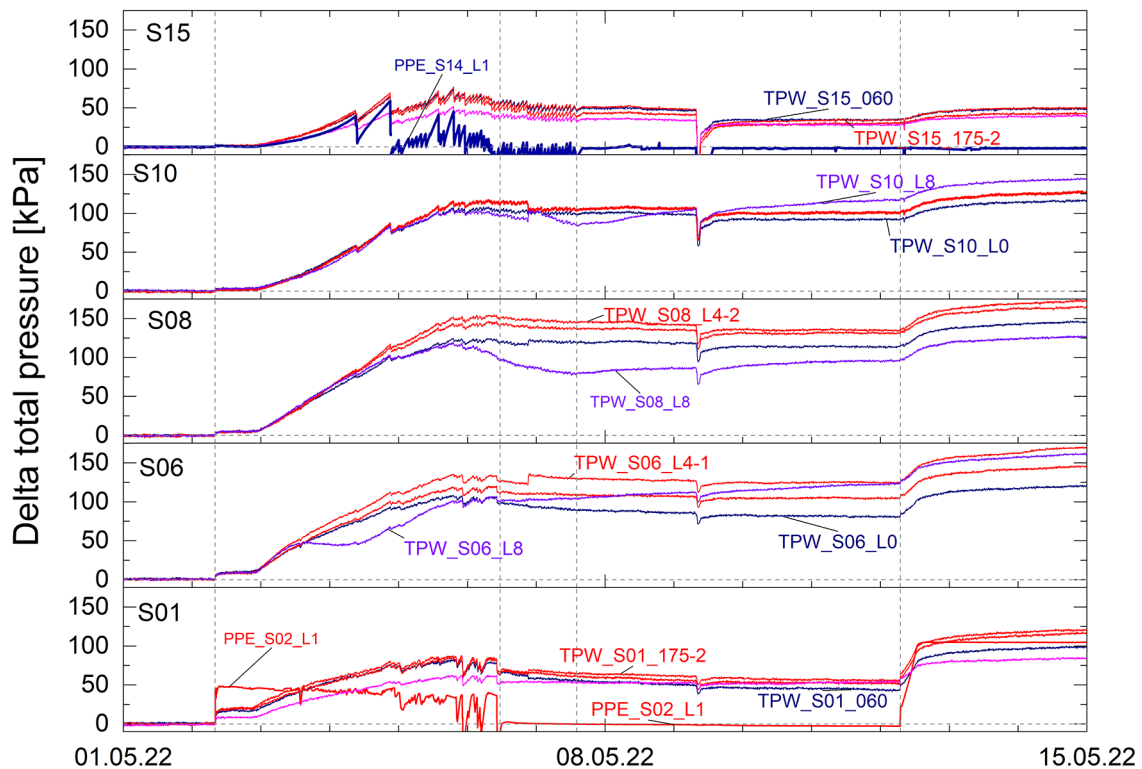


Fig. 3-8: Change in total pressure during GFT Phases 2 and 3

Tab. 3-5 lists the measured total pressure at 06.05.22 while. Tab. 3-6 gives the change in total pressure from 01.05.22. Tab. 3-7 and Tab. 3-8 show the corresponding measured values and changes on 12.05.22 (end of Phase 3).

Tab. 3-5: Total pressure (kPa) values on 06.05.22 at 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				2,287		2,402		2,171			
L7											
L6	2,492										2,870
L5											
L4	2,272/ 2,399			2,280		2,425/ 2,523		2,436/ 2,458			2,454/ 2,519
L3											
L2											
L1	2,492										2,661
L0				2,860		2,786		2,935			

Tab. 3-6: Total pressure (kPa) change from 01.05.22 00:00 to 06.05.22 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				100		113		99			
L7											
L6	45										60
L5											
L4	59/64			112		140/ 151		114/ 129			78/ 80
L3											
L2											
L1	64										73
L0				103		120		101			

Tab. 3-7: Total pressure (kPa) values on 12.05.22 at 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				2,303		2,385		2,194			
L7											
L6	2,476										2,865
L5											
L4	2,243/ 2,370			2,269		2,415/ 2,508		2,425/ 2,453			2,427/ 2,497
L3											
L2											
L1	2,464										2,630
L0				2,849		2,779		2,914			

Tab. 3-8: Total pressure (kPa) change from 01.05.22 00:00 to 12.05.22 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				116		96		122			
L7											
L6	29										55
L5											
L4	31/ 35			101		131/ 136		104/ 124			52/ 57
L3											
L2											
L1	36										43
L0				92		113		80			

3.4 Saturation response (TDR, Index tests)

A review of the TDR responses during Phases 2, 3 and 4 showed some changes in TDP_S10_L3 and TDP_S11_L3 but concluded that these did not provide any clear indications of either desaturation or wetting and might rather be indicative of instrumentation issues.

No hydraulic index tests were performed during this period.

No significant changes were observed in the measured RH from the two operational sensors in the GBM at L7 during this period.

3.5 Gas tracers and sampling

The first samples from the S14 extraction line for laboratory analyses were taken on 05., 11. and 12.05.22. They showed an increasingly dissolved helium content, indicating the presence of the tracer gas dissolved in the S14 porewater. The gas is likely to have entered the filter above the L1 extraction level and dissolved in the large volume of water within the S14 sand filter that was undersaturated with gas. The dissolved gas then mixed and diffused within the filter as water was drained at L1.

The outflow from PL_S02_L1 was collected in the mock-up tank. Sampling on 06.05.22 from the gas phase in the mock-up tank indicated a 1.5% helium fraction, confirming the success of the W-GX.

Sampling from the PPEs was not attempted until Phase 4.

3.6 Interpretation summary of the W-GX and gas breakthrough to S14

The W-GX was successfully accomplished and 300 l of water¹¹ were displaced by gas in S02 by 05.05.22 16:00 when gas was first produced from the S02 extraction at L1. Following the end of the W-GX, gas injection continued with rates rising to 150 mlN/min at the end of Phase 3.

The gas path from S02 to S14 was established within four days of the start of gas injection. This was observed as:

- a wide-spread increase in pressure in the sand/bentonite from 02.05.22 21:00 as water was displaced from the gas path,
- an early distinct pressure response at PP_S07_L4 on 04.05.22, followed by other responses in L4 closer to the S14 filter,
- some large pressure jumps at piezometers in L6,
- increasing extraction from the S14 filter to maintain 1,400 kPa pressure.

Constant pressure extraction was initiated on 06.05.22 and extraction was ~10 ml/min at the end of Phase 3. The gas path permeability quickly exceeded that of water with volumetric flowrates an order of magnitude above those prior to the start of the GFT (~0.1 ml/min).

3.6.1 Location of S02 – S14 gas flow path

The pressure data provide the best indication of the location of the gas flow path that was created during Phases 2 and 3. Fig. 3-9 and Fig. 3-10 show the change in measured pressure from 01.05.22 during the first few days of the GFT at L6 and L4. While most piezometers show a roughly linear increase in pressure from 02.05.22 21:00, the L4 piezometers from S06 to S12 and a small number of sensors at L6 show either an increase above the linear trend, or a sudden jump in pressure.

The first such strong response occurs in L4 at PPE_S07_L4, which shows an increasing trend followed by a peak pressure with a similar faster rise at the piezometers in S06, S08 and S09. Later peaked responses are seen at S10 and S12 (Fig. 3-10).

At L6, there is a strong response at PPE_S10_L6L-1 (but not PPE_S10_L6H-2) and PPE_S06_L6H-2 (but not PPE_S06_L6L-1). The response at PPE_S06_L6H-2 is particularly pronounced with a rapid increase of over 400 kPa. The response at PPE_S03_L6H-2 is notable for a peaked shape (Fig. 3-9) with pressure dropping from 05.05.22 19:00.

¹¹ See Rösli et al. 2025 field test documentation.

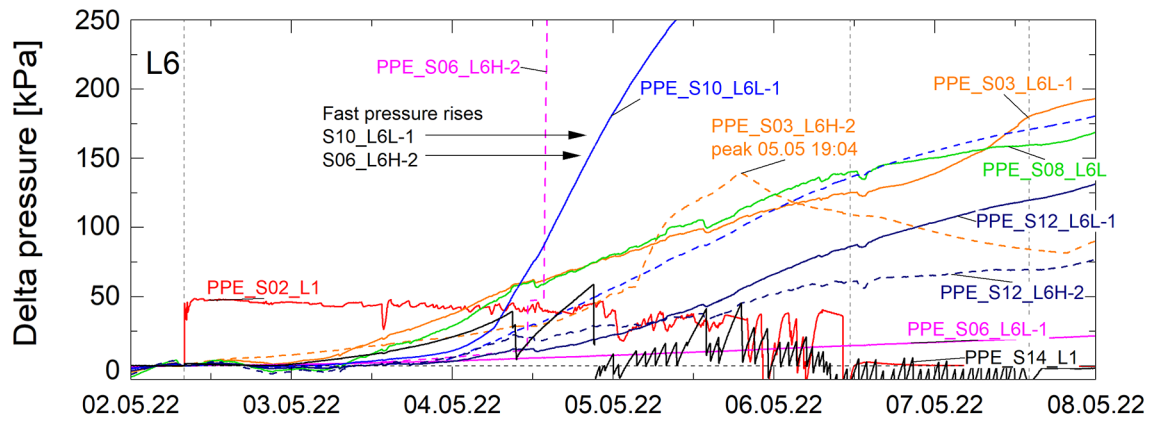


Fig. 3-9: Change in pore pressure from 01.05.22 at L6

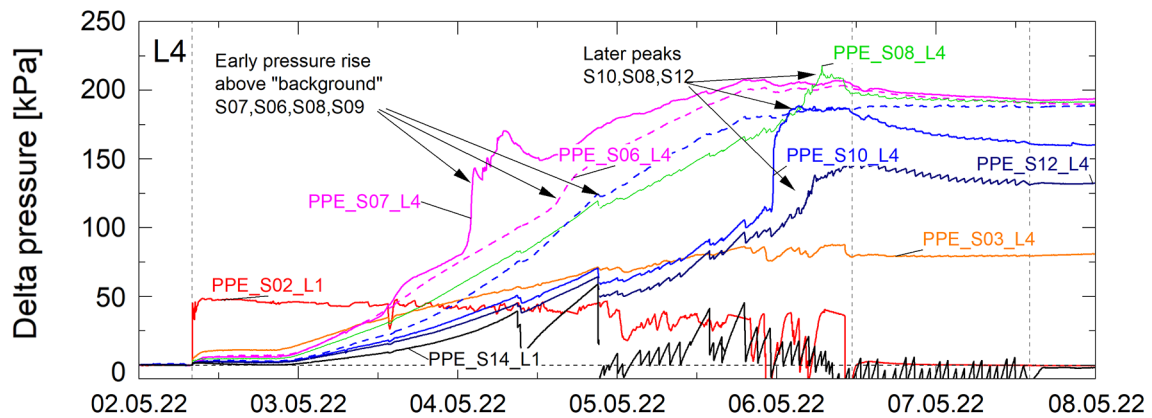


Fig. 3-10: Change in pore pressure from 01.05.22 at L4

A comparison of selected L4 piezometers with total pressure cells (TPWs) at the same section and level is shown in Fig. 3-11. The TPWs generally respond a little faster than the PPEs (particularly at S06) but then stabilise, while the PPEs show a more dynamic response with clear peaks observed at S08 and S10. The TPW responses are interpreted as representing the bulk pressure response to creation of the flow path, while the PPEs are sensitive to local pressure disturbances caused by the path.

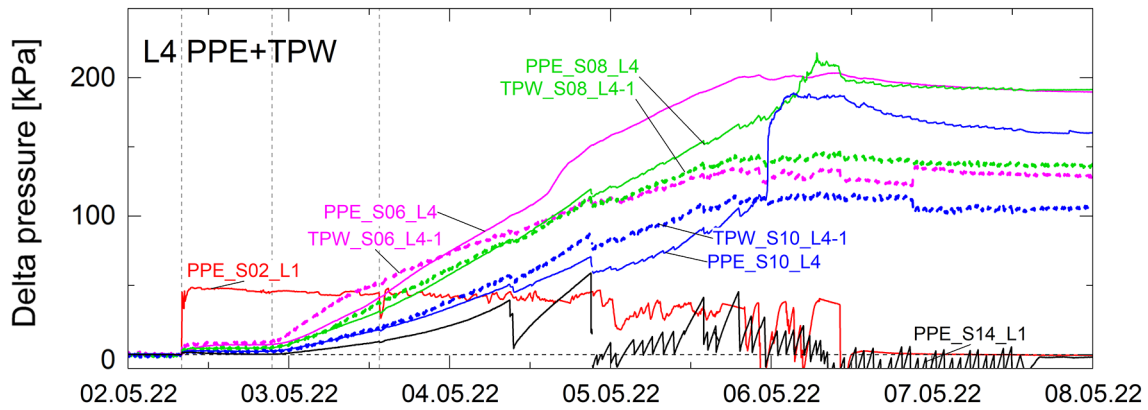


Fig. 3-11: Comparison of change in pore pressure from 01.05.22 for PPEs and TPW at L4

Fig. 3-12 summarises these observed local-scale pore pressure changes on a vertical section. Overall, they suggest the rapid development of a path from S06 to S14 close to L4 with connections up to L6. It is likely that the gas path includes locally lower entry pressure (more permeable) features in the sand/bentonite in the roughly metre-thick volume from L4 to L6. The relatively small volume of gas injected by 02.05.22 21:00 (Fig. 3-1), when the linear pressure rise started, suggests that the gas exit from the S02 filter was around L6.

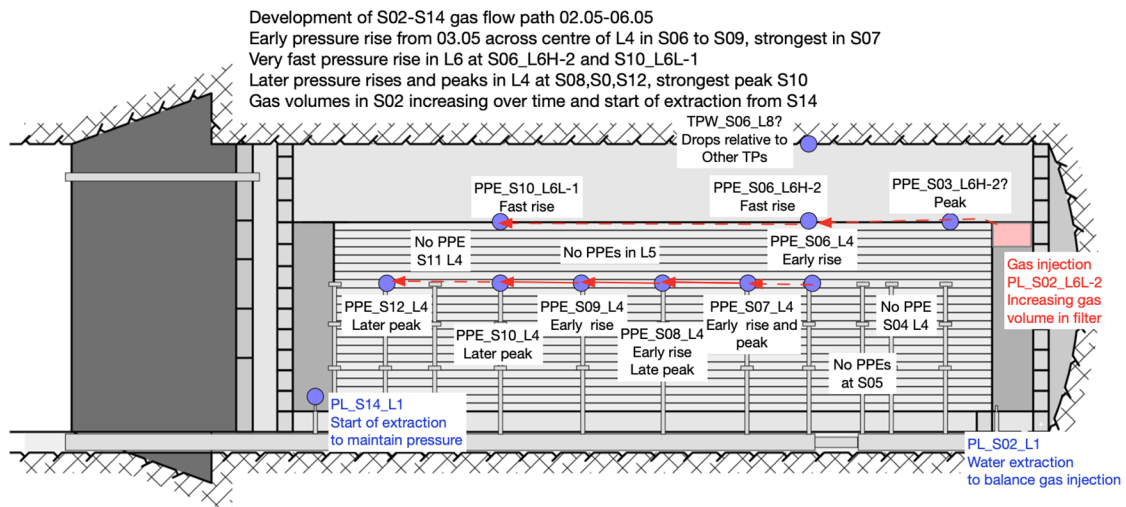


Fig. 3-12: Schematic vertical section showing pore pressure changes related to gas flow path from 03.05. to 08.05.22

If the stabilised pressure change by 08.05. observed in the TPWs (150-250 kPa) is considered indicative of the volume of water displaced V_{path} while forming the flow path, the path volume can be calculated as:

$$V_{path} = V_{S/B} S_{S/B} \Delta P$$

where $V_{S/B}$ is the volume of sand/bentonite, $S_{S/B}$ the storage coefficient and ΔP the change in hydraulic head (m). Assuming a storage coefficient of 10^{-5} m^{-1} , the estimated pore volume for the gas flow path is 7 – 10 l.

3.6.2 Gas entry into the sand/bentonite

Gas entry to the sand/bentonite around the filter will have occurred at high saturation due to the proximity to the pressurised filter which had been maintained at pressures above 1,800 kPa for almost three years (mid-2019). The observed PPE and TPW responses suggest that the first gas entry occurred before 03.05.22 13:00. At this time, the measured total pressure change is typically slightly larger than that observed at the PPEs and has propagated across the seal section (Fig. 3-13 and Fig. 3-14).

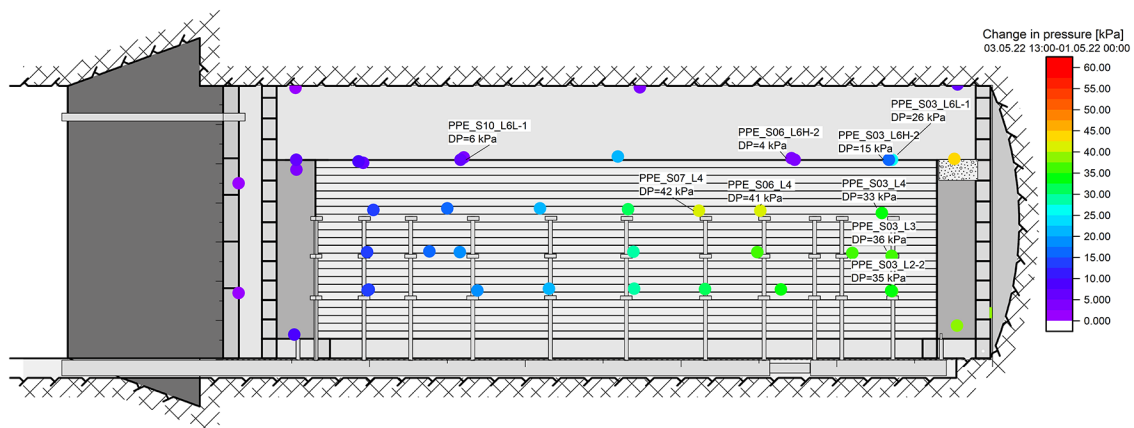


Fig. 3-13: Schematic vertical section showing pore pressure change from 01.05.22 to 03.05.22 13:00

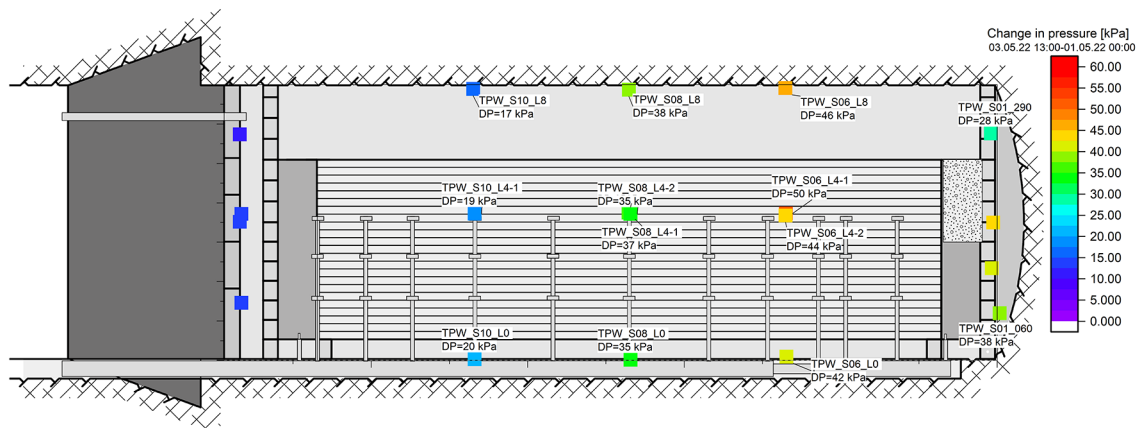


Fig. 3-14: Schematic vertical section showing total pressure change from 01.05.22 to 03.05.22 13:00

The measured pore pressure and pressure difference relative to PL_S02_L6L-1 are shown in Fig. 3-15 and Fig. 3-16. The pressure differences in S03 at L2 – L4 are below 250 kPa, while those at S03 L6 are much larger. The exact location of the gas entry into the sand/bentonite or the pressure at this point is unknown, but it is possible to infer that it is likely to be at the top of the filter and at pressures above those measured in the granular bentonite at S03_L6.

If the gas path was initially within the sand/bentonite-GBM interface at L6, it must then have branched into the body of the sand/bentonite to cause the reactions observed at L4. It is also possible that additional gas flow paths developed from the filter directly into the sand/bentonite as more water was extracted from the S02 filter.

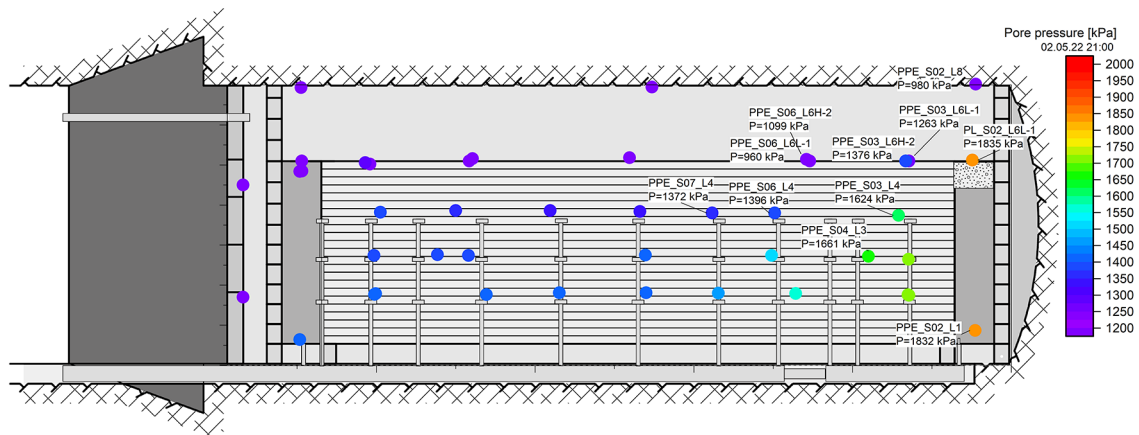


Fig. 3-15: Schematic vertical section showing measured pore pressure at 02.05.22 21:00

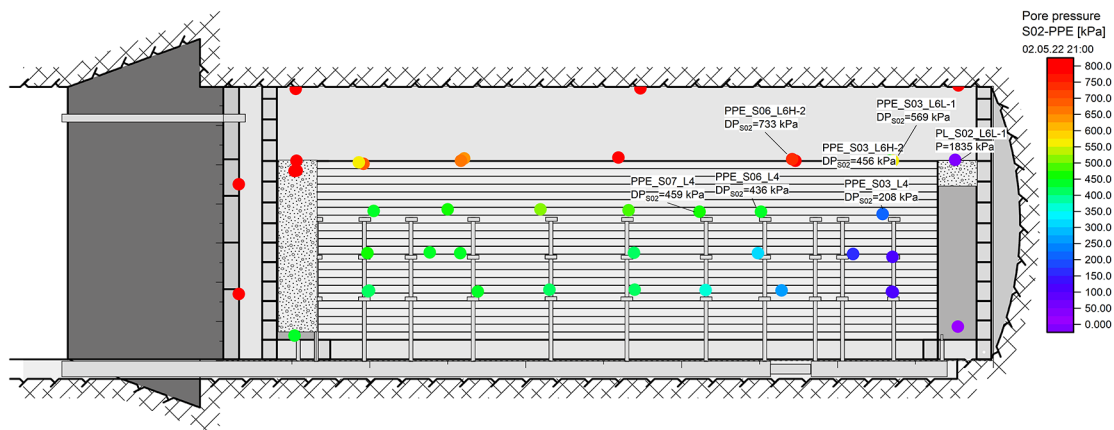


Fig. 3-16: Schematic vertical section showing pressure difference relative to S02 at 02.05.22 21:00

4 Phases 4 and 5 – Gas Mix #1 stable gas path with sampling (12.05.22 – 01.12.22)

4.1 Injection and extraction boundary conditions

Gas injection into S02 continued at a mean pressure of ~1,900 kPa using Gas Mix #1 ($N_2+2\%$ He). The S02 gas injection flowrate and S14 extraction flowrates are shown in Fig. 4-1. The S02 gas injection flow rate (and consequently S14 extraction rate) increased roughly linearly by a factor of 5 from ~150 mlN/min on 12.05.22 to 770 mlN/min on 01.12.22. Sinusoidal rate control was used for gas injection from 19.05.22 onwards with an amplitude of ± 80 mlN/min and a period of 333 minutes. The mean rate was progressively increased during the phase, while the sinusoidal amplitude and period were kept constant.

Both injection and extraction were largely stable during Phases 4 and 5, with only three significant interruptions (see grey markers in Fig. 4-1 and Fig. 4-2):

- 06.06.22 – 08.06.22 when the water level in S14 was sufficiently drawn down to result in clogging of the extraction line (PL_S14_L1). After the L1 extraction line was unclogged on 08.06.22, gas was produced. After this, the dominant flow from S14 was of gas with a small percentage of entrained water.
- 30.07.22 – 03.08.22 when failure of the S14 outflow valve resulted in the need to shut in the S02 gas injection,
- 14.11.22 – 16.11.22 when failure of the syringe pump resulted in a sudden drop in S14 pressure.

During most of the period, the outflow from S14 was controlled by the syringe pump to maintain a constant 1,400 kPa. However, between 15.06.22 and 16.08.22, the syringe pump was used for the initial PPE sampling campaign and flow was controlled by a pressure-controlled valve to the mock-up tank. The outflow during this period has been estimated (Rösli et al. 2025) and checked against the mock-up tank pressure record.

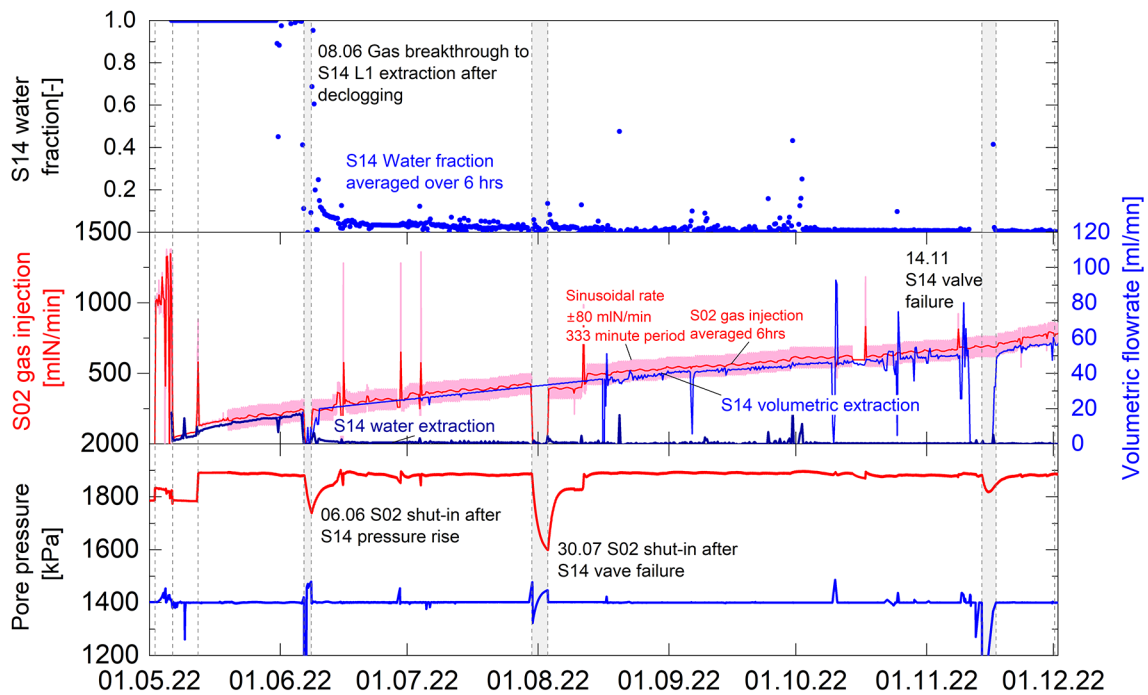


Fig. 4-1: S02 injection and S14 extraction rates during GFT Phases 4 and 5

In Fig. 4-2, the gas flow has been averaged and converted to equivalent volumetric flow at S14 pressure and temperature using the ideal gas law for comparison with the outflow from S14. The two are very highly correlated, indicating that almost all the gas flow from S02 is being produced from S14. Any gas not extracted from S14 is likely to have gone into solution in the porewater or into storage in the filters or gas flow path.

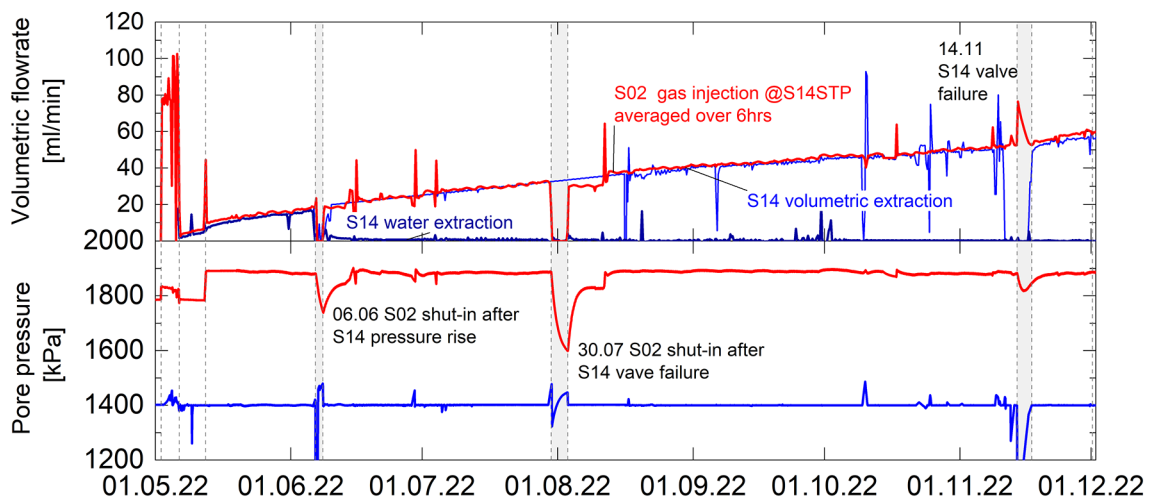


Fig. 4-2: Average volumetric flow rates and filter pressure during GFT Phases 4 and 5

Between 29.11.22 and 30.11.22, the Geomonitor DAS system was offline for a short period during an upgrade.

4.2 Pressure response

Fig. 4-3 shows the pressure profile along the GAST EBS on 01.05.22 and 01.12.22. Fig. 4-4 shows the pressure change since 01.05.22 (prior to the start of the W-GX). The overall pattern in L2, L3 and L4 is similar to that established early in the GFT (see Fig. 3-3 and Fig. 3-4). Fig. 4-6 and Fig. 4-7 show the measured pore pressure and pressure change since 01.05.22. Pressures are disturbed by the three interruptions mentioned earlier and by the pulse injection and pulse withdrawal (PI and PW) hydraulic index testing (see App. D) and PPE gas sampling. The different piezometer tests were:

- PI tests on 31.05.22 and 06.06.22. The L6 tests on 06.06. were performed in parallel with S14 de-clogging activities and used a relatively large delta pressure (up to ~800 kPa).
- PW tests on 06.06.22, 15.06.22 and 29. – 30.09.22: these tests were performed using a standard 2 ml withdrawal and can be compared with previous PW tests performed in March 2022 before the GFT.

PPE gas sampling in the flow field was initiated in Phase 5. Sampling requires significant time due to the line volumes associated with the piezometers (~100 ml), the sampler volume (25 ml) and the low flowrates from the sand/bentonite.

It is expected that the gas path will be discrete and of low volume. Where a piezometer is not close to a gas path, the low hydraulic conductivity of the sand/bentonite severely limits the flow, so that sampling is not possible. It was therefore necessary to select a small number of piezometers to sample during the phase: PPE_S10_L4, PPE_S08_L4 and PPE_S03_L3. After the successful sampling of PPE_S10_L4, PPE sampling was extended to include PPE_S03_L6L-1, PPE_S06_L4, PPE_S06_L6H-2 and PPE_S07_L2.

If the disturbances associated with sampling and testing are ignored, pore pressures are roughly stable with a slight decline. This is interpreted as the long-term response to the water displaced by formation of the gas path together with some effect of path development. The induced overpressure declines as water slowly leaks off into the surrounding GBM. The decline is greater for piezometers closer to S14 (S08 – S12) with pressure in sections S03 – S07 remaining more stable.

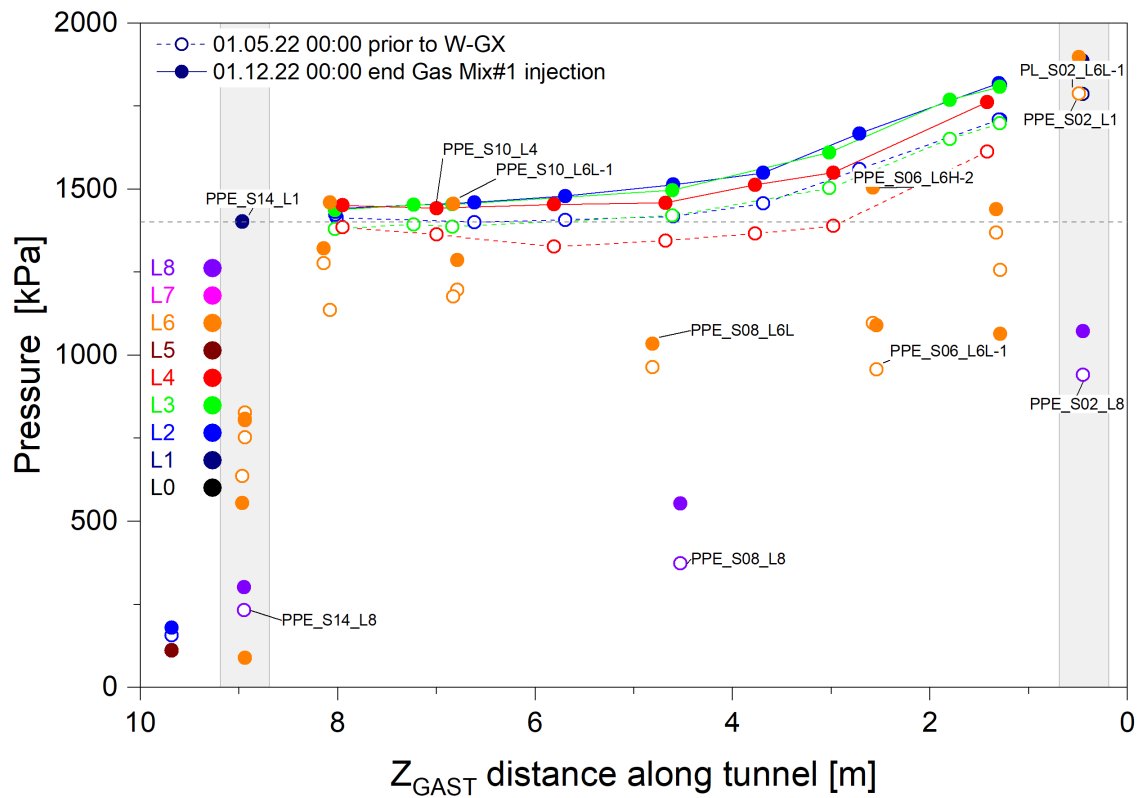


Fig. 4-3: Pressure profile along GAST ON 01.05.22 and 01.12.22

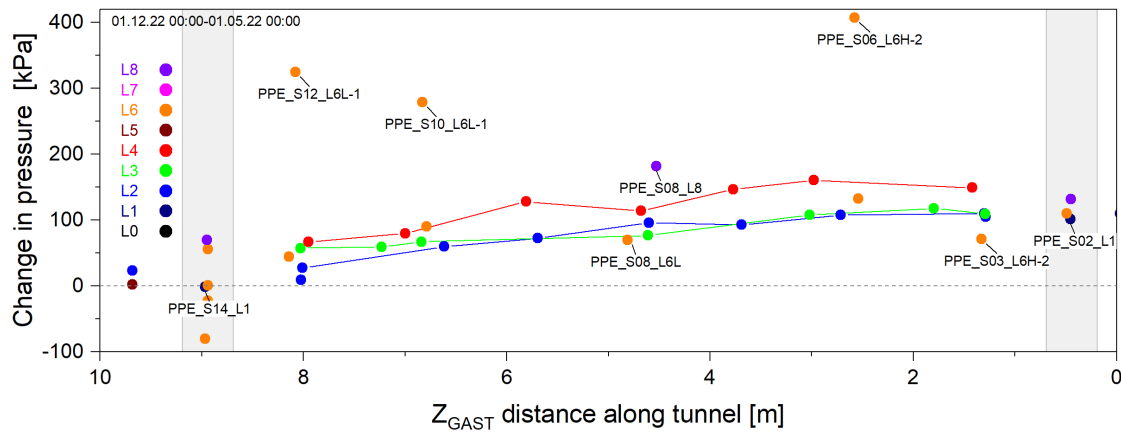


Fig. 4-4: Profile of change in pressure between 01.05.22 and 01.12.22 along GAST

The response to the different interruptions to injection are also clearly seen with the response largely controlled by distance to the S02 and S14 filters.

The convex shape of the pressure profile at L2, L3 and L4 indicates that the flow resistance across the seal is not uniform. Fig. 4-5 shows the profile on 01.12.22 and the expected profile for a) 1D uniform mass flow and b) 1D flow where the resistance to flow is greater between S02 and S08. For uniform 1D flow, the profile is slightly concave as volumetric flow increases as pressure decreases. The model profile with higher resistance to flow between S02 and S08 shows a much better match to the measured pressure. An alternative interpretation is that more gas is being transported between S02 and S08 than between S08 and S14 (i.e. there is some alternative path to S14 from S08).

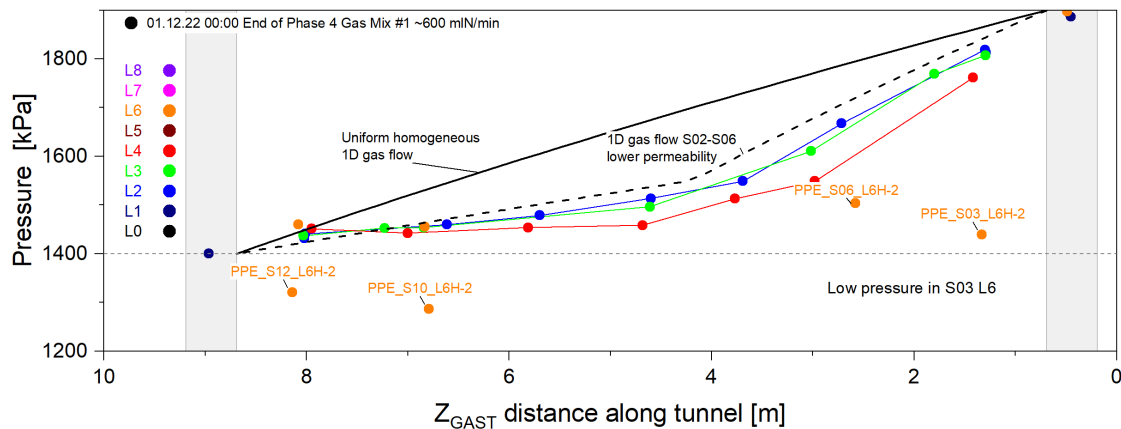


Fig. 4-5: Pressure profile on 01.12.22 and simple 1D flow model profiles

Pressure values and change from 01.05.22 are tabulated in Tab. 4-1 and Tab. 4-2.

Tab. 4-1: Pore pressure (kPa abs) values on 01.12.22 at 00:00

[illegible]

Tab. 4-2: Pore pressure change (kPa) from 01.05.22 00:00 to 01.12.22 00:00

[illegible]

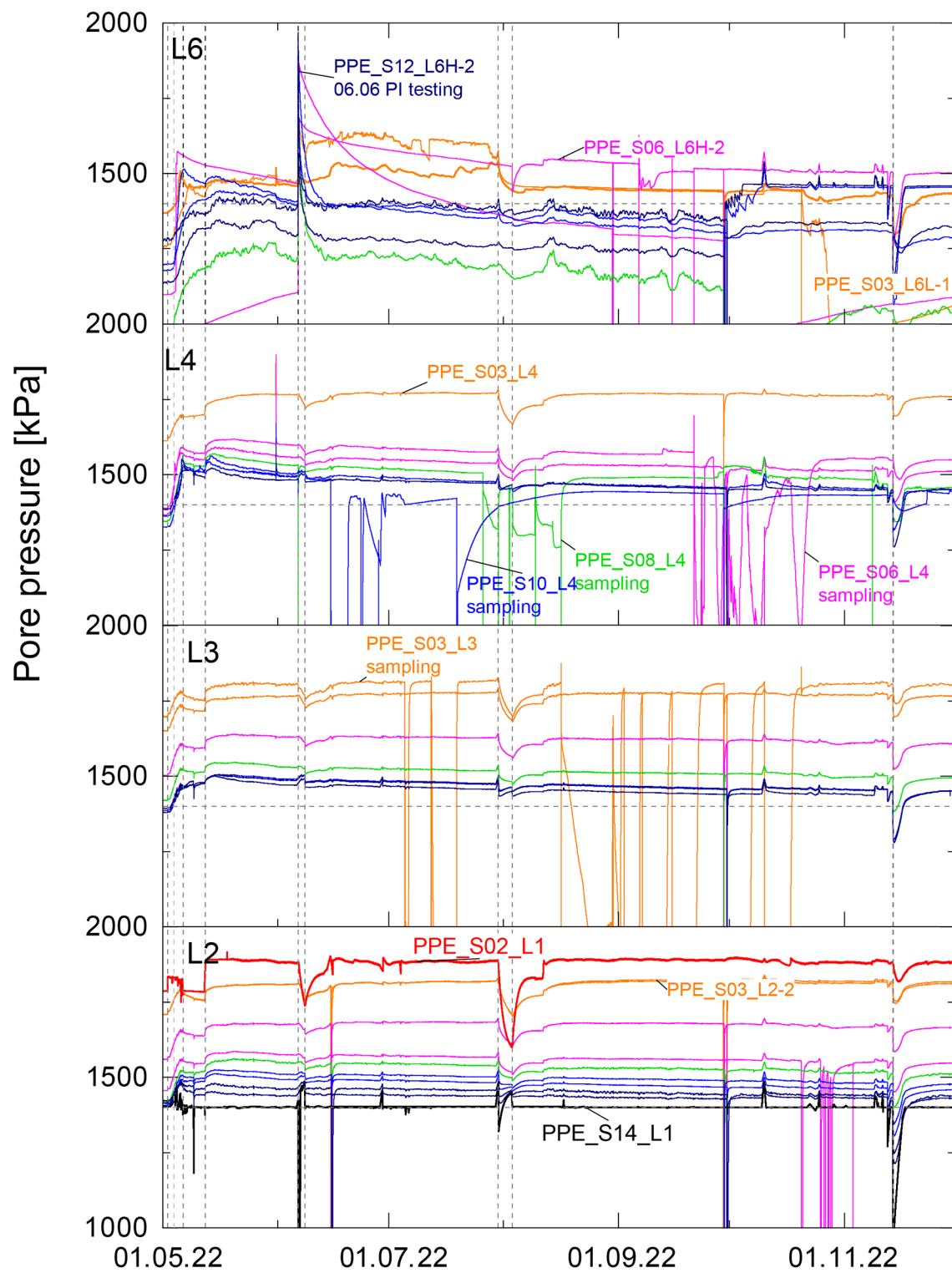


Fig. 4-6: Pore pressure during GFT Phases 2 – 5

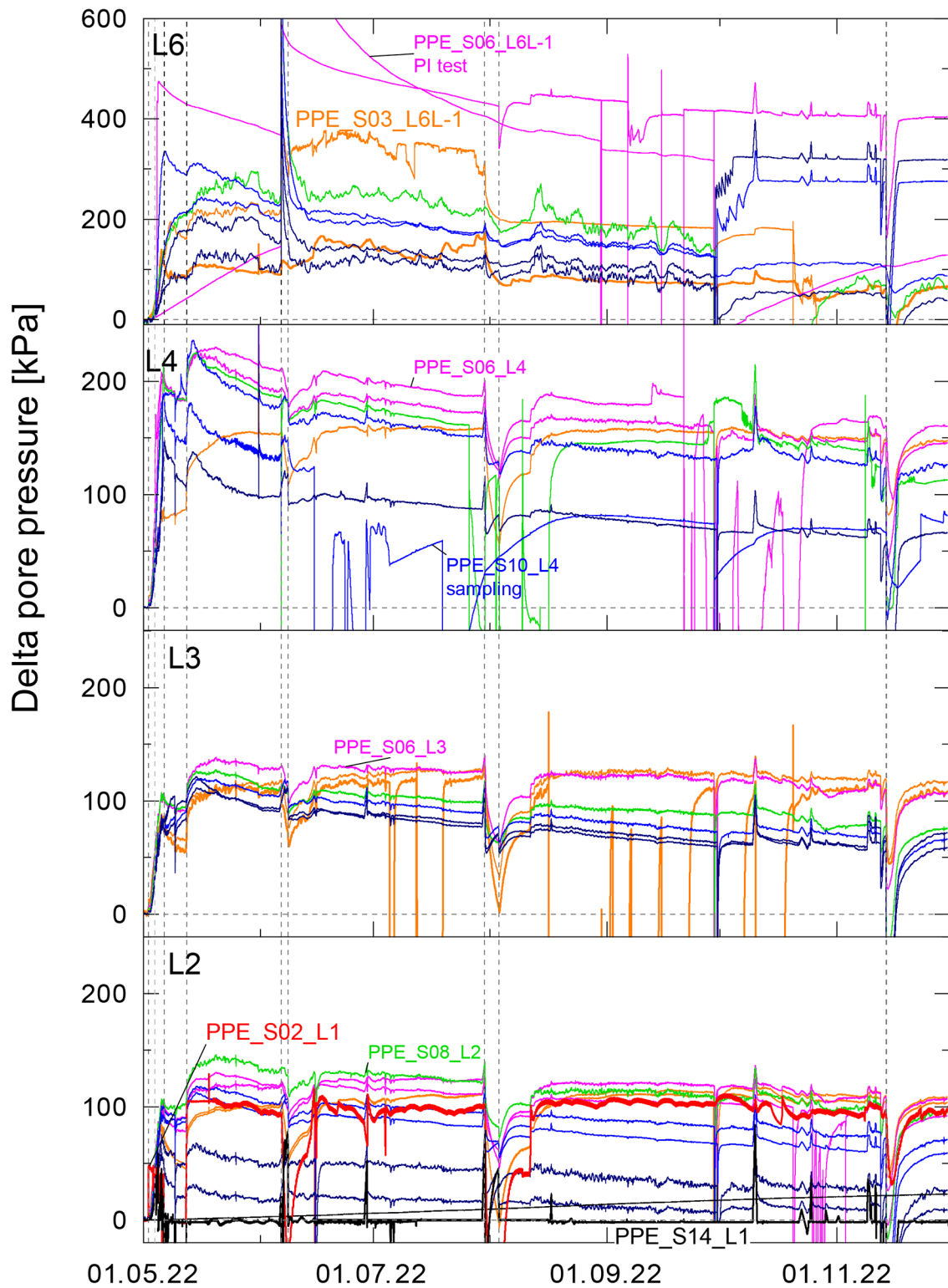


Fig. 4-7: Change in pressure during GFT Phases 2 – 5
Zero point on 01.05.22 at 00:00

4.3 Stress response

The measured changes in total pressures since the start of the GFT are shown in Fig. 4-8. The total pressures at the sidewall and base of the tunnel show a slight decline, but the TP cells at the top of the tunnel, in particular the radial cells at S06, S08, S10 and the axial cell at 290 cm in S01, show a strong linear increase in stress. The axial cell at 290 cm in S15 shows a slightly smaller increase. All the cells show responses to the three interruptions in injection. The rise in stress seen at the top of the tunnel does not correspond to the observed trend of pore pressure in the sand/bentonite and filters and could reflect the development of a trapped gas phase at or above L6. Although over 90% of the injected gas is extracted at S14, a small fraction of gas can build up within the experimental volume.

Total pressures on 01.05.22 and changes from the beginning of Phase 4 to the end of Phase 5 are tabulated in Tab. 4-3 and Tab. 4-4, respectively.

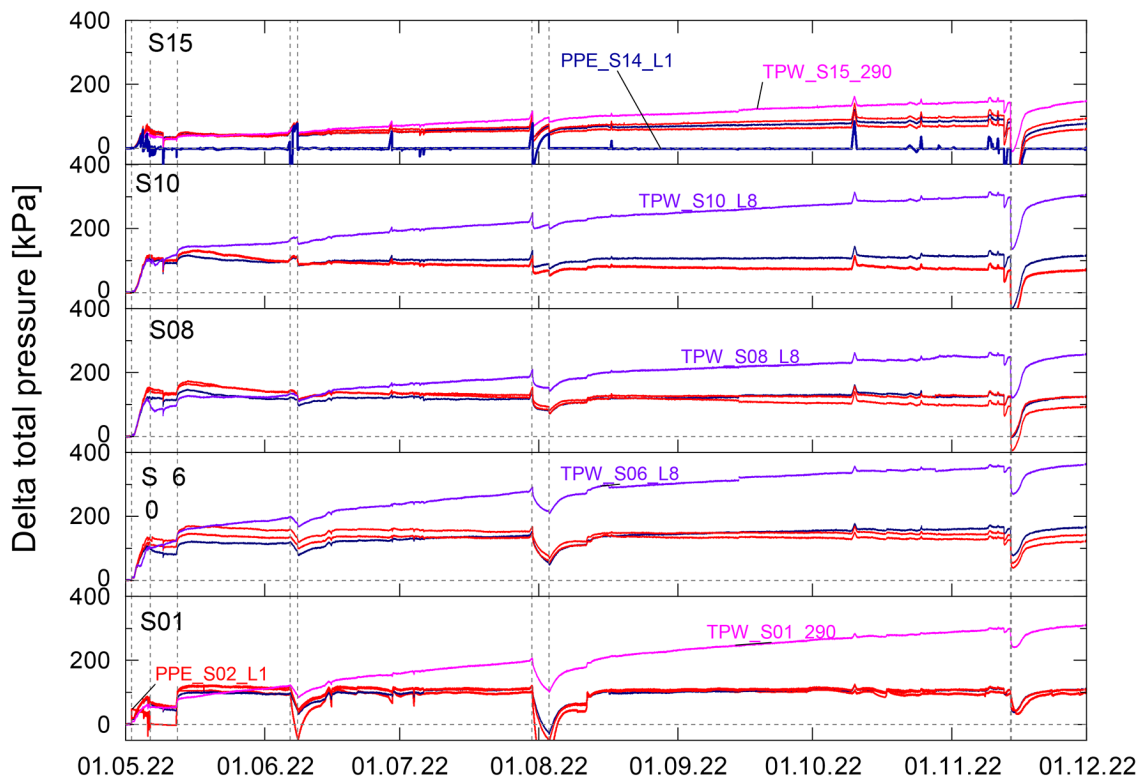


Fig. 4-8: Change in total pressure during GFT Phases 4 and 5

Tab. 4-3: Total pressure (kPa) values on 01.12.22 at 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8											
L7				*		*		*			3,122
L6	2,596										3,122
L5	2,302/ 2,400			2,239		2,409/ 2,467		2,444/ 2,471			2,485/ 2,550
L4											
L3											
L2	2,507										2,697
L1				2,873		2,791		3,000			
L0											

Tab. 4-4: Total pressure (kPa) change from 01.05.22 00:00 to 01.12.22 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				305		258		363			
L7											
L6	149			*		*		*			312
L5											
L4	60/ 94			71		95/ 124		123/ 142			110/ 111
L3											
L2											
L1	79										110
L0				116		124		166			

4.4 Saturation response (index tests, TDR)

The first campaign of hydraulic index testing during GFT was performed between 31.05.22 and 16.06.22 with a second repeat series performed on 29.09.22 and 30.09.22. These tests indicated an increase in compressibility at PPE_S10_L4 that led to the decision to start sampling from that PPE.

The response of the TDRs is presented in App. F. Changes in TDP traces during the period were identified in several sensors but typically did not show a clear change in travel time. The response of the TDL sensors to drainage of the S14 filter is discussed in Section 4.6.1. Significant saturation changes occurred in the S14 sand filter during drainage prior to the gas breakthrough at L1. Otherwise, saturation changes in the sand/bentonite are indicated by an increase in piezometer compressibility in L4 and L5, but no significant changes in water content are indicated by the TDP sensors. Successful gas sampling at PPE_S10_L4 and PPE_S06_L6H-2 confirmed the presence of a connected gas phase at these points. TDP_S10_L4-1 is located about 25 cm from PPE_S10_L4 and showed no significant change in trace shape or computed travel time, suggesting that gas paths are discrete and associated with only local scale desaturation.

Changes in GBM relative humidity (where monitored) were slow and very small. The two working RH sensors in the GBM at L7 in S03 and S10 remained above 94%, with RH_S03_L7-2 showing a slight reduction (~1%) in humidity from 07.07.22 with an accompanying increase in noise (the sensor temperature also rose slightly). The sensor in S10 showed a steady, slow increase in RH indicating an ongoing but very slow increase in saturation.

4.5 Gas tracers and sampling

Sampling from S14 extraction (PL_S14_L1) showed the presence of dissolved tracers (helium) in the water phase and subsequently in the free gas phase after breakthrough to L1 on 08.06.22. Helium was first detected in the extraction samples on 05.05.22 approximately three days after the start of the W-GX. Concentrations then increased, reaching 2% (the injected helium fraction) by July 2022. In the early phase of the W-GX, the argon concentration appeared to decrease. This decrease seen in the S14 extraction represents a shift from argon dissolving in the GAST sand/bentonite porewater prior to the GFT (see discussion of dipole test samples in App. E) to porewater (and later free gas) containing the injected gas. The observed trends are in good agreement with the qualitative on-site membrane module monitoring data.

Phase 5 saw the start of PPE sampling, with PPE_S10_L4 and PPE_S06_L6H-2 samples showing helium in the free gas phase. Other PPEs that were sampled produced only water with low helium concentrations (see Fig. 4-9).

Water samples from PL_S02_L1 showed dissolved He in the water phase in November 2022, indicating dissolution and mixing in the porewater within the filter.

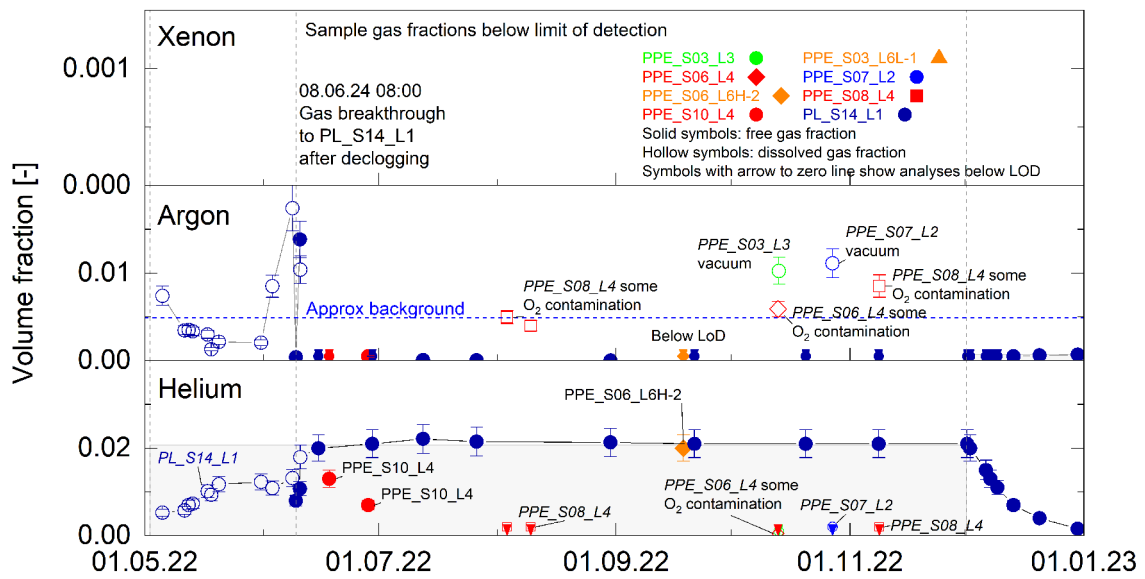


Fig. 4-9: S14 (PL_S14_L1) and PPE traced gas fractions during Phases 2 – 5

Dark blue symbols joined with a line are from S14. Hollow samples show dissolved gas fraction. Grey shading shows injection function. LOD: limit of detection.

4.6 Response to events during Phases 4 and 5 (analysis of shut-ins, pulses)

4.6.1 Drainage of S14 filter

Continuous water extraction from S14 continued from 07.05.22 until 06.06.22 when the extraction lines clogged. This occurred as the gas level in the filter approached the level of the extraction line. Fig. 4-10 shows the injection and extraction flowrates up to 12.06.22. When the lines clogged on 06.06.22, the total extracted volume from S14 was approximately 500 l¹². High-pressure water was injected into the PL_S14_L1 line to unclog the line. After the line was successfully unclogged on 08.06.22 at 08:01, the S14 outflow was predominantly gas.

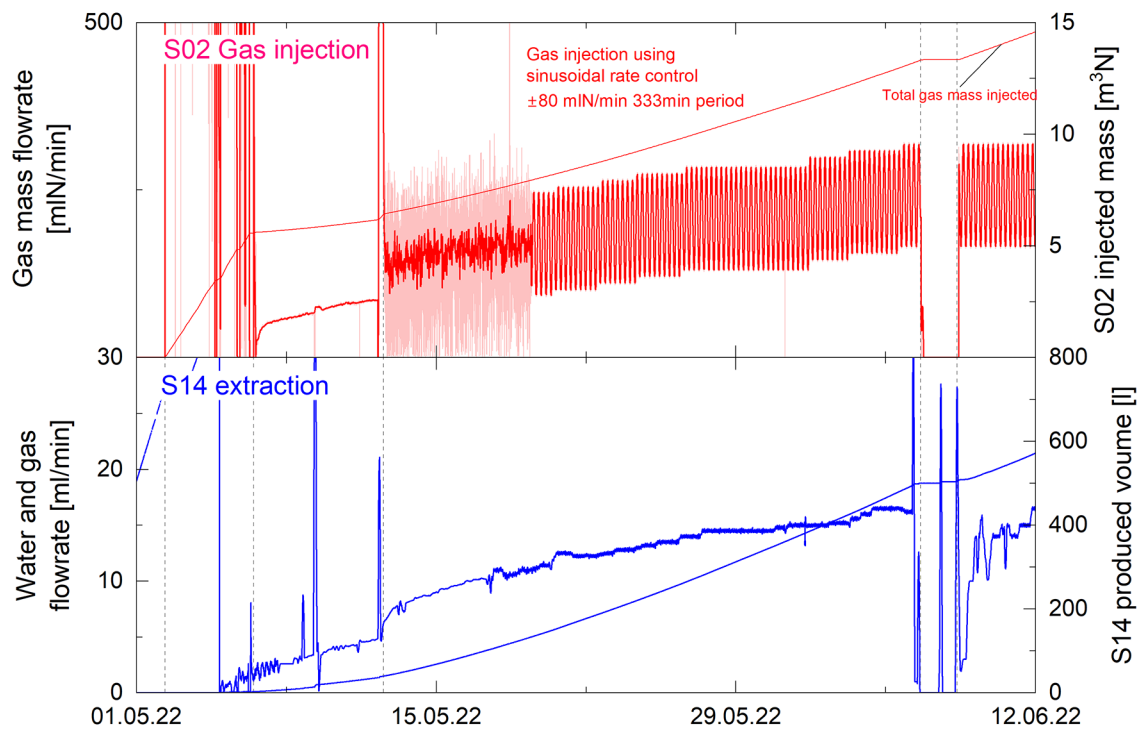


Fig. 4-10: S02 injection and S14 extraction rates during the early part of GFT Phase 4 (up to 12.06.22)

¹² This is significantly less than the estimated as-built filter porosity of 1,100 l, but is consistent with the possible reduced gas-accessible porosity filter observed in S02.

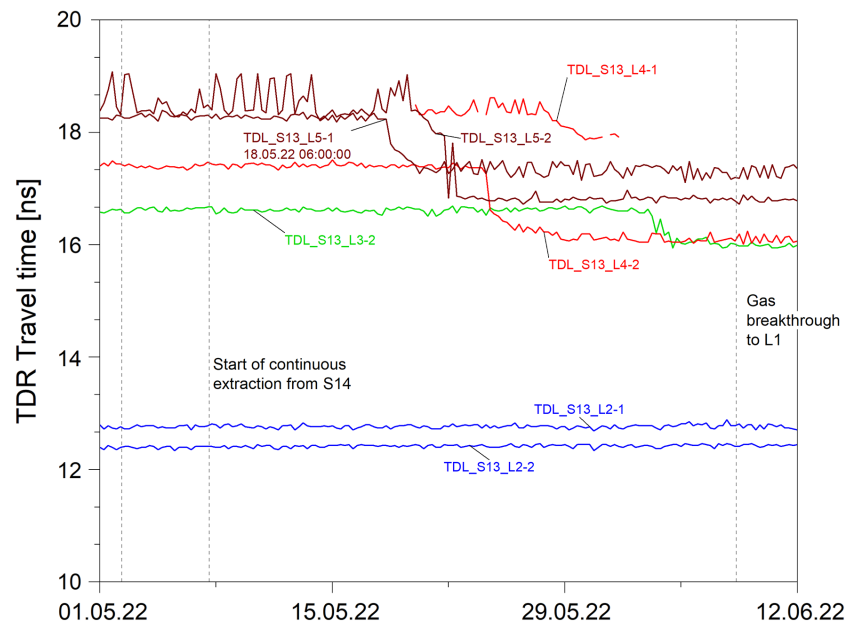


Fig. 4-11: Smoothed S13 TDL travel time from start of the GFT to 12.06.22

It was possible to monitor the drainage of the S14 filter using the TDL sensors on the filter-S/B interface at S13 (see App. F for a full discussion). Fig. 4-11 shows the reduction in travel time for the S13 TDL sensors from L5 (from 18.05.22) to L3 (03.06.22) as gas displaces the water in the filter. There is only a very gradual minor observed reduction in the L2 sensors' travel time – this may indicate either localised gas flow to the L1 outflow or reduced sensitivity of the L2 TDLs. The progressive downward movement of the gas front within the sand filter was captured by the TDLs at S13 as illustrated in Fig. 4-12.

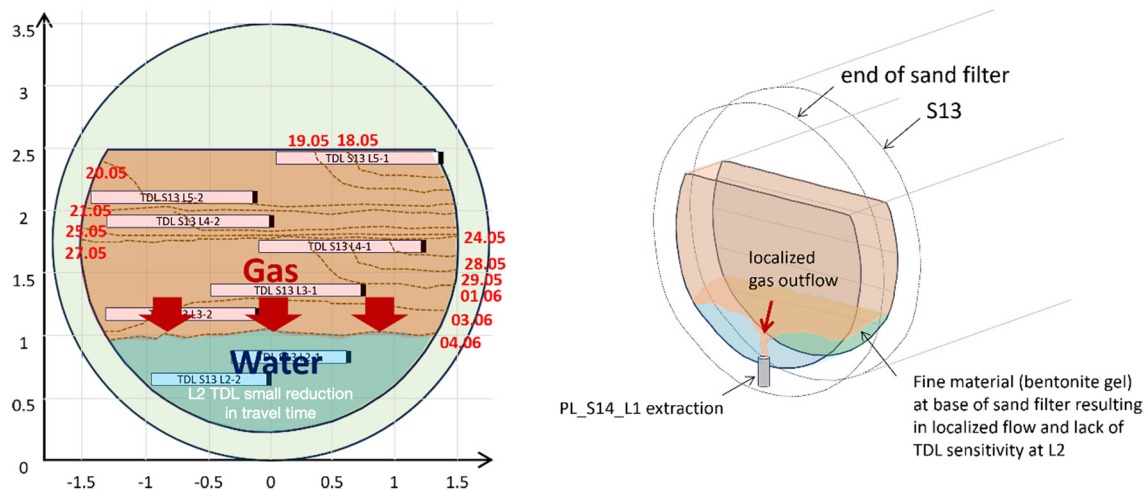


Fig. 4-12: S14 water level (left) evolution from TDL and (right) sketch of gas accumulation when the gas breakthrough took place on 08.06.22

4.6.2 Response to shut-in on 30.07.22

Fig. 4-13 shows the filter pressures during the shut-in of gas injection on 30.07.22 after pressure started to rise in S14 due to a valve failure. Pressure in S14 was manually reduced to 1,320 kPa after which the two pressures equilibrated over time towards the average pressure. Only partial equilibration occurred before the resumption of gas injection on 03.08.22.

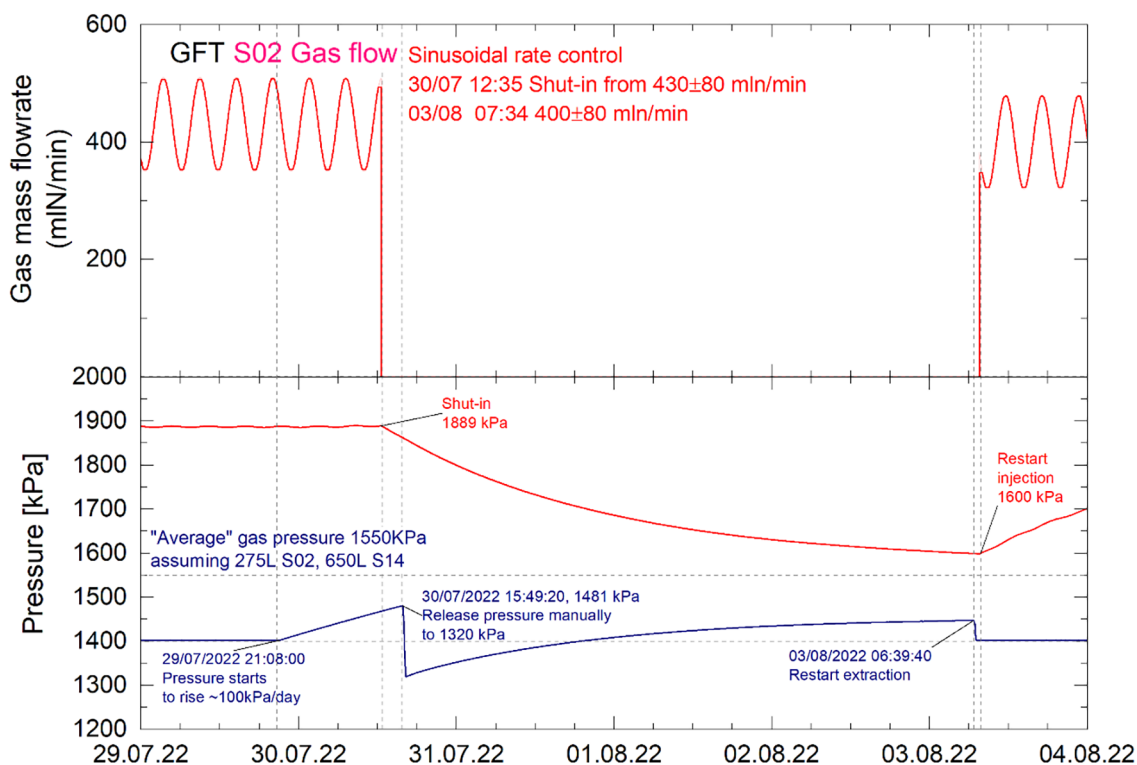


Fig. 4-13: Flow and filter pressure shut-in and restart (30.07.22 12:35 – 03.08.22 07:34)

Resumption of injection resulted in a quick return to the previous pressure conditions and flowrate, suggesting that the gas flow path remained essentially unchanged by the shut-in.

4.7 Interpretation summary

4.7.1 Gas flow path characteristics

During Phases 4 and 5, the gas path was stable and robust (recovering quickly after interruptions) with almost all gas injected at S02 being recovered from S14. The resistance to gas flow decreased with roughly linearly increasing injection flowrate over time for the same injection and extraction pressure. The short shut-ins did not appear to result in any significant changes in gas-path properties. The observed response to shut-in on 30.07.22 suggests that the gas path between the two filters remained connected over a range of filter pressures, allowing pressure to equilibrate between the two.

Water and later free gas samples from the S14 extraction (PL_S14_L1) showed increasing fractions of the gas tracer reaching ~100% of the injected concentrations as would be expected given the high gas recovery. Gas sampling at PPE_S10_L4 and PPE_S06_L6H-2 demonstrated the presence of free traced gases at these two piezometers. Sampling at other PPEs produced only water samples showing low helium concentrations.

The measured vertical stress at L8 continued to rise roughly linearly during the period although pressures were typically dropping. This perhaps indicates some volumetric expansion around L6 causing compression of the GBM and increased stresses.

4.7.2 Gas flow path summary data

Summary data for GFT Phases 3 – 5 are given in Tab. 4-5 (taken from Rösli et al. 2025, Tab. 4-14).

Tab. 4-5: Gas path summary GFT Phases 3 – 5 (Gas Mix #1 06.05.22 – 01.12.22)

Parameter	Value	Comment
Injection pressure (S02)	1,900 kPa	Constant pressure conditions maintained apart from short shut-ins for operational reasons
Extraction pressure (S14)	1,400 kPa	
Injection gas flow rate (S02)	87 – 800 mlN/min	Roughly linear increase in mean rate with sinusoidal component ± 80 mlN/min
Extraction volumetric rate	2.2 – 86 ml/min	Sinusoidal component from 17.05.22
Total gas injected	136.8 m ³ N	
Total gas extracted	119.6 m ³ N	Largely water up to 08.06.22, then gas
Overall recovery	87%	Average over Gas Mix #1 injection (Rösli et al. 2025, Tab. 4-14) Does not account for gas in S02 and S14 sand filters.
Extracted water volume	641.1 l	Water from drainage of S14 for L1 extraction and some flow from S/B
Tracer fraction (S14)	~100%	Tracer concentration from the L1 extraction increased over time reaching ~100% of injected concentration after L1 breakthrough (see Fig. 4-9)
Tracer fraction (PPEs)	PPE_S06_L6H-2 100%	Similar response to S14 L1 extraction
	PPE_S10_L4 tracer detected	Did not reach 100% injection concentration

Approximately 17.1 m³N gas was not recovered from S14 during this period. The uncertainty in the unrecovered gas is ~730 lN assuming an uncertainty in the two flow measurements of 0.4%, see App. B). This may be an underestimate as the accuracy of the extraction flow measurement was reduced for the period when the syringe pump was in use for sampling.

This unrecovered gas is likely to be made up of the following “sinks”:

- free gas in S14,
- additional free gas stored in S02 due to drainage and the increase in pressure since the W-GX,
- gas in the flow path,
- gas in solution in the S02 and S14 porewater,
- gas in solution in the sand/bentonite porewater,
- gas accumulated at the top of the sand/bentonite or lost to GBM or other leakage paths (e.g. geosphere and tunnels).

Tab. 4-6 and Tab. 4-7 give approximate estimates of the possible free gas and dissolved gas sinks. In total, they could account for up to 6.9 – 14.7 m³N of gas leaving somewhere between 2% and 8% of the gas accumulated within the seal section or lost to leakage.

Tab. 4-6: Estimates of unrecovered free gas mass

Assumes temperature of 13.5 °C

“Sink”	Mass of gas [IN]		Volume of gas [l]		Pressure [bar]	Comment
	Min.	Max.	Min.	Max.		
Gas in S14	6,670	8,671	500	650	14	
Additional gas in S02	0	359	300	325	19	
Gas in flow path	152	1,525	10	100	16	
Total	6,823	10,555				

Tab. 4-7: Estimates of unrecovered dissolved gas mass

Assumes gas solubility of 0.0145 IN/kg

“Sink”	Mass of gas [IN]		Volume of gas-accessible porewater [l]		Pressure [bar]	Comment
	Min.	Max.	Min.	Max.		
Porewater in S14	0	20	0	100	14	Remnant porewater not drained from S14
Porewater in S02	83	110	300	400	19	S02 porewater left in S02 after the W-GX
Porewater in sand/bentonite	0	4,051	0	17,450	16	Minimum assumes no dissolution, maximum uses total pore volume in sand/bentonite
Total	83	4,182				

5 Phases 6 and 7 – N₂ flush and switch to rate control (01.12.22 – 18.04.23)

5.1 Injection and extraction boundary conditions

Phase 6 started with the switch from Gas Mix #1 (N₂+2% He) to N₂ injection on 01.12.22 at 07:05. All other conditions remained the same, with a continuing increase in flow at stable injection and extraction pressures. The flushing of traced gas was monitored on-site with the miniRUEDI system (portable mass spectrometer) measuring composition in the gas headspace of the membrane module, and with periodic sampling at S14 extraction for quantitative laboratory analyses (see App. E). During the clean-up period, it was necessary to prepare for the second phase of tracer injection using Gas Mix #2, which required recalibration of the flowmeter to the new gas mix.

The ongoing increase in gas injection rates resulted in extraction rates at S14 close to the limit of the syringe pump. To ensure long-term continued testing (~4 months of injection with 2nd tracer mix plus clean-up with a second N₂ flush), it was decided to reduce the injection rate and to switch to controlling rates rather than filter pressure. This was expected to provide simpler operational conditions and higher quality flow and pressure data. The switch to controlled rates was performed when a mass flow meter (FG_Inj_Mass) was in operation as the Flow_HI flowmeter was being recalibrated. The switch to a fixed injection rate of 90 g/hr (equivalent 100 mlN/min) occurred on 22.03.23 with a second step reduction to 60 g/hr (800 mlN/min) on 23.03.23. The S02 and S14 filter pressure and flow rates are shown in Fig. 5-1.

