

Arbeitsbericht NAB 21-22

**TBO Bözberg-2-1:
Data Report**

**Dossier VI
Wireline Logging, Micro-hydraulic
Fracturing and Pressure-meter Testing**

April 2022

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

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**TB0 Bözberg-2-1:
Data Report**

**Dossier VI
Wireline Logging and Micro-hydraulic
Fracturing**

April 2022

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in situ testing, micro-hydraulic fracturing

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

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

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

This Dossier was prepared by a project team consisting of:

J. Gonus (petrophysics QC, theoretical concepts and log analysis)

E. Bailey (introductory chapters, BHI QC and project management)

J. Desroches (MHF QC and theoretical concepts)

R. Garrard (coordination and QC review)

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Petrophysical log graphic files were created using Geolog Emerson E&P Software - Emerson Paradigm and Terrastation.

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

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- Appendix D: Pre- vs. post-MHF borehole imagery
- Appendix E: MHF pressure-time and reconciliation plots
- Appendix F: PMT related pressure-time plots

Note: The Appendices A – F are only included in the digital version of this report and can be found under the paper clip symbol.

1 Introduction

1.1 Context

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

In this report, we present the results from the Bözberg-2-1 borehole.

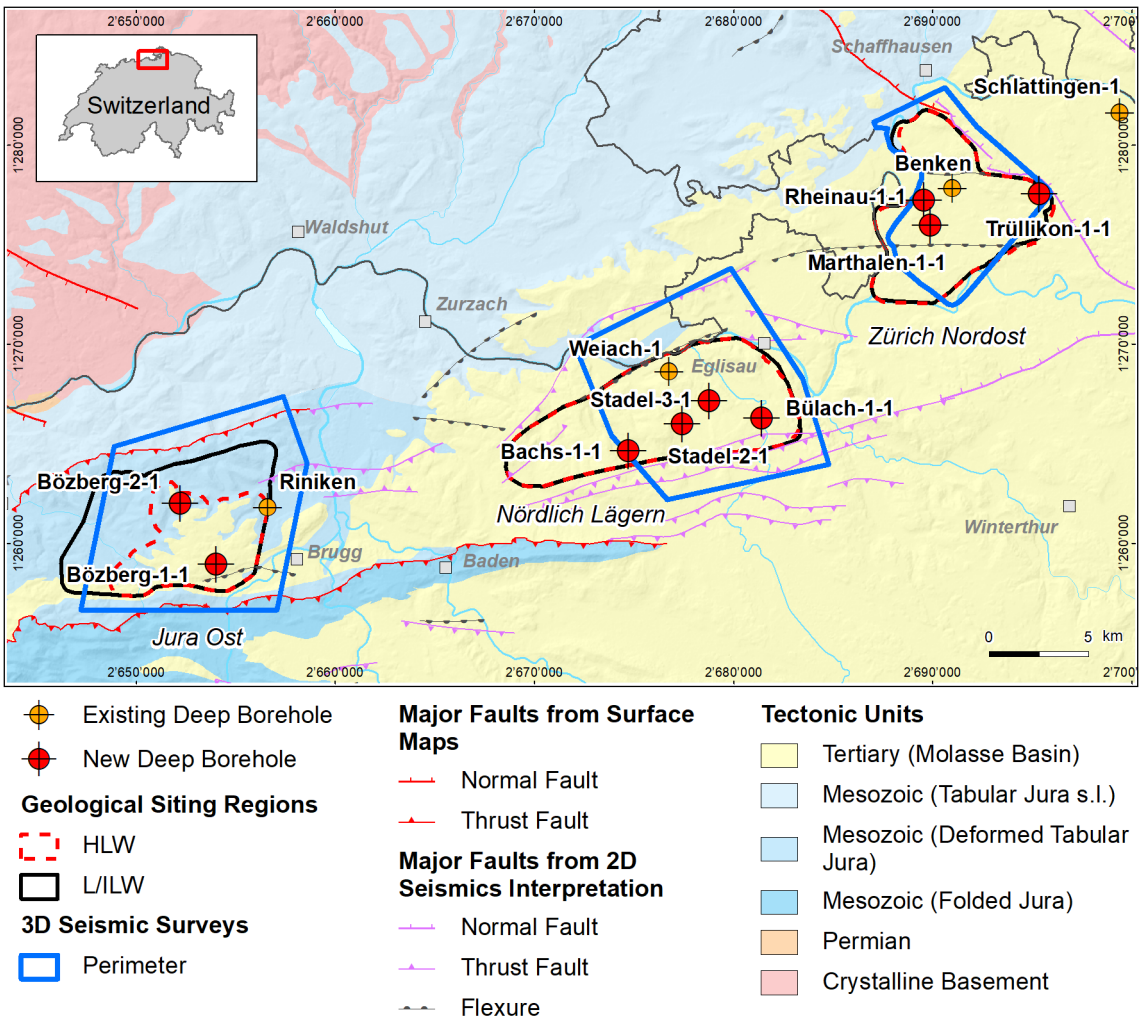


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Bözberg-2-1 (BOZ2-1) exploratory borehole is the fifth borehole drilled within the framework of the TBO project. The drill site is located in the northern part of the Jura Ost siting region (Fig. 1-2). The vertical borehole reached a final depth of 829.11 m (MD)¹. The borehole specifications are provided in Tab. 1-1.

Tab. 1-1: General information about the BOZ2-1 borehole

Siting region	Jura Ost
Municipality	Bözberg (Canton Aargau / AG), Switzerland
Drill site	Bözberg-2 (BOZ2)
Borehole	Bözberg-2-1 (BOZ2-1)
Coordinates	LV95: 2'652'218.764 / 1'261'985.437
Elevation	Ground level = top of rig cellar: 624.33 m above sea level (asl)
Borehole depth	829.11 m measured depth (MD) below ground level (bgl)
Drilling period	11th August – 14th December 2020 (spud date to end of rig release)
Drilling company	Daldrup & Söhne AG
Drilling rig	Wirth B 152t
Drilling fluid	Water-based mud with various amounts of different components such as ² : 0 – 370 m: Bentonite & polymers 370 – 615 m: Potassium silicate & polymers 615 – 829.11 m: Pure-Bore®

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. The comparison of the core versus log depth³ of the main lithostratigraphic boundaries in the BOZ2-1 borehole is shown in Tab. 1-2.

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

² For detailed information see Dossier I.

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

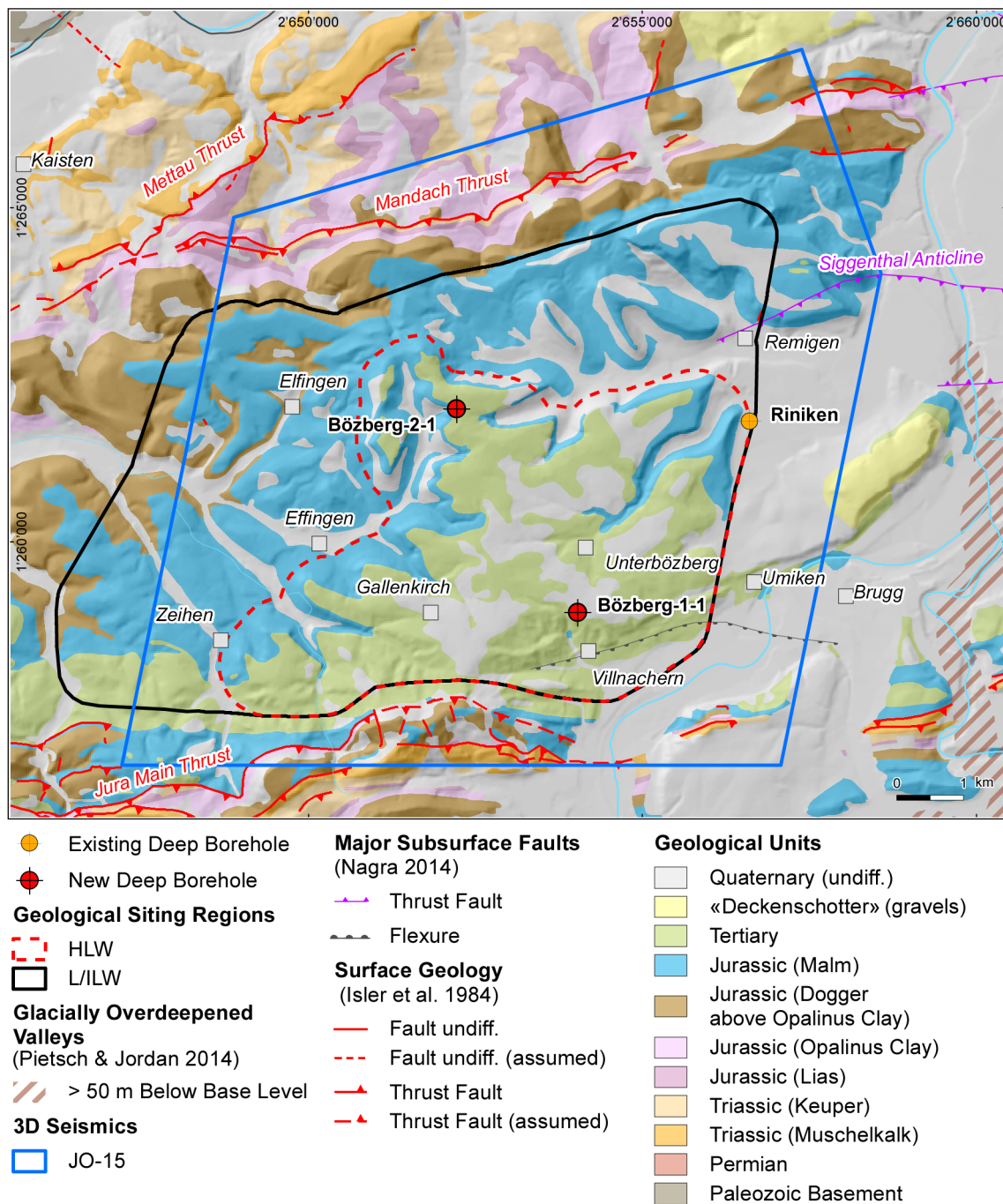


Fig. 1-2: Overview map of the investigation area in the Jura Ost siting region with the location of the BOZ2-1 borehole in relation to the boreholes Riniken and BOZ1-1

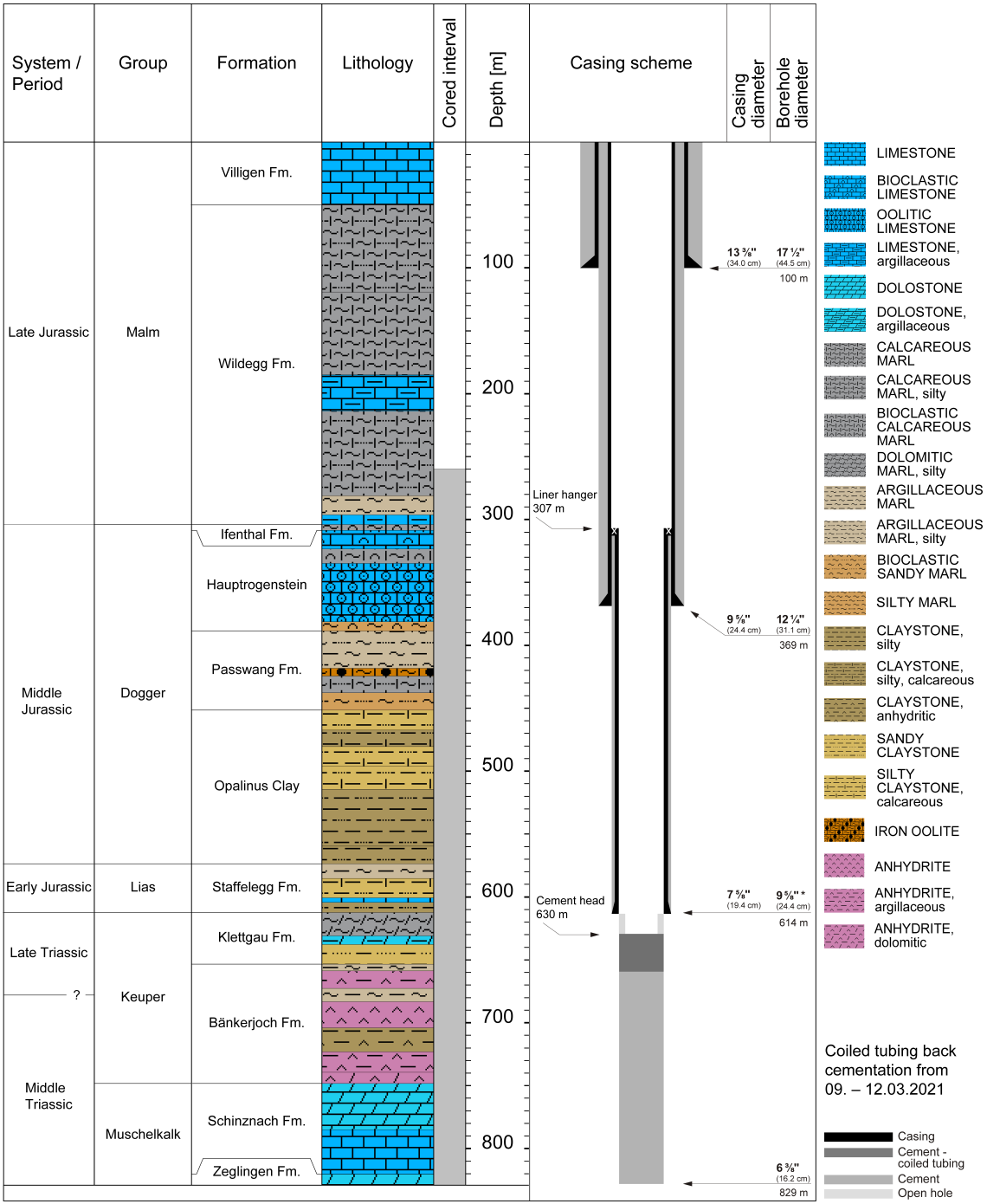


Fig. 1-3: Lithostratigraphic profile and casing scheme for the BOZ2-1 borehole⁴

⁴ For detailed information see Dossier I and III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the BOZ2-1 bore-hole⁵

System / Period	Group	Formation	Core depth in m (MD)	Log
Jurassic	Malm	Villigen Formation	50.0	—
		Wildegge Formation	303.95	304.38 —
	Dogger	Ifenthal Formation	308.70	309.07 —
		Hauptrogenstein	388.54	388.97 —
		Passwang Formation	451.54	451.90 —
		Opalinus Clay	573.68	573.89 —
	Lias	Staffellegg Formation	612.46	612.76 —
Triassic	Keuper	Klettgau Formation	653.45	654.70 —
		Bänkerjoch Formation	748.27	749.52 —
		Schinznach Formation	820.32	821.09 —
	Muschelkalk	Zeglingen Formation	829.11	829.88 —
			final depth	

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

1.3 Documentation structure for the BOZ2-1 borehole

NAB 21-22 documents the majority of the investigations carried out in the BOZ2-1 borehole, including laboratory investigations on core material. The NAB comprises a series of stand-alone dossiers addressing individual topics and a final dossier with a summary composite plot (Tab. 1-3).

This documentation aims at early publication of the data collected in the BOZ2-1 borehole. It includes most of the data available approximately one year after completion of the borehole. Some analyses are still ongoing (e.g. diffusion experiments, analysis of veins, hydrochemical interpretation of water samples) and results will be published in separate reports.

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

Tab. 1-3: List of dossiers included in NAB 21-22

Black indicates the dossier at hand.

Dossier	Title	Authors
I	TBO Bözberg-2-1: Drilling	P. Hinterholzer-Reisegger
II	TBO Bözberg-2-1: Core Photography	D. Kaehr & M. Gysi
III	TBO Bözberg-2-1: Lithostratigraphy	P. Jordan, P. Schürch, H. Naef, M. Schwarz, R. Felber, T. Ibele & M. Gysi
IV	TBO Bözberg-2-1: Microfacies, Bio- and Chemostratigraphic Analyses	S. Wohlwend, H.R. Bläsi, S. Feist-Burkhardt, B. Hostettler, U. Menkveld-Gfeller, V. Dietze & G. Deplazes
V	TBO Bözberg-2-1: Structural Geology	A. Ebert, L. Gregorczyk, S. Cioldi, E. Hägerstedt & M. Gysi
VI	TBO Bözberg-2-1: Wireline Logging, Micro-hydraulic Fracturing and Pressure-meter Testing	J. Gonus, E. Bailey, J. Desroches & R. Garrard
VII	TBO Bözberg-2-1: Hydraulic Packer Testing	R. Schwarz, M. Willmann, S. Reinhardt, S.M.L. Hardie, M. Voß & A. Pechstein
VIII	TBO Bözberg-2-1: Rock Properties, Porewater Characterisation and Natural Tracer Profiles	T. Gimmi, L. Aschwanden, L. Camesi, E. Gaucher, A. Jenni, M. Kiczka, U. Mäder, M. Mazurek, D. Rufer, H.N. Waber, P. Wersin, C. Zwahlen & D. Traber
IX	TBO Bözberg-2-1: Rock-mechanical and Geomechanical Laboratory Testing	E. Crisci, L. Laloui & S. Giger
X	TBO Bözberg-2-1: Petrophysical Log Analysis	S. Marnat & J.K. Becker
	TBO Bözberg-2-1: Summary Plot	Nagra

1.4 Scope and objectives of this dossier

The dossier at hand describes the acquisition, quality control and results of the Petrophysical Logging (PL), Micro-hydraulic Fracturing (MHF) and Pressure-meter Testing (PMT) wireline logging measurements performed in the BOZ2-1 borehole.

Petrophysical log measurements were acquired in open borehole conditions (no casing) with wireline conveyed logging tools to determine continuous profiles across the borehole of physical and chemical properties of the formation, including its mineralogy, clay types, porosity, fluid content, and acoustic properties. Petrophysical logs were further acquired to obtain high-resolution circumferential images of the borehole wall, as well as to measure borehole physical parameters such as its geometry, mud resistivity and mud temperature. In addition to the open hole logs, temperature logs were acquired post-completion to measure the undisturbed mud temperature.

A series of in situ stress measurements were performed using the micro-hydraulic fracturing technique to estimate the orientation and magnitude of the earth stress at different depths. The objectives of the MHF testing programme were to provide estimates of the in-situ stress state in the Opalinus Clay potential rock host and adjacent rock formations as well as calibration points for mechanical earth models (MEM) of the rock mass (both 1D and 3D).

Pressure-meter testing was performed at the same time as MHF testing using the same module that was used to perform sleeve fracturing and sleeve reopening during MHF operations. As this was a new application of the tool, the primary objectives of the PMT were to explore the best tool string combination and protocol to obtain an interpretable pressure record from which the in-situ shear modulus of the formation can be estimated. PMT results can then be used for comparison with future dilatometer tests which are planned in the Stadel-3-1 (STA3-1) and Stadel-2-1 (STA2-1) boreholes.

