

Arbeitsbericht NAB 21-20

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

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

September 2021

J. Gonus, E. Bailey, J. Desroches &
R. Garrard

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

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

www.nagra.ch

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J. Gonus¹, E. Bailey¹, J. Desroches¹ &
R. Garrard²

¹GPCI Geneva Petroleum Consultants International

²Nagra

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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)

Editorial work: P. Blaser and M. Unger

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 C: Composite log 1:1'000 scale
- Appendix D: Pre- vs. post-MHF borehole imagery
- Appendix E: MHF pressure-time and reconciliation plots

Note: Only in the digital version of this report Appendices A – E 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 Marthalen-1-1 borehole.

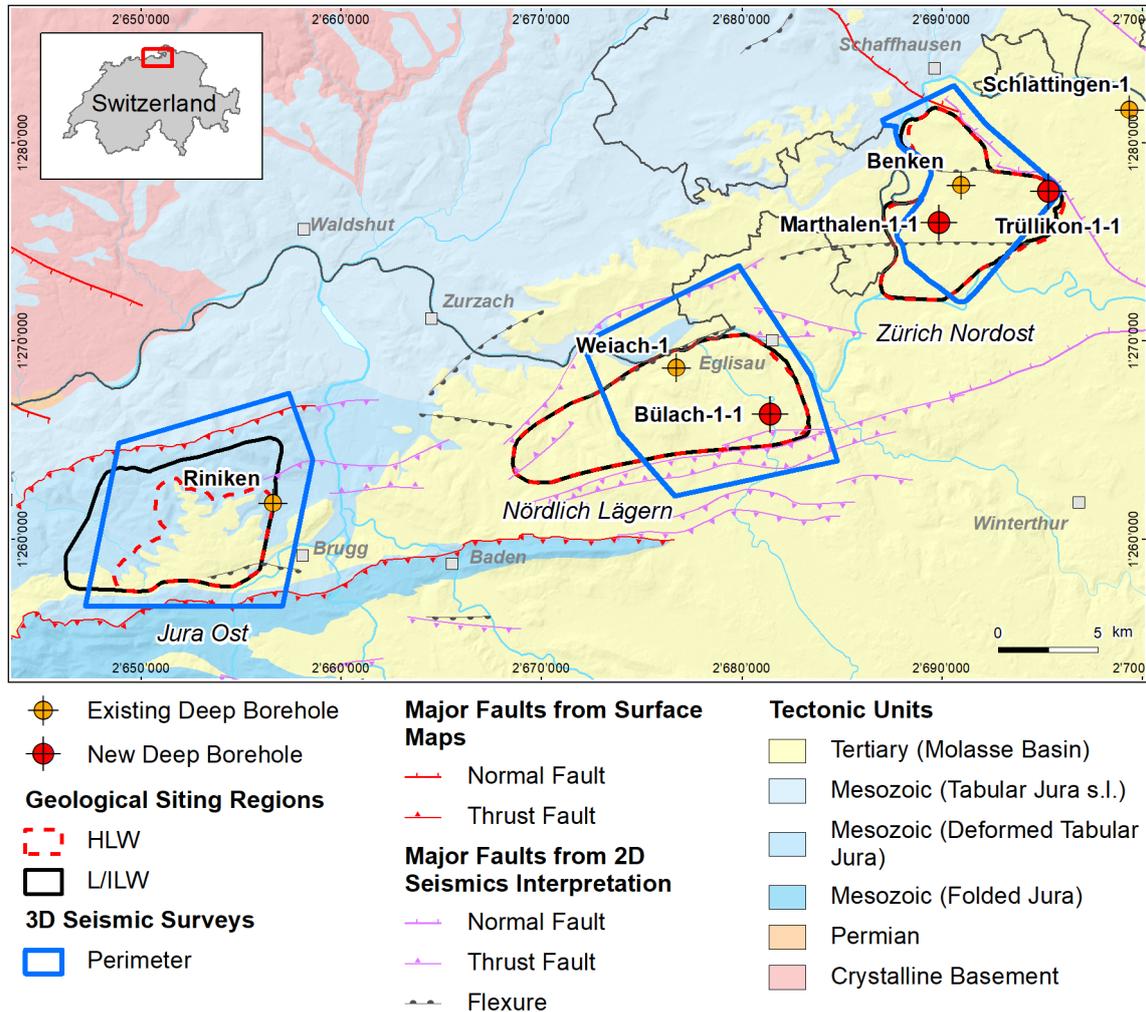


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

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

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

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

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

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

² For detailed information see Dossier I.

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

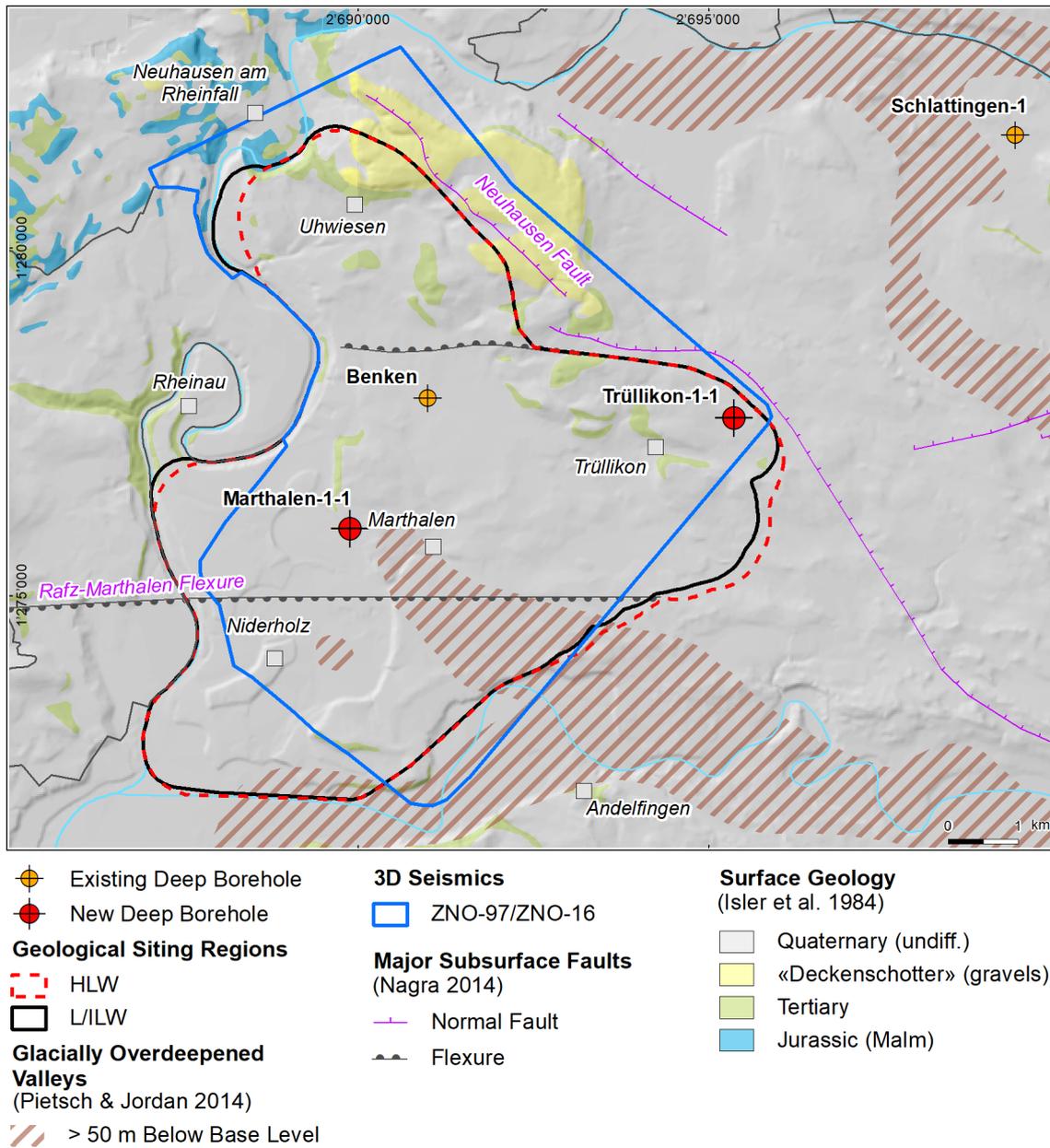


Fig. 1-2: Overview map of the investigation area in the Zürich Nordost siting region with the location of the MAR1-1 borehole in relation to the boreholes Benken, Schlattigen-1 and TRU1-1