Gas injection and extraction were shut in from 30.12.22 09:38 to 10.01.23 08:38. The shut-in was planned to allow a period with limited requirements for on-site intervention and provide additional characterisation of the gas path.

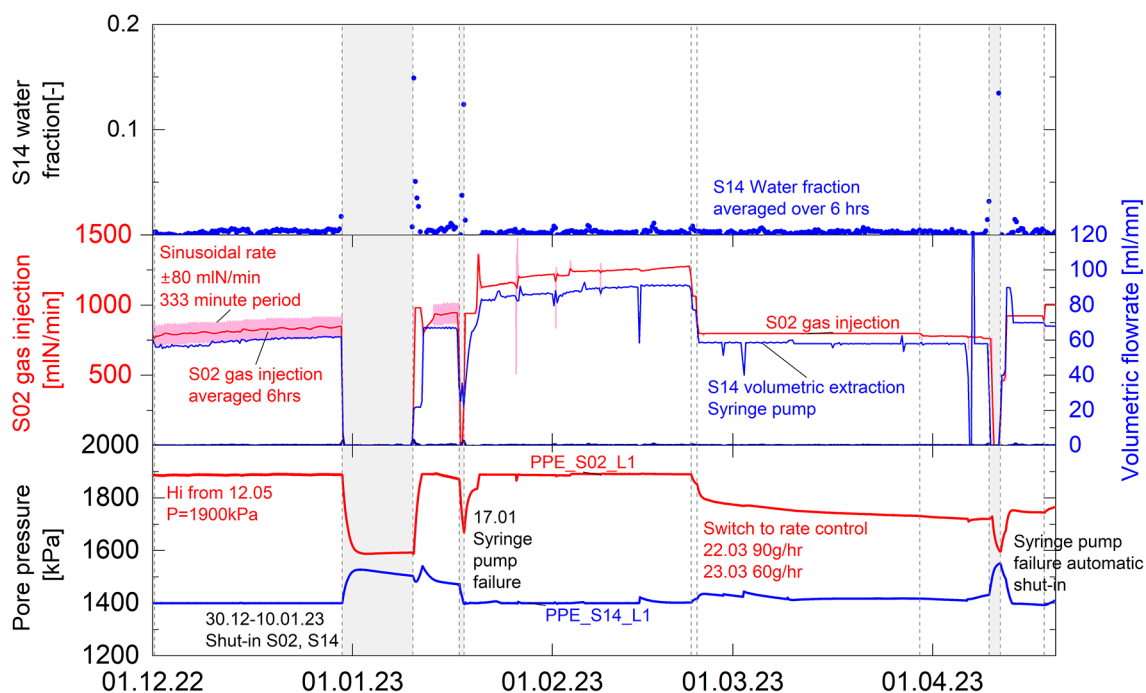


Fig. 5-1: Filter pressure, flow rates and S14 water fraction during Phases 6 and 7

5.2 Pressure response

Fig. 5-2 shows the pressure distribution across the seal section during Phases 6 and 7. The major change was the switch from constant pressure to constant injection rate and the consequent drop in S02 sand filter pressure. At L4, the pressure shows a clear gradient from S03 to S08 with a much lower gradient from S09 to S12. At levels L3 and L2, a pressure gradient from S09 to S12 is evident. The heterogeneous connectivity at L6 results in no clear pressure gradient across the seal at this level.

The gradients across the seal section showed a minor decrease with the reduction in injection rates, but no significant change in pattern with a steeper pressure gradient close to S02 and a shallow gradient close to S14 in L2, L3 and L4. As mentioned previously, uniform gas flow (homogeneous 1D) between the two filters would result in the gradient increasing towards S14 as the gas volume expands due to the drop in pressure. The pattern seen in Fig. 5-2 suggests a higher resistance to flow near S03.

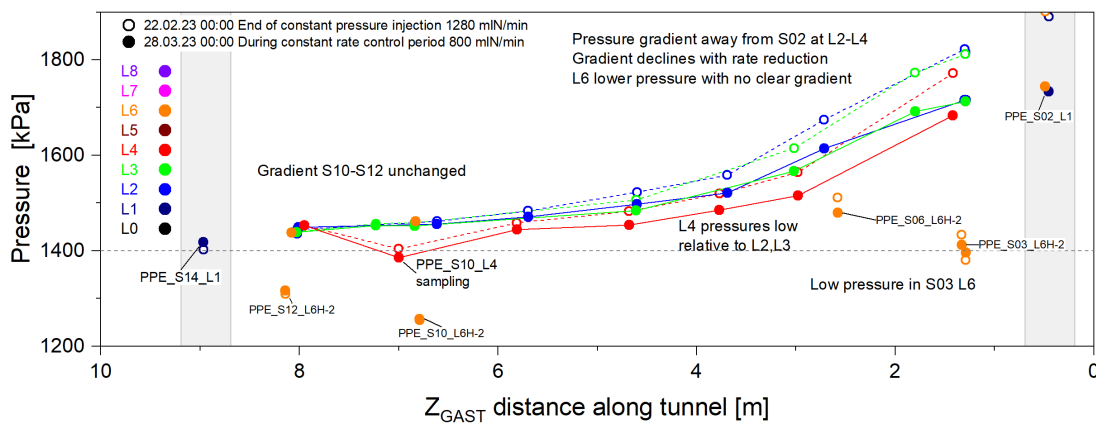


Fig. 5-2: Pressure profile across seal section during Phases 6 and 7

Pressure in the sand/bentonite was largely stable until the shut-in and rate changes (Fig. 5-3). Pressure data typically show quick recovery from the PW tests apart from some of the piezometers in L6 which are assumed to be in low-permeability GBM.

PW tests in L6 on 30.03.22 resulted in some long-term changes with a reduction in the pressure differences across L6. The pressure differences between PPE_S03_L6L-1, PPE_S06_L6H-2, PPE_S10_L6L-1, PPE_S12_L6L-1 and PPE_S12_L6H-2 drop, indicating potentially better connectivity between these piezometers. This appears to be due to local effects as the overall performance of the gas path remains largely unchanged (no effect on S02 and S14 pressure).

The pressure changes plotted in Fig. 5-4 show a pattern that is largely comparable with that seen in the absolute values but are influenced in L6 by pressure heterogeneity at the start of the GFT. L6 shows no clear gradient with low pressure (significantly below S02) measured in S03.

Pressure values on 18.04.23 and changes since 01.05.22 are tabulated in Tab. 5-1 and Tab. 5-2.

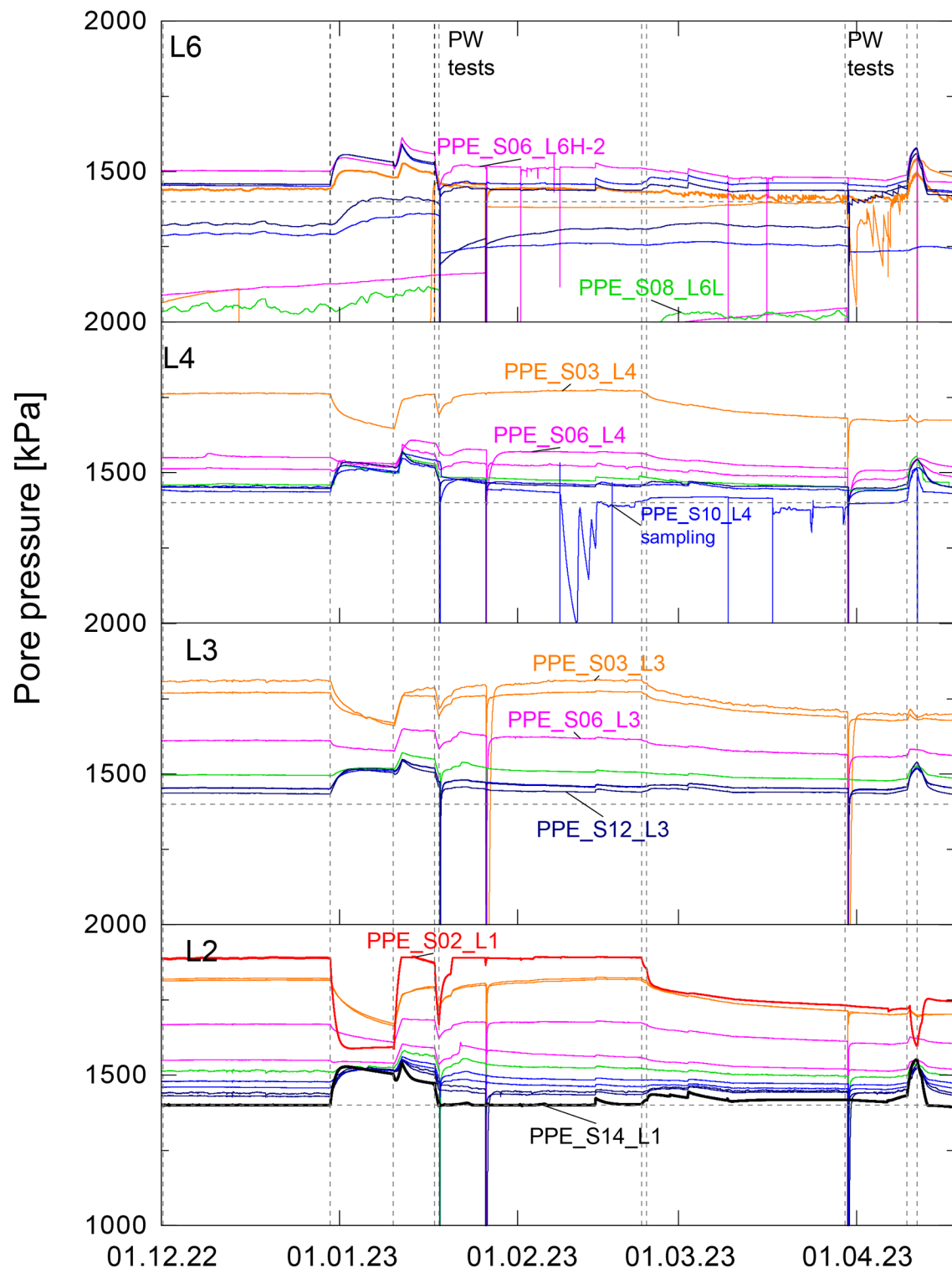


Fig. 5-3: Pore pressure during Phases 6 and 7

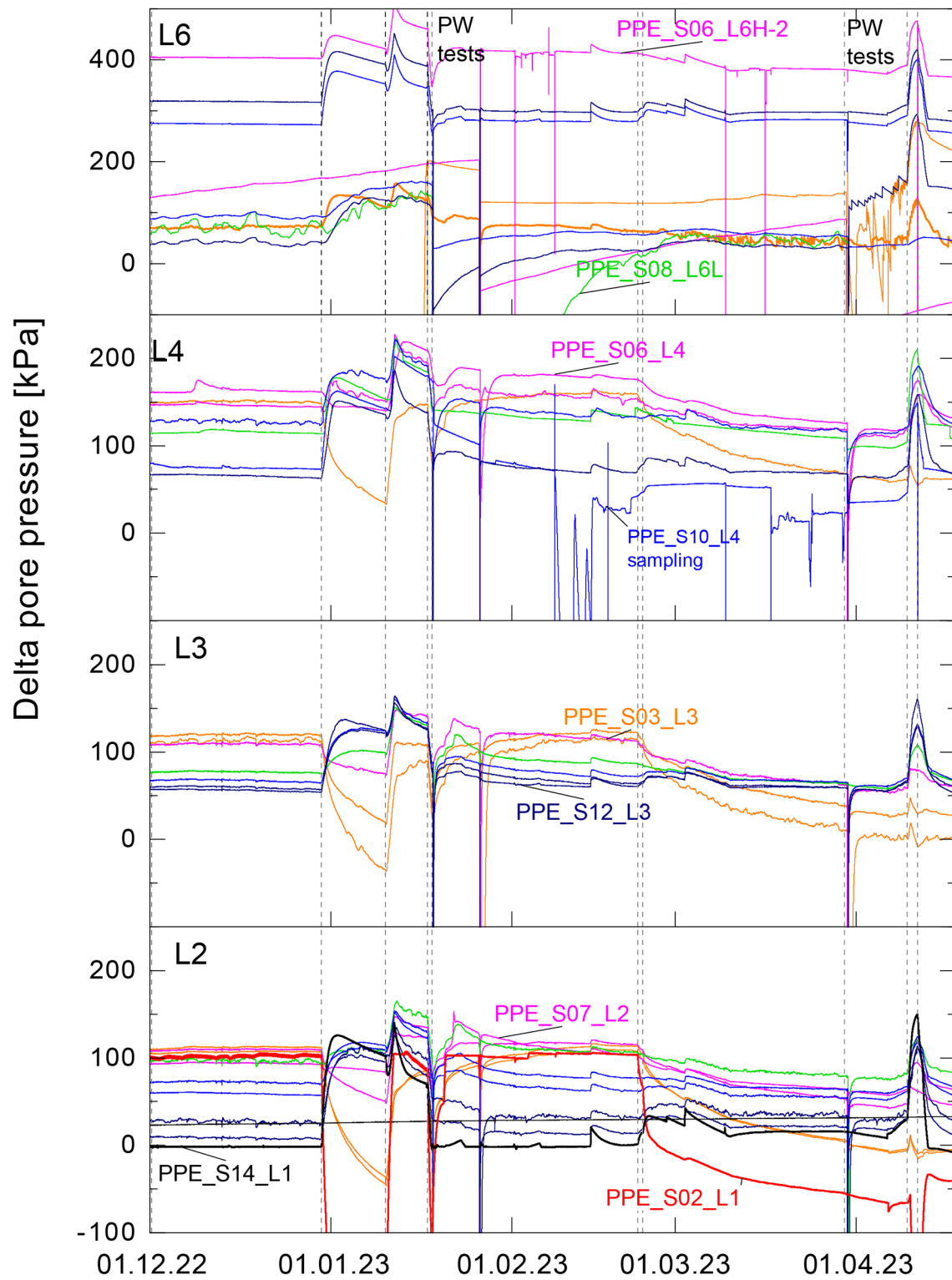


Fig. 5-4: Change in pore pressure during Phases 6 and 7 from the start of the GFT (01.01.22)

[illegible][illegible]

5.3 Stress response

Total pressures are stable and consistently above 2,000 kPa (Tab. 5-3). They show the influence of the shut-in and rate change (Fig. 5-5). Total pressure rises during the shut-in from S08 to S15 (influenced by the increase in S14 pressure), but declines in S01 and S06 (influenced by the drop in S02 pressure). There is an ongoing increase in the vertical stress measured at the tunnel roof in S06, S08 and S10 and in the axial stress measured at 290 cm in S01 and S15.

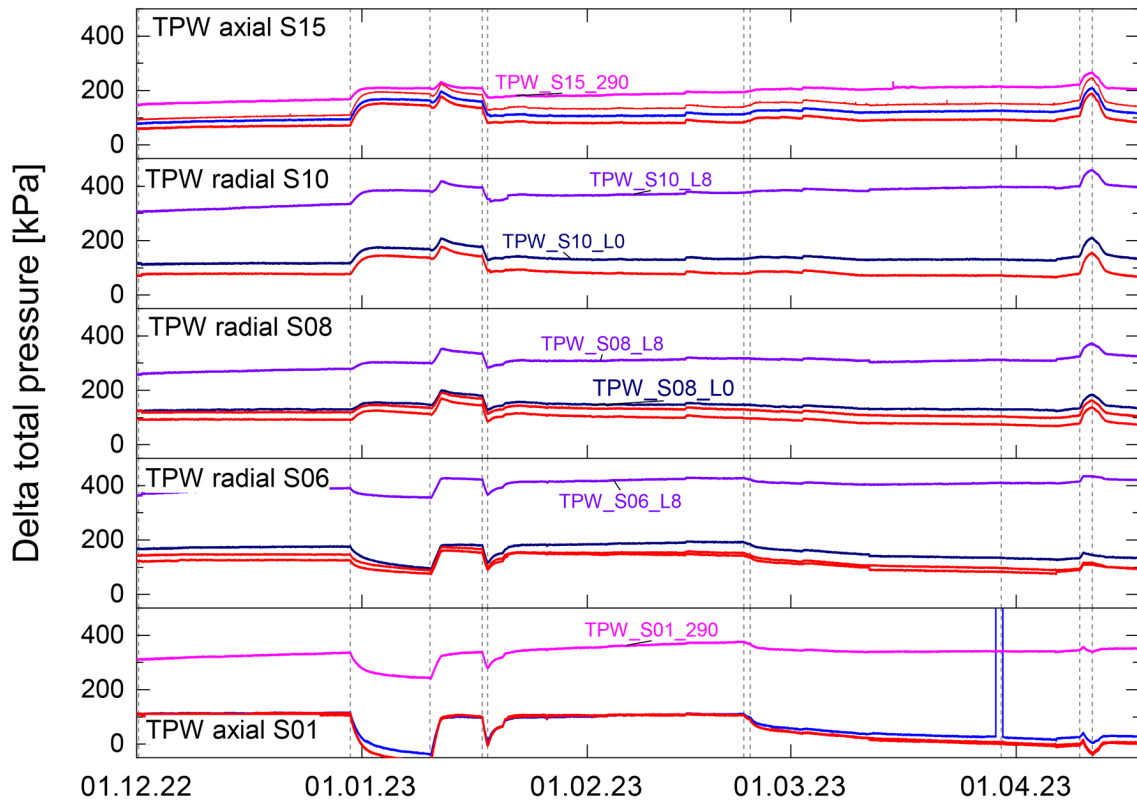


Fig. 5-5: Change in total pressure from start of the GFT during Phases 6 and 7

Total pressure values on 18.04.23 and changes since 01.05.22 are tabulated in Tab. 5-3 and Tab. 5-4.

Tab. 5-3: Total pressure (kPa) values on 18.04.23 at 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				2,582		2,614		2,492			
L7											
L6	2,653			*		*		*			3,162
L5											
L4	2,350/ 2,423			2,235		2,388/ 2,447		2,415/ 2,421			2,380/ 2,442
L3											
L2											
L1	2,545										2,614
L0				2,889		2,798		2,967			

Tab. 5-4: Total pressure (kPa) change from 01.05.22 00:00 to 18.04.23 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				395		325		420			
L7											
L6	206			*		*		*			352
L5											
L4	84/ 141			67		75/ 104		93/ 94			2/ 6
L3											
L2											
L1	117										27
L0				132		132		132			

5.4 Saturation response (TDR, index tests)

The response of the TDRs is presented in App. F. Changes in TDP traces during the period were identified in several of the sensors but typically did not show a clear change in travel time.

Two index testing campaigns were performed during this period on 18.01.23 and 30.03.23. Saturation changes in the sand/bentonite are indicated by an increase in piezometer compressibility in L4 and L6, but no large changes in water content are indicated by the TDP sensors. Continued gas sampling at PPE_S10_L4 and PPE_S06_L6H-2 confirmed the presence of a connected gas phase at these points.

The two RH sensors in the GBM at L7 in S03 and S10 remained above 94%. Data from RH_S03_L7-2 were somewhat noisy while the sensor in S10 showed a slow but steady increase in RH indicating ongoing but very slow saturation.

5.5 Gas tracers and sampling

Gas sampling from the S14 extraction (PL_S14_L1) clearly showed the tailing of the helium tracer used in Gas Mix #1. The tailing occurred over about a month, reflecting the expected mixing in the gas volumes in the S02 and S14 sand filters (Fig. 5-6).

Sampling from PPEs was limited, with only five samples taken (2 each in PPE_S06_L6H-1 and PPE_S10_L4 and one in PPE_S03_L6L-1). The samples were taken after the observed tailing in the extraction (PL_S14_L1) and showed low helium and argon concentrations, close to those in the injected N₂. This would indicate that the N₂ flush had been effective both in the sand filter pore volumes and in the flow path within the sand/bentonite. It is possible that some isolated pockets of traced gas were present in the sand/bentonite.

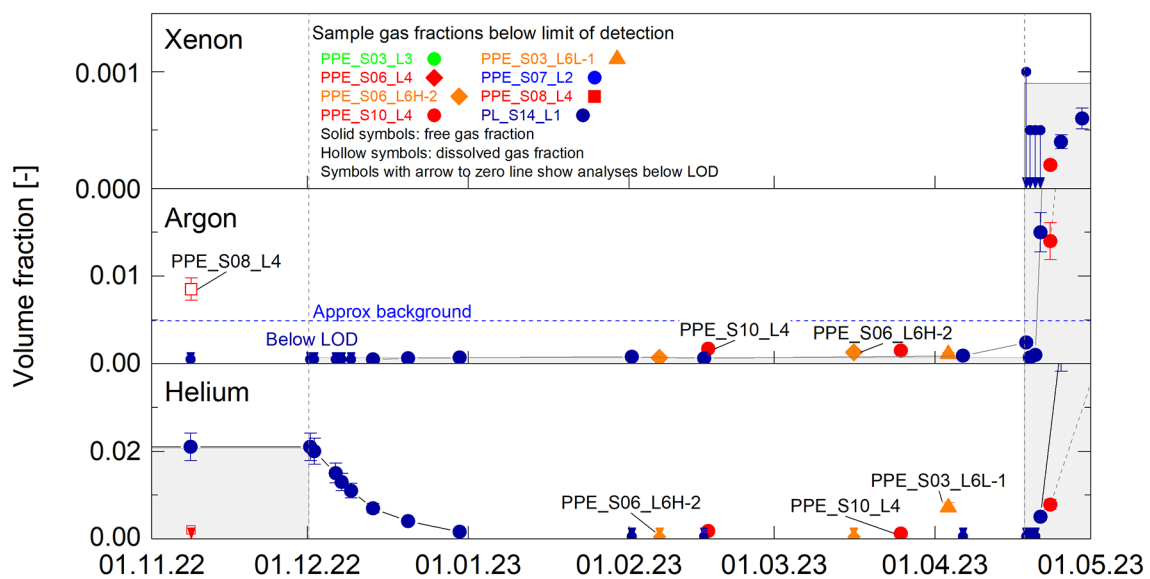


Fig. 5-6: S14 (PL_S14_L1) and PPE traced gas fractions during Phases 6 and 7

Dark blue symbols joined with a line are from S14. PPE samples are coloured by sensor level and labelled.

5.6 Response to events during Phases 5 and 6

5.6.1 Shut-in 30.12.22 – 10.01.23

Fig. 5-7 shows the filter pressure and gas injection rate during the shut-in and restart period. After the restart, pressure in S02 quickly recovered to 1,900 kPa but required ~20% higher rate than before the shut-in, possibly indicating a reduction in tortuosity of the gas path. Some adjustments in the extraction rate and a further short shut-in of S02 were required to stabilise the S14 pressure at ~1,400 kPa.

During the shut-in and after an initial equilibration period when the S02 and S14 pressures converge, the pressures stabilise with S02 slightly increasing from a minimum of ~1,590 kPa, while S14 declines slowly from a peak of ~1,530 kPa.

This behaviour is interpreted as indicating that the gas path has broken down (“snap-off”¹³). The pressure in S14 slowly leaks off while there is some back-flow from the higher-pressure parts of the sand/bentonite around the filter into S02.

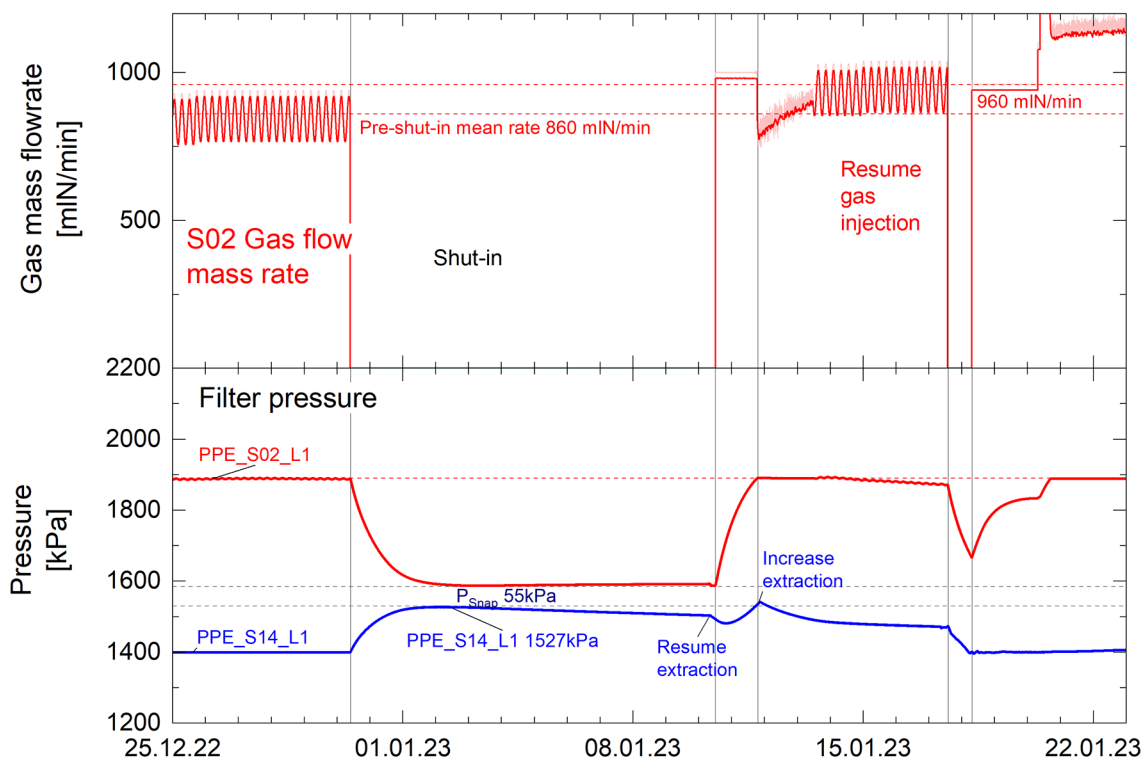


Fig. 5-7: Filter pressure and flow rates during shut-in and resumption of flow

¹³ For a discussion of “snap-off” pressures in laboratory testing, see Amann-Hildenbrand et al. (2012).

5.6.2 Rate changes on 22.03.23 and 23.03.23

The reduction in gas injection rate occurred on 22.03.23 (to 90 g/hr) and 23.03.23 (60 g/hr) and resulted in a relatively rapid reduction in pressure in S02 (Fig. 5-8). The S14 volumetric extraction rate was adjusted at the same time to roughly match the injection rate. There was a slight increase in S14 pressure due to ongoing flow from storage in S02 as the pressure decreased. Pressure in S14 was also affected by two syringe pump halts, which required manual restarts.

In the longer term, pressure in S14 stabilised at a little below 1,420 kPa while pressure in S02 showed a roughly linear decline of ~1 kPa/day which is interpreted as the influence of ongoing gas path development. Previously when the filter pressures were kept constant, this resulted in a roughly linear increase in rate over time. Once rates were controlled, changes in flow path resistance were seen as trends in the filter pressure.

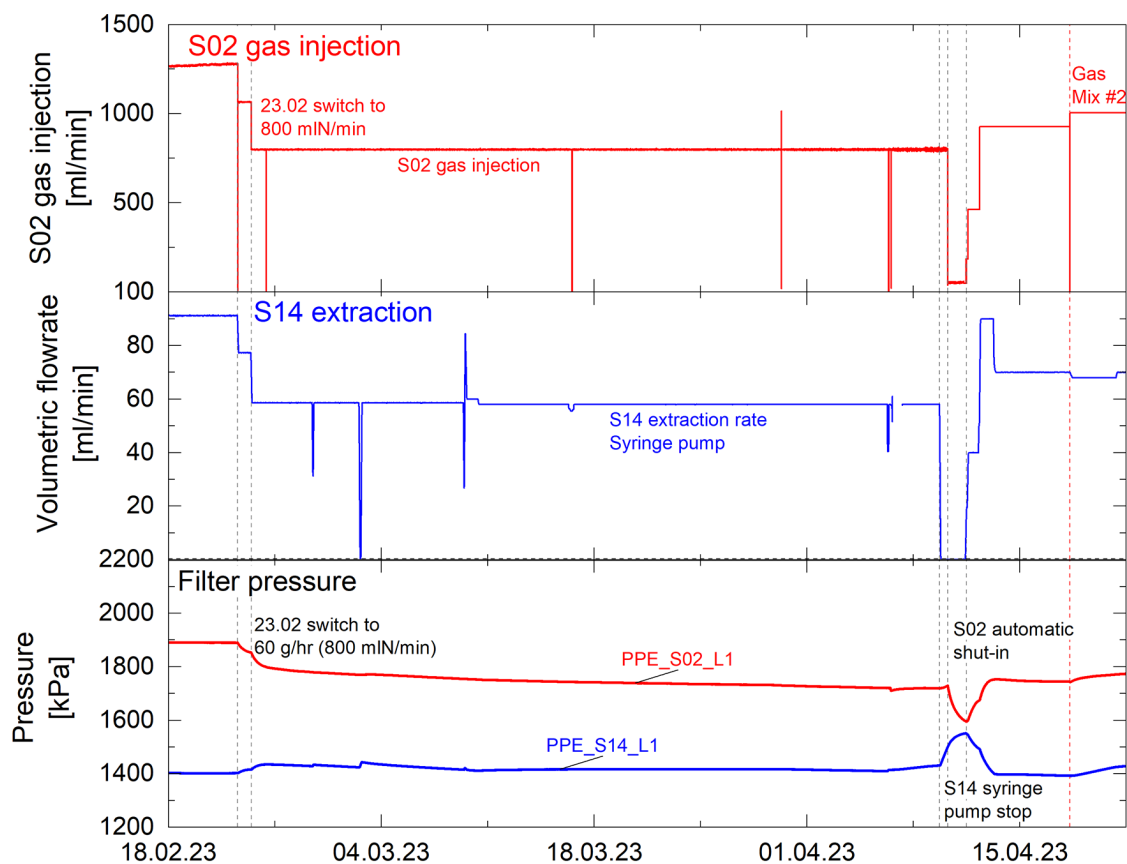


Fig. 5-8: Filter pressure and flow rates following the rate change on 22.03.2023

The influence of the rate change and associated filter pressure changes can be seen in the piezometer data shown in Fig. 5-9. At levels L2, L3 and L4, the response is largely controlled by the distance from S02 and S14, but in L6, there is a rather heterogeneous response with some piezometers clearly showing the influence of S14 pressure changes (PPE_S12_L6L-1, PPE_S10_L6L-1 and PPE_S06_L6H-2). This is consistent with the observed heterogeneous nature of gas paths in L6. The connection from S14 to PPE_S06_L6H-2 is striking given its location closer to S02 than S14.

A syringe pump halt on 09.04.23 resulted in increasing pressure in S14 and automatic shut-in of gas injection into S02 on 10.04.23 (Fig. 5-8). Extraction and gas injection were resumed on 11.04.23 and it was decided to increase the injection rate to 1,000 mL/min (as measured by the Bronkhorst flowmeter calibrated for the new mix) for the longer-term injection. The S14 extraction rate was adjusted accordingly. The injection and extraction rates are tabulated in Tab. 5-5. The switch to the Gas Mix #2 took place on 18.04.23.

Tab. 5-5: Flow rate changes at end of Phase 7

When	S02 injection [mL/min N ₂]	S14 extraction [mL/min]
09.04.23 18:16	840	Shut-in
10.04.23 06:00	Shut-in	Shut-in
11.04.23 12:00	200	20
11.04.23 14:00	500	40
12.04.23 08:36	1,000	90
13.04.23 07:23	1,000	Switch to 70
18.04.23 07:20	1,000 switch to Gas Mix #2	70

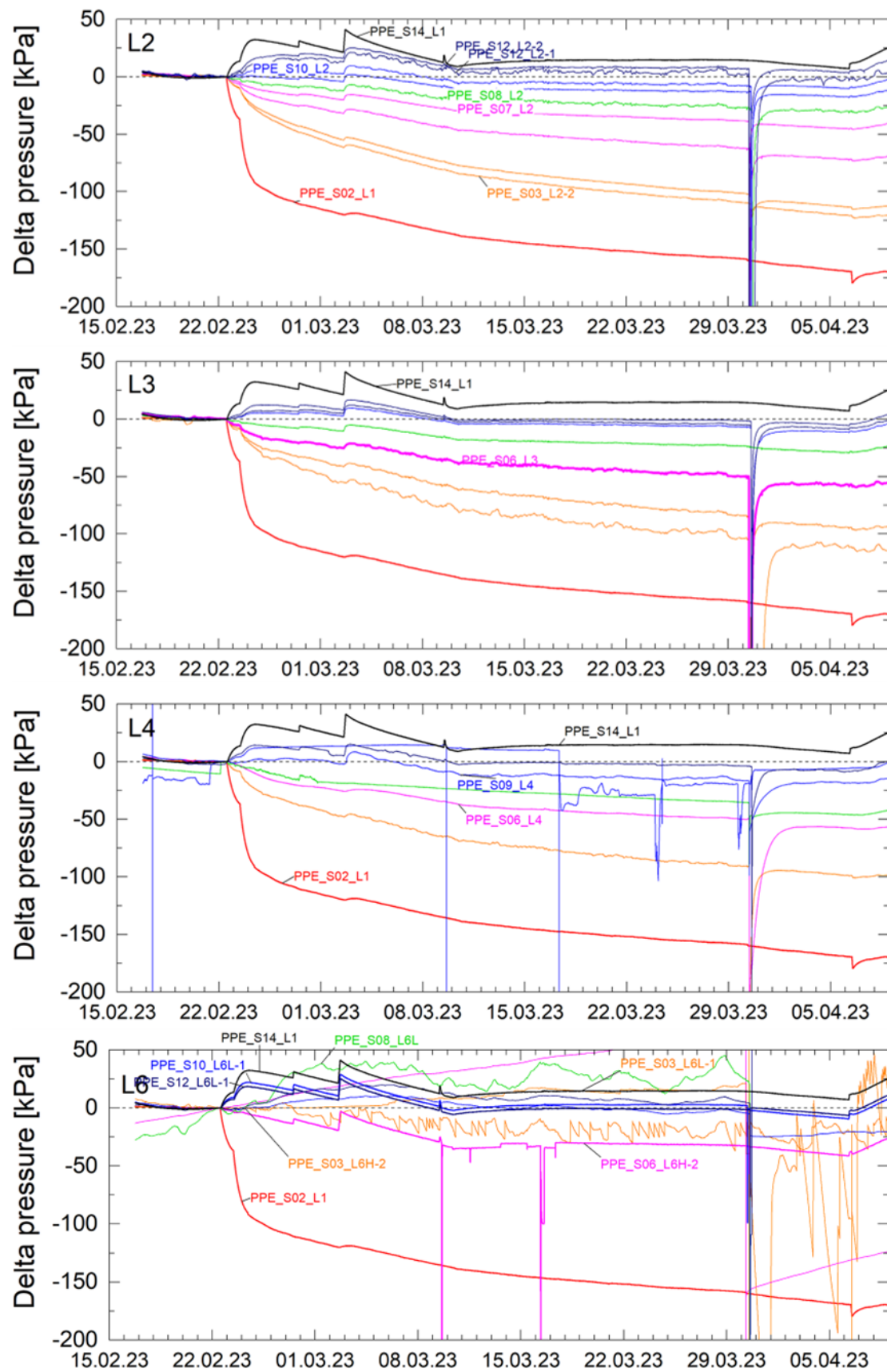


Fig. 5-9: Pressure change following the rate change on 22.02.2023

5.7 Interpretation summary

5.7.1 Gas flow path characteristics

The gas path developed in the previous phases was maintained through the period, and resistance to gas flow continued to decrease. There appears to have been a slightly increased gas permeability after the extended shut-in from 31.12.22 to 10.01.23. The pressure data show the heterogeneous nature of flow at L6, and some clear preferential connections can be seen in the responses to events.

The response to shut-in showed a break down (snap-off) of the gas path between the two filters at relatively low pressure, indicating continued gas flow under a low-pressure gradient. Analysis of the gas tracer data is likely to provide further insights into the nature of the flow path and mixing volumes in the two filters.

5.7.2 Gas flow path summary data

Summary data for GFT Phases 6 and 7 are given in Tab. 5-6 (taken from Rösli et al. 2025, Tab. 4-23).

Tab. 5-6: Gas path summary GFT Phases 6 and 7 (N₂ Flush #1 01.12.22 – 18.04.23)

Parameter	Value	Comment
Injection pressure (S02)	1,900 kPa	Constant pressure
	Reducing to 1,740 kPa	Constant rate
Extraction pressure (S14)	1,400 kPa	Constant pressure
	~1,400 kPa	Constant rate balanced to injection
Injection gas flow rate (S02)	800 mlN/min rising to 1,280 mlN/min*. Sinusoidal component until 17.01.23	Constant pressure (manual rate adjustment)
	1,000 mlN/min	Constant rate
Extraction volumetric rate	86 rising to 91 ml/min	Constant pressure
	Constant rate 70 ml/min	Constant rate balanced to injection
Total gas injected	167.0 m ³ N	
Total gas extracted	158.0 m ³ N	A small percentage of the volumetric extraction was made up of water vapour and water entrained in the gas outflow. This was separated in Mock-up tank
Overall recovery	95%	Average over N ₂ injection Tab. 4-14 Rösli et al. 2025
Extracted water volume	29.6 l	Water from ongoing drainage of S14 and some flow (including vapour) from S/B
Tracer fraction (S14)	Reduced to ~0% over about 4 – 6 weeks from the end of using Gas Mix #1	
Tracer fraction (PPEs)	Low tracer concentrations measured in PPE_S06_L6H-2, PPE_S10_L4, PPE_S03_L6L-1	

* The peak injection rate was ~1,380 mlN/min (close to the maximum of the flow controller) during recovery from the shut-in.

The overall recovery of 95% has increased relative to that in the previous phases, in part due to the stability of the gas volumes in the filters. There was no significant further drainage from the S14 sand filter during Phases 6 and 7, with a total water extraction of about 30 l, some of which was likely to have been transported into the filter as water vapour.

6 Phases 8 and 9: gas Mix #2 and N₂ flush (18.04.23 – 01.09.23)

6.1 Injection and extraction boundary conditions

Gas injection rates were maintained at a constant 1,000 mlN/min (accounting for the different gas mixes) during the two phases. Gas Mix #2 was composed of 73.2% nitrogen with 10.1% helium, 16.7% argon and 0.009% xenon while extraction from S14 was maintained at roughly equivalent volumetric flow rates. This resulted in a slow reduction in pressure in the S02 filter and an increase in the S14 filter as the gas flow path resistance decreased. Steady flow conditions (see Fig. 6-1) were therefore maintained throughout the period to facilitate interpretation of the tracer data.

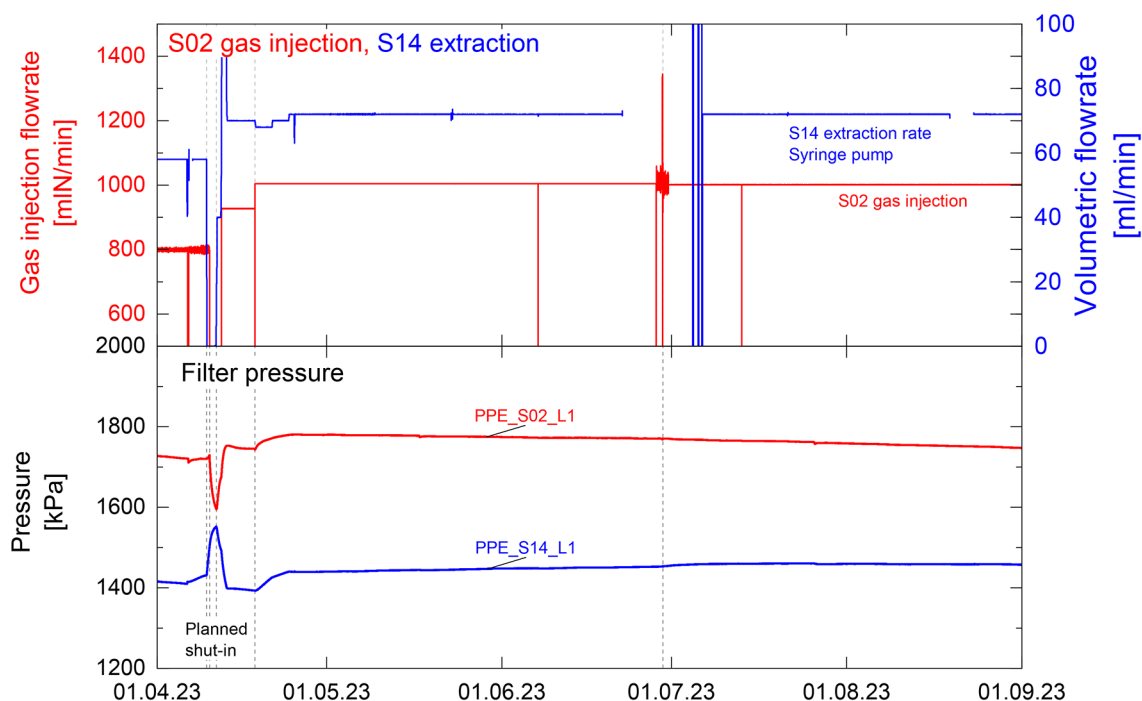


Fig. 6-1: Filter pressure and injection and extraction flow rates during Phases 8 and 9

6.2 Pressure response

Pore pressure in the seal section was largely steady during Phases 8 and 9 due to the steady flow conditions. The only disturbances relate to the campaign of PPE index testing on 06.07.23 (see App. D) and ongoing sampling to support the Gas Mix #2 tracer interpretation (App. E).

Fig. 6-2 shows the pressure distribution across the seal section on 01.05.23 (approximately 2 weeks after the start of Gas Mix #2) and 01.09.23 (just prior to shut-in). The overall pattern is very similar with a slight reduction in pressure over time due to the ongoing decrease in gas flow path resistance. Overall, the pressure data suggest that steady flow conditions existed during the Gas Mix #2 tracer injection and N₂ flush. Locally, there were disturbances due to sampling but these did not appear to affect the overall flow pattern.

The overall pattern is of slowly reducing pressures in S03 – S06 in L2, L3 and L4 and increasing pressures close to S14. L6 pressures are typically stable but heterogeneous with very low pressure in PPE_S08_L8.

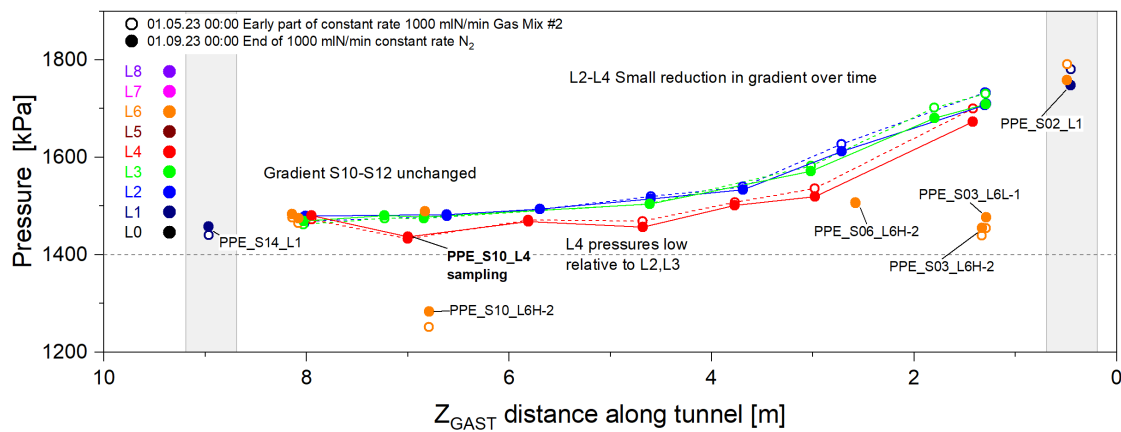


Fig. 6-2: Pressure distribution across seal sections during Phases 8 and 9

The response of PPE_S08_L4 shows the effect of gas sampling (Fig. 6-3). Prior to the start of sampling on 07.06.23, the piezometer pressure roughly followed PPE_S09_L4. During sampling, pressure rose towards that of PPE_S07_L4 and, about 10 days after sampling, jumped again to follow PPE_S07_L4. This is interpreted as a local gas breakthrough to the piezometer induced by sampling¹⁴. Samples from PPE_S08_L4 had previously been of water with dissolved gas tracers indicating proximity to the gas flow path. The samples taken from 07.06.23 to 20.06.03 showed gas plus some water, and all subsequent samples were dominantly gas.

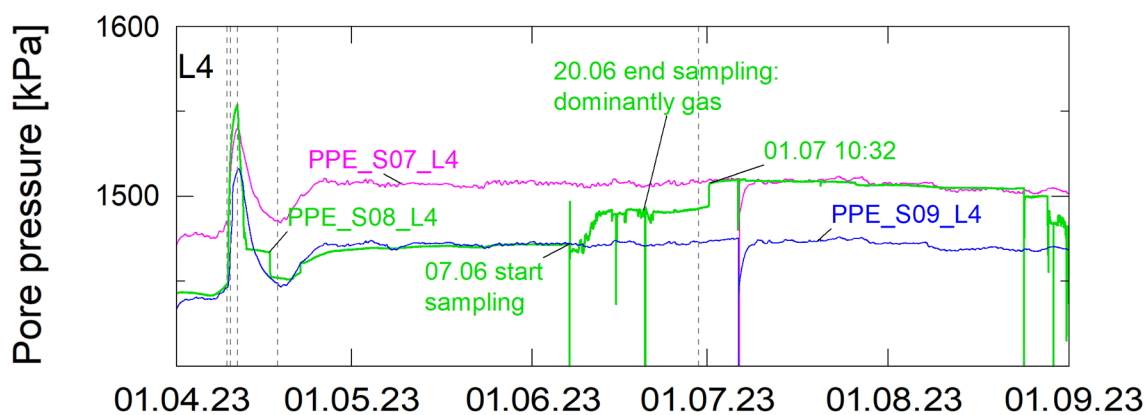


Fig. 6-3: PPE_S08_L4 change in response due to sampling

Pore pressure plots in absolute values (Fig. 6-4) and changes from the start of the GFT (Fig. 6-5) illustrate repeat manipulation effects from sampling PPE_S06_L6H-2 and PPE_S10_L4. Drawdowns and quick recovery from the PPE index testing campaign on 06.07.23 are also seen.

Pressure values on 01.09.23 and pressure change since 01.05.22 are tabulated in Tab. 6-1 and Tab. 6-2.

¹⁴ The removal of any remaining water in the hydraulic line could also have an effect, but this should be minor.

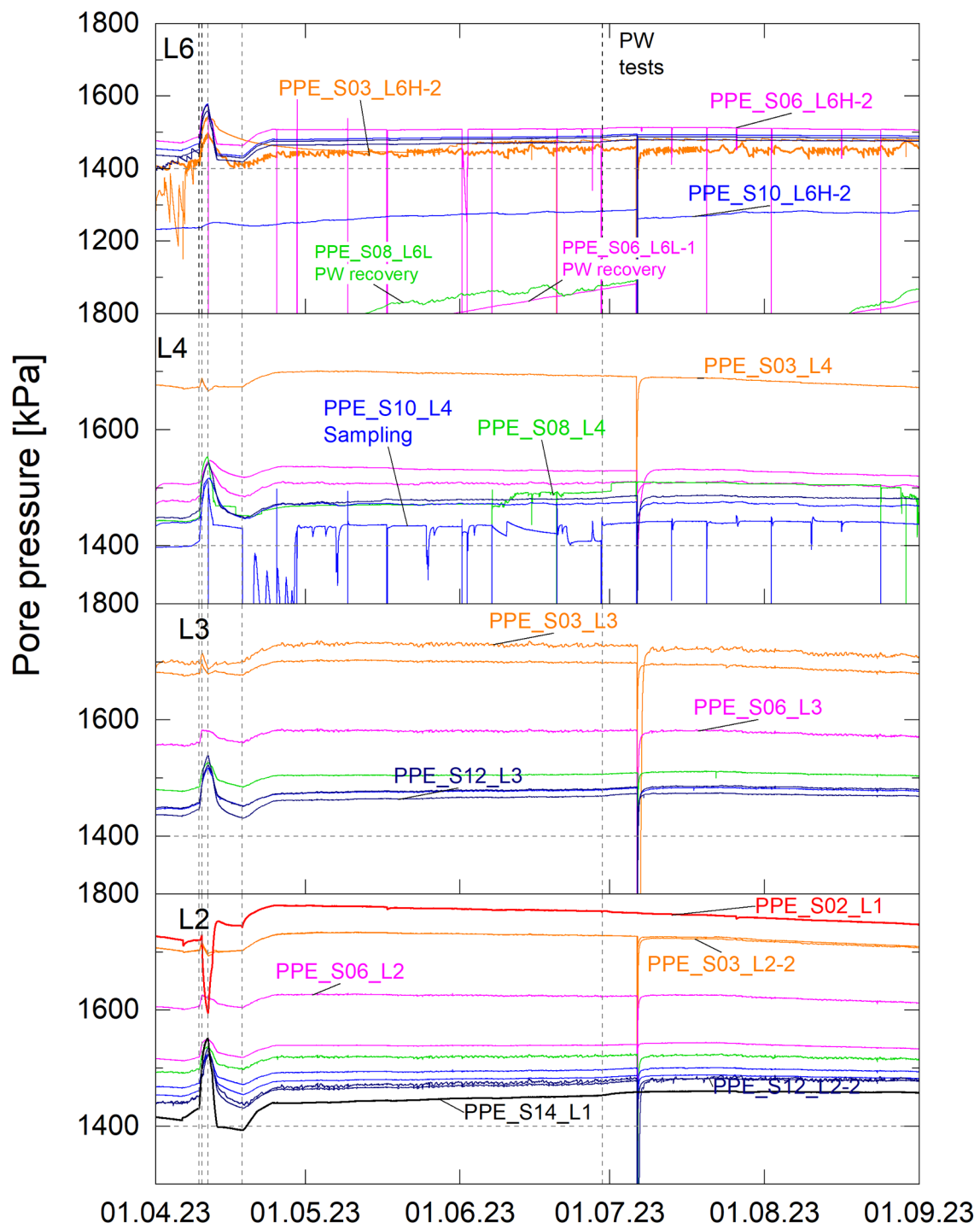


Fig. 6-4: Pore pressure during Phases 8 and 9

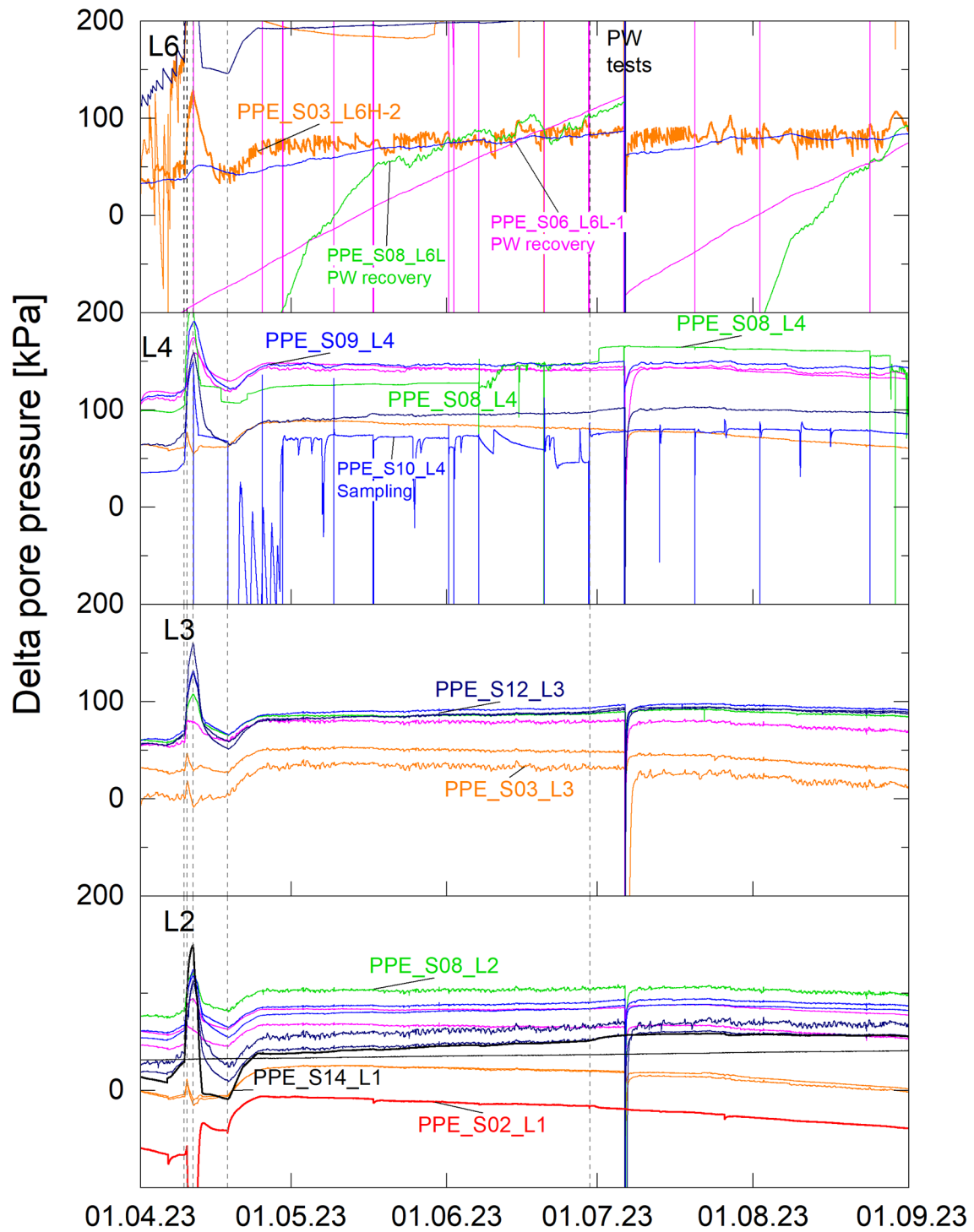


Fig. 6-5: Pore pressure change from start of the GFT (01.01.22) during Phases 8 and 9

Tab. 6-1: Pore pressure (kPa abs) values on 01.09.23 at 00:00

[illegible]

Tab. 6-2: Pore pressure change (kPa) from 01.05.22 00:00 to 18.04.23 00:00

[illegible]

6.3 Stress response

Total pressure, like the pore pressure, was largely steady during this period (see Fig. 6-6 and Tab. 6-3, Tab. 6-4). The vertical stress measured at the tunnel roof increased at about 0.5 kPa/day (at S06, S08 and S10), while other stresses were stable or increased at a significantly slower rate. This may reflect the ongoing saturation of the GBM in the head space and increasing pore pressure within the GBM or could be due to some additional loading perhaps as a result of the accumulation of gas somewhere within the GBM.

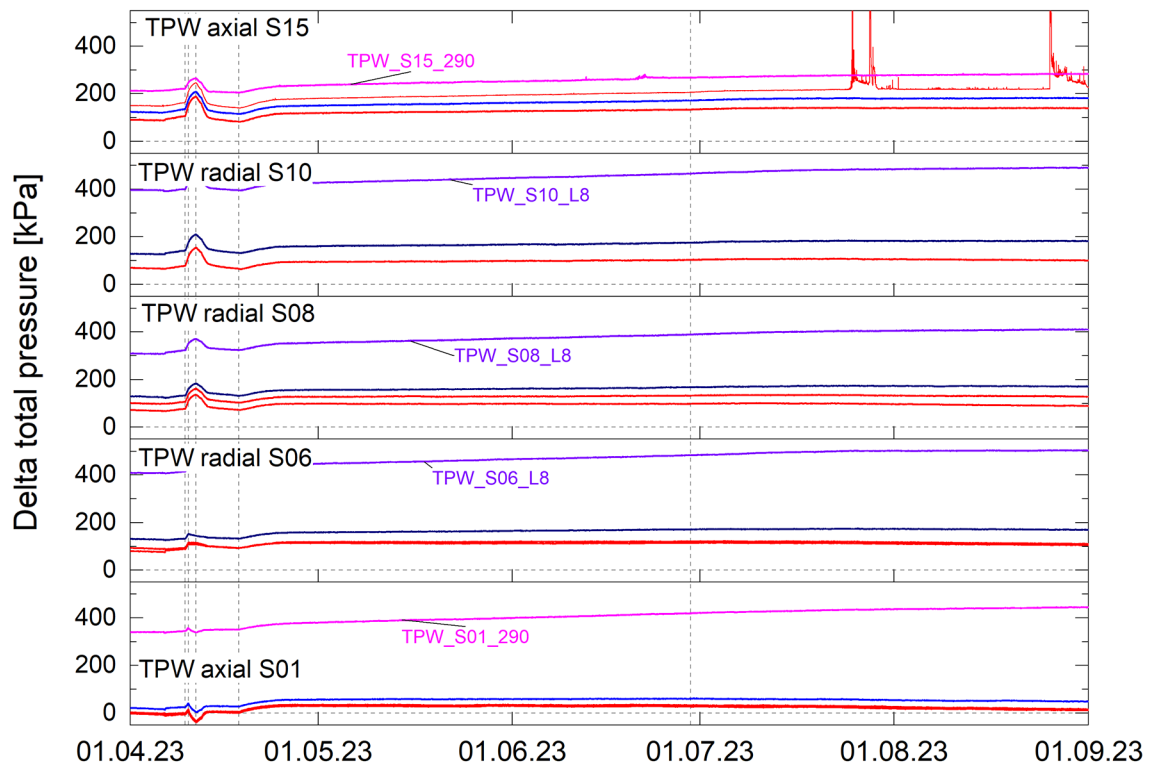


Fig. 6-6: Total pressure change from 01.05.22 during Phases 8 and 9

Tab. 6-3: Total pressure (kPa) values on 18.04.23 at 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06	S02	S01 axial
L8				2,676		2,700		2,575		
L7										
L6	2,732			*		*		*		3,256
L5										
L4	2,436/ 2,479			2,268		2,412/ 2,462		2,426/ 2,438		2,390/ 2,453
L3										
L2										
L1	2,611									2,635
L0				2,938		2,838		3,003		

Tab. 6-4: Total pressure (kPa) change from 01.05.22 00:00 to 18.04.23 00:00

TP	S15 axial	S14		S10	S09	S08	S07	S06		S02	S01 axial
L8				489		411		503			
L7											
L6	285			*		*		*			446
L5											
L4	139/ 227			101		90/ 128		105/ 109			12/ 16
L3											
L2											
L1	183										47
L0				181		172		169			

6.4 Saturation response (index tests, TDR)

A series of hydraulic index tests were performed in almost all PPEs within the seal section on 06.07.23 (GFT05). The measured compressibilities were largely unchanged at L2 and L3 but showed some increases in L4 and L6 (see App. D).

The response of the TDRs is presented in App. F. Changes in TDP traces during the period were identified in several of the sensors but typically did not show a clear change in travel time.

The two RH sensors in the GBM at L7 in S03 and S10 remained above 94% with RH_S03_L7-2 being somewhat noisy, while the sensor in S10 showed a slow but steady increase in RH, indicating ongoing but very slow saturation.

6.5 Gas tracers and sampling

Regular sampling of the S14 extraction (PL_S14_L1) and two PPEs (PPE_S10_L4 and PPE_S06_L6H-2) was performed during two separate phases. This was possible because of the availability of dedicated syringe pumps to perform the sampling and the ability of the selected PPEs to sustain sufficient gas production at moderate drawdowns. In addition, samples were also occasionally taken from other PPEs (PPE_S08_L4, PPE_S03_L6L-1). Sampling prior to the start of Phase 8 provided a baseline while sampling during Phases 8 and 9 cover the tracer breakthrough, stabilisation and tailing as shown in Fig. 6-7.

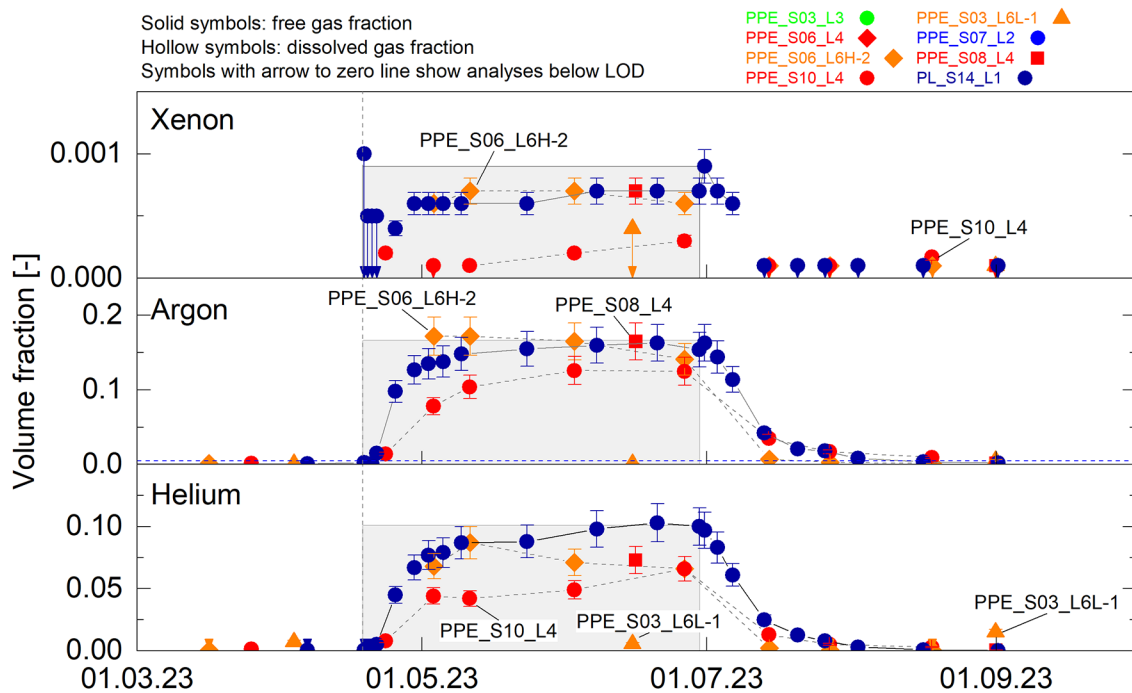


Fig. 6-7: S14 (PL_S14_L1) and PPE traced gas fractions during Phases 8 and 9

Dark blue symbols joined with a line are from S14. Grey-shaded region shows injection function.

Breakthrough to S14 extraction of all three tracers is observed relatively quickly, followed about a month later by a stabilisation period at close to the injected gas fraction. The tailing of the gas tracers after the start of the N₂ flush also occurs relatively rapidly, with concentrations decreasing to near-background values by 01.09.23. The overall response shows a period of about a month largely controlled by mixing (in the two filters and gas path), followed by near-complete recovery of the injected gas tracers.

The samples from PPE_S06_L6H-2 show a similar response to that of the S14 extraction, while samples from PPE_S10_L4 show a slower stabilisation to slightly reduced concentration, indicating greater retention (dissolution and diffusion in the water phase) in the gas pathway sampled by PPE_S10_L4.

Samples from PPE_S08_L4 showed a free gas phase with tracer fractions such as those measured in PPE_S06_L6H-2. The flow from PPE_S08_L4 had developed over time, initially producing only water, which indicated the local development of a gas path close to the piezometer influenced by the repeat sampling.

6.6 Response to events during Phases 8 and 9 (analysis of shut-ins, pulses)

Gas flow rates and steady flow conditions were maintained during the two phases with only minor disturbances. The main events were the changes in gas mix as discussed in the previous section.

6.7 Interpretation summary

6.7.1 Gas flow path characteristics

Resistance to gas flow across the seal section continued to reduce during the two phases of constant rate gas injection, resulting in a gradual reduction of the pressure gradient. The overall recovery of injected gas was 97%, an increase from that in the previous phases, suggesting that any leakage paths were either reduced or were stable during the period.

The focus of the two phases was the monitoring of the Gas Mix #2 tracer injection and the subsequent flush with N₂. This was accomplished with regular sampling of the S14 extraction line (PL_S14_L1) and two PPEs (PPE_S06_L6H-2 and PPE_S10_L4), plus occasional sampling in other PPEs.

The gas tracer data are consistent with a well-developed high-recovery gas path where the observed trends are dominated by mixing in the gas volumes in the S02 and S14 filters. The data from PPE_S06_L6H-2 show similar trends to those observed in the S14 extraction (PL_S14_L1) suggesting that the piezometer is representative of the gas flow path through the seal section.

Data from PPE_S10_L4 show a slower and lower breakthrough, indicating that this PPE could be less well connected to the main flow path with possibly greater tracer retention (dissolution in porewater). Occasional samples from PPE_S08_L4 are like those from PPE_S06_L6H-2.

The tracer data suggest a heterogeneous network of paths that are slowly developing over time (e.g. the increasing gas fraction from PPE_S08_L4).

6.7.2 Gas flow path data summary

Summary data for GFT Phases 8 and 9 are given in Tab. 6-5 (taken from Rösli et al. 2025, Tab. 4-30 and 4-35).

Tab. 6-5: Gas path summary GFT Phases 8 and 9 (Gas Mix #2 and N₂ Flush #2 18.04.23 – 01.09.23)

Parameter	Value	Comment
Injection pressure (S02)	1,750 – 1,780 kPa	Pressure gradient across seal decreased over time as resistance to gas flow dropped
Extraction pressure (S14)	1,400 – 1,450 kPa	
Injection gas flow rate (S02)	1,000 mlN/min	Constant rate
Extraction volumetric rate (S14)	70-72 ml/min	Constant rate
Total gas injected	196.6 m ³ N	
Total gas extracted	190.4 m ³ N	
Overall recovery	97%	Average over Gas Mix #2 and N ₂ Flush #2
Extracted water volume	17.4 l	Water from ongoing drainage of S14 and some flow (including vapour) from S/B
Tracer fraction (S14)	Reached 100% of Gas Mix #2 fractions prior to tailing to ~0% during N ₂ flush	
Tracer fraction (PPEs)	PPE_S06_L6H-2 largely similar to S14 response PPE_S08_L4 similar to S14 once gas phase sampled PPE_S10_L4 showed greater tracer retention	

7 Phases 10 and 11: flow path diagnostics and gas removal (01.09.23 – 01.01.24)

GFT Phases 10 and 11 focused on the characterisation of the gas flow path (step-rate nitrogen injection tests) and removal of gas prior to the start of resaturation. Gas tracer testing had been completed in Phase 9 and no further gas samples were taken during these phases. The objectives for Phase 10 were to:

- Test the robustness of the gas path after an extended shut-in,
- Examine rate dependence by using a series of step-rate injection tests.

The objective for Phase 11 was simply to remove as much gas as possible from the system prior to the start of resaturation.

7.1 Injection and extraction boundary conditions

7.1.1 Phase 10 flow path diagnostics

Following the end of the 1,000 mlN/min gas injection on 01.09.23, there was a 3-week shut-in followed by the multi-step gas injection into S02. The steps are listed in Tab. 7-1. This test had originally been planned with only three steps, but the pump failure during Step #3, together with the measured pressure responses, led to the addition of Step #4. The S14 volumetric extraction rates were specified, assuming near 100% recovery of the injected gas (as had been observed during the previous phases).

Tab. 7-1: Phase 10 flow steps

Flow Step	Start date	S02 N ₂ injection [mlN/min]	S14 volumetric extraction [ml/min]	Remark
	01.09.23 11:00	Shut-in from 1,000 mlN/min injection		
#1	22.09.23 06:00	1,380	99	Upper rate for flow controller
#2	29.09.23 12:00	540	39	
#3	06.10.23 12:00	180/45/180	13	Interrupted by S14 pump failure
#4	12.10.23 09:06	45	13/0	
	18.10.23 14:15	Shut-in		
	27.10.23	RW tests in selected PPEs: PPE_S03_L6L-1, PPE_S10_L4, PPE_S08_L4, PPE_S06_L6H-2, PPE_S12_L6L-1		
	27.10.23 12:40	S02 slug withdrawal test		

Following the step-rate tests, a series of controlled rate withdrawal (RW) tests were performed in selected PPEs on 27.10.23 to assess the ability to remove gas from the seal section via the piezo-meters. A gas slug withdrawal test was also performed in S02 to estimate the filter gas volume.

Fig. 7-1 shows the flowrates and filter pore pressure. Quasi-steady pressures are achieved quickly after the rate changes, indicating that the gas flow path is quickly re-established by balancing injection and extraction.

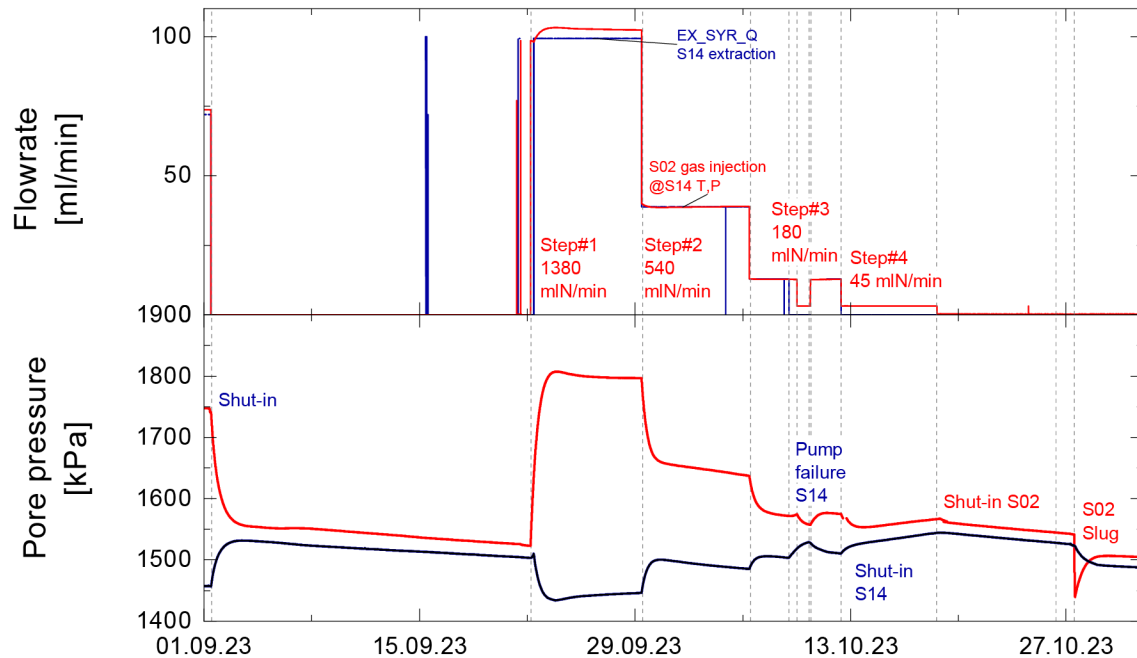


Fig. 7-1: S02 and S14 filter boundary conditions during Phase 10

7.1.2 Phase 11 gas extraction

Large gas volumes had been present in the S02 and S14 sand filters from June 2022 onwards. A smaller volume of gas was also present within the flow path. To facilitate the planned post-GFT resaturation and to limit the volumes of high-pressure gas present at the site, Phase 11 focused on gas removal.

While it was possible to perform a gas-water exchange (G-WX) in S02 by balancing gas extraction from the top of the filter and water injection at the base (essentially the opposite of the W-GX procedure discussed in Chapter 3), the lack of hydraulic lines at the top of the S14 sand filter meant that a different strategy was required to remove the gas from that filter. The overall approach adopted was as follows:

- Step #1: Gas injection into PL_S14_L1 to raise pressure with limited extraction from S02,
- Step #2: Water injection into PL_S14_L1 and gas extraction from S02 to displace gas from the S14 filter towards S02 (reverse gas flow from S14 to S02),
- Step #3: G-WX in S02,
- Step #4: Pulse tests to assess gas volumes remaining in S02 and S14 filters.

It was expected that some gas would be left at the top of the S14 and S02 sand filters, but this could be compressed and slowly dissolved once resaturation started. Note that after the GPT1 G-WX, about 50 l of gas were left at the top of the S02 filter, but by March 2022, prior to the GFT, filter pulse tests indicated little or no gas present. The different steps in Phase 11 are listed in Tab. 7-2.

Tab. 7-2: Phase 11 flow steps

Step	Start date	Remark
#1	01.11.23 10:00	Start of Step #1 with gas injection into PL_S14_L1
	01.11.23 15:33	Start of gas extraction from PL_S02_L6L-1
	02.11.23 16:25	Shut-in after syringe pump motor failure
	06.11.23 08:24	Resume gas injection into S14 and extraction from S02
#2	07.11.23 12:00	Switch to water injection in PL_S14_L1
	12.11.23 05:46	Shut-in after pressure rise in S14
	13.11.23 09:16	Restart injection at lower rate (pressure still increases)
	14.11.23 15:00	S14 pulse injection
	23.11.23 10:31	S14 Pulse extraction
#3	24.11.23 10:41	Start of S02 G-WX
	27.11.23 06:43	End of S02 G-WX
#4	29.11.23 09:15	Start of S02 pulse injection
	29.11.23 11:30	End of S02 pulse injection
	30.11.23 07:58	S14 extraction 80 ml/min
	30.11.23 11:33	End of S14 extraction

Fig. 7-2 shows the S02 and S14 flow and pressure during the reverse flow and S02 G-WX periods.