All PL, MHF and PMT testing were performed by the wireline logging company Schlumberger (SLB). Ad Terra Energy (formerly Geneva Petroleum Consultants International) were responsible for planning wireline operations, technical supervision at the worksite, quality assurance and control (QA-QC) of data, database management and general wireline logging support.

This dossier is organised as follows:

- Chapter 2: The sequence of events for PL and MHF testing operations, and associated log / data coverage is provided.
- Chapter 3: The QA-QC procedure used to assess the quality of the petrophysical logs is detailed. A continuous profile of each log across the entire measured depth of the borehole is quality-controlled, corrected and spliced together to generate a quality-controlled composite log. The results of the composite log are discussed. The composite log will then be used as the final log data for input into further data analysis processes such as formation evaluation (e.g. Stochastic Petrophysical Log Analysis described in Dossier X), calibration with seismic data and integration with sedimentology and structural geology data (from cores, cuttings, adjacent boreholes and regional geology).

- Chapter 4: Although Borehole Imagery (BHI) logs were acquired as part of the petrophysical logging, the objectives of BHI are related to both Structural Geology (analysis of image features described in Dossier V) and MHF (firstly the selection of stations for MHF stress measurements, then the analysis of fractures induced by MHF tests). Thus, the QC, processing and interpretation processes of BHI are described in a chapter separate from the QA-QC procedures of the other petrophysical logs in Chapter 3.
- Chapter 5: MHF test procedures and preliminary results are presented.
- Chapter 6: PMT procedures and preliminary results are presented.
- Finally, this report includes a set of appendices, where spliced PL, pre- and post-MHF borehole images and MHF / PMT data can be found.

2 Wireline logging and testing operations

The BOZ2-1 borehole was planned in 3 drilling sections (also commonly referred to as phases). After drilling the 12¼" pilot hole to 17.5 m MD, Section I was drilled destructively in 8½" to 260 m MD. Due to unstable conditions in the upper part of the borehole, the borehole was reamed (opened up) to 101 m MD with the 17½" drill bit and the 13¾" OD conductor casing installed. The rest of the section was continuously cored in 6¾" from 260 m to 370 m MD, before reaming to 8½" for petrophysical logging and MHF testing. The remainder of Section I was then reamed to 12¼" to accommodate the 9⅝" OD casing. Section II was continuously cored and logged in 6¾", before reaming to 8½" for MHF and PMT and finally underreaming to 9⅝" to install the 7⅝" liner. While coring Section III, mud losses were encountered in the Muschelkalk between 805 m and 829 m MD. Lost circulation material (LCM) was used to cure losses, which allowed coring to continue until final depth of 829.11 m MD. During the subsequent petrophysical logging in the 6¾" borehole, adverse hole conditions were encountered, which despite two wiper trips could not be improved. As a result, logging was limited to tools that do not contain a radioactive source and MHF / PMT were cancelled. Once open borehole logging / testing operations were completed, the borehole was backfilled with cement up to 660 m MD. One post-completion, petrophysical log was acquired to measure the undisturbed mud temperature. Detailed descriptions of the borehole design and mud conditions at the time of logging and testing are included in the Excel Composite Report (Appendix A), under the worksheets entitled 'Borehole design' and 'Hole & mud system'. Additional details about borehole configuration, casing and cementing scheme and mud parameters can be found in Dossier I.

Wireline logging and testing operations were divided into the following groups of activities:

- Petrophysical Logging (PL)
- Micro-hydraulic Fracturing (MHF)
- Pressure-meter Testing (PMT)
- *Technical Logging (TL)*
- *Vertical Seismic Profiling (VSP)*

Petrophysical logs are continuous measurements (normally recorded every half foot or approximately 15 cm) of mineralogy and physical properties of formation rocks, their contained fluids, and the borehole environment between the wireline conveyed logging tool sensors and the borehole wall. Petrophysical logs were acquired with conventional and advanced wireline-conveyed logging tools. Conventional tools measured Depth (measured depth [MD], or log depth, that is the depth reference for all wireline measurements), Total Gamma Ray (naturally occurring gamma radiation), Spontaneous Potential (electric potential difference between the formation and an electrode at surface), Temperature, Caliper (measurement of the borehole diameter), Inclino-meter (measurement of the borehole trajectory), as well as the standard "quad combo" tools: Resistivity (electrical resistivity at different depths of investigation in the formation), Sonic (compressional and shear wave slowness), Density (measurement of the bulk density and the photo-electric factor), and Neutron (measurement of the neutron hydrogen index, a proxy of porosity, as well as the sigma capture cross-section). Advanced tools measured the Spectral Gamma Ray (potassium, thorium and uranium contributions to the total naturally occurring gamma radiation), Elemental Spectroscopy, and Microresistivity and Ultrasonic borehole images. These logging tools and their main measurements are described in detail in the subsequent Chapter 3 – Petrophysical Logging and Chapter 4 – Borehole Imagery.

MHF involves using wireline-conveyed testing equipment to initiate and analyse the characteristics of micro-hydraulic fractures through several opening / closure cycles, to estimate the current stress state in the rock formation at the 1 m scale. Tests were conducted using the SLB Modular Formation Dynamics Tester (MDT), which uses packer modules, surface-controlled downhole valves, downhole pressure gauges and a downhole pump to initiate and propagate fractures at predefined discrete depths. MHF tests are described in Chapter 5 – Micro-hydraulic Fracturing.

PMT was conducted using the single packer module from the MDT tool that is used to perform sleeve fracturing and reopening operations during MHF testing. Different protocols were explored to find the optimal methodology for obtaining an interpretable pressure record in the formation of interest. PMT tests are described in Chapter 6 – Pressure-meter Testing.

As well as PL and MHF / PMT operations, wireline operations also included Technical Logging (TL) and Vertical Seismic Profiling (VSP). TL acquired data on the physical properties of the open borehole (geometry and trajectory) and the permanent casing installation. The borehole geometry was measured using calipers for both assessing the borehole condition (breakouts / wash-outs present) and determining the volume of cement needed for casing installations. The borehole inclination and azimuth were measured to confirm the borehole verticality and identify its trajectory. To assess the quality of the cement behind the casing, Cement Bond Logs (CBL) and acoustic impedance logs were acquired using sonic (MSIP) and ultrasonic imaging (USIT) tools. Borehole deviation surveys, cement volume calculations and CBL logs are described in Dossier I. VSP acquired high resolution borehole seismic measurements used for correlation with, and enhancement of, surface seismic data. VSP will be addressed in a separate document. TL and VSP are not described further in this report.

A summary of all wireline logging and testing activities carried out in the BOZ2-1 borehole is given in Tab. 2-1. Fig. 2-1 depicts graphically the log coverage for the PL, MHF / PMT campaigns. In total, 4 PL, 2 MHF and 1 PMT campaigns were undertaken. Open hole PL was conducted in Sections I to III of BOZ2-1, whereas MHF testing was limited to Sections I and II due to the adverse hole conditions encountered in Section III. PMT was focused on the Opalinus Clay host rock and therefore only undertaken in Section II. A more detailed analysis of the log measurement coverage is provided in Chapter 3.

Details of the logging runs, logging dates, wireline logging company, logging interval, logging suite and principal measurements acquired for PL and MHF / PMT operations are provided in Tab. 2-2. Mnemonics for each tool in the logging suite listed in this table are given in Tab. 2-3.

Tab. 2-1: Logging and testing activities during drilling of the BOZ2-1 borehole

Drilling phase / section	Permanent casing size Casing / liner shoe depth	Open hole interval and bit size	Start date	End date	Coring	Technical logging	Petrophysical logging	Micro-hydraulic fracturing	Pressure-meter testing	Vertical seismic profiling
I	13 $\frac{3}{8}$ " 0 to 100 m	100 to 102 m in 12 $\frac{1}{4}$ " 102 to 370 m in 8 $\frac{1}{2}$ "	11.08.2020	19.09.2020	×	×	×	×		
II	9 $\frac{5}{8}$ " 0 to 369 m	369 to 372 m in 8 $\frac{1}{2}$ " 372 to 615 m in 6 $\frac{3}{8}$ "	19.09.2020	19.11.2020	×	×	×			
		369 to 615 m in 8 $\frac{1}{2}$ "					×	×	×	
		369 to 370 m in 8 $\frac{1}{2}$ " 370 to 615 m in 9 $\frac{7}{8}$ "				×				
III	7 $\frac{7}{8}$ " 310 to 614 m	614 to 829.11 m in 6 $\frac{3}{8}$ "	19.11.2020	14.12.2020	×	×	×			×

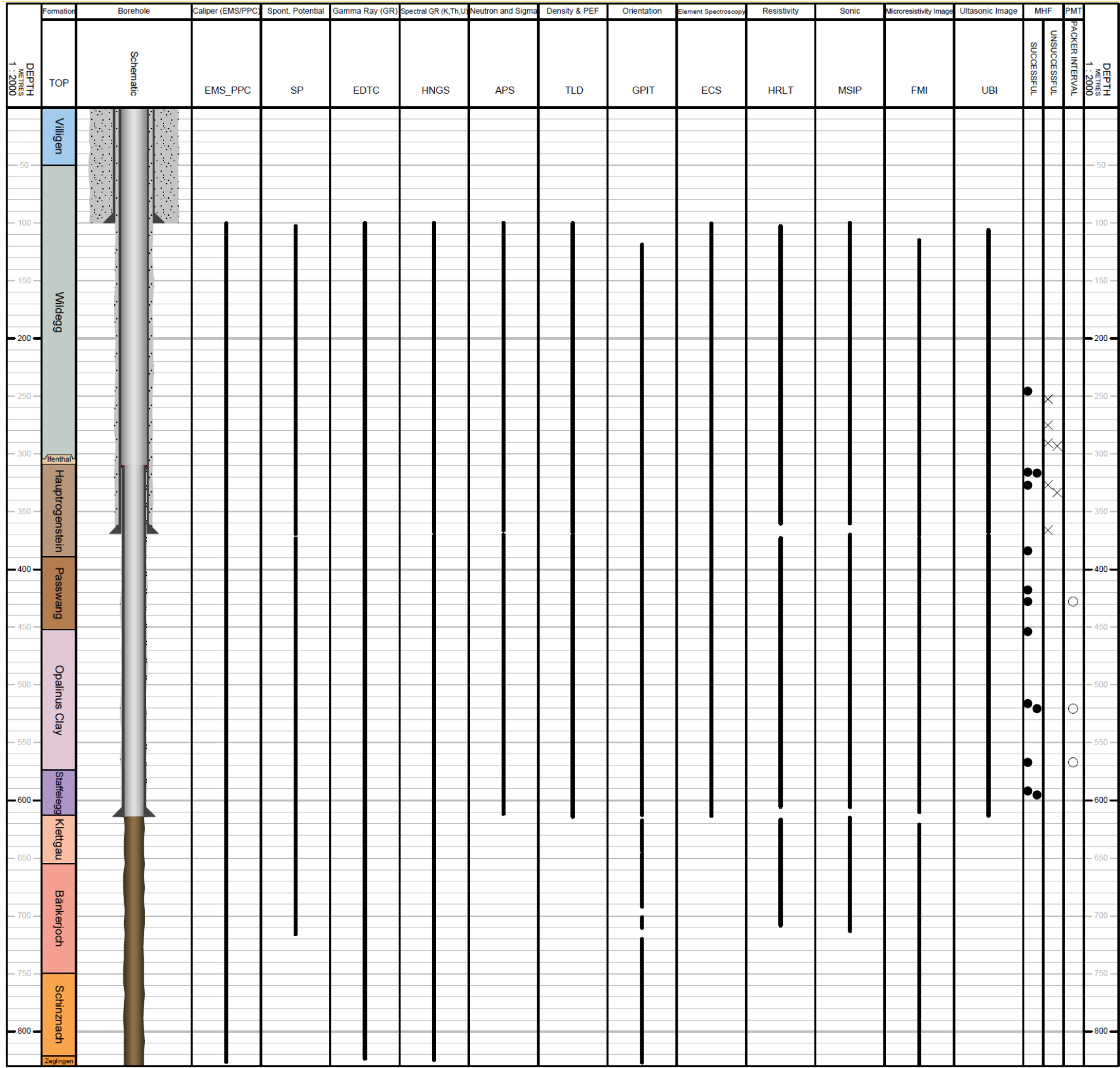


Fig. 2-1: Petrophysical log and MHF testing coverage at BOZ2-1 (scale of 1:2'000)

Tab. 2-2: Logging and testing sequence of events (only PL and MHF)

Phase / Section	Run	Operation	Logging date	Contractor	Logging interval [m MD]	Logging suite (see list of abbreviations)	Measurements															Remarks	
							Gamma ray	Resistivity	Microresistivity	Density	Sonic	Neutron hydrogen index	Sigma capture cross-section	Photoelectric factor	Spontaneous potential	Borehole imaging	Caliper	Spectral gamma ray	Elemental spectroscopy	Inclinometer	Temperature		MHF / PMT
I	1.1.1	PL	31.08.2020	SLB	115 to 370.2	FMI-EMS-EDTC-LEH.QT	×									×	×			×	×		GR reference for subsequent runs
	1.1.2		31.08.2020	SLB	100 to 368.22	PPC-MSIP-PPC-GPIT-EDTC-LEH.QT	×				×					×			×				
	1.1.3		01.09.2020	SLB	100 to 368.0	TLD-MCFL-EDTC-LEH.QT	×		×	×				×									
	1.1.4		01.09.2020	SLB	100 to 365.9	APS-EMS-EDTC-LEH.QT	×					×	×				×				×		
	1.1.5		01.09.2020	SLB	100 to 368.2	ECS-EDTC-LEH.QT	×												×				
	1.1.6		01.09.2020	SLB	100 to 367.51	HNGS-EDTC-LEH.QT	×											×					
	1.1.7		01.09.2020	SLB	100 to 370.19	SP-EMS-HRLT-EDTC-LEH.QT	×	×								×		×			×		
	1.2.1	PL	08.09.2020	SLB	100 to 369.1	EMS-EDTC-LEH.QT	×										×				×		
	1.2.2		08.09.2020	SLB	106.2 to 368.2	UBI-GPIT-EDTC-LEH.QT	×									×				×			
	1.2.3	MHF	08.09.2020	SLB	2 successful MHF tests out of 9 1 HTPF test	MRPA(dual)-MRPA(single)-MRSC(exit)-MRPO(HP)-4xMRSC(water)-MRSC(exit)-MRPC-EDTC-LEH.QT																×	Unable to breakdown formation
	1.3.1		11.09.2020	SLB		MRPA(dual)-MRPA(single)-MRSC(exit)-MRPO(HP)-MRSC(exit)-MRPO(XP)-4xMRSC(water)-MRSC(exit)- MRPC-EDTC-LEH.QT																×	Frac12K and XP pump added;
	1.3.2		11.09.2020	SLB																		×	Wiper trip before this run
	1.3.3	PL	12.09.2020	SLB		100 to 365.7	FMI-EDTC-LEH.QT	×									×	×			×		

Tab. 2-2: continued

Phase / Section	Run	Operation	Logging date	Contractor	Logging interval [m MD]	Logging suite (see list of abbreviations)	Measurements															Remarks			
							Gamma ray	Resistivity	Microresistivity	Density	Sonic	Neutron hydrogen index	Sigma capture cross-section	Photoelectric factor	Spontaneous potential	Borehole imaging	Caliper	Spectral gamma ray	Elemental spectroscopy	Inclinometer	Temperature		MHF / PMT		
II	2.1.1	PL	28.09.2020	SLB	373.5 to 610	FMI-EMS-EDTC-LEH.QT	×									×	×			×	×				
	2.1.2		28.09.2020	SLB	n/a	PPC-MSIP-PPC-GPIT-EDTC-LEH.QT	×				×						×			×				Run abandoned as lower PPC failed to close after main pass; tool string was pulled out of hole (POOH) and lower PPC removed	
	2.1.3		28.09.2020	SLB	369 to 614.02	MSIP-PPC-GPIT-EDTC-LEH.QT	×				×						×			×				Re-run with only upper PPC	
	2.1.4		29.09.2020	SLB	369 to 614.93	TLD-MCFL-EDTC-LEH.Q	×		×	×				×											
	2.1.5		29.09.2020	SLB	369 to 611.58	APS-EMS-EDTC-LEH.QT	×					×	×				×					×			
	2.1.6		29.09.2020	SLB	369 to 613.7	ECS-EDTC-LEH.QT	×												×						Main pass broken into two due to problems with power cycle
	2.1.7		29.09.2020	SLB	369 to 612.91	HNGS-EDTC-LEH.QT	×											×							
	2.1.8		30.09.2020	SLB	369 to 615.59	SP-HRLT-EMS-EDTC-LEH.QT	×	×								×		×				×			
	2.3.1	PL	06.11.2020	SLB	369 to 614.48	EMS-EDTC-LEH.QT	×										×					×			
	2.3.2		06.11.2020	SLB	370.5 to 613.2	UBI-GPIT-EDTC-LEH.QT	×									×				×					
	2.3.3	MHF	06.11.2020	SLB	9 successful MHF tests out of 9 3 PMT tests	MRPA(dual)-MRPA(single)-MRSC(exit)-2xMRSC(Forced Closure)MRPO(HP)-MRSC-MRPO(XP)-4xMRSC(water)-MRSC(exit)-MRPC-EDTC-LEH.QT																	×	Plus PMT reference test in casing.	
	2.3.4	PL	10.11.2020	SLB	373.1 to 612.5	FMI-EDTC-LEH.QT	×										×	×			×				

Tab. 2-2: continued

Phase / Section	Run	Operation	Logging date	Contractor	Logging interval [m MD]	Logging suite (see list of abbreviations)	Measurements															Remarks	
							Gamma ray	Resistivity	Microresistivity	Density	Sonic	Neutron hydrogen index	Sigma capture cross-section	Photoelectric factor	Spontaneous potential	Borehole imaging	Caliper	Spectral gamma ray	Elemental spectroscopy	Inclinometer	Temperature		MHF / PMT
III	3.1.1	PL	09.12.2020	SLB	621 to 828.4	FMI-EMS-EDTC-LEH.QT	×									×	×			×	×		Mud losses encountered before RIH; only main pass recorded as data quality affected by poor hole conditions; wiper trip to clean the hole prior to next run
	3.2.1		09.12.2020	SLB	614 to 829.79	EMS-EDTC-LEH.QT	×									×				×			Run added to evaluate the hole conditions after wiper trip
	3.2.2		10.12.2020	SLB	614 to 827.23	HNGS-EDTC-LEH.QT	×										×						Planned UBI run was abandoned due to poor hole condition and replaced with HNGS run
	3.2.4		10.12.2020	SLB	614 to 720.24	PPC-MSIP-PPC-GPIT-EDTC-LEH.QT	×					×					×				×		TD not reached and repeat pass cancelled due to adverse hole conditions; decision to do another wiper trip
	3.3.1		11.12.2020	SLB	614 to 718.72	SP-EMS-HRLT-EMS-LEH.QT	×	×								×		×				×	

Tab. 2-3: Tool mnemonics and measurement details

Logging tool	Wireline contractor	Mnemonic	Principal measurement
APS	SLB	Accelerator porosity sonde	Epithermal and thermal neutrons, sigma capture cross-section of thermal neutrons
ECS	SLB	Elemental capture spectroscopy sonde	Measurement of the relative dry weight element concentration (e.g. Si, Ca, Fe, S, Ti, Gd, Cl and H) and mineralogical model
EDTC	SLB	Enhanced digital telemetry cartridge	Gamma ray measurement of the total natural radioactivity
EMS	SLB	Environmental measurement sonde	6-arm caliper, temperature and mud resistivity
FMI	SLB	Fullbore formation microimager	Microresistivity imaging tool (pad contact)
GPIT	SLB	General purpose inclinometry tool	Orientation/inclination of the borehole
HNGS	SLB	Hostile natural gamma ray sonde	Spectral gamma ray measurements of natural radioactivity (potassium, thorium, uranium)
HRLT	SLB	High resolution laterolog array tool	Laterolog resistivity measurement at different depths of investigation
LEH.QT	SLB	Logging equipment head with tension	Head tension
MCFL	SLB	Microcylindrically focused log	Measures the invaded zone resistivity (RXO)
MRPA	SLB	Packer modules	Packer modules for stress measurements: - Dual (straddle) for MHF tests - Single for sleeve fracturing, sleeve reopening and PMT tests
MRPO	SLB	Pump out module	Downhole pump for MHF / PMT tests
MRSC	SLB	Sample chamber	Typically used to carry fluid for MHF / PMT, usually filled with water. Can also be configured as an exit port.
MSIP	SLB	Modular sonic imaging platform (sonic scanner)	Compressional, shear and Stoneley wave slowness measurements (monopole and dipole sources); cement bond log
PPC	SLB	Power positioning calipers	4-arm caliper that gives dual axis borehole measurements
SP	SLB	Spontaneous potential	Measurement of electrical potential difference between the borehole and the surface
TLD	SLB	Three-detector lithology density	Bulk density and photoelectric absorption factor measurement
UBI	SLB	Ultrasonic borehole imager	High-resolution acoustic (ultrasonic) images of the borehole

3 Petrophysical Logging (PL)

3.1 Petrophysical logging tools and measurements

Below the main petrophysical measurements acquired, and the downhole logging tools deployed are summarised. A detailed description of how the different tools measure the respective parameters and the underlying physics behind these measurements is not the focus of this report. Borehole imaging tools are described in Chapter 4.