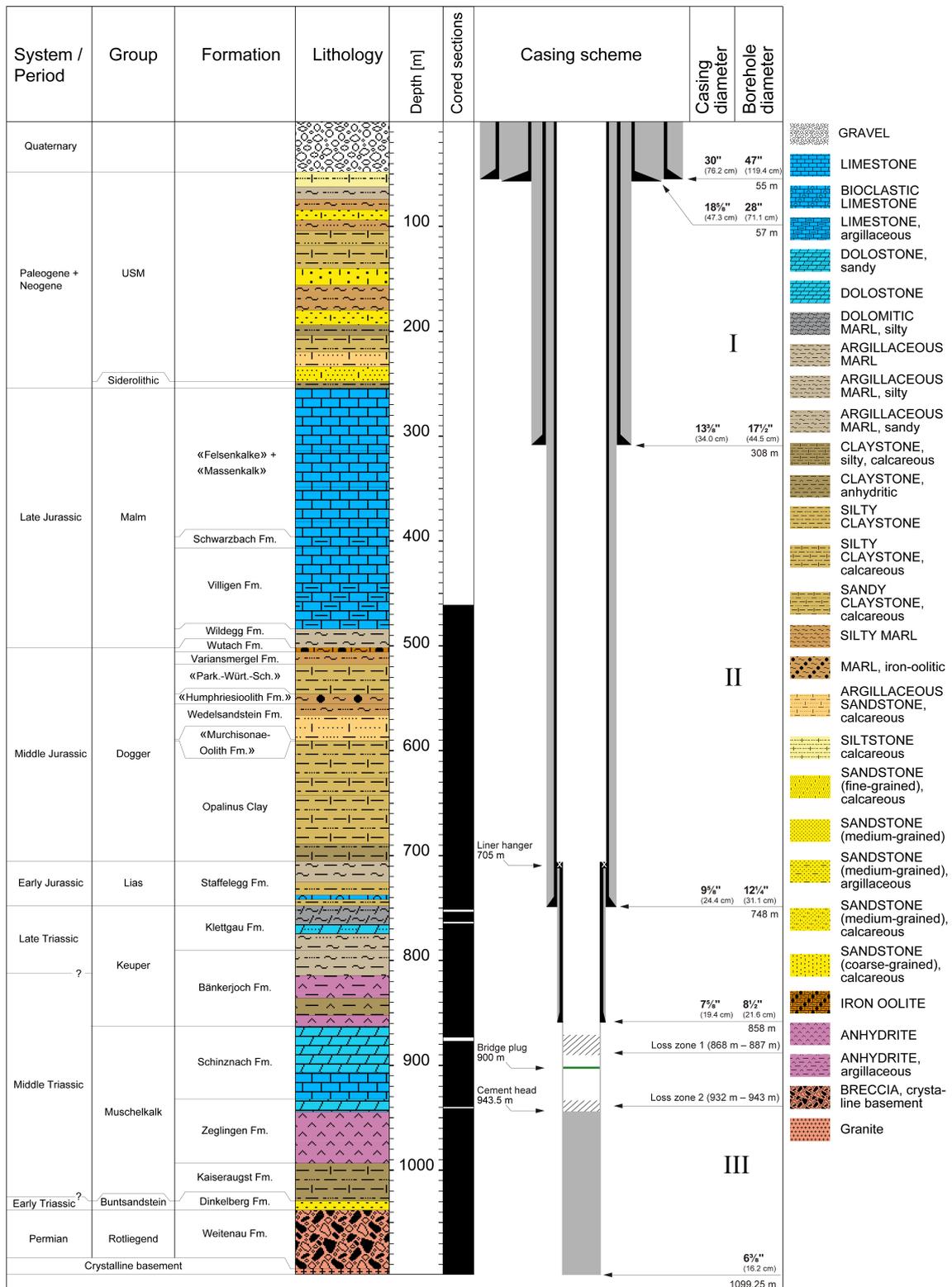


Fig. 1-3: Lithostratigraphic profile and casing scheme for the MAR1-1 borehole⁴

⁴ For detailed information see Dossier I and III.

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

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

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

1.3 Documentation structure for the MAR1-1 borehole

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

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

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

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

Black indicates the dossier at hand.

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

1.4 Scope and objectives of this dossier

The dossier at hand describes the acquisition, quality control and results of the Petrophysical Logging (PL) and Micro-hydraulic Fracturing (MHF) wireline logging measurements performed in the MAR1-1 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 and provide calibration points for mechanical earth models (MEM) of the rock mass (both 1D and 3D).

All PL and MHF testing were performed by the wireline logging company Schlumberger (SLB). Geneva Petroleum Consultants International (GPCI) 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 a 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.
- Finally, this report includes a set of appendices, where spliced PL, pre- and post-MHF borehole images and MHF data can be found.

2 Wireline logging and testing operations

The Marthalen-1-1 (MAR1-1) borehole was planned in 4 drilling sections (also commonly referred to as phases). After installation of the 30" outer diameter (OD) standpipe, Section I was drilled with the 23" and 17½" drill bits for installation of the OD 18⅝" and 13⅜" casings, respectively. Section II was drilled in 6½" from 312 to 460 m MD, cored in 6⅜" from 460 to 750 m MD and subsequently logged / tested. The borehole was then reamed (opened up) to 8½" and additional logging / testing undertaken, before reaming to 12¼" for installation of the 9⅝" casing. Section III was progressively cored in 6⅜" from 752 to 796 m MD, 796 to 877 m MD, 877 to 888 m MD, 888 to 1'054 m MD, 1'054 to 1'099 m MD and logged / tested after each interval was cored. Losses were encountered in two zones (868 to 887 m and 932 to 943 m) of Section III. Several attempts were made to cure losses using lost circulation material (LCM), while these attempts were unsuccessful, they did allow for coring to continue to final depth. The borehole was backfilled with cement from 1'099 to 943.5 m MD and two bridge plugs installed at 900 and 865 m MD. Section III was then reamed to 8½" and the 7⅝" liner installed. The upper bridge plug was later removed for installation of a long-term monitoring system. 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)
- *Technical Logging (TL)*
- *Vertical Seismic Profiling (VSP)*

Petrophysical logs are continuous measurements (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), Inclinator (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 photoelectric 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.