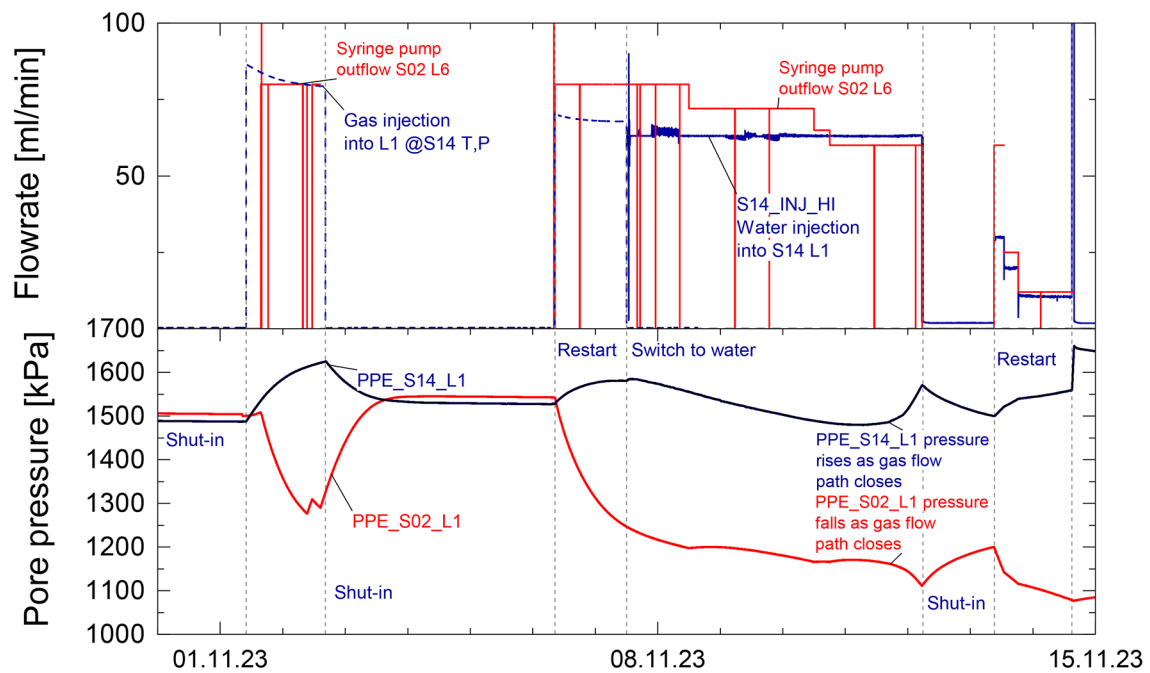


Fig. 7-2: S02 and S14 filter boundary conditions during Phase 11

During December, further attempts were made to extract gas from S02 but with no significant results. The inability to extract more gas led to the decision to start resaturation in January 2024. Gas was also extracted from PPE_S03_L6L-1 and PPE_S06_L6H-2 during late November and December 2023 (Fig. 7-3). Extended extraction from PPE_S06_L6H-2 was possible at ~1 – 2 ml/min at moderate drawdowns, but only a small amount of gas was extracted from PPE_S03_L6L-1.

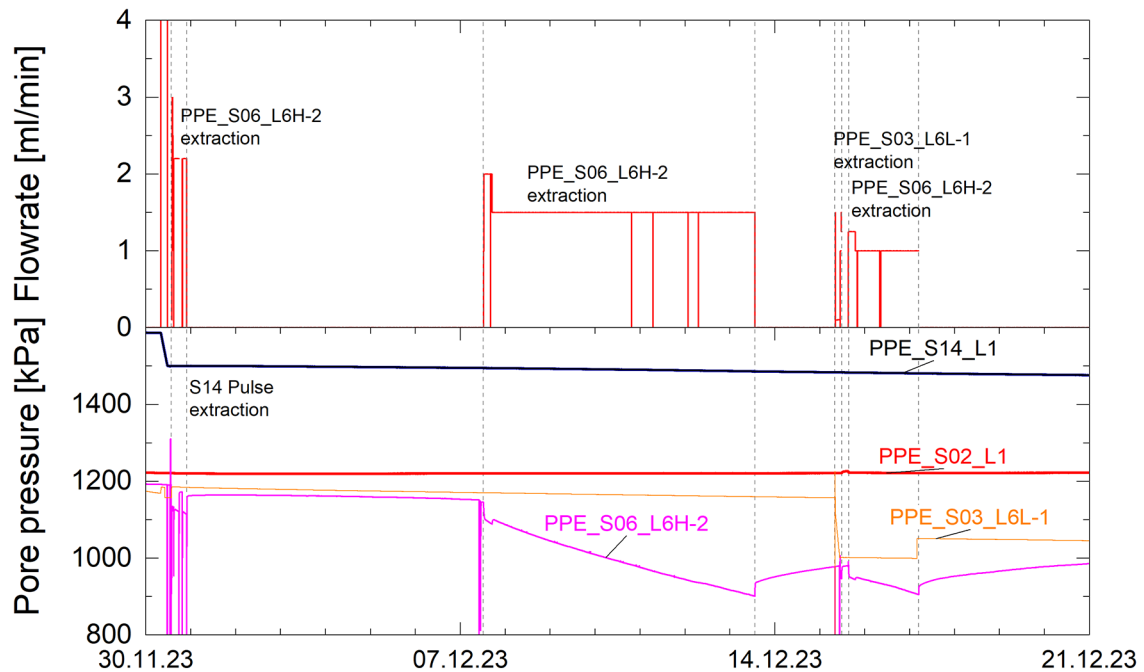


Fig. 7-3: Gas extraction from PPE_S03_L6L-1 and PPE_S06_L6H-2

7.2 Pressure response

Fig. 7-4 and Fig. 7-5 show the pressure distribution across the seal section at selected times during Phase 10:

- 21.09.23 at the end of the shut-in prior to the start of the step-rate injection tests,
- 29.09.23 at the end of the Step #1 at an injection rate of 1,380 mlN/min.

Fig. 7-4 shows the pressure gradient that developed during the Step 1 injection. As in previous injections, the gradient is steepest in L2 and L3 from S03 to S08 and flattens as it approaches S14. This indicates that the resistance to flow is greater close to S02. Pressure in L4 is lower but shows the same pattern. Pressure in L6 is heterogeneous and at S03 is disconnected to the S02 sand filter.

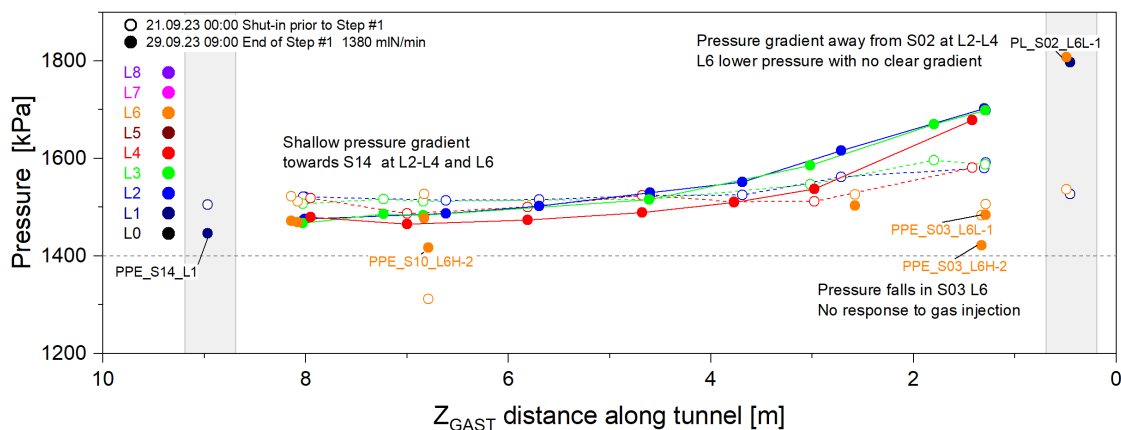


Fig. 7-4: Pressure distribution across seal prior to and during Phase 10 flow Step #1

Fig. 7-5 shows the pressure distribution during the reverse flow period on:

- 09.11.23 during the reverse flow period as pressures in S02 and S14 were falling,
- 14.11.23 after the gas flow path had closed due to resaturation of the S14 sand filter.

The reverse gradient (from S14 to S02) is clearly seen at L2, L3 and L4 on 09.11.23 after the switch to water injection in S14. Some L6 sensors also show similar pressures. By 14.11.23, when pressure had dropped and the gas path had closed, the gradient steepens in L2 – L4, while the L6 sensor pressures dropped significantly below those in the lower layers. Pressure in PPE_S08_L4 dropped relative to the other sensors, perhaps showing a preferential connection to S02. At both times, there is a steep pressure drop into S02.

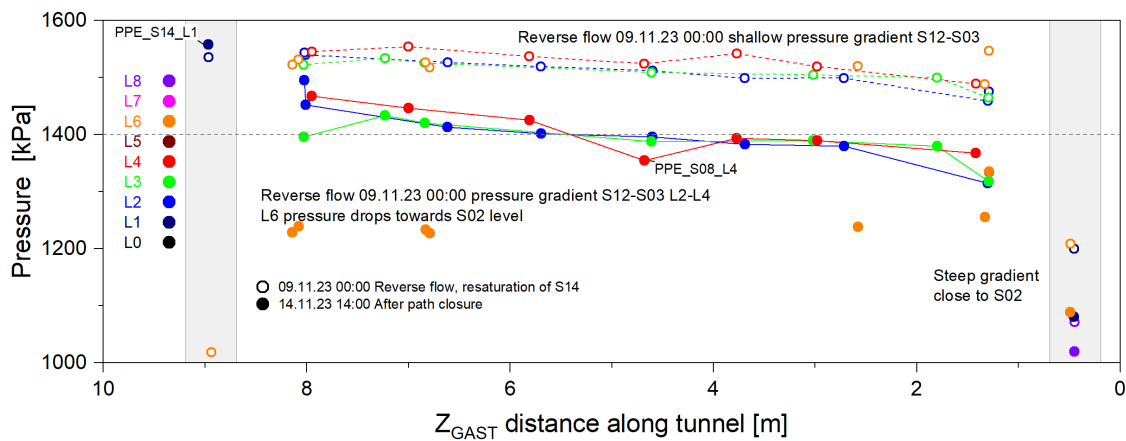


Fig. 7-5: Pressure distribution across seal during reverse flow period (Phase 11)

The measured pore pressure in the seal section (Fig. 7-6) was strongly influenced by the large changes in filter pressure shown in Fig. 7-2. Responses were controlled by the level and distance from the filter. At L2, responses were largely controlled by the distances from S02 and S14 with piezometers in S03 – S07 being influenced by S02 and piezometers from S09 – S12 being influenced by S14. At L3 and L4, responses between S02 and S07 show the influence of distance from S02, but responses between S08 and S12 showed only small differences. During December 2023, PPE_S10_L4 showed an extended recovery indicating a low permeability connection to recharge and considerable storage (possibly indicating a volume of trapped gas).

At L6, a group of piezometers show very similar pressures (PPE_S03_L6L-1, PPE_S06_L6H-2, PPE_S10_L6L-1, PPE_S12_L6L-1 and PPE_S12_L6H-2). PPE_S03_L6H-2 follows a similar trend but with significant noise and a saw-tooth component that appeared in mid-November 2023. The similar response suggests that they are linked by a low resistance path. The pressure differences within this group increased in December, perhaps due to the large difference in pressure between S02 and S14.

The pressure changes in L6 shown in Fig. 7-7 are influenced by pressure heterogeneity at the start of the GFT. At L4, there is a noticeable separation between S03 and the other sections.

At L2 and L3, pressure changes are similar in S08 – S12 during shut-in and at low flow but then separate as rates increase. Pressure changes in S03 – S07 are largely controlled by the distance from the S02 filter. More detailed discussion of the responses to individual events are given in Section 7.6.

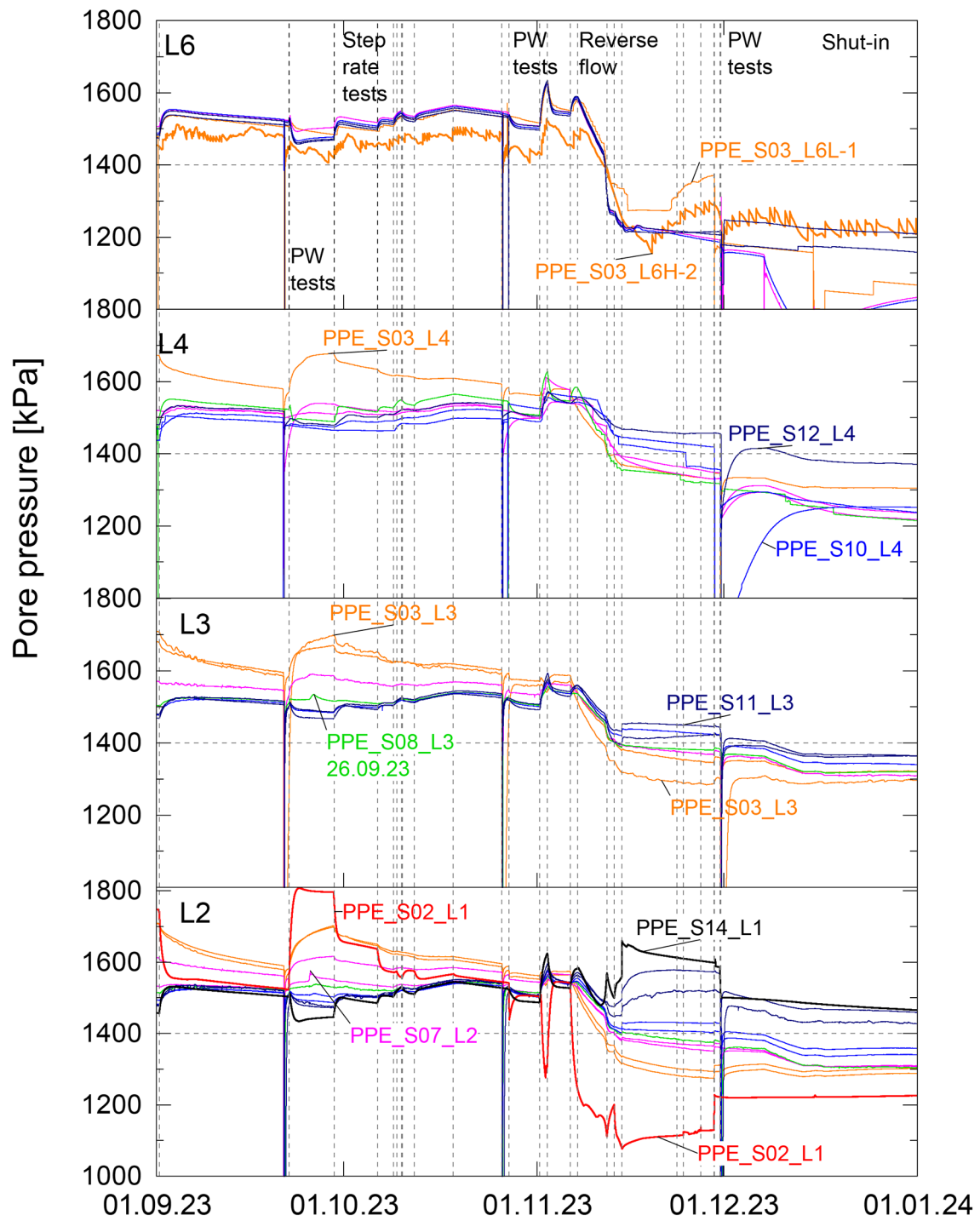


Fig. 7-6: Pore pressure during Phases 10 and 11

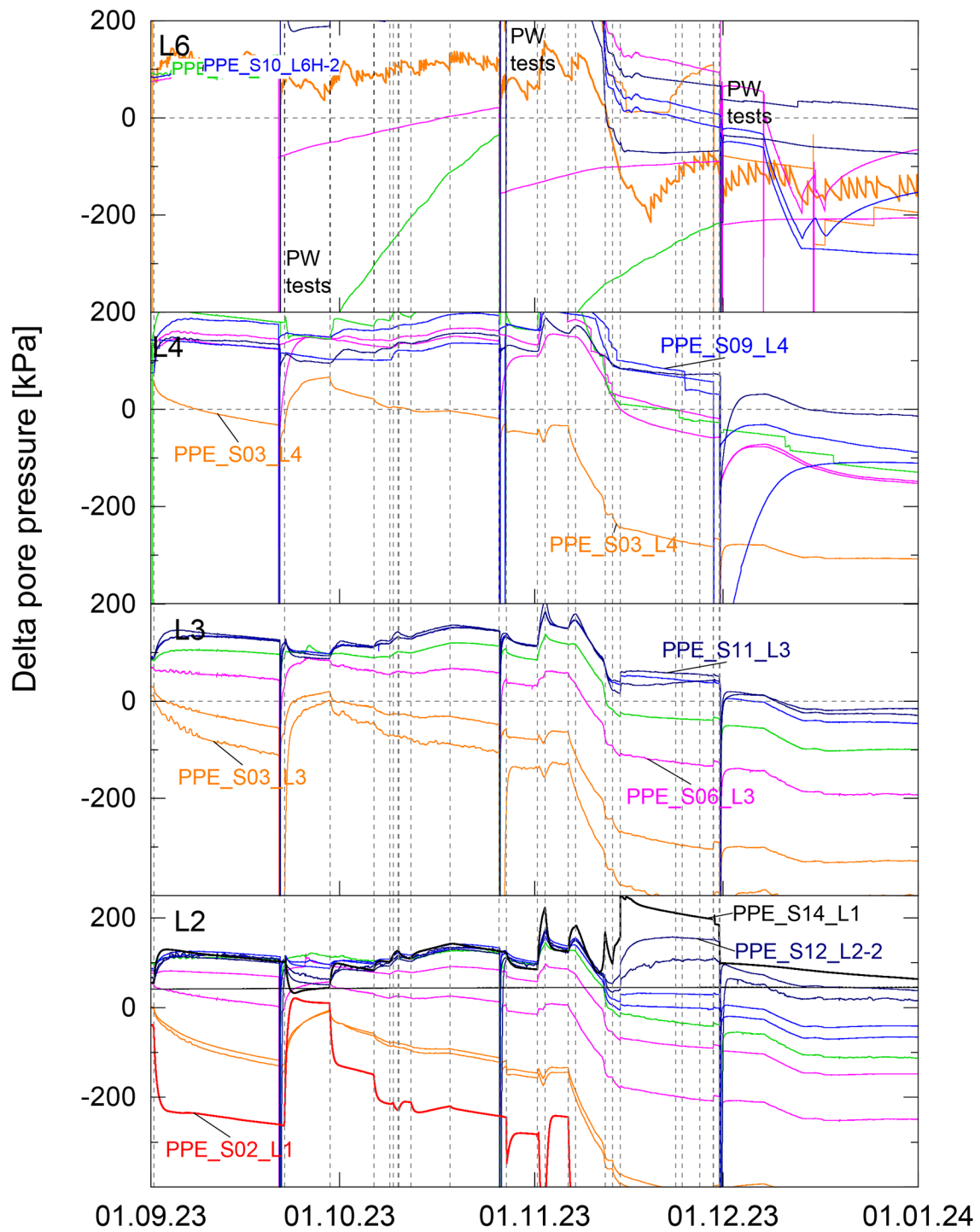


Fig. 7-7: Change in pore pressure since the start of the GFT during Phases 10 and 11

7.3 Stress response

The measured total stress is strongly influenced by the filter pressure changes as shown in Fig. 7-8. In addition to these responses, some small events are visible in two of the S15 sensors. The short duration and large magnitude of the events suggest that they are related to either the sensor itself or the local conditions around the sensors.

Large changes in total pressure are seen in the axial sensors at S01 caused by the large changes in the S02 sand filter pressure.

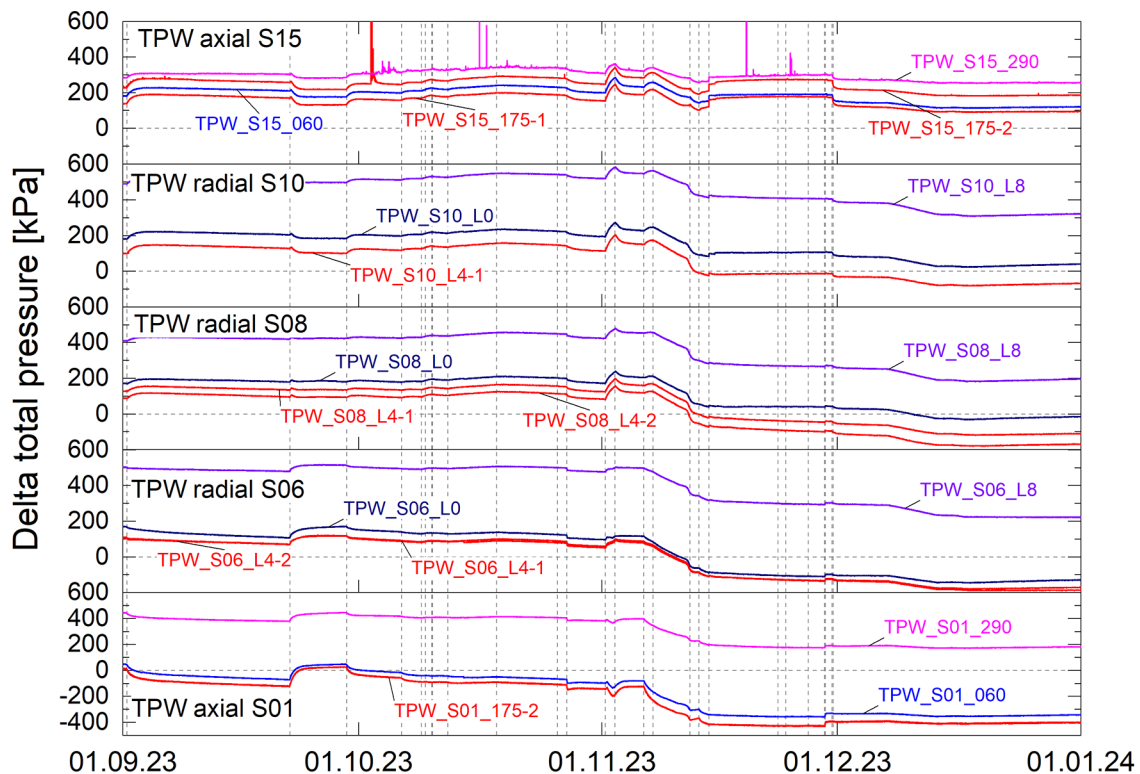


Fig. 7-8: Change in total pressure since the start of the GFT (01.05.22) during Phases 10 and 11

7.4 Saturation response (TDR, index tests)

Hydraulic index testing campaigns were performed on 21.09.23 (CGFT06), 26.10.23 (CGT07) and 30.11.23 (CGFT08). They indicated no change in L2 or L3, but an ongoing increase in compressibility in L4 and L6.

The response of the TDRs is presented in App. F. Changes in TDP traces during the period were identified in several of the sensors but typically did not show a clear change in travel time. Several of the TDL sensors at S13 showed a strong response to water injection into S14 as the water level in the S14 filter rose (see App. F).

Of the two operational RH sensors at the start of the GFT, RH_S03_L7-2 approached 96% RH during Phases 10 and 11, while RH_S10_L7-2 approached 100% in late October/early November 2023 and subsequently stopped recording.

7.5 Gas tracers and sampling

Following the nitrogen flushing in Phase 9, no sampling was performed during Phase 10 or 11.

7.6 Response to events during Phases 10 and 11 (analysis of shut-ins, pulses)

7.6.1 Step-rate tests

The objective of the step-rate tests was to identify any rate/pressure dependence of the gas flow path. Although the steps were relatively short, pressure equilibrated relatively quickly. Fig. 7-9 shows the pressure difference across the seal section during Phase 10. The pressure difference at the end of each step is tabulated in Tab. 7-3.

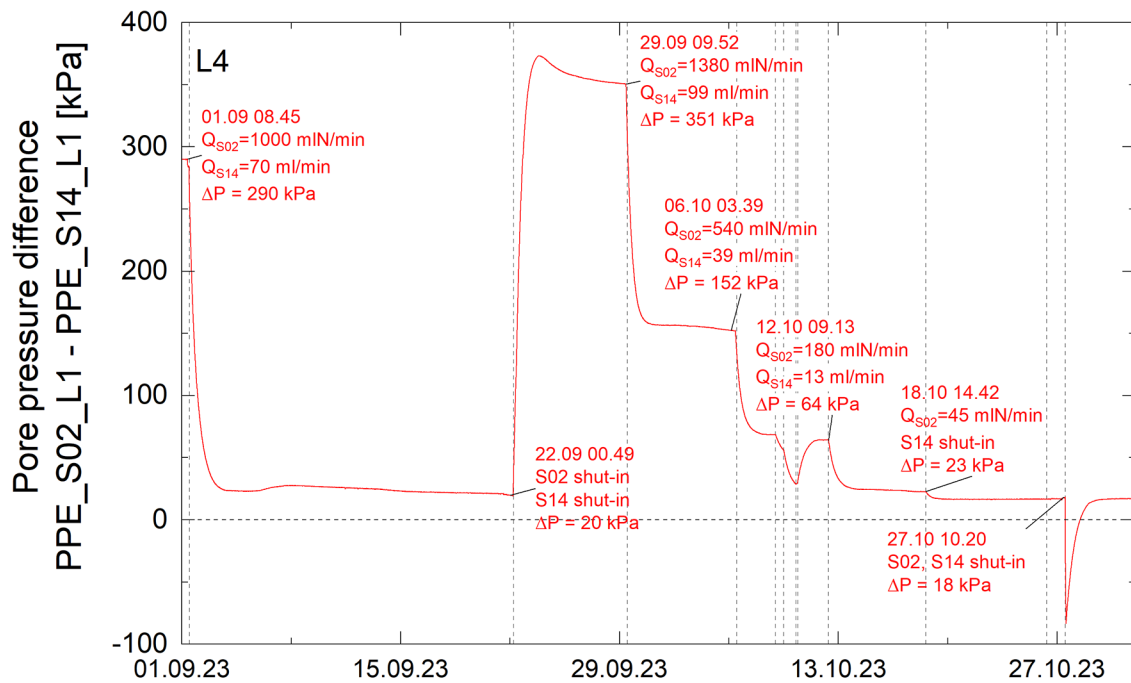


Fig. 7-9: Pressure across seal section (PPE_S02_L1-PPE_S14_L1) during Phase 10 step tests

Tab. 7-3: Pressure difference across seal at end of Phase 10 step tests

	ΔP (S02-S14) [kPa]	Q_{S02} [mlN/min]	Q_{S14} [ml/min]	Comment
End of Phase 9	290	1,000	70	End of N ₂ flush
End of shut-in	20	Shut-in	Shut-in	Stable 21-day shut-in
End of Step #1	351	1,380	39	Balanced rates
End of Step #2	152	540	13	Balanced rates
End of Step #3	64	180		Balanced rates (interrupted by shut-in)
End of Step #4	23	45	Shut-in	Stable pressure difference as pressure in S14 rose
Shut-in	18	Shut-in	Shut-in	Prior to filter pulse test

The pressure difference between the filters is roughly linear with flow, indicating that the flow path resistance was roughly constant during the step-rate tests.

In Steps #1, #2 and #3, the S14 volumetric extraction rate was chosen to balance the injection. At the lowest injection rate (Step #4 at 45 mlN/min), the S14 extraction was shut in and pressure rose in the S14 sand filter as gas continued to enter the filter, albeit with only a very small pressure gradient. This indicates that the S02 – S14 path still dominates the flow of gas. Fig. 7-10 shows the filter pressure, flow and calculated effective permeability $\times$ area¹⁵. The effective permeability $\times$ area values stabilise at the end of the first two steps once the initial transient ends and steady pressure conditions are achieved. The values for the later steps are somewhat lower but could have been affected by the disruption to flow and the subsequent shut-in of S14 extraction.

¹⁵ This is calculated from the flow rate, pressure difference between the filters, viscosity and path length assuming steady flow conditions (see definition in App. H.2).

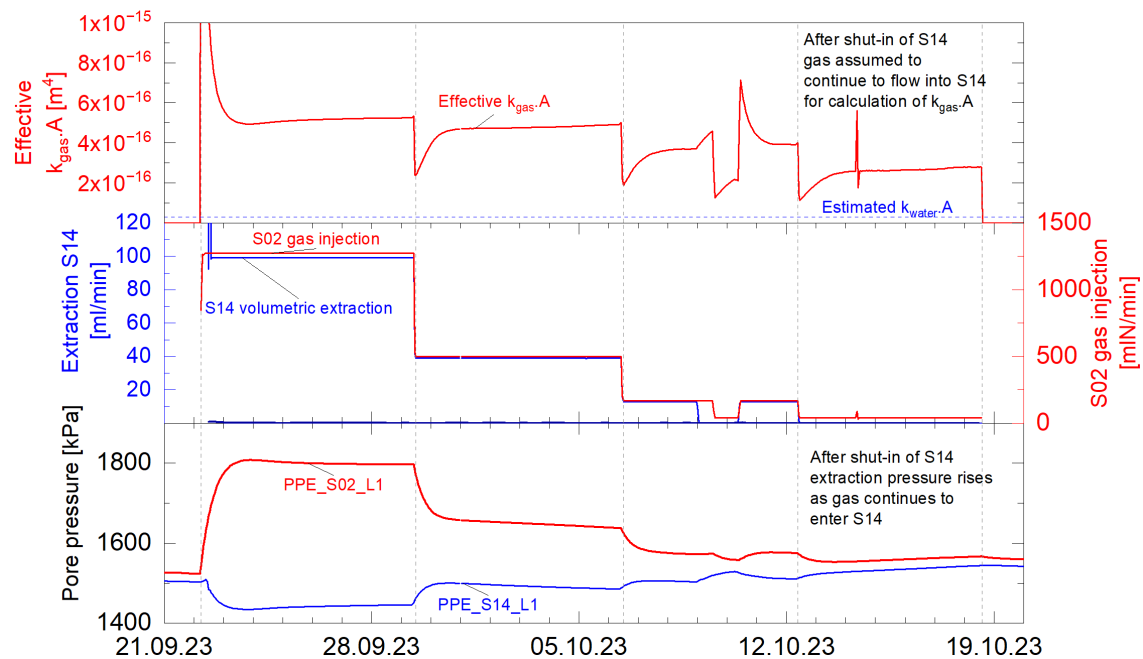


Fig. 7-10: Pressure, flow and estimated effective gas permeability×area during step-rate tests

7.6.2 RW tests in selected PPEs

The RW tests were performed as controlled rate extractions using the syringe pump. The tests lasted approximately one hour, and rates were reduced if pressure dropped significantly. The highest stable gas rates were from PPE_S03_L6L-1, PPE_S06_L6H-2 and PPE_S10_L4 (Tab. 7-4). The tests established the possibility of extracting gas from the PPEs at moderate rates.

Tab. 7-4: RW tests in selected PPEs (27.10.23)

PPE	Pressure [kPa]	Flow rate [ml/min]	Remark
PPE_S03_L6L-1	1,450	10	Stable gas extraction at 10 ml/min
PPE_S10_L4	1,050	7	Rate reduced to 7 ml/min
PPE_S08_L4	1,050	2.5	Rate reduced to 2.5 ml/min
PPE_S06_L6H-2	1,136	9	Stable gas extraction at 9 ml/min
PPE_S12_L6L-1	1,040	1.3	22 ml of water collected

7.6.3 S02 slug withdrawal test

The aim of the test was to establish the gas volume in the S02 sand filter. Unfortunately, there was some leakage from the needle valve during the initial pressure drop (~40 kPa). Once the leak was spotted, the flow rate was controlled with a 2-way valve and pressure dropped a further 60 kPa (total pressure drop ~100 kPa). If the initial pressure drop is ignored, the measured pressure change is linear with volumetric extraction with a compressibility of 253 ml/kPa equivalent to a gas volume in the S02 filter of ~370 l.

7.6.4 Gas and water injection into the S14 filter

Fig. 7-11 shows the filter flowrates and pressures during the reverse flow period. Gas injection into S14 started on 01.11.23 at 10:00. Once S02 pressure started to rise, extraction from S02 (PL_S02_L6L-2) was started using the syringe pump. Repeat failures of the syringe pump motor led to the decision to shut in on 02.11.23 at 16:25. Injection and extraction were restarted on 06.11.23 following replacement of the syringe pump. The S14 injection was switched to water on 07.11.23 at 12:00, with gas being displaced from S14 and extracted from S02 L6. The water injection rate was set to 63 ml/min, but the data were rather noisy. The S02 extraction rate was reduced from 80 ml/min to 72 ml/min (08.11.23 12:00) and then 65 ml/min (10.11.23 12:00). While the pressures dropped, the pressure difference between the two filters roughly stabilised at ~320 kPa with 72 ml/min extraction from S02 and 63 ml/min water injection in S14 (see Fig. 7-12).

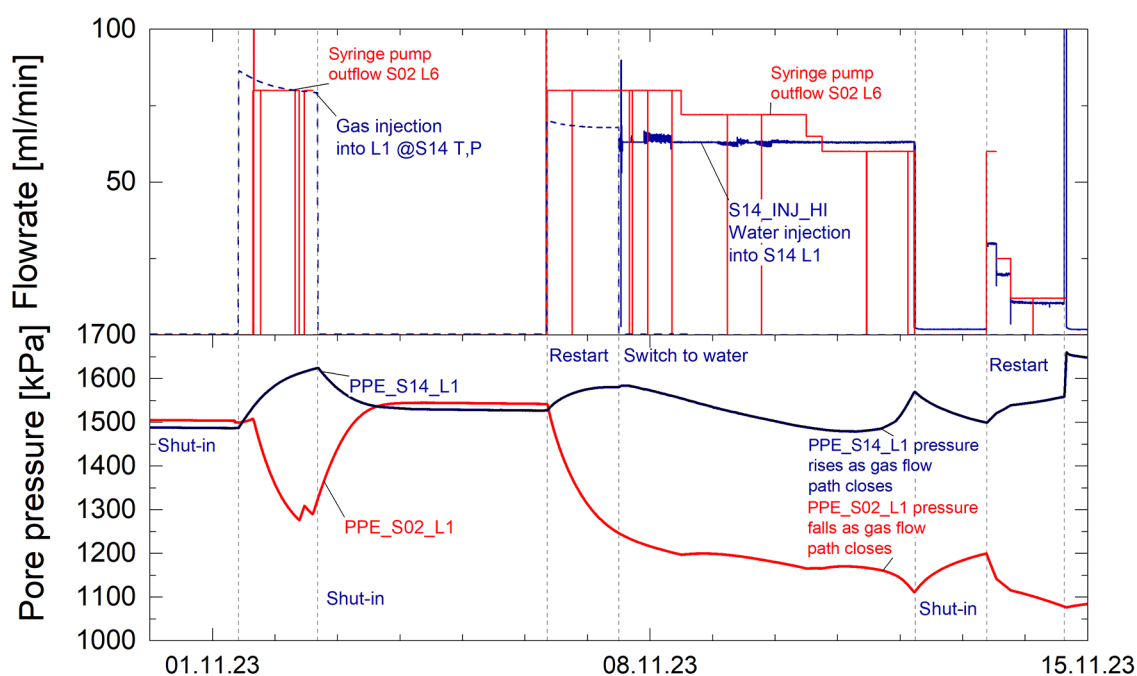


Fig. 7-11: S02 and S14 filter boundary conditions during the GFT Phase 11 reverse flow period

On 11.11.23, pressure in S14 started to rise while pressure in S02 dropped, indicating that the gas path had closed, resulting in a net injection into S14 and reduced flow from S14 into S02. The pressure rise steepened, indicating further closure and the injection and extraction were shut in on 12.11.23 at 05:30. An attempt to restart the reverse flow at lower flow rates was made on 13.11.23, but the same pattern of rapid pressure rise in S14 and pressure reduction in S02 indicated the continued closure of the gas flow path from S14.

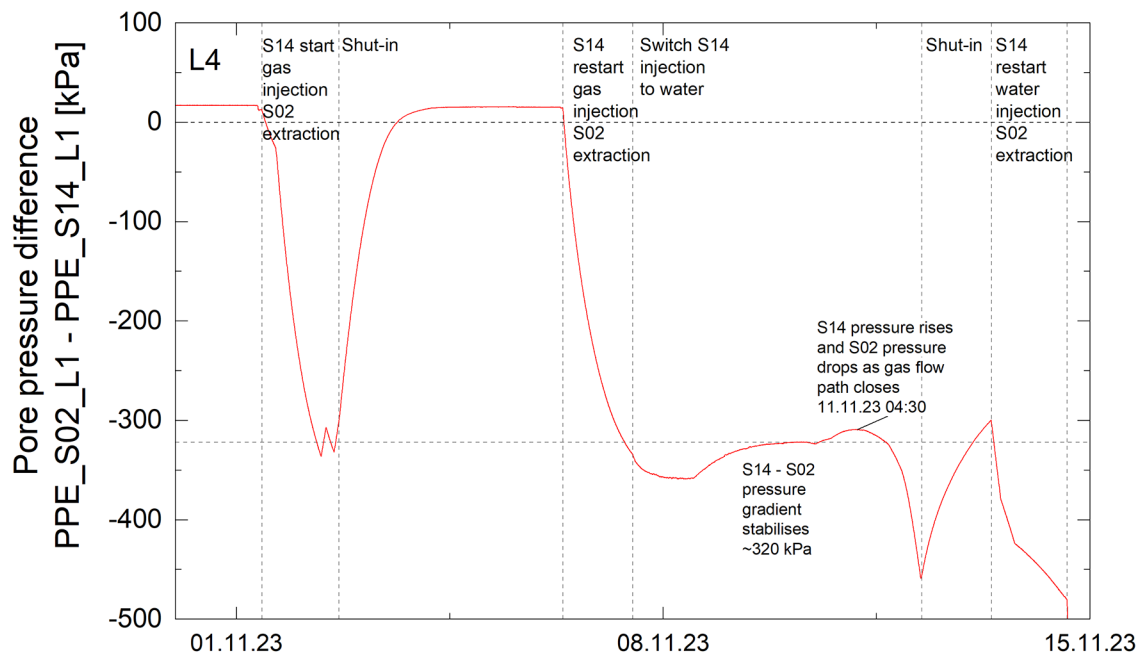


Fig. 7-12: Pressure across seal section (PPE_S02_L1-PPE_S14_L1) during Phase 11 reverse flow period

The PPE behaviour during flow reversal and flow path closure at L4 and L6 is shown in Fig. 7-13 and Fig. 7-14. At L4, pressure typically followed the S14 trend until closure of the gas path when the L4 pressures continued to drop while S14 pressure rose. PPE_S08_L4 initially showed a pressure close to that of PPE_S14_L1 until closure. PPE_S07_L4 and PPE_S10_L4 showed breaks in pressure prior to closure. None of the L4 PPEs showed a clear response to the S14 pulse test on 14.11.23.

Pressure at L6 shows a slightly different pattern with a group of PPEs (PPE_S03_L6L-1, PPE_S06_L6H-2, PPE_S10_L6L-1, PPE_S12_L6L-1 and PPE_S12_L6H-2) following PPE_S14_L1 but then diverging and dropping towards the pressure in S02 as the gas path into S14 closes. PPE_S203_L6H-2 shows a lower rather noisy pressure but also follows the group trend. The group of PPEs show only a very small response to the S14 pulse test on 14.11.23.

Pressure at L2 and L3 shows a more distributed trend, controlled by distance from the filters with ongoing connection to S14 after closure (e.g. showing response to the 14.11.23 pulse test in S14).

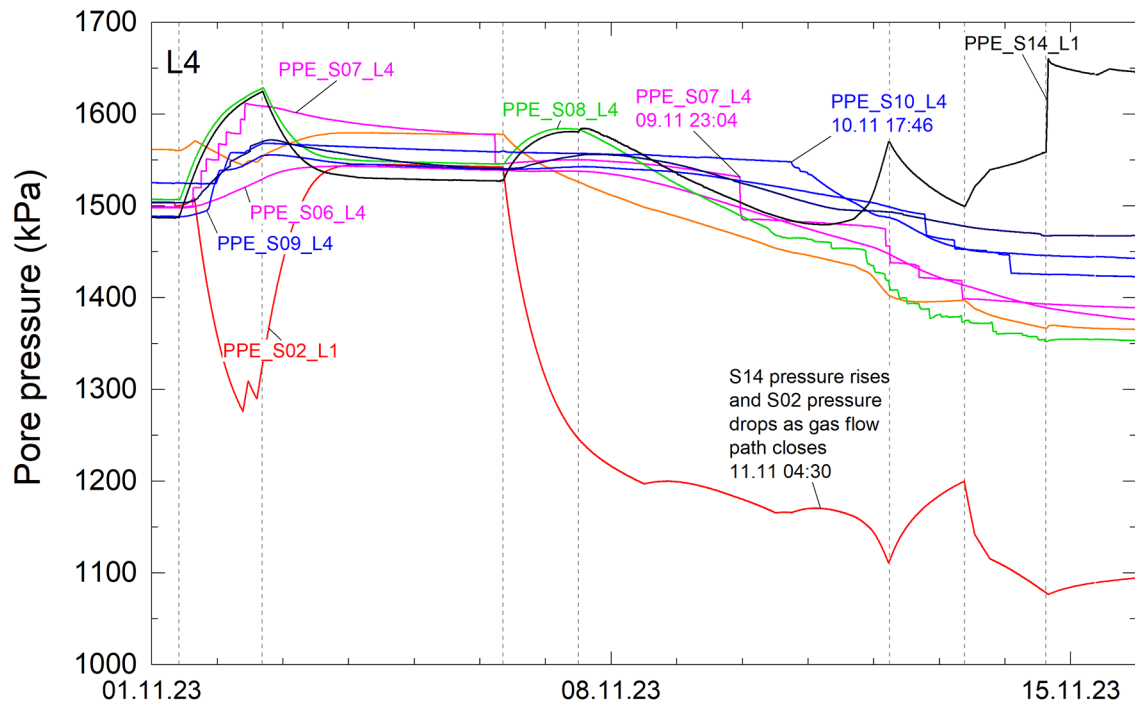


Fig. 7-13: Pore pressure in seal section at L4 during Phase 11 reverse flow period

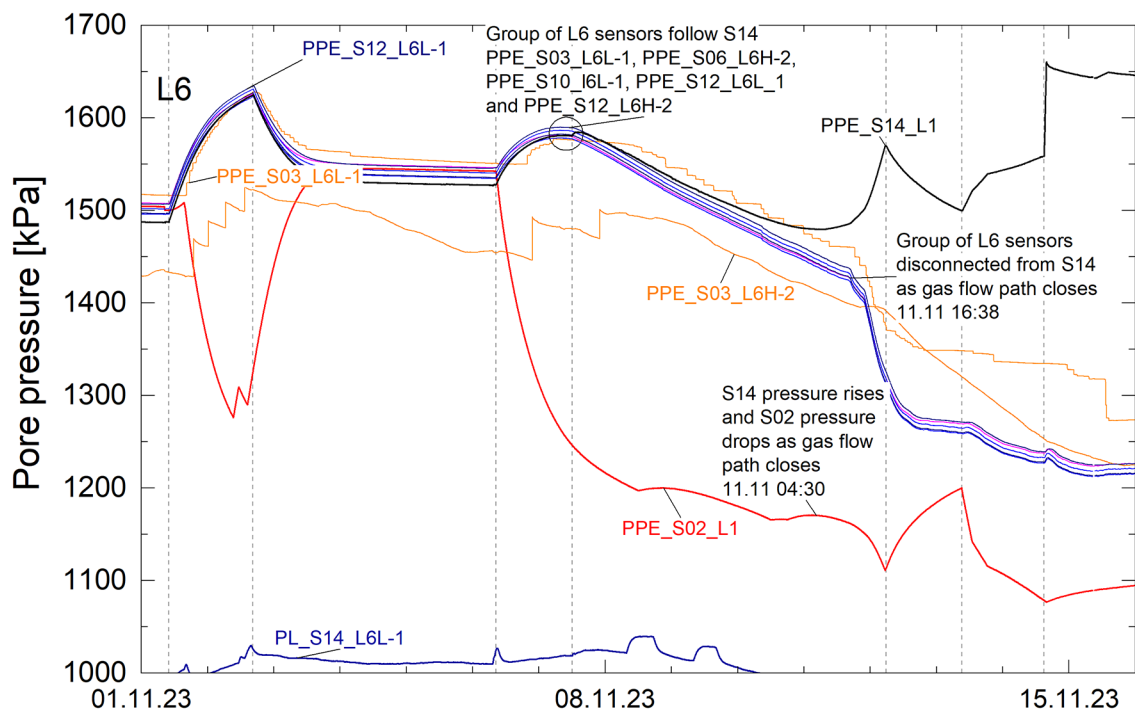


Fig. 7-14: Pore pressure in seal section at L6 during Phase 11 reverse flow period

During the water injection into the S14 filter, and “reverse” gas flow from S14 to S02, some of the TDL sensors that had previously indicated desaturation recovered as the water level within the filter rose (see Appendix F.5). Fig. 7-15 shows the interpreted evolution of water level in S14 during the reverse flow period. The start of the rise in level occurred soon after the switch to water injection on 07.11.23. The peak water level was reached on 11.11.23 at 06:00 shortly after the start of the rise in pressure in S14. The interpreted situation in the S14 filter after the end of reverse flow is illustrated in Fig. 7-16.

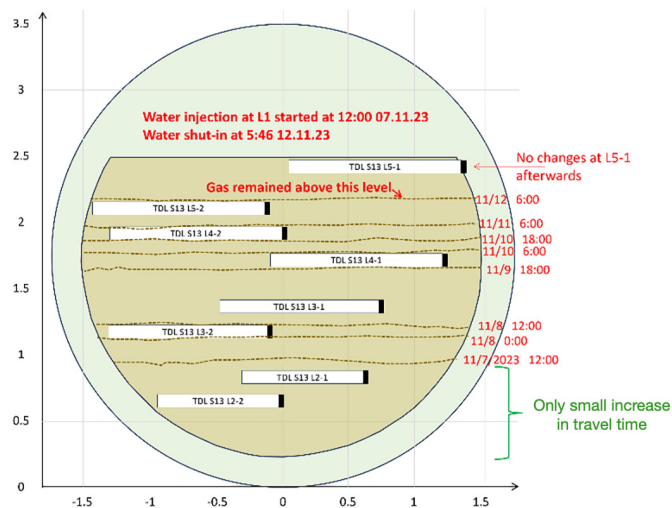


Fig. 7-15: Evolution of water level in S14 sand filter as interpreted from TDL data

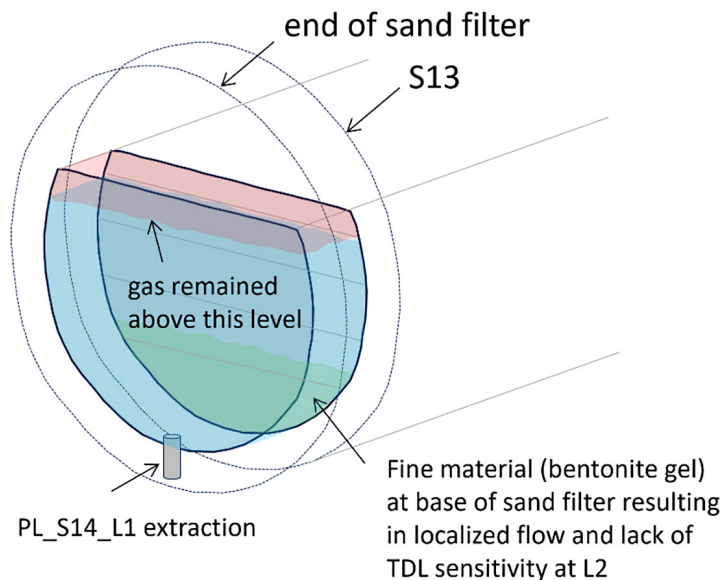


Fig. 7-16: Situation in S14 filter on 11.11.23 at 06:00 as interpreted from TDL data

Two filter pulse tests were performed in S14 on 29.11.23 and 30.11.23 indicating gas volumes of 283 and 269 l, respectively. This confirmed the TDL interpretation and suggested that the gas flow path exit from S14 was within the sand/bentonite at about L5. A total of 458 l of water were injected into S14 during the reverse flow period, which is ~200 l less than the estimated gas volume in the filter.

7.6.5 Gas-water exchange (G-WX) in S02

Following the closure of the gas path, it was decided to perform a G-WX in S02 to extract gas from the filter. The G-WX was performed from 24.11.23 11:22 to 27.11.23 06:43 when the S02 pressure became unresponsive to the extraction rate. In all, 277.4 l of water were injected and 74 l of water extracted (net 203 l), while 193 l of gas (at S02 temperature and pressure) were extracted. A filter pulse test was performed on 29.11.23 with an estimated gas volume in the filter of 130 l, approximately 200 l less than was indicated by the pulse test on 24.11.23.

7.7 Interpretation summary

7.7.1 Gas flow path characteristics

The step-rate tests performed during Phase 10 showed roughly constant permeability and recovery for a range of pressure gradients. Even at very low pressure differences between the two filters (~20 kPa), gas was able to flow from S02 to S14.

RW tests on selected PPEs demonstrated the ability to extract gas at moderate rates of ~10 ml/min from piezometers in L4 and L6. These rates are significantly higher than the water flow rates during the dipole test of ~2 ml/hr, demonstrating the flow path's high permeability to gas in the sand/bentonite and at the sand/bentonite-GBM interface.

During Phase 11, it was possible to reverse the flow between the filters and displace gas from S14 and extract from S02 at moderate rates (~60 ml/min). It seems reasonable to assume that this was via the same gas path as the long-term flow from S02 to S14 prior to this. However, the gas path closed quickly when water levels in the S14 filter rose to around L5, trapping about 300 l of gas in the filter.

7.7.2 Gas flow path summary data

Summary data for GFT Phases 10 and 11 are given in Tab. 7-5 and Tab. 7-6.

Tab. 7-5: Gas path summary GFT Phase 10 (N₂ step-rate injection tests 01.09. – 22.09.23)

Parameter	Value	Comment
Injection pressure (S02)	1,750 – 1,780 kPa	The pressure gradient across the seal decreased over time as resistance to gas flow dropped
Extraction pressure (S14)	1,400 – 1,450 kPa	
Injection gas flow rate (S02)	1,380, 540, 180, 45 mlN/min	Series of constant rate steps
Extraction volumetric rate (S14)	99, 39, 13, 0 ml/min	Adjusted to balance constant injection rates
Total gas injected	21.6 m ³ N	
Total gas extracted	20.1 m ³ N	
Overall recovery	93%	Average over Phase 10
Extracted water volume	2.6 l	Water from drainage of S14 from L1 extraction and some flow from S/B
Tracer fraction (S14)	N/A	No sampling performed as emphasis was on flow path diagnostics
Tracer fraction (PPEs)	N/A	

Tab. 7-6: Gas path summary GFT Phase 11 reverse flow step

Parameter	Value	Comment
Injection pressure (S14)	1,480 – 1,620 kPa	Pressure in filters drop during S02 net extraction
Extraction pressure (S14)	1,110 – 1,550 kPa	
Injection gas flow rate (S14)	Max. 1,200 mlN/min	Initial gas injection to raise S14 pressure and start reverse flow
Injection water flow rate (S14)	Max. 90 ml/min	Water injection to resaturate and flush gas from S14
Extraction volumetric rate (S02)	60 – 80 ml/min	Extraction from S02
Total gas injected (S14)	3,870 lN	Initial gas injection
Total water injected (S14)	458 l	
Total gas extracted (S02)	8,626 lN	
Extracted water volume	743 l	Only gas produced. No recorded water production.
Tracer fraction (S14)	N/A	No sampling performed as emphasis was on flow path diagnostics
Tracer fraction (PPEs)	N/A	

7.8 State of the in-situ experiment post-Gas Flow Test

7.8.1 Residual free gas

Residual pockets of gas are present in the top of the S02 and S14 sand filters and are likely to be present locally within the sand/bentonite (Tab. 7-7). It is also possible that there has been a slow build-up of gas that has leaked off from the main S02 – S14 flow path. Approximately 5% of the gas was not recovered and although some gas is likely to have dissolved in the porewater, a volume of trapped gas could exist above the sand/bentonite as suggested by the observed increase in measured stress at the top of the tunnel in S06, S08 and S10. Gas may also have leaked off into the geosphere around the end of the WT drift.

The remaining gas in the filters can be compressed by raising pressure (as happened in S02) and will over time dissolve and diffuse away. In the meanwhile, it will result in increased sand-filter compressibility and could result in a barrier to water flow into the GBM and the top of the sand/bentonite. The long-term evolution of pressures (and comparison with pre-GFT pressure distribution) could provide information on the distribution of the gas and any ongoing leakage from the gas volumes. Repeat filter pulse tests and long-period sinusoidal injections can be used to measure the filter gas volumes over time.

Tab. 7-7: Residual gas volumes

	Approximate volume [l]	Pressure [kPa]	Remark
Top of S02 filter	130	1,205	Pulse
Top of S14 filter	269	1,502	Pulse 30.11.23
Flow path L2-L6	Small?	1,200 – 1,500	Estimate
Gas “leak-off”		Approximately 20,000 IN of gas not recovered	

7.8.2 Gas in solution

Gas will have dissolved and diffused and advected in the seal section porewater. The speed of dissolved gas transport will be controlled by the transport diffusivity and the advective flow within the sand/bentonite. The extent of the dissolved gas plume could be mapped by porewater sampling from selected PPEs, but sampling will be slow due to the low permeability to water of the sand/bentonite and the relatively large pore volume associated with the hydraulic lines.

Dissolved gas may have been transported by diffusion and slow advection through the GBM into the rock where it may have exsolved depending on the local pore pressure. Free gas could also have leaked into the geosphere where it would dissolve in the groundwater and be transported in the fracture system and diffuse into the matrix.

8 Summary preliminary interpretation

8.1 Conditions at the start of the GFT

Evidence on system saturation

The data indicate that the saturation state of the sand/bentonite was high prior to the GFT. There has been almost continuous high-pressure water injection into the filters since mid-2018, thereby minimising persistent effects from GPT1. Evidence for the high saturation at the different instrumentation levels within the sand/bentonite includes:

- baseline PPE compressibility below $2 \times 10^{-12} \text{ m}^3/\text{Pa}$ at (L2 – L4),
- stable and high TDR travel times (L2 – L5),
- piezometer responses to large-scale pulse tests (L2 – L4),
- long-term stable hydraulic gradient with pore pressures above 1,400 kPa (L2 – L4),
- low effective hydraulic conductivity limiting the injection rates even at high injection pressure,
- the observed relatively uniform pressure response to gas path development (L2 – L4).

At the interface between the sand/bentonite and the granular bentonite at L6, the impact of possible partial saturation includes:

- higher compressibility in the PPEs at L6,
- heterogeneous pore pressure with some piezometers measuring ~1,000 kPa (about 300 kPa lower than piezometers in L4). This lower measured pressure at L6 may in part be due to the piezometer filter emplacement within the GBM.

The granular bentonite above L6 was likely to include some remaining, partially saturated zones. The two operating relative humidity sensors at L7 in S03 and S10 showed values above 94%. Pressure at L8 was typically low, reflecting the slow saturation of the GBM and flow to/from the geosphere above the tunnel and to the tunnel around S14 (via the instrumentation ducts).

System status

Responses from the water injections showed very little interference between filters, demonstrating their hydraulic separation. It is therefore believed that the leak event in 2014 after sealing mainly impacted the local properties between the S14 and S12 filters, particularly around the base of the sand/bentonite and the connection to the main duct where the rupture is believed to have occurred. Locally faster pressure responses are seen in PPE_S12_L2-2, which could be related to the leak path from the filter.

Gas entry effectively started from the S02 filter, which is believed to be structurally intact and unaffected by the leakage event. Thus any potential impact from the leakage on GFT is believed to be minor due to the end-to-end nature of flow from S02 to S14 and the gas path location in the upper part of the sand/bentonite.

8.2 Gas path key findings

Key findings for the gas flow path in the seal section from the GFT can be summarised in three points:

1. The gas path formed quickly with no significant entry pressure and is located between L4 and L6. This interpretation is based on the following observations:
 - The gas path formed rapidly during the water-gas exchange, when S02 injection pressure was only slightly higher than that prior to the start of injection,
 - Abrupt pressure responses were first observed in the L4 and L6 piezometers,
 - The greatest changes in pressure from the start of the GFT were observed at L4 and L6.
 - Traced gas has successfully been sampled from piezometers in L4 and L6.
2. The gas path is highly permeable compared to the water permeability of the seal section. The basis for this interpretation is that:
 - Water injection rates prior to the GFT were typically below 0.2 ml/min for similar pressure conditions. During the GFT, volumetric rates of gas injection into S02 and extraction from S14 were ~100 ml/min for significant periods.
 - The flow resistance to gas flux across the seal decreased during the GFT. The observed volumetric flow rate increased during the constant pressure period and, more generally, the product effective permeability $\times$ area increased during the GFT (see App. H.2.2). For the most part, there was a roughly linear increase over time but there also appeared to have been a ~20% increase after the December 2022 shut-in.
3. The gas path is interpreted as being of a low volume, relative to the large volumes of gas in S02 (~300 l) and S14 (~650 l). The basis for this interpretation is:
 - the rapid creation of the path during the water-gas exchange,
 - the rapid response in S14 to changes in S02 injection,
 - the relatively small pressure increase (100 – 200 kPa) during the creation of the flow path.

It should be noted that the gas mass balance does not significantly constrain the flow path gas volume, because of uncertainties on the larger gas volumes in the filters.

8.2.1 Gas path localisation

Evidence from PPE gas sampling

The detection of gas tracers in samples taken from PPE_S06_L6H-2, PPE_S08_L4 and PPE_S10_L4¹⁶ provides direct evidence of the location of the injected gas within the seal. Although gas sampling drawdowns were limited to reduce any local compaction, it is possible that the gas path was locally affected by sampling in these PPEs (e.g. development of free gas phase at PPE_S08_L4). However, this is thought to be a relatively minor effect.

¹⁶ Some helium was also detected in samples from PPE_S03_L6L-1, but these samples also showed an increasing presence of methane, indicating a local gas phase not well connected to the gas flow path.

Similarly, the lack of gas produced when sampling PPE_S03_L3, PPE_S06_L4 and PPE_S07_L2 suggests that, at least locally, the gas path is absent around these PPEs.

Evidence from gas path initialisation

Gas injection pressures were adjusted twice during GFT Phases 2 and 3: (1) at the start of the W-GX on 02.05.22 by ~50 kPa and (2) the subsequent increase from 1,800 kPa to 1,900 kPa on 12.05.22 by ~100 kPa.

About 24 hours after adjustment (1) a linear pressure rise was observed in S/B piezometers and several of the TPWs around the seal section. At the end of the pressure rise, pressures had equalised across the vertical sections (L2 – L4) while the horizontal pressure gradient between S02 and S14 remained essentially unchanged.

The linear changes in pressure induced during Phases 2 and 3 are interpreted as being caused by the expulsion of porewater from the gas flow path. Although the overall pattern is relatively uniform (due to the diffusion of the pressure disturbance), the earliest pressure responses occurred at PPE_S06_L4 and PPE_S07_L4 and then appear to have propagated towards S14 (as shown in Fig. 8-1). Pressure responses in L2 and L3 were more diffusive and did not show the same rapid rise as those in L4. The observed spatial distribution of pressure in the sand/bentonite (L2, L3 and L4) at the end of the W-GX (by 06.05.22) and the induced pressure changes were relatively uniform (see Fig. 3-3 and Fig. 3-4).

Significantly larger pressure changes occurred at the S/B-GBM interface at PPE_S06_L6H-2 and PPE_S10_L6L-1, although these were later than the earliest responses in L4. The pressure change at PPE_S06_L6H-2 was particularly abrupt (~400 kPa increase by 04.05.22 15:00 see Fig. 8-1). A smaller peaked response was seen in PPE_S03_L6L-1. Changes at the S/B-GBM interface were among the largest and most heterogeneous, partly due to the lower measured pressure at the start of the GFT.

The early piezometer data suggest a path from S06 to S12 located at L4, and a more heterogeneous path at L6 from S06 to S10. There are no distinct pressure responses that would indicate the location of the gas path from the S02 sand filter to S06 or S07.

Although a larger pressure change is associated with adjustment (2), pressure response in the S/B is comparatively homogeneous and lacks the abrupt pressure increase signals. This is interpreted as an indication that a gas path across the seal section had largely formed by this time (12.05.22 12:50).

There is no clear evidence of significant desaturation from the TDP sensors in the sand/bentonite during the early phases of the GFT when the gas path was formed. Changes are typically erratic or of minor magnitude (see Appendix F.3).

In conclusion, development of one or more discrete flow paths in the upper part of the sand/bentonite during the W-GX is the most likely explanation for the observed pattern of pressure response. Given the delayed and heterogeneous pressure responses at L6, direct gas flow from the filter along L6 appears unlikely. The path would have to start above the water level in S02 and would then have to connect to the L4 flow feature.

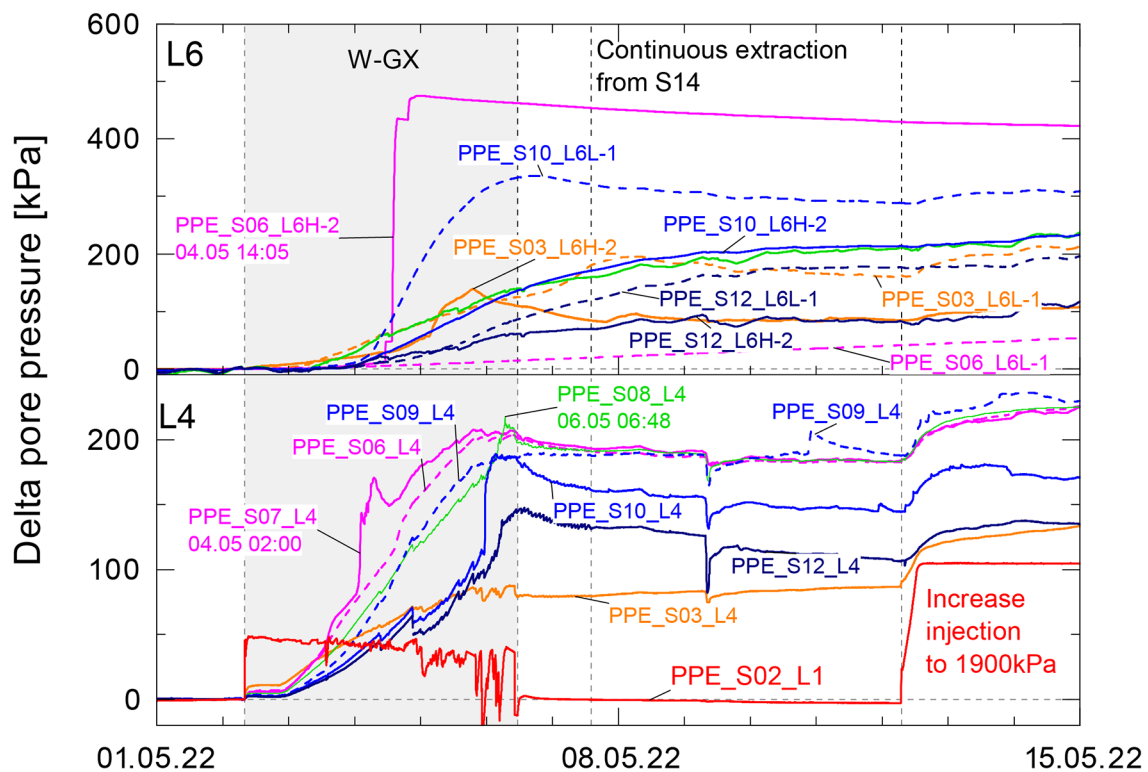


Fig. 8-1: Pressure change (from 01.05.22) during the S02 W-GX and early gas injection for the L4 and L6 piezometers

Evidence from observed stress responses

Total pressure cells on the tunnel walls, floor and roof all showed stresses significantly higher than the pore pressure within the seal section throughout the GFT (Fig. 8-2). An early short linear pressure rise during GFT Phases 2 – 3 was observed, similar to but slightly in advance of the piezometers. This is interpreted as relating to the bulk pore pressure response in the sand/bentonite to water expulsion from the gas flow path. Subsequently cells at the roof showed an extended long-term linear increase of a little over 0.5 kPa/day until pressures decreased significantly in Phases 10 and 11. This could be due to ongoing saturation of the headspace GBM driven by water expelled from the sand/bentonite or could indicate some build-up of gas trapped within the GBM.

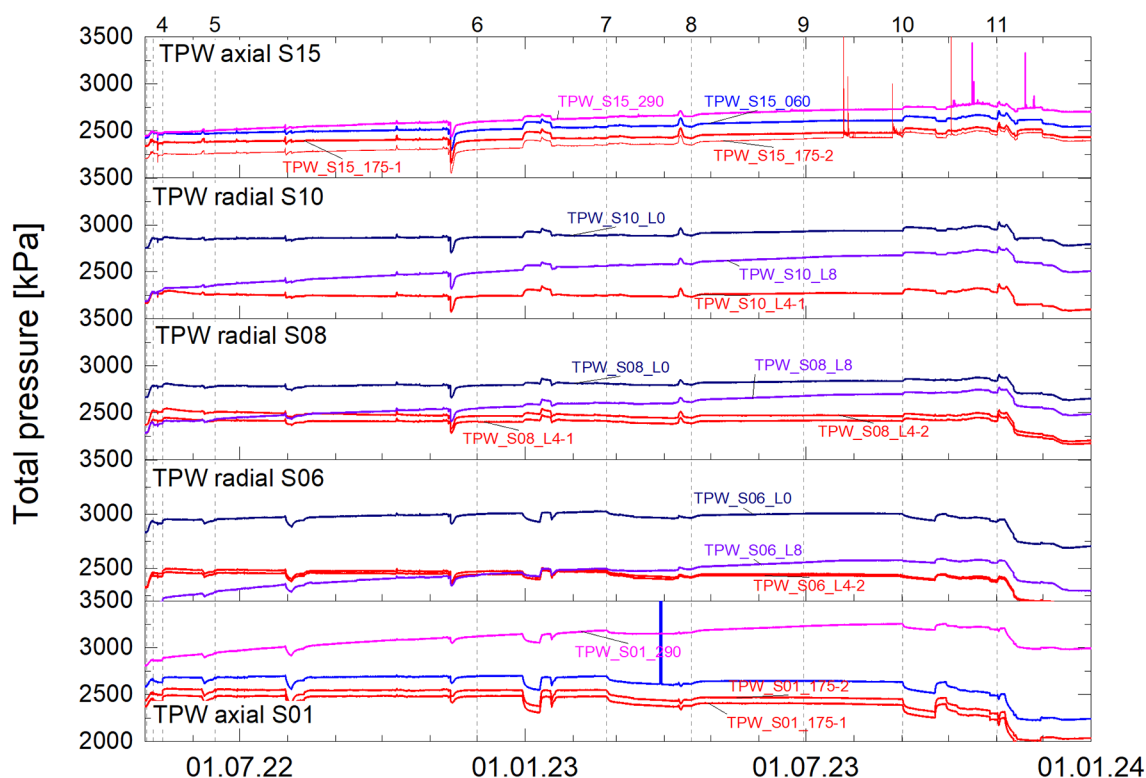


Fig. 8-2: Total pressure measurements since 01.05.22

Evidence from S14 (extraction side)

App. F.4 summarises the TDL responses to S14 drainage and resaturation, providing indications for water level changes in S14. The sensors show a consistent pattern during drainage with the first response to gas seen at the right side of TDL_S13_L5-1 (2.43 m) and then in the progressively lower sensors in L4 and L3. Although the two sensors in L2 show no response, a gas path must have developed down to PPE_S14_L1 where gas was extracted as of 08.06.22, indicating inhomogeneous desaturation of the filter or lack of sensitivity in the two lower TDLs.

During water injection in November 2022, a reversed pattern (App. F.5) recorded the filter water level rise from L3 up to TDL_S13_L5-2 at 2.11 m but with no change observed at the higher sensor TDL_S13_L5-1 (Fig. 8-3) at 2.43 m, which is consistent with gas being trapped in the S14 filter. This suggests that the gas path out of the filter during resaturation was somewhere between 2.11 m and 2.43 m¹⁷ and that this path closed once the water level reached the outflow point as it was not possible to push any more gas out of the filter after this. The observed stability of the gas path during the GFT suggests that this was likely also the main gas inflow point to the filter during drainage and subsequent gas extraction.

¹⁷ These are the as-built elevations of the sensors. The likely deformation of the sand filter due to swelling of the bentonite block walls adds some uncertainty to the actual levels of the sensors during the GFT.

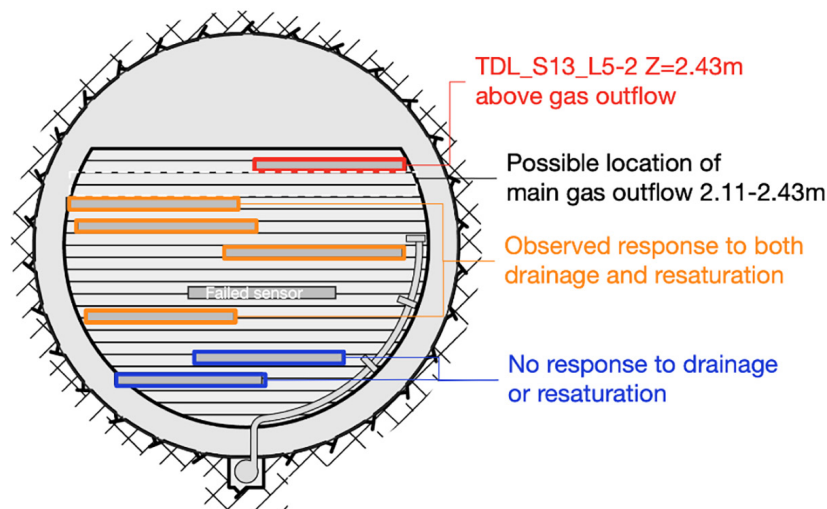


Fig. 8-3: Summary of S13 TDL responses to drainage and resaturation

Expectation of flow path geometry

The vertical compaction of the sand/bentonite is likely to have led to the development of layering fabric within the sand/bentonite and consequent anisotropy in flow properties. This anisotropy has been observed in the long-term pressure response and has been implemented in flow models of GAST. It is therefore likely that any heterogeneity in gas entry pressure and/or effective permeability relates to features parallel to layering.

With the exception of the instrumentation risers and the seismic array in S05, instrumentation and construction features were performed at the layer top and would be unlikely to have created sub-vertical preferential flow features. Special care was taken in the compaction around the risers to minimise the likelihood of any preferential paths between the main duct and upper layers.

The discussion in previous sections focused on the vertical location of the gas flow path (in particular the relationship to instrumentation levels) but the lateral location is less well constrained. Sensors have typically been located towards the central section/axis of symmetry of the sand/bentonite¹⁸ (see App. A for instrument section layouts) with only some TDPs installed off that axis. Of the PPEs that produced gas, PPE_S06_L6H-2 is relatively close to the GBM, while PPE_S08_L4 and PPE_S10_L4 are close to the tunnel axis. The lack of sensors close to the interface with the surrounding GBM makes it difficult to assess the lateral location of the gas flow path.

Variations in compaction across the layers particularly close to the contact with the GBM might result in preferential flows at the margins of the sand/bentonite layers. Such a path would be consistent with observations from the S14 sand filter TDLs during drainage and resaturation but would not explain sampling of a free gas phase in the centre of the sand/bentonite body (e.g. PPE_S10_L4).

¹⁸ In part this was a deliberate decision to avoid preferential connections to the risers.

Summary of sensor observations

Fig. 8-4 shows the key sensor observations relevant to the location of the gas path. These include:

- early pressure responses to gas path formation,
- gas tracer samples from PPEs,
- TDL monitoring of S14 drainage and resaturation.

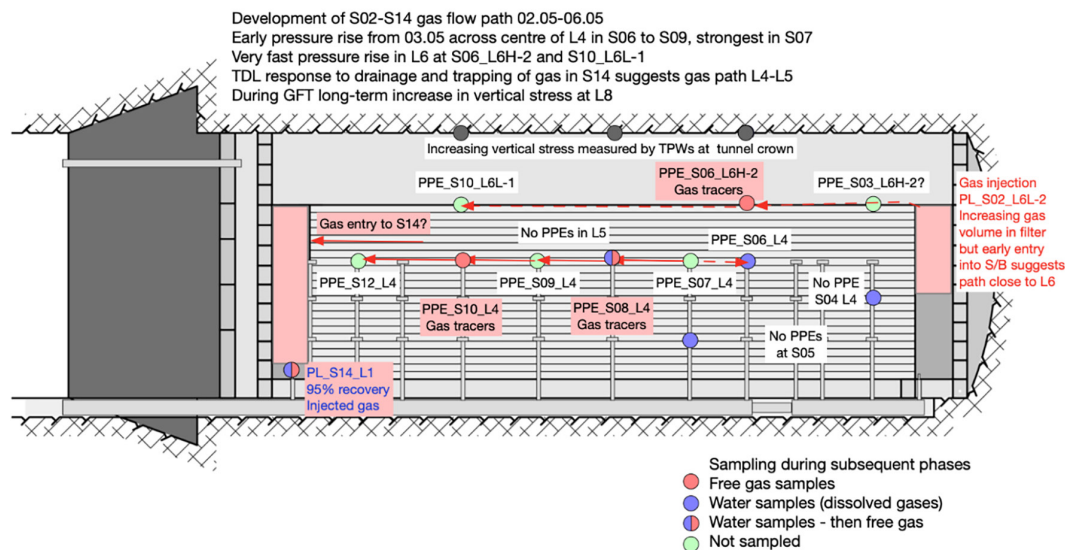


Fig. 8-4: Schematic vertical section showing sensor observations during the GFT related to gas path location

A schematic concept for the gas path from S02 to S14, based on Fig. 8-4, is shown in Fig. 8-5. The gas path extends from S02 in the upper part of the sand/bentonite around L6, but then develops from S06 to S14 between L6 and L4. The path then connects to the S14 filter somewhere around L5 as suggested by the observed closure of the gas path and the TDL data (Fig. 8-3). Parts of the path are more transmissive and better connected than others, resulting in varying tracer retention along the gas path as seen in the tracer sampling data.