- **Borehole deviation / orientation** (GPIT – General Purpose Inclinerometry Tool). The GPIT outputs inclinometer measurements. Tool orientation is defined by three parameters: tool deviation, tool azimuth and relative bearing. Borehole trajectory is calculated from the inclinometer measurements. Inclinometer measurements serve to reference the oriented logs (e.g. borehole imagery and sonic dipole logs).
- **Caliper log** (EMS/PPC – Environmental Measurement Sonde/Powered Positioning Caliper). The caliper log uses several coupled pairs of mechanical arms (2 pairs with PPC, 3 pairs with EMS) to continuously measure the borehole shape in different orientations.
- **Density** (TLD – Three-detector Lithology Density). TLD is an induced radiation tool that measures the bulk density of the formation and the photoelectric factor (PEF). It uses a radioactive source to emit gamma photons into the formation. The gamma rays undergo Compton scattering by interacting with the atomic electrons in the formation. Compton scattering reduces the energy of the gamma rays in a stepwise manner and scatters the gamma rays in all directions. When the energy of the gamma rays is less than 0.5 MeV, they can undergo photoelectric absorption by interacting with the electrons. The flux of gamma rays that reach each of the detectors of the TLD is therefore attenuated by the formation, and the amount of attenuation is dependent upon the density of electrons in the formation, which is related to its bulk density. The bulk density of a rock is the sum of the minerals (solids) and fluids volumes (porosity) times their densities. Hence, the formation density tool is key for the determination of porosity, the detection of low-density fluids (gasses) in the pores and mineralogical identification. In addition, the TLD provides the **photoelectric absorption index** (photoelectric factor – PEF), which represents the probability that a gamma photon will be photoelectrically absorbed per electron of the atoms that compose the material. The PEF characterises the mineralogy. The TLD tool is housed in the High-Resolution Mechanical Sonde that also includes the Micro-Cylindrically Focused Log (MCFL) sonde, that measures the **microresistivity** or alternatively, the resistivity very close to the borehole wall (RXOZ). The bulk density was integrated over depth, to provide the overburden pressure or vertical stress (Sv).
- **Element Spectroscopy** (ECS – Elemental Capture Spectroscopy). The ECS is also an induced radiation tool with a radioactive neutron source. The ECS measures the concentration of a series of elements in the formation (Si, Ca, Fe, S, Ti, Gd, Cl, H) by analysing the gamma ray spectrum of back scattered gamma rays. Special processing techniques allow under certain circumstances the measurement of supplementary elements such as Al, Mg, K and Na. The element spectroscopy measurements are provided in dry weight concentrations. SLB uses an algorithm in the field to derive a model of dry weight fractions of preset minerals from the dry weight element concentrations: clay, clastics (quartz – feldspar – mica, QFM), carbonates, anhydrite / gypsum, salt / evaporite, pyrite, siderite and coal. Advanced models can discriminate limestone and dolomite from carbonates, as well to provide a more quantitative clay measurement. It is important to note that mineralogy model processing is qualitative and should be viewed as an indicator of lithology and not used in any quantitative analysis. Quantitative analysis of the ECS dry weight elements needs to be calibrated against core data.

Dossier X details stochastic processing and interpretation of the ECS dry weight proportions, combined with conventional petrophysical log response, to generate a quantified lithology determination.

- **Gamma Ray** (GR, from the EDTC – Enhanced Digital Telemetry Cartridge). This log measures the total naturally occurring gamma ray radioactivity in the formation rocks (potassium, thorium and uranium are the most common radioactive elements in Earth's crust), which can be used to determine the volume of clay minerals (that contains those elements). The GR log is not valid for clay determination if other minerals contain those elements in significant amounts (e.g. potassic feldspars, organic matter, phosphates). The GR is run with all logging runs because it is used for depth correlation between runs, thanks to its excellent vertical resolution and character. Note this is not to be confused with the Spectral Gamma Ray which is a different tool detailed further below.
- **Neutron Hydrogen Index, commonly named Neutron** (NHI, from the APS – Accelerator Porosity Sonde). A particular accelerator called a Minitron generates high energy neutrons (14 MeV) that are emitted into the formation. Elastic collisions with the atom nuclei slow down the neutrons, a process that is more efficient with nuclei whose mass is close to that of neutron, i.e., hydrogen (the lightest element). Five detectors count the neutrons back from the formation at different distances from the Minitron, allowing for an environmental compensation of the signal. The received signal is mostly (but not only, for example the chlorine atoms bring a significant contribution) dependent on the hydrogen concentration in the formation, hence the Hydrogen Index (HI) measurement: the larger the count, the lower the HI and its uncertainty. The APS tool can measure both an epithermal HI (APLC curve) and a thermal HI (FPLC). The hydrogen content in rocks is mostly in the fluids contained within, generally water or hydrocarbons, which have a HI close to 1 v/v. Nevertheless, some fluids like gas and high salinity brines have a HI lower than 1 v/v and must be corrected for when interpreting the results. In addition, many hydrated minerals are encountered in sedimentary or crystalline rocks, e.g. clay minerals, gypsum, iron-hydroxides, coals, zeolites, micas and amphiboles. The NHI is commonly used to quantify the fluid volume (porosity) and as a lithological indicator (clay content, hydrogen-rich minerals), mostly in combination with the bulk density measurement.
- **Resistivity** (HRLT – High Resolution Laterolog array Tool). The HRLT measures electrical resistivities at different depths of investigation in the formation. When drilling mud filtrate invades the formation and it has a salinity that contrasts with that of the formation fluids (the chlorine ion Cl^- changes significantly the resistivity of a medium), the resistivities provide an invasion profile. Processing allows the extrapolation of the resistivity measurements far into the formation providing the true formation resistivity, as well as close to the tool providing the microresistivity or resistivity close to the borehole wall. Resistivity is used to interpret the saturation in water or hydrocarbons in pore spaces and for mineralogical identification (e.g., carbonates, clays, salt).
- **Sigma Formation Capture Cross-Section** (SIGF, from APS). In addition to the HI, the APS also measures the sigma formation capture cross-section (SIGF), that is defined as the relative ability of a material to "capture" or absorb free thermal neutrons. SIGF values vary widely with elements, and it can be used to determine the mineralogy and formation fluid contents.
- **Sonic** (MSIP – Modular Sonic Imaging Platform, also named Sonic Scanner). The MSIP measures how fast compressional and shear waves travel in the formation. A pulse sound is emitted from several tool transmitters in all directions. Tool receivers record the waves after they have travelled through a known path in the formation to the borehole wall. Waves travel at different velocities in the drilling fluid (between the tool and the borehole wall) and in the formation. Subtracting the travel time recorded by the near transmitter-receiver pairs from the

travel time recorded by far transmitter-receiver pairs provides the travel time spent in the formation only and thus discards the wave propagation in the fluid. Travel times are converted to wave slowness logs (inverse of velocity) based on the tool geometry. Compressional and shear wave slowness are used to interpret porosity, aid in mineralogy determination, for geo-mechanical and rock strength properties and they serve as calibration for seismic surveys. Other wave propagation such as flexural waves can be used to analyse the acoustic shear anisotropy properties of the formation. The MSIP log products require processing of the raw data to detect the different wave arrivals and transform the multiple transmitter-receiver recordings into unique slowness logs. Field processing products are basic and advanced processing products, such as the anisotropy analysis can be requested at a later stage.

- **Spectral Gamma Ray (SGR)**, from the HNGS – Hostile Natural Gamma Ray Sonde). In addition to the total gamma ray, the HNGS measures the energy spectrum of the formation gamma rays. As the three main radioactive elements (potassium, thorium and uranium) are characterised by a different gamma energy, the tool can quantify those elements' content. Those concentrations can be used to quantify potassium-, uranium- or thorium-rich minerals (e.g. different clay minerals, potassic feldspars, organic matter, phosphates). The HSGR log is the sum of potassium, thorium and uranium gamma ray contributions to the total spectral gamma ray. Note that the total gamma ray from the GR and SGR tools are not necessarily quantitatively equivalent because these tools use different detectors, technologies, tool housing and calibrations. The HCGR log is the result of the HSGR log without the uranium contribution. The shading from HCGR to HSGR in log plots helps identify zones that may contain uranium-bearing organic matter and phosphates.
- **Spontaneous Potential (SP)**. The SP log is a continuous measurement of the electric potential difference between an electrode in the SP tool and a surface electrode. Adjacent to shales, SP readings usually define a straight line known as the shale baseline. Next to permeable formations, the curve departs from the shale baseline; in thick permeable beds, these excursions reach a constant departure from the shale baseline, defining the "sand line". The deflection may be either to the left (negative) or to the right (positive), depending on the relative salinities of the formation water and the mud filtrate. If the formation water salinity is greater than the mud filtrate salinity (the more common case), the deflection is to the left. The movement of ions, essential to develop an SP, is possible only in rocks with some permeability, a small fraction of a millidarcy is sufficient. There is no direct relationship between the magnitude of the SP deflection and the formation's permeability or porosity.
- **Temperature (TMP)**. The temperature log is acquired with the EMS tool that includes a temperature sensor. It is a measurement of the temperature in the borehole environment; thus, it is largely influenced by the temperature of mud. Since the temperature is affected by material outside the casing, a temperature log is sensitive to not only the borehole but also the formation and the casing – formation annulus. Mud temperature is generally less than that of fluids in the formation, but the temperature of the static mud is assumed to converge to the formation temperature after an infinite time. In practice, temperature logs are acquired several times after the last mud circulation, and the formation temperature is modelled based on the observed trend of temperature vs. time at each depth. On one hand, the temperature log is interpreted by looking for larger scale anomalies, or departures, from a reference gradient. This can give indications for permeable zones with fluid flow or for flow barriers hindering cross formational flow. On the other hand, localised smaller scale anomalies may correspond to the entry of borehole mud in the formation or fluid flow from the formation to the borehole. The temperature log should be interpreted together with structural geology, hydrogeology, and the other logs (e.g. images, resistivity logs).

3.2 Log data quality

3.2.1 Quality control procedures

Quality control (QC) of log data is important to guarantee their accuracy, repeatability, traceability, relevance, completeness, sufficiency, interpretability, clarity and accessibility. The generic QC procedures that were followed for each log dataset are presented as follows:

1. Digital data in .dlis format are loaded into a petrophysics software (Paradigm – Geolog) and checked for completeness (Are principal log channels, parameters and constants given?) and accessibility (Do the data load correctly when imported? Is the depth sampling rate steady and valid?).
2. Sufficient data: Do the first and last readings correspond to the interval of logs laid-out in the work programme?
3. Depth match is checked: main pass (or downlog pass if first run in hole) versus reference run, repeat pass(es) versus reference run. GR log of the EDTC tool is always used for correlation because it has excellent vertical resolution and sufficient character. Schlumberger depth matches data in the field but sometimes additional depth-matching is required during QC. Such depth shifts are recorded in Appendix A8 – Table of post-acquisition depth shifts.
4. Are the callipers well calibrated? This is checked by comparing calliper measurements against the nominal inner diameter of the casing.
5. Borehole shape is checked: Are there washouts? Is the borehole on gauge? Undergauge? Ovalised? Are there breakouts? Hole restrictions? If the borehole shape is not gauge, the log quality can be degraded.
6. Cable tension is checked: does the cable tension show any overpulls or stick and pull events? These events can cause a locally discontinuous depth log measurement and alter the tool positioning which impacts the log quality. The tension log is also used to check that the logger depth is consistent with the tension pick-up.
7. Graphic files (log plots) are checked for completeness, consistency and accuracy. In particular, the following sections of the graphic files are checked:
 - 7.1 Header: e.g. logging date, run number, mud parameters
 - 7.2 Borehole sketch and size / casing record: hole bit sizes and depths, casing sizes, weight and depth
 - 7.3 Borehole fluids: accuracy of mud physical parameters
 - 7.4 Remarks and equipment summary: serial numbers of equipment, completeness and accuracy of remarks
 - 7.5 Depth control parameters: right depth control procedure and log of reference
 - 7.7 Summary of run passes: top and bottom of pass, automatic bulk shift applied
 - 7.7 Log (content and display): mnemonics, description, unit, scale, colour and label of logs; display of logs, log quality control (LQC) or data copy indicator curves provided (if applicable)
 - 7.8 Channel processing parameters, tool control parameters: corrections or offsets applied to measurements, modes of acquisition, etc.
 - 7.9 Accelerometer and magnetometer crossplots provided (if applicable)
 - 7.10 Calibration reports: validity of master calibration and before calibration (if applicable), all calibrations within tolerances

8. Data repeatability for main vs. repeat passes (or downlog pass if applicable) is checked for a selection of important logs.
9. Were required, environmental corrections applied with the correct parameter values (e.g. mud salinity, mud weight, drill bit size, tool standoff, pressure / temperature).
10. Were processing parameters correctly applied (e.g. ECS minerals model options, MSIP time windows, APS lithology conversions)?
11. Data consistency is checked, including a comparison with logs from other runs via log plot and crossplots and the description of the cuttings for lithology. Are logs representative of expected lithologies and do they respond consistently?
12. Are orientation, accelerometer and magnetometer data accurate? This is essential for all data-sets that need to be oriented (e.g. borehole imagery [FMI/UBI], dipole sonic).
13. Mud resistivity and borehole temperature are checked for repeatability and checked against collected mud samples and thermometers in the logging head.
14. Quality of automatic picking on processing products (if applicable), e.g. compressional and shear wave slowness picking on semblance projections for sonic logs.

3.2.2 Bad-hole flags

To complete the data QC process, bad-hole flags were created to highlight zones where the log quality was degraded by 'bad-hole' conditions and should be viewed with caution. The methodology is presented in Tab. 3-1 and explained in detail in Appendix A7 – Badhole & unfit data flags.

Bad hole is a common issue with logging. It means that the borehole conditions are inadequate for obtaining optimum quality petrophysical logs that truly represent the formation that is being logged. The tools that either measure petrophysical properties in a space volume or must be in continuous contact with the borehole wall during logging (eccentered tools) are the most affected by bad hole. Washouts and rugose hole are the most common features that degrade the quality of the logs resulting for example in the underestimation of density and overestimation of sonic slowness.

Tab. 3-1: Bad-hole flag methodology

Bad-hole logic	Logs used	Cutoff/method
Overgauge flag	Caliper	Borehole diameter is greater than 115% of nominal drill bit size
Rugosity flag	Density correction (HDRA), acquired with TLD	The density correction log is calculated from the difference between the short- and long-spaced density measurements, an indicator of borehole rugosity and density quality. Density is not reliable when $HDRA > 0.025 \text{ g/cm}^3$
Neutron standoff	Neutron standoff (STOF), acquired with APS	Neutron tool should be flushed with borehole wall or should have pre-determined physical standoff. If unintentional standoff, $STOF > 0.35''$, bad hole is flagged
Density-neutron flag	Density (RHOZ) and neutron (APLC)	Systematic identification of outliers in density-neutron crossplot and comparison with analogue data from adjacent boreholes

3.3 Composite log generation

The objective of the composite log dataset is to provide a traceable quality-controlled, edited, corrected and merged dataset for all petrophysical logging data recorded across the entire length of the borehole. Petrophysical tools acquire many logs that are not directly related to petrophysical properties but are needed to control that the tool sensors worked well (e.g. mechanical or electronics status of the sensors). In addition, some logs are acquired several times in a section (e.g. GR, Temperature). Ad Terra selects a collection of the most relevant logs for formation evaluation, correlation and calibration with core or seismic data. Some 89 representative logs are thus extracted for each borehole section. These logs are:

1. quality controlled (procedures in Section 3.2.1)
2. edited e.g. to keep data points that are true responses of the borehole and formation environment
3. further corrected for the borehole environment or artefacts
4. merged into composite logs that cover the entire or most of the borehole
5. The generated composite log dataset is generated and delivered in standard digital (LAS – Log ASCII Standard) and graphic (PDF log plot) format.

A more detailed procedure for the generation of the composite log is detailed in the next subchapter. In addition, a complete report in Excel format is provided (see Appendix A) which details all relevant information about the logs and the acquisition runs. Appendix A5 – Composite log generation worksheet specifically details how the composite log dataset was generated through merging techniques.