As well as PL and MHF 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 / washouts 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) were acquired using a sonic tool. 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 MAR1-1 borehole is given in Tab. 2-1. Fig. 2-1 depicts graphically the log coverage for the PL and MHF testing campaigns. In total, 5 PL and 2 MHF testing campaigns were undertaken. Open hole PL was conducted in Sections II and III, whilst MHF testing was only carried out 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 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 MAR1-1 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 | Vertical seismic profiling |
|--------------------------|--|---------------------------------|------------|------------|--------|-------------------|-----------------------|----------------------------|----------------------------|
| I | 13 3/8" 0 to 308 m | 0 to 309 m in 17 1/2" | 30.01.2020 | 22.02.2020 | | × | | | |
| II | 9 5/8" 0 to 748 m | 309 to 312 in 12 1/4" | 22.02.2020 | 18.05.2020 | × | × | × | × | |
| | | 312 to 460 m in 6 1/2" | | | | × | × | × | |
| | | 460 to 750 m 6 3/8" | | | | × | | | |
| III | 7 7/8" 705 to 858 m | 309 to 312 in 12 1/4" | 18.05.2020 | 14.07.2020 | | × | | | |
| | | 312 to 750 m in 8 1/2" | | | | × | × | | |
| | | 309 to 750 m in 12 1/4" | | | | × | | | |
| | | 750 to 877 m in 6 3/8" | | | | × | × | × | |
| | | 750 to 888 m in 6 3/8" | | | × | × | × | | |
| | | 750 to 1'054 m in 6 3/8" | | | × | × | × | × | |
| | | 750 to 858.8 m in 8 1/2" | | | × | × | × | | |
| | | 858.8 to 1'099 m in 6 3/8" | | | × | × | × | | |

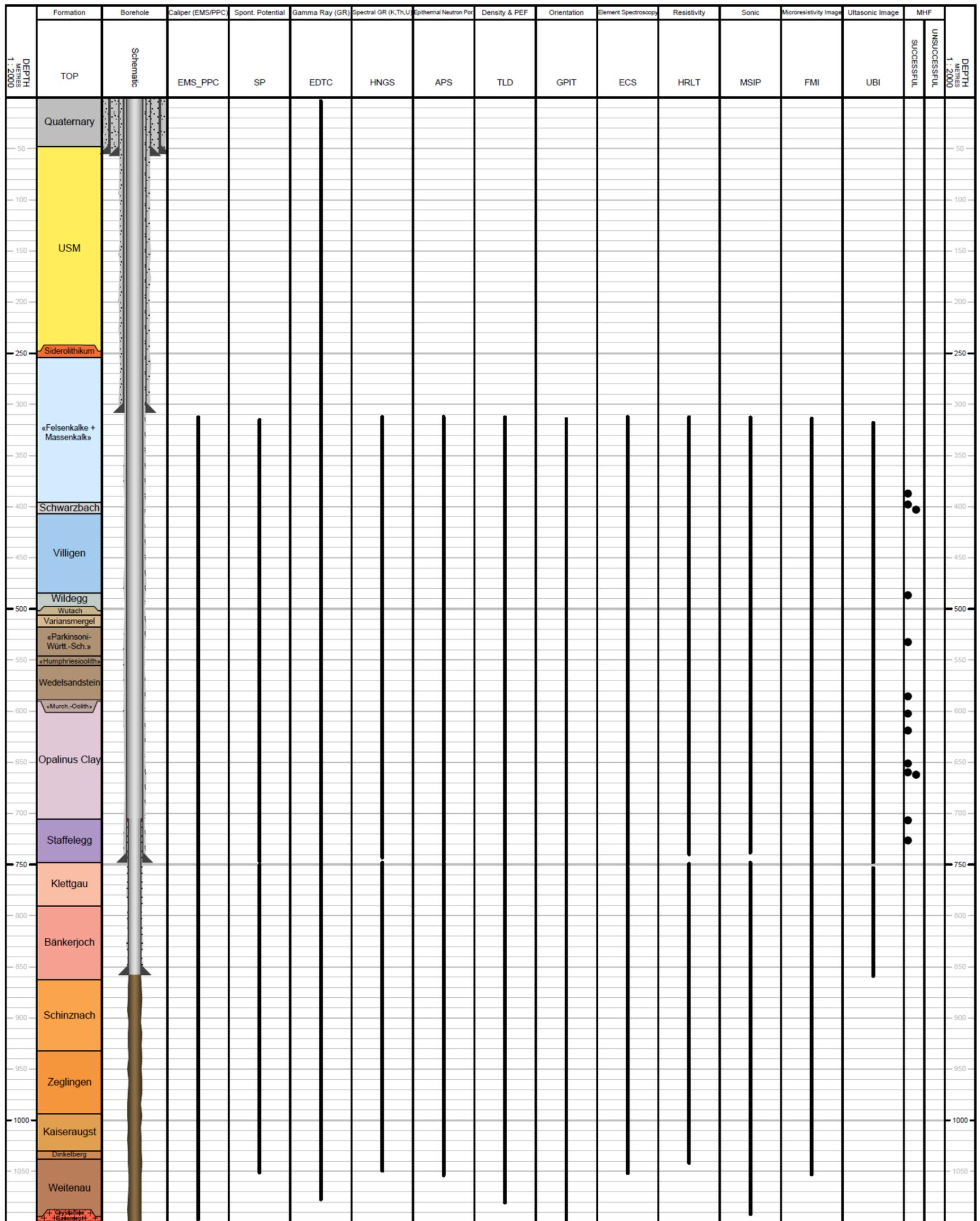


Fig. 2-1: Petrophysical log and MHF testing coverage at MAR1-1 (scale of 1:2'000)

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 | | | |
| III con- tinued | 3.3.5 | PL | 01.07.2020 | SLB | 820 to 1'050 | APS-EMS-EDTC-LEH.QT | × | | | | | × | × | | | | | × | | | | | | | | |
| | 3.3.6 | | 01.07.2020 | SLB | 855 to 1'052 | ECS-PPC-EDTC-LEH.QT | × | | | | | | | | | | | | × | | | | | | | |
| | 3.3.7 | | 01.07.2020 | SLB | 850 to 1'049 | HNGS-PPC-EDTC-LEH.QT | × | | | | | | | | | | | | × | × | | | | | | |
| | 3.3.8 | | 01.07.2020 | SLB | 820 to 1'042 | SP-EMS-HRLT-EDTC-LEH.QT | × | × | | | | | | | | × | | | | × | | | | × | | |
| | 3.4.1 | PL | 04.07.2020 | SLB | 1000 to 1'080 | PPC-MSIP-PPC-GPIT-TLD-MCFL-EDTC-LEH.QT | × | | × | × | × | | | × | | | | | | | × | | | | | |
| | 3.7.1 | PL | 10.07.2021 | SLB | 1 to 894 | EMS-EDTC-LEH.QT | × | | | | | | | | | | | | | | | | | × | | Post-completion |

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 or reopening |
| MRPO | SLB | Pump out module | Downhole pump for MHF tests |
| MRSC | SLB | Sample chamber | Typically used to carry fluid for MHF tests, 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 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 modes are also recorded by the MSIP (oriented shear waves, Rayleigh waves, Stoneley waves). Oriented shear waves can be used to analyse the acoustic 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 versus reference run. First run in hole is by convention, the reference for subsequent runs. GR log of the EDTC tool is always used for depth correlation because it has an 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 App. A8 – Table of post-acquisition depth shifts
4. Are the calipers well calibrated? This is checked by comparing caliper 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? When the borehole shape is not gauge, the log quality can be degraded.
6. 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 log quality.
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
 - 7.6 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 Parameters are checked including channel processing and tool control: corrections or offsets applied to measurements, modes of acquisition etc.
- 7.9 Calibration reports are checked for completeness and 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 datasets 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 (eccentred 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 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 (e.g. Benken) |

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). GPCI selects a collection of the most relevant logs for formation evaluation, correlation and calibration with core or seismic data. Some 87 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 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 MAR1-1 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 – 1/4 ft) were resampled to the standard rate of 0.1524 m (1/2 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.