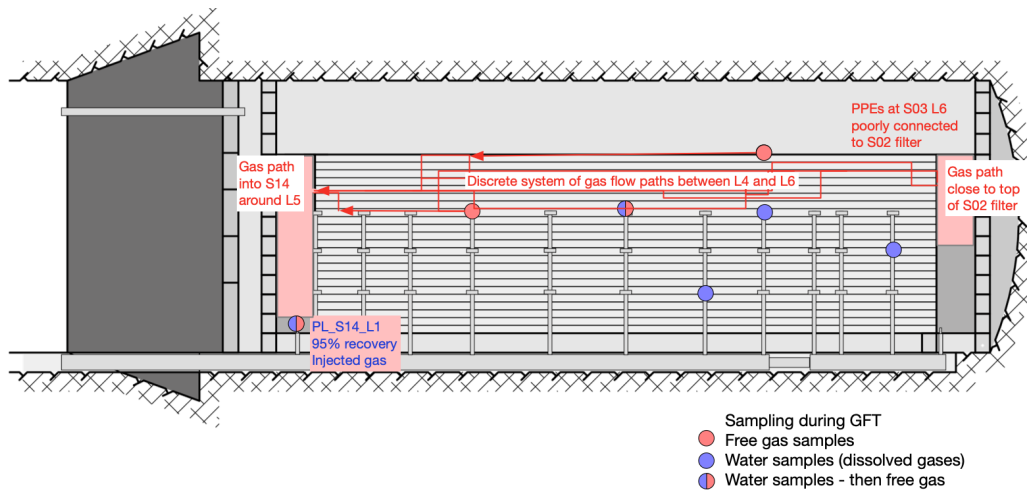


Fig. 8-5: Vertical section illustrating the concept for the GFT gas path

8.2.2 Gas path development and effective properties

The gas path from the S02 sand filter to the S14 filter formed quickly during GFT Phases 2 and 3. In Phases 4 to 6, a constant pressure difference was maintained between the filters, and increasing injection rates were required to maintain the pressure difference. To simplify operations and manage the gas supply of Gas Mix #2, it was necessary to switch to controlled injection rates with varying pressures for Phases 6 to 9.

The continuing decrease in the resistance to gas flow resulted in an increase in the gas injection and extraction rates while the pressure difference was maintained (Phases 5 – 7 in Fig. 8-6). Pressure differences decreased while the flow rates were kept constant (Phases 8 and 9 in Fig. 8-6). The effective permeability $\times$ area¹⁹ increased steadily throughout Phases 1 – 9 of the GFT, roughly increasing by a factor of 20 from $\sim 2.5 \times 10^{-17} \text{ m}^4$ in Phase 3 after the W-GX to $\sim 5 \times 10^{-16} \text{ m}^4$ during Phase 9. The steady increase seen in Fig. 8-6 suggests slow ongoing processes rather than any specific flow path growth events. Transient effects influence the calculated values during the Phase 10 step-rate tests but the stabilised values are close to those for Phase 9.

Locally, the gas flow path was observed to develop around PPE_S08_L4 with initial production of water samples followed by free gas samples. The processes by which the gas path developed are likely to include gas invasion of macropores in the sand/bentonite (resulting in higher connectivity), drying of the sand/bentonite and bentonite shrinkage.

¹⁹ This is calculated from the flow rate, pressure difference between the filters, viscosity and path length (see definition in App. H.2). An effective permeability can be calculated if the flow path cross-section area is known or can be assumed.

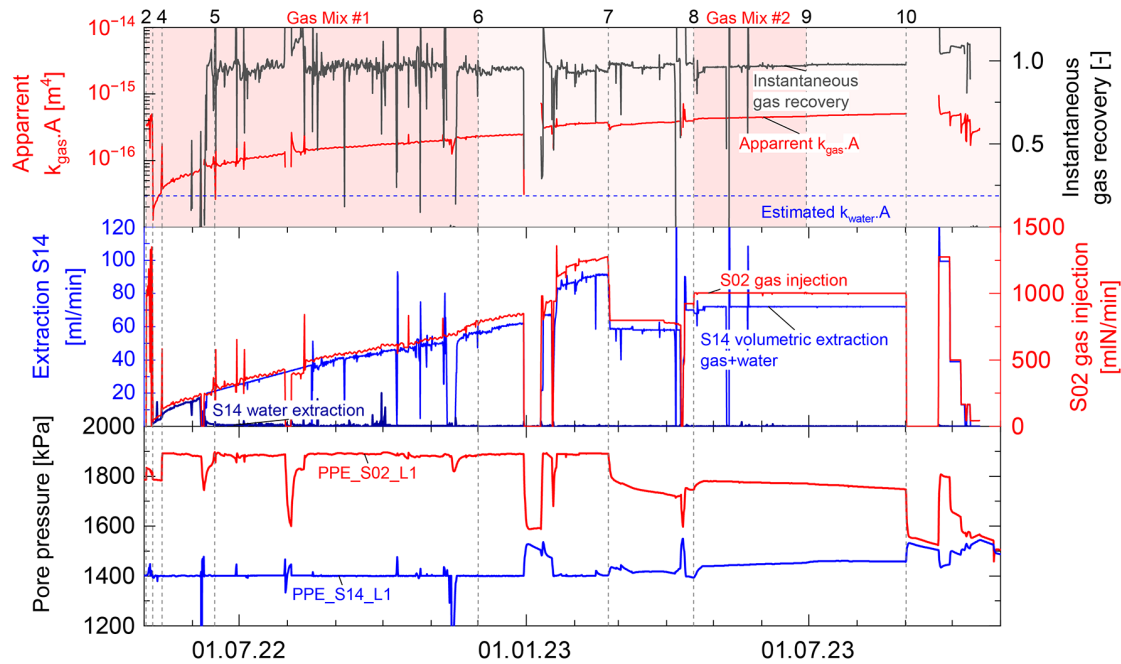


Fig. 8-6: Flow rates (centre) and pressures (bottom) up to the end of GFT Phase 10, together with effective permeability $\times$ area and instantaneous recovery (top)

In Phase 10, a series of short constant rate steps were used to determine the impact of injection rate and pressure. This showed roughly constant resistance to gas flow at a range of pressure and flow rates (Fig. 7-10) over the short period of the step-rate tests. This suggests that the path was relatively insensitive to gas pressure.

The instantaneous gas recovery was typically high ($>95\%$) from July 2022 (Phase 5) onwards²⁰. Small uncertainties in the flowmeter calibrations ($\sim 1\%$) resulted in uncertainty in the estimated recovery but almost all the injected gas was recovered from the L1 extraction. The overall gas mass recovery is estimated at 95% at the end of Phase 10 when accounting for the gas present in the two sand filters.

8.2.3 Gas entry pressure into the sand/bentonite

Gas entry pressure is typically estimated from laboratory measurements of the water retention curve (or soil-water characteristic curve SWCC) relating water content (or saturation) to suction, using either graphical or analytic methods (Soltani et al. 2021). In the field, specially designed borehole test sequences incorporating hydraulic tests, gas injection and recovery have been used to estimate entry pressures via diagnostic analysis and modelling (Finsterle & Pruess 1995, Senger et al. 1998, Marschall et al. 2005).²¹

The observed response to gas injection during both the GFT and the previous GPT1 identified gas entry into the sand/bentonite from piezometer measurements. While it could be possible to derive estimates of gas entry values by detailed modelling, it is only possible to give an upper bound from the measurements based on the earliest piezometer responses in S03 – S07.

²⁰ See Chapter 7 for a discussion of recovery during the reverse flow period.

²¹ Other approaches have used correlations (Marschall et al. 2005) with permeability or particle size (Sakaki et al. 2014).

The pressure distribution around S02 at about the time when gas entered the sand/bentonite is shown in Fig. 8-7. The breakthrough pressure for gas to enter L4 depends on the distance from the S02 filter with a pressure difference of less than 200 kPa at S03. The breakthrough pressure across the whole sand/bentonite seal section is 435 kPa.

The entry pressure will be lower than the breakthrough pressure and is likely to be below ~200 kPa as observed in small-scale laboratory samples (Manca 2016). It is possible that the entry pressure is considerably lower than this given the rapid propagation across the seal and the small snap-off pressures²² observed together with the relative insensitivity to injection pressure seen in the Phase 10 step-rate tests.

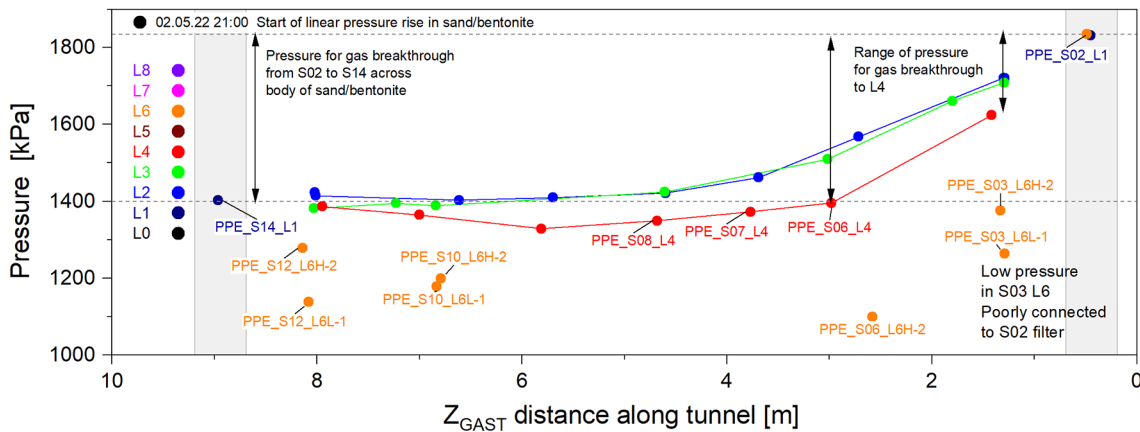


Fig. 8-7: Schematic vertical section showing pressure profile and breakthrough pressures on 02.05.22 at 21:00

8.2.4 Gas flow in the GBM

There is no evidence of gas flow through the GBM surrounding the sand/bentonite. The two operating RH sensors stayed above 94% (Fig. 8-8) during the GFT, with one sensor becoming inoperative as it approached 100% relative humidity. Total pressure cells were typically stable (at the tunnel wall) or showed a slow increase (at the tunnel roof) perhaps indicating ongoing saturation of the large GBM volume above the sand/bentonite

Given the high gas recovery from S14 and the observed responses in L4 and L6, it seems likely that the bulk of the GBM was highly saturated and acted as a barrier to gas flow during the GFT.

²² Amann-Hildebrand et al. (2012) suggest that the snap-off pressure is approximately half that of the drainage capillary breakthrough pressure in a rock of comparable water permeability to the sand/bentonite.

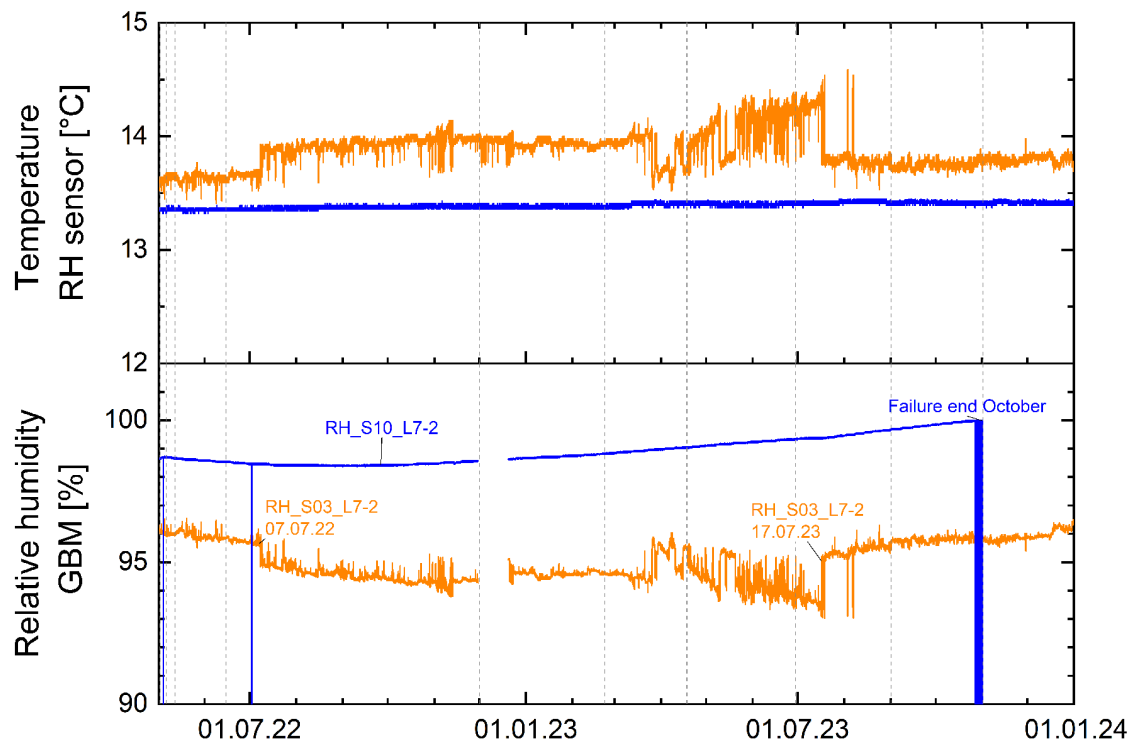


Fig. 8-8: RH and temperature from operating RH sensors during the GFT

8.2.5 Gas flow in the geosphere

The focus of the GAST in-situ test is on flow within the sand/bentonite seal body. Only limited monitoring of the geosphere has been performed. Pressure responses in borehole intervals close to the seal section (e.g. SB 80.003-i1) show a pressure rise during the GFT and possible responses to the Phase 10 flow steps. It is therefore possible that some of the gas not recovered from S14 migrated (either in solution or as free gas) through the GBM into the geosphere where it will have slowly dissolved and been transported with the groundwater.

8.3 Comparison with GPT1

GPT1 was performed in early 2018 and envisaged as a small-scale preparatory gas injection to characterise gas entry into the sand/bentonite (Lanyon & Herbert 2021). Problems occurred during the S02 W-GX that resulted in some gas remaining trapped in the S02 filter while problems with water extraction could be resolved. When the W-GX was resumed on 01.02.18 and after approximately 250 l of gas had been injected into S02, a sudden gas breakthrough into the sand/bentonite occurred on 02.02.18 with pressure responses at L4 (PPE_S07_L4) and L6 (large pressure jump PPE_S06_L6H-2). Once it was clear that gas had entered the sand/bentonite, it was decided to perform a series of constant-rate gas injections. These continued until 18.03.18. The presence of gas at L4 (PPE_S08_L4) and L6 (PPE_S06_L6H-2) was subsequently confirmed by PPE sampling after the end of gas injection.

There are clear similarities between the two sets of PPE responses to gas injection around S02 suggesting that, at least locally, the gas followed a similar path when entering the seal section at relatively low pressure. The different S14 boundary conditions controlled the outflow path with S14 being maintained above the S02 injection pressure in GPT1, while it was maintained at a significantly lower pressure during the GFT (initially 400 – 500 kPa below S02). The gas path in the GFT therefore connected S02 to S14 and created the intended end-to-end flow.

Tab. 8-1 provides a short comparison of GPT1 and GFT parameters and observations. Further detailed comparisons could provide additional evidence for the existence of features around S02 that were activated during GPT1 and then possibly reactivated by gas injection during the GFT. Any gas path through the GBM was likely to be less active during the GFT due to the presence of a strong “sink” (S14 filter) and ongoing saturation of the GBM in the intervening 4 years.

Tab. 8-1: Comparison of GPT1 and the GFT

	GPT1	GFT
Saturation state	High in S/B Ongoing in GBM (>75% in 12 operating sensors)	High in S/B Largely complete in GBM (RH>94% in last 2 operating sensors)
Initial pressure [kPa]	1,100 (S02)	1,800 (S02)
Injection pressure	1,150/1,200 kPa	1,850/1,900 (declining after switch to constant rate)
Gas entry into seal	During extended W-GX (extraction flow clogging problems)	During S02 W-GX
Early pressure responses	L4 (PPE_S07_L4) and L6 (PPE_S06_L6H-2 jump)	L4 (PPE_S07_L4) and L6 (PPE_S06_L6H-2 jump)
Gas injection rate [mlN/min]	Multiple constant pressure injections Max. 400 (smoothed mean value)	Constant pressure and late constant injection rates. Max 1,380 (Step 1 Phase 10)
Gas volume [lN] injected	13,228	527,516 (end Phase 10)
Gas volume in S02 filter [l]	After W-GX and prior to gas entry 250 l	W-GX 289 l increasing over time.
Gas volume in S14 filter	N/A	Drainage to L1 ~650 l
Localisation of path	At top of sand/bentonite or around L6	Between L4 and L6
Fate of injected gas	Largely uncertain – S14 pressure maintained above injection pressure	End-to-end flow with high recovery of injected gas
Recovery	Low – only gas from S02 and selected piezometers recovered	>95% of injected gas recovered from S14
Gas leakage to tunnel	Not monitored	Continuous monitoring showed no evidence of leakage to tunnel
Gas in S/B	Extraction of gas from PPE_S08_L4	Confirmation of gas tracers in PPE_S08_L4 and PPE_S10_L4
Gas transport monitoring	No gas tracers used	Continuous monitoring of extraction from S14 and selected PPEs
Geosphere responses	Small responses seen in SB 80.003i1 (10 – 20 kPa)	General pressure rise and response to testing events (SB 80.003)

8.4 GFT gas volumes and recovery

Tab. 8-2 gives the estimated injected gas and extracted gas and water volumes up until the end of Phase 10. This corresponds to the period of gas injection into S02 and recovery from S14. During Phase 11, the gas injection direction was reversed and gas was recovered from S02.

The lower recovery for Gas Mix #1 relates to the drainage of the S14 filter from L1. Once a stable gas volume was present in S14, recovery was ~95%. The estimate of total unrecovered gas in Tab. 8-2 includes the gas volumes within S02 and S14. Including some partial recovery during the subsequent reversal of flow and S02 G-WX, the overall recovery of 93% is an underestimate of the performance. Comparison of the gas-saturated filter porosity during the GFT (Fig. C-9) with the residual gas volumes in Tab. 7-7 indicates that about 50% filter gas was recovered and 50% remained trapped within the two filters. Taking all gas-saturated filter volumes into account (~900 l), the resulting gas recovery is ~95%.

This unrecovered gas is likely to be free gas trapped within the seal section, gas in solution within porewater, and some may have migrated in solution out of the seal section during the ~18 months of gas injection.

Tab. 8-2: Gas and water volumes and recovery at the end of Phase 10

At the end of Phase 10, there were significant gas volumes in the S02 and S14 sand filters comparable to the water volumes extracted from the two filters, equivalent to ~15,000 IN. If these volumes are included in the total gas recovered, the recovery factor would be 95%.

Phase	Start	End	Gas injected S02		Gas extracted S14		Unrecovered gas	Recovery fraction	Water extracted S02	Water Extracted S14
			IN	l [S02 TP]	ln	L [S14 T,P]	IN		l	l
W-GX (Gas Mix #1)	02.05.22 08:00	06.05.22 11:22	5,525.1	301.6			5,525.1		301.0	2.9
Gas Mix #1	06.05.22 11:22	01.12.22 07:05	136,776.1	7,763.1	119,643.9	9,153.7	17,132.2	87%	-	641.1
N ₂ Flush #1	01.12.22 07:05	18.04.23 07:20	167,040.9	9,727.8	158,047.2	11,999.0	8,993.8	95%	-	29.6
Gas Mix #2	18.04.23 07:20	29.06.23 12:16	104,417.9	6,273.1	100,305.5	7,448.7	4,112.4	96%	-	10.5
N ₂ Flush #2	29.06.23 12:16	01.09.23 11:00	92,195.3	5,589.3	90,101.5	6,622.8	2,093.7	98%	-	6.9
Phase 10 (N ₂)	22.09.23 10:00	18.10.23 14:35	21,560.7	1,327.5	20,093.7	1,475.6	1,467.0	95%	-	2.6
Total			527,516.0		488,191.7		39,324.3	93%	301.0	693.6

9 Concluding remarks

9.1 Gas transport in the GAST seal

The GFT successfully demonstrated end-to-end gas flow at flow rates and saturation conditions relevant to the expected repository environment. The gas flow path within the saturated sand/bentonite seal section was, as expected, discrete and heterogeneous, but was characterised in terms of effective properties and detected at various points within the sand/bentonite (at L4) and at the sand/bentonite GBM interface (L6).

The gas flow path is believed to be of low volume with little desaturation of the bulk of the sand/bentonite. The path developed very quickly (within a week) while the resistance to gas flow significantly decreased over the remaining 1.5 years. The speed of development and low pore volume indicate a localised discrete path that is likely to have exploited heterogeneity in porosity and bentonite content within the seal section. Such heterogeneity likely relates to construction-induced variability as suggested by quality control measurements of dry density (Rüedi et al. 2012), but may also have developed during the early saturation period.

In total, over 527 m³N (volume normalised to standard pressure) of gas were injected up to the end of Phase 10 (Tab. 8-2). An additional 3.9 m³ N of gas were injected during the reverse gas flow in Phase 11. Gas injection rates into the S02 filter increased during the GFT with the highest sustained rates of 1,380 mL/min in Phase 10. This is equivalent to 725 m³N/yr. Almost all this gas was recovered from S14. The pressure difference across the 8 m of seal during this high injection rate was ~350 kPa. The high permeability to gas was maintained during subsequent lower injection rates at pressure differences below 60 kPa.

It is likely that the gas path would have become more permeable if gas injection had continued. Further, the gas path was resistant to interruptions (2 – 3-week shut-in periods) and quickly resumed flowing at the previously established flow rates and permeability. The gas path also appeared to function in the reverse direction (S14 to S02) during the short reverse gas flow period in Phase 11. The long-term end-to-end flow established during the GFT demonstrates the ability of the seal to support significantly higher volumetric gas flows than the water flows established prior to the GFT due to the significantly higher effective permeability of the seal to gas than water.

9.2 GFT outcomes

The GFT demonstrated the ability of the sand/bentonite to transport large volumes of gas at repository-relevant flowrates across an 8-m-long sand/bentonite seal at low entry pressure and relatively small gradients.

Major achievements include:

- successful full-scale, high-recovery gas tracer test performed over 1.5 years within the sand/bentonite seal section,
- development and application of real-time monitoring and sampling of tracer gases that allowed the unambiguous detection of end-to-end gas flow and of the injected gas within the sand/bentonite,
- provision of high-quality dataset for interpretation and modelling of gas flow in sand/bentonite.

The dataset from the GFT has already provided input for two-phase flow modelling experiments using both a TH focus on gas tracer transport and THM models. This first set of models was performed in parallel with the testing and needs further calibration to provide input towards potential quantitative interpretation of the GFT.

In summary, the GAST in-situ test provides repository-relevant information in that it successfully demonstrates the effective functioning of the sand/bentonite seal at a realistic scale. Furthermore, compared to the deep geological repository, GAST represents considerably less favourable conditions in that:

- Saturation of the sand/bentonite will be significantly lower than the nearly fully saturated conditions achieved prior to the GFT.
- In the repository, there is a potential leakage path along the EDZ, while in GAST, the GBM effectively limits gas transport out of the sand/bentonite.
- Lower swelling pressures are expected due to saturation with the Opalinus Clay porewater rather than the Grimsel groundwater used at GAST, which is likely to have maximised the swelling potential of the sand/bentonite.

The GAST demonstration under these less favourable conditions supports the robustness of the safety concept for an L/ILW repository.

10 References

- Amann-Hildenbrand, A., Ghanizadeh, A. & Krooss, B.M. (2012): Transport properties of unconventional gas systems. *Marine and Petroleum Geology* 31/1, 90-99. DOI: 10.1016/j.marpetgeo.2011.11.009.
- Bird, R.B., Stewart, W.E. & Lightfoot, E.N. (2007): *Transport phenomena*. Revised second edition. John Wiley & Sons Inc, New York, Chichester, Weinheim, Brisbane, Singapore, Toronto.
- Finsterle, S. & Pruess, K. (1995): Solving the Estimation-Identification Problem in Two-Phase Flow Modeling. *Water Resources Research* 31/4, 913-924. DOI: 10.1029/94WR03038.
- Fredlund, D.G. & Rahardjo, H. (1993): *Soil mechanics for unsaturated soils*. John Wiley & Sons, New York.
- Lanyon, B. & Senger, R.K. (2015): GAST (GAs-permeable Seal Test) Data interpretation of the monitoring period April 2012 to March 2014. *Nagra Arbeitsbericht NAB 14-64*.
- Lanyon, G.W. & Herbert, A.W. (2021): GAST: GPT1 Interpretation Report. *Nagra Arbeitsbericht NAB 19-28*.
- Lanyon, G.W., Herbert, A.W. & Reinicke, A. (2022): GAST Status Report. *Nagra Arbeitsbericht NAB 21-17*.
- Manca, D. (2016): Gas Transport and related Chemo-Hydro-Mechanical Response of Sand Bentonite Mixture. *Nagra Technical Report NTB 16-07*.
- Marschall, P., Horseman, S. & Gimmi, T. (2005): Characterisation of gas transport properties of the Opalinus clay, a potential host rock formation for radioactive waste disposal. *Revue de l'Institut Français du Pétrole IFP: Gas-water-rock interactions induced by reservoir exploitation, CO2 sequestration, and other geological storage*. IFP International Conference, November 18-20, 2003, Rueil-Malmaison (Part 1 and 2). Special Issue of Oil & Gas Science and Technology. Editions TECHNIP 60/1, 121-139.
- Rösli, U., Gisiger, J., Kontar, K., Giroud, N. & Spillmann, T. (2019): GTS Phase VI: GAST Project: WP3: Data acquisition and reporting 2017-2018. *GAST Annual Report Monitoring Period: 01.01.2017 - 15.06.2018*. *Nagra Arbeitsbericht NAB 18-42*.
- Rösli, U., Gisiger, J., Kontar, K., Giroud, N. & Spillmann, T. (2020): GTS Phase VI - GAST Project: GAST Annual Report Monitoring Report: 01.01.2016-21.12.2016. *Nagra Arbeitsbericht NAB 17-15*.
- Rösli, U., Gisiger, J., Kontar, K. & Spillmann, T. (2018a): GTS Phase VI : GAST Project: GAST Annual Report Monitoring Period: 01/01/2015 – 31/12/2015. *Nagra Arbeitsbericht NAB 17-14*.
- Rösli, U., Gisiger, J., Lanyon, G.W., Tomonaga, Y., Stopelli, E. & Spillmann, T. (2025): GAST – Gas Flow Test Data Report. *Nagra Arbeitsbericht NAB 23-15*.

- Rösli, U., Gisiger, J., Palacios Jimenez, B., Martínez, L.V. & Spillmann, T. (2018b): GTS Phase VI : GAST Project : GAST Annual Report Monitoring Period: 01/04/2014 – 31/03/2015. Nagra Arbeitsbericht NAB 18-44.
- Rüedi, J., Teodori, S., Trick, T., Steiner, P., Garcia Sineriz, J.-L., Wetzig, V. & Reinhold, M. (2011): GAST (Gas-Permeable Seal Test) Design Report. Nagra Arbeitsbericht NAB 11-24.
- Rüedi, J., Teodori, S.-P., Spillmann, T., Reinhold, M., Trick, T., Keller, M., Steiner, P., Isler, S., Gräfe, K., García-Siñeriz, M.J.-L., Palacios Jimenez, B., Jacobs, F., Eiholzer, L., Maurer, H., Tisato, N. & Marelli, S. (2012): Gas-Permeable Seal Test at GTS: As built report. Nagra Arbeitsbericht NAB 12-59 App.
- Schlaeger, S. & Spillmann, T. (2015): Grimsel Test Site: GAST TDL and TDP Raw Data Report for July 2012 – July 2014. Nagra Arbeitsbericht NAB 14-63.
- Schneeberger, R., Kober, F., Lanyon, B., Mäder, U.K., Spillmann, T. & Blechschmidt, I. (2019): Grimsel Test Site: Revisiting the site-specific geoscientific knowledge. Nagra Technical Report NTB 19-01.
- Senger, R., Marschall, P. & Lavanchy, J.M. (1998): Gas threshold pressure tests in deep boreholes for determining two-phase flow properties of the host rock at the proposed L/ILW repository, Switzerland. Scientific basis for nuclear waste management XXI: symposium held September 28-October 3, 1997, Davos, Switzerland. MRS Symposium Proceedings 506, 829-838.
- Soltani, A., Azimi, M., Boroomandnia, A. & O'Kelly, B.C. (2021): An objective framework for determination of the air-entry value from the soil–water characteristic curve. Results in Engineering 12. DOI: 10.1016/j.rineng.2021.100298.
- van Meir, N., Sakaki, T., Spillmann, T., Rösli, U., Gisiger, J., Kontar, K., Steiner, P. & Lanyon, G.W. (2017): GAST (Gas-Permeable Seal Test) Wellhead installation and connection to GeoMonitor DAS. Nagra Arbeitsbericht NAB 16-03.

App. A Instrumentation layouts

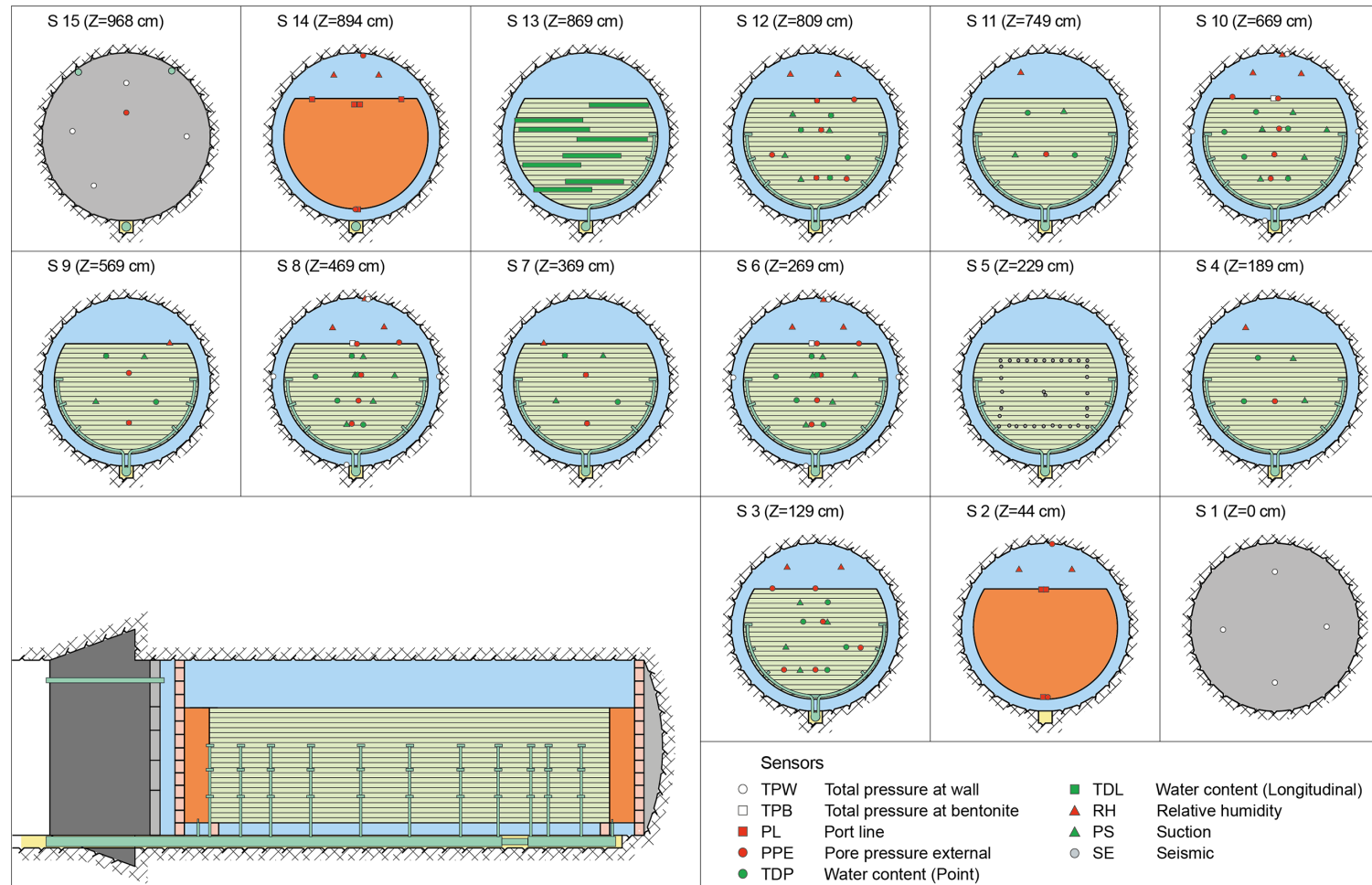
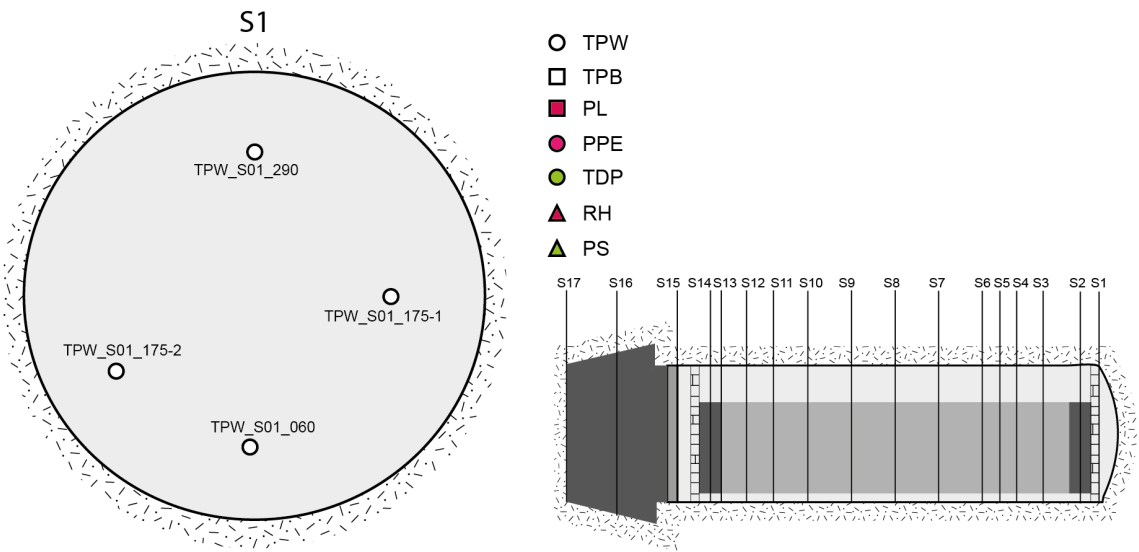
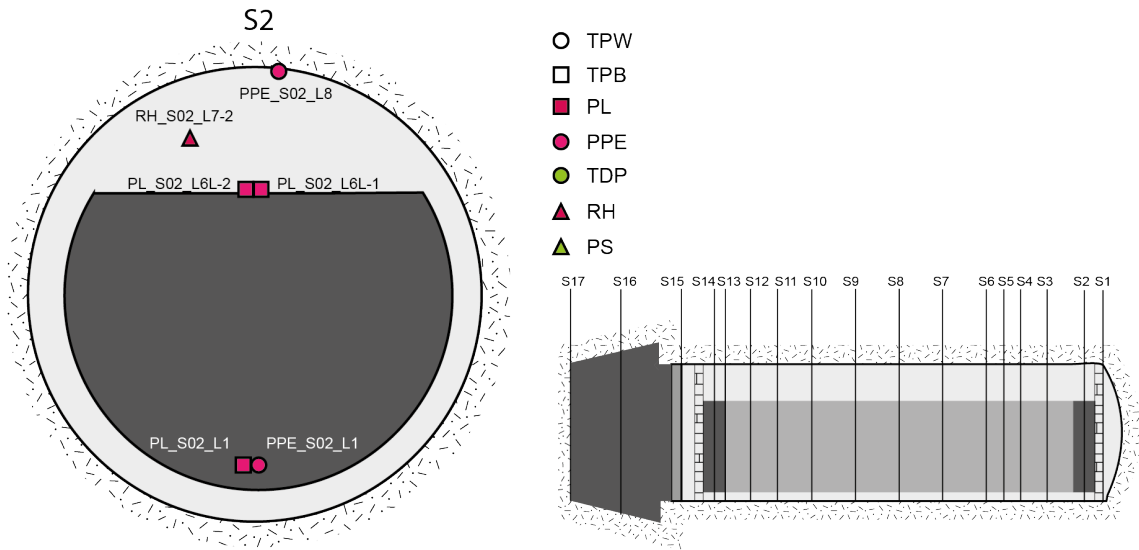


Fig. A-1: Overview of GAST sections

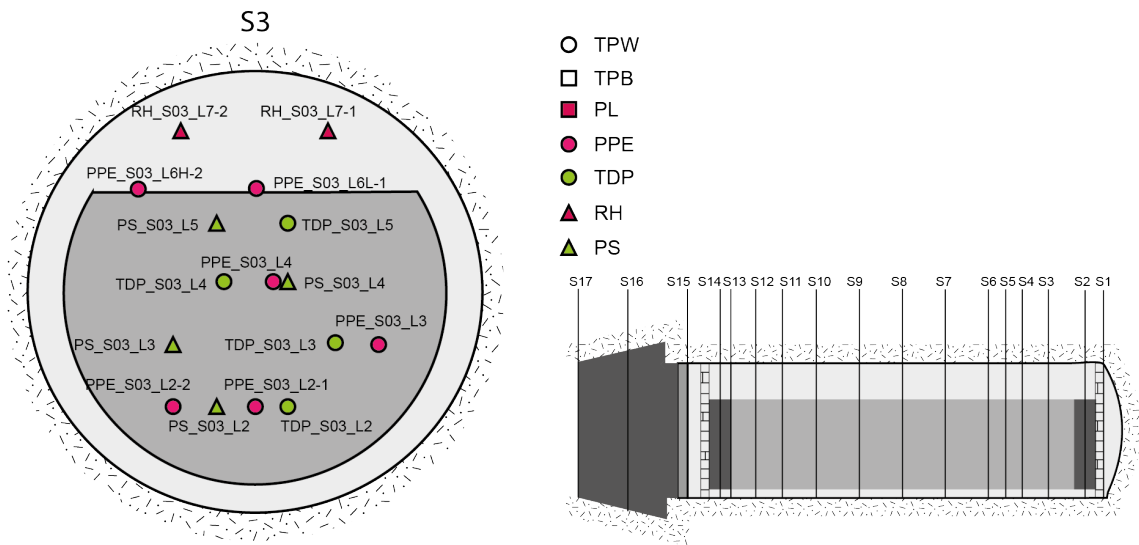
A.1 Section S01



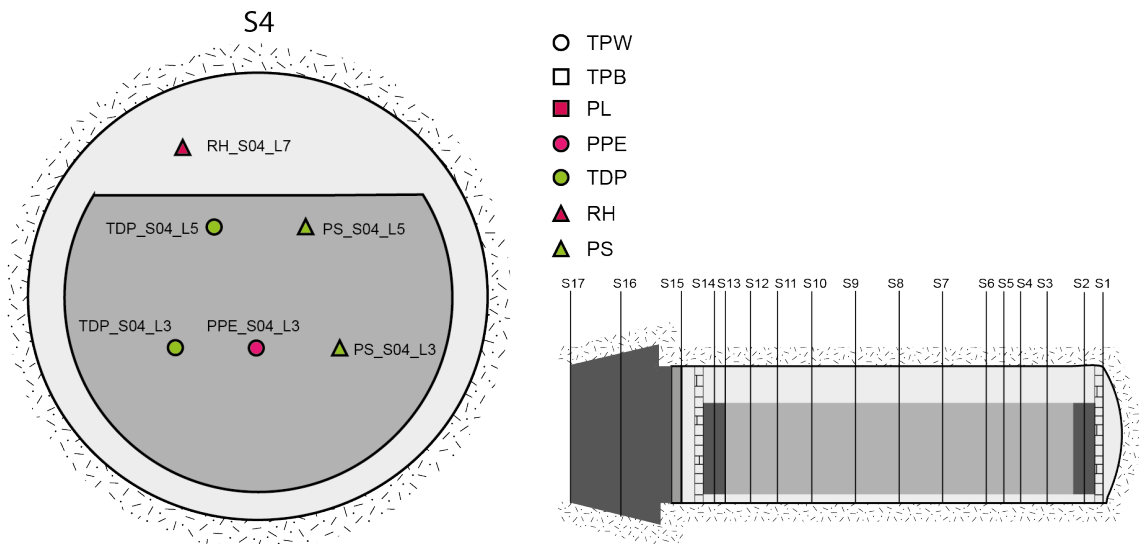
A.2 Section S02



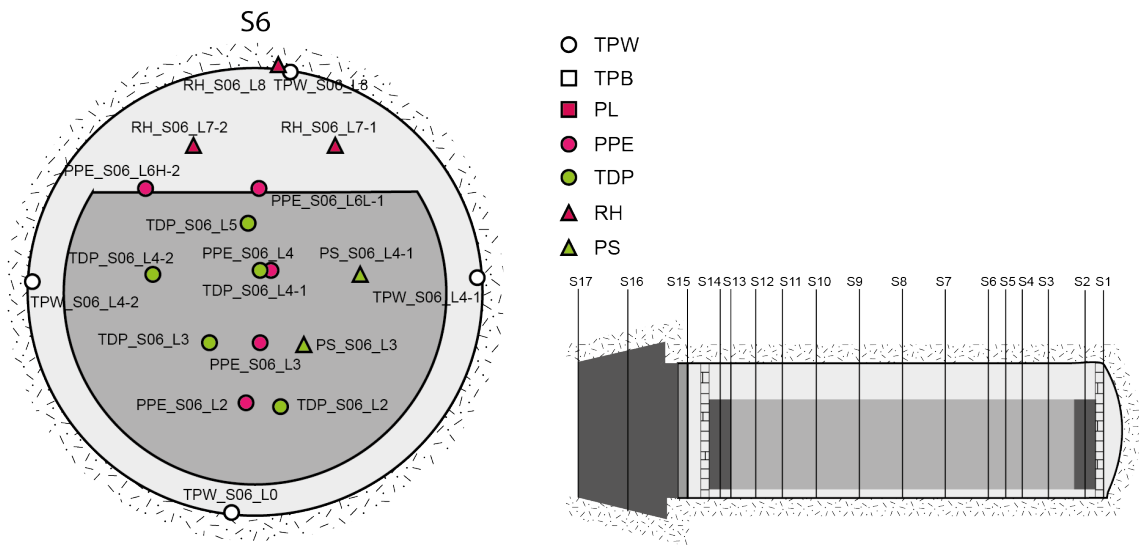
A.3 Section S03



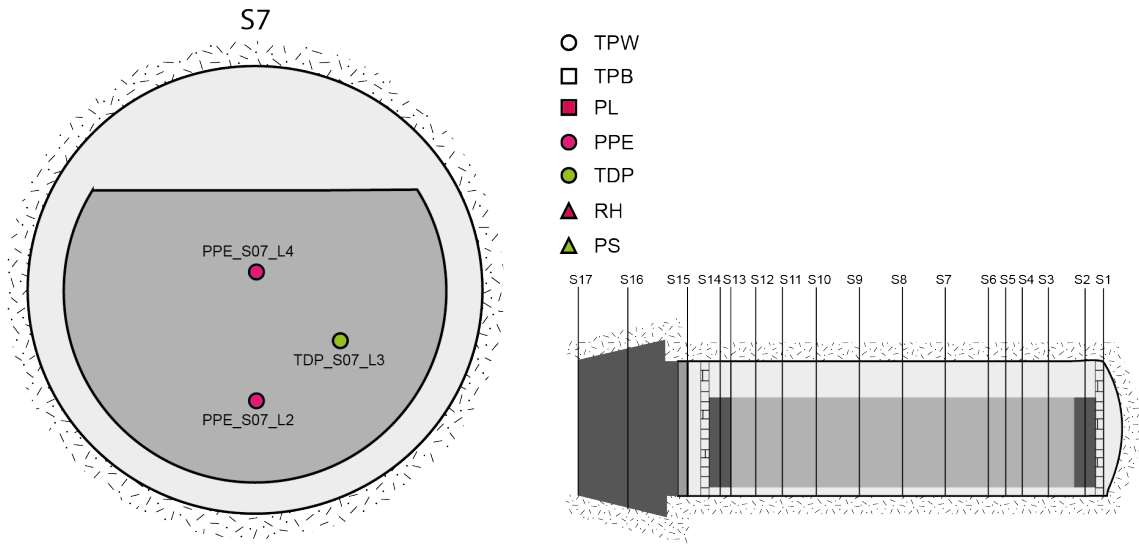
A.4 Section S04



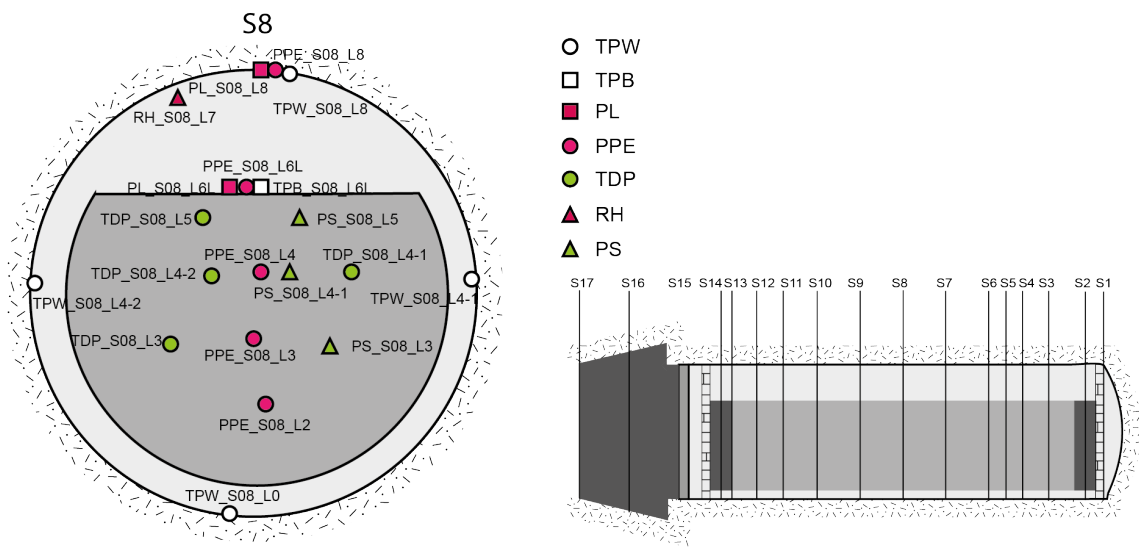
A.5 Section S06



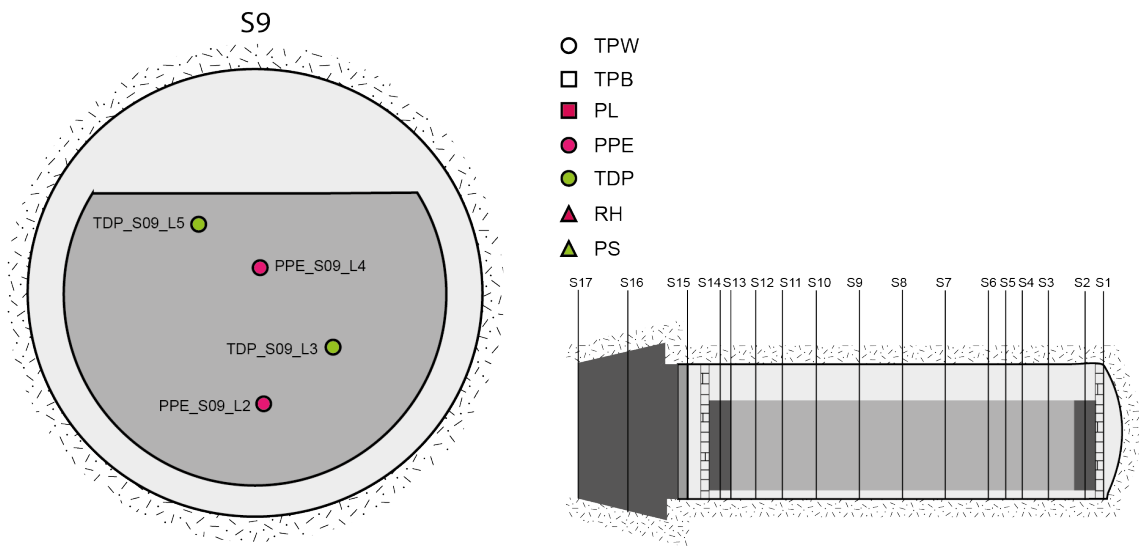
A.6 Section S07



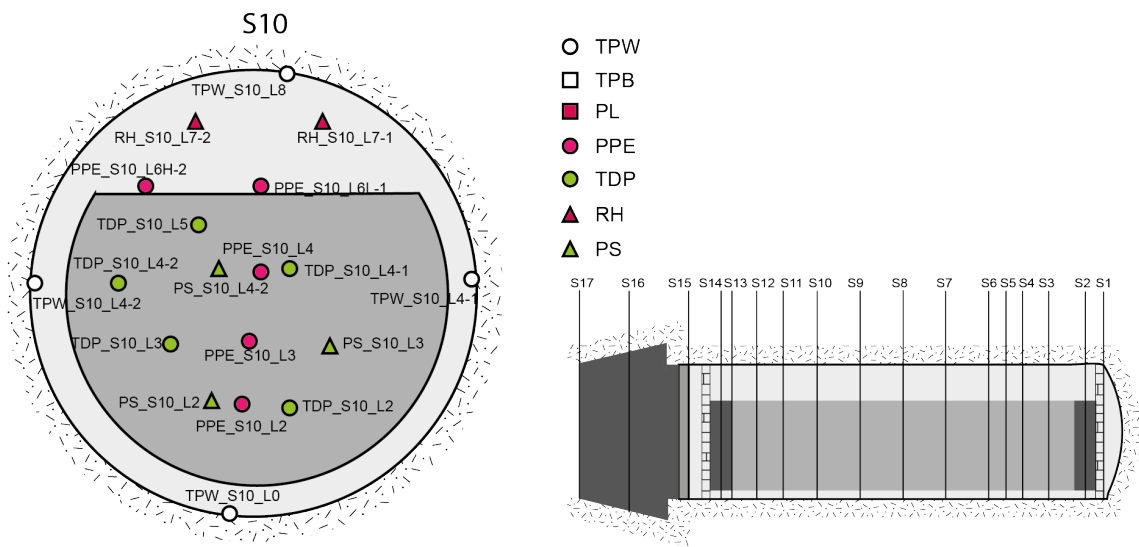
A.7 Section S08



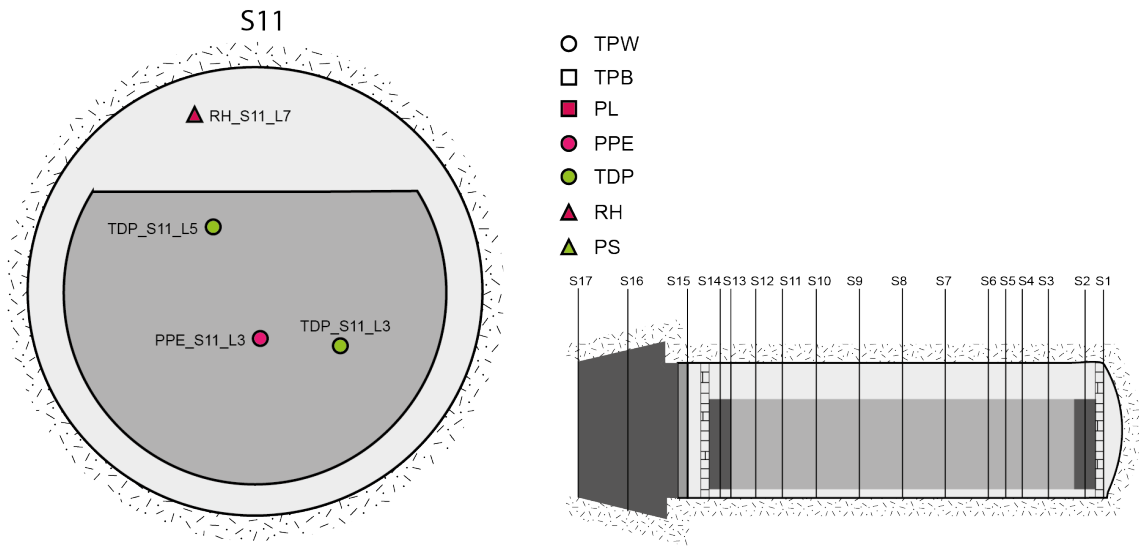
A.8 Section S09



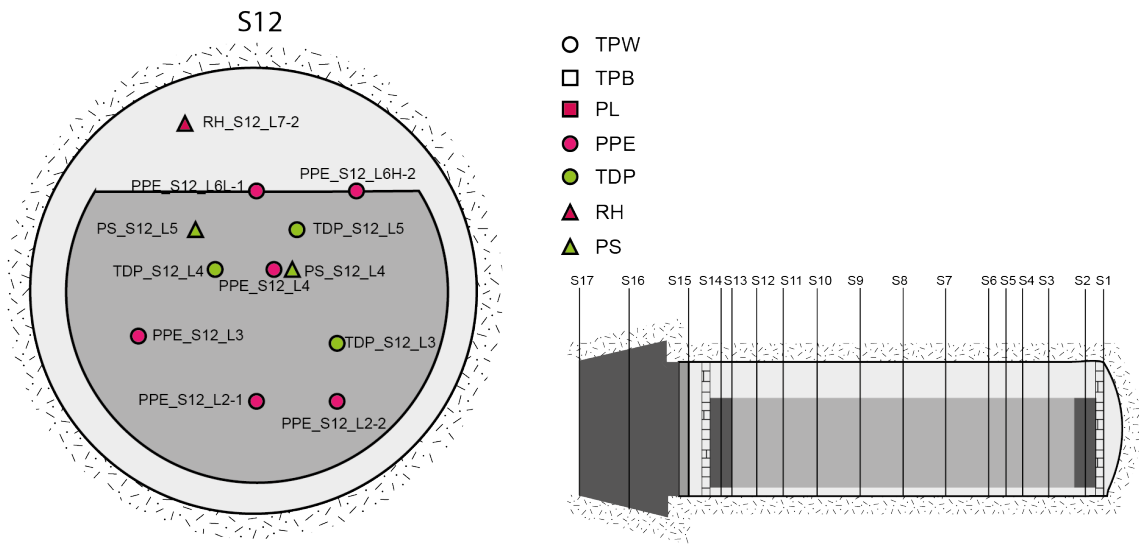
A.9 Section S10



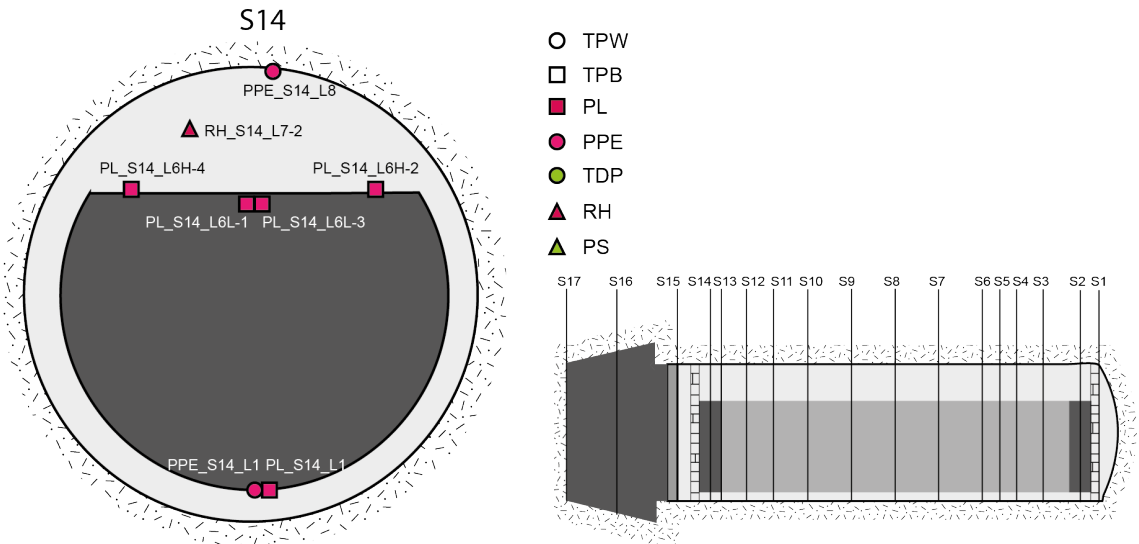
A.10 Section S11



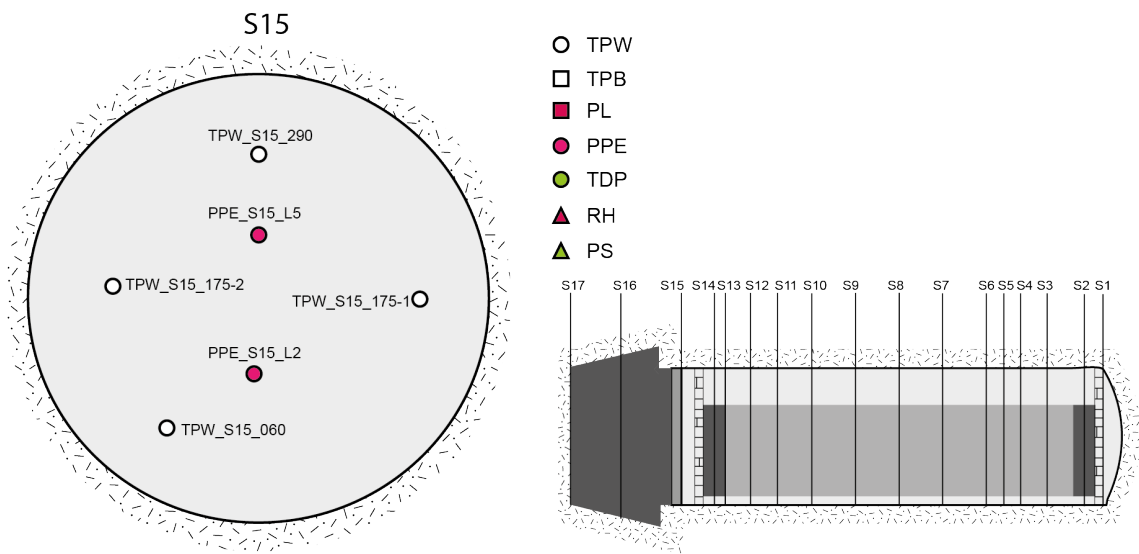
A.11 Section S12



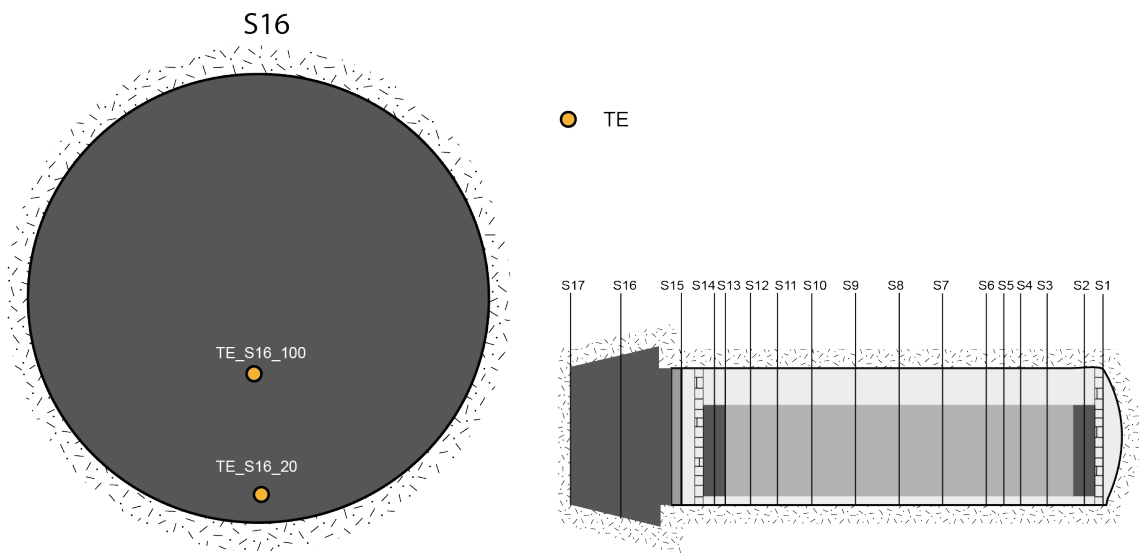
A.12 Section S14



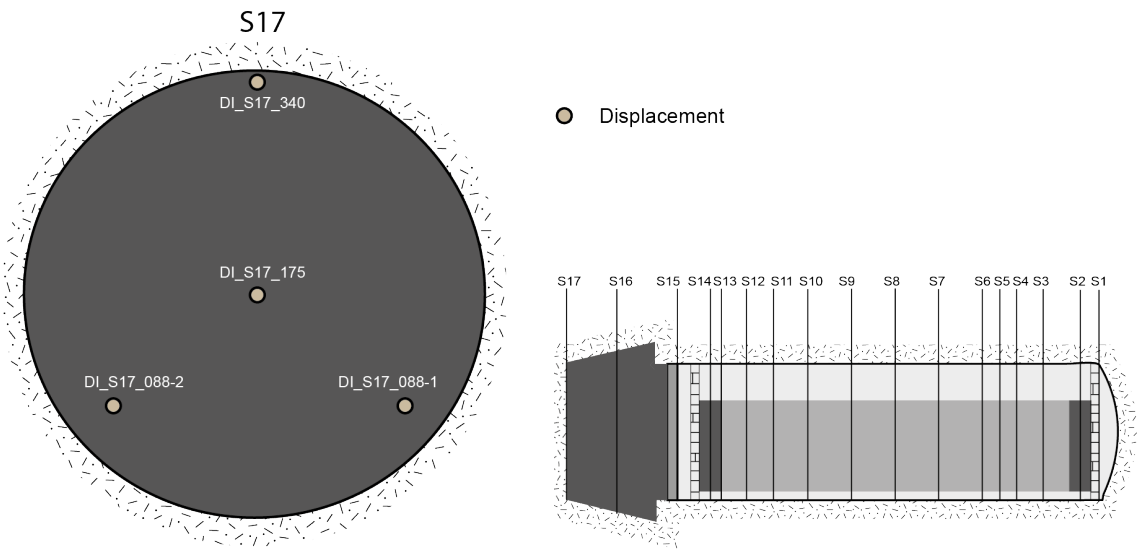
A.13 Section S15



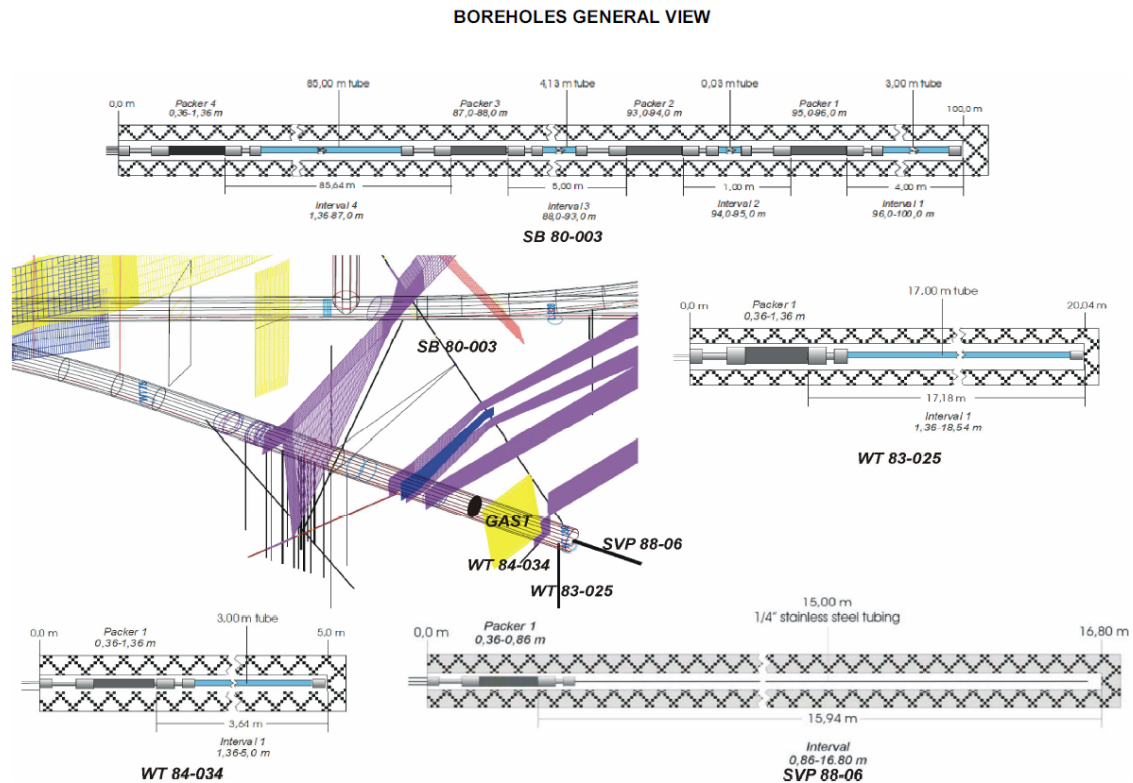
A.14 Section S16



A.15 Section S17



A.16 Boreholes



A.17 Piezometer and hydraulic lines

Data from the pressure sensors provide key information on the location and properties of the gas flow path. This short section provides additional information on the emplacement of the piezometers together with a list of the piezometers indicating the material in which they were emplaced (Tab. A-1).

A.17.1 Piezometer emplacement

L2 – L4 in the sand/bentonite body

Piezometers and hydraulic lines were emplaced within a shallow groove excavated in the top lift of the sand/bentonite after compaction to the level (see Fig. A-2). The groove connecting back to the riser was then backfilled with bentonite. Following this, the sensors were covered with the next lift of sand/bentonite, which was then compacted. The sensors are therefore surrounded by sand/bentonite.

L6 at the sand/bentonite-GBM interface

The Level 6 piezometers were emplaced on top of the uppermost lift and fixed with a clamp (see Fig. A-1). No groove was excavated and the GBM was then placed on top of the piezometers and compacted. They are therefore likely to be surrounded by GBM at least on top and on the sides.

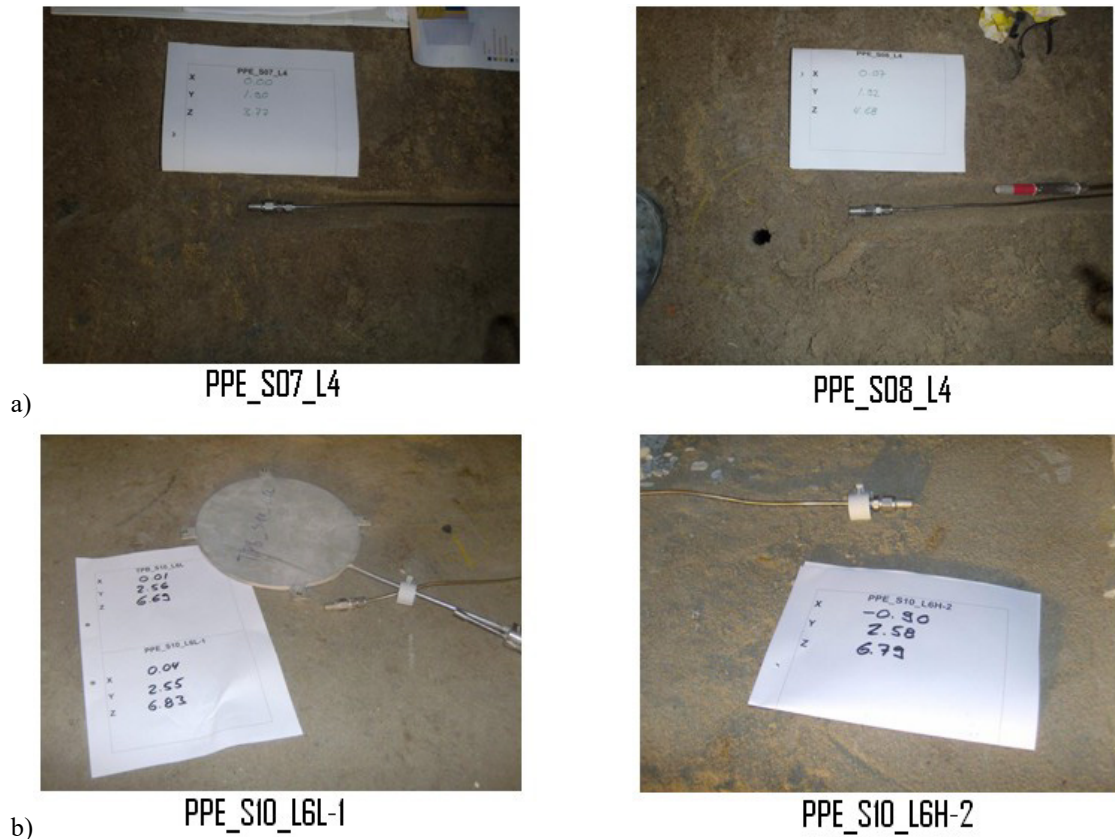


Fig. A-2: Photographs of selected piezometers upon emplacement in a) L4 and b) L6
(from Rüedi et al. 2012)

L8 and S15 – GBM interface

The piezometers/port lines at L8 (in S02, S08, S14) were clamped to the roof of the tunnel prior to the final GBM emplacement using an auger. Piezometers at S15 were fixed to the rear wall of the plug prior to backfilling with GBM.

Tab. A-1: Port lines, piezometers and differential pressure gauges

Sensor	Section	Level	Material	Remarks	GFT sampling	DAS monitoring
Port lines						
PL_S02_L1	S02	L1	S02 sand filter	Water injection/extraction at base of S02 sand filter	11	-
PL_S02_L6L-1	S02	L6	S02 sand filter	Injection/extraction of gas at top of filter GFT W-GX and S02 slug test		Y
PL_S02_L6L-2	S02	L6	S02 sand filter	Injection/extraction of gas at top of filter for GPT1, GFT		-
PL_S08_L6L	S08	L6	S/B-GBM interface			-
PL_S08_L8	S08	L8	Rock-GBM interface	Water injection tests in 2016		-
PL_S14_L1	S14	L1	S14 sand filter	Injection/extraction (both water and gas) at base of S02 sand filter	56	-
PL_S14_L6H-2	S14	L6	Outside filter in GBM?	Low pressure. Poor connection to sand filter		Y
PL_S14_L6H-4	S14	L6	Outside filter in GBM?	Low pressure. Poor connection to sand filter		Y
PL_S14_L6L-1	S14	L6	Outside filter in GBM?	Low pressure. Poor connection to sand filter		Y
PL_S14_L6L-3	S14	L6	Outside filter in GBM?	Low pressure. Poor connection to sand filter		Y
Piezometers						
PPE_S02_L1	S02	L1	S02 sand filter	S14 sand filter pressure monitoring at L1		Y
PPE_S02_L8	S02	L8	Rock-GBM interface	At tunnel roof above S02		Y
PPE_S03_L2-1	S03	L2	S/B			Y
PPE_S03_L2-2	S03	L2	S/B			Y

Tab. A-1: Cont.

Sensor	Section	Level	Material	Remarks	GFT sampling	DAS monitoring
PPE_S03_L3	S03	L3	S/B	Water sample (vacuum)	1	Y
PPE_S03_L4	S03	L4	S/B			Y
PPE_S03_L6H-2	S03	L6	S/B-GBM interface	Potential interaction/leak in wellhead		Y
PPE_S03_L6L-1	S03	L6	S/B-GBM interface	High methane content in free gas samples	4	Y
PPE_S04_L3	S04	L3	S/B			Y
PPE_S06_L2	S06	L2	S/B	Dipole Test injection. GFT water sample		Y
PPE_S06_L3	S06	L3	S/B			Y
PPE_S06_L4	S06	L4	S/B	Water sample during GFT	1	Y
PPE_S06_L6H-2	S06	L6	S/B-GBM interface	Free gas samples similar to S14 extraction. Large pressure jump early in GPT1 and GFT.	12	Y
PPE_S06_L6L-1	S06	L6	S/B-GBM interface			Y
PPE_S07_L2	S07	L2	S/B	Dipole Test extraction. GFT water sample	1	Y
PPE_S07_L4	S07	L4	S/B			Y
PPE_S08_L2	S08	L2	S/B			Y
PPE_S08_L3	S08	L3	S/B			Y
PPE_S08_L4	S08	L4	S/B	Initial water samples then free gas during GFT. Gas production post-GPT1 and GFT	5	Y
PPE_S08_L6L	S08	L6	S/B-GBM interface			Y
PPE_S08_L8	S08	L8	Rock-GBM interface	Low pressure at tunnel crown		Y
PPE_S09_L2	S09	L2	S/B			Y

Tab. A-1: Cont.