3.3.1 Generic process

The following steps were conducted to generate the composite log dataset:

1. A bit size log was generated according to the borehole design at the time of logging (see Appendix A2 – Borehole design).
2. Logs were depth-shifted as required (see Appendix A8 – Post-acquisition depth shifts).
3. First and last readings were edited to remove values acquired before the tool sensors started reading the borehole (e.g. constant values just before/after the sensor is switched off/on) and/or before the tools started to move upward (e.g. stationary measurements close to total depth). Log readings were further edited if they did not read the borehole formation environment, e.g. logs can be impacted by the nearby casing shoe and cement, become decentralised when there are changes in the borehole diameter, or sediment infills at bottom of the borehole.
4. All logs that were not valid in cased hole were discarded. For the BOZ2-1 composite log dataset, this included all logs except for the total gamma ray log (ECGR_EDTC) from the EDTC and borehole temperature (TMP) from the EMS.
5. Bad-hole flags were created based on advanced log analysis to highlight zones where the log quality was affected by bad-hole conditions.
6. Total gamma ray log (ECGR_EDTC) was corrected for the radioactive potassium silicate in the drilling mud using the borehole potassium corrected total spectral gamma ray log (HSGR) for calibration. It was further normalised to account for attenuated readings in cased hole intervals according to standard practice. The corrected gamma ray log was then renamed GR_KCOR.
7. Poor quality sonic slowness data (DTCO, DTSM) caused by imprecise automatic picking were removed and interpolated where applicable.
8. The edited and corrected logs from each section were merged. Merging points were chosen carefully to optimise log coverage and composite log consistency. See Appendix A5 – Composite log generation.
9. Standardised log names, units and descriptions were used.
10. Logs acquired at higher resolution (e.g. RHO8, PEF8 have sample rates 0.0508 m – ½ ft) were resampled to the standard rate of 0.1524 m (½ ft), because the digital LAS format cannot support mixed sample rates.
11. Final log plots at a scale of 1:200 m MD, 1:1'000 m MD and 1:2000 m MD were produced in PDF graphic file format along with digital data in LAS format.

The composite Excel report and log plots at a scale of 1:200 m and 1:1'000 m MD and TVD can be found in Appendix A, Appendix B and Appendix C, respectively. Tab. 3-2 lists and describes all the log curves / channels that are provided in the composite log set.

Tab. 3-2: Composite log LAS channel listing

Curve / channel	Units	Description
DEPTH	M	
APLC	V/V	Near/array Corrected Limestone Porosity (Epithermal HI)
BS	IN	Bit Size
DEVI	DEG	Borehole deviation
DTCO	US/F	Delta-T Compressional
DTSM	US/F	Delta-T Shear
DWAL_MGWALK	W/W	Dry Weight Fraction Pseudo Aluminium (SpectroLith MWGALK Model)
DWAL_WALK2	W/W	Dry Weight Fraction Pseudo Aluminium (SpectroLith WALK2 Model)
DWCA_MGWALK	W/W	Dry Weight Fraction Calcium (SpectroLith MGWALK Model)
DWCA_WALK2	W/W	Dry Weight Fraction Calcium (SpectroLith WALK2 Model)
DWCL_MGWALK	W/W	Dry Weight Fraction Chlorine Associated with Salt (SpectroLith MGWALK Model)
DWCL_WALK2	W/W	Dry Weight Fraction Chlorine Associated with Salt (SpectroLith WALK2 Model)
DWFE_MGWALK	W/W	Dry Weight Fraction Iron + 0.14 Aluminum (SpectroLith MGWALK Model)
DWFE_WALK2	W/W	Dry Weight Fraction Iron + 0.14 Aluminium (SpectroLith WALK2 Model)
DWGD_MGWALK	PPM	Dry Weight Fraction Gadolinium (SpectroLith MGWALK Model)
DWGD_WALK2	PPM	Dry Weight Fraction Gadolinium (SpectroLith WALK2 Model)
DWHY_MGWALK	W/W	Dry Weight Fraction Hydrogen Associated with Coal (SpectroLith MGWALK Model)
DWHY_WALK2	W/W	Dry Weight Fraction Hydrogen Associated with Coal (SpectroLith WALK2 Model)
DWK_MGWALK	W/W	Dry Weight Fraction Potassium (SpectroLith MGWALK Model)
DWMG_MGWALK	W/W	Dry Weight Fraction Magnesium (SpectroLith MGWALK Model)
DWSI_MGWALK	W/W	Dry Weight Fraction Silicon (SpectroLith MGWALK Model)
DWSI_WALK2	W/W	Dry Weight Fraction Silicon (SpectroLith WALK2 Model)
DWSU_MGWALK	W/W	Dry Weight Fraction Sulphur (SpectroLith MGWALK Model)
DWSU_WALK2	W/W	Dry Weight Fraction Sulphur (SpectroLith WALK2 Model)
DWTI_MGWALK	W/W	Dry Weight Fraction Titanium (SpectroLith MGWALK Model)
DWTI_WALK2	W/W	Dry Weight Fraction Titanium (SpectroLith WALK2 Model)
FLAG_BADHOLE_OVERGAUGE		Overgauge Borehole Bad-Hole Flag
FLAG_BADHOLE_RUGO		Rugose Borehole Bad-Hole Flag
FLAG_BADHOLE_STOF		Neutron Porosity Standoff Bad-Hole Flag
FLAG_UNFIT_ND		Flag that indicates unfit neutron-density data for deterministic log evaluation
FPLC	V/V	Near/Far Corrected Limestone Porosity (Thermal HI)

Tab. 3-2: continued

Curve / channel	Units	Description
GR_KCOR	GAPI	Total natural radioactivity corrected for the borehole potassium (EDTC)
HAZI	DEG	Borehole azimuth
HCGR	GAPI	HNGS Computed Gamma Ray
HDAR	IN	Hole Diameter from Area
HDRA	G/C3	Density Standoff Correction
HFK	%	HNGS Formation Potassium Concentration
HSGR	GAPI	HNGS Standard Gamma-Ray
HTHO	PPM	HNGS Formation Thorium Concentration
HURA	PPM	HNGS Formation Uranium Concentration
PEF8	B/E	High Resolution Formation Photoelectric Factor
PEFZ	B/E	Standard Resolution Formation Photoelectric Factor
RD1	IN	Radius 1
RD2	IN	Radius 2
RD3	IN	Radius 3
RD4	IN	Radius 4
RD5	IN	Radius 5
RD6	IN	Radius 6
RHGE_MGWALK*	G/C3	Matrix Density from Elemental Concentrations (SpectroLith MGWALK Model)
RHGE_WALK2*	G/C3	Matrix Density from Elemental Concentrations (SpectroLith WALK2 Model)
RHO8	G/C3	High Resolution Formation Density
RHOZ	G/C3	Standard Resolution Formation Density
RLA0	OHMM	Apparent Resistivity from Computed Focusing Mode 0
RLA1	OHMM	Apparent Resistivity from Computed Focusing Mode 1
RLA2	OHMM	Apparent Resistivity from Computed Focusing Mode 2
RLA3	OHMM	Apparent Resistivity from Computed Focusing Mode 3
RLA4	OHMM	Apparent Resistivity from Computed Focusing Mode 4
RLA5	OHMM	Apparent Resistivity from Computed Focusing Mode 5
RT_HRLT	OHMM	HRLT True Formation Resistivity
RXO8	OHMM	Invaded Formation Resistivity filtered at 8 inches
RXOZ	OHMM	Invaded Formation Resistivity filtered at 18 inches
RXO_HRLT	OHMM	HRLT Invaded Zone Resistivity
SIGF	CU	Formation Capture Cross-Section
SP	MV	Spontaneous Potential
STOF	IN	Effective Standoff in Limestone
STPC	V/V	Corrected Standoff Porosity
SV	MPa	Overburden vertical stress (Sv)
TMP	DEGC	Mud Temperature at the time of logging

Tab. 3-2: continued

Curve / channel	Units	Description
U8	B/C3	High Resolution Volumetric Photoelectric Factor
UZ	B/C3	Volumetric Photoelectric Factor
WANH_MGWALK *	W/W	Dry Weight Fraction Anhydrite/Gypsum (SpectroLith MGWALK Model)
WANH_WALK2 *	W/W	Dry Weight Fraction Anhydrite / Gypsum (SpectroLith WALK2 Model)
WCAR_MGWALK *	W/W	Dry Weight Fraction Carbonate (SpectroLith MGWALK Model)
WCAR_WALK2 *	W/W	Dry Weight Fraction Carbonate (SpectroLith WALK2 Model)
WCLA_MGWALK *	W/W	Dry Weight Fraction Clay (SpectroLith MGWALK Model)
WCLA_WALK2 *	W/W	Dry Weight Fraction Clay (SpectroLith WALK2 Model)
WCLC_MGWALK *	W/W	Dry Weight Fraction Calcite (SpectroLith MGWALK Model)
WCOA_MGWALK *	W/W	Dry Weight Fraction Coal (SpectroLith MGWALK Model)
WCOA_WALK2 *	W/W	Dry Weight Fraction Coal (SpectroLith WALK2 Model)
WDOL_MGWALK *	W/W	Dry Weight Fraction Dolomite (SpectroLith MGWALK Model)
WEVA_WALK2 *	W/W	Dry Weight Fraction Salt (SpectroLith WALK2 Model)
WPYR_MGWALK *	W/W	Dry Weight Fraction Pyrite (SpectroLith MGWALK Model)
WPYR_WALK2 *	W/W	Dry Weight Fraction Pyrite (SpectroLith WALK2 Model)
WQFM_MGWALK *	W/W	Dry Weight Fraction Quartz+Feldspar+Mica (QFM) (SpectroLith MGWALK Model)
WQFM_WALK2 *	W/W	Dry Weight Fraction Quartz+Feldspar+Mica (QFM) (SpectroLith WALK2 Model)
WSID_MGWALK *	W/W	Dry Weight Fraction Siderite (SpectroLith MGWALK Model)
WSID_WALK2 *	W/W	Dry Weight Fraction Siderite (SpectroLith WALK2 Model)

* Qualitative data should only be used as a lithology indicator.

3.3.2 Gaps in log coverage

Optimising the petrophysical log and MHF testing coverage was an objective of the logging and testing campaigns, in particular for the potential Opalinus Clay rock host. Despite best efforts, gaps in log coverage are an inherent limitation in wireline logging operations.

Complete log coverage at changes in drilling section is possible if the acquisition of the lowermost part of the drilling section is repeated later with the acquisition of the uppermost part of the drilling section below. Logs acquired with the same sensor, which overlap over two sections can then be merged providing complete coverage. This is not always possible due to limitations related to tool string geometry, borehole conditions and borehole design. Examples include:

- Cuttings infill the bottom of the hole preventing the tool string from reaching total depth.
- The tool string should not tag the bottom hole with certain fragile tools (e.g. UBI).
- The offset of the sensors relative to the bottom of the tool string.
- The rathole clearance (space between casing shoe and the bottom of the drilled hole) available for logging in the section below is too short. If the casing shoe is too close to the bottom of the section and the lowermost part of the open hole was not logged before casing installation, some log coverage will be lost.
- The rathole available for logging in the section below is first enlarged, and its diameter is different (e.g. 12¼") from that of the cored section below (6⅞"). Abrupt changes in borehole size are not favourable for logging because they are often associated with bad hole and eccentric tools in contact with the borehole wall acquire logs of degraded quality, causing gaps in log coverage.

The above factors were taken into consideration in the design of work programmes. For each logging campaign, project guidelines defined the balance between the optimisation of log coverage (short tool strings, more runs, longer campaign) and saving rig time and associated costs (slightly longer tool strings, less runs, shorter campaign).

For the main drilling sections where petrophysical logs were acquired (Section I to TD), a summary of the meterage of logged data and the percentage of total depth this data represents, is summarised in Tab. 3-3. The Opalinus Clay and bounding formations (Dogger – Lias) were examined in greater detail. Almost complete log coverage was acquired in these formations.

Tab. 3-3: Summary of petrophysical log coverage from drilling Section I to TD

Measurement	Section I to TD (100.0 m to 829.11 m MD)		Opalinus Clay and Bounding Formations (Dogger to Lias) (304.38 m to 612.76 m MD)	
	Meterage [m]	Coverage [%]	Meterage [m]	Coverage [%]
Caliper	722.08	99.0	304.12	98.6
Borehole orientation	701.04	96.2	301.83	97.9
Total Gamma Ray	723.44	99.2	308.38	100.0
Spontaneous Potential	607.01	83.3	302.74	98.2
Spectral Gamma Ray	719.18	98.6	303.05	98.3
Density	511.96	70.2	307.76	99.8
Photoelectric Factor	511.96	70.2	307.76	99.8
Microresistivity	511.91	70.2	308.17	99.9
Neutron (NHI)	507.34	69.6	303.09	98.3
Sigma Formation Capture Cross-Section	507.34	69.6	303.09	98.3
Resistivity	581.25	79.7	284.30	92.2
Sonic	593.45	81.4	289.03	93.7
Element Spectroscopy	511.45	70.1	307.51	99.7
Ultrasonic Borehole Imagery	504.70	69.2	306.52	99.4
Microresistivity Borehole Imagery	699.10	95.9	294.08	95.4

The depths at which there were gaps in log coverage in the final composite dataset are detailed in Appendix A5 – Composite log generation.

3.4 Petrophysical logging results and description

The main features of the petrophysical logs of the composite dataset are described below by litho-stratigraphic units.

3.4.1 Malm: Villigen Formation and Wildegg Formation (0 to 304.38 m MD)

No valid logs were acquired above the 13 $\frac{3}{8}$ " casing set at 100 m MD in the Wildegg Formation, in Section I of the borehole.

Log responses reflect the borehole lithology well except in the 12 $\frac{1}{4}$ " rat hole immediately below the 13 $\frac{3}{8}$ " casing and two zones with breakouts in the upper Wildegg Formation, where the borehole wall rugosity and overgauge hole deteriorated the response of the TLD and APS tool logs (density, photoelectric factor, microresistivity, and neutron).

Logs in the Wildegg Formation are characterised by (Fig. 3-1):

- Low to moderate clay content: low to moderate total GR (GR_KCOR: 9 to 82 GAPI; mean = 46 GAPI), spectral GR (e.g. thorium HTHO: 0.7 to 11.2 ppm; mean = 5.1 ppm) and sigma (SIGF: 10.1 to 31.5 CU; mean = 20.5 CU).
- Calcite is the dominant mineral: narrow density-neutron separation when displayed in a limestone-compatible scale in low clay limestone (190 m to 210.7 m MD), the calcium dry weight fraction (DWCA) and photoelectric factor (PEFZ) are reading values close to that of pure calcite (0.394 W/W and 5.1 B/E, respectively).
- In the low clay limestone (GR_KCOR < 15 GAPI), porosity is moderately low, density is moderately high (rarely lower than 2.56 g/cm³; mean: 2.59 g/cm³) and sonic (DTCO) rarely exceeds 78 μ s/ft.

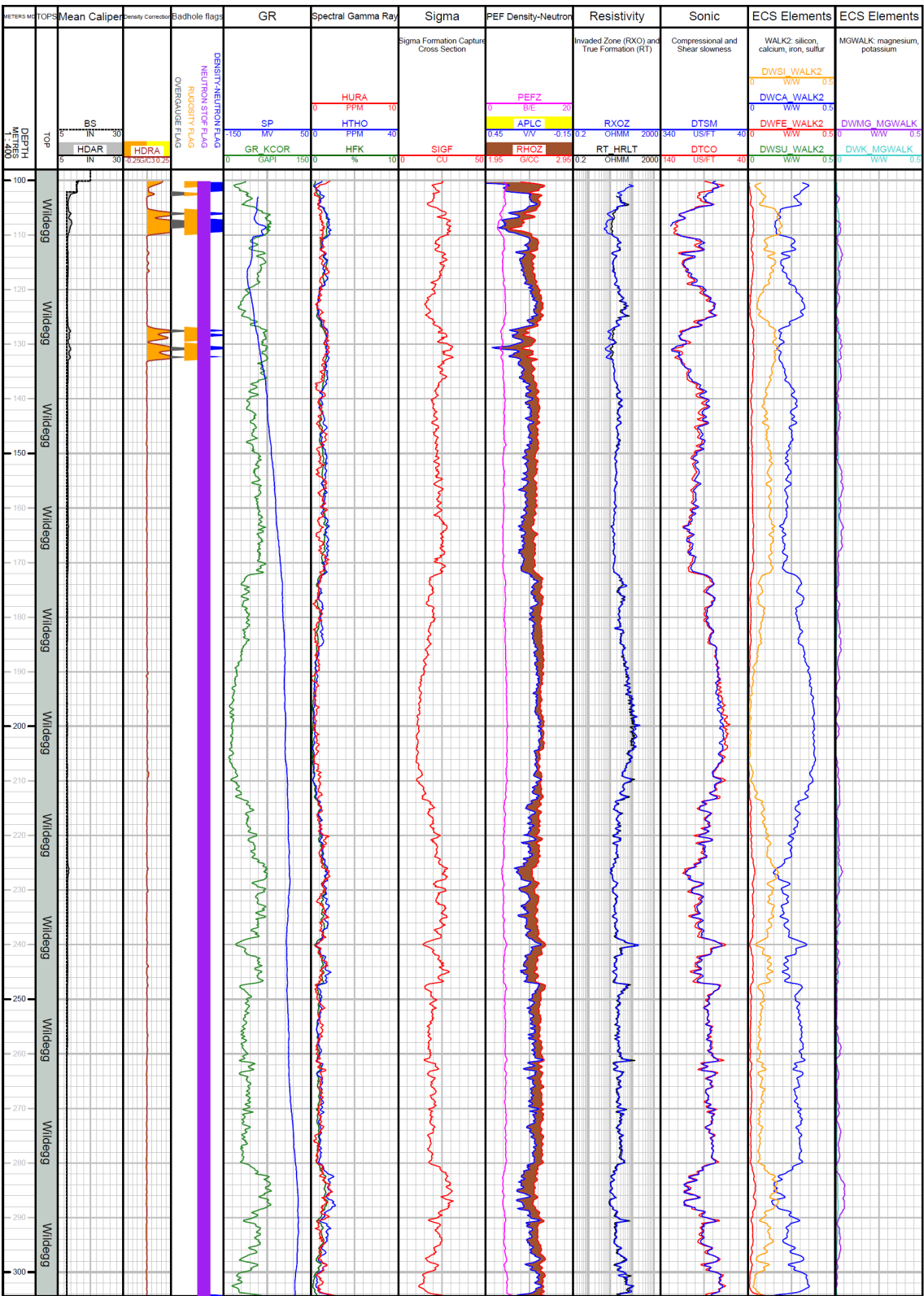


Fig. 3-1: Main logs of the composite dataset in the Wildegg Formation

3.4.2 Ifenthal Formation to Passwang Formation (304.38 to 451.90 m MD)

The top of the Dogger (Ifenthal Formation) can be identified by an increase in total GR, a wide separation in the density-neutron logs (displayed in a limestone-compatible scale) and an increase in iron concentration (DWFE), all indicative of siderite, iron oxide or hydroxide bearing rocks (Fig. 3-2).