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 Aluminium (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 |
| SV | MPa | Overburden vertical stress (Sv) |
| TMP | DEGC | Mud Temperature |
| U8 | B/C3 | High Resolution Volumetric Photoelectric Factor |

Tab. 3-2: continued

| Curve / channel | Units | Description |
|-----------------|-------|---|
| 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 (6⅜"). 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, 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, with only relatively small gaps (most less than 5 m) in log coverage between borehole sections.

Tab. 3-3: Summary of Petrophysical Log Coverage from Drilling Section II to TD

| Measurement | Section II to TD (309 m – 1'099 m MD) | | Opalinus Clay and Bounding Formations (Dogger – Lias) (501.92 m – 747.89 m MD) | |
|--|--|----------|--|----------|
| | Meterage | Coverage | Meterage | Coverage |
| Caliper | 783.18 | 99.1% | 244.84 | 99.5% |
| Borehole orientation | 784.71 | 99.3% | 245.97 | 100.0% |
| Total Gamma Ray | 768.47 | 97.3% | 245.97 | 100.0% |
| Spontaneous Potential | 732.12 | 92.7% | 244.84 | 99.5% |
| Spectral Gamma Ray | 732.11 | 92.7% | 241.18 | 98.1% |
| Density | 768.01 | 97.2% | 245.97 | 100.0% |
| Photoelectric Factor | 768.01 | 97.2% | 245.97 | 100.0% |
| Microresistivity | 766.64 | 97.0% | 245.97 | 100.0% |
| Neutron (NHI) | 739.59 | 93.6% | 244.23 | 99.3% |
| Sigma Formation Capture Cross-Section | 739.59 | 93.6% | 244.23 | 99.3% |
| Resistivity | 719.38 | 91.1% | 238.03 | 96.8% |
| Sonic | 768.84 | 97.3% | 236.15 | 96.0% |
| Element Spectroscopy | 736.70 | 93.3% | 245.97 | 100.0% |
| Ultrasonic Borehole Imagery | 565.00 | 71.5% | 245.97 | 100.0% |
| Microresistivity Borehole Imagery | 739.01 | 93.5% | 245.97 | 100.0% |

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 lithostratigraphic units.

3.4.1 Cenozoic: Quaternary, OMM, USM, and Siderolithikum (0 to 254 m MD)

Only the total GR was acquired in cased hole of Section I of the borehole. The log quality was influenced by the large drill bit size (17.5") and the attenuated GR emitted by the formation through the cemented casing. The total GR log could therefore only be used qualitatively in the Molasse, Siderolithic and transition to Malm units.

3.4.2 Malm: «Felsenkalke» + «Massenkalk» to Wildegg Formation (254 to 501.92 m MD)

No valid logs were acquired above the 7 $\frac{5}{8}$ " auxiliary casing set at 311.7 m MD in Section II of the borehole.

Log responses reflect the borehole lithology well, except for some short bad-hole zones in the «Felsenkalke» + «Massenkalk» and Schwarzbach Formation, where the borehole wall rugosity deteriorated the response of the TLD and APS tool logs (density, photoelectric factor, micro-resistivity, and neutron).

Logs in the Malm units have an overall similar log signature characterised by (Fig. 3-1):

- Generally low clay content except in the Schwarzbach and Wildegg Formations: low total GR (GR_KCOR: 0 to 57 GAPI; mean = 9 GAPI), spectral GR (e.g. thorium HTHO: 0.2 to 8.6 ppm; mean = 1.1 ppm) and sigma (SIGF: 6.9 to 22.5 CU; mean = 10 CU). Clay content increases in the Schwarzbach Formation and the Wildegg Formation (GR_KCOR: 13 to 30 GAPI; mean = 19 GAPI).
- Calcite is the dominant mineral: an almost perfect overlap in the neutron-density limestone-compatible scale (density [RHOZ] and neutron [APLC] readings in pure limestone are 2.71 g/cm³ and 0.0 v/v, respectively), the calcium dry weight fraction (DWCA) is close to that of pure calcite (0.394 W/W), as is the photoelectric factor (PEFZ) – pure calcite value of 5.1 B/E.
- In the low clay units (GR_KCOR < 15 GAPI), porosity is low, density is high (rarely lower than 2.63 g/cm³; mean: 2.68 g/cm³) and sonic (DTCO) rarely exceeds 61 μ s/ft.

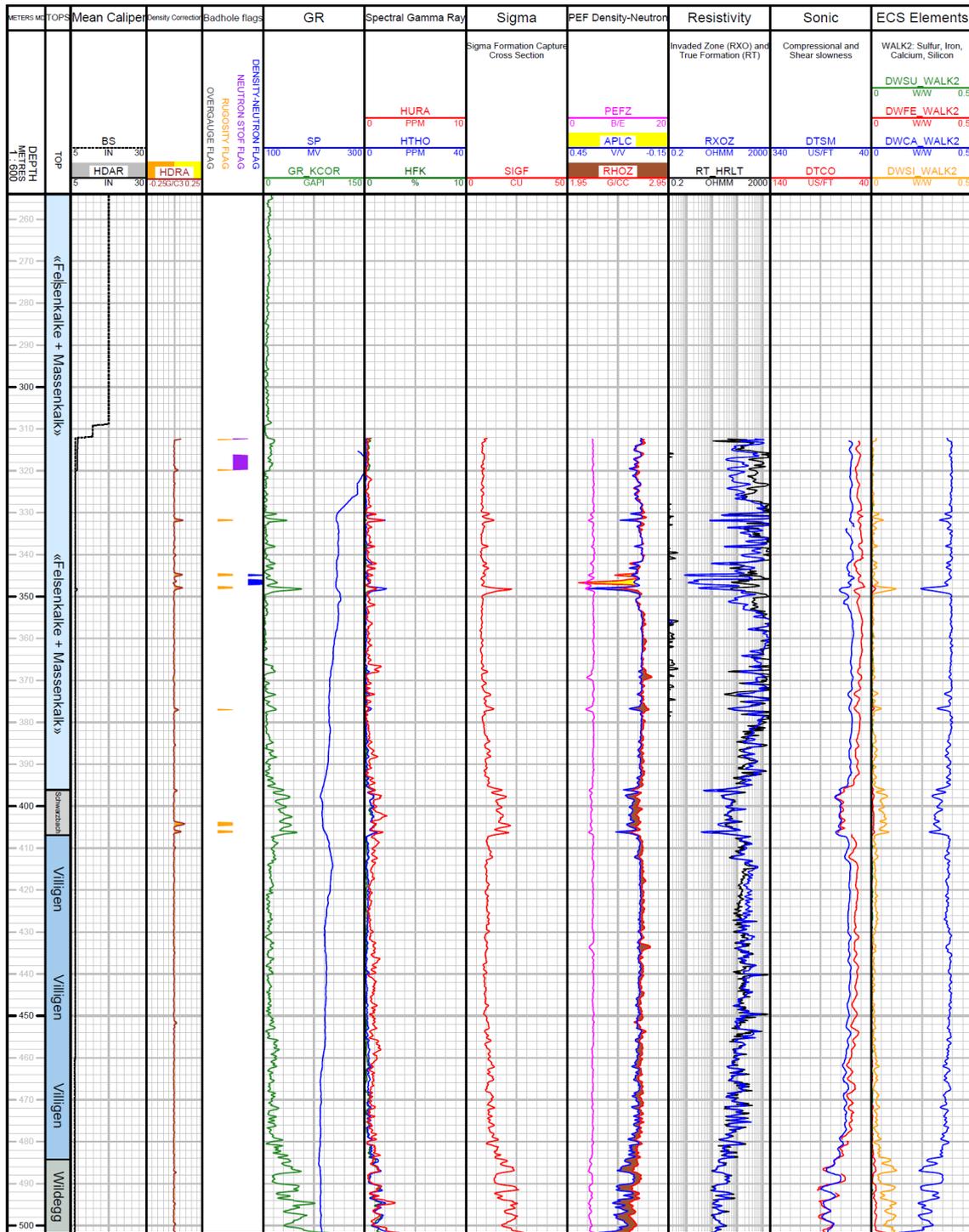


Fig. 3-1: Main logs of the composite dataset in the «Felsenkalk» + «Massenkalk» to Wildegg Formation