Sensor	Section	Level	Material	Remarks	GFT sampling	DAS monitoring
PPE_S09_L4	S09	L4	S/B			Y
PPE_S10_L2	S10	L2	S/B			Y
PPE_S10_L3	S10	L3	S/B			Y
PPE_S10_L4	S10	L4	S/B		13	Y
PPE_S10_L6H-2	S10	L6	S/B-GBM interface			Y
PPE_S10_L6L-1	S10	L6	S/B-GBM interface			Y
PPE_S11_L3	S11	L3	S/B			Y
PPE_S12_L2-1	S12	L2	S/B			Y
PPE_S12_L2-2	S12	L2	S/B			Y
PPE_S12_L3	S12	L3	S/B			Y
PPE_S12_L4	S12	L4	S/B			Y
PPE_S12_L6H-2	S12	L6	S/B-GBM interface			Y
PPE_S12_L6L-1	S12	L6	S/B-GBM interface			Y
PPE_S14_L1	S14	L1	S14 filter	S14 sand filter pressure monitoring at L1		Y
PPE_S14_L8	S14	L8	Rock-GBM interface	Low pressure in GBM above S14 filter		Y
PPE_S15_L2	S15	L2	Plug retaining wall	Low pressure in GBM at plug wall		Y
PPE_S15_L5	S15	L5	Plug retaining wall	Low pressure in GBM at plug wall		Y

Tab. A-1: Cont.

Sensor	Section	Level	Material	Remarks	GFT sampling	DAS monitoring
<i>Differential pressure gauges</i>						
DP-2 tank	S02,S14	L1	S02 , S14 sand filter outflows	Water level in mock-up tank measuring cumulative water outflow during W-GX, G-WX and extraction from S14		Y
DP-4	S02,S14	L1 – L6	S02 sand filter L1 – L6	Water level gauge measuring differential pressure L1 – L6 in S02 sand filter		Y

App. B Flow data treatment

Authors: G.W. Lanyon, J. Gisiger, U. Rösli

B.1 Background

The injection and extraction boundary conditions to the GFT are fundamental to understanding the observed responses and the interpretation of the test. Flow data were acquired using multiple flow measurement systems. Water injection was measured in ml/min using flowmeters/controllers. Injected water (Grimsel groundwater or GGW) was usually taken from the BOADUS borehole at the GTS. Gas injection was measured using mass flowmeters (thermal pulse or Coriolis force) and recorded as ml/min of gas at STP²³ (mlN/min). The injected gas was provided from “bundles” of gas bottles of N₂, or the two special-purpose gas mixes (see Tab. B-1).

Syringe pumps were used for the volumetric extraction of gas, water or mixes of the two and from the filters in S02 and S14 and sampling from PPE lines. The volume extracted was a mix of gas and liquid water at either the filter or sampling pressure. Separation of the two phases occurred in a large tank (the “mock-up tank”) equipped with pressure and differential pressure gauges, at atmospheric pressure. The water level in the mock-up tank was measured and used to estimate the gas and water fractions.

Most PPE samples were extracted using syringe pumps with flow rates chosen to maintain pressure above 900 kPa (a “drawdown” of ~500 kPa) to limit local degassing and compaction, but a small number of PPE samples were taken using a vacuum to maximise the abstraction.

Tab. B-1: Injected gas composition from laboratory sampling of gas bundles

	N ₂ [vol.%]	He [vol.%]	Ar [vol.%]	Xe [vol.%]	
Gas Mix #1	97.9%	2.07%	0.0%	0.00%	Phases 2 – 5 02.05.23 08:00 – 01.12.23 07:05
N ₂ #1	99.9%	0.00%	0.1%	0.00%	Phases 6, 7
Gas Mix #2	73.2%	10.1%	16.7%	0.09%	Phase 8 18.04.23 07:20 – 29.06.23 12:16
N ₂ #2	99.9%	0.02%	0.1%	0.00%	Phases 9, 10, 11

²³ Standard temperature and pressure (STP) were taken as P_{STP} = 101.3 kPa, T_{STP} = 0 °C as used by Bronkhorst (<https://www.bronkhorst.com/en-gb/service-support-en/technologies/volume-flow-versus-mass-flow/>):

B.2 Relevant datasets

Flow data have been compiled into two main datasets that have been used for modelling and interpretation.

B.2.1 Mass balance dataset

A significant effort was made to provide an accurate “mass balance” for GFT Phases 2 – 9, excluding the initial W-GX (see Rösli et al. 2025). High time-resolution data (~20 s) were collated into a series of spreadsheets for injection and extraction for the four main gas injection periods (Tab. B-2). For gas injection, the data from the different flowmeters (and calibration periods) were combined into a cumulative injection mass (LN) and corresponding injection flowrate.

For extraction, the cumulative extracted volume and the extraction pressure (PPE_S14_L1) from the syringe pump and mock-up tank were combined to provide a cumulative gas (LN) and water (L) extraction and corresponding flow rates.

Tab. B-2: Mass balance workbooks

File	Phases	Content
GPT_Extraction_M1_v4	2 – 5	S14 filter pressure, S14 volumetric extraction and mock-up tank water level/cumulative extraction
GPT_Extraction_N1_v4	6 – 7	
GPT_Extraction_M2_v4	8	
GPT_Extraction_N2_v4	9	
GPT_Injection_calculation_M1_v2	2 – 5	S02 filter pressure, injection flowrate (mLN/min) and cumulative injection (LN)
GPT_Injection_calculation_N1_v2	6, 7	
GPT_Injection_calculation_M2_v2 (includes worksheets data for M2 and N2)	8, 9	

The data from the mass balance workbooks were then combined with the gas tracer composition (Tab. B-1) into workbooks for input to the TOUGH2 gas tracer modelling. The gas flows were estimated as:

$$Q_{gas} = (q_{Syringe} - q_{Mock-up}) \frac{P_{Syringe} T_{STP}}{P_{STP} T_{Syringe}}$$

where $T_{Syringe}$ is taken to be 289.15 K, equivalent to 16 °C. The syringe pump temperature is estimated from the measured temperature at the miniRUEDI sensor in the tunnel. Uncertainty in the temperature is estimated at ± 1 °C equivalent to $\pm 0.4\%$ on the flowrate or cumulative total. $P_{Syringe}$ is taken as the measured PPE_S14_L1 pressure (kPa abs) at the gauge in the tunnel.

For the period from 15.06.22 to 16.08.22, it was necessary to estimate the volumetric outflow from S14 as the only syringe pump was in use for sampling (subsequently two additional syringe pumps were acquired). During this period, the mass balance uses a regression approach to provide an overall estimate. The regression estimate of outflow cannot reproduce short-term variations but has been checked against periodic flow measurements made while the syringe pump was unavailable.

B.3 Measurement of gas injection into S02

Measurement with FLOW_LOW

For a short period after the end of the water-gas exchange from 06.05.22 14:07 to 12.05.22 07:15, gas injection into PL_S02_L6L-1 was controlled by the FLOW_LOW controller.

No problems were encountered with the FLOW_LOW controller and no further calibrations were performed. The total gas injection during this period was small at ~600 IN.

Measurement with FLOW_HI

The Bronkhorst EL-FLOW Select F-201CV flowmeter (FLOW_HI) has been used during most of the GFT to measure gas injection into PL_S02_L6L-1. The flowmeter is a highly accurate thermal mass flow controller. The controller was originally calibrated for N₂ and then for Gas Mix #2. After usage, “as-found” calibrations were performed in March and September 2023. The measurement uncertainty at calibration based on 95% confidence bands was reported as 0.4%Rd²⁴.

Measurement with FG_InJ_Mass

For a short period between 26.01.23 and when the Bronkhorst flow controller was being recalibrated at the manufacturer, an Alicat Coriolis Force mass flow controller was used to control N₂ injection into PL_S02_L6L-1. The accuracy of the Alicat flow controller is quoted as the greater of 0.5%Rd. and 0.5%FS.

The Alicat measures gas flow in g/hr which was converted to mLN/min using a factor of 13.33 based on literature values for N₂ density at STP. However, a field calibration performed prior to removal of the Bronkhorst flow controller with the two flowmeters “in series” showed a ratio of 15.1 between the two measurements. The reason for this higher conversion factor is unknown but is thought to be an artefact of the flow controller setup, as measurements made immediately prior to the switchover on 26.01.23 showed values close to the literature value of 13.33.

B.3.1 Measurement of water and gas extraction from S14

Measurement of S14 outflow with syringe pump (EXT_SYR_Q and EXT_SYR_V)

For the majority of the GFT, outflow from PL_S14_L1 was controlled using a syringe pump, giving the instantaneous flow rate (EX_SYR_Q) and cumulative volume (EX_SYR_V). Flowrates have typically been estimated from the derivative of EX_SYR_V or smoothed versions of EX_SYR_Q.

²⁴ The definition of Reading (Rd) is “Closeness to the actual value expressed as percentage of the actual value.” <https://www.bronkhorst.com/en-gb/blog/flow-meter-accuracy-repeatability-en/>

Measurement of S14 outflow between 15.06.22 and 16.08.22

From 15.06.22 07:40, the syringe pump was removed from the outflow and used to control gas sampling from selected piezometers. It was not returned to the outflow until 16.08.22 12:18 when other syringe pumps became available for sampling.

During this period, the outflow was vented directly through the mock-up tank to the tunnel. Attempts were made to perform automatic flow measurements by controlling the outflow for the mock-up tank but these did not provide useful data. Instead, periodic measurements of the gas outflow rate were made by shutting in the mock-up tank and then monitoring the observed pressure increase.

In order to provide a complete time history of the outflow suitable for model input, the cumulative volumetric outflow during the period from 15.06.22 to 16.08.22 has been estimated by regression and checked against the periodic flow measurements as described in Rösli et al. 2025

The regression cannot reproduce short-term variations in outflow due to changes in injection rate or outflow conditions (e.g. shut-in) but hopefully provides a robust estimate of the overall production during the period. The short-term accuracy of the flow estimate can be estimated from a comparison with the periodic flow mock-up tank flowrate measurements.

Outflow fraction of gas and water

The syringe pump extracts a fixed volume of water and gas. The water fraction extracted from S14 varied over time. At the start, the extracted fluid was only water and remained so until the gas breakthrough on 08.06.22 at 08:01 (there may have been some small fraction of entrained gas bubbles immediately prior to this). After the breakthrough, the outflow was dominantly gas.

The water fraction after breakthrough can be estimated from the water level gauge (DP-2) of the mock-up tank. The mock-up tank was used as a gas-water separator for most of the tests. The water in the tank corresponds to both liquid water from the outflow and any water vapour that may have condensed in the separator.

The measured mock-up tank level (DP-2) has been converted into a cumulative produced volume.

It is likely that the water fraction changed immediately after shut-in of the extraction due to local recovery of the water level around the top of the extraction line (PL_S14_L1) within the S14 filter. This short-term variation in water fraction will not be fully represented in the smoothed cumulative production curve.

The gas volume fraction is assumed to be the total volumetric extraction minus the water fraction.

B.3.2 Conversion of gas flow rate between ml/min and mlN/min

The flowrate extracted from PL_S14_L1 as measured by the syringe pump is the volumetric rate in ml/min. To convert it into a gas mass flowrate (in mlN/min), it is necessary to compensate for:

- the water content of any produced volume,
- the volumetric change from conditions at STP due to temperature and pressure.

The flowrate of liquid water has been estimated from the measured water column level in the mock-up tank to which the outflow discharged. The treatment of the data from the mock-up tank is described in Rösli et al. (2025):

$$Q_{gas} = (q_{Syringe} - q_{Mock-up}) \frac{P_{Syringe} T_{STP}}{P_{STP} T_{Syringe}}$$

$T_{Syringe}$ is taken to be 289.15 K equivalent to 16 °C. The syringe pump temperature has been estimated from the measured temperature at the miniRUEDI sensor in the tunnel. Uncertainty in the temperature is estimated at ± 1 °C equivalent to $\pm 0.4\%$ on the flowrate or cumulative total. $P_{Syringe}$ is taken as the measured PPE_S14_L1 pressure (kPa abs).

B.3.3 Summary

The estimated uncertainties in the different flow measurements are listed in Tab. B-3. They are $\sim 0.4\%$ of the recorded value. This could potentially be a large fraction of the gas “lost” during the GFT (e.g. dissolved in porewater, or trapped in the sand/bentonite or GBM) due to the high recovery of gas observed.

Tab. B-3: Summary of flow measurement uncertainty

Measurement		Uncertainty	Comment
Gas injection rate FLOW_HI	mlN/min	$\pm 0.4\%$ Rd	
Gas injection rate FG_Inj_Mass	mlN/min	$\pm 0.5\%$ Rd	Small possibility that flow was $\sim 13\%$ higher than estimated based on in-series calibration against FLOW_HI
Volumetric outflow from S14 syringe pump	ml/min	$\pm 0.4\%$ Rd	Uncertainty on temperature Some additional uncertainty during the early phase of the GFT and immediately post-shut-in on water content of outflow.
Volumetric outflow from S14 15.06.22 to 16.08.22	ml/min		Regression provides overall estimate that cannot reproduce short-term variations
Water outflow from S14 syringe pump	ml/min	$\pm 0.4\%$ Rd	Uncertainty on temperature Some additional uncertainty during the early phase of the GFT and immediately post-shut-in on water content of outflow.
Gas outflow from S14 syringe pump	mlN/min	$\pm 0.4\%$ Rd	Uncertainty on temperature Some additional uncertainty during the early phase of the GFT and immediately post-shut-in on water content of outflow.

App. C Estimation of gas volumes in filters

Authors: G.W. Lanyon, A. Herbert, J. Gisiger, U. Rösli

C.1 Background

During the GFT, gas was injected into the S02 sand filter and, for a short period during Phase 11, into the S14 sand filter. These injections ensured that the sand/bentonite face was exposed to a large volume of gas, i.e. by area rather than point source. The initial gas injection into S02 occurred during the W-GX when water was withdrawn from PL_S02_L1 at the base of the sand filter and injected into PL_S02_L6L-2 near the top of the sand filter, until gas was produced from PL_S02_L1.

With the exception of PPE sampling, extraction was also from either the S14 sand filter or the S02 filter during W-GX and G-WX activities. The only hydraulic lines within the S14 sand filter are located at L1. For this reason, gas extraction required “drainage” of much of the S14 sand filter. Significant gas volumes were therefore present within the two sand filters during much of the GFT and controlled by:

- injection into and extraction from the two filters,
- gas flow from S02 to S14,
- water flow out of S02 filter,
- water flow into S14 and any water leakage from S14.

Fig. C-1 illustrates the main flows in/out of the filters once S14 had drained (08.06.22).

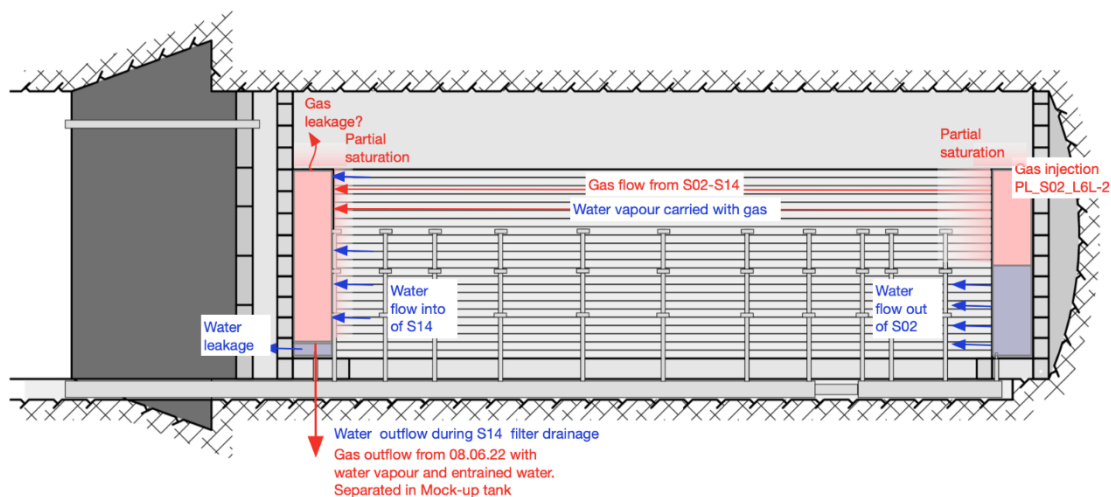


Fig. C-1: S02 estimated gas volume and injection rate

The gas and water volumes in the filter will control: the mixing of gases in the filter volume, gas dissolution in filter porewater and compressibility of the filter. To interpret the GFT, it is therefore necessary to have quantitative estimates of the gas volumes present in the two filters. The gas volume has either been measured directly by integration of injected/extracted volumes or via the compressibility of the filters as listed in Tab. C-1.

Tab. C-1: Gas volume estimation methods

Filter gas volume estimation		Gas volume estimation method
Water outflow during W-GX	S02	Measurement of cumulative water volume extracted during the W-GX
Sinusoidal injection rate of gas	S02	Estimate of filter compressibility based on response to S02 gas injection from 19.05.22 to 17.01.23 with ~333-minute period and ± 80 mlN/min amplitude. Mean flow rate varied over time.
Water drainage prior to gas breakthrough	S14	Measurement of cumulative water volume extracted prior to gas breakthrough the PL_S14_L1 on 08.06.22
Filter pulse tests	S02, S14	Estimate of filter compressibility from response to rapid injection/extraction into filters to measure ΔP for given ΔV
Sinusoidal injection rate of water	S02	Estimate of filter compressibility from response to S02 water injection from 19.01.24 to 01.02.24
Differential pressure L6 – L1	S02	The differential pressure between L6 at the top of the sand filter and L1 at the base of the filter under steady conditions can be used to indicate the “water level” within the filter.

C.1.1 Filter compressibility and gas volume

Pulse tests and sinusoidal rate tests were performed prior to and during the GFT to estimate the gas volume in the filters. Pulse tests were performed with both water injection (into L1) and gas injection (into L6 in S02). The compressibility $\Delta V / \Delta P$ was estimated either from the estimated ΔV and ΔP given in the Solexperts site log or from regression over the early part of high-resolution data (where available). The compressibility is related to saturation S and pore volume V by:

$$C = V \left(S C_w + \frac{(1-S)}{P} + C_p \right) \quad (A-1)$$

$$C = V_w (C_w + C_p) + V_{gas} \left(\frac{1}{P} + C_p \right) \quad (A-2)$$

$$C = (V - V_{gas}) (C_w + C_p) + V_{gas} \left(\frac{1}{P} + C_p \right) \quad (A-3)$$

$$V_{gas} = \frac{C - V(C_w + C_p)}{\left(\frac{1}{P} - C_w \right)} \quad (A-4)$$

At a pressure of ~1,000 kPa, the gas compressibility ($1/P$) is significantly greater than water compressibility (C_w) and

$$V_{gas} \sim P(C - V(C_w + C_p)) \quad (A-5)$$

The term $V(C_w + C_p)$ is the compressibility determined at full saturation, where:

- C is compressibility (m^3/Pa).
- V is pore volume (m^3) estimated at 1.127 m^3 .
- V_{gas} is gas-filled pore volume (m^3).
- V_w is water-filled pore volume (m^3).
- S is saturation (-).
- C_w is water compressibility (Pa^{-1}) taken to be $4.6\text{E-}10 \text{ Pa}^{-1}$.
- C_p is pore compressibility (Pa^{-1}).
- P is the absolute pressure (Pa).

C_p was estimated from the pulse test performed on 12.12.17 when it was assumed that the S02 filter was fully saturated, i.e. $S=1$. The compressibility measured was 3.46 ml/kPa . This corresponds to a C_p value of $2.61\text{E-}9 \text{ Pa}^{-1}$. This method assumes that the gas phase compressibility is given by $1/P$ according to the ideal gas law and that dissolution effects can be neglected. For a discussion of the effect of dissolution on compressibility of air-water mixtures, see Fredlund & Rahardjo (1993).

The filter pulse tests performed before and during the GFT are listed in Tab. C-2.

C.1.2 Idealised filter and sand/bentonite geometry

Fig. C-2 shows the idealised cross-section for the sand filters and sand/bentonite. It is based on the as-built geometry and may no longer be representative of the geometry during the GFT due to differential compaction of the materials.

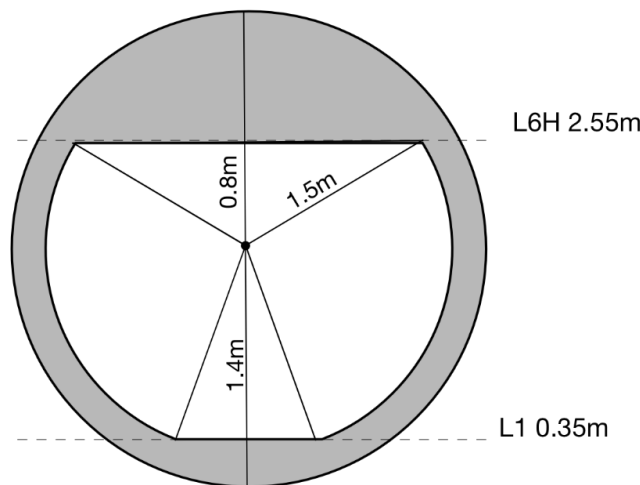


Fig. C-2: Idealised sand filter and sand/bentonite cross-section

The area of the filter below the level Y_{GAST} (ranging from 0.35 – 2.55 m) can be calculated as:

$$A(Y_{GAST}) = \left(\pi - \cos^{-1} y/r_f \right) r_f^2 + y \sqrt{r_f^2 - y^2} - A_{L1}$$

where $y = Y_{GAST} - 1.75$, $r_f = 1.5$ and

$$A_{L1} = \left(\pi - \cos^{-1} 1.4/r_f \right) r_f^2 - 1.4 \sqrt{r_f^2 - 1.4^2} = 0.0723$$

Assuming a constant porosity ϕ and width w , the filter pore volume below level Y_{GAST} can be calculated as $\phi.w.A(Y_{GAST})$.

Tab. C-2: Filter pulse tests

Event	Start	End	P ₀ [kPa]	P ₁ [kPa]	ΔP [kPa]	ΔVol [l]	C _{Simp} [ml/kPa]	C _{reg} [ml/kPa]	V _{gas} [l]
S14 injection test	07.12.21 11:35	07.12.21 11:41	1,795.3	2,190.6	395.3	2.5	6.4	5.8	4.7
	07.12.21 11:35	07.12.21 11:41	2,181.6	1,795.1	-386.5	-2.4	6.2	5.7	4.4
S14 pre-GFT Pulse #1	15.03.22 15:16	15.03.22 15:50	1,426.7	1,551.2	124.5	0.6	4.9	4.9	2.1
S14 pre-GFT Pulse #2	18.03.22 13:51	18.03.22 14:18	1,420.9	1,555.5	134.6	0.7	4.8	4.9	2.1
S14 GFT Pulse #1	09.05.22 07:43	09.05.22 08:14	1,400.9	1,332.0	-68.9	1.0	14.5	14.6	15.1
S14 GFT Pulse #2	12.05.22 08:06	12.05.22 08:35	1,396.6	1,374.6	-21.9	0.7	30.2	28.1	34.1
S14 GFT Pulse #3	23.11.23 10:31	23.11.23 11:03							
S14 GFT Pulse #4	29.11.23 14:13	29.11.23 15:21	1,598.5	1,604.2	5.7	1.0	171.3	180.1	283.1
S14 GFT Pulse #5	30.11.23 07:58	30.11.23 11:33	1,586.5	1,501.6	-84.9	15.2	-178.9	177.3	268.6
<i>S02 pulse tests</i>									
S02 pre-GFT Pulse #1	18.03.22 11:00	18.03.22 11:19	1,794.3	1,909.9	115.7	0.6	5.6	5.6	3.9
S02 GFT Pulse #1	12.05.22 07:00	12.05.22 07:15	1,783.7	1,809.9	26.2	3.3	127.3	126.2	220.5
S02 GFT Pulse #2	18.05.22 10:10	18.05.22 10:18	1,891.7	1,916.7	25.0	3.1	124.7	126.2	233.9
S02 GFT Pulse #3	24.11.23 10:41	24.11.23 11:22	1,114.7	1,116.9	2.1	0.6	285.8	301.9	333.2
S02 GFT Pulse #4	29.11.23 09:15	29.11.23 11:28	1,128.9	1,205.1	76.1	8.8	115.1	115.2	130.5

C.2 S02 gas volume and “water level”

C.2.1 S02 filter pulse tests

A filter pulse test was performed in S02 on 18.03.22 approximately 6 weeks before the start of the W-GX. Analysis of the test suggested a compressibility of 5.6 ml/kPa and gas volume of 4.4 l (assuming a saturated filter compressibility of 3.46 ml/kPa). It is possible that the gas volume is an overestimate and that there was no significant gas volume associated with the filter.

Subsequent filter pulse tests were performed after the end of the W-GX to estimate the gas volume associated with the S02 filter. After this, no more pulse tests were performed until Phase 11 of the GFT prior to and after the G-WX in November 2023.

C.2.2 Sinusoidal rate gas-injection tests in S02

From 19.05.22, gas injection into the top of S02 (PL_S02_L6L-1) used a specified mean mass rate plus a sinusoidal component with an amplitude of 80 mlN/min and a duration of 333 minutes²⁵. The aim was to provide information on S02 compressibility changes and hence the gas volume in S02. The mean rate was increased during 2022 to ~700 mlN/min by November 2022 (Fig. C-3), but the sinusoidal component remained identical. The sinusoidal injection was finished at the end of 2022 with the switch to the FG_Inj_Mass flow controller.

The pressure and flow data from this period were analysed using a moving-window FFT routine to calculate the components of the injection flow and the filter pressure related to the 333-minute test period. The compressibility of the filter C_{S02} was estimated as:

$$C_{S02} = \frac{\left(Q_{333}^{amp} / \omega \right)}{P_{333}^{amp} \left(P_{S02} / P_{STP} \right)}$$

where ω is the angular frequency, Q_{333}^{amp} is the mass flow amplitude (80 mlN/min), P_{S02} is the mean S02 filter pressure, P_{STP} is the pressure at STP and P_{333}^{amp} is the estimated amplitude of the 333-minute component of the S02 filter pressure computed from the moving window FFT. The filter gas volume can then be estimated from the compressibility as described in App. C.1.1.

As the mean flow rate changes throughout the test period, the gas volume is only calculated for intervals where the estimated flow rate component is close to 80 mlN/min. The estimated gas volume is shown in Fig. C-3. The gas volume is ~275 l for the first few months and then shows a slight increase to ~300 l in November 2022. It is in good agreement with the measured injection and outflow from S02 during the gas water exchange (see Tab. C-3).

²⁵ For a short period on 19.05., the sinusoidal parameters had an amplitude of 40 mlN/min for a duration of 60 minutes, but these were changed to give a larger amplitude pressure change.

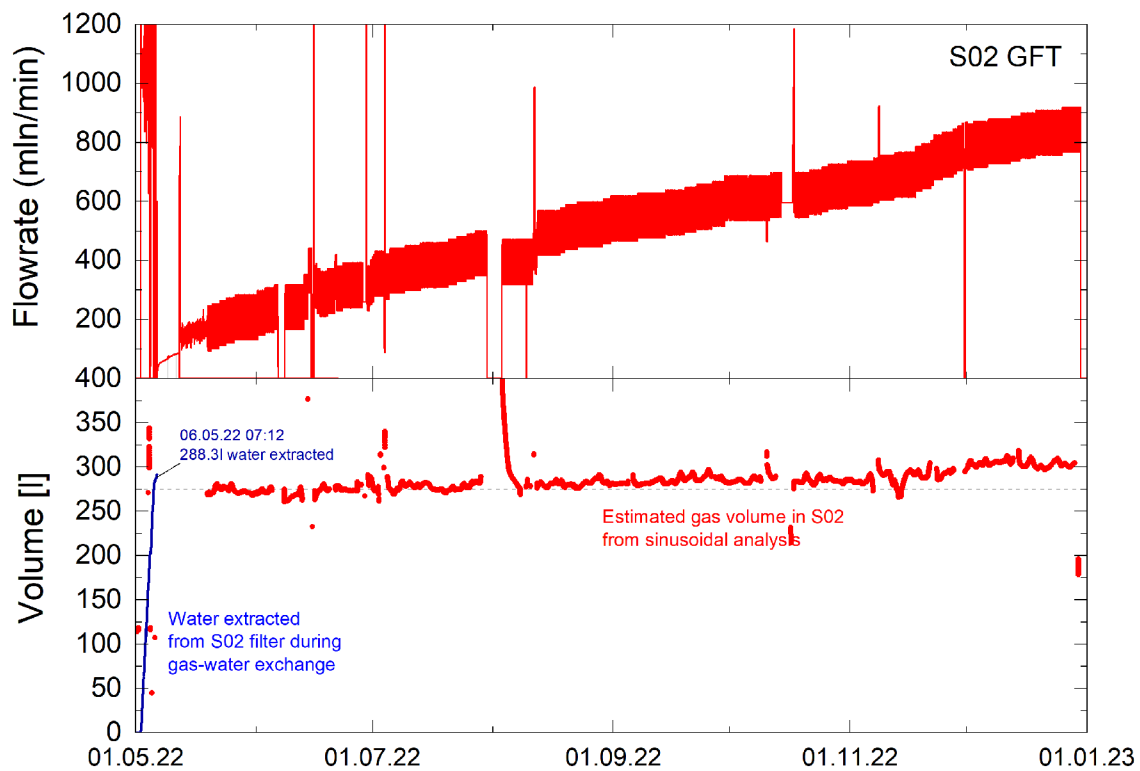


Fig. C-3: S02 estimated gas volume and injection rate

During 2023, the gas injection flowrate was set to a series of constant rate steps without any sinusoidal component. This was partly driven initially by a change in flowmeter and later by the switch to constant rate control of the injection from Phase 7 onwards. Gas volume in S02 was, however, estimated based on pulse tests.

Tab. C-3: Volume calculation during W-GX (Phase 2) between 02.05.22 and 06.05.22 11:22 (from Rosli et al. 2024).

Port	Type	Flow rate	Flow volume [l]	Pressure [bar]	Volume [l]	Sample volume [l]	Total volume [l]
PL_S02_L6L-1	Injection	1,000 mlN/min	5,525.1	18.3	301.6		
PL_S02_L1	Extraction	~60 → 0 ml/min	299.603	18.2		0.600/ 0.250/ 0.350/ 0.193	300.996
DP-2 Tank	Extraction		212.137 + 76.753	18.2			289.900*
PL_S14_L1 until 06.05.22 06:57	Extraction	Ø 12 ml/min	2.448	~14		0.050/ 0.125/ 0.203/ 0.100	2.926

* Uncertainty with regard to baseline value of DP-2 Tank

Uncertainty in the estimated gas volume results from:

- Estimation of the pressure amplitude corresponding to the sinusoidal rate (e.g. due to the use of the FFT). Inaccuracy in the applied rate signal and processes would result in a non-sinusoidal pressure response in the filter (e.g. leak-off and dilution). Varying the FFT parameters used (e.g. changing the length of the moving window and varying the assumed period from 330-336 minutes) resulted in only very minor changes in the calculated gas volume of ~5 l.
- Calculation of the gas volume from the calculated compressibility. This is largely due to the assumed value of $V(C_w + C_p)$ which is taken as 3.46 ml/kPa, derived from pulse testing prior to GPT1. The pre-GFT pulse test on 18.03.22 showed a slightly higher filter compressibility of .6 ml/kPa, which would result in a reduction in volume of ~4 l compared to the value used in the analyses.

The uncertainty in the gas volume is therefore taken to be ± 10 l.

C.2.3 Responses in other piezometers

Small sinusoidal responses are observed in neighbouring piezometers with the most consistent being at L2 and L4 in S03 (Fig. C-4). The piezometers at L6 in S03 show much noisier signals with greater variability in the 333-minute components.

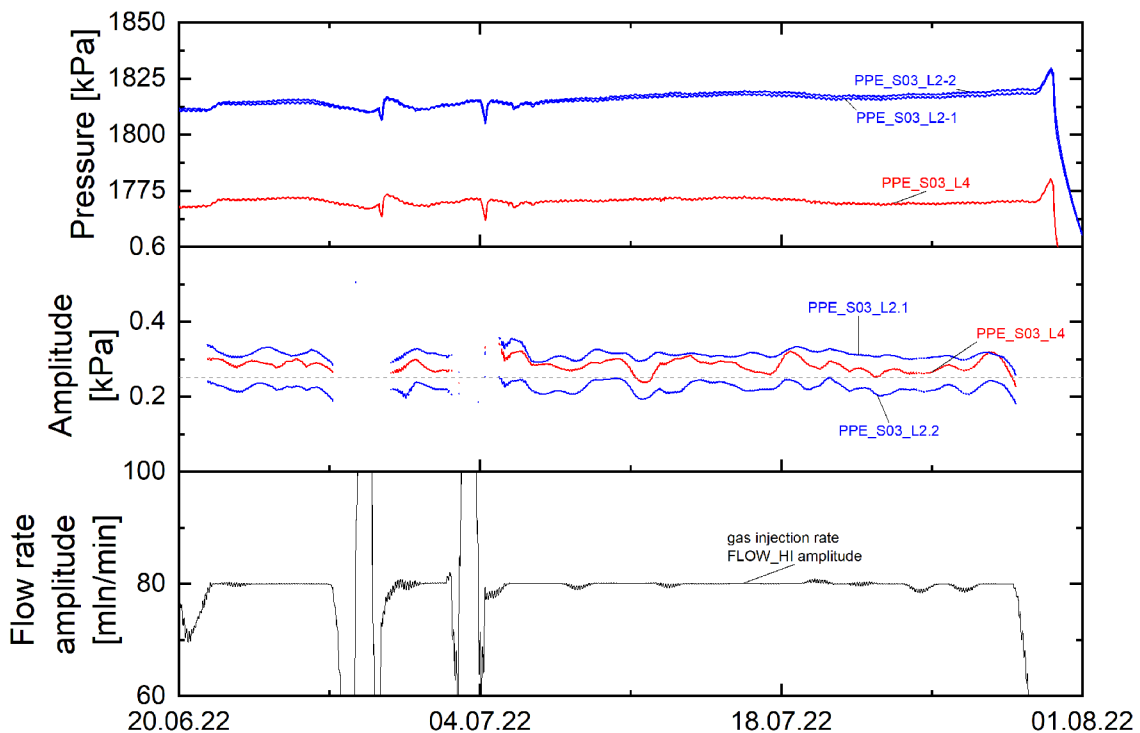


Fig. C-4: FFT analysis of gas injection flow and selected piezometers in S03

C.2.4 Differential pressure across S02 and water level

The differential pressure between L6 and L1 in S02 can be estimated from the DP-4 differential pressure gauge and from the pressure difference between PL_S02_L6L-1 and PPE_S02_L1. The DP-4 gauge was installed on 08.04.22 to support monitoring of the W-GX water-gas exchange in S02. The gauge measures the water column height in mm and was mounted about 1 cm above the tunnel floor (~49 cm below the concrete floor). The differential pressure can also be calculated from the pressure transducers PPE_S02_L1 and PL_S02_L6L-1 after accounting for the gauge and filter elevations, line saturation and gauge offsets (see Fig. C-5).

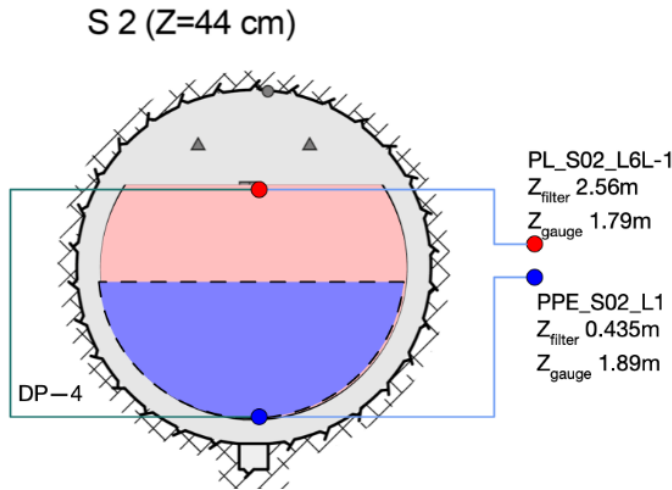


Fig. C-5: Differential pressure measurements in S02. Figure shows the “idealised” water level

The offset between the two gauges (kPa) is the sum of the gauge offset G_{atm} (calibrated at atmospheric pressure) and the line offset L_{off} due to the density of fluid within the lines between the filter and the gauge.

$$T_{off} = (G_{atm_{L1}} - G_{atm_{L6}}) + (L_{off_{L1}} - L_{off_{L6}})$$

The water level Z_{wl} (relative to the GAST coordinate system) can be calculated as:

$$Z_{wl} = Z_{L1} + \frac{(P_{L1} - P_{L6}) + T_{off}}{\rho_w g}$$

The uncertainty in calculated water level is due to:

- Surveying errors (<1 – 2 cm) in the gauge and filter heights.
- Uncertainty in gauge offset – these were measured relative to atmospheric in 2015.
- Uncertainty in saturation and fluid density within lines. The PP_S02_L1 line is likely to be fully water-saturated while the PL_S02_L6L-1 line could contain gas.
- Dynamic effects related to gas injection.

The measured offsets and elevations are given in Tab. C-4. Significant uncertainties are associated with the saturation of PL_S02_L6L-1 and the relevant gauge offsets at $\sim 1,800 - 1,900$ kPa for the two gauges, respectively. The value of T_{off} would vary from 14 to 22 kPa dependent on the PL_S02_L6L-1 line saturation, resulting in an uncertainty of ~ 700 mm in water level.

Tab. C-4: Gauge offsets and elevation for PPE_S02_L1 and PL_S02_L6L-1

Line	State	Gauge offset [kPa@atm]	Filter height [m]	Gauge height [m]	Gauge-filter [m]
PPE_S02_L1	Water-filled	6.53	0.435	1.48	1.045
PL_S02_L6L-1	Gas-filled?	2.47	2.56	1.79	-0.77

Fig. C-6 shows the measured (DP-4) and calculated water level (mm) during the GFT. The DP-4 sensor was disconnected in November 2022. The value of T_{off} used to calculate the water level was adjusted to match the DP-4 data. The adjustment is within the range of uncertainty due to line saturation and gauge offsets.

Prior to the W-GX, the data indicate a water level close to that of the PL_S02_L6L-1 sensor (i.e. near the top of the sand filter). The water level returns to a similar level after the G-WX in November 2023 (see Fig. C-8).

During the W-GX, when gas was being injected at L6 and water extracted at L1, the measured differential pressure was influenced by the dynamics of the downward gas movement which could be channelled due to heterogeneity in the filter and fingering of the gas. However, under steady injection (without extraction) and during shut-ins, a roughly horizontal water level could be expected within the permeable parts of the filter.

The calculated water level is noisier but otherwise shows a very similar response to the early part of the test, with an initial drop of ~ 2 m during the W-GX with water extraction from L1. This is followed by a slow recovery until June 2022 when the rate of change slows with the differential pressure stabilising at about L3. During shut-ins, the DP-4 data show an increase of ~ 100 mm with a smaller response seen in the calculated water level. Water levels recover quickly when injection is resumed. The drop in calculated water level on 06.09.22 is unexplained with no related site activity at that time.

The pressure difference during the shut-ins may be a better guide to the water level within the filter than those measured during gas injection due to dynamic effects in the pressure associated with the gas injection. The true water level may therefore be $\sim 10 - 15$ cm above that calculated during gas injection.

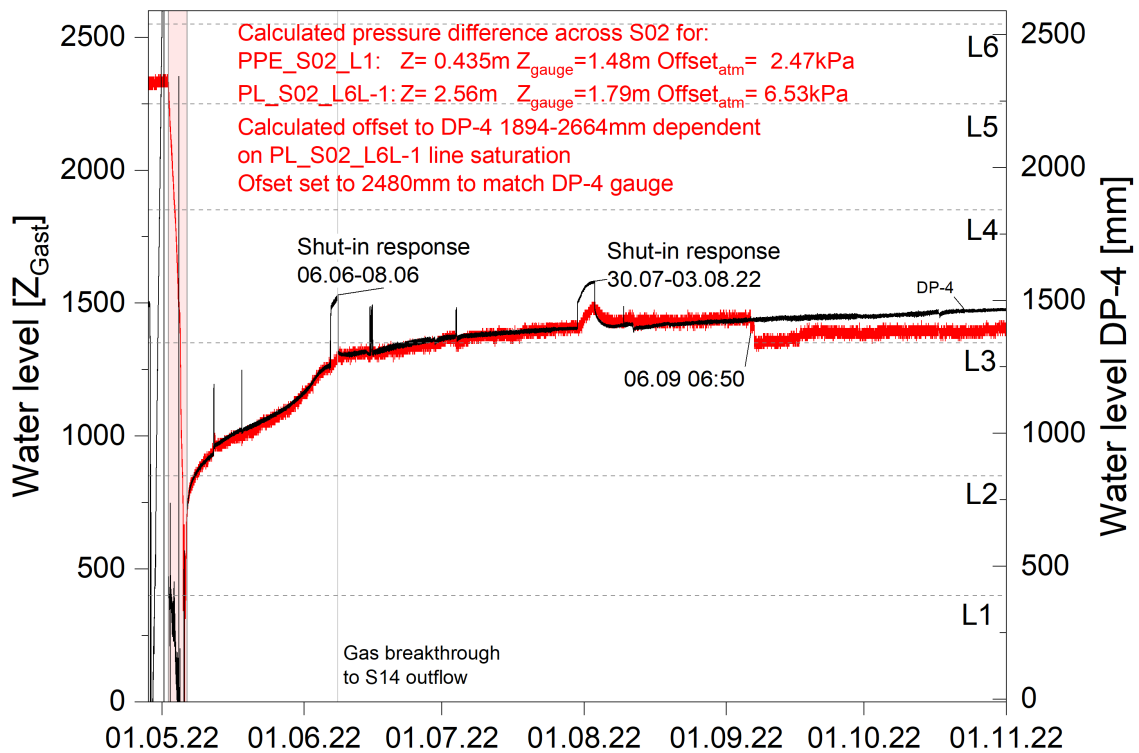


Fig. C-6: Differential pressure in S02 from DP-4 and calculated pressure difference

Fig. C-8 shows the calculated water level during the entire duration of the GFT. The data suggest that although water levels took a long time to recover from the initial W-GX (perhaps due to slow equilibration in low-permeability parts of the filter), the water level was roughly constant at a level above L3 during the GFT, reflecting the limited exchange of water between the filter and the sand/bentonite.

The gas volume in the filter can be estimated from the pressure differential, assuming the presence of a well-defined water level, a uniform porosity and as-built geometry. Fig. C-7 provides an approximate guide to the likely gas pore volume in the filter for a given water level.

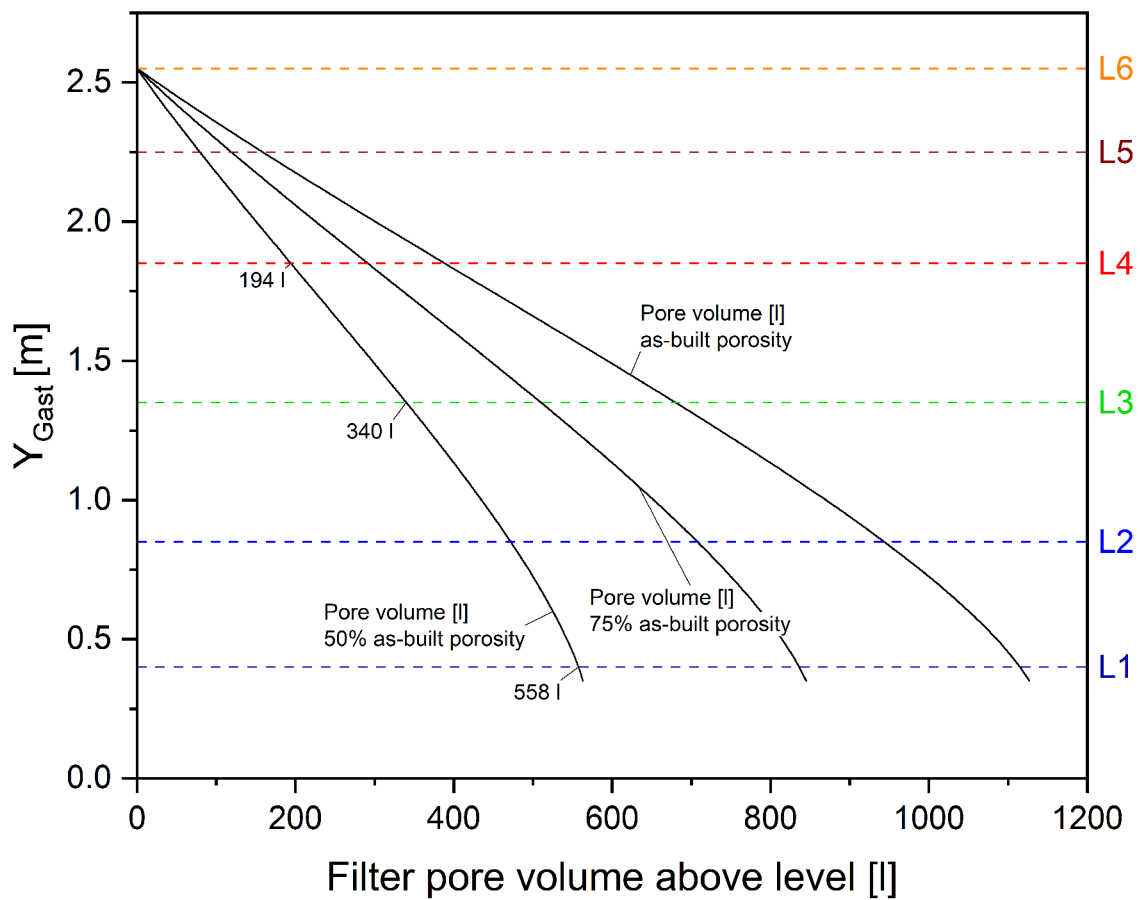


Fig. C-7: Estimated pore volume in sand filter above a level. Assumes uniform porosity and as-built geometry

The estimated gas-accessible pore volume at L3 (assuming 50% of the as-built porosity) is 340 l, while 15 cm above, at 1.5 m, the pore volume is estimated at 297 l, which is in good agreement with the injected gas volume during the W-GX. However, there is significant uncertainty on both the filter geometry and gas-accessible porosity after more than 10 years of saturation.

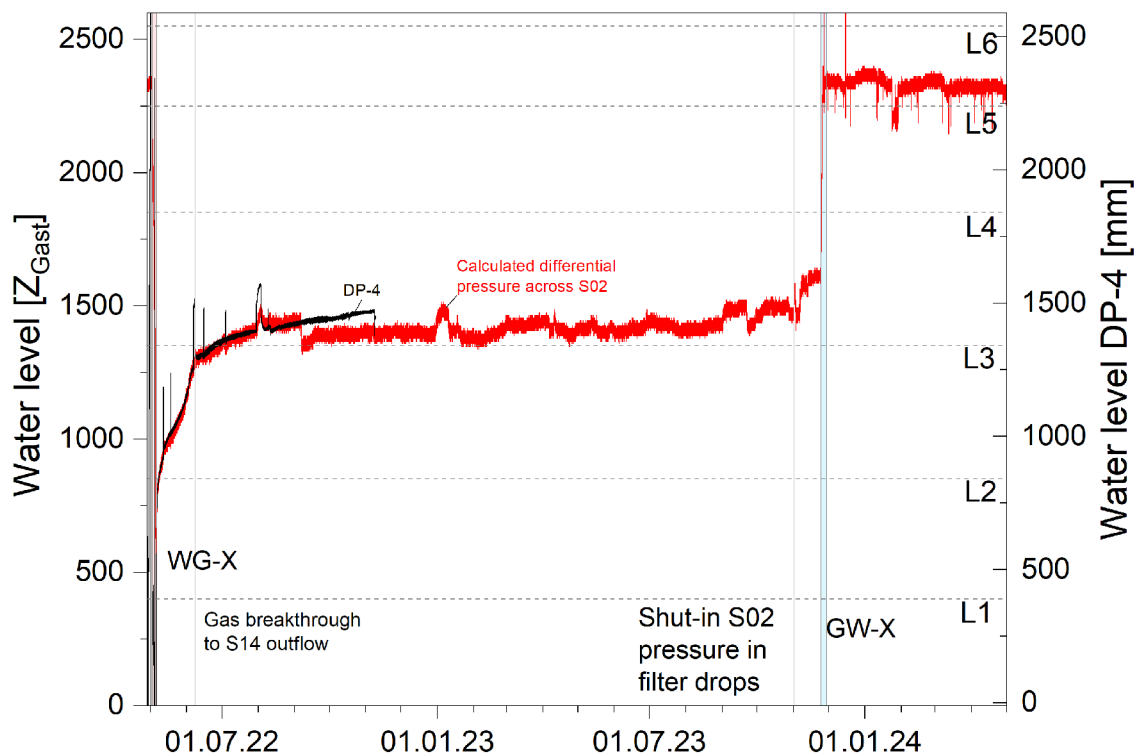


Fig. C-8: Calculated water level from S02 pressure difference
DP-4 data also shown.

C.3 S14 gas volume and “water level”

C.3.1 S14 filter pulse tests

Filter pulse tests were performed in S14 on 15.03.22 and 18.03.22, approximately 6 weeks before the start of the W-GX in S02. Analysis of the tests suggested a compressibility of 4.8 – 6.2 ml/kPa and a gas volume of 2 – 5 l, assuming a saturated filter compressibility of 3.46 ml/kPa. It is possible that the gas volume is an overestimation and that no significant gas volume was associated with the filter at the start of the gas injection into S02.

Subsequent filter pulse tests were performed after the start of water extraction from S14 in early May 2022 to estimate the gas volume present in the filter and compare it with the measured extracted water volume. After 08.06.22, when gas broke through to the L1 extraction line, filter pulse tests were impractical because of the large gas volume present (>600 l). Further filter pulse tests were not performed in S14 until Phase 11, when an attempt was made to degas the S14 filter by water injection into S14 and gas extraction from S02. Three tests were performed between 23.11.23 and 30.11.23. Instrumentation problems were encountered with the first of these tests but the other two tests showed a reduced gas volume of 270 – 280 l.

C.3.2 Sinusoidal volumetric extraction S14

During the drainage of the S14 filter from 17.05.22 until 15.06.22, the syringe pump was used to maintain volumetric extraction with a sinusoidal amplitude of 4 ml/min and duration of 120 minutes. The mean rate was adjusted to maintain ~1,400 kPa pressure (PPE_S14_L1). As the gas volume in S14 increased, the amplitude of the resulting pressure variations decreased due to the increasing compressibility. The pressure data from PPE_S14_L1 were noisy and the calculated amplitude of the 120 minutes component was less than 1 kPa.

The inferred gas volume in S14 from the sinusoidal analysis was unreliable because of the small pressure variation. In addition, the pressure sensor (PPE_S14_L1) was close to the extraction line (PL_S14_L1) and may have been inherently noisier than the S02 data.

C.4 Summary

C.4.1 S02 gas and water volume

During the W-GX, 288.9 l of water had been extracted from S02 and replaced with gas. Some of this gas had also entered the sand/bentonite. Analysis of the sinusoidal pumping suggests an initially slightly decreased gas volume of ~275 l associated with the sand filter (Fig. C-9). Over time, this steadily increased to ~300 l by the end of sinusoidal pumping. The cause of the increase is probably water flow out of the S02 filter driven by the pressure gradient. This can be estimated as

$$Q_{S02}^{water} = K_h^{s/b} A_w \frac{P_{S02} - P_{S03}}{9.81(Z_{S02} - Z_{S03})}$$

where $K_h^{s/b}$ is the horizontal hydraulic conductivity of the sand/bentonite, A_w is the cross-sectional area of the water-filled part of the S02 filter, and P_{S02} and P_{S03} are the pore pressures in S02 and S03.

During the W-GX, the water level in the filter was locally drawn down to the extraction at L1 by the end of the exchange. Measurements of the differential pressure across the filter (L1 – L6) suggest that the water level then recovered slowly to a little above the L3 level by the time of gas breakthrough to the S14 extraction. The water level then remained largely steady at this level until November 2022, when a reverse gas flow and subsequent G-WX were performed. The steady water level suggests that the gas volume changed only very slightly until this time.

During the reverse gas flow in Phase 11, only gas was extracted from PL_S02_L6L-2 and no significant volumes of water were produced. The pulse test performed after reverse flow but prior to the G-WX indicated a free gas volume of 333.2 l in the S02 sand filter (3497 lN).

During the G-WX (24. – 27.11.23), 192.7 l of gas were extracted (2,889 lN), approximately balancing the net water injection of 203.5 l (Tab. C-5). The pulse test performed after the G-WX indicated a gas volume of 130.5 l (1,385.2 lN), i.e. a reduction of 202.7 l which is broadly consistent with the water extracted during the G-WX.

Tab. C-5: S02 fluid flow during G-WX

	Injected	Extracted	Net	
Water [l]	277.4	73.9	203.5	G-WX: Water injection at L1 and extraction at L6
Gas [ln]		2,889.0		G-WX: Gas extraction at L6
Gas [l]		192.7		

Fig. C-9 shows the measured gas volumes (pulse test and sinusoidal estimates) together with a trend based on the S02 extraction at the W-GX and G_WX and incorporating water leak-off for $K_h^{s/b}$ of 2×10^{-11} m/s and 5×10^{-11} m/s, respectively. Overall, the estimated trend is in reasonable agreement with the measured gas volumes.

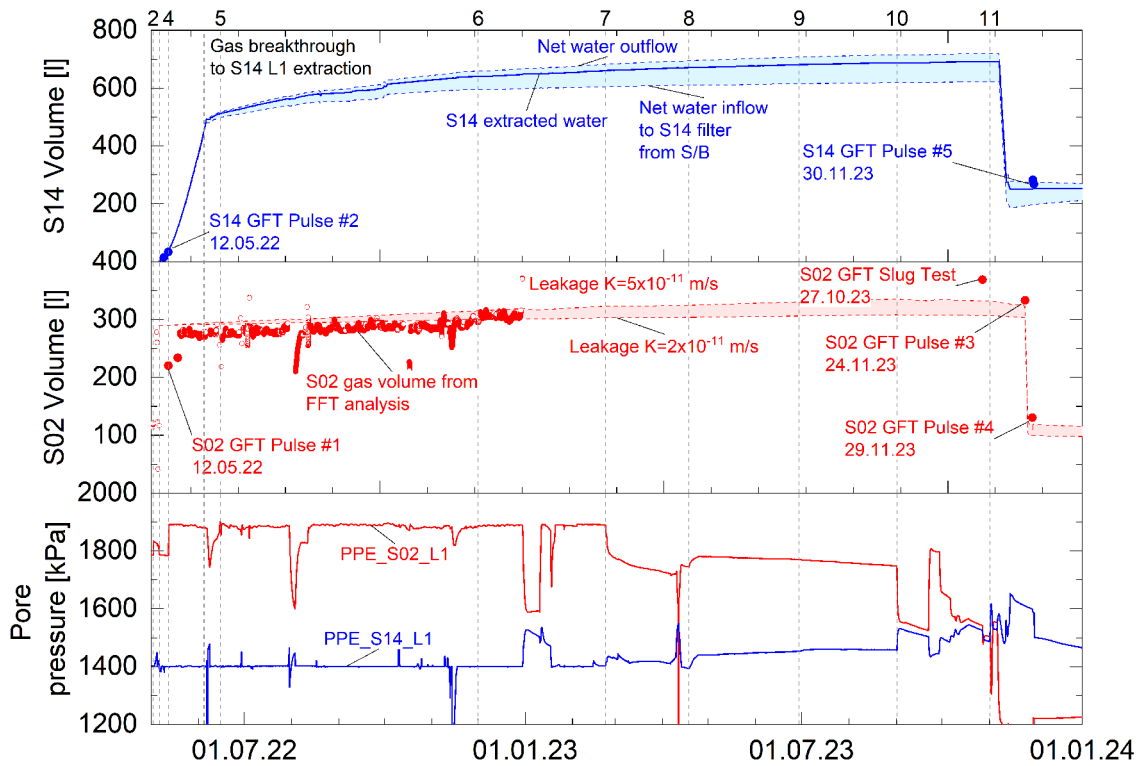


Fig. C-9: Estimated gas volumes for S02 and S14 during the GFT

C.4.2 S14 gas and water volumes

The data support a relatively consistent picture of the gas volume associated with the S14 sand filter. Water extraction to maintain constant pressure started during the S02 W-GX, and continuous extraction started on 07.05.22. It is likely that this was due to the flow of a small amount of water expelled from the gas path into S02 but also due to a free gas phase of injected gas. Pulse tests on 09.05. and 12.05.22 indicate gas volumes in the filter that are in good agreement with the extracted water volume (Fig. C-10). Estimates of gas volume in the filter from analysis of the sinusoidal pumping are also initially in good agreement with the extracted volumes but become less reliable as the extraction continues.

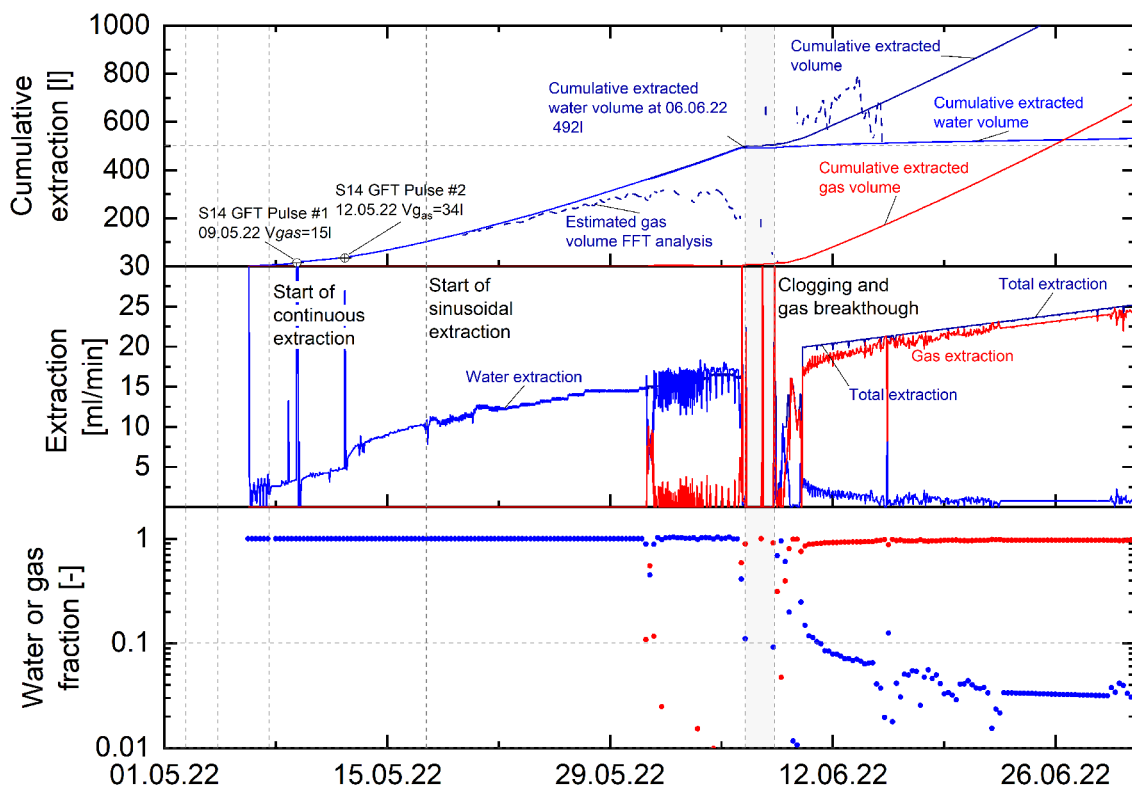


Fig. C-10: S14 extraction gas/water fraction, gas, water and total extraction rate and cumulative volumes

The arrival of a free gas phase in S14 (i.e. gas breakthrough to the S14 filter rather than to the L1 extraction) is likely to have occurred prior to the start of constant pressure extraction (06.05.22, 07:54) when ~2 l of water had already been extracted from the filter. This volume is more than might have been expected to flow from the sand/bentonite into the S14 filter and occurs after the first sample to show dissolved helium in the S14 water.

Water was not collected in the mock-up tank until 31.05.22, so it is not possible to quantify the gas volume produced prior to this but this is thought to be very small as the outflow was dominantly water. By the time of the gas breakthrough to L1 extraction on 08.06.22, about 500 l of water had been extracted from S14. After the breakthrough, the dominant flow was of gas although some water continued to flow. By 01.09.23, a volume of 688 l of water had been

extracted. It is likely that the majority of the additional water came from drainage of the S14 sand filter but some water will also have been carried by the gas from S02 (as water vapour or droplets) or have come from the sand/bentonite.

Taking a similar approach to estimating the water flow into the filter to that used for S02, we can estimate the inflow from the sand/bentonite to S14 when $P_{S12} > P_{S14}$ as:

$$Q_{S14}^{water} = K_h^{s/b} A_w \frac{P_{S12} - P_{S14}}{9.81(Z_{S14} - Z_{S11})}$$

Fig. C-9 shows the estimated gas volume in S14 based on the measured water outflow (mock-up tank) and the estimated water in-/outflow. Again, the trends are reasonably consistent with the pulse test estimates.

Tab. C-6: Estimated gas volume in S14 during the GFT

	Cumulative extraction Syringe Pump [l]	Mock-up water level [l]	Pulse gas volume [l]	Comment
18.03.22 13:51			<2	Likely overestimate
04.05.22 08:58				Start of extraction (50 ml)
04.05.22 09:54				Further extraction (125 ml)
05.05.22 13:54				Water sample PL_S14_L1 shows low level of dissolved He
06.05.22 07:54	2.0			Start of constant head extraction
07.05.22 14:06	6.0			Start of continuous extraction
09.05.22 07:43	14.5		15	Pulse test (1,350 kPa)
12.05.22 08:06	36.9		34	Pulse withdrawal test
31.05.22 07:00	361.1			Mock-up tank added to separate gas
08.06.22 08:01	505.5	492.4		Unclogging of PL_S14_L1 and start of gas production
08.06.22 – 29.11.23	<i>Measured water outflow from the mock-up tank</i>			
29.11.23 14:13			283	Pulse test
30.11.23 07:58			268	Pulse test

App. D Hydraulic index testing (PPEs)

Authors: G.W. Lanyon, J. Gisiger, U. Rösli

D.1 Results of PPE index testing

Small-scale hydraulic “index” testing of the piezometers (PPEs) in the seal section was performed throughout the GFT. This was a continuation of earlier tests to determine the saturation of the hydraulic lines (post-GPT1, Lanyon & Herbert 2021) and more extended tests to determine local-scale permeability (Lanyon et al. 2022). Testing was performed as either pulse injection (PI) or pulse withdrawal (PW) tests using either a water column flowmeter (PI tests) or a fixed volume (~2 ml) extraction (see Rösli et al. 2025 for details). Analysis of the tests was limited to estimating the compressibility ($\Delta V/\Delta P$) and a qualitative evaluation of the speed of pressure recovery. The measured pressure recoveries are shown in Rösli et al. 2025

An initial set of PW tests in almost all the piezometers in the sand/bentonite and at L6 were performed in March 2022 prior to the start of the GFT. After the start of GFT, multiple testing campaigns were performed creating a time history of the measured compressibility for the piezometers (Tab. D-1) as shown in Fig. D-2.

Tab. D-1: Hydraulic index test campaigns, prior to, during and after the GFT

Campaign	Start	End	Number of tests	Comment
Pre-GFT	08.03.22	21.03.22	32	Prior to the GFT
GFT01PI	31.05.22	06.06.22	16	Initial injection tests
GFT01PW	06.06.22	15.06.22	9	Two PWs performed on 06.06.22
GFT02	29.09.22	30.09.22	30	
GFT03	18.01.23	26.01.23	31	
GFT04	30.03.23	30.03.23	29	
GFT05	06.07.23	06.07.23	30	
GFT06	21.09.23	21.09.23	32	
GFT07	26.10.23	26.10.23	34	
GFT08	30.11.23	30.11.23	32	
Post-GFT	03.05.24	03.05.24	32	

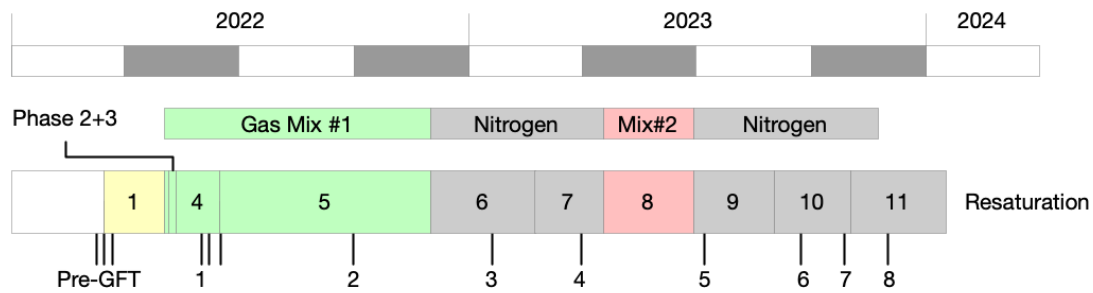


Fig. D-1: Timeline of index testing during GFT phases

The compressibility is influenced by the line saturation and the state of the filter in the seal section. The compressibility of the hydraulic line is expected to vary between $\sim 10^{-13}$ for a water-filled 2.4 mm diameter line and $\sim 10^{-10}$ (m^3/Pa) for a gas-filled line at 1,400 kPa abs (assuming minimal compressibility of the steel line). Where a PPE was sampled either by pump or vacuum, the compressibility may have been altered by either drawing gas into the line or by degassing within the line. For this reason, care should be taken in interpreting the compressibility where sampling occurred.

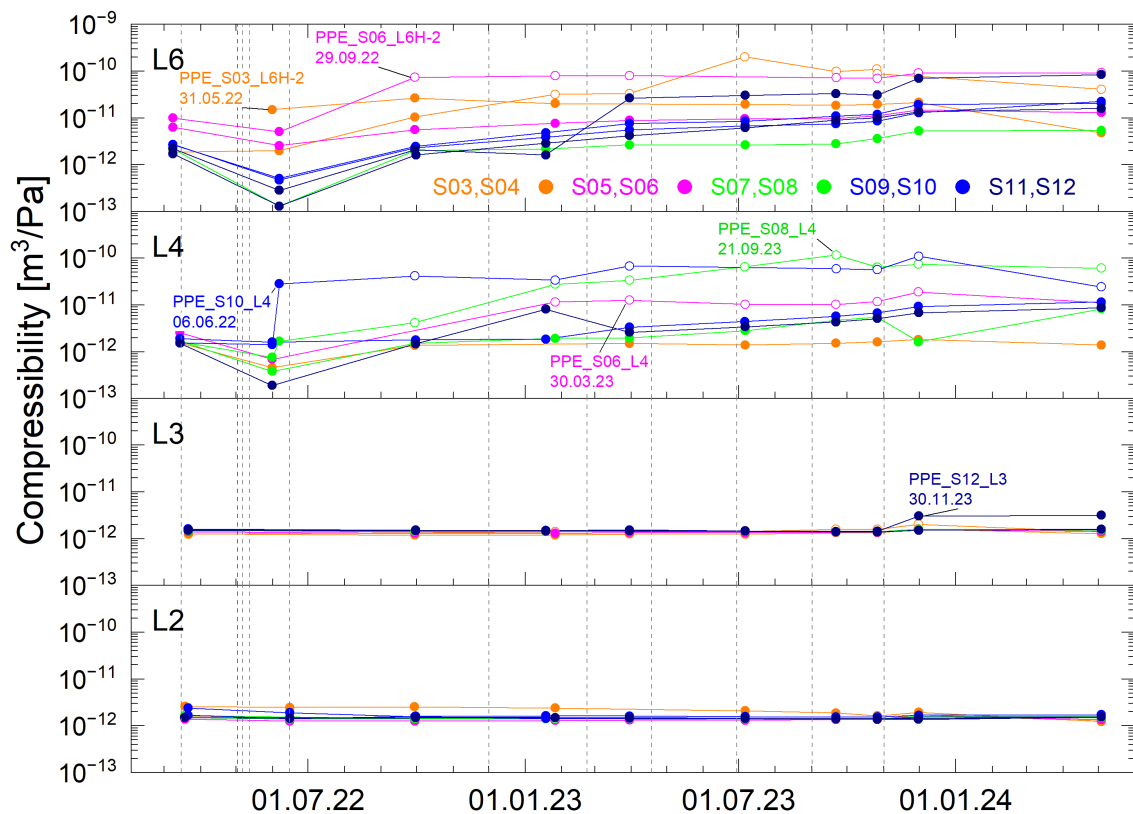


Fig. D-2: Time histories of PPE compressibility from index testing for L2, L3, L4 and L6

Lines and symbols for each PPE coloured by instrument section. Hollow symbols show lines that were sampled.

The typically low permeability of the sand/bentonite means that even for an extraction of 2 ml, the measured pressure can be drawn down to close to the GTS atmospheric pressure. The compressibility derived from the early PI tests (31.05. – 06.04.22) is typically lower than that from PW tests. This could indicate degassing due to the large drawdowns during the PWs.

Initially, the measured compressibility at GFT01 was one indicator used to select particular PPEs for subsequent sampling, including PPE_S10_L4, and PPE_S06_L6H-2. However, in later campaigns, a more general increase in compressibility is seen in the piezometers in L4 and L6. Fig. D-3 shows only the test performed prior to sampling of the respective PPE. The compressibility of the PPEs in L2 and L3 is largely unaltered during the test with the exception of PPE_S12_L3 which can have been influenced by the presence of the large gas volume in the S14 filter.

In part, the late time increase could be due to lower pore pressure causing higher compressibility of any gas bubbles, but the changes in pore pressure during the GFT are relatively small compared to the change in compressibility as shown in Fig. D-4

The spatial pattern of measured compressibility before and at the end of the GFT is shown in Fig. D-5. The overall spatial evolution of compressibility for all the testing campaigns listed in Tab. D-1 is shown in Fig. D-6.

The high compressibility measured at PPE_S03_L6H-2 is believed to relate to a possible leak in the wellhead. Anomalous pressure responses have been observed in PPE_S03_L6H-2 (Section 2.2.3) and methane has been detected in samples taken from a nearby piezometer.

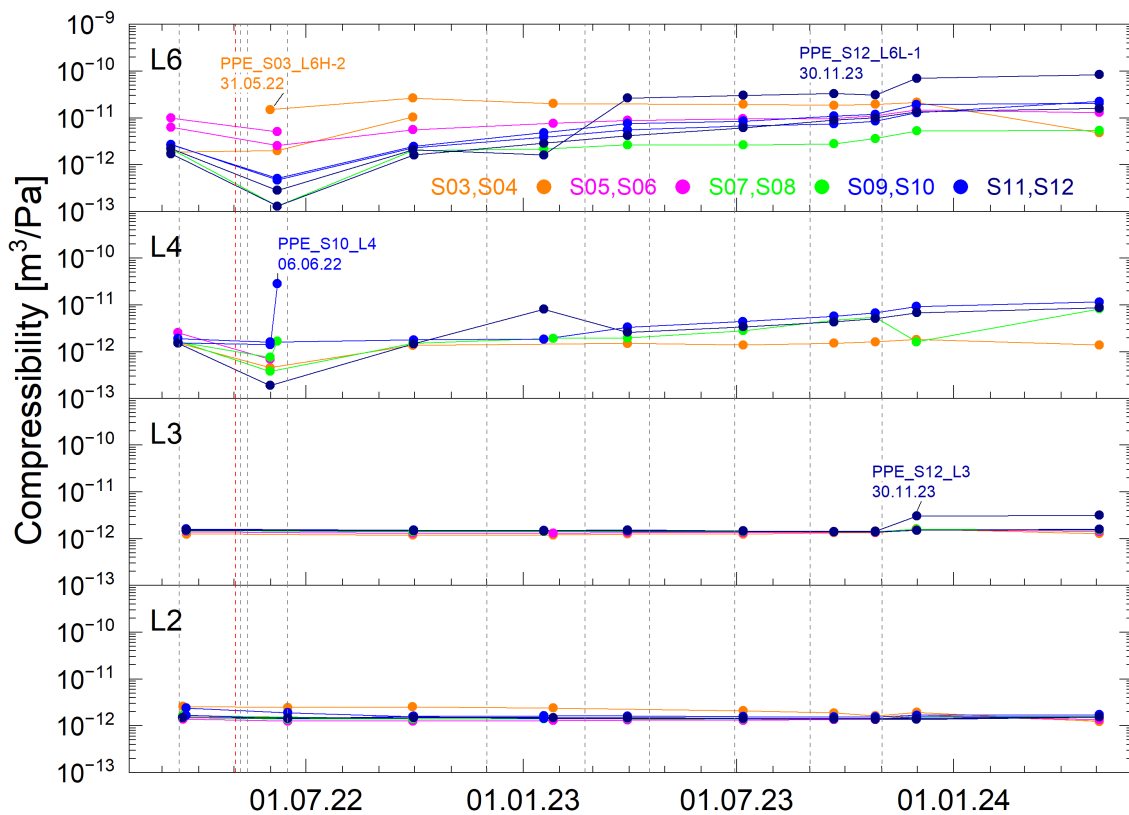


Fig. D-3: Time histories of PPE compressibility from index testing for L2, L3, L4 and L6

D.2 Interpretation of PPE index testing

The measured compressibility for PPEs either prior to sampling (or where the PPE was not sampled) shows a strong dependence on sensor level. At L2 and L3, the measured compressibility stayed close to pre-GFT values except for PPE_S12_L3 at the very end of the GFT, which could have been affected by the presence of a large gas volume in the S14 filter (about 0.6 m away).