Due to good-hole conditions, log responses reflect the borehole lithology well from the Ifenthal Formation to the Passwang Formation. Logs have the following attributes:

- Moderately low (Hauptrogenstein Formation) to moderately high (Passwang Formation) clay content as shown by the total GR (18 to 114 GAPI), SIGF (10.5 to 38.6 CU) and HTHO (2.9 to 24.8 ppm).
- The occurrence of siderite, iron oxide or hydroxide is typical in these formations: a wide separation in the density-neutron, high total and spectral GR (especially thorium HTHO up to 24.8 ppm and uranium HURA up to 5.3 ppm), high iron concentration (DWFE: above 0.04 W/W) and high photoelectric factor (PEFZ up to 8.7 B/E).
- The matrix mineralogy is dominated by calcite: in the lowest clay and low iron zones PEFZ is in the range of 3.4 to 5.7 B/E, while calcium is relatively high (DWCA: up to 0.35 W/W; 0.394 W/W in pure calcite), which is typical of marls. Towards the base of the Passwang Formation, the separation between the density-neutron is lower while silicon is relatively high (DWSI: up to 0.30 W/W; 0.467 W/W in pure quartz), indicating a more siliciclastic component in the matrix mineralogy.
- The spectral GR potassium (HFK) and thorium (HTHO) logs suggest the presence of both non-potassic (e.g. kaolinite, smectite) and potassic (e.g. illite) clay minerals in the clay-rich zones.

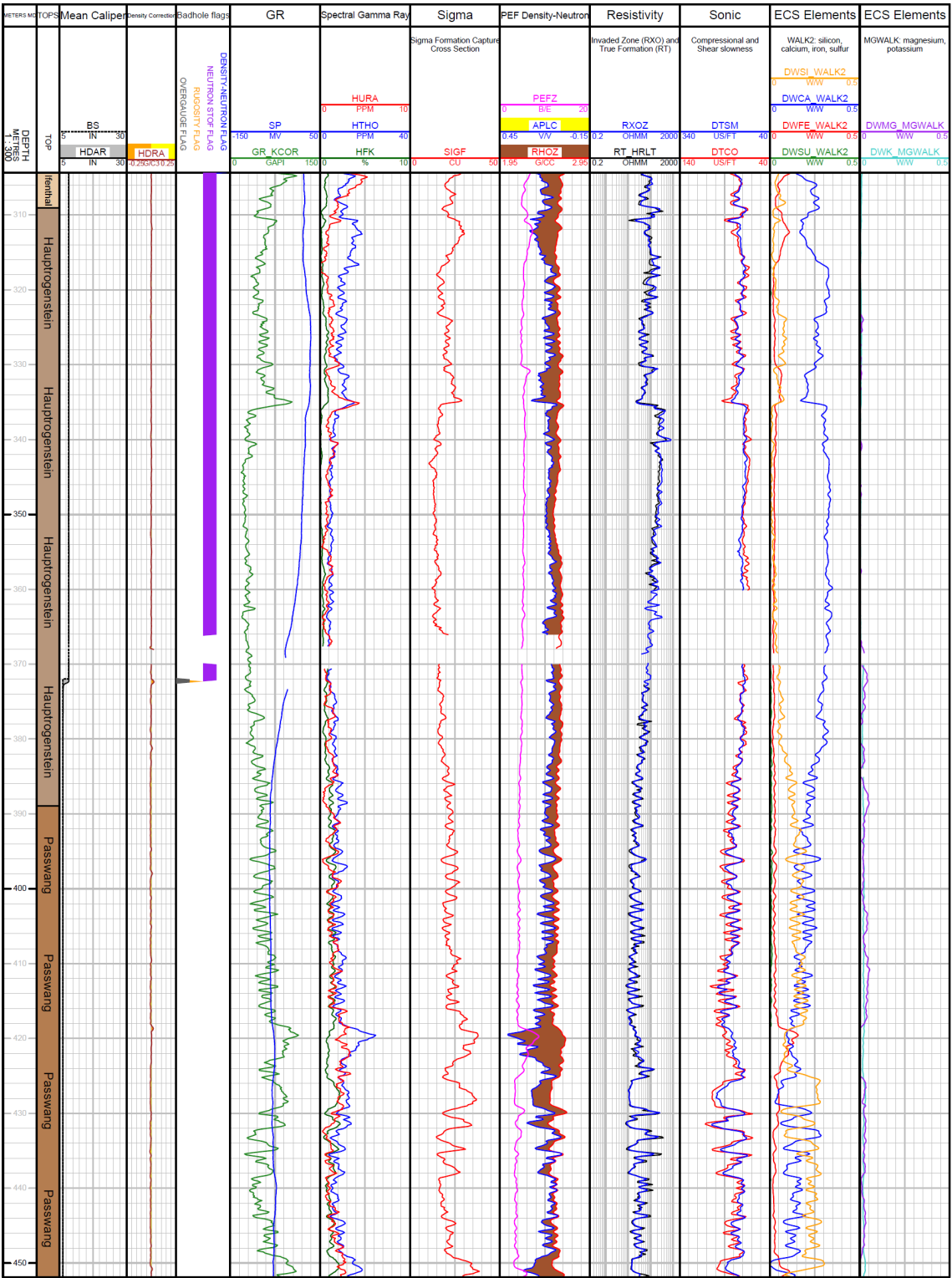


Fig. 3-2: Main logs of the composite dataset in the Ifenthal Formation to Passwang Formation

3.4.3 Opalinus Clay (450.91 to 573.89 m MD)

The top Opalinus Clay is characterised by an increase in clay content, as observed by the increase in total GR (GR_KCOR), a wider neutron-density separation in a limestone-compatible scale and decrease in calcium concentration (DWCA).

Log responses reflect the borehole lithology well because hole conditions were excellent for wire-line logging. In the Opalinus Clay, logs have the following attributes (Fig. 3-3):

- Consistently moderate to high clay content: GR_KCOR ranges from 71 to 119 GAPI; SIGF correlates very well (positively) to GR_KCOR, ranging from 27.1 to 47.4 CU; the compressional wave slowness DTCO was high (slow formation) and generally above 90 $\mu\text{s}/\text{ft}$; the density-neutron separation is typical of lithologies with high clay content.
- Several carbonate streaks can be observed at 467.7, 472.7, 475.5 and 480.5 m MD characterised by an increase in density and decrease in neutron with values approaching those of pure calcite (RHOZ: 2.71 g/cm^3 ; APLC: 0.0 v/v), an increase in calcium (DWCA up to 0.13 W/W) and an increase in resistivity logs (e.g. RT_HRLT).
- While the clay content is relatively homogeneous throughout, the Opalinus Clay can be subdivided into three zones based on the log response:
 - The upper interval from 451.9 m to 468.2 m MD contains a higher carbonate content, as indicated by the higher ECS calcium (DWCA: 0.05 W/W to 0.13 W/W), the lower ECS silicon (DWSI: 0.17 W/W to 0.26 W/W) and the higher resistivity (RT_HRLT > 13 Ohm.m).
 - The middle interval from 468.2 m to 512.5 m MD is characterised by a cyclic downwards increase in clay content (and decrease in carbonate content), as indicated by the density-neutron separation increasing downwards and the increase in sigma (SIGF) and sonic (DTCO, DTSM). This suggests sequential changes in the depositional settings of the Opalinus Clay.
 - The lower interval from 512.5 m to 573.89 m MD has the highest clay content, a low carbonate content and more homogeneous log attributes: lower resistivity (RT_HRLT < 13 Ohm.m), high total GR (GR_KCOR: 85 to 119 GAPI), high thorium (HTHO: 12.7 to 18.2 ppm), high sigma (SIGF: 33.3 to 47.4 CU) and low ECS calcium (DWCA < 0.07 W/W).
- The spectral GR potassium (HFK) and thorium (HTHO) logs suggest the presence of both non-potassic (e.g. kaolinite, smectite) and potassic (e.g. illite) clay minerals.
- Matrix mineralogy is complex. Both calcium (DWCA) and silicon (DWSI) concentrations are often higher than those in smectite clays (DWCA: 0.00 to 0.13 W/W; DWSI: 0.17 to 0.29 W/W; excluding the carbonate streaks), which suggest siliciclastic and carbonate components in the matrix.

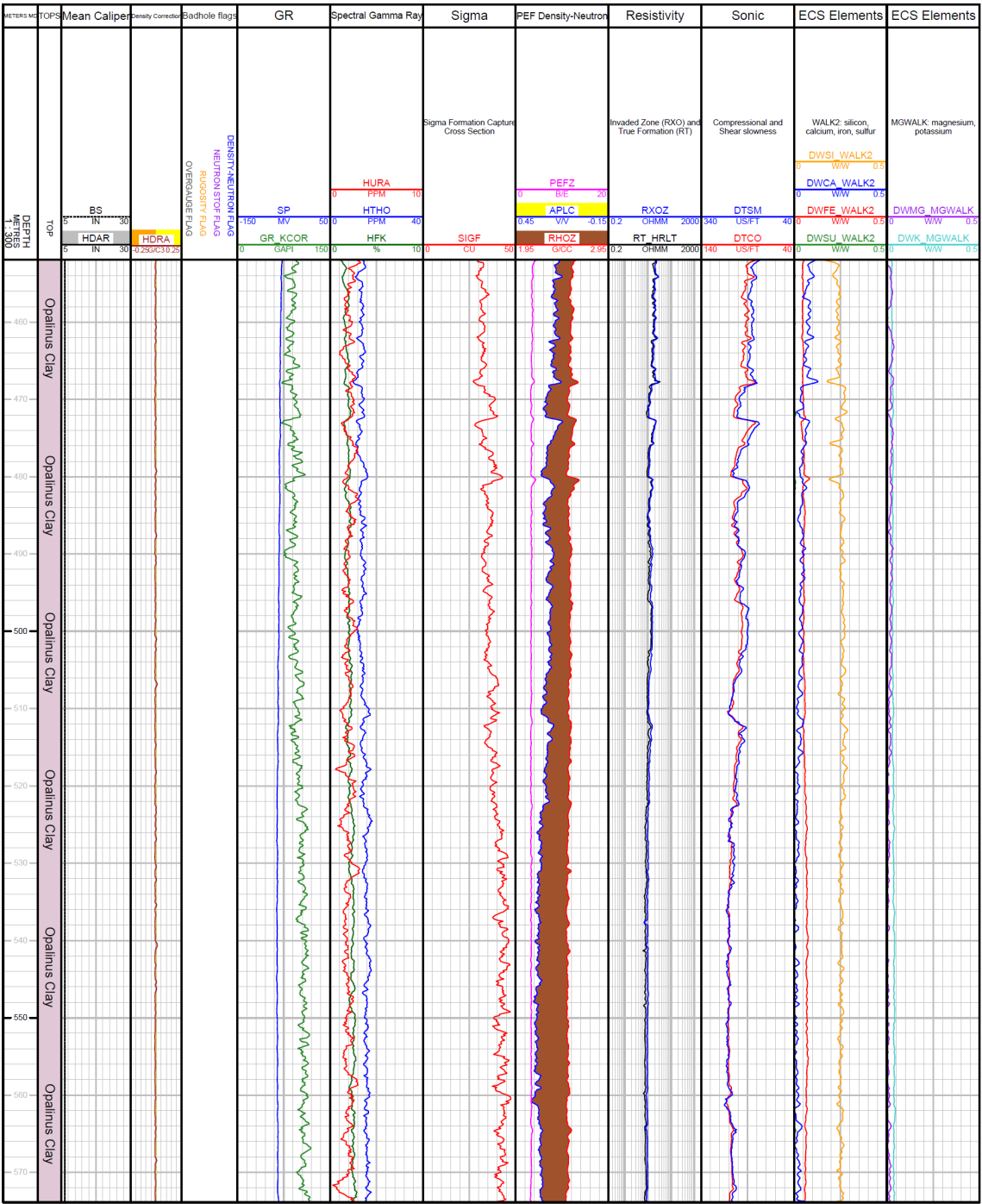


Fig. 3-3: Main logs of the composite dataset in the Opalinus Clay

3.4.4 Staffelegg Formation (573.89 to 612.76 m MD)

The top of the Lias (Staffelegg Formation) can be identified by a decrease in total GR (GR_KCOR) and sigma (SIGF), a narrower separation in the density-neutron logs in a limestone-compatible scale and an increase in calcium contents (DWCA) (Fig. 3-4).

Hole conditions were good in the Staffelegg Formation. Logs respond well to the borehole lithology having the following attributes:

- Highly variable clay content: total GR (45 to 142 GAPI), sigma (14.1 to 49.7 CU) and thorium (2.9 to 17.1 ppm), e.g. low clay content in the Beggingen Member (601.04 to 604.45 m MD) but intermediate to high clay content in the Schambelen Member (604.45 to 612.76 m MD).
- Organic matter is likely present: the high total GR zones (GR_KCOR > 120 GAPI) correspond with the uranium peaks (HURA: up to 14.2 ppm).
- Pyrite is an important accessory mineral in several members of the Staffelegg Formation (Gross Wolf, Rietheim, Grünschholz/Breitenmatt/Rickenbach and Schambelen Members): Sulphur concentration (DWSU) ranges from 0 to 0.02 W/W; the photoelectric factor (PEFZ), a reactive marker of pyrite, reaches high values of 6.1 B/E.
- Matrix mineralogy is dominated by carbonate: calcium (DWCA) varies between 0 and 0.31 W/W (pure calcite: 0.394 W/W); however, mineralogy remains complex, the multi-mineral interpretation detailed in Dossier X will help to better understand this complex mineralogy.

3.4.5 Klettgau Formation (612.76 to 654.70 m MD)

A limited suite of logs was acquired in the bottom of the Lias (Staffelegg Formation) because the rathole clearance below Section II was insufficient. The top of the Triassic (Klettgau Formation) was logged in an overgauge open hole which degraded log quality. Thus, the change in log attributes between the two formations could not be discerned.

Hole conditions were degraded in the Klettgau Formation, resulting in wireline conveyance problems (overpulls, stick and pull events, tools being held up), especially in the Ergolz Member. From the top of the Klettgau Formation downwards, wireline logs were limited to the total GR, the spectral GR, resistivity (RT_HRLT) and sonic, because hole conditions were too adverse to risk running tools carrying a radioactive source (i.e. APS, TLD, ECS).

Based on their limited availability, logs show the following attributes (Fig. 3-5):

- Highly variable clay content: total GR ranges from 11 to 290 GAPI and thorium from 0.4 to 16.2 ppm; clay indicators have a bimodal distribution that reflect zones with a low clay content (632.27 to 639.13 m MD, Gansingen Member) and zones with intermediate to high clay contents (612.76 to 632.27 m MD: Gruhalde Member; 639.13 to 657.7 m MD: Ergolz Member).
- Organic matter is likely present at the base of the Ergolz Member: the highest total GR readings (GR_KCOR > 142 GAPI) correspond with high uranium peaks (HURA: up to 17.0 ppm).
- Matrix mineralogy cannot be discussed given the limited log availability.

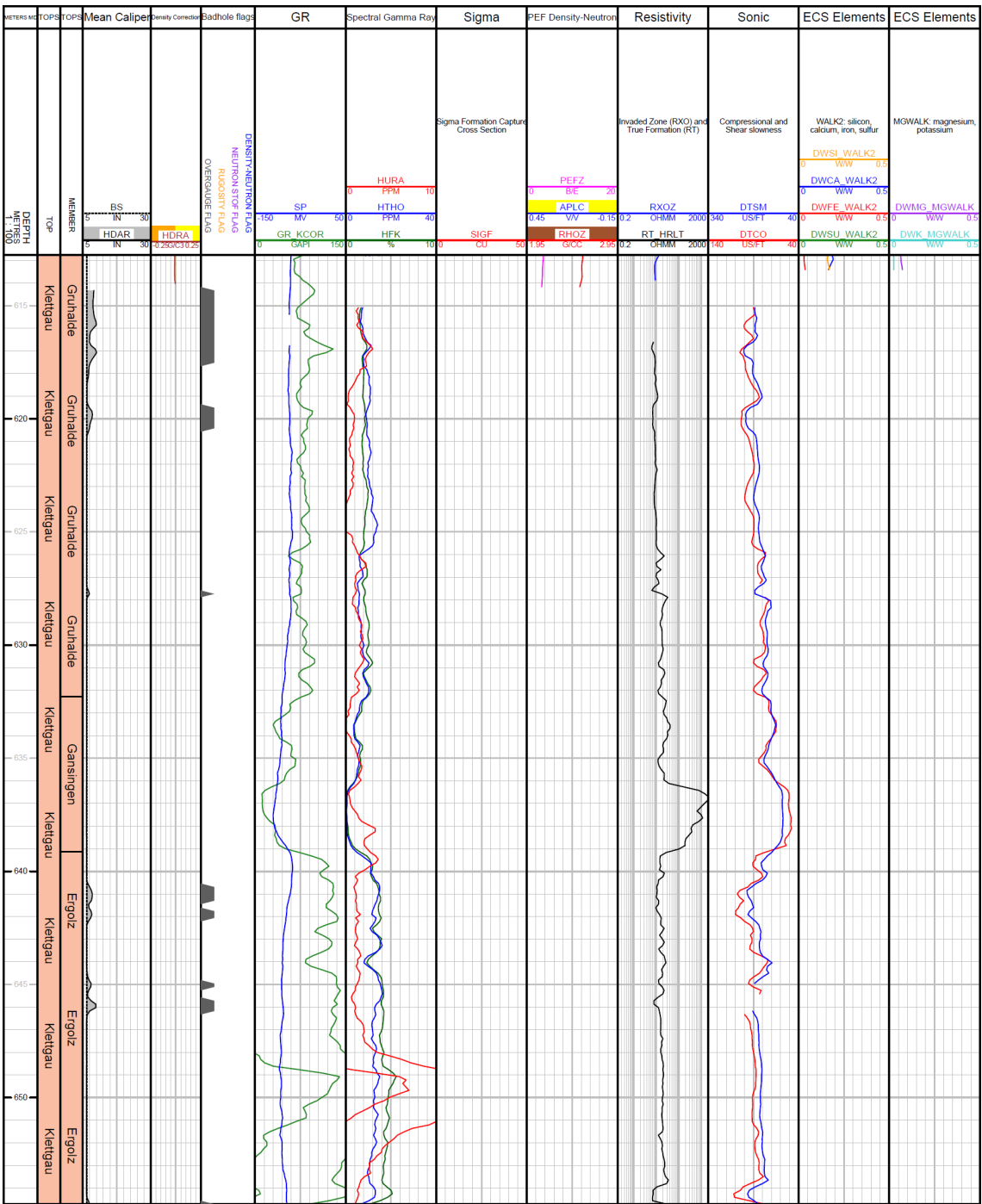


Fig. 3-5: Main logs of the composite dataset in the Klettgau Formation

3.4.6 Bänkerjoch Formation (654.70 to 749.52 m MD)

The top of the Bänkerjoch Formation is characterised by a shift to lower values of total GR (GR_KCOR) and thorium (HTHO). These log characteristics show the onset of the significant concentrations of anhydrite in this formation in contrast with the higher clay contents of the lower Bänkerjoch Formation.

Available logs were limited to total GR (GR_KCOR), spectral GR (e.g. thorium: HTHO), resistivity (e.g. RT_HRLT) and sonic (DTCO, DTSM).