3.4.3 **Wutach Formation to «Murchisonae-Oolith Formation» (501.92 to 590.37 m MD)**

The top of the Dogger (Wutach Formation) can be identified by an increase in total GR, a wide separation in the neutron-density logs in a limestone-compatible scale and 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 Wutach Formation to the «Murchisonae-Oolith Formation». Logs have the following attributes:

- Highly variable clay content that is moderate to low in parts of the Wedelsandstein Formation and high in the «Parkinsoni-Württembergica-Schichten» («Park.-W.-Sch») unit and Variansmergel Formation. Excluding the zones that contain siderite, iron oxides or hydroxides (DWFE < 0.05 W/W), the total GR ranges from 28 to 108 GAPI, SIGF from 13.9 to 37.9 CU and HTHO from 3.6 to 15.2 ppm. The «Humphriesioolith Formation» and Wedelsandstein Formation contain less clay than the «Park.-W.-Sch» unit above.
- The occurrence of siderite, iron oxide or hydroxide is typical in these formations. In the Wutach Formation, parts of the lower «Park.-W.-Sch» unit and the «Humphriesioolith Formation»: a wide separation in the neutron-density, high total and spectral GR (especially thorium HTHO up to 28.7 ppm and uranium HURA up to 5.3 ppm), high iron concentration (DWFE: above 0.05 W/W) and high photoelectric factor (PEFZ up to 8.5 B/E).
- The matrix mineralogy is dominated by calcite: in the lowest clay zones the PEFZ is in the range of 2.9 to 5.4 B/E, while calcium is relatively high (DWCA: up to 0.24 W/W; 0.394 W/W in pure calcite), which is typical of marls. In the Wedelsandstein Formation, the separation between neutron-density is quasi absent, an indication of pure limestone if calcite was the only matrix mineral, however, the clay content is moderate to low. This indicates a siliciclastic component in the matrix mineralogy, that is consistent with the rather high silicon concentration (DWSI: up to 0.32 W/W; 0.467 W/W in pure quartz).
- The spectral GR potassium (HFK) and thorium (HTHO) log signatures in the clay-rich units suggest that non-potassic smectite (e.g. montmorillonite) is the dominant clay type.

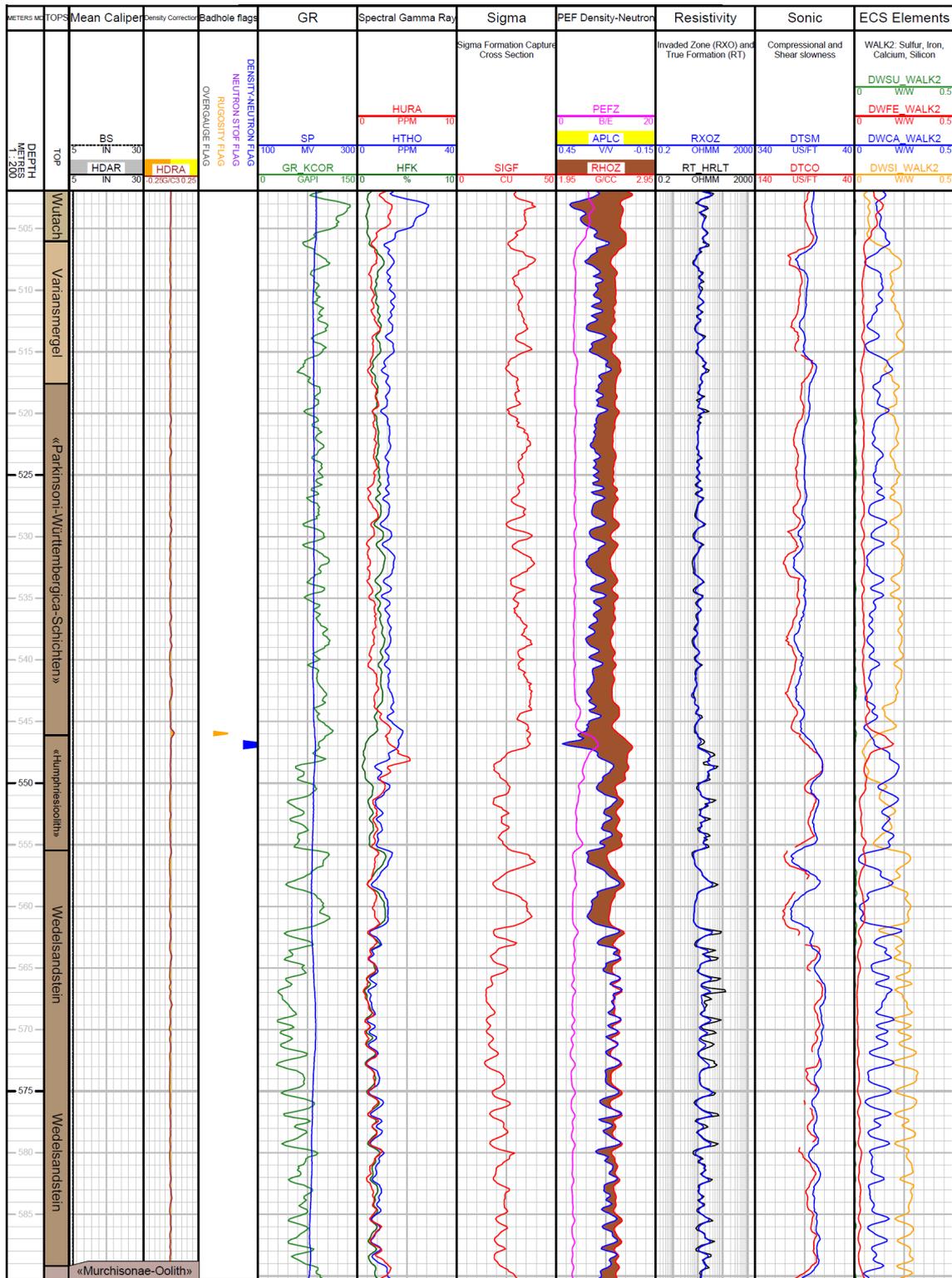


Fig. 3-2: Main logs of the composite dataset in the Wutach Formation to «Murchisonae-Oolith Formation»

3.4.4 **Opalinus Clay (590.37 to 705.52 m MD)**

The top Opalinus Clay is characterised by an increase in clay content, as observed by the decrease in resistivity (e.g. RT_HRLT), a wider neutron-density separation in a limestone-compatible scale and significant 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: the total GR (GR_KCOR) ranges from 63 to 118 GAPI; sigma (SIGF) correlates very well (positively) to GR_KCOR, ranging from 24.8 to 44.2 CU; the compressional wave slowness DTCO was high (slow formation) and generally above 92 $\mu\text{s}/\text{ft}$; the density-neutron separation is typical of lithologies with high clay content.
- Several carbonate streaks can be observed at 597.2, 600.5, 603.5, 609.4 and 623.8 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 0.14 W/W); an increase in resistivity logs (e.g. RT_HRLT).
- While the clay content is relatively homogeneous throughout, two distinct trends can be observed. In the upper part of the formation above 660 m MD, clay content varies with carbonate content and generally remains lower than in the lower Opalinus Clay. Below 660 m MD, the clay content gradually increases with depth as shown by the gradual widening of the density-neutron separation and increase in sigma. Carbonate streaks are absent in the lower part of the formation.
- The spectral GR potassium (HFK) and thorium (HTHO) log signatures in the clay-rich units suggest that non-potassic smectite (e.g. montmorillonite) is the dominant clay type.
- Matrix mineralogy is complex. Both calcium (DWCA) and silicon (DWSI) concentrations are often higher than those in smectite clays (DWCA: 0.00 to 0.09 W/W; DWSI: 0.16 to 0.30 W/W; excluding the carbonate streaks), which suggests siliciclastic and carbonate components in the matrix.