At L4, there is a trend for increasing compressibility from S07 to S12. In particular, PPE_S10_L4 showed an early increase in compressibility (among other features of the piezometer response) from 06.06.22 in the first measurement campaign after the start of the GFT (~1 month after the start of gas injection). The presence of gas near the piezometer filter was confirmed by subsequent gas sampling from 15.06.–28.06.22 at an initial extraction flow of ~6 µl/min that increased over time to ~12 µl/min.

At L6, the piezometer compressibility from S02 to S06 was already high, possibly pointing to the presence of partially saturated zones (perhaps residual gas pockets from GPT1 or local methanogenesis in the case of PPE_S03_L6L-1). From S08 to S12, compressibility was initially identical to that measured at the lower levels, but then increased during the GFT, indicating the presence of gas across the level at the top of the sand/bentonite. For some PPEs, the increase in compressibility was relatively rapid (e.g. PPE_S06_L6L-1) while for others it was more gradual. The increase cannot be explained by changes in pore pressure alone but indicates a significant change in saturation around the PPE filter or within the hydraulic line.

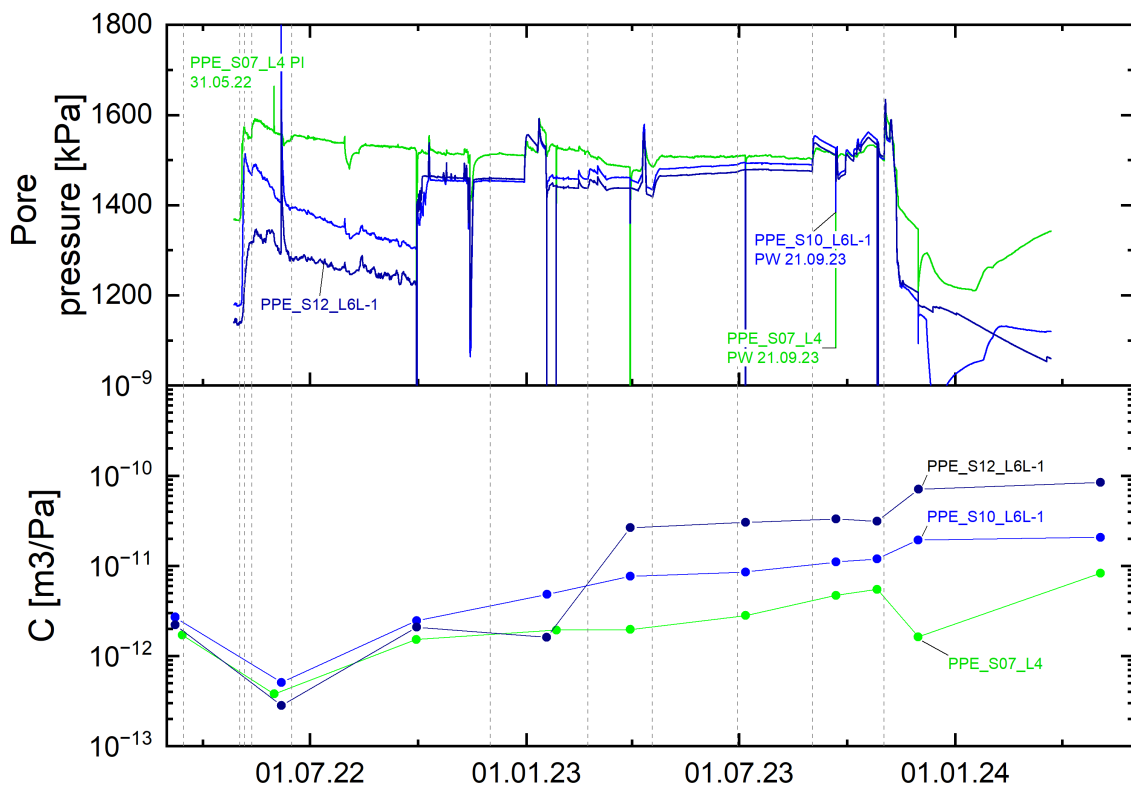


Fig. D-4: Time histories for selected PPEs of compressibility and pore pressure

Interference effects between PPEs were not observed, and no detailed analysis of the pressure recovery from each PW test was performed although extended recoveries indicating low permeability were observed at several sensors in L6.

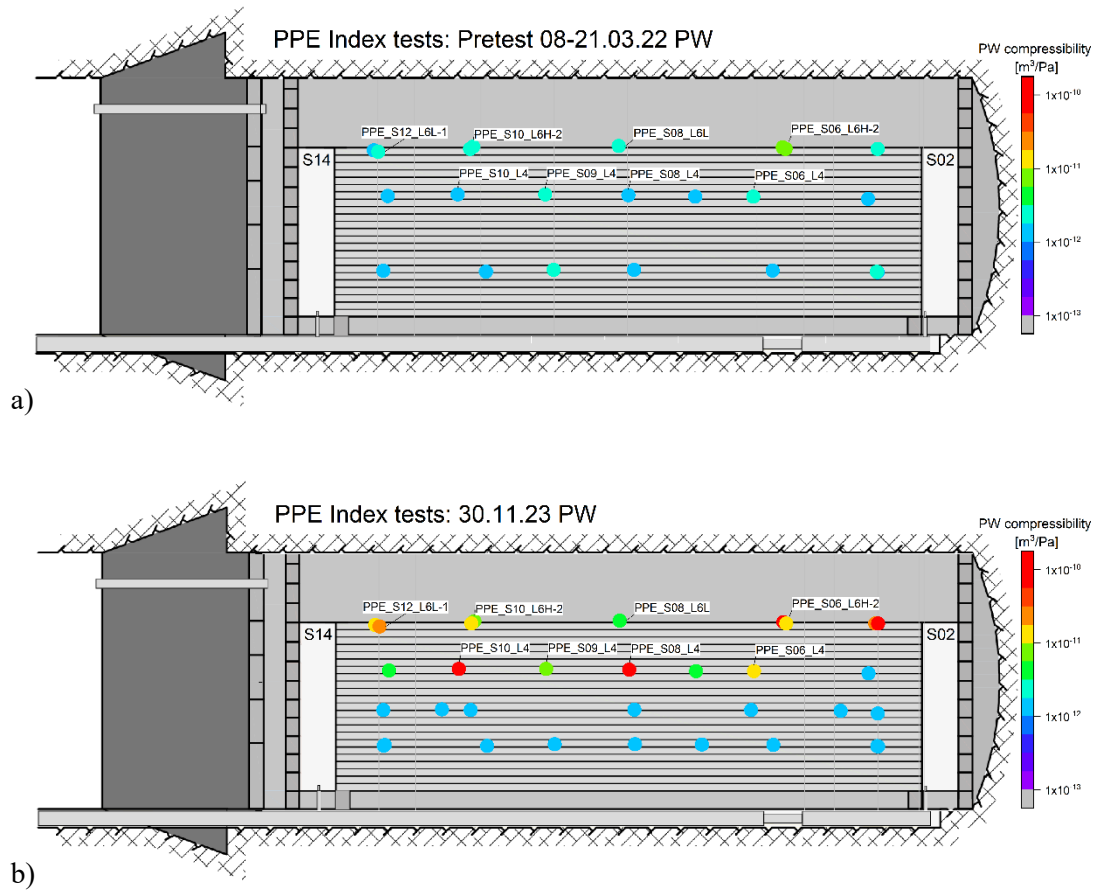
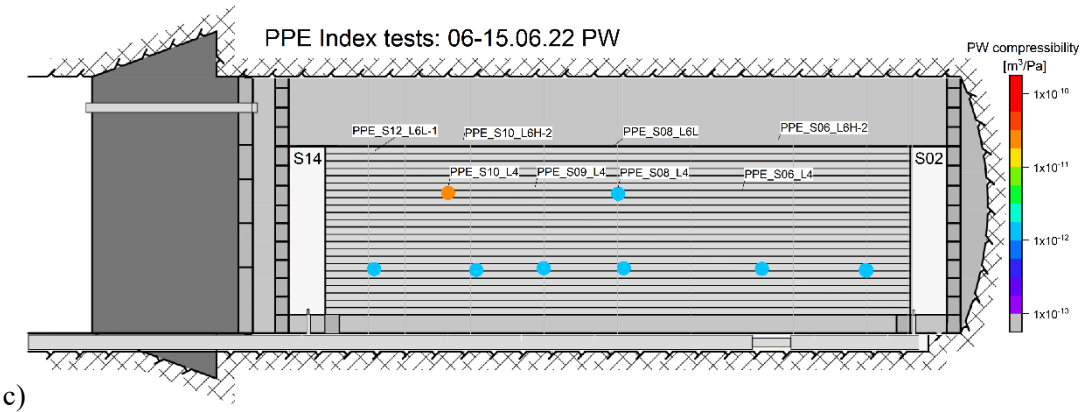
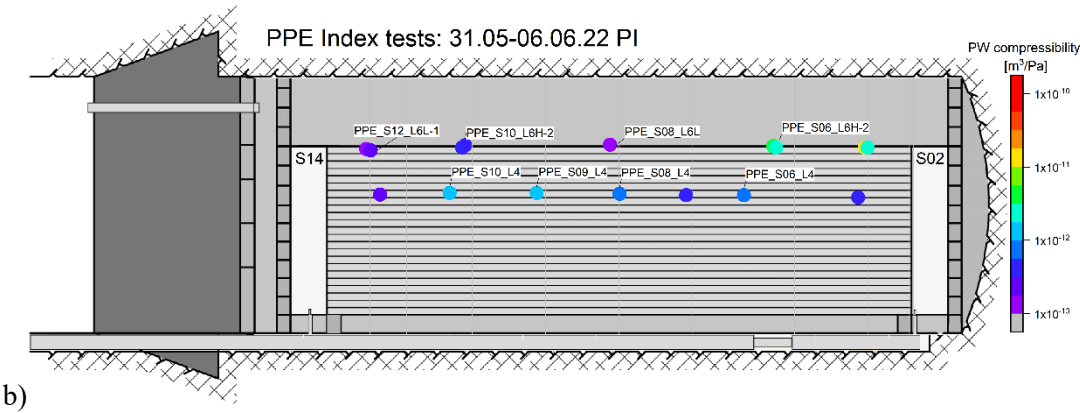
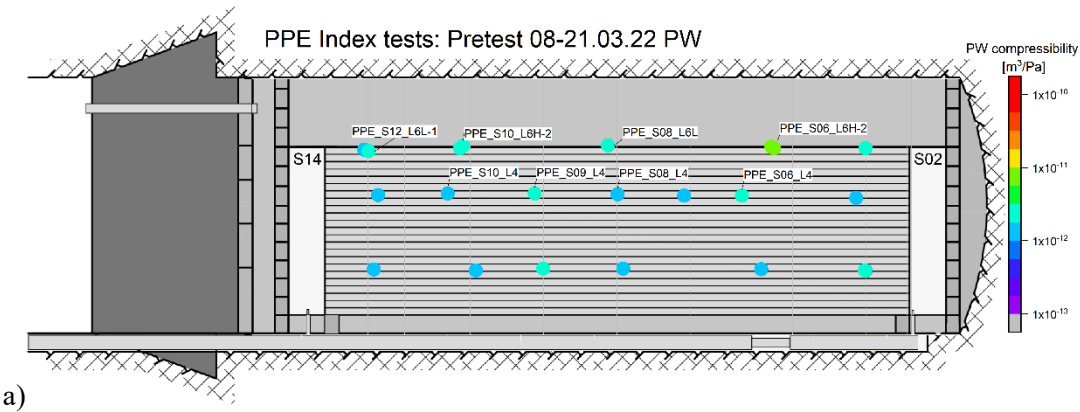
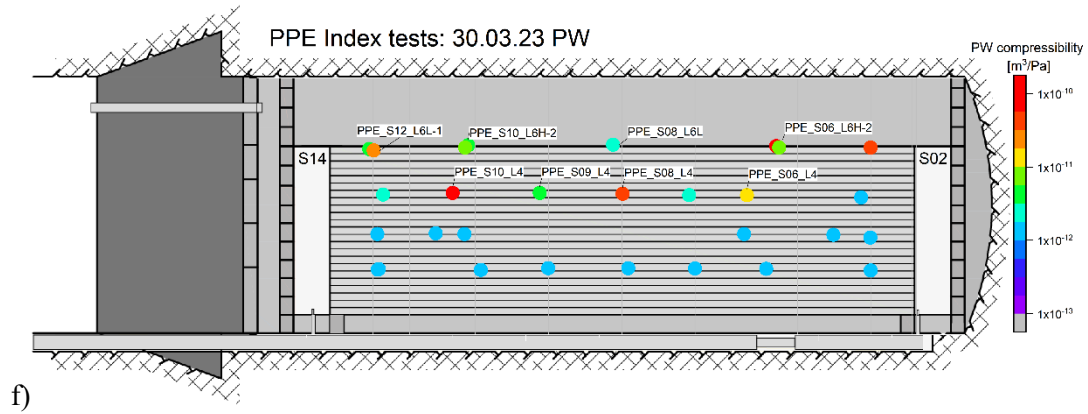
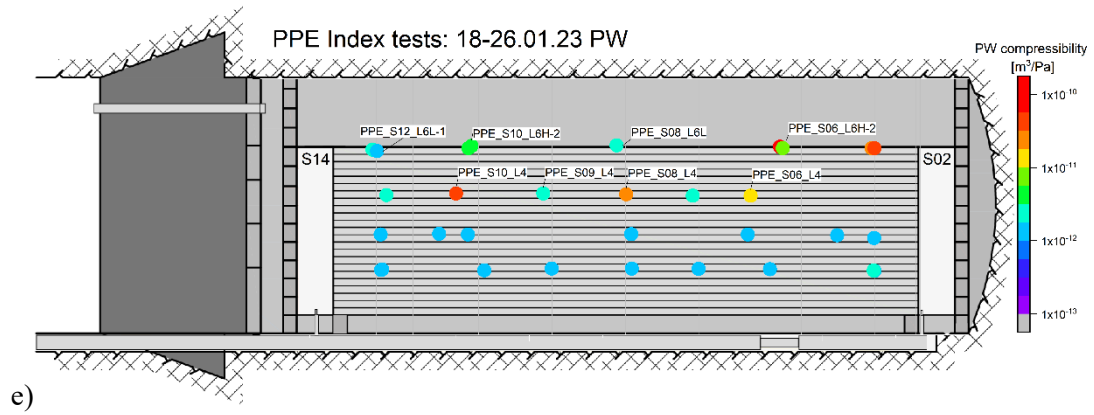
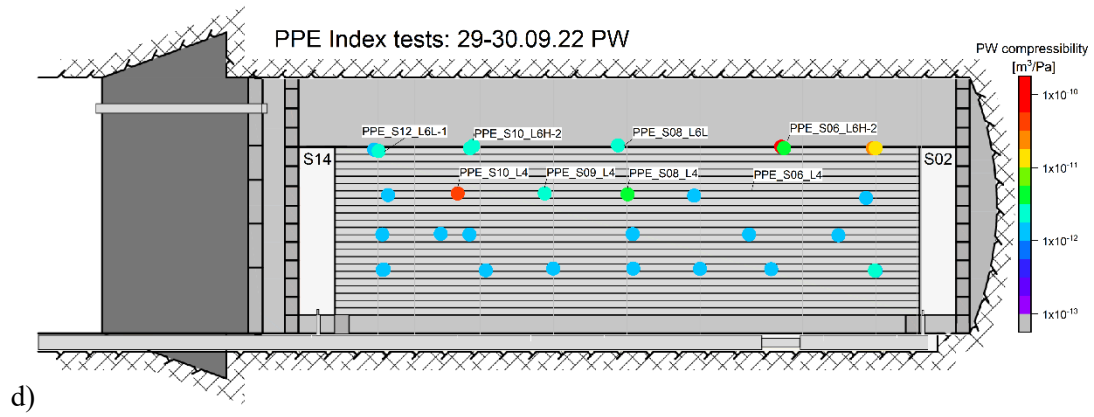
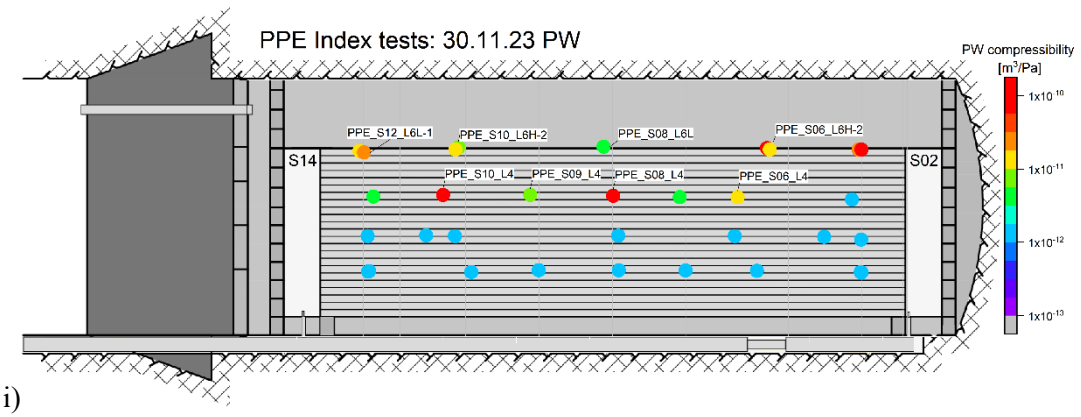
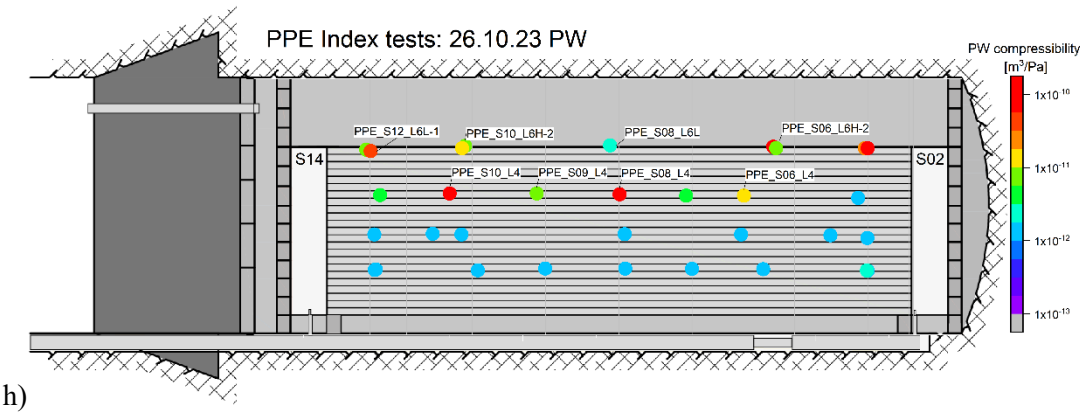
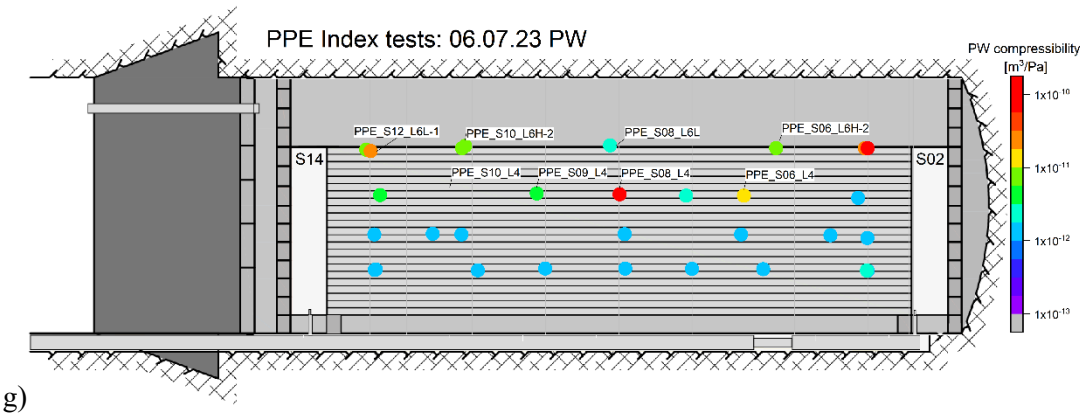


Fig. D-5: Spatial pattern of PPE compressibility from index testing a) prior to the GFT and b) at the end of the GFT on 30.11.23







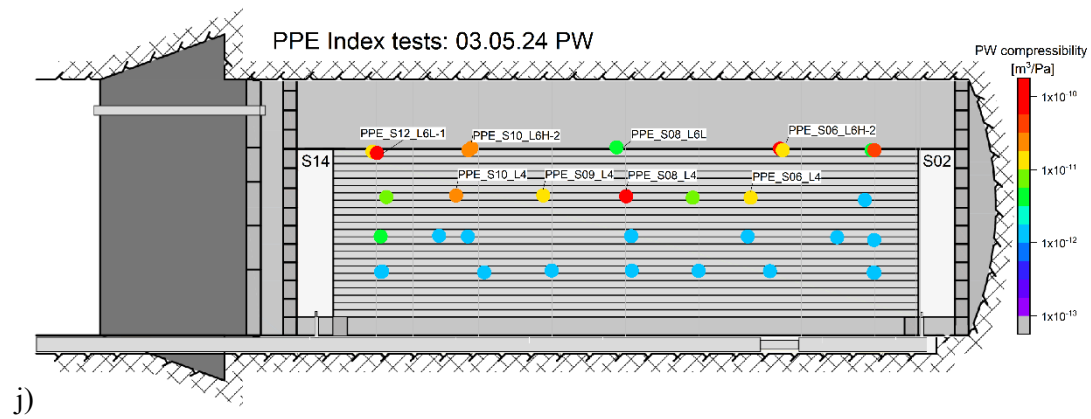


Fig. D-6: Evolution of spatial pattern of PPE compressibility from index testing for all campaigns

App. E Gas tracers

Authors: G.W. Lanyon, E. Stopelli

E.1 Results from gas tracer injection and sampling

The GFT includes two periods of gas tracer injection using different tracer mixtures: Gas Mix #1 (nominal 2% helium in nitrogen N₂) and Gas Mix #2 (nominal 10% helium, 15% argon, 0.1% xenon in nitrogen). The gas mix tracer injection periods were both followed by pure nitrogen injections to flush the tracers from the S02 and S14 filters and gas path.

The gas tracers were monitored using an on-site miniRUEDI system providing continuous monitoring of:

- the extraction from the S14 filter (PL_S14_L1) via coupling with a “membrane module”, and
- measurement points in the tunnel to identify any possible leakage around the plug or via the instrumentation ducts.

No significant leakage into the WT drift was detected during the test at any of the monitoring points. Monitoring of the S14 extraction using the custom-made membrane module was useful in providing a qualitative near-real-time guide to dissolved gas concentrations during the very early test period and, subsequently, to concentrations in the free gas phase produced from PL_S14_L1.

In addition to the online monitoring, samples were taken for laboratory analysis from:

- the gas bottle bundle used for injection,
- the L1 in the S02 sand filter (PL_S02_L1),
- the extraction line (PL_S14_L1) from the S14 sand filter, and
- selected PPEs.

Comparison of the S14 quantitative laboratory analyses with results from the on-site measurements of miniRUEDI on the gas phase of the membrane module showed that there are “memory” effects and artefacts (e.g. pressure control via the valve on gas headspace of the module) that bias the membrane module data such that it should only be used qualitatively. Therefore, the laboratory analyses are preferred for interpretation work.

E.1.1 Dipole test and baseline dissolved gas content

The GAST sand/bentonite seal section and the surrounding granular bentonite were emplaced in 2012. Saturation of the seal section started in July 2012 by water injection into the S14 sand filter. Saturation was halted in January 2014 after a leak into the WT drift but then resumed in September 2015. Since then, saturation has continued with water injection into one or both S02 and S14 filters. During the GPT1 gas test, gas was injected into S02 but water injection into S14 continued. The sources of injection water are listed in Tab. E-1.

Tab. E-1: Water sources for saturation of the GAST seal section

Period	Water source	Pumping/flow control
to 22.03.21	GTS main system	From 06.09.16 300 l tank + dosage pump
22.03.21 – 17.08.21	BOUS 85.003	300 l tank pressurised with nitrogen
17.08.21 onward	BOADUS 96.001	Pressure reduction valve and controller

Literature data on dissolved gases in Grimsel borehole water are reported in Rösli et al. 2025 together with data from a sample collected from the ADUS 96.001 borehole (see Fig. E-1) for membrane module testing.

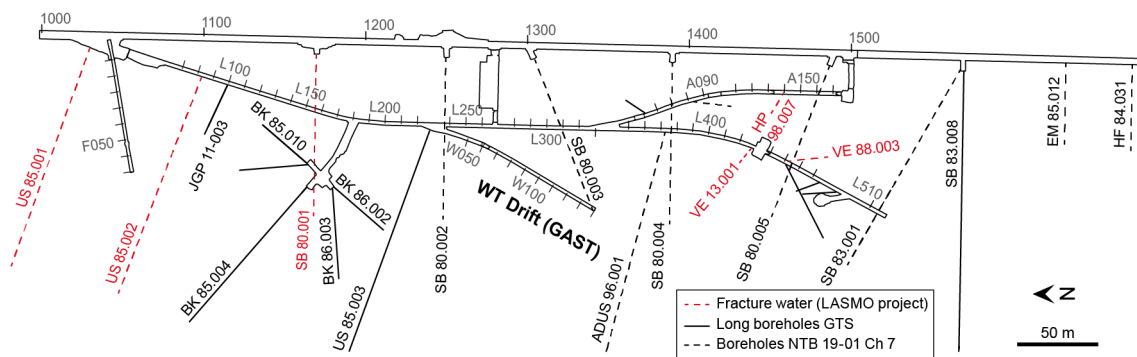


Fig. E-1: WT drift and location of the ADUS 96.001 borehole (BOADUS)

Other boreholes shown here relate to monitoring of groundwater at the GTS (see Schneeberger et al. 2019, Chapter 7).

Prior to the start of the GFT, a long-term dipole test was performed at L2 within the sand/bentonite. The dipole test was performed between PPE_S06_L2 (injection with BOADUS water) and PPE_S07_L2 (extraction) from 20.12.21 to 14.03.22. Initially a pressure difference of 200 kPa (1,800–1,600 kPa) was established, but very low flow rates (~10s ml/week until 10.03.22 when the flow rate increased to ~300 ml/week) resulted in the decision to increase the gradient with a final 1,300 kPa difference (2,000 – 700 kPa) from 27.01.22. A 1-NSA solution tracer was injected in PPE_S06_L2 from 13.01.22, but not detected at extraction. One objective of the dipole test was to sample the sand/bentonite porewater. The samples have been used to provide a baseline for dissolved gases in the sand/bentonite porewater to support the interpretation of the gas tracers.

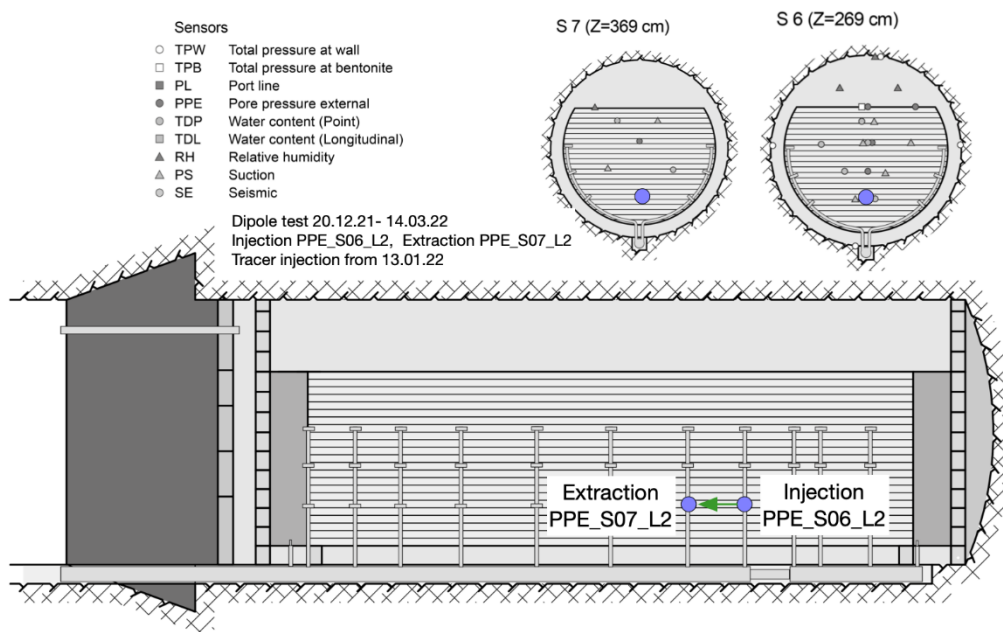


Fig. E-2: Dipole test layout

The data from the three dipole test samples have been used to derive an estimate of the baseline dissolved gas content as listed in Tab. E-2. While there is some uncertainty on the interpretation of the dipole test with large changes in flow conditions over time, for the current work, an average of the three dipole samples is thought to provide the best estimate of the background dissolved gas concentrations in the sand/bentonite porewater.

Tab. E-2: Dipole test dissolved gas content and baseline estimate

When the composition in [%] is calculated from dissolved species abundance in solution, numbers are reported in *italics*.

Sample date	Dissolved gas content [cm ³ STP/kg]					Dissolved gas fraction [%]			
	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
14.02.2022 07:45	n.d.	0.02	n.d.	11.4	11.6	<i>n.d.</i>	<i>0.17</i>	<i>n.d.</i>	<i>98.4</i>
23.02.2022 14:52	n.d.	0.04	n.d.	17.7	18	<i>n.d.</i>	<i>0.22</i>	<i>n.d.</i>	<i>98.4</i>
14.03.2022 09:07	n.d.	0.2	n.d.	17.6	18.6	<i>n.d.</i>	<i>1.08</i>	<i>n.d.</i>	<i>94.8</i>
Baseline (average)		0.09		15.57	16.0 7		<i>0.49</i>		<i>97.20</i>

The data indicate porewater containing mostly dissolved nitrogen and a small amount of argon. The porewater is saturated with nitrogen at a pressure above that of the atmospheric pressure at the GTS (~82 kPa) and a little over the STP. This seems reasonable given the likely dissolution in the porewater of any air trapped in the sand/bentonite and the injection of water pressurised with nitrogen during 2021.

E.2 Gas tracer measurements

Only a qualitative interpretation of the data is given here. The period covered is from the start of the GFT (02.05.22) to the end of sampling (01.09.23). Gas injection was shut in on 01.09.23 prior to a period of nitrogen gas injection flow testing. The focusing for this was on developing an understanding of the transient response to changes in injection rate. After this, the main effort went into removing gas from the filters and gas path prior to resaturation.

E.2.1 Injected gas mix samples

The GFT gas injection mixes as specified are listed in Tab. E-3. Analyses of the samples taken from the gas bundles showed some small deviations from the specification, consistently indicating a minor argon content in the nitrogen gas bundles and a slightly higher than specified argon content in Gas Mix #2. It was decided to use the laboratory analyses to describe the injected gas within this interpretation study and the modelling work as listed in Tab. E-4. The interpretation focuses on the gas fractions of the three tracer gases helium, argon and xenon. The analyses of other gases are discussed in Rösli et al. 2025.

Tab. E-3: Specified GFT gas mix volume fractions

	Nitrogen	Helium	Argon	Xenon
Gas Mix #1	98%	2%	-	-
N ₂ Flush	100%	-	-	-
Gas Mix #2	74.9%	10%	15%	0.1%

Tab. E-4: Definition of GFT gas mixes used in this interpretation study based on laboratory analyses results

	N₂ [vol.%]	He [vol.%]	Ar [vol.%]	Xe [vol.%]
Gas Mix #1	97.9%	2.07%	0.0%	0.00%
N ₂ #1	99.9%	0.00%	0.1%	0.00%
Gas Mix #2	73.2%	10.1%	16.7%	0.09%
N ₂ #2	99.9%	0.02%	0.1%	0.00%

E.2.2 S14 extraction samples

As mentioned earlier, the on-site monitoring of membrane module data should only be treated qualitatively, as a guide to the trend and the emphasis is placed on the laboratory samples. Rösli et al. 2025 provide an estimate of the error associated with the laboratory analyses of 4 to 15%.

Water injection into S14 stopped on 03.05.22, one day after the start of the water-gas exchange in the S02 filter. Pressure started to rise in S14 on 05.05.22, and periodic water extractions from the S14 filter were initiated to maintain a constant 1,400 kPa pressure. On 07.05.22, a continuous water extraction from S14 was started using a syringe pump. On 09.05.22, the miniRUEDI membrane module was connected to the extraction providing monitoring of dissolved gases. The mean extraction from S14 increased over time and on 17.05.22, a continuous sinusoidal flow was started with an amplitude of ± 4 ml/min. The measured sinusoidal pressure variation was used to estimate the gas volume within the filter.

On 06.06.22, the extraction line from S14 (PL_S14_L1) clogged and extraction stopped. Gas injection into S02 was then halted to limit the pressure increase in S14. The extraction line from S14 (PL_S14_L1) was successfully unclogged on 08.06.22 (using BOADUS water injection into the line) after which the outflow was predominantly gas. It is likely that drainage of the filter had led to a build-up of fine material around the outlet that clogged as the water level reached the outlet.

Following gas breakthrough, control of the outflow was mostly performed using a syringe pump where the volumetric extraction could be controlled. The water produced in the outflow was separated from the gas in the mock-up tank (see Rösli et al. 2025). Fig. E-3 shows the estimated gas and water outflows from S14 during the GFT. The fraction of water decreased from a few percent immediately after unclogging on 06.06.22 to $\sim 0.1\%$ by September 2023. The total water volume extracted from S14 to 01.09.23 was ~ 690 l, the dominant part of which (>490 l) was extracted prior to 06.06.22.

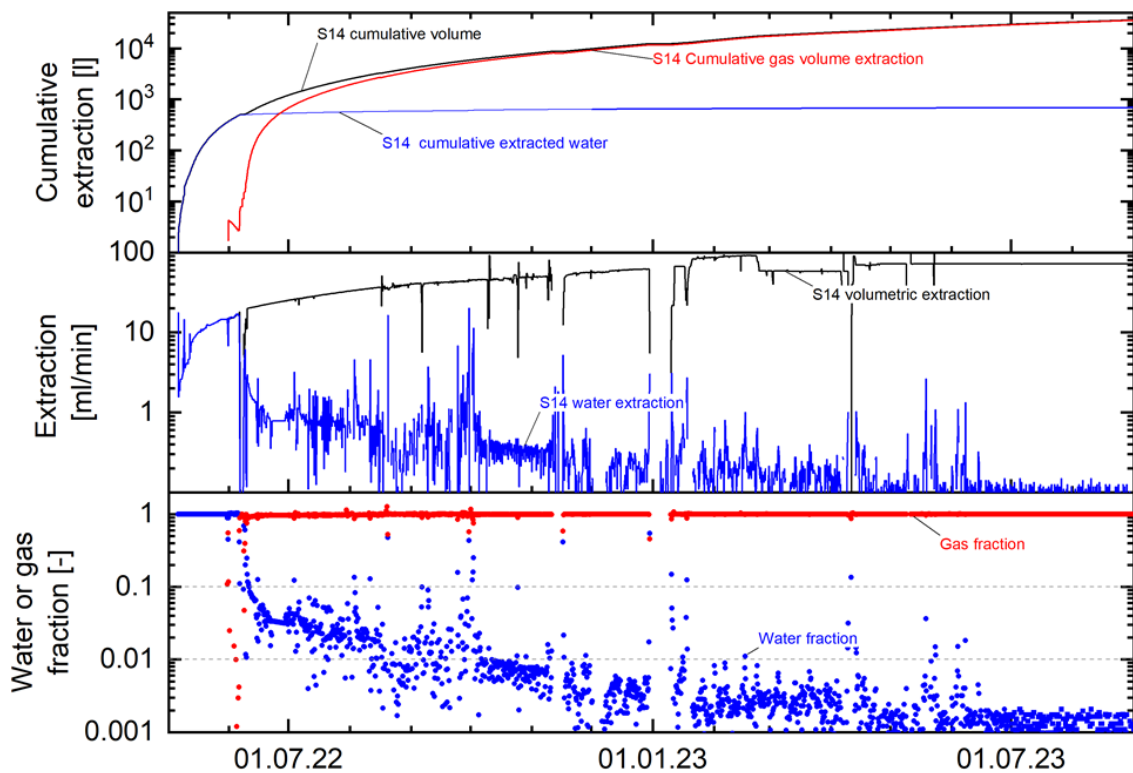


Fig. E-3: Water and gas extracted from S14

Fig. E-4 shows the produced S14 tracer gas fractions from both quantitative laboratory analyses and the qualitative monitoring (using miniRUEDI) of the gas phase of the membrane module. The gas fractions measured in May and early June 2022 correspond to dissolved gases while, after this, they largely reflect the free gas phase extracted from S14. The membrane module data typically overestimate xenon and argon fractions while underestimating the helium fraction in Gas Mix #2. The laboratory samples show an initial mixing period followed by gas concentrations corresponding closely to those of the injected gas tracers. This is consistent with the overall high estimate of recovery of injected gas.

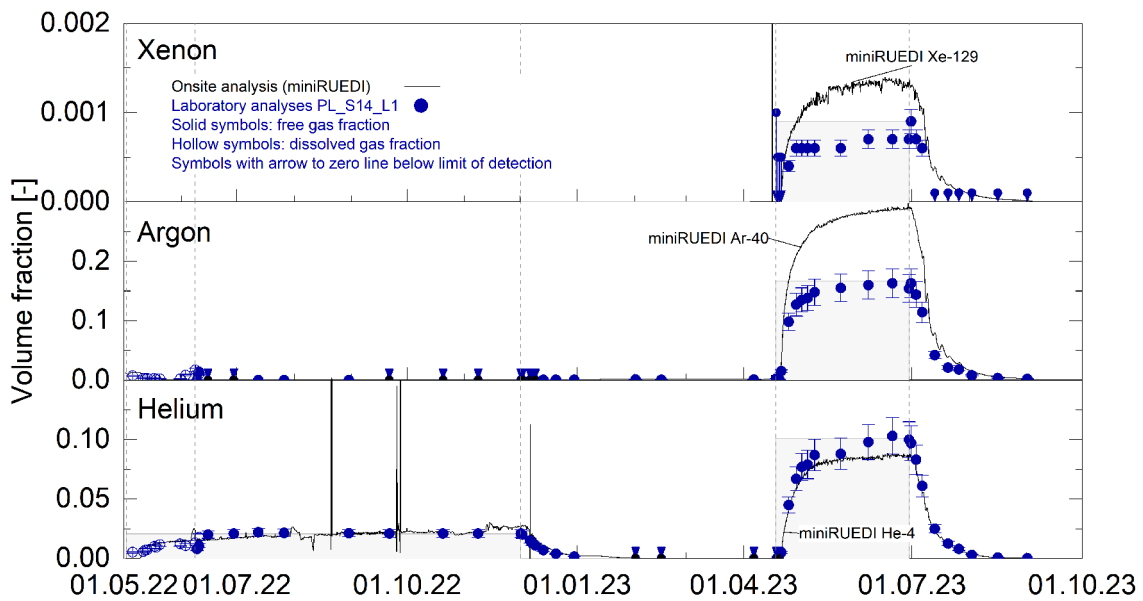


Fig. E-4: Tracer gas fraction in S14 samples and from the miniRUEDI membrane module
Grey shading shows injected gas fractions.

Fig. E-5a shows the gas tracer volume fractions from the first two months of Gas Mix #1 injection. A minor concentration of dissolved helium is already observed in one of the first samples taken on 05.05.22. Subsequent samples show a consistent increase towards the injected volume fraction once gas production from S14 starts. Argon shows a small initial decline at values around the estimated background prior to some higher values around the time of gas breakthrough, likely due to field operations involving the flushing of the PL_S14_L1 extraction line with BOADUS water.

Fig. E-5b shows the data from the end of Gas Mix #1 with a clear reduction in helium being observed within a week of switching gas injection. The tailing is likely to be influenced by mixing in both the S02 and S14 sand filters which contained relatively large volumes of gas at this point (S02 ~300 l, S14 ~650 l). The observed slight increase in argon may be due to the small percentage of argon present in the injected nitrogen see Tab. E-4.

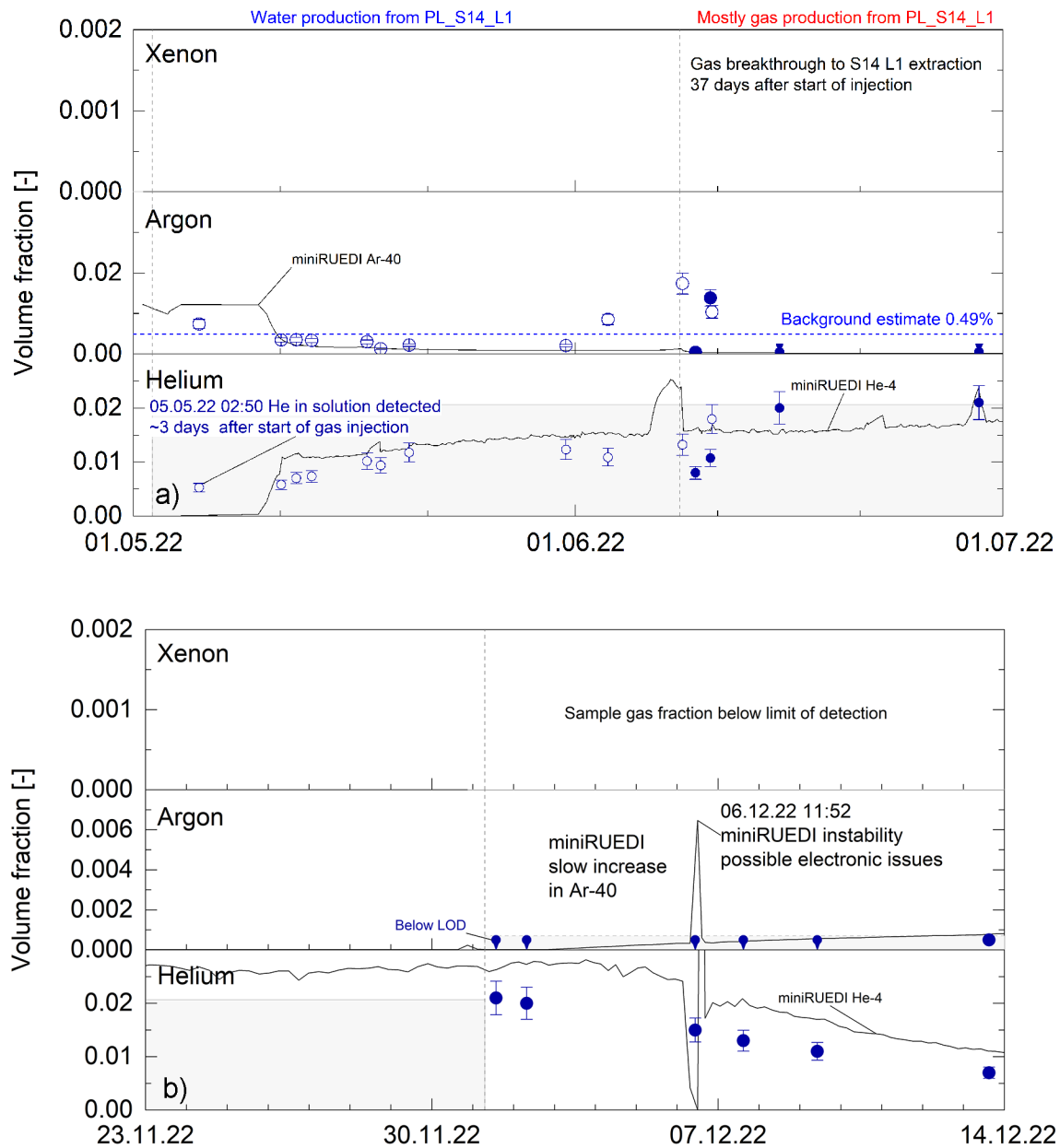


Fig. E-5: Tracer gas fractions in S14 samples for the breakthrough and tailing of Gas Mix #1
LOD: limit of detection

Fig. E-6a shows the Gas Mix #2 breakthrough. Both helium and argon start to increase within 3 days of the start of the Gas Mix #2 injection. Xenon shows a similar trend, but the early response is hidden by the relatively high limit of detection of the early samples (laboratory methods were subsequently improved for the xenon concentration measurements). A consistent pattern with a relatively fast onset of tailing is also seen in Fig. E-6b.

Overall, the S14 samples show consistent breakthroughs and tailing of the gas tracers within 3 – 5 days of the change in gas injection. After about a month, measured volume fractions reach those of the injected mixtures.

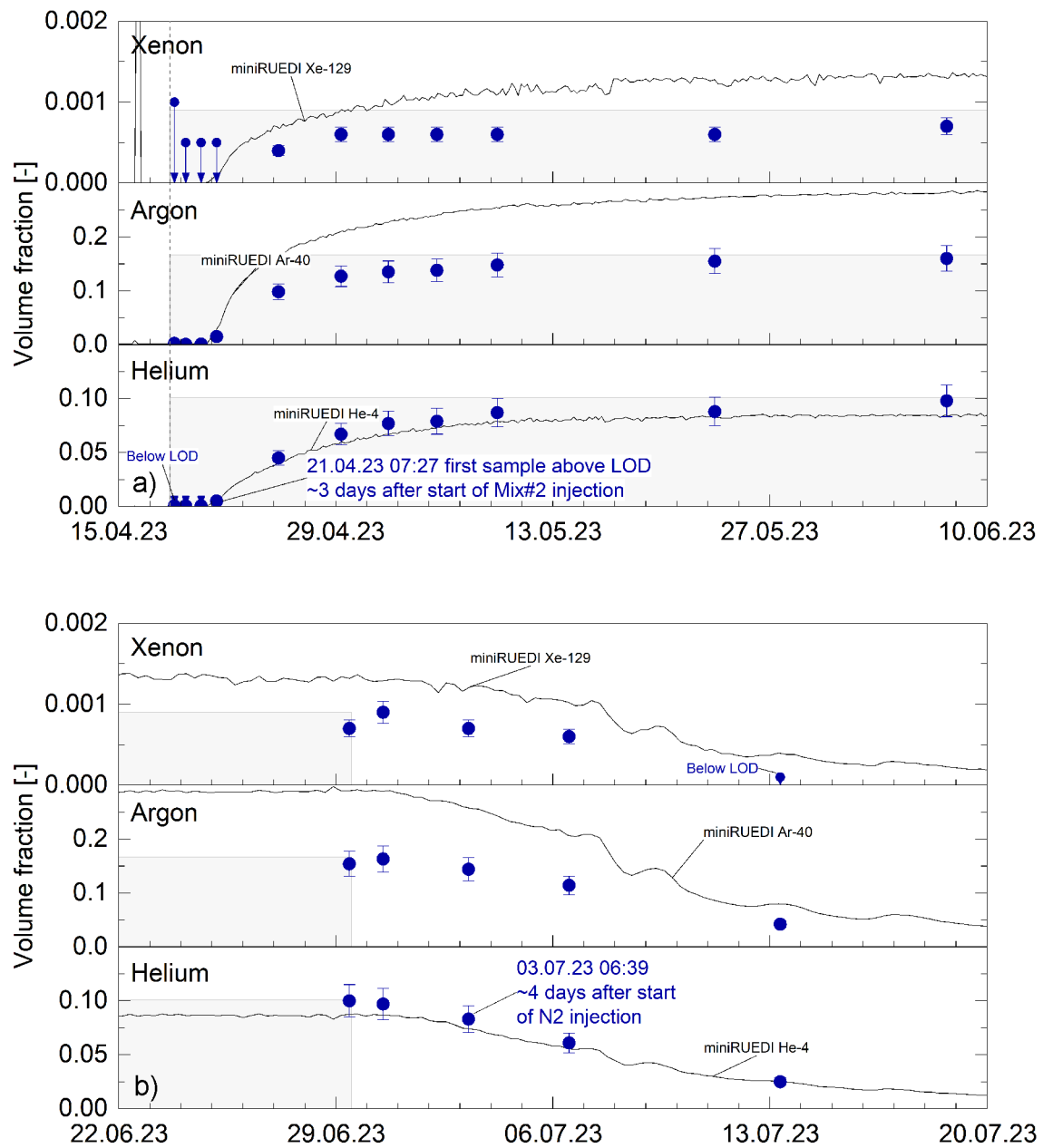


Fig. E-6: Tracer gas fractions in S14 samples for the breakthrough and tailing of Gas Mix #2

E.2.3 PPE samples

Following the tracer gas breakthrough to S14 extraction, it was decided to try to sample gas from the piezometers within the seal section to confirm and characterise the gas flow path. Previous extraction tests (e.g. the dipole test) had shown that sampling times were likely to be long due to the low permeability to water of the sand/bentonite and the relatively large line volumes (~100 ml) so that only a small number of PPEs could be sampled. Index PI/PW tests were performed on most of the PPEs between 31.05.22 and 15.06.22 as input to the selection of PPEs for sampling.

PPEs were selected on the basis of the observed pressure response to the GFT, the PI/PW response, and the previous response to GPT1 (see Tab. E-6). Sampling was started in PPE_S10_L4 on 15.06.22 immediately after the PI/PW tests. Initially, sampling was performed using the syringe pump previously controlling extraction from S14. The drawdown was limited to 900 kPa to minimise degassing effects and possible local compaction around the PPE filter. This required manual adjustment of the syringe pump flowrates. The sample was taken once the lines and equipment had been flushed by the produced fluid. In some cases, the extraction rate was so low that sampling was performed with a vacuum (PPE_S03_L3 and PPE_S07_L2). Once sampling was completed, the syringe pump was relocated to sample a different PPE. Piezometers PPE_S03_L6L-1, PPE_S06_L4 and PPE_S07_L2 were included in the sampling performed from October 2022 after the first round of PPE sampling, which took place between June and September 2022.

Tab. E-5: Initial selection of PPEs for sampling during the GFT (June 2022)

PPE	GFT reaction	PI/PW response/ compressibility	Comment
PPE_S03_L3	Y	N/A	Noisy pressure and stepped response to S02 shut-in on 06.06.22
PPE_S03_L6H-2	Y	High pre-GFT	High compressibility and previous anomalous behaviour
PPE_S06_L6H-2	Y	High pre-GFT	Gas extracted during GPT1
PPE_S08_L4	Y	No change	Gas extracted during GPT1
PPE_S09_L4	Y	No change	Additional L4 option
PPE_S10_L4	Y	Increase in compressibility	Noisy pressure, attenuated response to S14 extraction and PW response. Considered best option for sampling.

Prior to the injection of Gas Mix #2, additional syringe pumps had been acquired and it was possible to maintain a constant extraction from PPE_S06_L6H-2 and PPE_S10_L4. This allowed regular sampling during the Gas Mix #2 injection and the subsequent flushing by nitrogen. In addition to this continuous extraction and sampling, additional samples were taken from PPE_S03_L6L-1 and PPE_S08_L4 during this period.

Fig. E-7 shows the pressure and flow during sampling of PPE_S10_L4 in a) June/July 2022 when first sampled and b) during March – September 2023 when a continuous extraction was maintained. The drawdown needed to maintain a flow of ~0.01 ml/min was considerably greater for the first sample than that subsequently needed. Despite the large drawdown during the first sampling, no significant effects are seen in neighbouring piezometers.

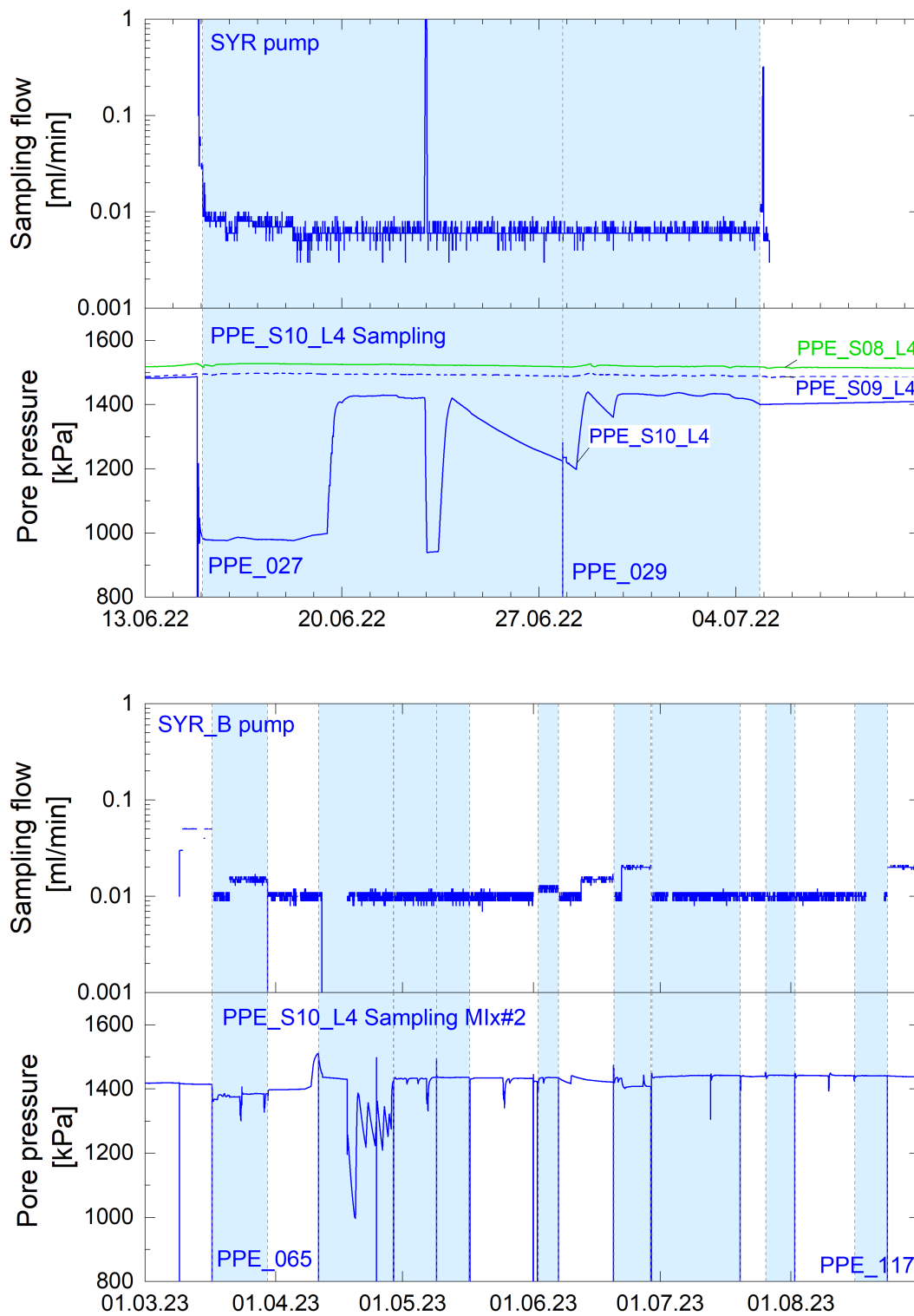


Fig. E-7: PPE_S10_L4 sampling

a) first sample during injection of Gas Mix #1, b) continuous extraction and sampling during Gas Mix #2 injection

Tab. E-6: PPEs sampled during the GFT

PPE	GFT samples	Comment
PPE_S03_L3	1	Low flow, vacuum extraction of water sample
PPE_S03_L6L-1	4	Repeat sampling of free gas phase during the GFT close to S02 injection.
PPE_S06_L4	1	Water sample
PPE_S06_L6H-2	12	Repeat sampling of produced gas during the GFT with continuous extraction from 11.04.23
PPE_S07_L2	1	Low flow, vacuum extraction of water sample. Test of extraction from L2 + comparison with the dipole test
PPE_S08_L4	5	Repeat sampling during the GFT, initially water samples but later free gas production
PPE_S10_L4	13	Repeat gas sampling during the GFT with continuous extraction from 11.04.23

Fig. E-8 shows the sample gas fractions for helium, argon and xenon for both S14 extraction and the sampled PPEs. Fig. E-8a shows the Gas Mix #1 samples. Higher helium concentration are measured in PPE_S10_L4 from June 2022, while a concentration close to the injection fraction is measured in PPE_S06_L6H-2. Samples from other piezometers are below the detection limit for helium.

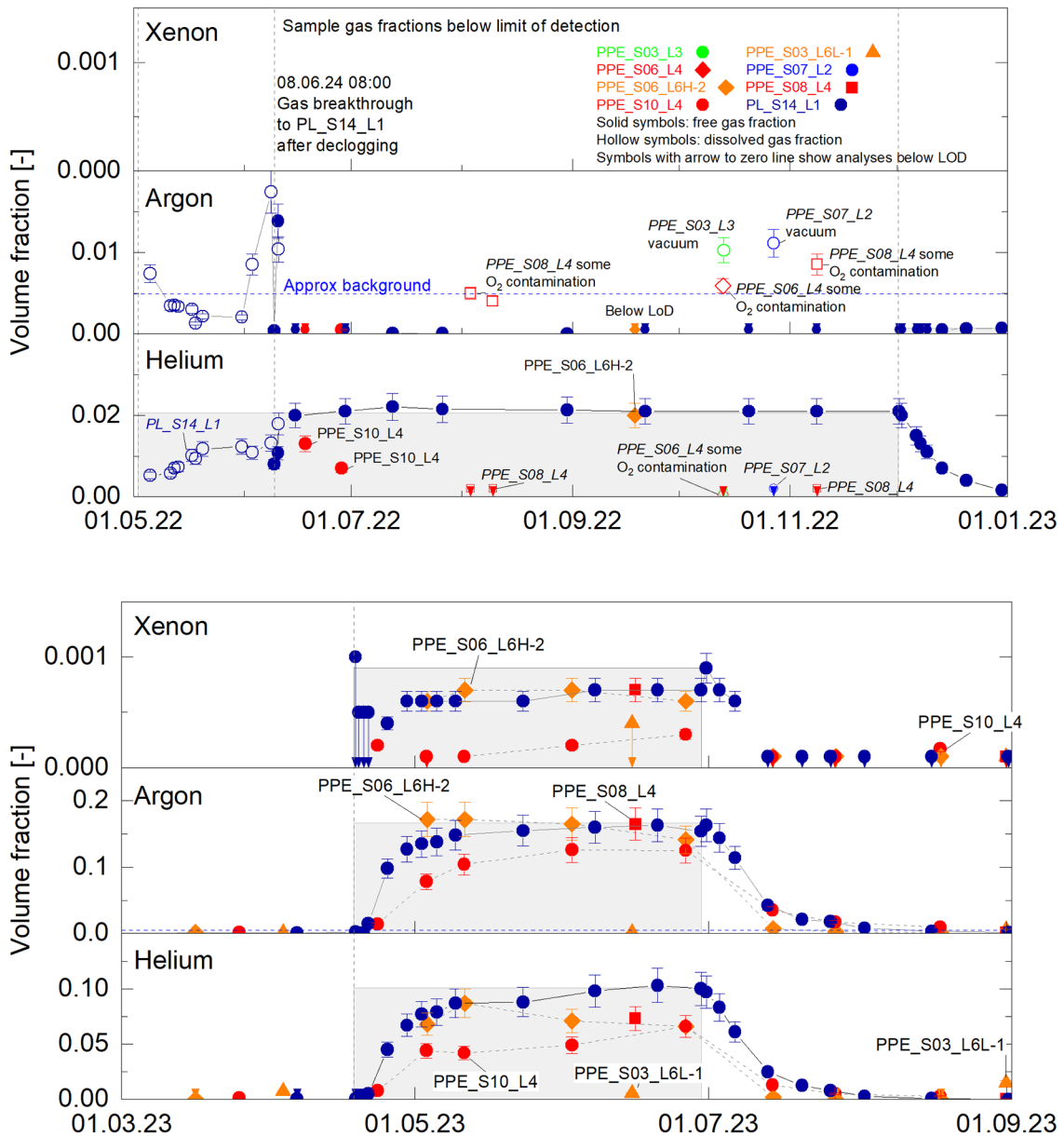


Fig. E-8: Tracer gas fractions for samples from S14 and PPEs: a) Gas Mix #1, b) Gas Mix #2
Grey shading shows injection function.

Fig. E-8b shows the Gas Mix #2 samples. All three tracer gases are detected at PPE_S06_L6H-2, PPE_S08_L4 and PPE_S10_L4. Low but measurable concentrations of helium and argon were measured at PPE_S03_L6L-1 before, during and after the Gas Mix #2 injection.

The Gas Mix #2 samples from S14 (PL_S14_L1) and the two PPEs with continuous extraction (PPE_S06_L6H-2 and PPE_S10_L4) are compared in Fig. E-9 together with “perfect mixing” curves for mixing solely in the S02 filter gas volume for the PPEs, and in both S02 and S14 filter volumes for the S14 extraction. The gas mix fractions have been normalised to the injection values (Tab. E-4). In S14, argon and helium normalised fractions are very similar in timing and value, while xenon shows a slightly lower normalised fraction.

The samples from PPE_S10_L4 show a slower and lower normalised gas fraction for all three gas tracers but more so for helium and xenon. Samples from PPE_S06_L6H_2 show a response similar to that of S14, although data are missing for the early period due to air contamination of the first sample during Gas Mix #2.

The mixing curves show a good agreement with the observed breakthrough and tailing, although the data from early S14 extraction show some small mismatch, potentially indicating gas tracer retention processes.

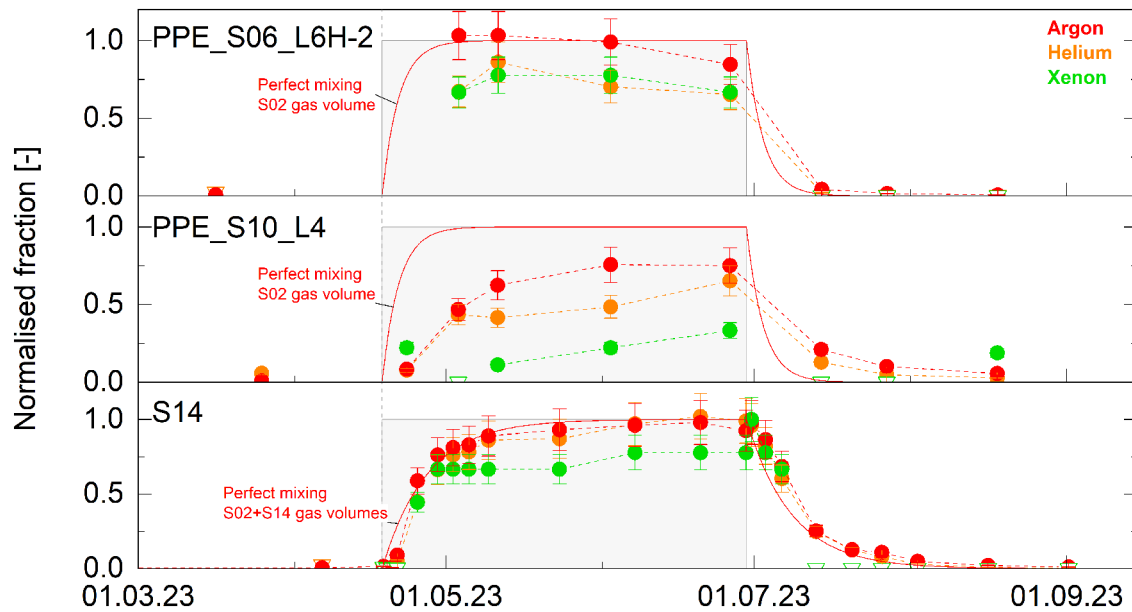


Fig. E-9: Normalised tracer gas fractions for samples from S14, PPE_S06_L6H_2 and PPE_S10_L4

The PPE sampling is summarised in Tab. E-7 and illustrated in Fig. E-10.

Tab. E-7: Summary of PPE gas sampling during Gas Mix #1 and Gas Mix #2 injection

PPE	GFT Samples	Comment
PPE_S03_L3	1	No presence of He tracer during Gas Mix #1 injection (water sample, sampled under vacuum)
PPE_S03_L6L-1	4	Free gas phase sampled. Low but measurable helium detected before, during and after Gas Mix #2, high fraction of methane.
PPE_S06_L4	1	No significant tracer detected during Gas Mix #1 injection (water sample)
PPE_S06_L6H-2	12	All samples with free gas phase. Measured gas concentrations similar to S14 extraction, reaching values of injected Gas Mix #1 and Gas Mix #2
PPE_S07_L2	1	No presence of He tracer during Gas Mix #1 injection (water sample, sampled under vacuum)
PPE_S08_L4	5	First 3 samples water, free gas in 2 later samples. High concentrations of all tracers measured during Gas Mix #2 injection, behaviour more similar to PPE_S06_L6H-2 than to PPE_S10_L4
PPE_S10_L4	13	All samples with free gas phase. Measured gas concentrations slightly lower than the S14 extraction, reaching 30 – 75% of the values of injected Gas Mix #1 and Gas Mix #2

E.3 Interpretation of gas tracer data

Transport of the gas tracers will be subject to retention by mixing with the gas phase in the S02 and S14 filters and gas path together with dissolution and diffusion in porewater. Sorption of the noble gas tracers is not expected under saturated conditions, and the high observed recovery suggest that this was not significant.

The observed gas tracer production from S14 is consistent with our understanding of one or more high-permeability gas paths between S02 and S14 with large gas volumes in the two filters that result in significant mixing.

Both the sampling and interpretation are more difficult for the PPEs. In particular:

- It was not possible to sample all PPEs.
- It is likely that the act of sampling at least locally affected the gas paths by creating local “sinks” and increasing gas saturation around the PPE filter and in the lines. Over time, repeated sampling in PPE_S08_L4 resulted in sampling of a free gas phase in the final two samples.
- Extraction of the samples was affected by the relatively large line volumes with varying flow rates and pressures, resulting in uncertainty on the delays associated with transport in the line and consequently the time that the gas was extracted from the sand/bentonite.
- Local conditions around the mm-scale PPE filter tips are likely to have influenced flow rates and local saturation.

Taking this into account, the data clearly show the presence of gas tracers in the body of the sand/bentonite and significant differences between piezometers, thus suggesting a heterogeneous gas path.

The similarity between the measured gas fractions from PPE_S06_L6H-2 and PL_S14_L1, in contrast to those from PPE_S10_L4, suggest that multiple flow paths are located between L4 and L6 with different velocities and retention (exchange with gas in solution in the porewater)

In summary, the injection and sampling of multiple gas tracers has demonstrated:

- The high recovery of injected gas from S14 and the impact of mixing in S02, S14 and, to a lesser extent, the gas pathway.
- The presence of gas paths from S02 around L6 at the top of the sand/bentonite and L4 in the body of the sand/bentonite.
- Gas paths are heterogeneous with variability in productivity and tracer concentrations even in nearby PPEs at the same level (e.g. PPE_S06_L4, PPE_S08_L4 and PPE_S01_L4).

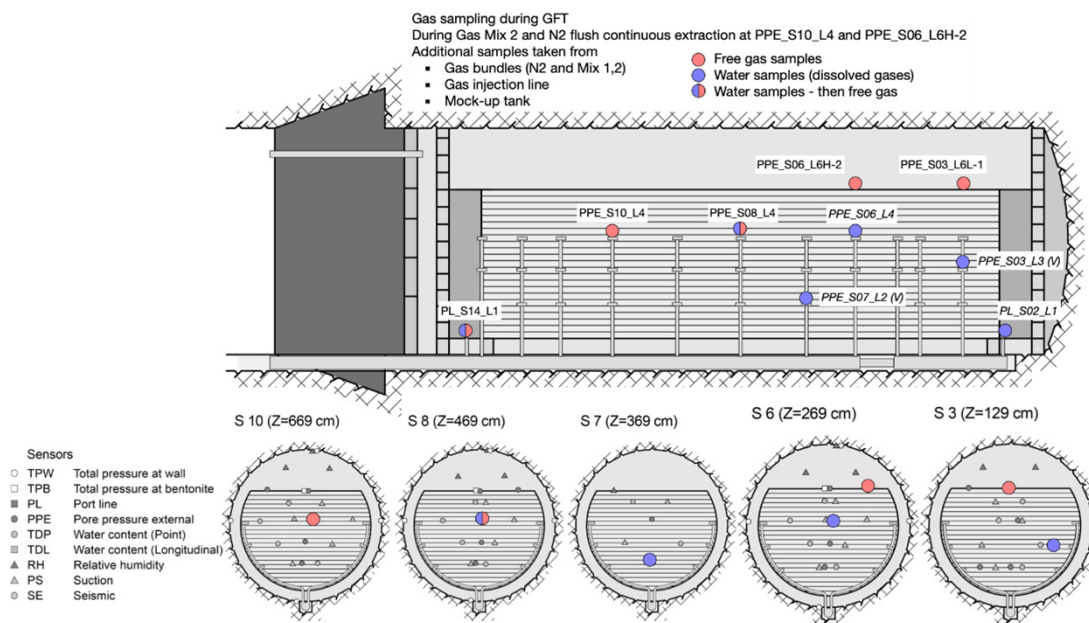


Fig. E-10: Location and types of gas sampling during the GFT

E.3.1 Methane and PPE_S03_L6L-1

Four gas samples were taken from PPE_S03_L6L-1 during the GFT. Unfortunately, the first sample was not analysable as the container was open when it arrived at the laboratory. The three later samples included helium (0.56 – 1.5%) and argon (0.11 – 0.55%), but no xenon above the limit of detection. There was, however, no clear correlation with the timing of the different gas tracer injections.

Uniformly, the gas samples contained a relatively high percentage of methane (15 – 29%). Small amounts of dissolved methane had been detected in samples from the S02 extraction at L1 (600 – 1,600 vpm), while samples from other PPEs typically contained very low methane concentrations. PPE_S08_L4 showed an initial concentration of ~3% dissolved gas which declined strongly over time (Fig. E-11) with a final free gas sample showing a fraction of only 1 vpm methane.

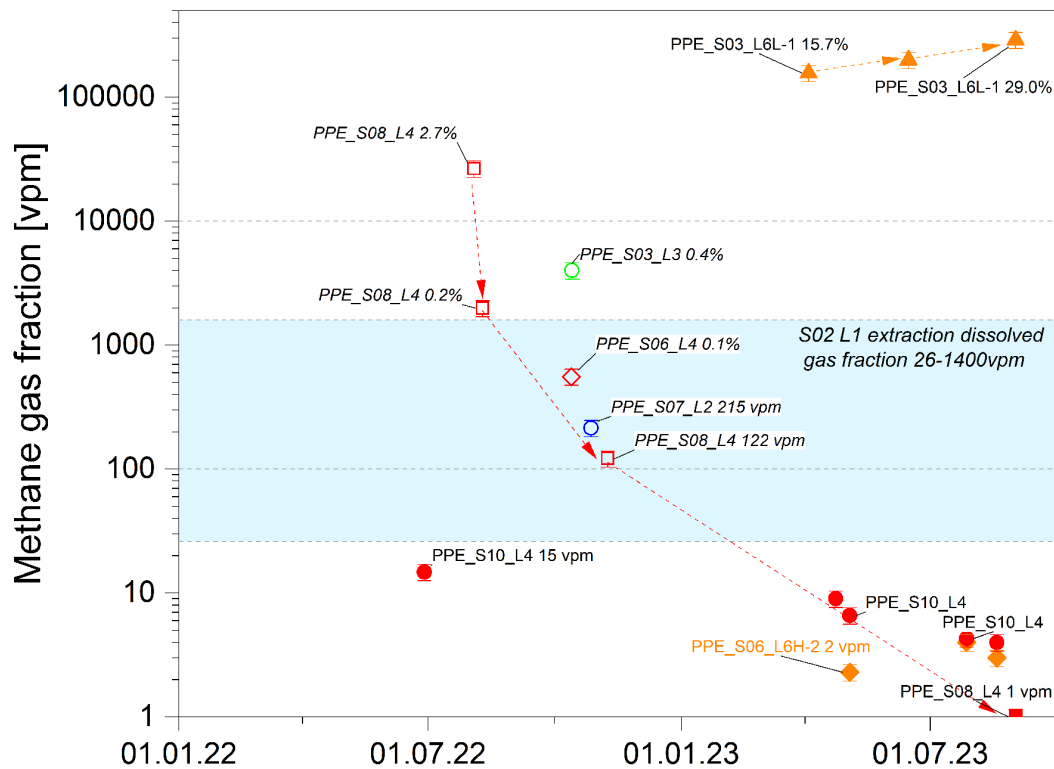


Fig. E-11: Sample methane gas fraction during the GFT (only samples above the limit of detection)

Hollow symbols dissolved gas phase. Solid symbols free gas phase.

PPE_S03_L6L-1 also showed detectable concentrations of ethane and propane. The methane is likely to have derived from methanogenesis, which is confirmed by the ^2H and ^{13}C analyses on methane (Rösli et al. 2025). Methanogenesis could have been promoted by the localised presence of organic material, perhaps related to the bentonite gel sealing of the risers or other materials used in sealing (e.g. resins in the upper instrumentation ducts or wellhead).