Hole conditions were mostly good in the Bänkerjoch Formation and logs responded well to bore-hole lithology. Based on their limited availability, logs show the following attributes (Fig. 3-6):

- Rapid variations in most logs (total GR, resistivity [RT_HRLT], sonic [DTCO, DTSM]) at the metre scale or less, which suggest two main alternating lithologies. Regional knowledge and wellsite geological description suggest that one is dominated by anhydrite and the other by clays.
- Highly variable clay content: total GR (5 to 122 GAPI) and thorium (0.3 to 11.3 ppm),
- Due to the limited vertical resolution of the logging tool, often higher than 10" (e.g. HNGS 12"), the alternating lithologies are not necessarily correctly reflected in the logs. The logging tools average the physical and chemical properties over a fixed volume, which means that centimetre scale beds are represented as a mixture of anhydrite and clays for a given depth.

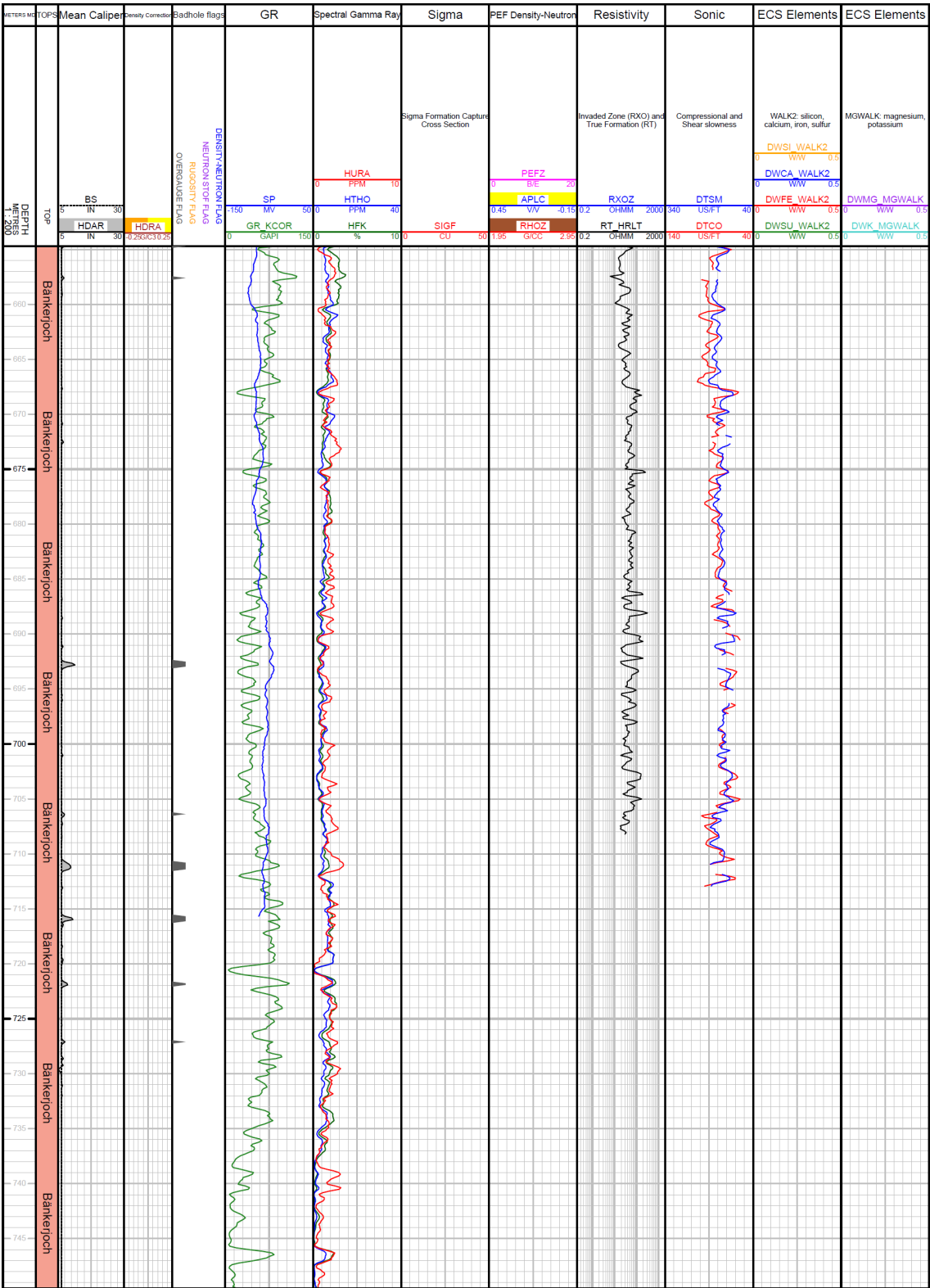


Fig. 3-6: Main logs of the composite dataset in the Bänkerjoch Formation

3.4.7 Schinznach Formation (749.52 to 821.09 m MD)

The top of the Schinznach Formation is identified by a decrease in total GR (GR_KCOR) and thorium (HTHO) below the lowest anhydrite bed of the Bänkerjoch Formation.

Available logs were limited to total GR (GR_KCOR) and spectral GR (e.g. thorium: HTHO).

Hole conditions were mostly good in the Schinznach Formation and logs responded well to the borehole lithology. Based on their limited availability, logs are characterised by the following attributes (Fig. 3-7):

- Low to moderately low clay contents as shown by the total GR (GR_KCOR: 9 to 33 GAPI), and thorium (HTHO: 0 to 1.9 ppm), except in the interval from 749.5 to 754 m MD in the Asp Member where a clay-rich layer is present.

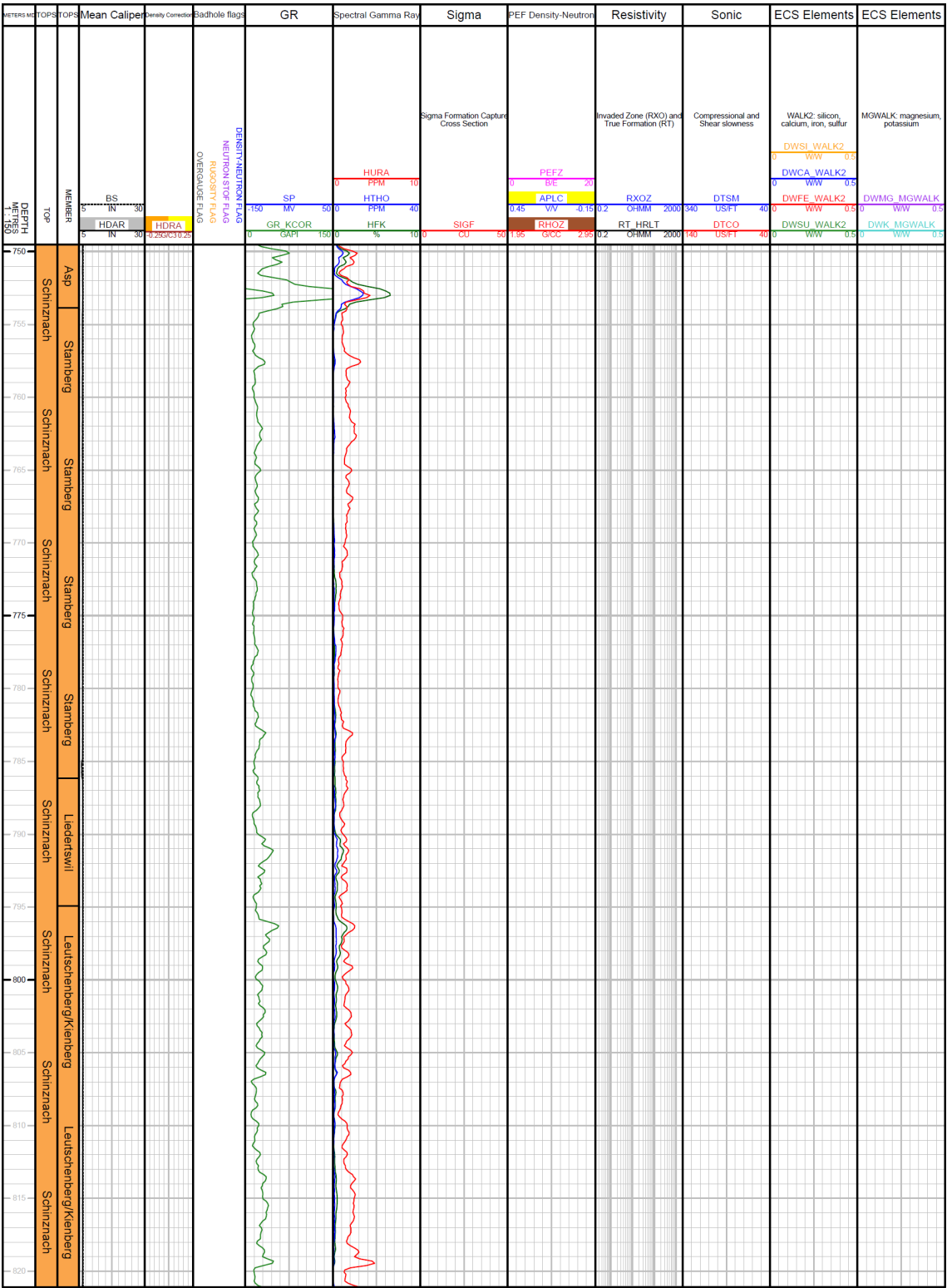


Fig. 3-7: Main logs of the composite dataset in the Schinznach Formation

3.4.8 Zeglingen Formation
(821.09 to 829.88 m MD)

Available logs were limited to total GR (GR_KCOR) and spectral GR (e.g. thorium: HTHO). Since the clay content was invariably low in the lower Schinznach Formation and in the upper Zeglingen Formation, wireline logs could not identify the top of the Zeglingen Formation.

Hole conditions were good except in the short interval from 821.09 to 826.3 m MD. Based on their limited availability, logs in the Zeglingen Formation are characterised by the following (Fig. 3-8):

- Low to moderately low clay content: total GR (GR_KCOR: 15 to 34 GAPI) and thorium (HTHO: 0.2 to 0.7 ppm).

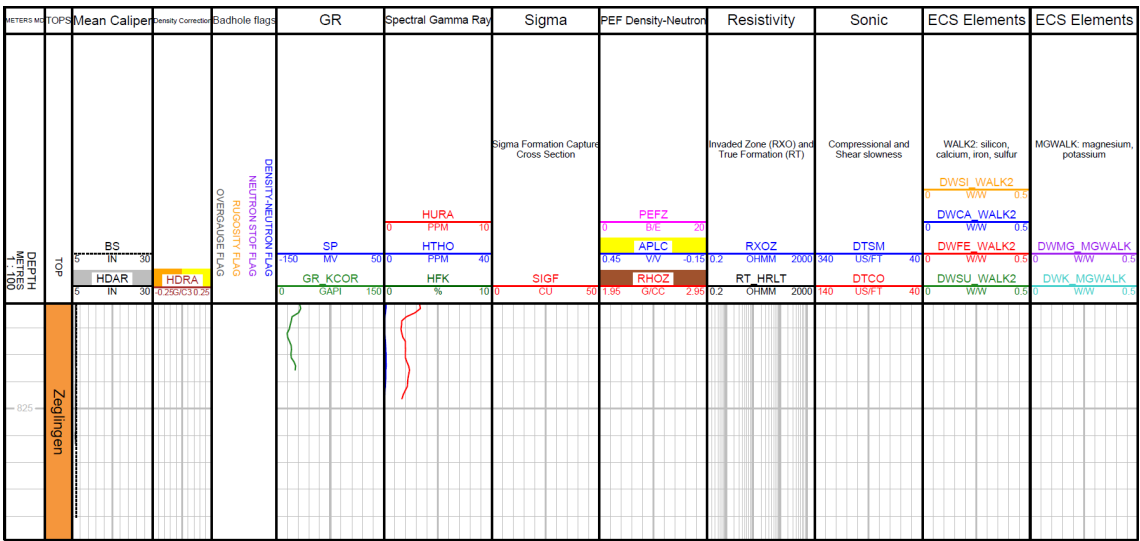


Fig. 3-8: Main logs of the composite dataset in the Zeglingen Formation

3.5 Post-completion mud temperature

A temperature log was acquired by Schlumberger post-completion (in cased hole) on 03.11.2021 (Run 3.4.1) to measure the undisturbed temperature of the mud after the last mud circulation on 13.12.2020. Temperature was measured using the EMS tool, which has an accuracy of $\pm 1^\circ\text{C}$ and resolution of 0.1°C . In Fig. 3-9, only the downlog from Run 3.4.1 is plotted as it is believed to be the most representative of the formation temperature. It was acquired at a slow rate of 193 m/hr to avoid mixing of the hydrostatic mud column. The fluid level during logging was at 160.9 m MD as shown by the change in temperature at this depth. The maximum temperature of 34.09°C was recorded at TD. In the Opalinus Clay, the temperature varies between 24.40 and 32.20°C and the average geothermal gradient is $\Delta T/\Delta D = 0.063^\circ\text{C/m}$. The overall temperature gradient is higher in the clay-rich units of the Dogger (e.g. Opalinus Clay) compared to the calcareous units of the Dogger (Hauptrogenstein).

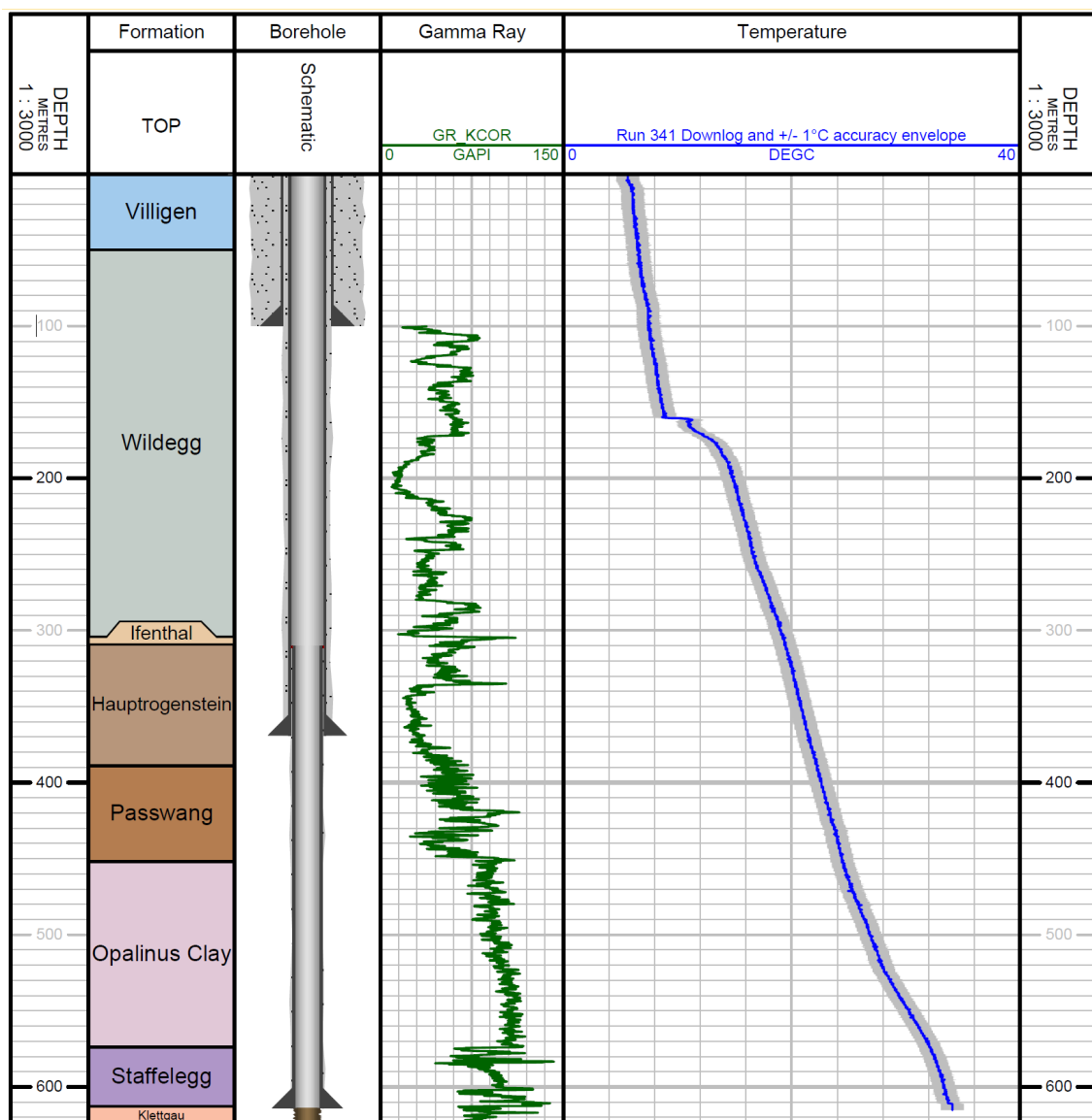


Fig. 3-9: Post-completion temperature log from the downlog pass of Run 3.4.1 (03.11.2021)
A $\pm 1^\circ\text{C}$ accuracy envelope is drawn in grey around the temperature log.

4 Borehole Imagery (BHI)

Borehole imaging tools produce high resolution circumferential images of the borehole wall by measuring either resistivity with tool pad contact or ultrasonic velocity. For the BOZ2-1 borehole, SLB's Fullbore Formation MicroImager (FMI) and Ultrasonic Borehole Imager (UBI) were used. The FMI comprises of four pads that measure the formation resistivity via an array of buttons (24 per pad) that are pressed against the borehole wall, providing a vertical resolution of 2.5 mm and 80% coverage in an 8" hole diameter. The UBI has a rotating sub that sends out acoustic pulses to the formation and measures the amplitude and travel time of the returning signals, providing 5 mm vertical resolution and 100% borehole coverage. In general, fractures, faults and bedding are more easily identifiable using the FMI than the UBI as the microresistivity images provide better contrast. However, borehole wall features can be missed if they are located in an area not covered by the tool pad, which is why FMI and UBI images should be used together for image interpretation. In addition, breakouts are typically poorly resolved on microresistivity images because fracturing and spalling associated with these breakouts result in poor contact of the tool pads with the borehole wall.

BHI was used to:

- identify and characterise geological, sedimentological and structural features including bedding, fault planes / zones and fractures
- identify stress-induced borehole phenomena such as tensile drilling-induced fractures and breakouts
- perform core goniometry
- select MHF and PMT locations (referred to as stations herein)
- detect and orient fractures induced by MHF stress measurements

For details on the first three uses of BHI, please refer to Dossier V. Only the latter two will be discussed further in the present Dossier.

The BHI, that was acquired pre-MHF, was quality-controlled (QCed), processed and interpreted by NiMBUC Geoscience in a limited amount of time (i.e. rush processing and basic quicklook interpretation). The aim of this quicklook interpretation was to provide a general and quick picture of existing borehole / rock heterogeneities (breakouts, natural and induced fractures etc.) for the selection of MHF and PMT stations immediately after BHI log acquisition and prior to MHF / PMT. In Fig. 4-1, the workflow used by NiMBUC Geoscience is described. Final processed and spliced pre-MHF image logs are included in Dossier V (Appendix B and Appendix C).