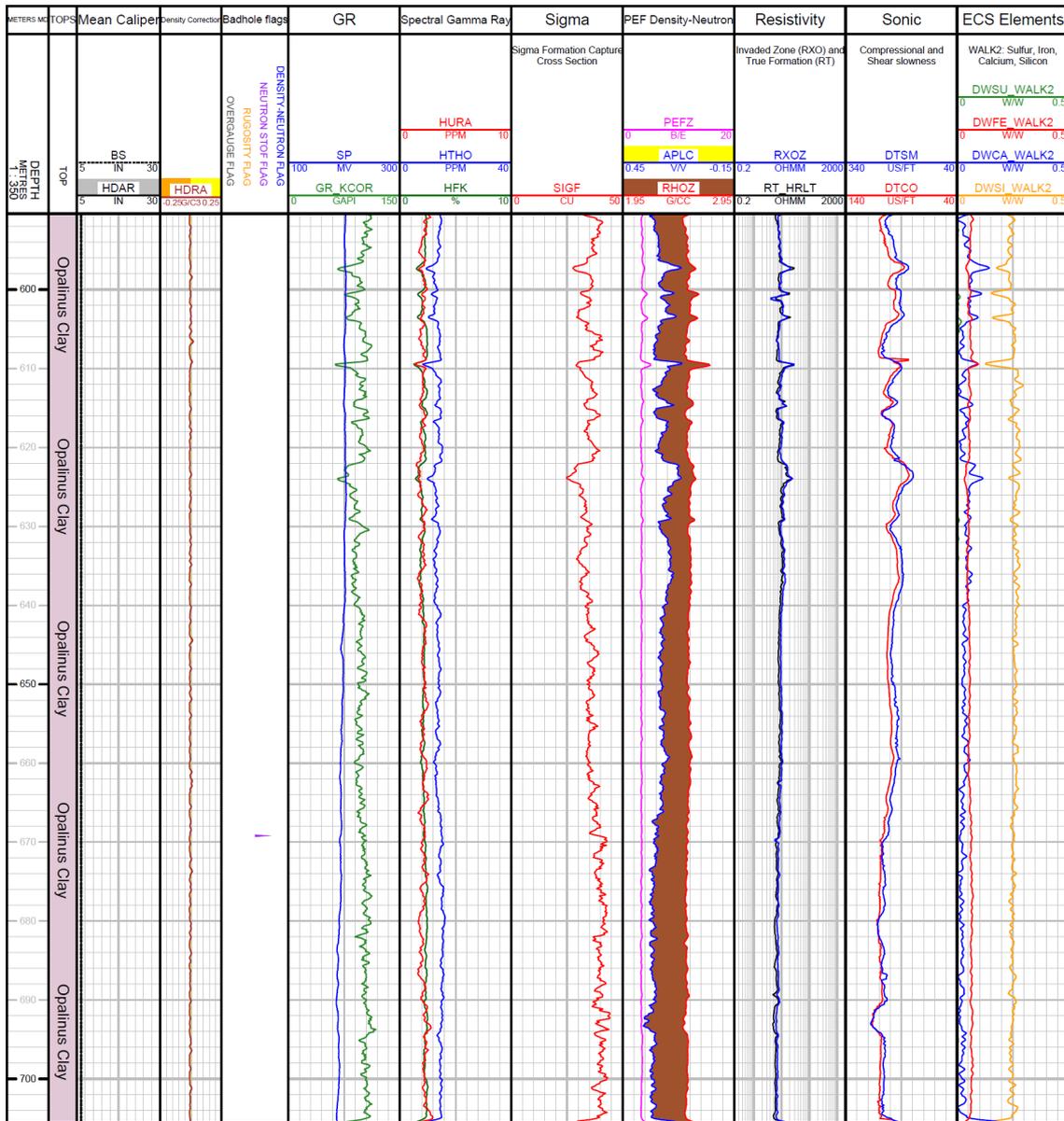


Fig. 3-3: Main logs of the composite dataset in the Opalinus Clay

3.4.5 Staffelegg Formation (705.52 to 747.89 m MD)

The transition between the Dogger and the Lias (Staffelegg Formation) is gradual from 705 to 705.6 m MD. The top of the Staffelegg Formation can be identified by the decrease in clay content as shown by the total GR (GR_KCOR), thorium (HTHO), sigma (SIGF) and the density-neutron separation (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 (50 to 152 GAPI), sigma (14.0 to 45.7 CU) and thorium (3.9 to 15.3 ppm), e.g. low clay content in the Beggingen Member (737.74 to 741.98 m MD) but intermediate to high clay content in the Frick Member (725.09 to 737.74 m MD).
- Organic matter is likely present: the high total GR zones (GR_KCOR > 110 GAPI) correspond with the uranium peaks (HURA: up to 13.3 ppm).
- Pyrite is an important accessory mineral in several members of the Staffelegg Formation (Gross Wolf, Rietheim, Grünschholz and Schambelen Members): Sulphur concentration (DWSU) ranges from 0 to 0.03 W/W; the photoelectric factor (PEFZ), a reactive marker of pyrite, reaches high values of 6.2 B/E.
- Matrix mineralogy is dominated by carbonate: calcium (DWCA) varies between 0 and 0.33 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.