The increasing concentration of methane together with the low gas tracer concentrations suggest that PPE_S03_L6L-1 was sampling an isolated partially saturated zone not connected to the main GFT gas flow path but associated with local methanogenesis.

App. F TDR data

Authors: T. Sakaki, S. Schläger, G.W. Lanyon

F.1 Introduction

Time domain reflectometers were installed within the sand/bentonite (S/B) seal section to monitor changes in water content. The TDR probes are linked to a pulse generator and multiplexer by a coaxial cable. The reflection of the generated pulse is sensitive to conditions around the probe. The reflected signals (reflectogram) or traces are acquired at regular intervals and analysed to determine the travel time along the probe. Estimation of travel time is typically based on the “first derivative” calculated over a measurement window. Problems may arise from misplacement of the measurement window or from additional reflections caused by conditions along the probe and at sensor head (e.g. water invasion). As part of the interpretation work, the TDR data have been reviewed to identify possible responses to the GFT and to assess the reliability/stability of the data prior to the GFT.

A total of 30 “point” (TDP) sensors were installed within the sand/bentonite at L2, L3, L4 and L5 and a further 8 “longitudinal” (TDL) sensors were installed at S13 on the exterior of the geotextile containing the S14 sand filter. The TDLs are PE-insulated 3-wire band TDRs (TDL) with relatively long electrodes (between 0.92 and 1.3 m) aligned in the horizontal direction as in Fig. F-1(left) and Fig. F-2 to detect gas flow paths. The TDP sensors were 3-rod TDRs with short metal rods (0.3 m, Fig. F-1 right). Those sensors were horizontally emplaced at various positions within the layered sand/bentonite body (as in Fig. F-3 - Fig. F-4) for point measurements (TDP) to observe local water saturation in the S/B seal. The position coordinates and length of the TDL and TDP sensors are tabulated in Tab. F-1.



Fig. F-1: TDR sensors. Left) TDLs at S13, right) TDP

From Rüedi et al. (2012)

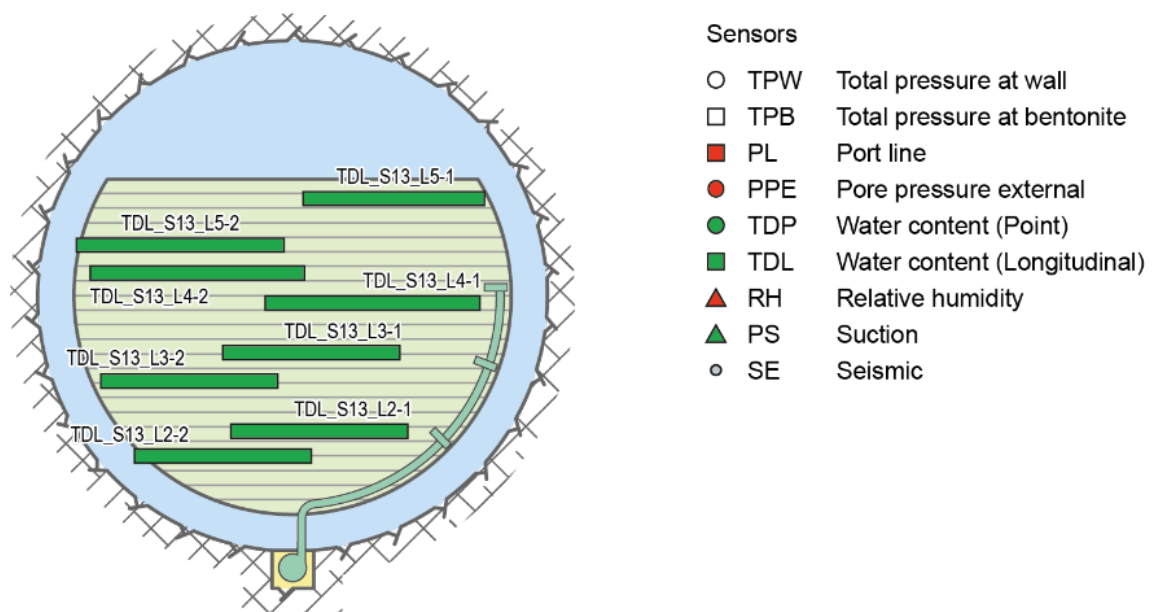


Fig. F-2: Cross-sectional view of the TDL sensor positions at S13

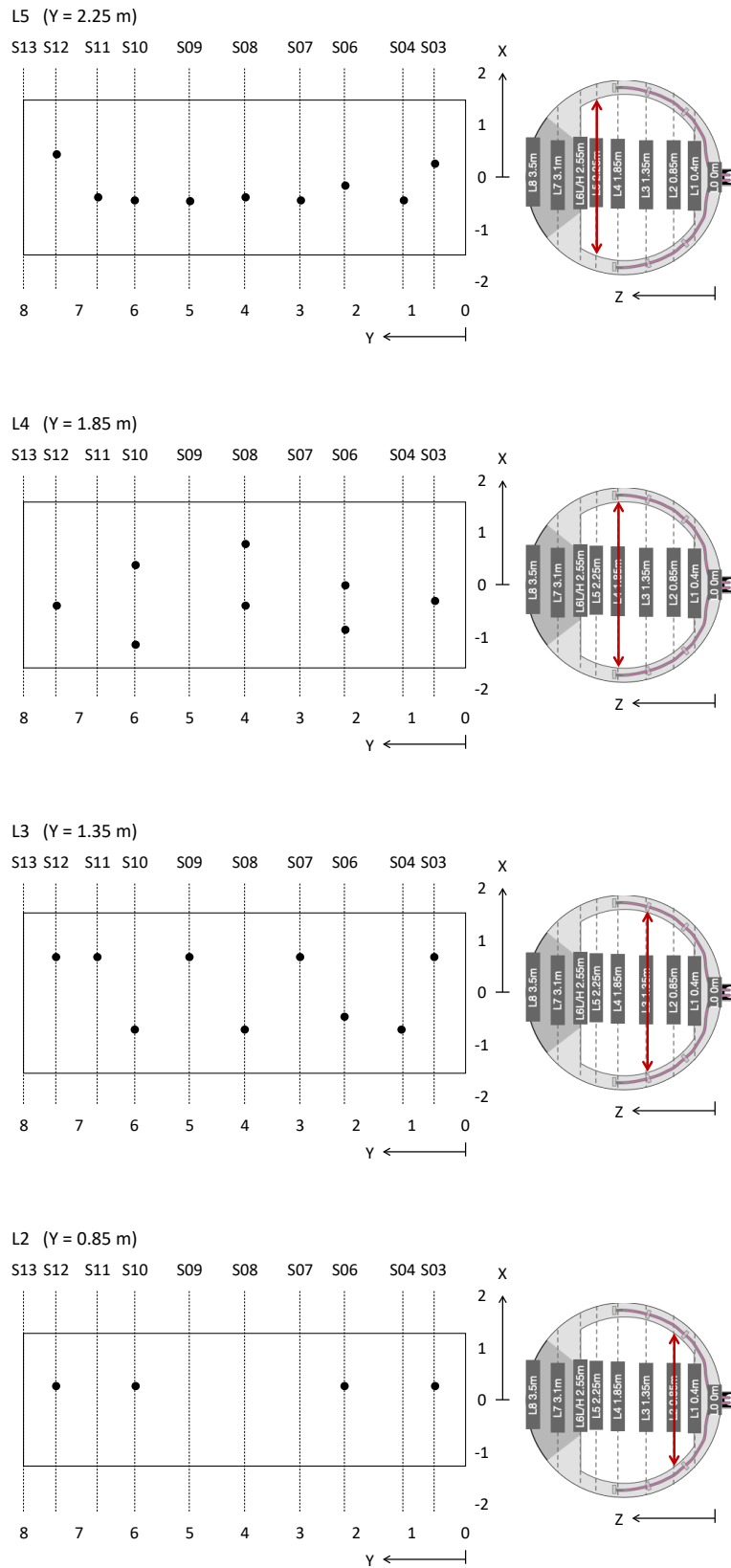


Fig. F-3: Plan view of TDP positions in layers L2, L3, L4 and L5

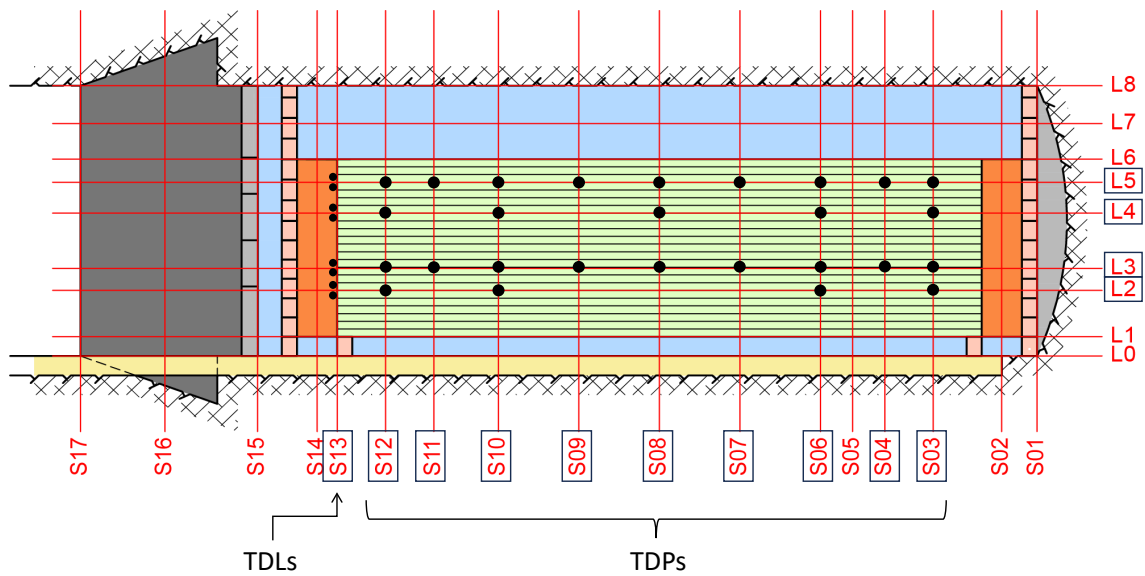


Fig. F-4: Side view of the positions of the TDLs and TDPs

Tab. F-1: Position and length of the TDL and TDP sensors

Sensor	Section	Level	X [m]	Z [m]	Y [m]	Length [m]	
TDL_S13_L2-1	S13	L2	0.16	8.77	0.84	0.92	
TDL_S13_L2-2	S13	L2	-0.49	8.77	0.66	0.92	
TDL_S13_L3-1	S13	L3	0.13	8.71	1.37	1.2	Failed
TDL_S13_L3-2	S13	L3	-0.71	8.72	1.18	1.2	
TDL_S13_L4-1	S13	L4	0.55	8.74	1.72	1.3	
TDL_S13_L4-2	S13	L4	-0.65	8.7	1.92	1.3	
TDL_S13_L5-1	S13	L5	-0.7	8.74	2.43	1.3	
TDL_S13_L5-2	S13	L5	-0.78	8.71	2.11	1.3	
TDP_S03_L2	S03	L2	0.246	1.283	0.849	0.3	
TDP_S03_L3	S03	L3	0.64	1.36	1.34	0.3	
TDP_S03_L4	S03	L4	-0.26	1.38	1.86	0.3	
TDP_S03_L5	S03	L5	0.24	1.37	2.27	0.3	
TDP_S04_L3	S04	L3	-0.64	1.95	1.36	0.3	
TDP_S04_L5	S04	L5	-0.35	1.79	2.28	0.3	
TDP_S06_L2	S06	L2	0.15	2.697	0.87	0.3	
TDP_S06_L3	S06	L3	-0.4	2.93	1.37	0.3	
TDP_S06_L4-1	S06	L4	0.01	2.81	1.9	0.3	
TDP_S06_L4-2	S06	L4	-0.84	3.1	1.87	0.3	
TDP_S06_L5	S06	L5	-0.09	2.92	2.28	0.3	
TDP_S07_L3	S07	L3	0.66	3.76	1.35	0.3	
TDP_S07_L5	S07	L5	-0.44	3.56	2.3	0.3	
TDP_S08_L3	S08	L3	-0.65	4.6	1.37	0.3	
TDP_S08_L4-1	S08	L4	0.77	4.82	1.9	0.3	
TDP_S08_L4-2	S08	L4	-0.33	4.87	1.91	0.3	
TDP_S08_L5	S08	L5	-0.39	4.58	2.33	0.3	
TDP_S09_L3	S09	L3	0.61	5.91	1.35	0.3	
TDP_S09_L5	S09	L5	-0.43	5.56	2.31	0.3	
TDP_S10_L2	S10	L2	0.275	6.63	0.863	0.3	
TDP_S10_L3	S10	L3	-0.64	6.71	1.34	0.3	
TDP_S10_L4-1	S10	L4	0.28	6.84	1.92	0.3	
TDP_S10_L4-2	S10	L4	-1.05	6.57	1.85	0.3	
TDP_S10_L5	S10	L5	-0.41	6.75	2.27	0.3	
TDP_S11_L3	S11	L3	0.65	7.44	1.34	0.3	
TDP_S11_L5	S11	L5	-0.36	7.42	2.24	0.3	
TDP_S12_L2	S12	L2	0.3	8.05	0.893	0.3	
TDP_S12_L3	S12	L3	0.67	8.12	1.34	0.3	
TDP_S12_L4	S12	L4	-0.3	8.09	1.91	0.3	
TDP_S12_L5	S12	L5	0.32	8.1	2.21	0.3	

F.1.1 Potential mechanisms for water content change around TDRs

TDR traces and calculated travel time are sensitive to the local water content around the probe. The potential mechanisms for water content change are listed in Tab. F-2. Although there is currently no material specific calibration for the TDRs in the sand/bentonite or at the filter-sand/bentonite interface, an increase in water content change can be expected to result in an increased change in tracer and travel time. As injected gas penetrated through the S/B seal and reached the S14 sand filter, TDLs at S13 responded, indicating a change in water content within a relatively short period of time (during GFT Phases 3, 4 and 5). However, TDP responses are less straightforward to interpret. The clear TDL responses are probably due to large saturation changes in the S14 sand filter (drainage and resaturation) while saturation changes in the S/B are likely to be localised and of smaller magnitude (see Tab. F-2).

Tab. F-2: Possible mechanisms for water content change during the GFT

Material	Mechanism	Water content	Travel time	Comment
Sand/bentonite	Wetting	Increase	Increase	Limited extent due to expected high saturation prior to the GFT
	Drying	Decrease	Decrease	Limited extent unless “dry” gas can enter directly into S/B.
	Gas path creation	Decrease	Decrease	Likely small change due to exclusion of gas from microporosity
	Compaction	Decrease	Decrease	Controlled by effective stress changes. Increased pore pressure due to water expulsion from the gas path would reduce effective stresses and result in small increase in porosity/water content
	Dilation	Increase	Increase	
Sand filter	Drainage	Decrease	Decrease	Potentially significant changes in water content
	Resaturation	Increase	Increase	

F.1.2 Time periods for gas and water injections

In order to better illustrate how the sensors behaved during the key phases, the TDR traces and travel time data are presented for three selected time periods shown below. For each period, TDR traces from the red-circled dates in Fig. F-5 are presented.

- gas injection period 1 (short) during Phases 3, 4 and 5
- gas injection period 2 (long) from Phases 1 through 10
- water injection period during Phase 11

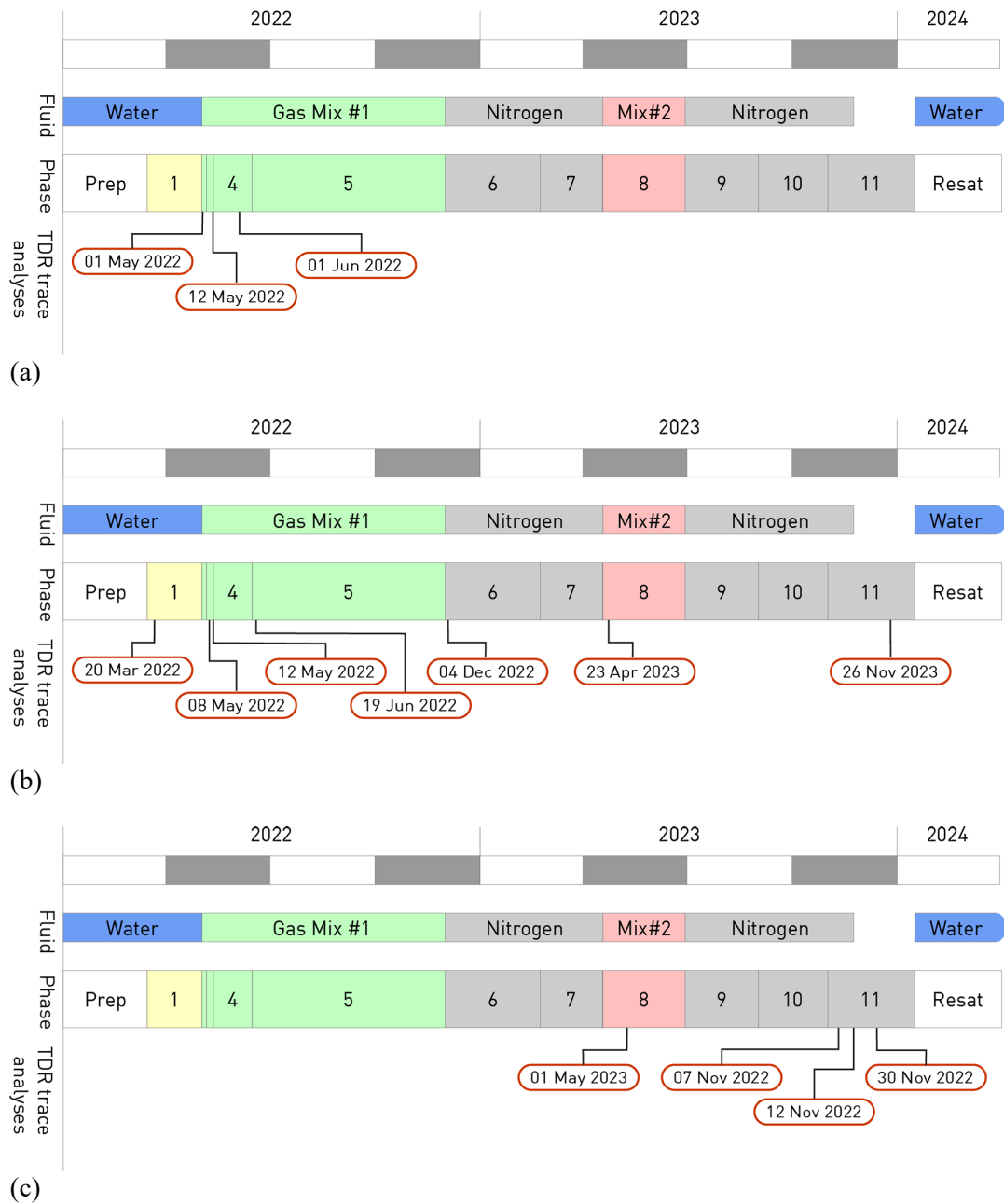


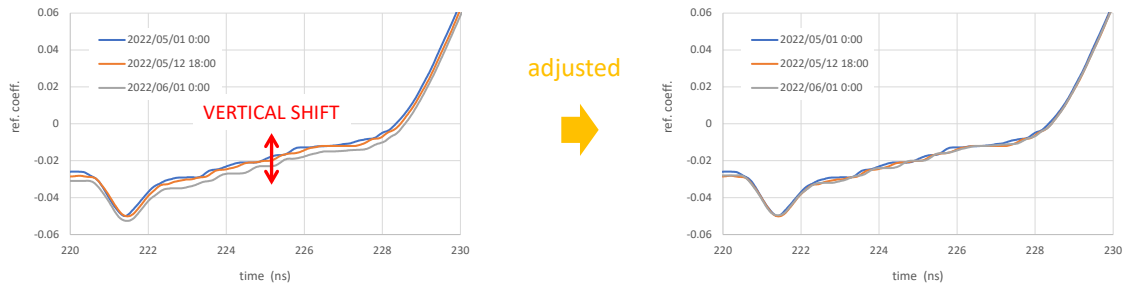
Fig. F-5: Dates for TDR traces analysed

(a) short gas injection period, (b) Long gas injection period, (c) water injection period. Traces for the red-circled dates were plotted and analysed.

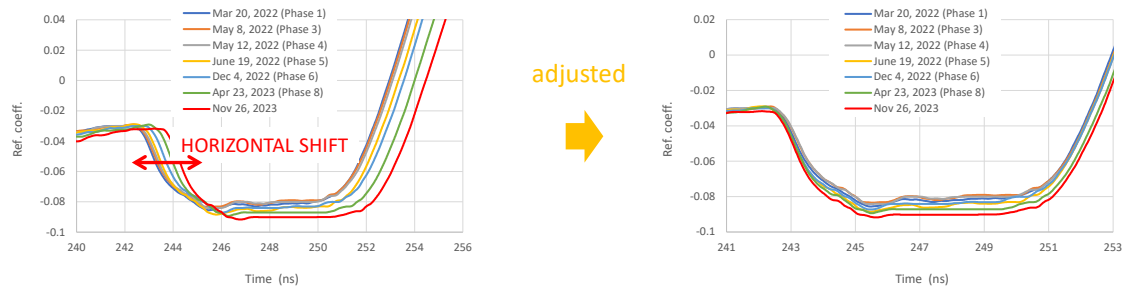
F.1.3 Adjustment of TDR traces for drift/shift over time

Some of the TDR traces showed drift/shift over time. To accurately identify whether or not the TDR traces showed a change due to the gas/water flow that might have developed near the sensors, the raw TDR traces were first checked for time drift/shift. If such a drift/shift was recognised, the traces were adjusted. The observed drift was mainly classified into three types as described below (Fig. F-6): vertical shift, horizontal shift, and both. When either of these types was observed, the traces were manually adjusted by offsetting in the corresponding direction(s).

a) Vertical shift



b) Horizontal shift



c) Vertical and horizontal shifts

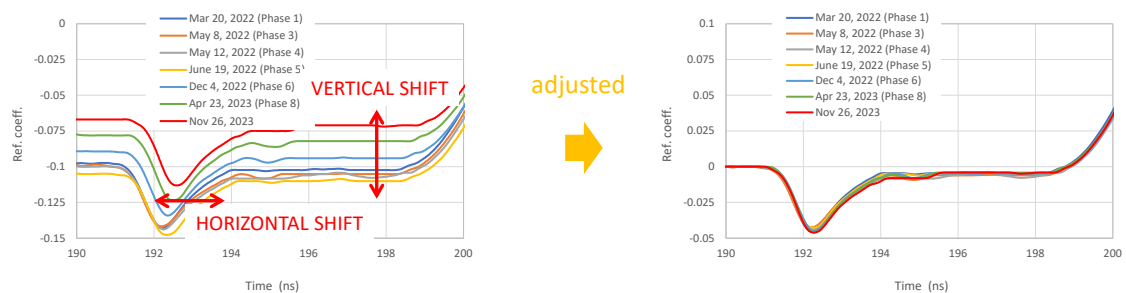


Fig. F-6: Adjustment of drift/shift in the traces with time

F.1.4 Travel time calculation

Travel time (TT) for the electromagnetic pulse to propagate between the start and end of the TDR electrodes is automatically calculated. In this report the TT results for the relevant GFT phases were also presented in the next section.

F.2 TDR stability prior to the GFT

The travel time results are presented in two time periods covering; a) the entire experimental period from 2012, and b) 2022 onwards (GFT period). Before analysing the TDR waveforms from the GFT phases presenting the main interest of this report, waveforms during the period prior to the GFT were examined (Fig. F-7). The different phases shown are:

- saturation phase 1: July 2012 – January 2014
- saturation phase 2: September 2015 – December 2018
- resaturation phase: January 2018 – December 2020
- equilibration phase: December 2020 – May 2022

The results of this waveform examination during the resaturation and equilibration phases are summarised in the next section with the objective of assessing the pre-GFT saturation state of the sand/bentonite. Stable high values of travel time, together with stability of the TDR traces, are taken to indicate high saturation.

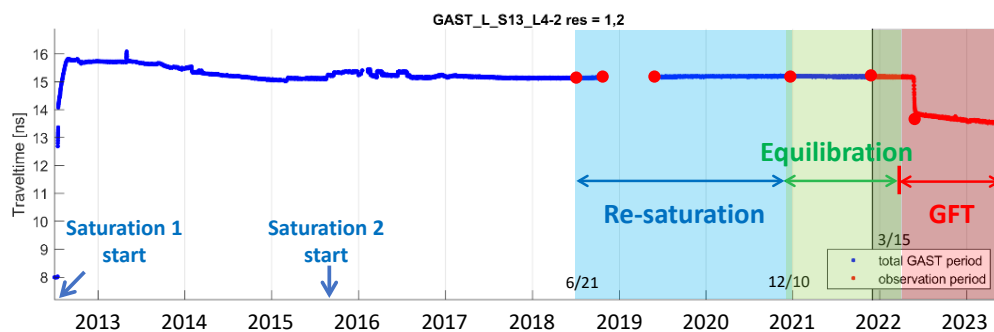


Fig. F-7: Resaturation and equilibration phases prior to the GFT phases

F.2.1 Assessment of stability/reliability

In the original waveform processing, signal quality identification numbers were defined in Schlaeger & Spillmann (2015) and used here to indicate the reliability of the trace data and travel time.

1. perfect analysis
2. good analysis
3. vague analysis, initial offset
4. vague analysis, window mismatch
5. no analysis, noisy data
6. no analysis, short circuit
7. no analysis, open circuit

These values were subsequently grouped into three groups in term of reliability: good (1 and 2), vague (3 and 4), and poor (5, 6 and 7). Fig. F-8 and Fig. F-9 show the travel time, signal quality and TDR traces for TDP_S10_L5 and TDP_S11_L5 as examples. TDP_S10_L5 shows poor to

fair stability during the resaturation and equilibration period but poor stability during the GFT. In contrast, TDP_S11_L5 shows valid travel times and good signal stability throughout the monitoring period from saturation to the GFT.

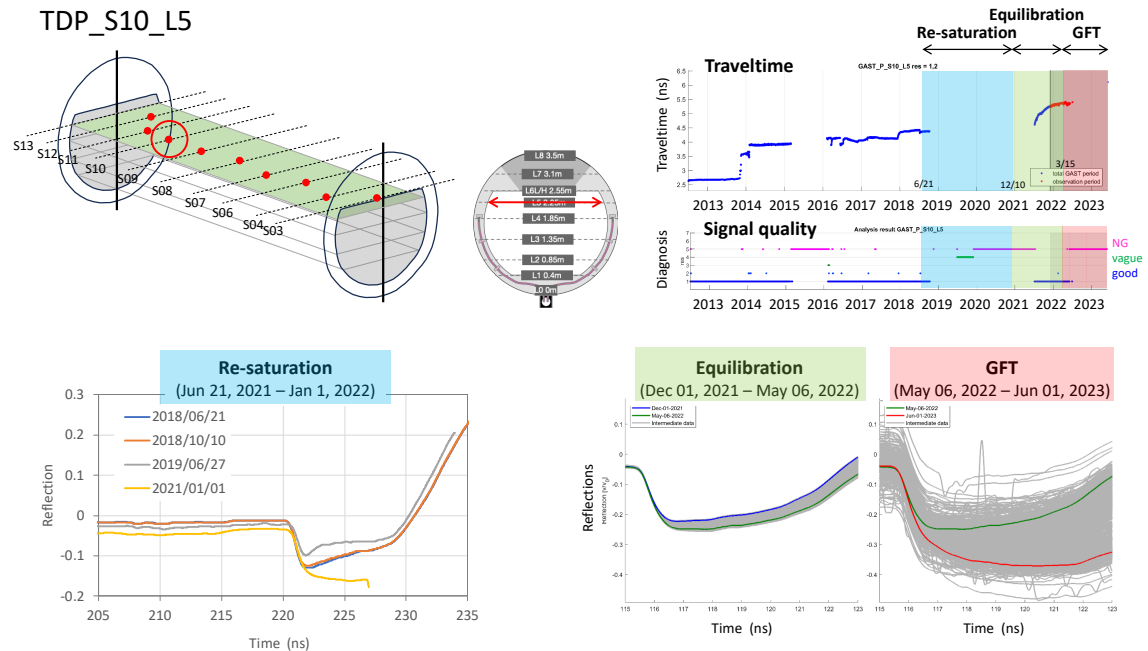


Fig. F-8: Stability assessment for TDP_S10_L5

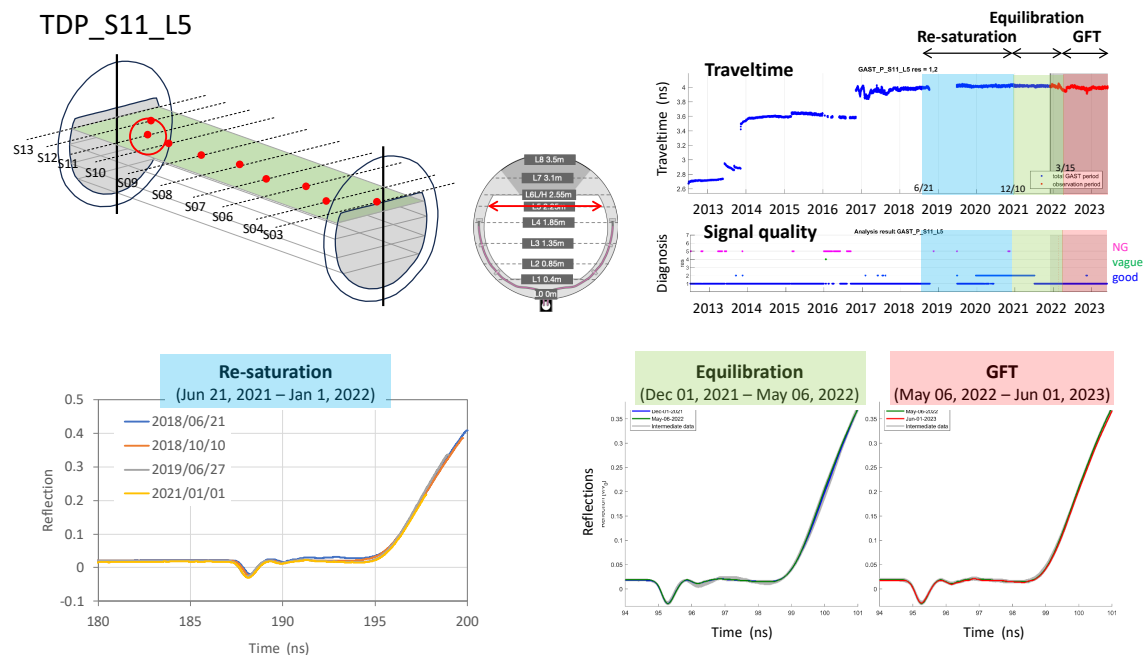
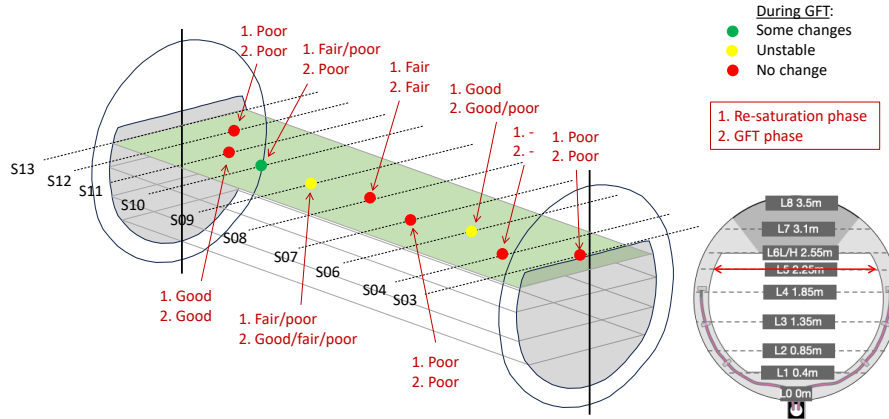


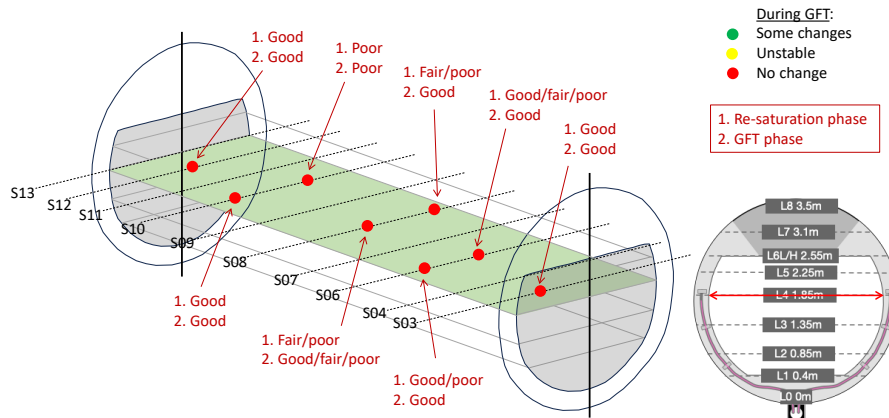
Fig. F-9: Stability assessment for TDP_S11_L5

Fig. F-10 summarises the reliability/stability estimates for the TDPs at the different levels (L2 – L5) for both the resaturation phase and the GFT.

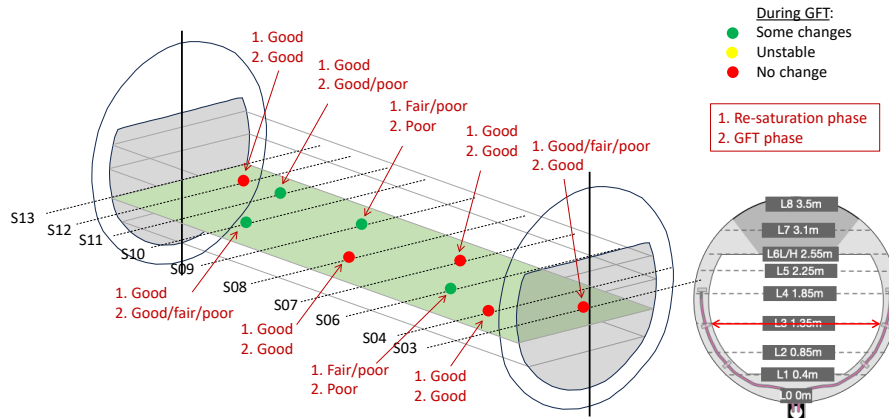
a)



b)



c)



d)

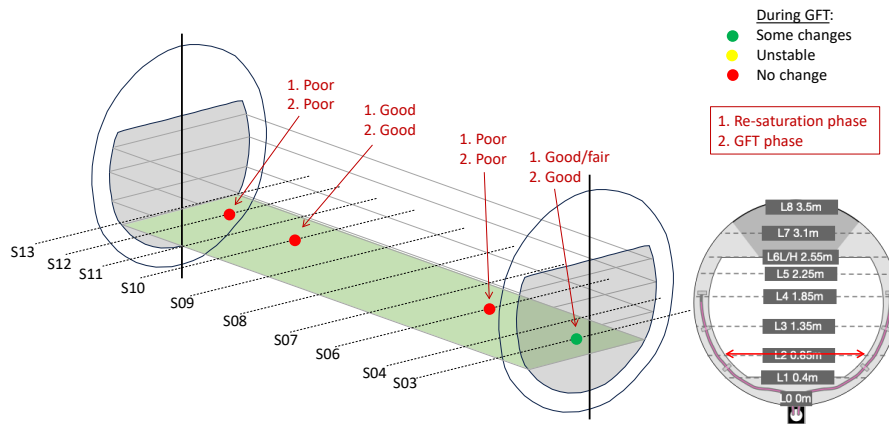


Fig. F-10: Summary of TDP stability/reliability: a) L5, b) L4, c) L3, d) L2

The quality of the TDR data for TDPs and TDLs is summarised in Tab. F-3. TDPs that showed some changes during the GFT phases were found to have either good or fair/poor stability/reliability. In L3, for example, two were good, while two were not. TDPs that showed “no changes” ranged from good to poor. All TDLs were in good condition except for L3-1. It is worth noting that during the resaturation phase, only some sensors showed a minor increase in travel time.

The waveforms prior to the resaturation phase indicated that water content in the S/B seal significantly increased during the initial saturation Phases 1 and 2. Therefore, before initiating the GFT phases, it can be concluded that the S/B seal had been close to full saturation.

Tab. F-3: Summary of the stability/reliability of TDPs and TDLs

Sensor	Section	Level	Resaturation/equilibration	GFT	Remark
TDP_S03_L2	S03	L2	Good/fair	Good	
TDP_S03_L3	S03	L3	Good/fair/poor	Good	
TDP_S03_L4	S03	L4	Good	Good	
TDP_S03_L5	S03	L5	Poor	Poor	Failed
TDP_S04_L3	S04	L3	Good	Good	
TDP_S04_L5	S04	L5	n/a	n/a	
TDP_S06_L2	S06	L2	Poor	Poor	Failed
TDP_S06_L3	S06	L3	Fair/poor	Poor	
TDP_S06_L4-1	S06	L4	Good/poor	Good	
TDP_S06_L4-2	S06	L4	Good/fair/poor	Good	
TDP_S06_L5	S06	L5	Good	Good/poor	
TDP_S07_L3	S07	L3	Good	Good	
TDP_S07_L5	S07	L5	Poor	Poor	Failed
TDP_S08_L3	S08	L3	Good	Good	
TDP_S08_L4-1	S08	L4	Fair/poor	Good/fair/poor	
TDP_S08_L4-2	S08	L4	Fair/poor	Good	
TDP_S08_L5	S08	L5	Fair	Fair	
TDP_S09_L3	S09	L3	Fair/poor	Poor	
TDP_S09_L5	S09	L5	Fair/poor	Good/fair/poor	
TDP_S10_L2	S10	L2	Good	Good	
TDP_S10_L3	S10	L3	Good	Good/fair/poor	
TDP_S10_L4-1	S10	L4	Good	Good	
TDP_S10_L4-2	S10	L4	Poor	Poor	Failed
TDP_S10_L5	S10	L5	Fair/poor	Poor	
TDP_S11_L3	S11	L3	Good	Good/poor	
TDP_S11_L5	S11	L5	Good	Good	
TDP_S12_L2	S12	L2	Poor	Poor	Failed
TDP_S12_L3	S12	L3	Good	Good	
TDP_S12_L4	S12	L4	Good	Good	
TDP_S12_L5	S12	L5	Poor	Poor	Failed

Tab. F-3: Cont.

Sensor	Section	Level	Resaturation/equilibration	GFT	Remark
TDL_S13_L2-1	S13	L2	Good	Good	
TDL_S13_L2-2	S13	L2	Good	Good	
TDL_S13_L3-1	S13	L3	Poor	Poor	Failed
TDL_S13_L3-2	S13	L3	Good	Good	
TDL_S13_L4-1	S13	L4	Good/fair/poor	Good	
TDL_S13_L4-2	S13	L4	Good	Good	
TDL_S13_L5-1	S13	L5	Good	Good	
TDL_S13_L5-2	S13	L5	Good	Good	

F.3 TDP responses during the GFT

The GFT period is split into two parts. Fig. F-11 shows an example of Part 1 (GFT Phases 2, 3 and 4) and Part 2 (GFT Phases 1 – 11) periods.

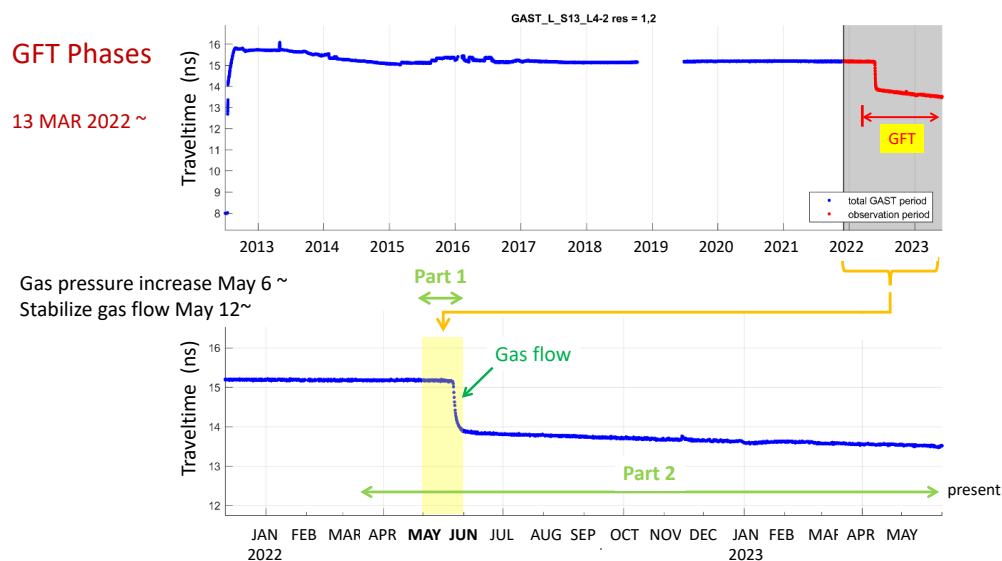


Fig. F-11: Example of travel time plot for the GFT phases

The GFT phases are shown in the grey-shaded region. Part 1: covers Phases 2, 3 and 4, while Part 2 covers Phases 1 – 11.

During the GFT phases, the majority of the TDPs showed no recognisable changes. In this section, the results from the remaining sensors with some changes are presented. In the results, the position of the sensor (upper left), TT (upper right), traces during Phases 2, 3 and 4 (lower left) and traces during Phases 1 – 11 (lower right) are presented.

F.3.1 TDP sensors showing instability during gas injection

At the two TDP sensors S06_L5 and S09_L5, the TDR traces became unstable. Note that these sensors did *not* show a sign of gas flow near the sensor positions during Phases 2, 3 and 4. The TT shown in the upper right exhibited scatter, which also supports the instability of these sensors. The changes in the shape of the traces suggest that some technical issues could have occurred to these sensors (e.g. water intrusion).

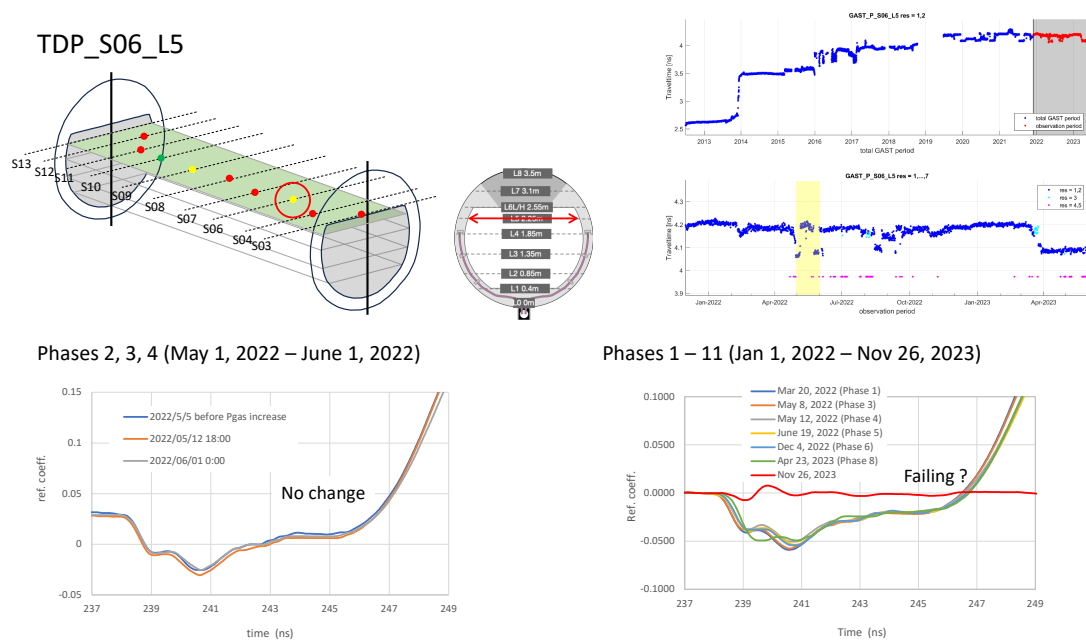


Fig. F-12: TDR sensor showing instability during the GFT phases (TDP_S06_L5)

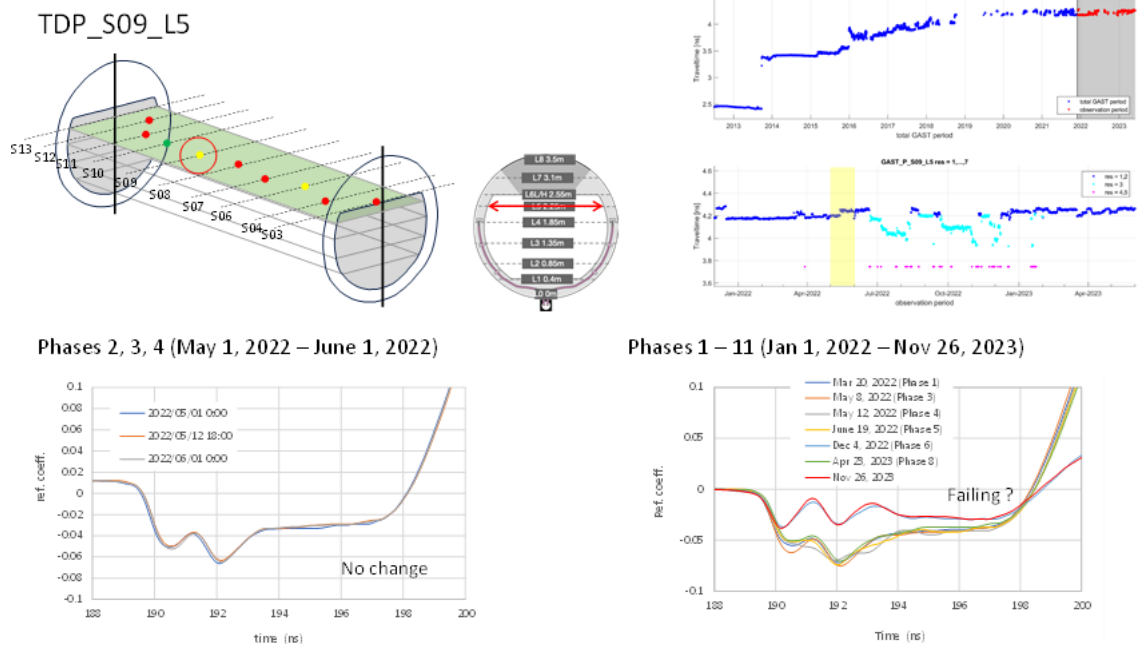


Fig. F-13: TDR sensor showing instability during the GFT phases (TDP_S09_L5)

F.3.2 TDP sensors showing changes during gas injection

Several TDPs showed changes in the TDR traces which could be due to changes in the moisture conditions around the sensors. Those are presented and discussed below.

TDP_S03_L2 is located near the bottom of the S/B seal and about 0.6 m from the S02 filter (gas injection at L6). Although TT did not show a clear change during Phases 2, 3 and 4 (yellow-shaded), the changes in the TDR traces indicated slow wetting of the S/B around the sensor (Fig. F-14). Although difficult to see, the TT (upper-right figure) seems to be increasing slowly during the entire GFT phases, which is consistent with the changes in the TDR traces (lower-right figure).

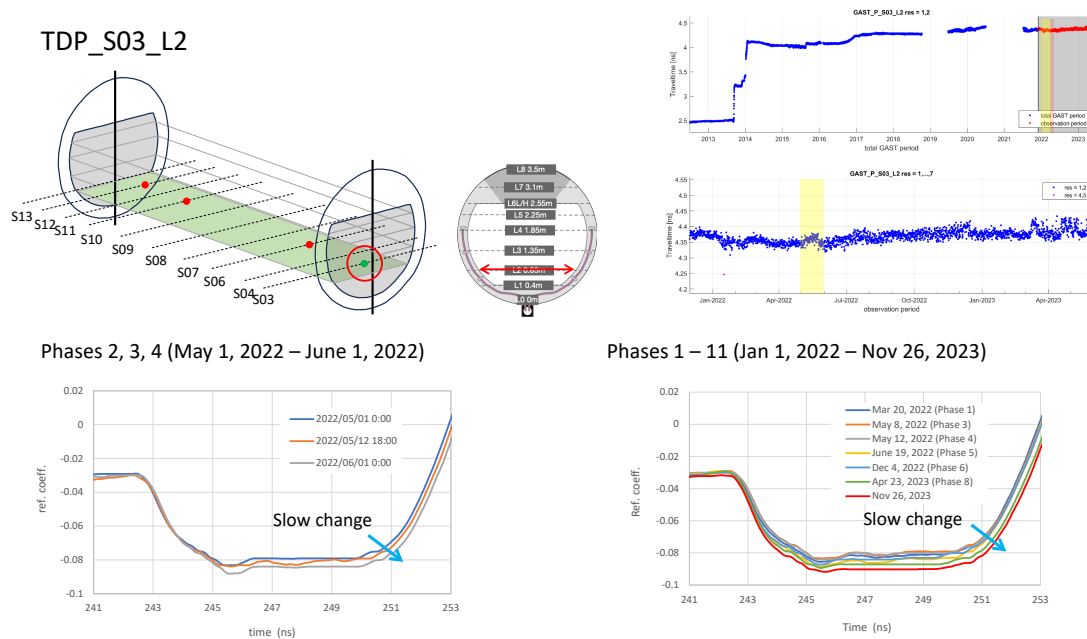


Fig. F-14: TDR sensor showing changes during the GFT phases (TDP_S03_L2)

TDP_S06_L3 traces showed changes that could have resulted from changes in the conditions of both gas and water (Fig. F-15). During Phases 2, 3 and 4, there was no change in TT (yellow-shaded) and traces (lower left). In Phase 6, however, the trace indicated desaturation around the sensor which was also confirmed in the relatively sudden decrease in TT (upper right). Also noticeable change is that from Phase 5 to Phases 6 to 8, the traces indicated S/B wetting. This was indeed confirmed in the gradual increase in TT (green-shaded).

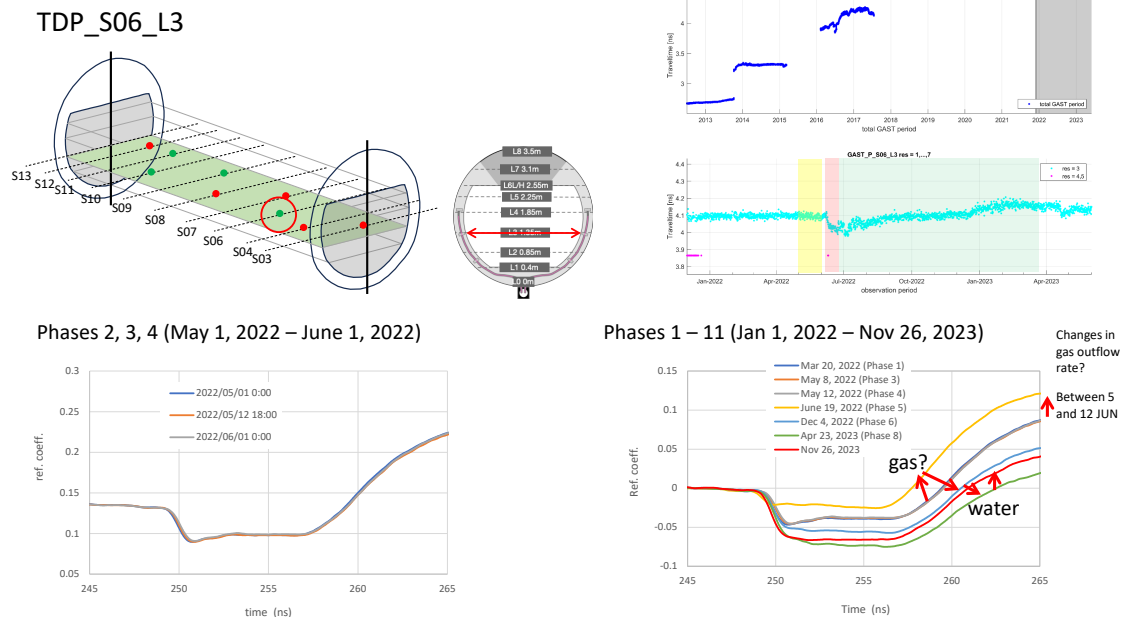


Fig. F-15: TDR sensor showing changes during the GFT phases (TDP_S06_L3)

TDP_S09_L3 showed no changes during Phases 2, 3 and 4 (Fig. F-16). Over time, the changes in the TDR trace shape could indicate possible changes in the moisture conditions in the S/B around the sensor. The general trend that the traces exhibited mainly indicated gradual wetting of the S/B. The TT, on the other hand, showed a contradictory trend where TT slowly decreased with time. This made the interpretation difficult, however, the S/B seal at this position could have been experiencing some changes due to the gas injection.

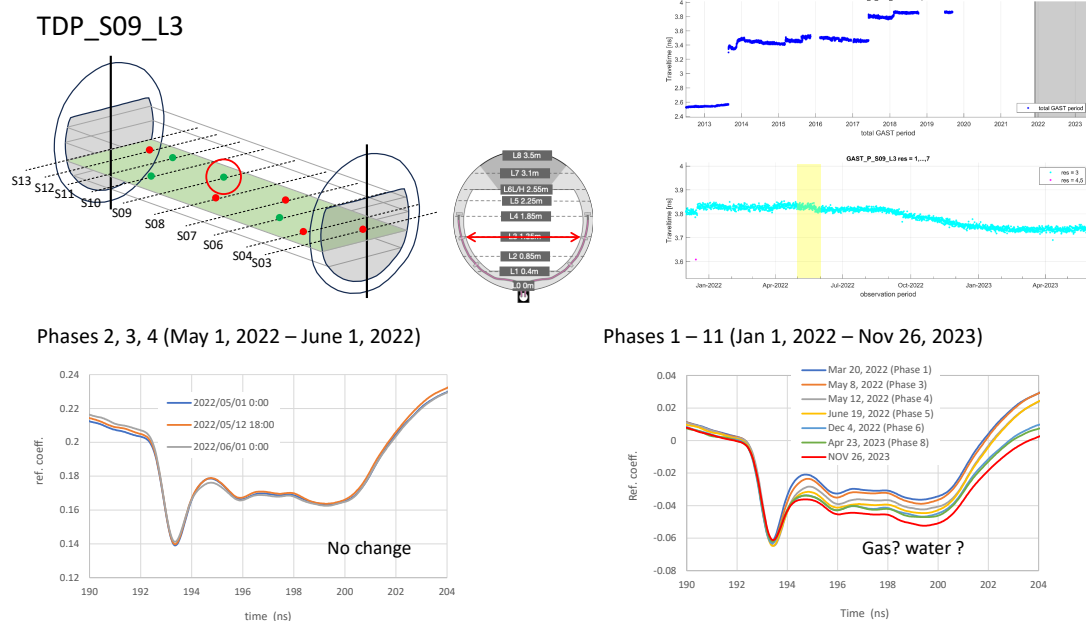


Fig. F-16: TDR sensor showing changes during the GFT phases (TDP_S09_L3)

TDP_S10_L3 showed changes in Phases 2, 3 and 4 (Fig. F-17). The change continued afterwards until Phase 11. The traces generally indicated that the S/B seal was wetting during the gas injection, which is also supported by the gradual increase in TT.

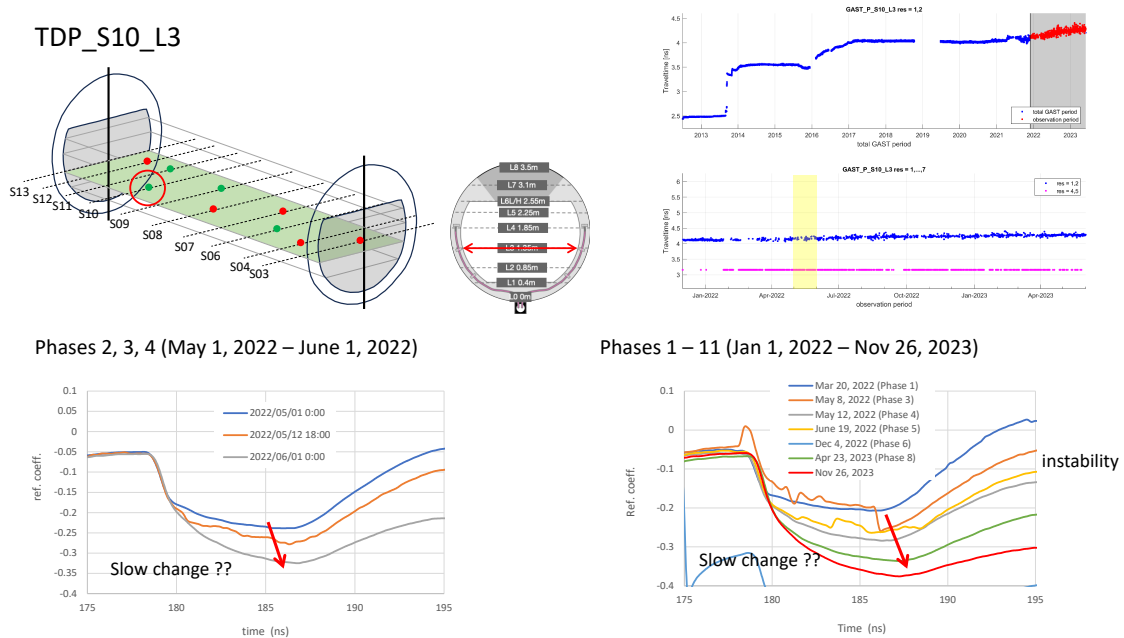


Fig. F-17: TDR sensor showing changes during the GFT phases (TDP_S10_L3)

TDP_S11_L3 traces were difficult to interpret (Fig. F-18). During Phases 2, 3 and 4, some change was observed in the traces but those did not support any physical changes in the S/B seal. Over time, the traces kept showing a similar type of differences, but they did not show any clear indication of either desaturation or saturation. Note that TT showed a very gradual decrease which could have been inferring desaturation of the S/B around the sensor. However, it was not evident enough to be confirmed.

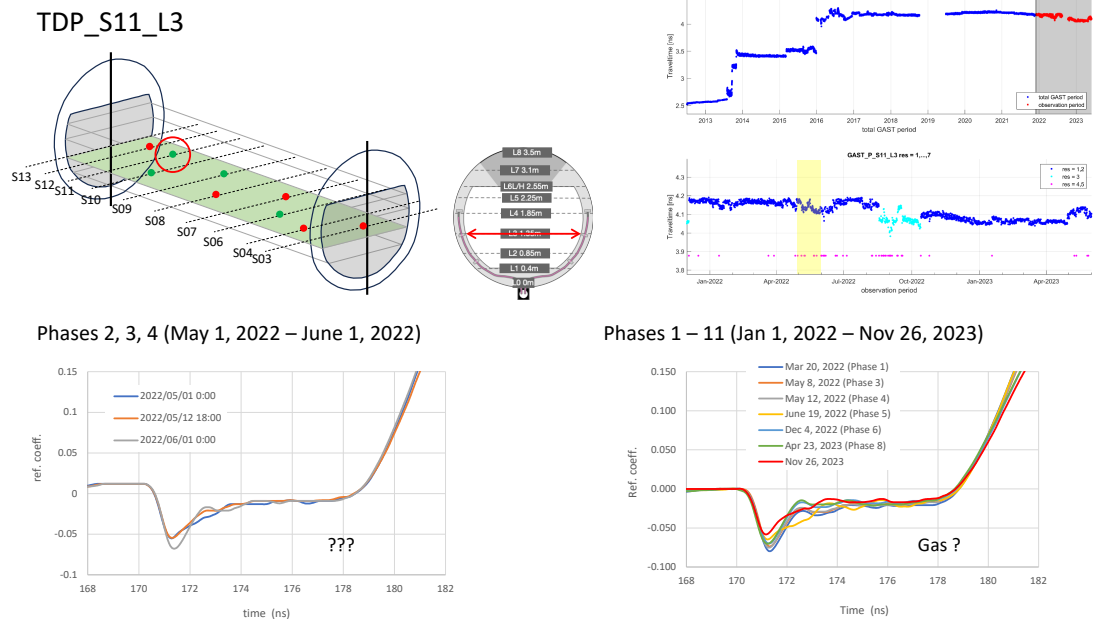


Fig. F-18: TDR sensor showing changes during the GFT phases (TDP_S11_L3)

TDP_S10_L5 shows no changes in the traces and TT during Phases 2, 3 and 4 (Fig. F-19). From Phase 6, the trace showed changes indicating wetting of the S/B. However, TT was inconsistent in the sense that TT decreased. Looking at the projection of the trace on 04.12.22 (Phase 6), the sensor might have been experiencing a technical issue rather than changes in the S/B seal.

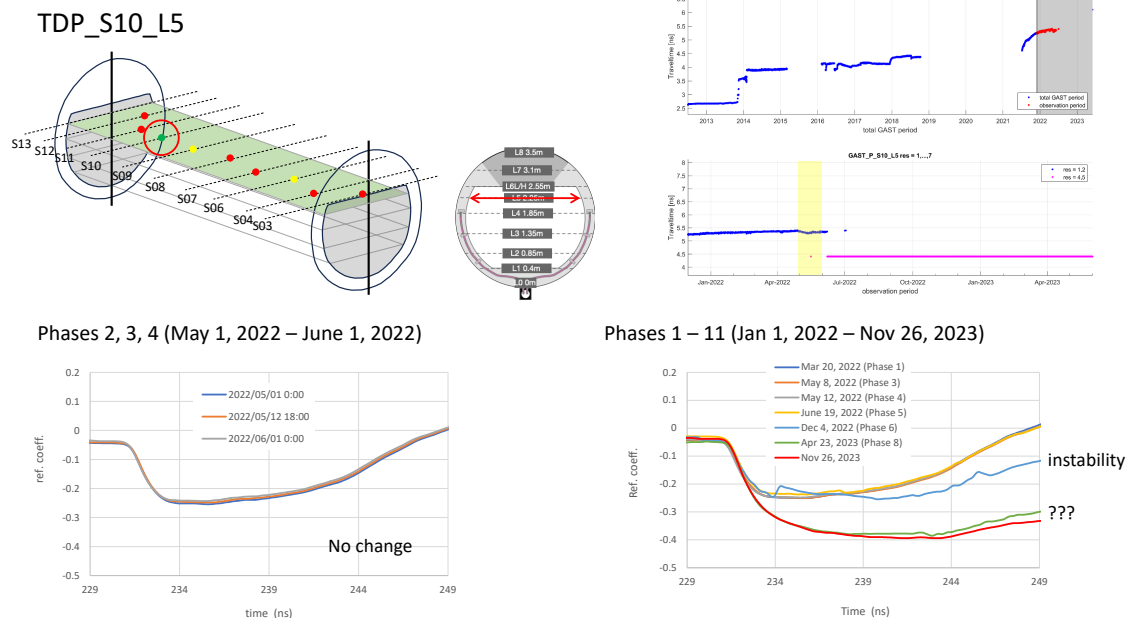


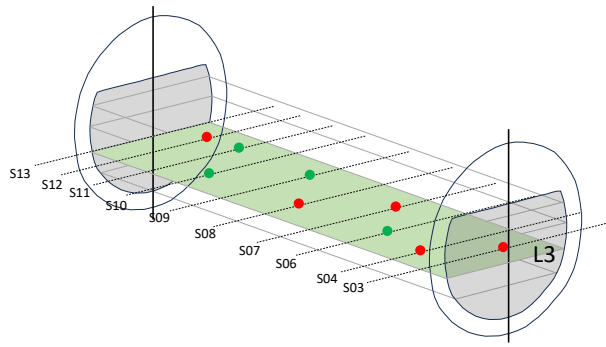
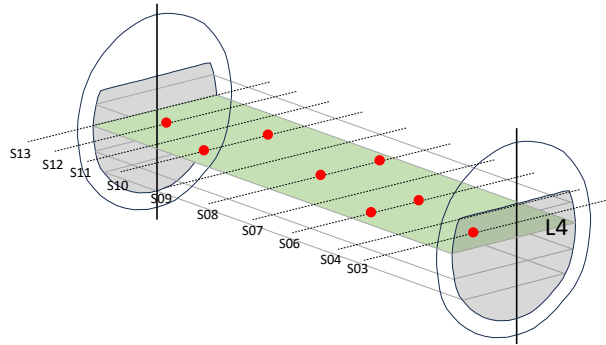
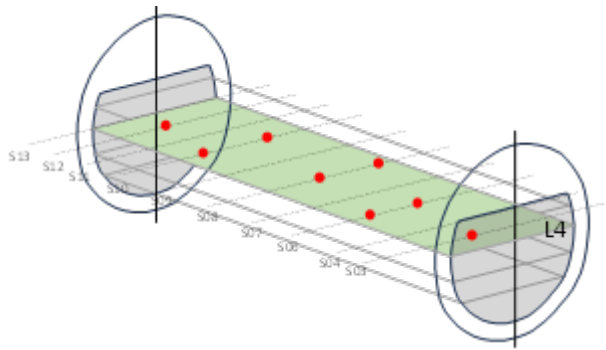
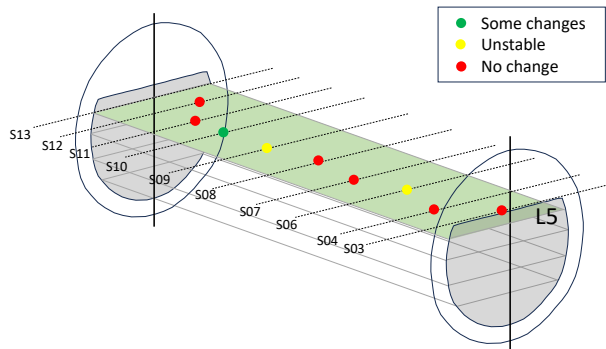
Fig. F-19: TDR sensor showing changes during the GFT phases (TDP_S10_L5)

In this section, TDPs with some changes during the GFT phases were presented. The changes in the TDR traces during the gas injection were not straightforward enough to directly infer physical changes resulting from gas injection. It is noteworthy, however, that four of the TDPs described in this section were located in L3, several of which suggested a gradual increase in water content. Others were in L2 or L5. The two sensors that showed instability were both from L5. Sensors showing changes are concentrated in L3 but did not consistently show desaturation or respond during Phases 2, 3 and 4 when the main gas path was believed to have formed. Any changes could therefore relate either to the slow development of the gas path or to ongoing changes in the TDRs themselves.

Tab. F-4: Summary of TDP sensors showing changes during the GFT

Category	TDR sensor	Phases 2, 3 & 4	Phase 1 – 11
Instability	TDP_S06_L5	No signs of gas flow during Phases 2, 3 & 4	Scatter in TT and instability in trace shapes
	TDP_S09_L5		
Potential changes	TDP_S03_L2		Increasing TT suggesting ongoing wetting during the GFT
	TDP_S06_L3		Decrease in TT suggesting desaturation during Phase 6 followed by wetting.
	TDP_S09_L3	No changes	Later changes in trace shape, with TT showing gradual wetting?
	TDP_S10_L3	Some changes	Changes continuing into Phase 11. Changes in trace shape and TT indicating gradual wetting
	TDP_S11_L3	Some changes	Difficult to interpret. No consistent indication of wetting or desaturation. Changes in TT indicate possible, very gradual desaturation.
	TDP_S10_L5	None	Changes in trace shape in Phase 6 and after, but inconsistent TT decrease. Possible technical issue.

Fig. F-20 shows a 3D map of the TDPs that showed some changes during gas injection. Although not all TDPs that showed changes (green circles) could be directly related to the development of gas paths (i.e., decrease in water content), most changes took place in L3.



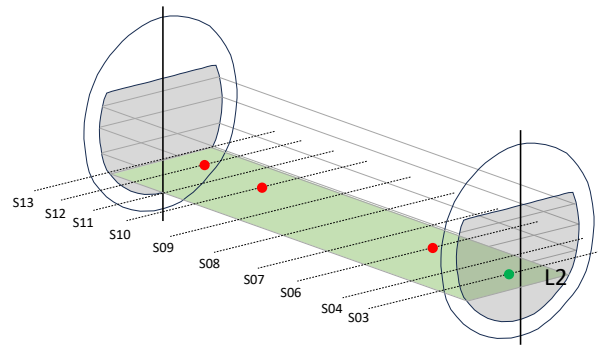


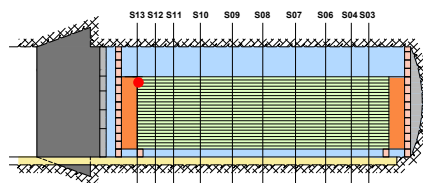
Fig. F-20: 3D map of the TDPs that showed some changes during gas injection

F.4 TDL sensor responses during gas injection

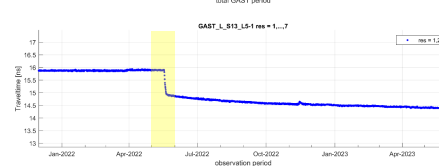
In contrast to the TDPs described above, the TDLs at the S/B-filter interface (S13) with longer horizontal electrodes showed distinct changes in the TDR traces. The responses are presented and discussed below. Note here that TDL_S13_L3-1 (marked with X in the figures) had failed during the early phase of the in-situ experiment, and is not discussed further. The results for each TDL include position, TT evolution and changes in the traces for short and longer time periods during the GFT phases.

TDL_S13_L5-1 (Fig. F-21) is located at the highest position in S13. Gas injection into the S02 filter was initiated on 02.05.22 (Phase 2), and the injection pressure was increased to 1,900 kPa between 06.05.22 (Phase 3) and 12.05.22 (Phase 4). The TDR traces started showing signs of water drainage and gas accumulation from 18.05.22 at the right side of the filter. By 20.05.22, the traces suggest that gas accumulated along the entire length of TDL_S13_L5-1. This change is also confirmed in a relatively sharp drop in the TT in the yellow-shaded interval (May 2022).

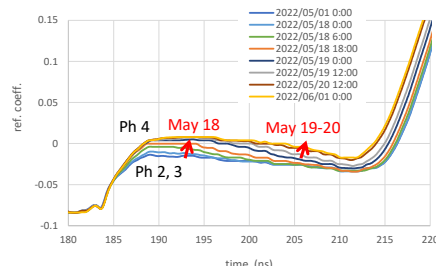
TDL_S13_L5-1



L5 (200 cm)
L4 (180 cm)
L3 (135 cm)
L2 (85 cm)



Phases 2, 3, 4 (May 1, 2022 – June 1, 2022)



Phases 1 – 11 (Jan 1, 2022 – Nov 26, 2023)

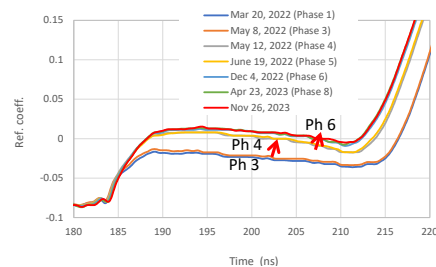


Fig. F-21: TDL sensor responses during the GFT phases (TDL_S13_L5-1)

TDL_S13_L5-2 (Fig. F-22) covers the left side of S13 at L5 slightly below L5-1. During the gas injection Phases 2, 3, and 4, the TDR traces started showing signs of gas accumulation on 20.05.22 from the right side of the filter. By 21.05.22, the traces suggest that gas accumulated along the entire length of TDL_S13_L5-2. This change is also confirmed in a relatively sharp drop in the TT in the yellow-shaded interval (May 2022).