The post-MHF imagery underwent a similar workflow to the pre-MHF imagery, however, only the intervals that underwent stress testing were interpreted. These will be detailed in a future MHF interpretation report. To determine whether fractures were generated or enhanced (opened further), the pre- and post-MHF imagery was plotted side-by-side, along with the MHF test interval, packer positions and core photographs (see Appendix D).

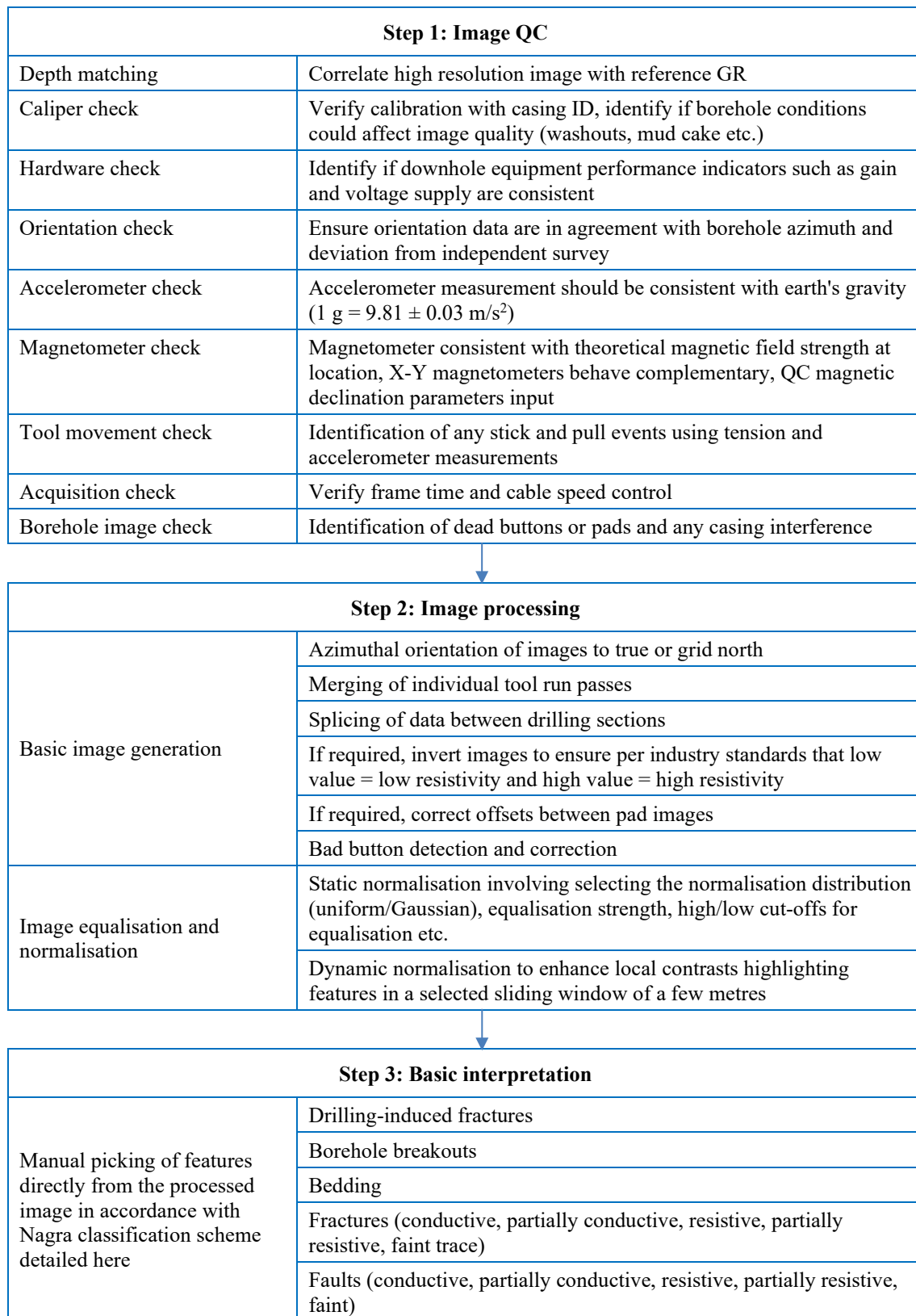


Fig. 4-1: Borehole image processing workflow

5 Micro-hydraulic Fracturing (MHF)

5.1 Introduction and objectives

A series of stress measurements were performed in the BOZ2-1 borehole using the Micro-hydraulic Fracturing (MHF) technique. MHF testing in boreholes is the only direct method available for measuring rock stress magnitude at great depth. An overview of the methodology can be found in Haimson (1993), Desroches & Kurkjian (1999) and Haimson & Cornet (2003) and references therein. Recent updates on the methodology, some of which having been specifically designed for this project, can be found in Desroches et al. (2021a, 2021b).

The objectives of the testing programme are to acquire data to:

- provide estimates of the in situ stress state in the Opalinus Clay and adjacent rock formations, and
- provide calibration points for mechanical earth models (MEM) of the rock mass (1D, 3D). See Bérard & Prioul (2016) for an overview of mechanical earth models and Plumb et al. (2000) for a definition of an MEM.

Key features include:

- Core images and BHI (FMI and UBI) were used to select the appropriate test depths closest to where geomechanical lab test samples were taken.
- The MHF protocol that was used, was tailored in real-time to bracket the far-field closure stress as closely as possible.
- Post-MHF imaging logs were run to determine the trace of the newly created fractures, enabling better allocation of the MHF closure stress to a principal stress direction.
- Sleeve fracturing was regularly used to focus the test on the desired interval; sleeve reopening was used to allow the estimation of the maximum horizontal stress when the MHF tests yielded an estimate of the minimum horizontal stress.

5.2 MHF theory

MHF tests an interval of approximately 1 m which is sealed above and below by packers that are approximately 0.5 m in length (exact dimensions are dependent on the configuration of the tool string). A schematic, showing the first two hydraulic fracturing cycles for a typical MHF test, is presented in Fig. 5-1. Once the interval is sealed, a micro-hydraulic fracturing cycle begins with pressurising the interval (1st step) until fracture initiation. Fluid keeps being injected to extend the micro-hydraulic fracture into the formation by a couple of decimetres (2nd step). Injection is then stopped to allow fracture closure, and pressure fall-off is observed (3rd step). Similar steps are repeated to further extend and refine the testing of the micro-hydraulic fracture until the test is deemed satisfactory. Tests performed in this borehole have included more complex testing techniques as reported in Desroches et al. (2021a).

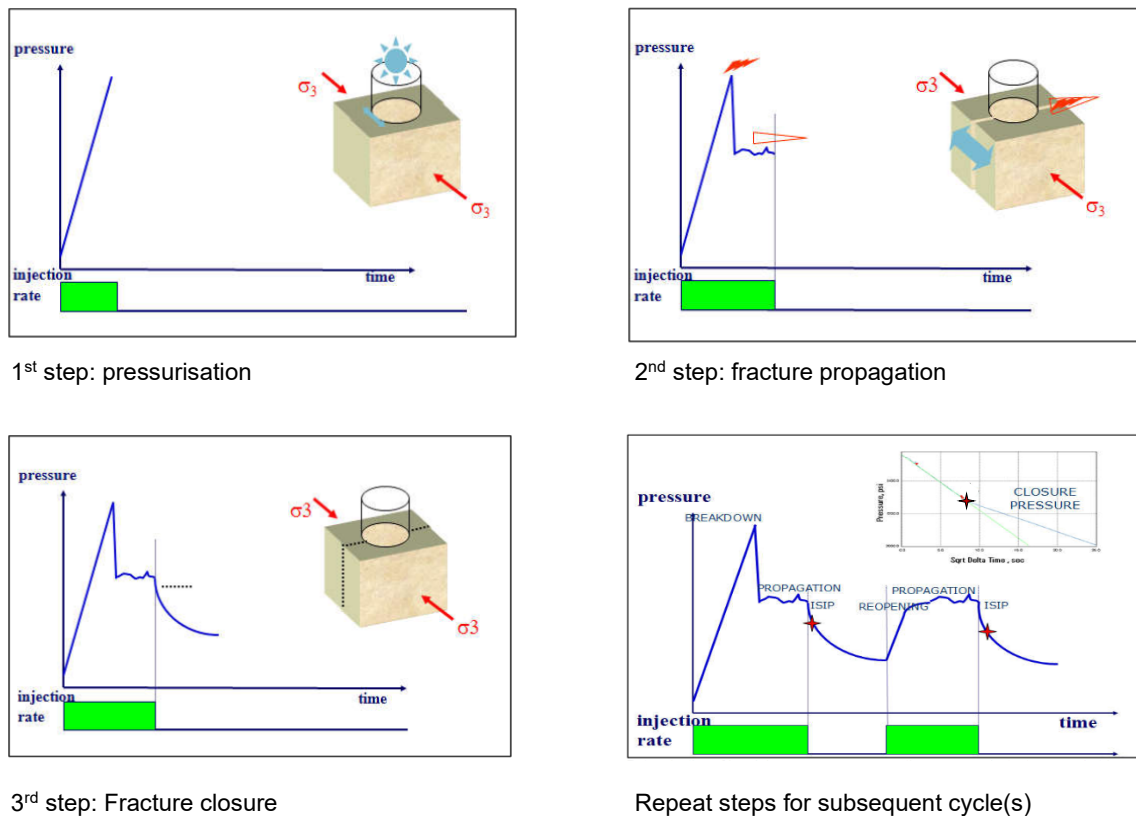


Fig. 5-1: Schematic showing the response of the interval pressure to fluid injection in the interval as a function of time during an MHF test and associated formation response (courtesy of SLB)

5.3 Test protocol

Each test consisted of a succession of steps according to the general test procedure described in Desroches & Kurkjian (1999), Haimson & Cornet (2003) and Wileveau et al. (2007). Although a general procedure was followed for each test, the steps were tailored in real-time to ensure that the pressure records provided the best possible estimate for closure stress (see Desroches et al. 2021b). As a result, the number of steps and their nature varied from test to test.

The steps undertaken during a stress test were as follows:

- Depth correlation: validate the cable depth by comparing GR logs with the reference GR log of the borehole.
- Sleeve fracturing: this step is analogous to sleeve reopening (see below) but performed prior to the micro-hydraulic fracturing operation. The single packer is placed in front of the desired depth and applies pressure to focus the initiation of a longitudinal fracture at the desired interval. Note that this part of the sequence is not carried out if a pre-existing fracture (natural or drilling-induced or -enhanced) is present in the test interval.
- Packer inflation and leak-off test: the straddle packer is positioned so that the centre of the interval is in front of the desired depth. Packers are inflated to a differential pressure of 300 to 500 psi and the integrity of the seal is observed. The integrity of the seal is further validated by a short injection into the interval.

- Breakdown cycle (steps 1 to 3 in Fig. 5-1): the first cycle in a test during which a hydraulic fracture is propagated was counted as a breakdown cycle (even if technically there is no breakdown, e.g. because a pre-existing drilling-induced fracture was tested). To ensure that cycles are not counted more than once, there was only one breakdown cycle per test. Whether it starts with a step-rate test or ends with a slamback / rebound test (see below), it is still only counted as one breakdown cycle.
- Reopening cycle: any subsequent injection / shut-in cycle during which a fracture is propagated and that neither starts with a step-rate test nor ends with a slamback / rebound test (see below) is counted as a reopening cycle.
- Slamback / rebound test: at the end of an injection cycle during which a fracture was propagated (but not for the first time), the interval is quickly opened and closed for a fast depressurisation, and pressure rebounds from a value close to borehole hydrostatic pressure. The slamback occurs immediately after the injection stopped, and the rebound is observed until a plateau is reached. If the injection cycle starts with a step-rate test, it is only counted as a step-rate test and not as a slamback / rebound test.
- A new procedure ('forced closure') was introduced in the BOZ1-1 borehole and retained for subsequent boreholes. Because it also involves withdrawing fluid from the interval, cycles with forced closure were not counted separately but were also counted as S/R tests.
- Step-rate test: an injection cycle during which the rate was increased (or decreased) in steps with at least three different flow rates during the cycle is called a step-rate test. An injection cycle during which the rate was only changed once cannot be counted as a step-rate test because it does not allow a step-rate interpretation.
- Sleeve reopening: the single packer is moved in front of the previously tested interval and pressure is applied with the aim of detecting and reopening the fracture created during the micro-hydraulic fracturing cycles.

In Fig. 5-2, an example of the pressure record for a MHF test performed in the BOZ2-1 borehole is presented (Station 4-3, Run 2.3.3). Fig. 5-2a shows the pressure in the interval, Fig. 5-2b the fluid injection rate as a function of time (pump speed is in blue, pump piston direction in yellow/colourless; for explanations see Appendix E), Fig. 5-2c the injected volume as a function of time and Fig 5-2d, also called a reconciliation plot, displays the characteristic pressures estimated for all cycles for which a fracture was created / tested. For this test, there were a total of 5 MHF cycles, labelled 6 to 10. The first cycles are not analysed as they correspond to the packer inflation and leak-off test. Fracture breakdown took place during cycle 6, which corresponds to the breakdown / propagation cycle depicted in the theory schematic (Fig. 5-1). Cycles 7 and 9 are reopening tests, cycles 8 and 10 are step-rate tests. A slamback / rebound test was performed at the end of cycles 9 and 10, and a forced closure procedure was performed at the end of cycle 7. The characteristic pressures presented in Fig. 5-2d reflect the stress acting on the fracture: they validate the creation of a hydraulic fracture and exhibit a rather constant behaviour, especially for the last 2 cycles, which supports that an estimate of the far-field stress can be obtained from the test.

The raw MHF pressure-time and reconciliation plots for all tests conducted in the BOZ2-1 borehole are included in Appendix E. In Tab. 5-1, a summary of the steps taken for each MHF station is given, along with the associated formation / unit that was tested. Stations are presented in operational order of the first attempt for each station.

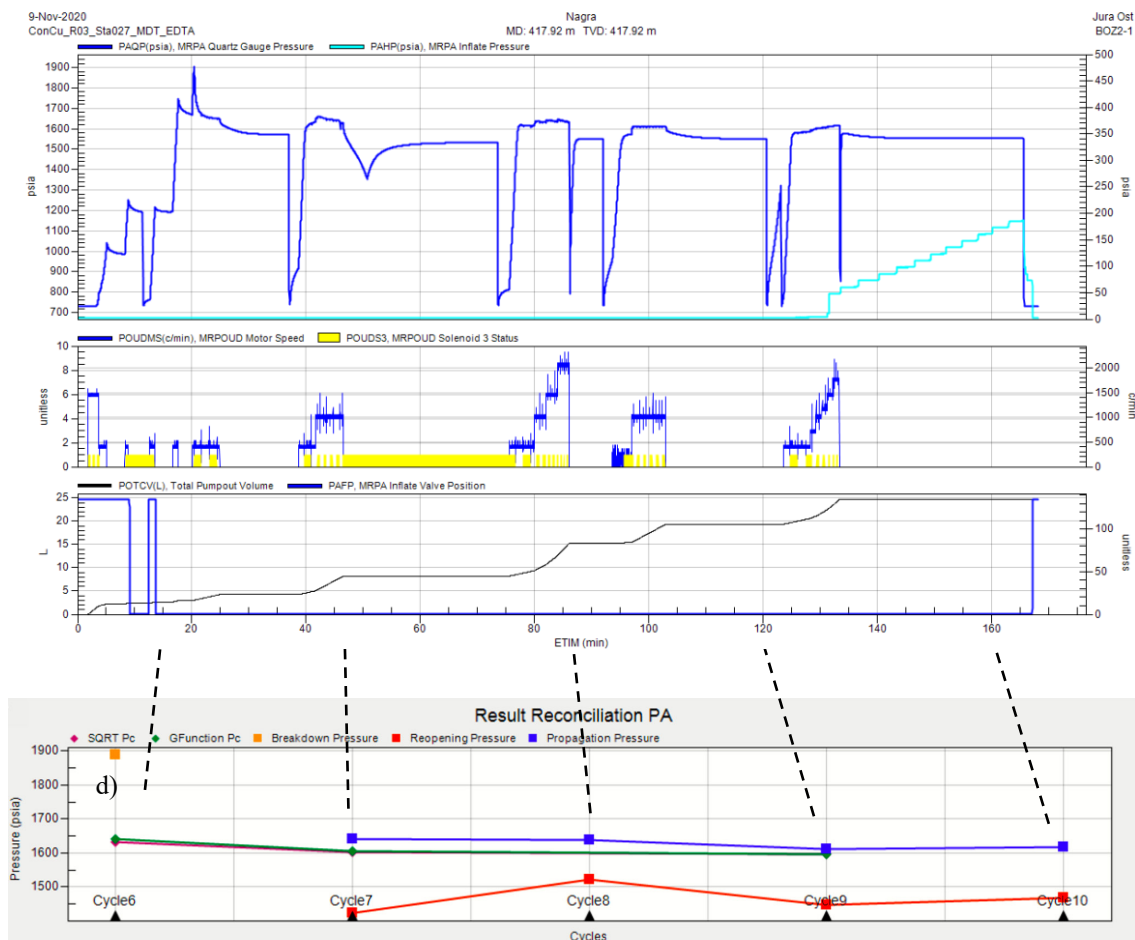


Fig. 5-2: Example of pressure record for MHF test from BOZ2-1 (Station 4-3, Run 2.3.3)

Pc stands for closure pressure.

Tab. 5-1: Summary of MHF station locations and operations carried out for each section of the BOZ2-1 borehole

Phase / Section	Station	Formation / unit	Middle interval depth [m]	Sleeve fracturing cycles	Break-down cycles	Reopening cycles	Slamback / rebound tests	Step-rate tests	Sleeve reopening cycles
I (Runs 1.2.3, 1.3.1 & 1.3.2)	1-1	Hauptrogenstein	366.00	0	0	-	-	-	-
	1-2	Hauptrogenstein	333.50	2	0	-	-	-	-
	1-3	Hauptrogenstein	326.80	2	0	-	-	-	-
	1-3a	Hauptrogenstein	327.10	3	1	7	0	1	2
	2-1	Hauptrogenstein	315.75	2	1	1	0	1	-
	2-1b	Hauptrogenstein	316.60	-	-	-	1	1	2
	3-1	Wildegge Fm.	293.20	2	0	-	-	-	-
	3-2	Wildegge Fm.	275.15	2	0	-	-	-	-
	3-7	Wildegge Fm.	290.65	2	0	-	-	-	-
	3-3 (HTPF)	Wildegge Fm.	245.70	-	1	3	0	1	-
	3-3a	Wildegge Fm.	252.65	3	0	-	-	-	-
II (Run 2.3.3)	1-1	Opalinus Clay	516.10	2	0	2	2	1	3
	1-2	Opalinus Clay	520.50	3	1	1	2	2	2
	1-3	Opalinus Clay	567.00	2	1	0	2	2	2
	1-4	Opalinus Clay	453.80	2	1	1	1	2	2
	2-1	Staffelegg Fm.	591.80	2	1	4	0	3	2
	3-1	Hauptrogenstein	383.90	2	1	2	1	2	3
	4-1	Passwang Fm.	427.80	2	1	1	2	2	3
	4-3	Passwang Fm.	417.80	0	1	1	1	2	2
	2-3	Staffelegg Fm.	595.20	2	1	5	3	1	2

5.4 MHF results

18 tests were attempted (some in two stages), with 12 of them being successful, from the Wildegge Formation (50 m) down to the Staffelegg Formation (612.46 m). Tests without the ability to breakdown the formation or with an inability to maintain a high-pressure seal were deemed unsuccessful. Any other test where a closure stress could be estimated was deemed successful.