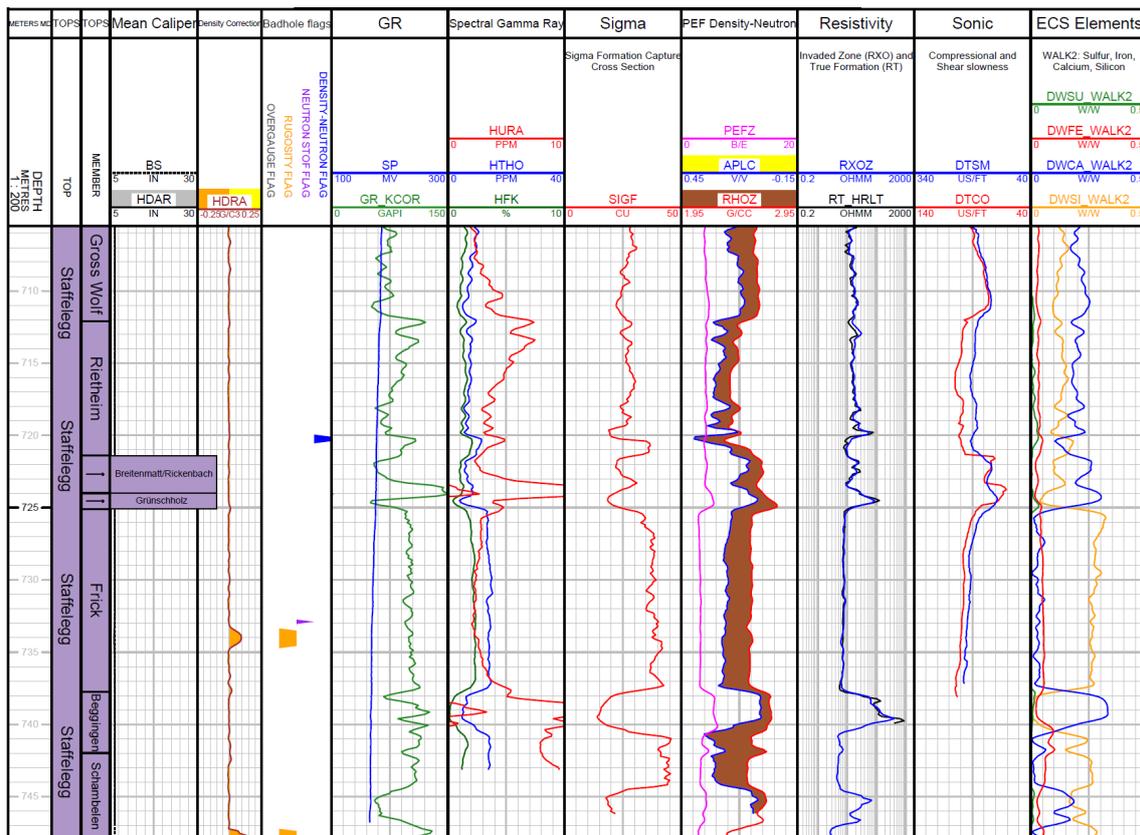


Fig. 3-4: Main logs of the composite dataset in the Staffelegg Formation

3.4.6 Klettgau Formation (747.89 to 790.34 m MD)

The bottom of the Lias (Staffelegg Formation) could not be logged in open hole because the rathole clearance below Section II was insufficient. The top of the Triassic (Klettgau Formation) was logged in an enlarged open hole (rathole). Thus, the change in log attributes between the two formations could not be discerned.

Hole conditions were degraded in most of the formation as indicated by the bad-hole flags (Fig. 3-5). Bad-hole conditions affected log responses to lithology, particularly the density (RHOZ) and neutron (APLC) logs. Logs in the Klettgau Formation show the following attributes:

- Highly variable clay content: total GR ranges from 0 to 162 GAPI, sigma from 8.0 to 38.3 CU and thorium from 0.3 to 15.2 ppm; clay indicators have a bimodal distribution that reflect zones with low clay content (from 765.7 to 775.0 m MD, Seebi Member; 782.4 to 784.5 m MD, Gansingen Member), and zones with intermediate to high clay contents (747.89 to 765.7 m MD: Gruhalde Member; 775.0 to 782.4 m MD: Gruhalde Member; 784.5 to 790.34 m MD: Ergolz Member).
- Carbonate is the main matrix mineral in the upper Klettgau Formation down to 772.3 m MD, indicated by the intermediate to high calcium concentration (DWCA: 0.09 to 0.36 W/W; pure calcite: 0.394 W/W). The carbonate has a dolomitic signature, as shown by the photoelectric factor (PEFZ) whose mean value (3.4 B/E) is close to that of pure dolomite (3.1 B/E).
- In the intervals 772.3 to 782.4 m MD and 784.5 to 790.34 m MD, the calcium concentration is low (mean DWCA: 0.07 W/W) and the silicon concentration increases up to 0.35 W/W, this is also true of the zones with low clay content. This suggests that the matrix mineralogy is dominated by siliciclastic minerals such as quartz. The almost density-neutron "crossover" (density is to the left of neutron in the limestone-compatible scale: yellow shading) in presence of clays (yet limited) also supports the presence of quartz e.g. from 772.5 to 773.7 m MD.
- In between these two quartz intervals, high sulphur (DWSU: up to 0.22 W/W) and low iron (DWFE) concentrations are present in the Gansingen Member (from 728.72 to 784.21 m MD), which suggests a unit composed of anhydrite (pure anhydrite: 0.234 W/W sulphur).
- Organic matter is likely present: the total GR is higher (GR_KCOR up to 162 GAPI) than expected in rocks with high clay content.

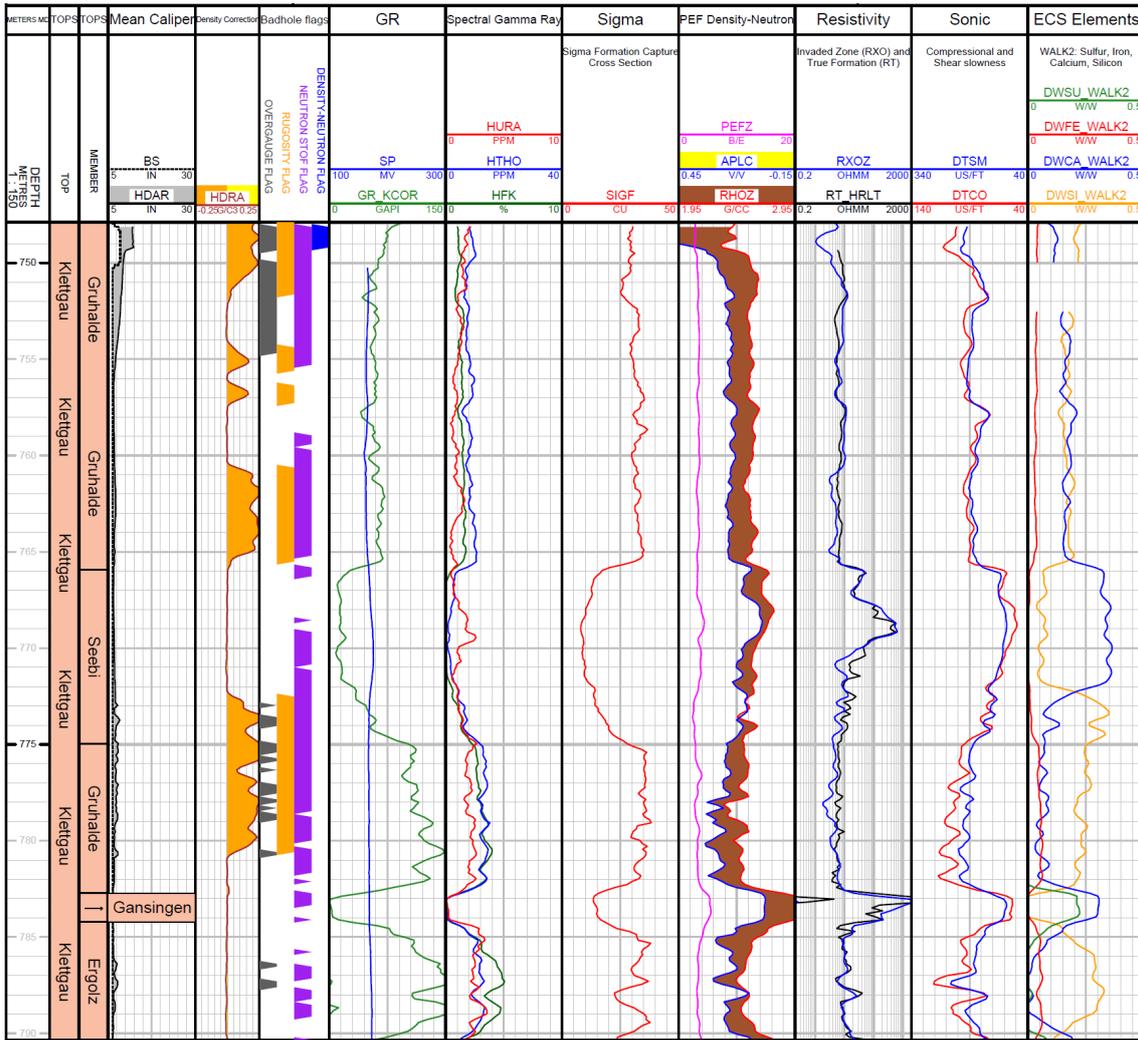


Fig. 3-5: Main logs of the composite dataset in the Klettgau Formation

3.4.7 Bänkerjoch Formation (790.34 to 862.77 m MD)

The top of the Bänkerjoch Formation is characterised by a shift to lower values of total GR (GR_KCOR), potassium (HFK) and sigma (SIGF). At the same time, sulphur (DWSU) and calcium (DWCA) concentrations increase. These log characteristics show the onset of the significant concentrations of anhydrite of this formation.