TDL_S13_L5-2

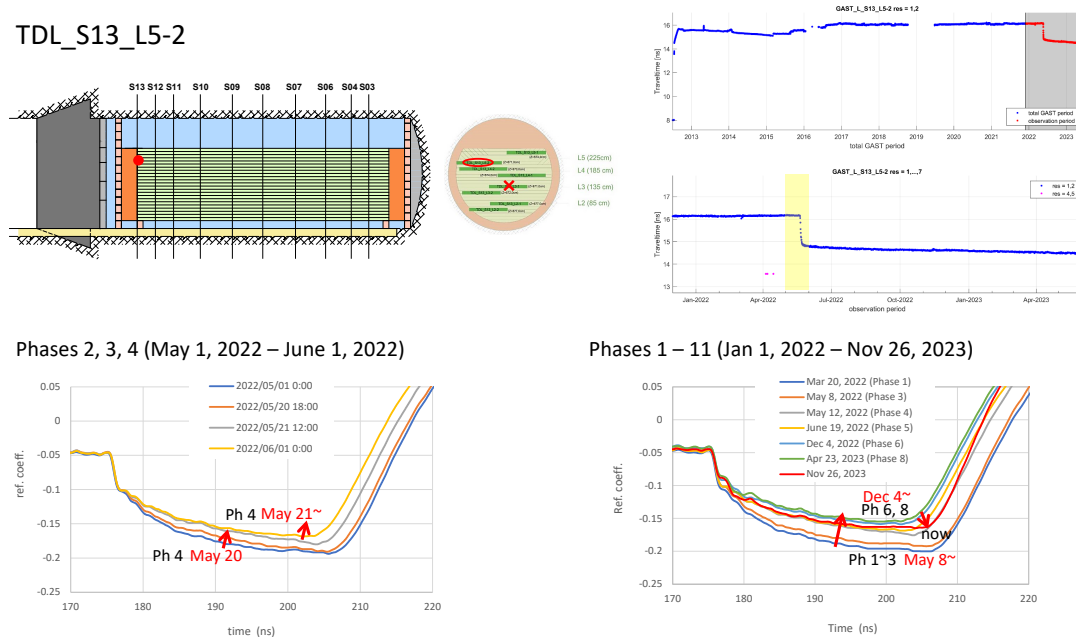
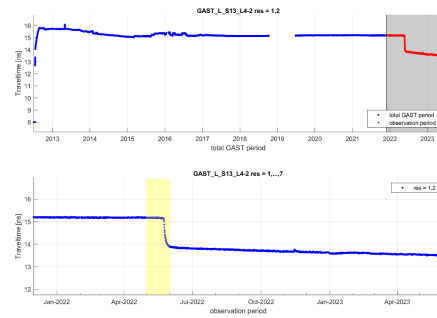
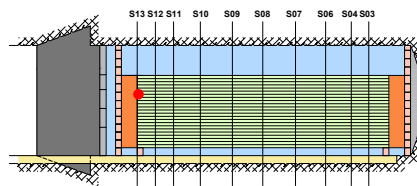


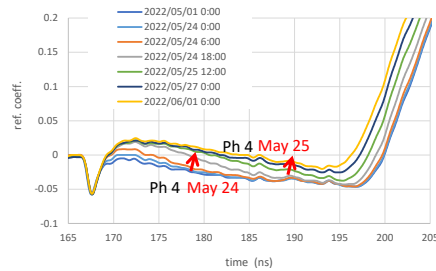
Fig. F-22: TDL sensor responses during the GFT phases (TDL_S13_L5-2)

TDL_S13_L4-2 (Fig. F-23) covers the left side of S13 at L4. During the gas injection Phases 2, 3 and 4, the TDR traces started showing sign of gas accumulation on 24.05.22 from the right side of the filter. By 25.05.22, the traces suggest that gas accumulated along the entire length of TDL_S13_L4-2. This change is also confirmed in a relatively sharp drop in the TT in the yellow-shaded interval (May 2022).

TDL_S13_L4-2



Phases 2, 3, 4 (May 1, 2022 – June 1, 2022)



Phases 1 – 11 (Jan 1, 2022 – Nov 26, 2023)

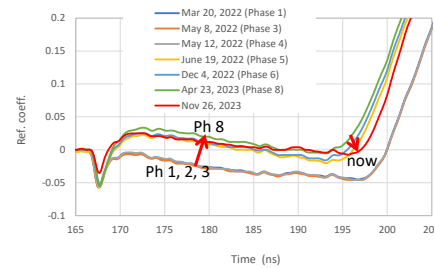
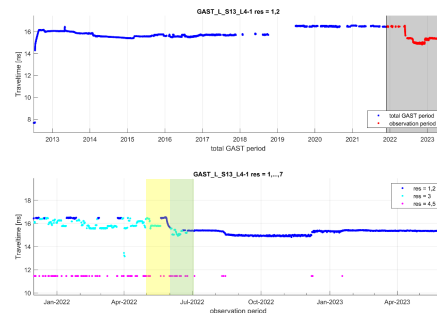
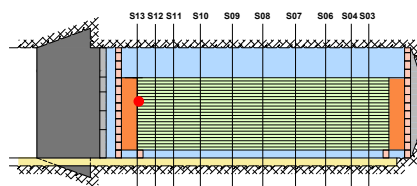


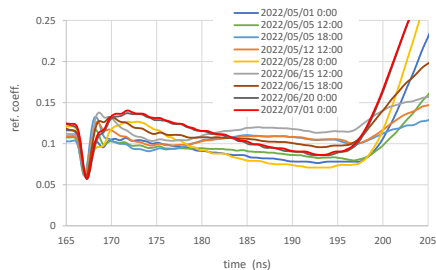
Fig. F-23: TDL sensor responses during the GFT phases (TDL_S13_L4-2)

TDL_S13_L4-1 (Fig. F-24) covers the right side of S13 at L4. During the gas injection Phases 2, 3 and 4, the TDR traces started showing sign of gas accumulation on 28.05.22 from the right side of the filter. By 03.06.22, the traces suggest that gas accumulated along the entire length of TDL_S13_L4-1. This change was confirmed as a drop in the TT in the green-shaded interval (June 2022).

TDL_S13_L4-1



Phases 2, 3, 4 (May 1, 2022 – June 1, 2022)



Phases 1 – 11 (Jan 1, 2022 – Nov 26, 2023)

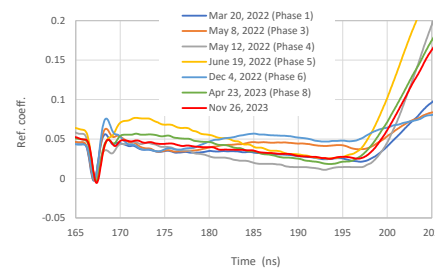


Fig. F-24: TDL sensor responses during the GFT phases (TDL_S13_L4-1)

TDL_S13_L3-2 (Fig. F-25) covers the left side of S13 at L3. During the gas injection Phases 2, 3 and 4, the TDR traces started showing sign of gas accumulation on 03.06.22 from the left side of the filter. By 04.06.22, the traces suggest that gas accumulated along the entire length of TDL_S13_L3-2. This change is also confirmed in a relatively sharp drop in the TT in the green-shaded interval (June 2022).

TDL_S13_L3-2

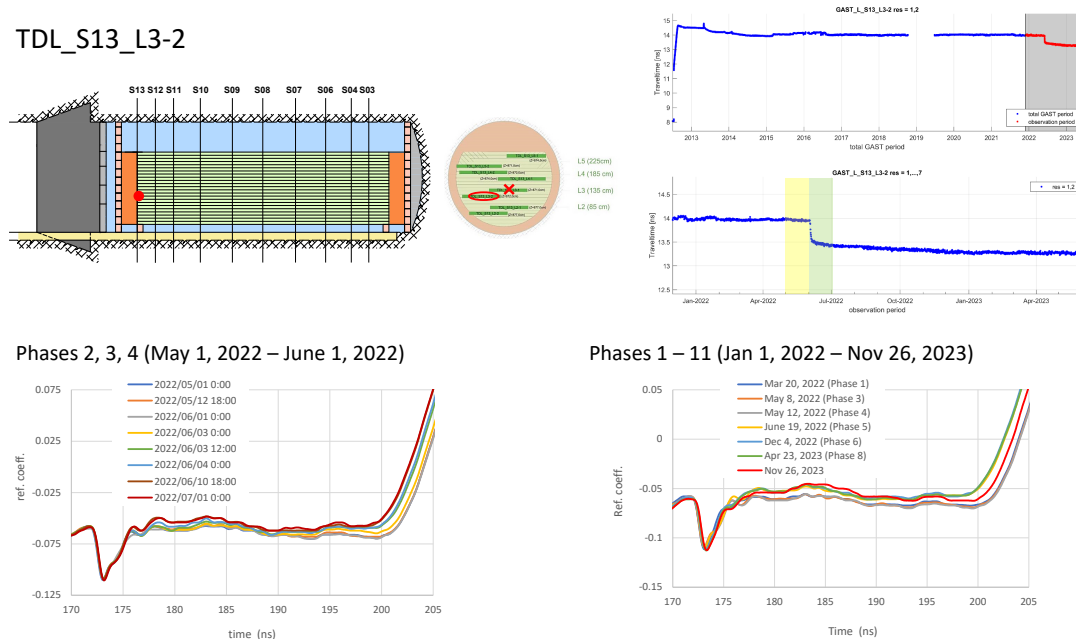
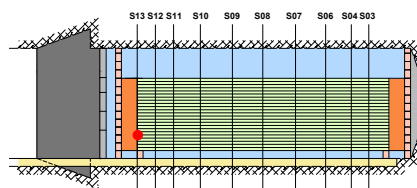


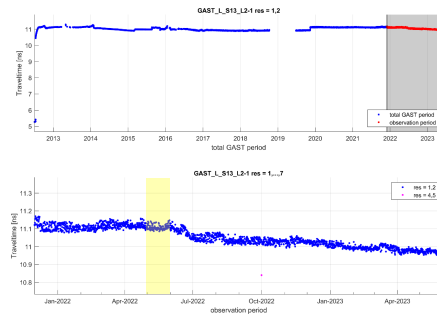
Fig. F-25: TDL sensor responses during the GFT phases (TDL_S13_L3-2)

TDL_S13_L2-1 (Fig. F-26) covers the right side of S13 at L2. During the gas injection Phases 2, 3 and 4, the TDR traces showed only small indications of gas accumulation at this level.

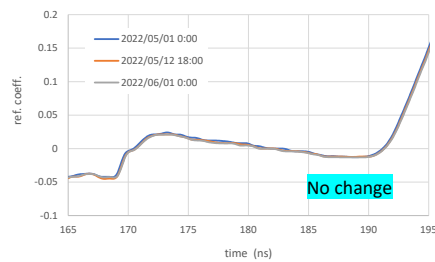
TDL_S13_L2-1



L5 (225cm)
L4 (185 cm)
L3 (135 cm)
L2 (85 cm)



Phases 2, 3, 4 (May 1, 2022 – June 1, 2022)



Phases 1 – 11 (Jan 1, 2022 – Nov 26, 2023)

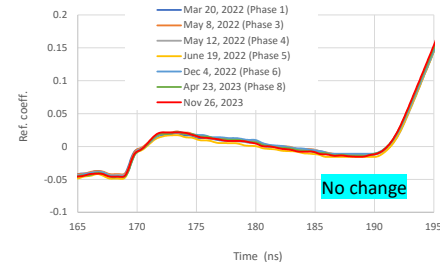
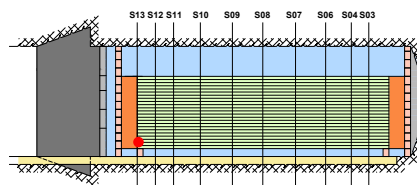


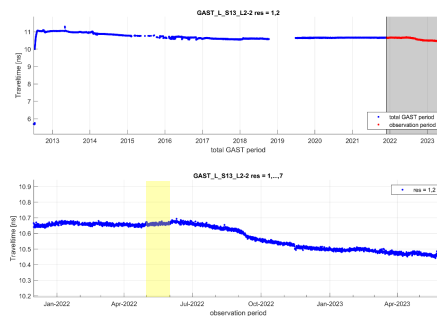
Fig. F-26: TDL sensor responses during the GFT phases (TDL_S13_L2-1)

TDL_S13_L2-2 (Fig. F-27) covers the left side of S13 at L2. This is the lowest TDL in terms of its position in S13. During the gas injection Phases 2, 3, and 4, the TDR traces showed no sign of gas accumulation at this level.

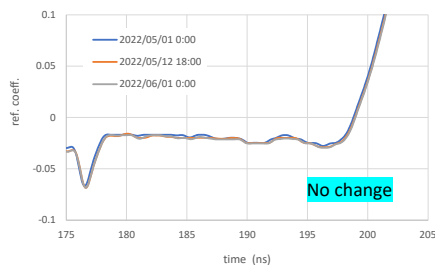
TDL_S13_L2-2



L5 (225cm)
L4 (185 cm)
L3 (135 cm)
L2 (85 cm)



Phases 2, 3, 4 (May 1, 2022 – June 1, 2022)



Phases 1 – 11 (Jan 1, 2022 – Nov 26, 2023)

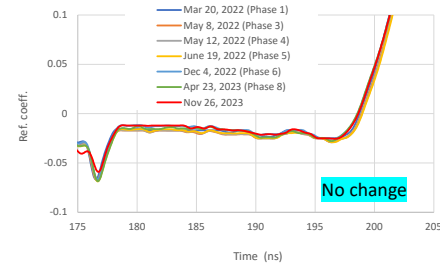


Fig. F-27: TDL sensor responses during the GFT phases (TDL_S13_L2-2)

Based on the above-mentioned findings, the transient changes of the position of gas-water interface in the filter at S13 were mapped in Fig. F-28. The general trend of the gas accumulation indicated that the flux of gas into the filter might have been occurring on the right side of the seal from 18.05.22 (observed at the L5 sensor), gradually moving downwards to the L3 sensors by 04.06.22. The development shown in Fig. F-28 suggests that it is possible that gas entry was localised around TDL_S13_L4-1 and that gas then moved upwards to L5. However, entry at L3 is also possible.

The gas extraction port (PL_S14_L1) is located close to the bottom of the sand filter. The TDLs S13_L2-1 and L2-2 did not capture the accumulation of the gas at this elevation (as shown in Fig. F-28). It is possible that the base of the sand filter contained fine material and bentonite gel from the adjacent bentonite blocks or S/B seal such that the desaturation at this level was smaller than at higher levels, and the TDLs were no longer able to capture water/gas accumulation. Nonetheless, the gas breakthrough to the L1 extraction occurred on 08.06.22. Therefore, it is possible that a localised gas pathway formed toward the extraction port PL_S14_L1. To visualise the situation, a 3D image of the gas accumulation at the time when the gas breakthrough took place is presented in Fig. F-29.

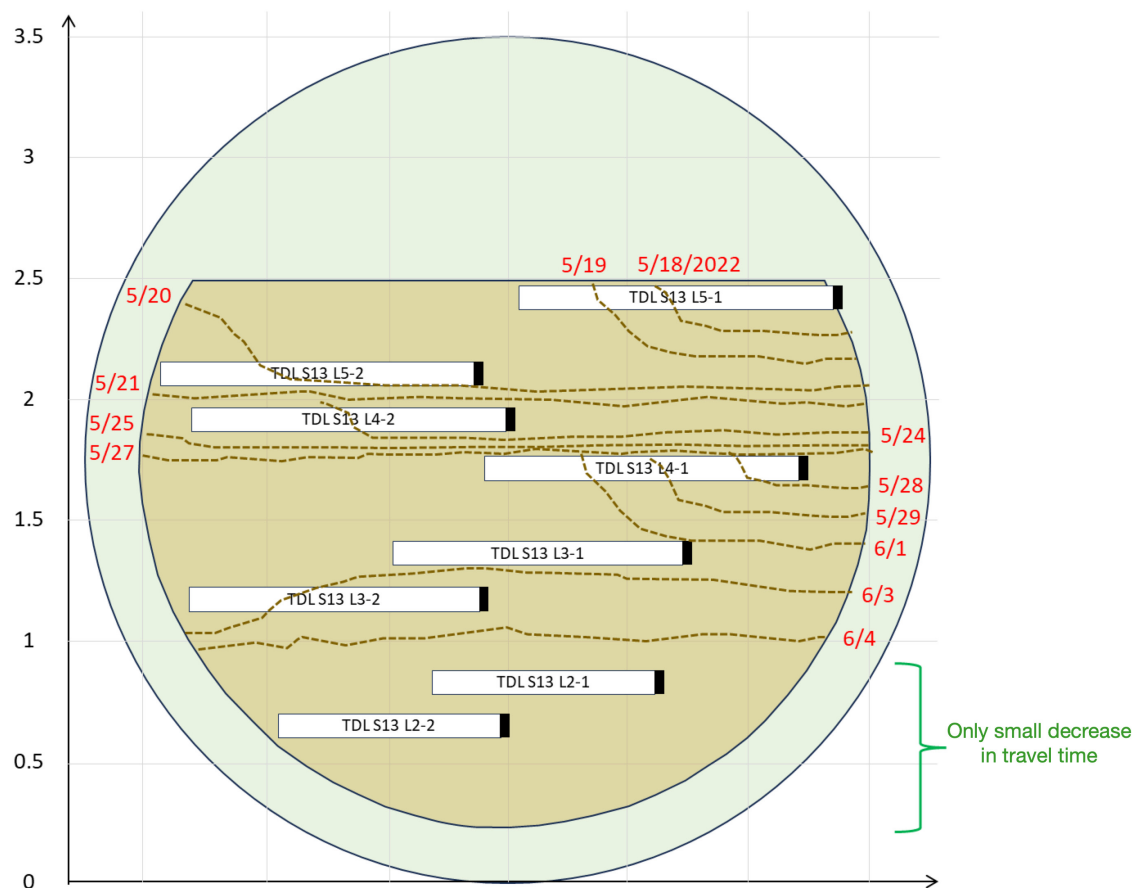


Fig. F-28: Map of gas accumulation during Phases 2, 3 and 4

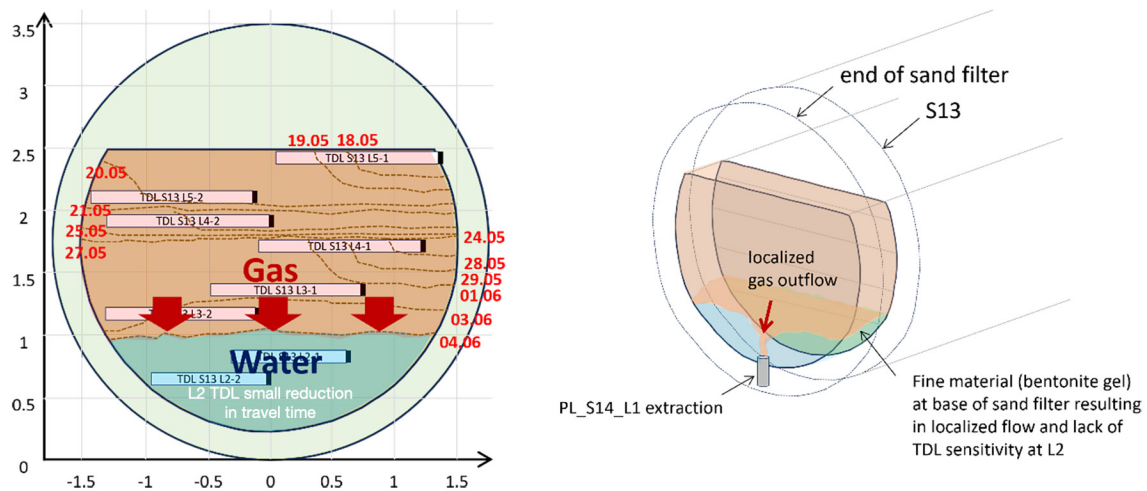


Fig. F-29: 3D image of gas accumulation when the gas breakthrough took place on 08.06.22

F.5 TDR responses during the water injection phase (Phase 11)

During GFT Phase 11, in order to remove gas from S14 and flush it back towards S02, water was injected into the base of S14 (PL_S14_L1), creating a pressure gradient from S14 towards S02.

The TDP response during Phase 11 (water injection) was even less obvious than during gas injection. However, the TDLs clearly captured the water rise in the filter. The key results are presented below.

F.5.1 TDP sensors showing changes during water injection (Phase 11)

Two TDPs showed changes in the TDR traces which might be due to the changes in the moisture conditions around the sensors. Those are presented and discussed below. TDP_S10_L3 (Fig. F-30) yielded traces during the water injection phase with changes suggesting an increase in water content around the sensor. It was, however, difficult to confirm the water content increase in the TT. The causes of the observed response are unidentified.

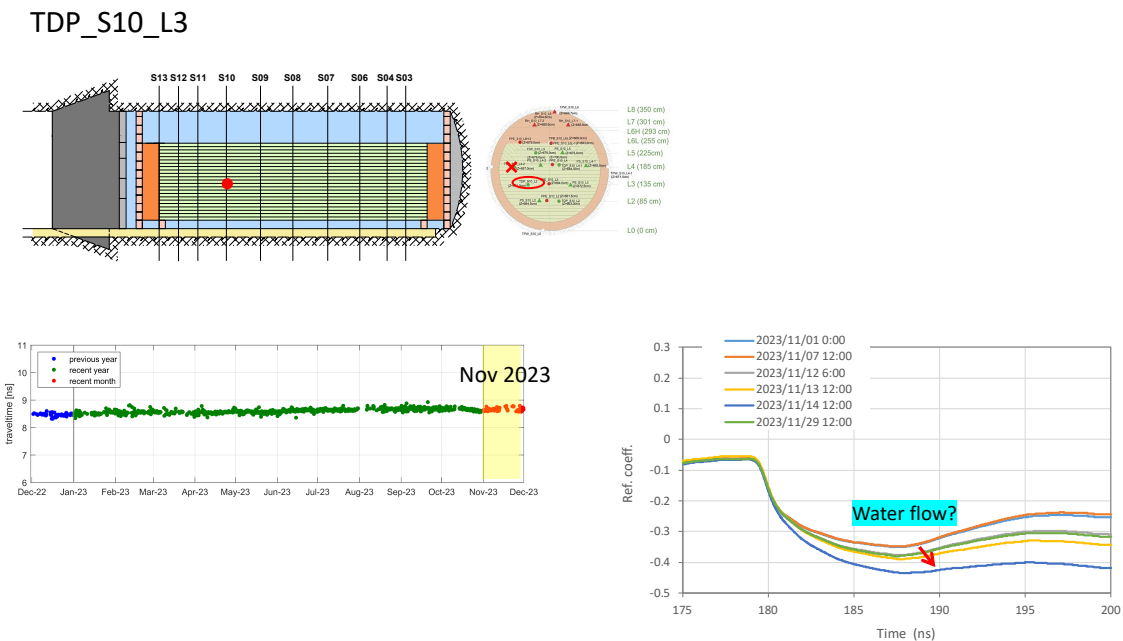


Fig. F-30: TDR sensor showing changes during the GFT phases (TDP_S10_L3)

TDP_S10_L5 (Fig. F-31) is another sensor that showed changes in the traces during the water injection phase, suggesting an increase in water content around the sensor. For this sensor, TT was not calculated.

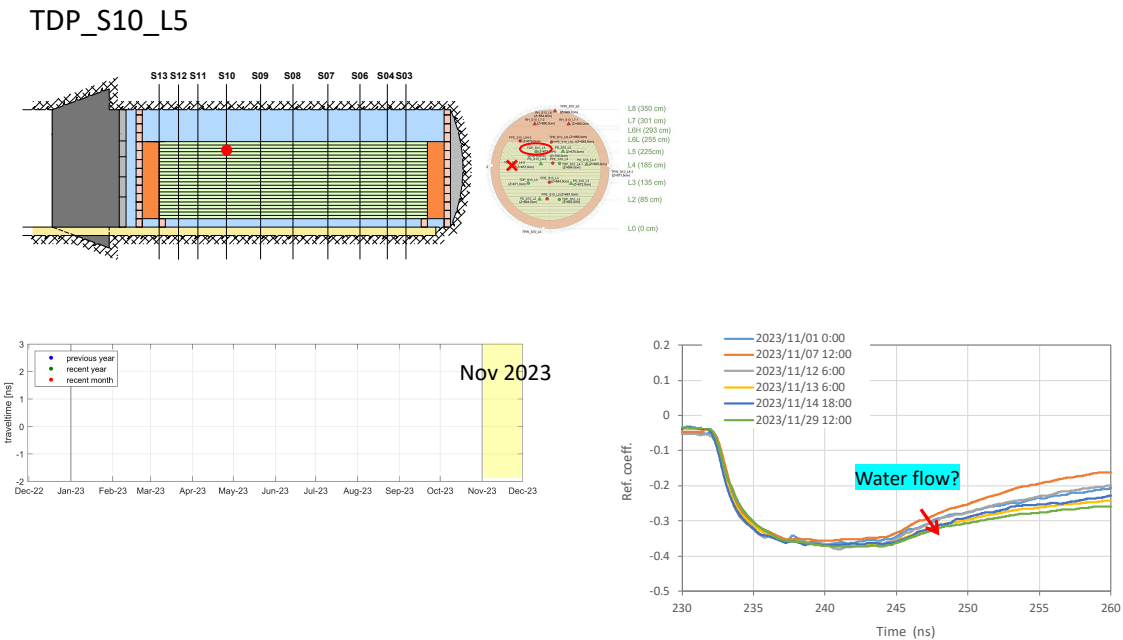


Fig. F-31: TDR sensor showing changes during the GFT phases (TDP_S10_L5)

F.5.2 TDL sensor responses during water injection (Phase 11)

During the water injection into the base of S14, TDLs at the S/B-filter interface (S13) showed distinct changes in the TDR traces. They are presented and discussed below. The results for each TDL include position, TT evolution and changes in the traces during GFT Phase 11.

TDL_S13_L2-1 (Fig. F-32) and TDL_S13_L2-2 (Fig. F-32) showed only a very small gradual response during the gas injection phases and therefore only a minor increase in travel time during water injection.

TDL_S13_L2-2

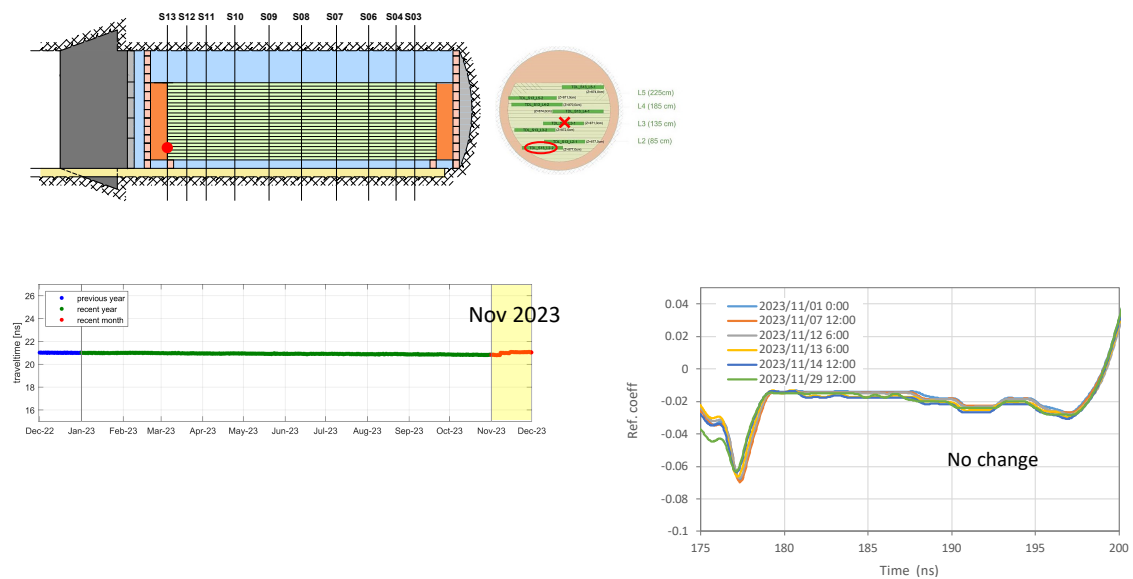


Fig. F-32: TDL sensor responses during the GFT phases (TDL_S13_L2-2)

TDL_S13_L2-1

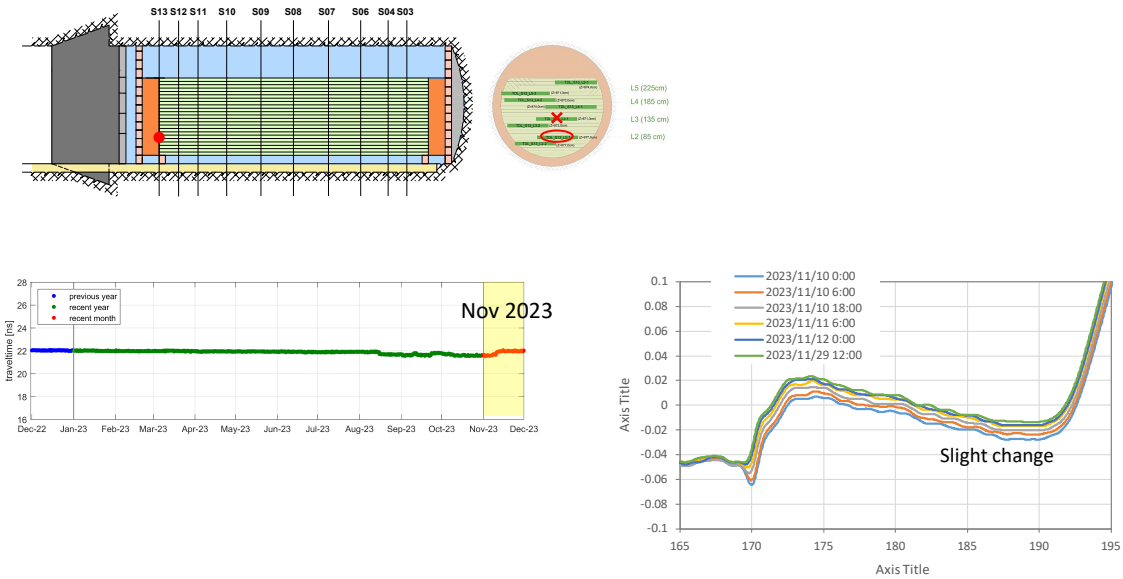


Fig. F-33: TDL sensor responses during the GFT phases (TDL_S13_L2-1)

TDL_S13_L3-2 (Fig. F-34) indicated that the sensor was below the water level in the filter on 08.11.23 (one day after water injection started on 07.11.23). The changes in the traces indicated an increase in water content around the sensor which resulted in a sharp increase in TT.

TDL_S13_L3-2

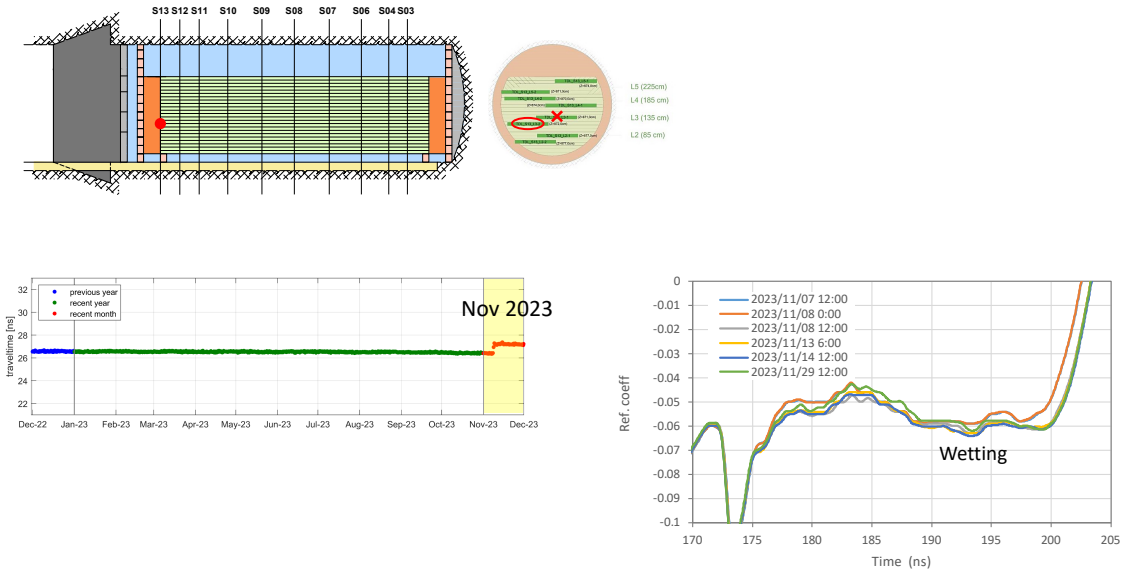


Fig. F-34: TDL sensor responses during the GFT phases (TDL_S13_L3-2)

TDL_S13_L4-1 (Fig. F-35) showed that water level in the filter reached this level between 09.11.23 and 10.11.23. The changes in the traces indicated an increase in water content around the sensor which resulted in a sharp increase in TT.

TDL_S13_L4-1

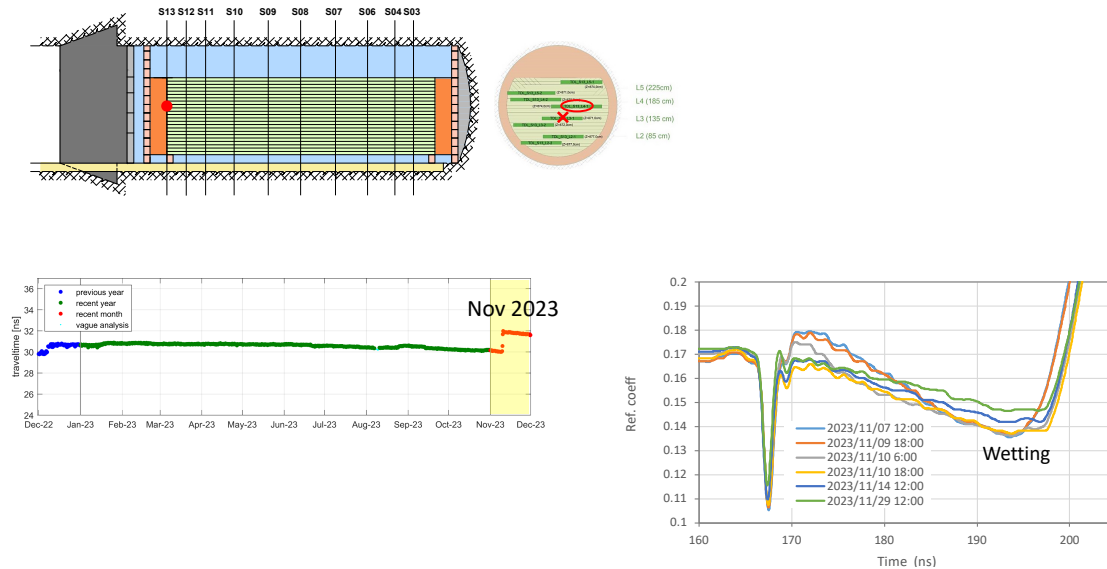


Fig. F-35: TDL sensor responses during the GFT phases (TDL_S13_L4-1)

TDL_S13_L4-2 (Fig. F-36) showed that the water level in the filter reached this level between 11.11.23 and 12.11.23. The changes in the traces clearly indicated an increase in water content around the sensor which resulted in a sharp increase in TT.

TDL_S13_L4-2

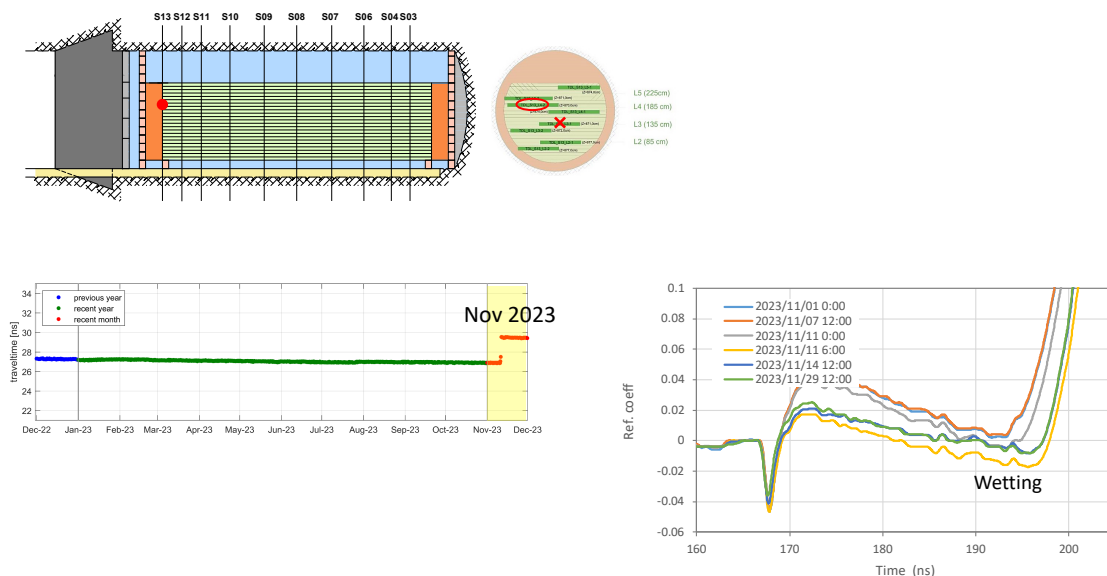


Fig. F-36: TDL sensor responses during the GFT phases (TDL_S13_L4-2)

TDL_S13_L5-2 (Fig. F-37) showed that water level in the filter reached this level between 11.11.23 and 12.11.23. The changes in the traces clearly indicated an increase in water content around the sensor which resulted in a sharp increase in TT.

TDL_S13_L5-2

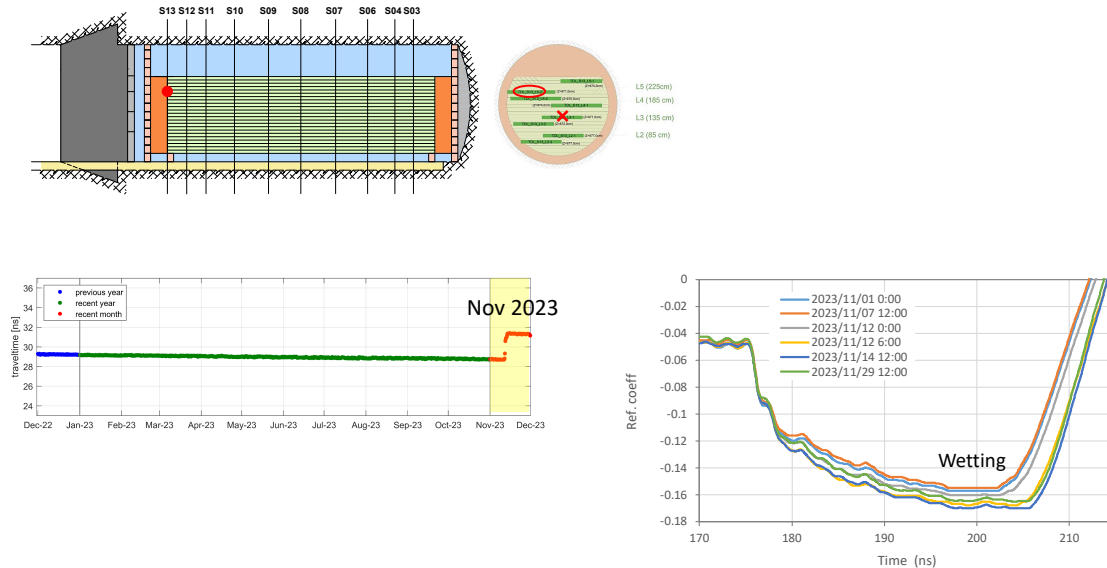


Fig. F-37: TDL sensor responses during the GFT phases (TDL_S13_L5-2)

TDL_S13_L5-1 (Fig. F-38) showed that THE water level in the filter never exceeded the sensor level after 12.11.23. The traces showed no identifiable changes. Correspondingly, there was no change in TT (except for a small step increase followed by a gradual decrease in mid-November, which could have been due to the gas possibly touching a part of the TDL electrodes and disappearing during redistribution).

TDL_S13_L5-1

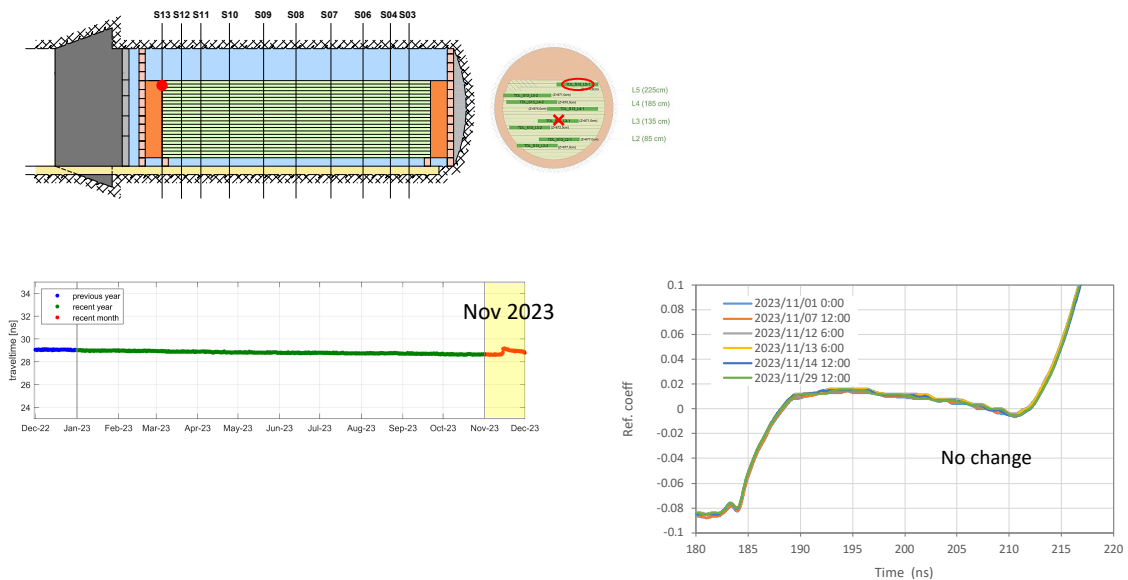


Fig. F-38: TDL sensor responses during the GFT phases (TDL_S13_L5-1)

Based on the above-mentioned observations, the transient changes of the position of the gas-water interface in the S14 filter at S13 were mapped in Fig. F-39. The general trend during the water injection showed a rather uniform rise across the sand filter width. The gas around TDL_S13_L5-1 never disappeared during water injection. Therefore, some gas remained in the sand filter somewhere at or above the line shown in the figure.

As with the gas breakthrough, a 3D image of the water accumulation at the end of gas displacement by water injection into S14 (12.11.22) is presented in Fig. F-40.

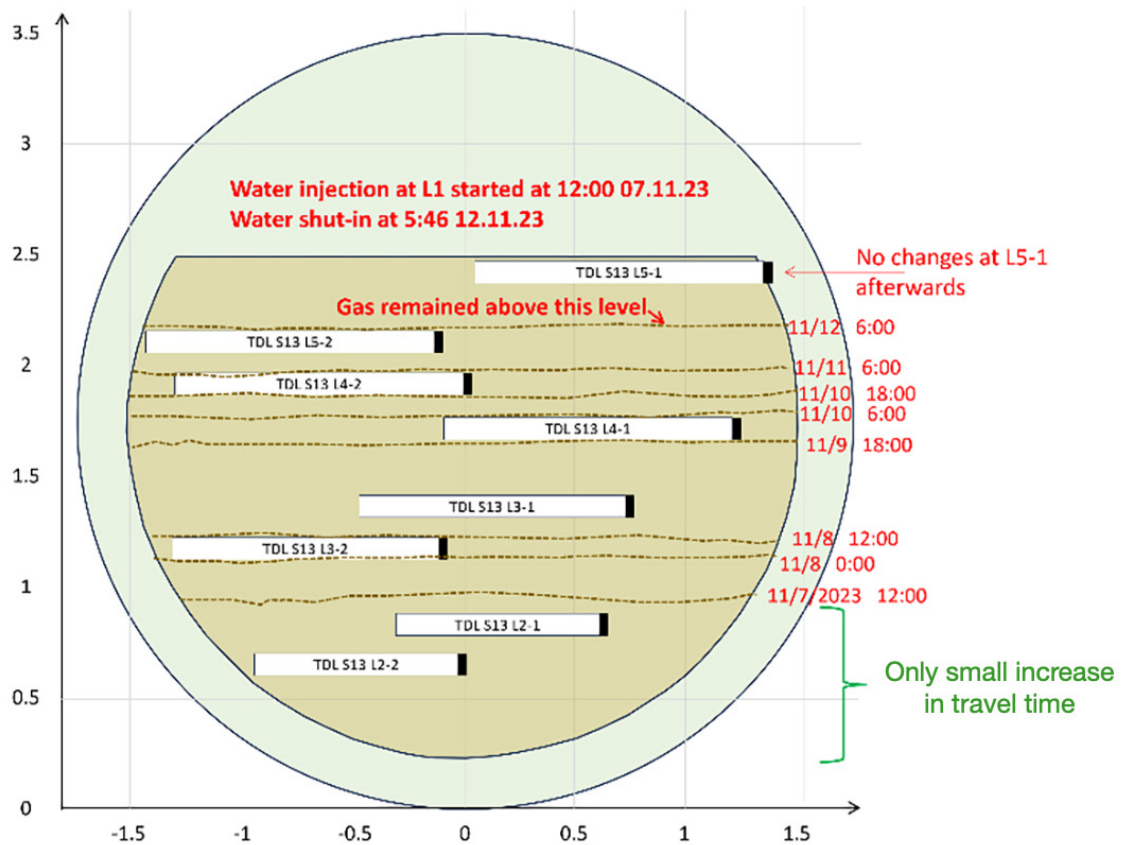


Fig. F-39: Map of water accumulation during Phase 11

At the end of gas displacement by water injection into S14
(12 Nov 2022)

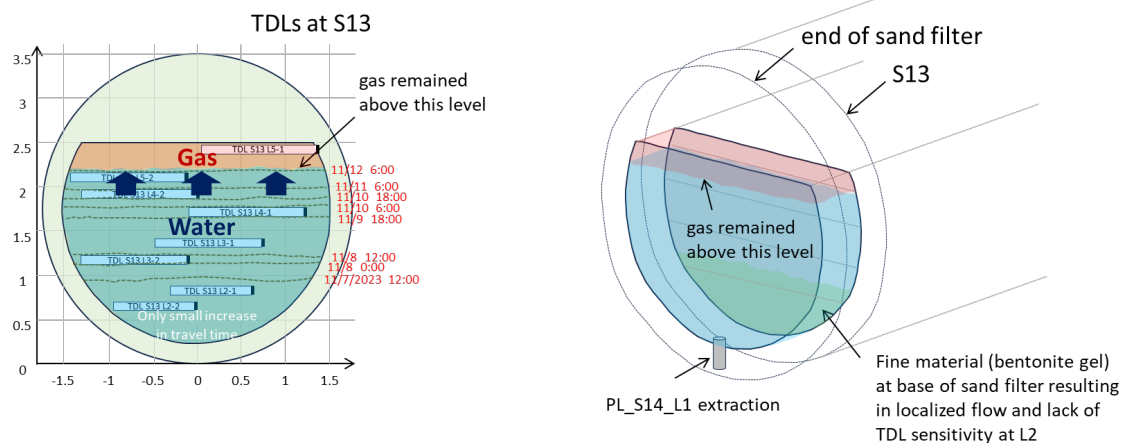


Fig. F-40: 3D image of water accumulation at the end of gas displacement by water injection into S14 on 12.11.23

F.6 Summary

A review of the overall evolution of the TDR showed that most TDRs showed a significant increase in water content prior to GPT1 and that only a small number of TDRs showed even a minor increase in water content during the subsequent resaturation and equilibration periods. This indicates that the bulk of the sand/bentonite seal was highly saturated (i.e., sufficiently close to full saturation) prior to the start of the GFT.

A detailed examination of TDP traces and travel time during the GFT identified minor changes in a small number of sensors (mostly at L3) and instability in two sensors at L5. Observed changes suggested both wetting at some TDPs and desaturation at others, with some sensors showing indications of both wetting and desaturation during the GFT. Changes in travel time were, however, small. While it was possible to identify such small changes, it is difficult to identify an unequivocal response indicating the presence of a gas path. This is consistent with the expectation of a localised gas path with only small changes in the bulk water content of the sand/bentonite. A total of 30 TDPs generally functioned well in capturing the saturation process of the S/B seal, but were too sparse to detect a localised gas flow path and posed an issue in their long-term durability (e.g., water intruding into the sensor head), which made interpretation more difficult.

In contrast, the TDL sensors at S13 at L3 – L5 clearly responded to the drainage and resaturation of the S14 sand filter. Drainage occurred during May and early June 2022 and shows a good correlation with the ongoing extraction of water from the base of S14 (line PL_S14_L1). Resaturation of the S14 sand filter (water injection in PL_S14_L1) during Phase 11 occurred between 07.11.23 and 9.11.23 and again correlates well with the timing of TDL responses.

The TDLs at L2 do not show the same magnitude of response despite their location above L1. This could be due to either

- localised flow paths for gas at the base of the filter, e.g. due to possible build-up of fine material, or
- lack of sensitivity of the TDLs at this level as it is possible that some deformation of the filter and geotextile occurred during the 12 years of emplacement.

The two TDP sensors in S10 at L3 and L5 showed some minor changes during Phase 11 indicating wetting, however, travel time changes were small.

App. G Geosphere and drainage data

Author: G.W. Lanyon

G.1 Geosphere pressure

The geosphere around GAST is monitored with a small number of boreholes as shown in Fig. G-1.

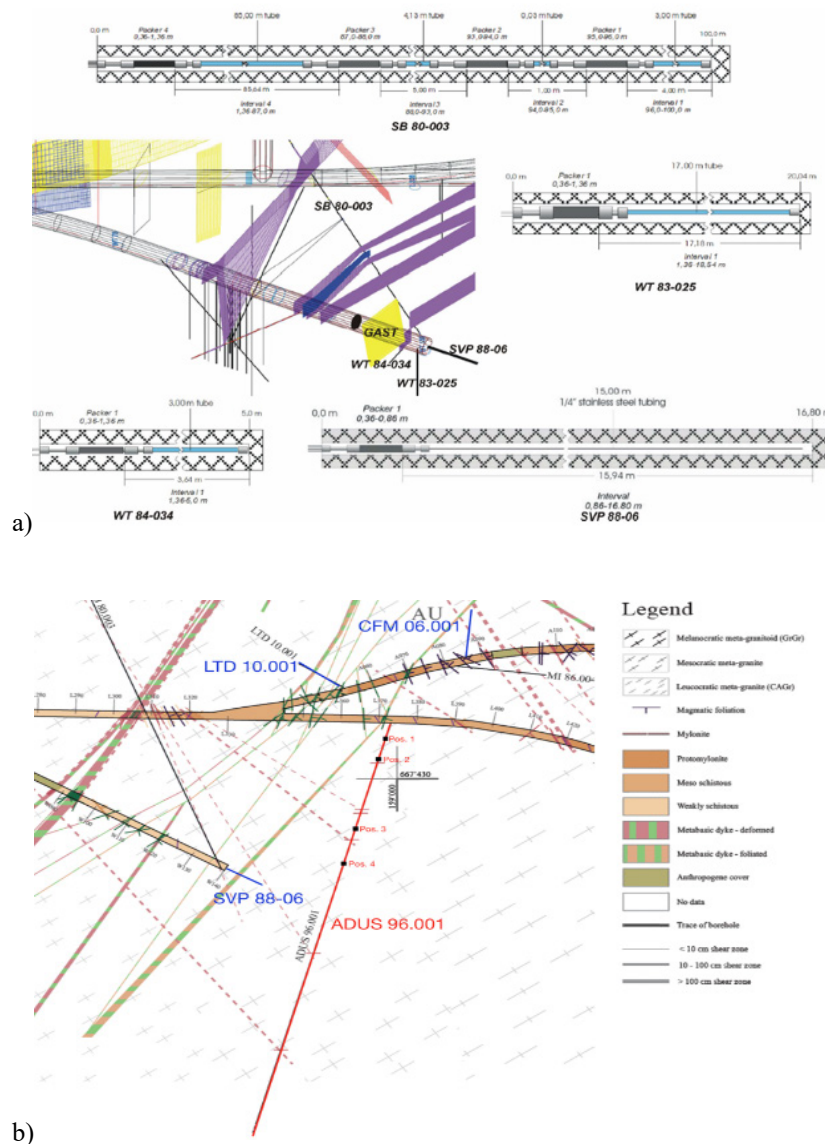


Fig. G-1: Location of boreholes surrounding GAST

Tab. G-1 lists the intervals and estimated mid-points in the GAST coordinate system. Borehole SB80.03 crosses above the WT drift at approximately $Z_{\text{Gast}} = 2.8$ m (equivalent to S06). WT84.034 is drilled approximately radial to the WT drift from $Z_{\text{Gast}} = 4.2$ m (roughly mid-way between S07 and S08).

Tab. G-1: Borehole interval mid-points around GAST

		Start	End	Length	X _{Gast}	Z _{Gast}	Y _{Gast}
SB 80.003	i1	96	100	4	0.0	2.8	5.6
SB 80.003	i2	94	95	1	-2.1	5.6	5.6
SB 80.003	i3	88	93	5	-4.6	8.7	5.5
SB 80.003	i4	1.36	87	85.64	-33.4	45.0	4.7
WT 83.025	i1	1.36	20.04	18.68	0.0	2.8	-10.5
WT 84.034	i1	1.36	5	3.64	5.2	4.2	1.2
SVP 88.006	i1	0.86	16.8	15.94	-0.1	-9.6	3.3

SVP 88.006, WT 84.034 and WT 83.025 boreholes

The data from the three boreholes around the end of the tunnel are shown in Fig. G-2.

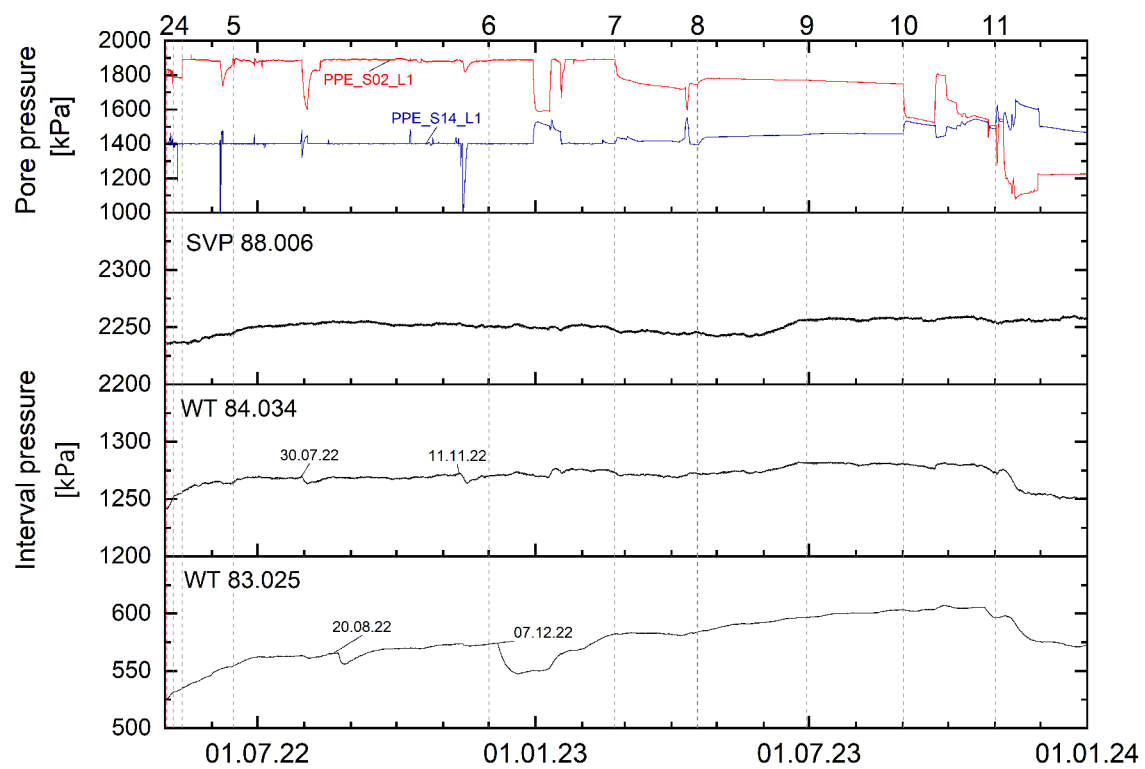


Fig. G-2: Interval pressure from the short boreholes surrounding GAST

Pressures are likely to be heterogeneous due to the fractured nature of the rock and the presence of the open WT drift and access tunnel. Borehole SVP 88-06 at the end of the WT drift is believed to be connected to a structure linked to the ADUS borehole and has shown strong reactions to testing and changes in the ADUS packer completions (depending on the isolation/connection of different flow features in the ADUS). The ADUS borehole has been a source of high-pressure water for GAST and other experiments. Overall, the data suggest pressures between 0.5 and 2.5 MPa around GAST, with the highest pressure measured in SVP 88.006 at the end of the tunnel.

WT 83.025 does not show any obvious correlations with filter pressure during most of the GFT although some possible interaction seems to occur at the end of 2023 when pressure in S02 filter was reduced to ~1,100 kPa. Small pressure drops of 5 – 20 kPa in August and December 2022 occur during steady pressures in the two filters.

Minor variations in the WT 84.034 interval pressure (~5 kPa) during the GFT could indicate some interaction with the filter pressures. Again, pressure drops at the end of 2023 when S02 pressure was low. There are no signs of any correlation with filter pressure in the SVP 88.006 pressure, which varies between 2,235 and 2,260 kPa during the GFT.

SB 80.003 borehole

The SB 80.003 borehole is one of the 6 exploratory boreholes (SB: *Sondierbohrungen* – Juchli-stock) drilled prior to GTS excavation. It is equipped with 4 monitoring intervals and crosses above the WT drift at about S06. Interval I4 is a long interval from near the borehole mouth to 87 m.

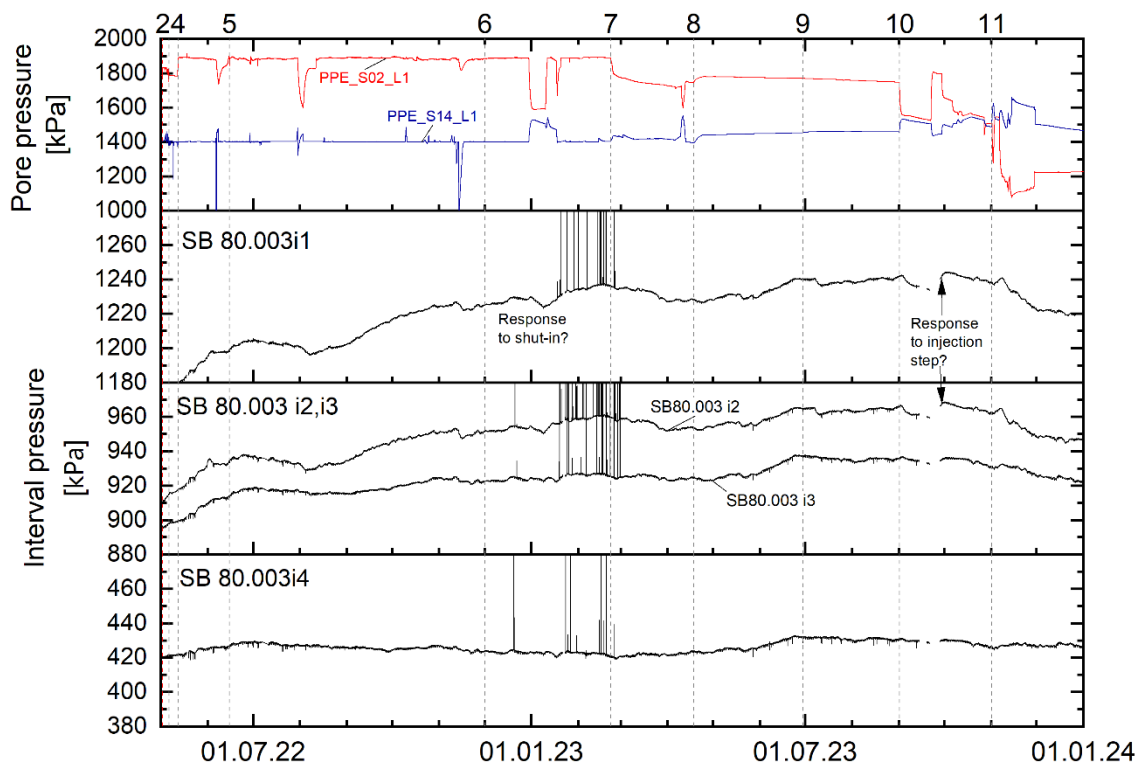


Fig. G-3: Interval pressure from SB 80.003 intervals (i1,i2,i3 close to GAST)

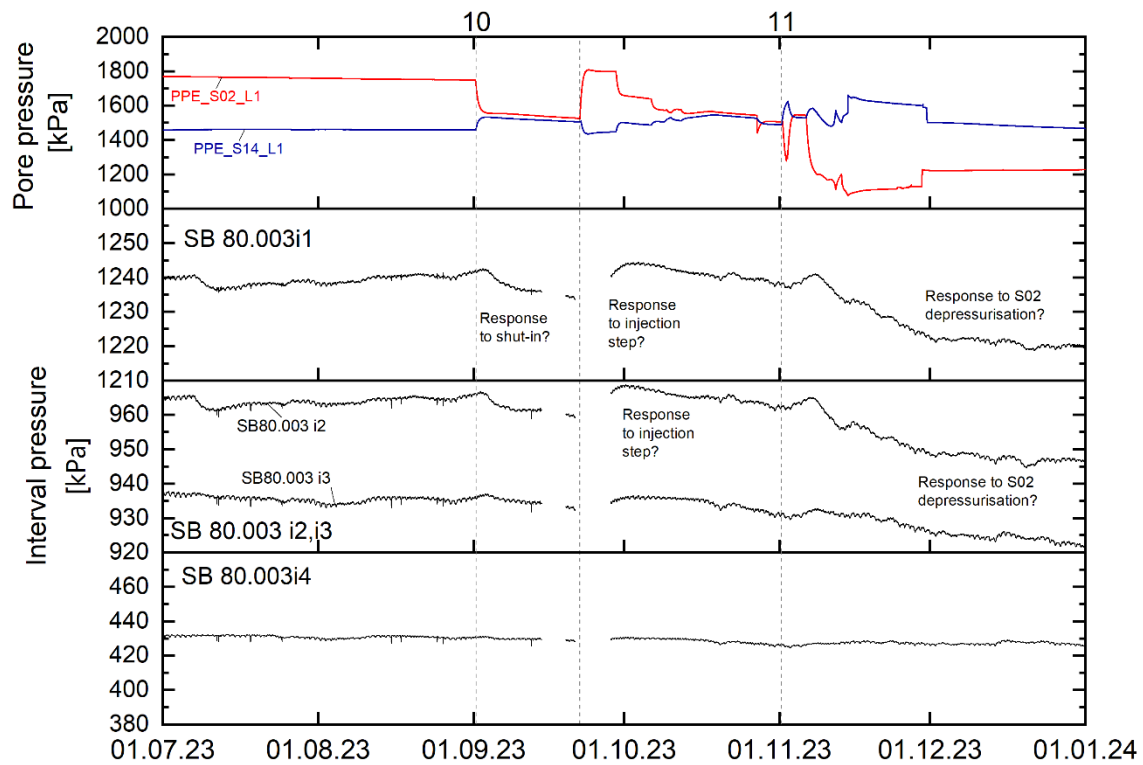


Fig. G-4: Interval pressure from the SB 80.003 borehole intervals during Phases 10 and 11 of the GFT

The responses observed in i1,i2 and i3 during Phases 10 and 11 of the GFT indicate a diffuse connection but clearly show the major pressure changes in S02.²⁶ Unfortunately, there was a loss of data at the start of Phase 10 step-rate injection tests so the nature of the response is unclear.

G.2 Geosphere drainage

The geosphere drainage system is intended to capture water from flowing fractures that intersect the end of the WT drift. The water is then taken along a line in the base of the trench (below the main duct) and is monitored in the WT drift. Flow from the fractures is expected (due to the higher pressure in the geosphere around the end of the tunnel) and is known to be influenced by the SVP 88.06 borehole (flow decreases if this borehole is opened). Since 2015 the salinity of this water has increased, indicating that there is some component of bentonite porewater in the produced water and hydraulic communication with the GAST EBS (see Lanyon & Herbert 2021). The communication appears to be periodic with pulses of higher salinity water being observed.

²⁶ Previous investigations have shown that the rock around the end of the WT drift is sensitive to operations in the BOADUS borehole and further investigations are needed to check the influence of any actions in the BOADUS borehole during the GFT.

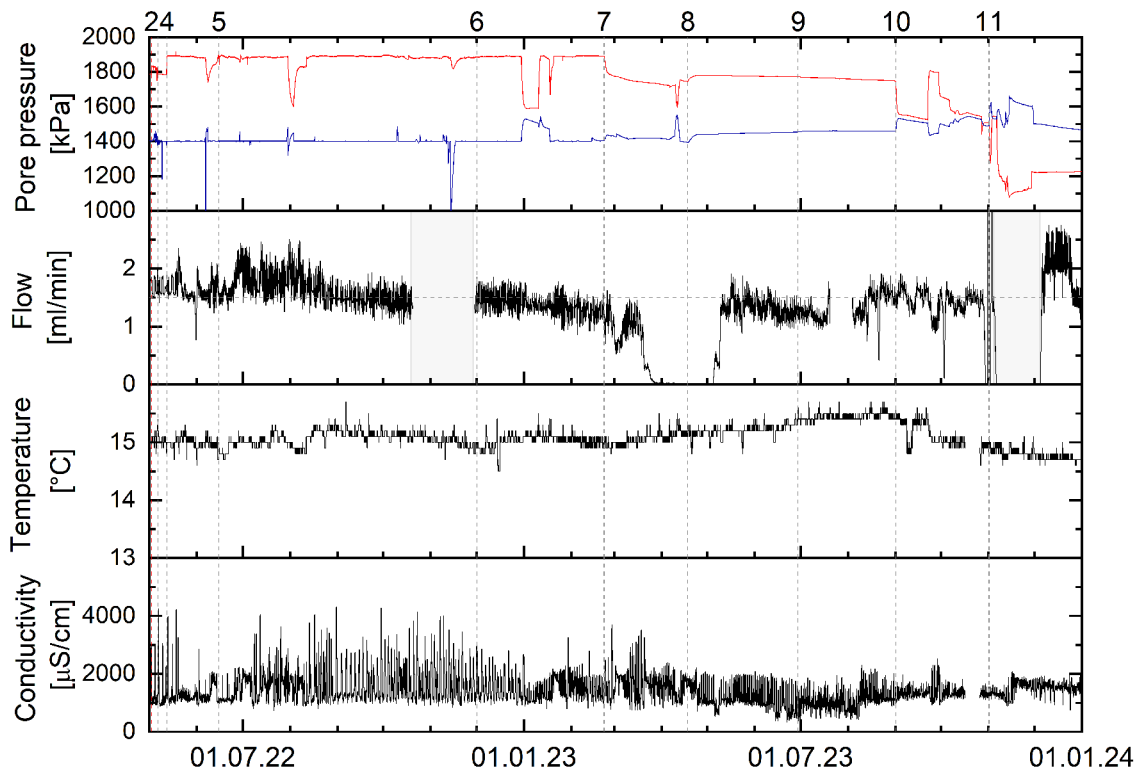


Fig. G-5: GAST drainage line flow, temperature and electrical conductivity during the GFT. The S02 and S14 filter pressures are shown for comparison purposes

The outflow from the drainage line is usually about 1 ml/min and is monitored for electrical conductivity and temperature. The flow is measured with a “see-saw” flowmeter and occasional data gaps occur if this becomes clogged. The flowmeter was out of action for about a month in late 2023. There is a data gap from late October to late November 2022 and the flowmeter was out of action at the end of 2023. The reduction in flow in March to May 2023 seems to be real although similar drops have been seen in January 2021 and during GPT1 (see Lanyon & Herbert 2021).

During the GFT, the outflow temperature is roughly constant at a little above 15 °C, slightly below the temperature in the tunnel and above that measured in the GAST seal section. The EC shows the “normal” pulse pattern varying between 2,000 and 5,000 $\mu\text{S}/\text{cm}$. The height of the EC pulses seems to decrease in late 2022 and stays below 3,000 $\mu\text{S}/\text{cm}$ for the remainder of the GFT. Higher EC was detected in 2024.

In summary, drainage outflow has largely continued, as would be expected, during the GFT with some minor changes in the EC of the outflow. There was a clear drop in flow during spring 2023, but similar periods have been observed before. It was not possible to correlate them with specific conditions in the experiment or geosphere.

The drainage lines are located at the tunnel wall and below the main duct, outside the ring of the GBM, and it is thought unlikely that they play any significant role in the GFT.

App. H Effective properties for sand/bentonite and gas path

Author: G.W. Lanyon

H.1 Hydraulic conductivity/permeability

Lanyon et al. (2022) suggest ranges for the effective hydraulic conductivity of the sand/bentonite from laboratory studies, in-situ test flow measurements during saturation, and small-scale testing in the PPEs. They further compare these with estimates derived from inverse modelling of the in-situ test. The suggested property ranges are listed in Tab. H-1.

Tab. H-1: Effective hydraulic properties of the sand/bentonite (GAST in-situ experiment)

Property	Best estimate	Range	Comment
Hydraulic conductivity [m/s] Horizontal/normal to compaction_	3.5×10^{-11}	$2 - 5 \times 10^{-11}$	See Fig. H-1 and Lanyon et al. (2022)
Hydraulic conductivity [m/s] Vertical /parallel to compaction_		$<1.3 \times 10^{-11}$	
Storage [m^{-1}]	1×10^{-5}	$4 \times 10^{-6} - 2 \times 10^{-5}$	
Hydraulic diffusivity [m^2/s]	3.5×10^{-6}	$3-7 \times 10^{-6}$	

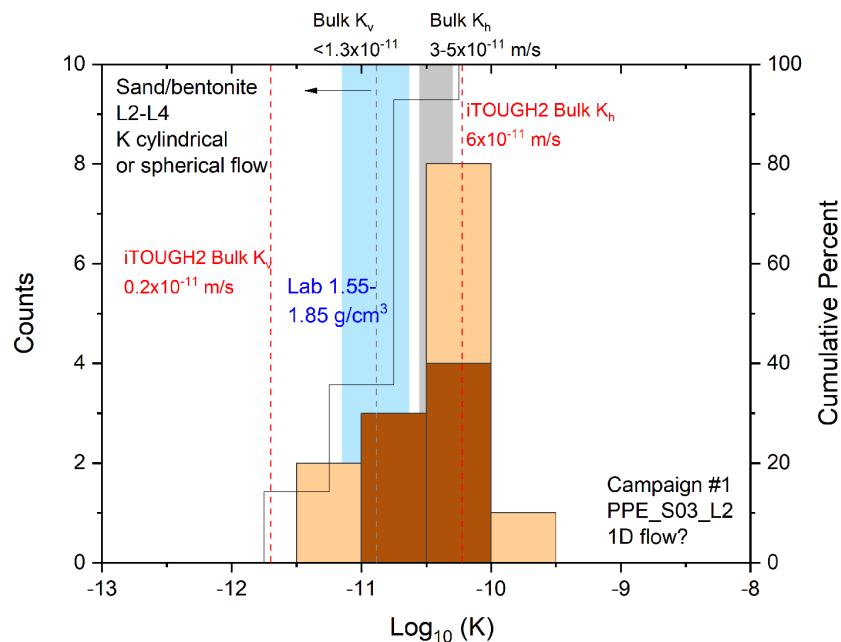


Fig. H-1: Sand/bentonite hydraulic conductivity from laboratory tests, in-situ estimates and small-scale PPE tests

Inverse model estimates from TOUGH2 also shown. Taken from Lanyon et al. (2022).

H.2 Gas path effective properties

Two measures of the effective properties of the gas-flow path have been derived using time-averaged (6 hours) data. The measured data have been used to calculate the “instantaneous” gas recovery (the ratio of the gas mass injected over a 6-hour period to that recovered) and the effective permeability×area of the path.

H.2.1 Instantaneous gas recovery

The instantaneous gas fraction is calculated as:

$$F_{gas} = \frac{Q_{S14}}{Q_{STP}} \frac{P_{Syringe} T_{STP}}{P_{STP} T_{Syringe}}$$

$$F_{gas} = \frac{Q_{Syringe}}{Q_{STP}} \frac{P_{Syringe} T_{STP}}{P_{STP} T_{Syringe}}$$

where $P_{Syringe}$ is taken as the PPE_S14_L1 pressure and $T_{Syringe}$ is 16 °C. The calculated quantity is unreliable when flow rates change rapidly. Where the syringe pump flowrate is calculated from the cumulative volume, the quantity can be noisy but is most representative during the period when constant rates are used for both injection and extraction.

F_{gas} is sensitive to any miscalibration of the gas flowmeter or syringe pump (assumed small). During the period from 26.01.23 to 22.03.23 when the Alicat flowmeter (FG_Inj_Mass) was used in constant pressure mode, a somewhat lower value of F_{gas} is calculated which indicates that the conversion to mL/min used could overestimate the gas flow.

H.2.2 Effective permeability×area

The effective permeability×area $k_{gas}A$ was calculated directly²⁷ from the measured gas flow rate and the pressures in the S02 and S14 filters (PPE_S02_L1 and PPE_S14_L1) as:

$$k_{gas}A = \frac{2Q_{STP}P_{STP}\nu L_{path}}{(P_{S02}^2 - P_{S14}^2)}$$

where:

P_{S02}, P_{S14} : pressure at L1 in the two filters (Pa)

L_{path} : path length S02-S14 (8 m)

P_{STP} : STP pressure (101.3 kPa)

Q_{STP} : volumetric flow at STP (m³N/s)

ν : nitrogen viscosity (1.74×10⁻⁵ Pa.s)

²⁷ See (Bird et al. 2007) Chapter 2 for the mass rate of flow of an ideal gas in laminar flow in a long circular tube.

The calculation assumes uniform, steady isothermal flow conditions, 100% recovery of the gas (no losses) and constant gas viscosity. It is intended to be used as an indicator of the change in resistance to gas flow across the sand/bentonite during the GFT. It is important to note that the effective permeability is not an intrinsic property of the medium but a measure of the flow capacity of the gas phase in the presence of water and is therefore saturation-dependent.

Detailed estimates of the permeability of the sand/bentonite to gas would require more elaborate models accounting for geometry of the flow path, gas saturation, gas losses and variations in gas viscosity. Tab. H-2 gives indicative cross-section areas of the sand/bentonite but the flow-path geometry is uncertain.

Tab. H-2: Cross-section area of sand/bentonite

	Area [m ²]	Remark
Total cross-section of sand/bentonite	5.74	Observations suggest that the path is localised and heterogeneous such that the flow path “area” may vary across the seal and may only be a small fraction of the total area of the sand/bentonite
Cross-section L3 – L6	3.47	
Cross-section L4 – L6	2.0	