Tab. 5-2 presents a quicklook interpretation of the MHF results which includes the 'breakdown pressure', the closure stress range and associated comments. The 'breakdown pressure' is taken as the maximum pressure reached during the first hydraulic fracturing cycle. If no fracture was propagated, that value is still reported but followed by an asterisk. A classical breakdown pressure interpretation should not be applied to these pressure values because sleeve fracturing was performed prior to hydraulic fracturing. Recorded 'breakdown pressures' are therefore technically reopening pressures. The closure stress acts normal to the fracture surface. Its range was determined from the pressure records and expressed with a lower and an upper bound.

Tab. 5-2: Quicklook interpretation of MHF results for the BOZ2-1 borehole

Section Run Diameter	Station	Formation	Depth [m]	Breakdown pressure [MPa]	Closure stress range [MPa]	Comments
I Runs 1.2.3, 1.3.1 & 1.3.2 8½" bit size	3-3	Wildegge Fm.	245.7	21.78	9.45 – 10.35	HTPF: upper bound for minimum stress
	3-3a	Wildegge Fm.	252.65	31.38*	n/a	MHF companion to HTPF 3-3. However, no breakdown
	3-2	Wildegge Fm.	275.15	21.82*	n/a	No breakdown
	3-7	Wildegge Fm.	290.65	27.59*	n/a	No breakdown
	3-1	Wildegge Fm.	293.2	21.75*	n/a	No breakdown
	2-1 2-1b	Hauptrogenstein	315.75 316.6	19.88 11.70	4.15 – 7.05	On the higher end of the predicted range
	1-3 1-3a	Hauptrogenstein	326.8 327.1	27.97* 31.03	11.4 – 14.2	No breakdown for the first stage; consistent propagation pressure even if outside of the predicted range for the second stage.
	1-2	Hauptrogenstein	333.5	28.39*	n/a	No breakdown
	1-1	Hauptrogenstein	366.0	26.17*	n/a	No breakdown
II Run 2.3.3 8½" bit size	3-1	Hauptrogenstein	383.9	14.76	6.55 – 7.17	S_{hmin} likely
	4-3	Passwang Fm.	417.8	13.02	10.13 – 11.3	Possibly S_{hmin} or S_v
	4-1	Passwang Fm.	427.8	12.53	10.2 – 11.35	Possibly S_{hmin} or S_v
	1-4	Opalinus Clay	453.8	12.82	7.9 – 8.62	S_{hmin} likely
	1-1	Opalinus Clay	516.1	17.22	9.9 – 11.0	S_{hmin} likely
	1-2	Opalinus Clay	520.5	14.39	10.0 – 11.18	S_{hmin} likely
	1-3	Opalinus Clay	567.0	12.72	10.3 – 11.0	S_{hmin} likely
	2-1	Staffelegg Fm.	591.8	38.04	9.34 – 17.7	Multiple closure signatures
	2-3	Staffelegg Fm.	595.2	36.58	10.9 – 13.38	S_{hmin} likely
Total number of tests						18
Total number of successful tests						12
Success rate (actual vs. attempted) & (actual vs. desired from initial plan)						67% & 67%

Fig. 5-3 plots the closure stress ranges from the quicklook analysis as a function of depth together with the overburden vertical stress (S_v), estimated from integration of the density logs over depth, and the maximum pressures measured during the formation integrity tests (FIT).

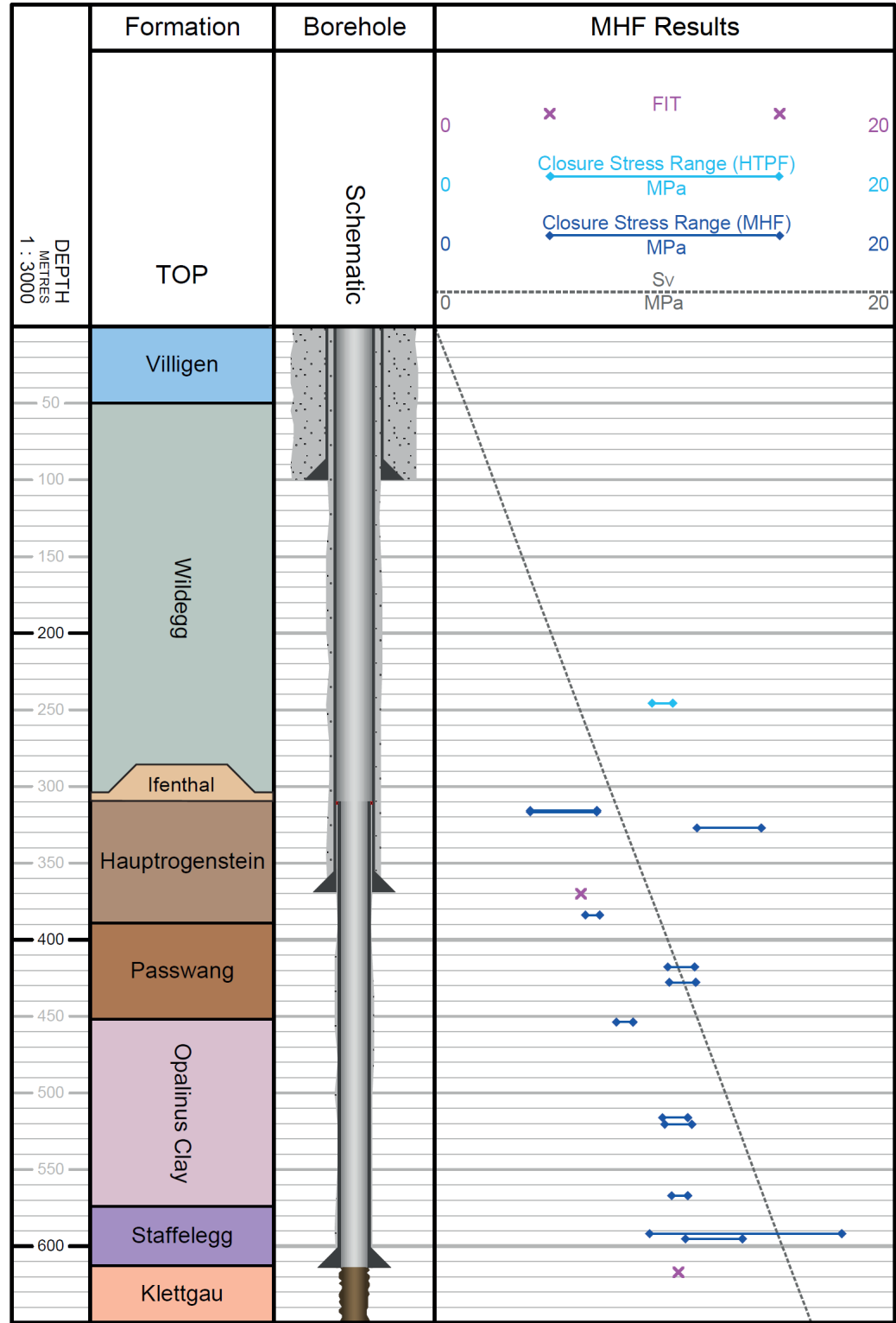


Fig. 5-3: Comparison of the quicklook closure stress range obtained from the BOZ2-1 MHF tests with the overburden vertical stress (Sv) from the integration of density over depth and the maximum pressures attained during the formation integrity tests (FIT)

Quicklook analysis of the post-MHF borehole imagery showed that new or enhanced features (longitudinal) could be observed at successful station locations. Conversely, in unsuccessful tests, no new feature could be observed. Fig. 5-4 presents the pre- and post-MHF images for Station 1-4 (Run 2.3.3). New fracture segments induced by the MHF test can be seen on both the static and the dynamic post-FMI images (two rightmost tracks). Note that there were no pre-existing fractures on the pre-MHF images. The MHF test led to the creation of sub-vertical conductive fractures at the wellbore which are mostly visible from the middle of the interval to the top of the top packer. The azimuth of these new fracture traces indicates the azimuth of the maximum horizontal stress. A comparison of all the pre- and post-MHF borehole images is included in Appendix D.

Interpretation of sleeve fracturing / sleeve reopening tests was not performed as part of the acquisition programme and is not included in this report.

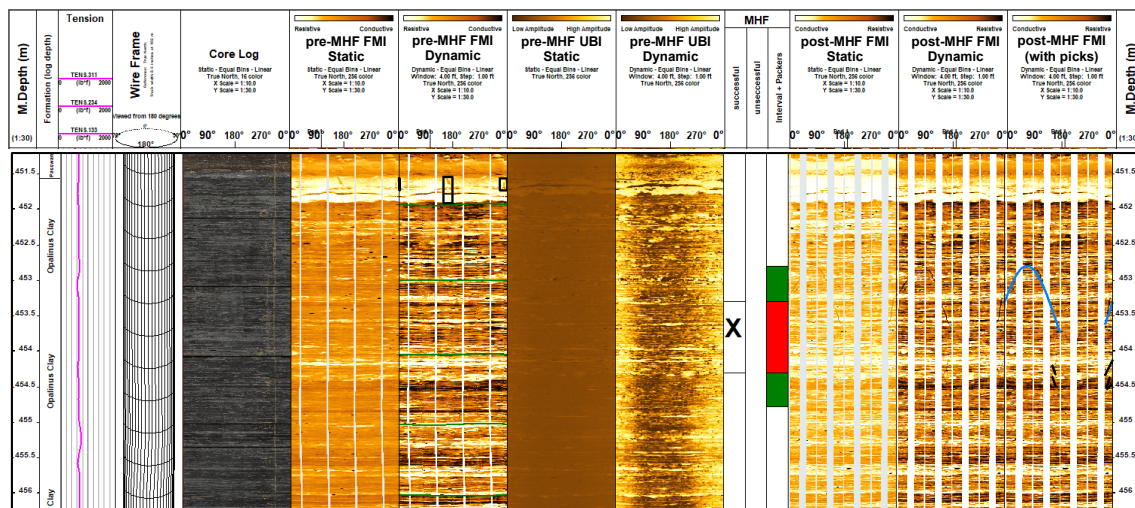


Fig. 5-4: Example of pre- vs. post-MHF images from BOZ2-1 (Station 1-4 from Run 2.3.3, Section II)

Pre- and post-MHF images are presented on the left and right of the MHF columns, respectively.

New fracture traces created by the MHF test are shown in blue picked by NiMBUC Geo-science on the post-FMI dynamic image.

6 Pressure-meter Testing (PMT)

6.1 Introduction and objectives

PMT tests were conducted to estimate the in situ shear modulus by testing a larger volume of rock than is possible during laboratory tests of core samples and at larger strains than during sonic logging. Testing was performed during MHF operations using the single packer module that is used to perform sleeve fracturing and sleeve reopening as discussed in Chapter 5. The main aim of the BOZ1-1 and BOZ2-1 PMT programmes was to select the best possible combination of hardware / test protocol for comparison with future dilatometer tests planned in the STA2-1 and STA3-1 boreholes.

Results from the previous PMT campaign in the BOZ1-1 borehole provided a complete validation of the Frac12k packer deployed without a dummy packer but with the auto retract mechanism (ARM). The BOZ2-1 testing programme aimed to provide the same qualification for the standard 7" packer (IPCF-PC-700), without a dummy packer but with the ARM.

6.2 Test protocol

A series of cycles with increasing maximum pressure were conducted to avoid creating a tensile fracture during the first cycle.

All tests were initiated with a packer inflation procedure, the aim of which was to ease the packer into place at the station location.

After packer inflation was complete, a series of inflation / deflation cycles were undertaken using the reduced protocol that was developed during the BOZ1-1 PMT programme as a means of performing faster tests that could be done directly prior to the MHF sleeve fracturing test. This is in line with what is presented in the ASTM Standard D8359-20, "Standard test method for determining in situ rock deformation modulus and other associated rock properties using a flexible volumetric dilatometer" (2020).

Note that in the text below "pressure" refers to the packer inflation pressure as defined above. The packer inflation pressure is the differential pressure between the hydrostatic pressure in the borehole and the absolute fluid pressure in the packer: it is the pressure difference seen by the packer membrane.

Packer inflation:

- The packer is first inflated to a pressure of 250 psi; fall-off is observed for 5 min. The packer is then de-pressurised.
- The packer is re-inflated again to a pressure of 250 psi; fall-off is observed for 5 min. The packer is not de-pressurised before the next steps.

Reduced protocol:

- The packer is inflated to increasing pressure levels, typically in steps of 500 psi (e.g. 1'000 psi, 1'500 psi, 2'000 psi).
- For each inflation cycle, the packer is inflated at a constant flow rate to the desired level; fall-off is observed for 3 min.

- The packer is then deflated down to a pressure level of 30 psi to 50 psi to ensure that full contact between the packer and the borehole is maintained.
- The packer is then inflated to the next desired pressure level; fall-off is observed for 3 min followed by partial deflation, until the final desired pressure is reached.

For PMT dedicated stations, the maximum inflation pressure for the entire test is to be kept lower than the sleeve fracturing breakdown pressure. All PMT tests were, however, integrated with a sleeve fracturing (SF) test. Under these circumstances, the maximum inflation pressure need not be limited as sleeve fracturing cycles follow immediately after the PMT protocol.

6.3 Results

A total of three PMT measurements and 1 reference PMT casing test were carried out using the 7" IPCF packer and MRPO module fitted with a high-pressure displacement unit (HPDU) and a constant displacement pump. Details of the PMT related operations are reported in Tab. 6-1. Note that, for comparison with MHF tests, the pressures that are reported in the description of the protocol are the inflation or differential pressures – not the absolute fluid pressure in the packer.

Tab. 6-1: PMT details

Section Run Diameter	Formation	Middle packer depth [m]	Protocol adjustments
II Run 2.3.3 8½" bit size	Opalinus Clay	520.5 (prior to SF at Station 1-2)	Packer inflation protocol, followed by three cycles up to an inflation (differential) pressure of, 1'000 psi, 1'500 psi and 2'500 psi, respectively.
	Opalinus Clay	567.0 (prior to SF at Station 1-3)	Packer inflation protocol, followed by two cycles up to an inflation (differential) pressure of 1'000 psi, 2'000 psi, respectively.
	Passwang Fm.	427.8 (prior to SF at Station 4-1)	Packer inflation protocol, followed by two cycles up to an inflation (differential) pressure of 1'000 psi and 2'000 psi, respectively.
	Casing test	360.0 (after MHF Station 2-3)	Packer inflation protocol, followed by five cycles up to an inflation (differential) pressure of 1'000 psi, 1'500, 2'000 psi and 2'500 psi, respectively.

An example of the pressure record of PMT for the reduced protocol integrated with a sleeve fracturing test is presented in Fig. 6-1. First the packers were inflated to a low inflation pressure twice, to ease their position against the borehole wall as per inflation protocol described earlier. Three inflation cycles were then performed up to differential pressures of 1'000 psi, 1'500 psi and 2'500 psi, respectively, with full packer deflation in between. These three cycles were then followed by regular sleeve fracturing (SF) cycles without moving the tool.

An example of a possible interpretation methodology is presented in ASTM D8359-20 (2020). Interpretation of the PMT is being performed separately by Schlumberger as part of a special project with Nagra and further results are therefore not reported here. In particular, refinement of results in consideration of the calibration tests is still under investigation. Preliminary results from the PMT test done in the Passwang Formation of the BOZ2-1 borehole have been presented in

Elkhoury et al. (2022), where the shear modulus at 427.8m was evaluated to be 4.5 ± 0.4 GPa. Similarly, the shear modulus for the PMT done in the Opalinus Clay at 520.5m was evaluated to 8.4 ± 1.2 GPa whereas that at 567.0m was evaluated to 7.8 ± 1.3 GPa.

Run 2.3.3, STA07, SF – Pre MHF, 520.50 m MD
Station Summary

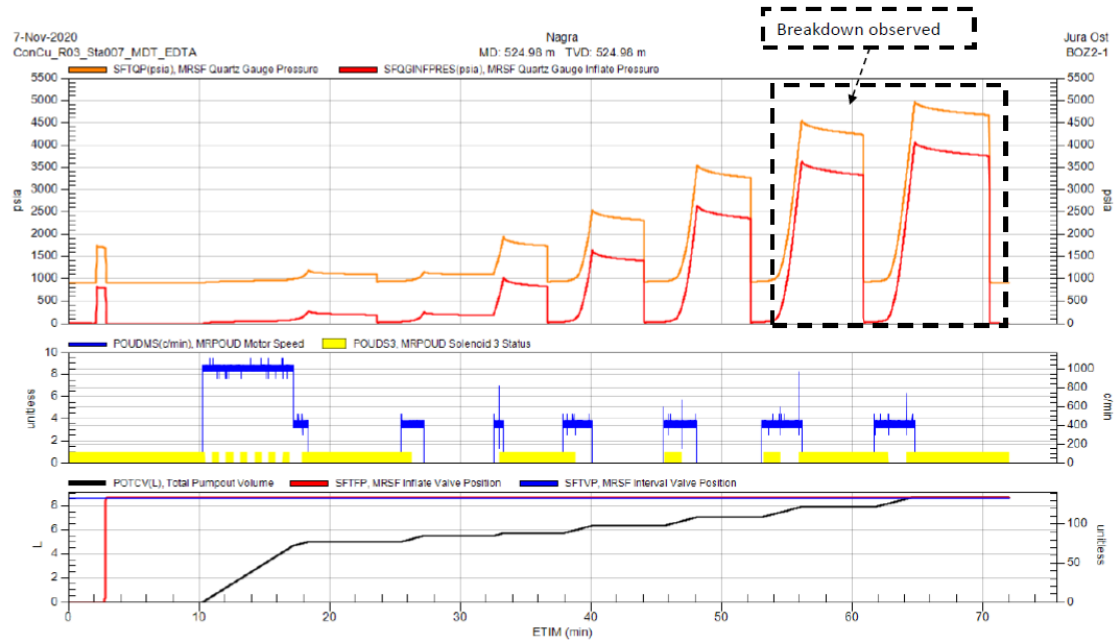


Fig. 6-1: Time summary plot for PMT-SF operation carried out before MHF Station 1-2 (Run 2.3.3)

Top plot: packer inflation pressure (red) and packer absolute pressure (orange)

Middle plot: pump speed (blue) and piston direction (yellow / colourless)

Bottom plot: total injected volume (black); the SF part of the test, performed after the PMT is highlighted by a black dashed rectangle.

7 References

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