Hole conditions were mostly good in the Bänkerjoch Formation and logs responded well to borehole lithology. Logs show the following attributes (Fig. 3-6):

- Rapid variations in most logs at the metre scale or less, which suggests two main alternating lithologies. One having high sulphur (DWSU: up to 0.23 W/W) and calcium concentrations (DWCA: up to 0.33 W/W), high photoelectric factor (PEFZ: up to 5.3 B/E) and intermediate to low total GR which suggest predominantly anhydrite bearing beds. The alternate beds have higher clay contents as indicated by the lower sulphur and calcium concentrations, high silicon (DWSI: up to 0.32 W/W) and intermediate to high total GR.
- The density-neutron separation in the limestone compatible scale remains similar for both beds but logs shift from left to right for the clay and anhydrite dominant endmembers, respectively.
- Due to the limited vertical resolution of the logging tool, often higher than 10" (e.g. APS: 14"), 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.

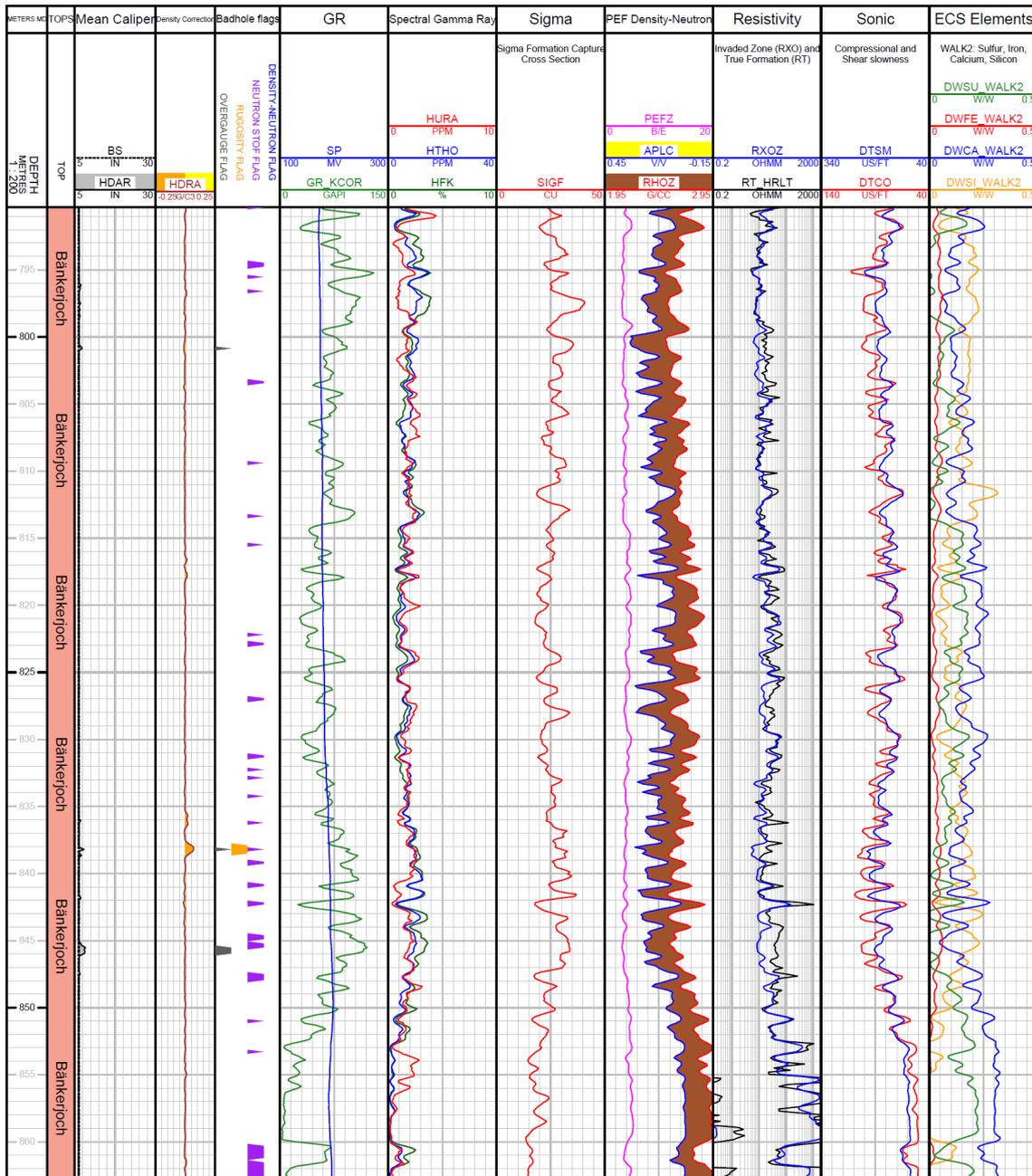


Fig. 3-6: Main logs of the composite dataset in the Bänkerjoch Formation

3.4.8 Schinznach Formation (862.77 to 932.47 m MD)

The top of the Schinznach Formation is identified by the disappearance of the sulphur content (DWSU) and a decrease in the photoelectric factor (PEFZ) and sigma (SIGF) below the lowest anhydrite bed of the Bänkerjoch Formation.

Bad-hole conditions affected the log responses in the upper Stamberg Member (867.1 to 877.7 m MD) rendering the neutron and density logs unusable. Outside this zone, hole conditions were generally good and logs responded well to the borehole lithology. Logs in the Schinznach Formation are characterised by the following attributes (Fig. 3-7):

- Low to moderately low clay contents as shown by the total GR (GR_KCOR: 11 to 68 GAPI), sigma (SIGF: 7.2 and 21.8 CU) and thorium (HTHO: 0.5 to 6.3 ppm), except in the interval from 865.7 to 867.5 m MD in the Asp Member where a clay-rich layer is present.
- Carbonate is the main matrix mineral as shown by the fast sonic (DTCO, DTSM), low silicon (DWSI) and high calcium concentrations (DWCA: up to 0.40 W/W; pure calcite is 0.394 W/W for comparison).
- From the top of the Schinznach Formation to 906.4 m MD, the carbonate has a dolomitic signature as shown by the photoelectric factor (PEFZ) whose mean value of 3.0 B/E is close to that of pure dolomite (3.1 B/E), whilst the density-neutron separation is positive, and the clay content is low. The large separation between the shallow (RXOZ) and deep (RT_HRLT) resistivities indicate invasion of mud filtrate into the permeable formation across several zones.
- From 906.4 m MD to the bottom of the Schinznach Formation, the mean photoelectric value (4.4 B/E) is close to that of pure calcite (5.1 B/E) and the density-neutron separation is slightly positive or absent suggesting that the carbonates contain limestones and dolomitic limestones.

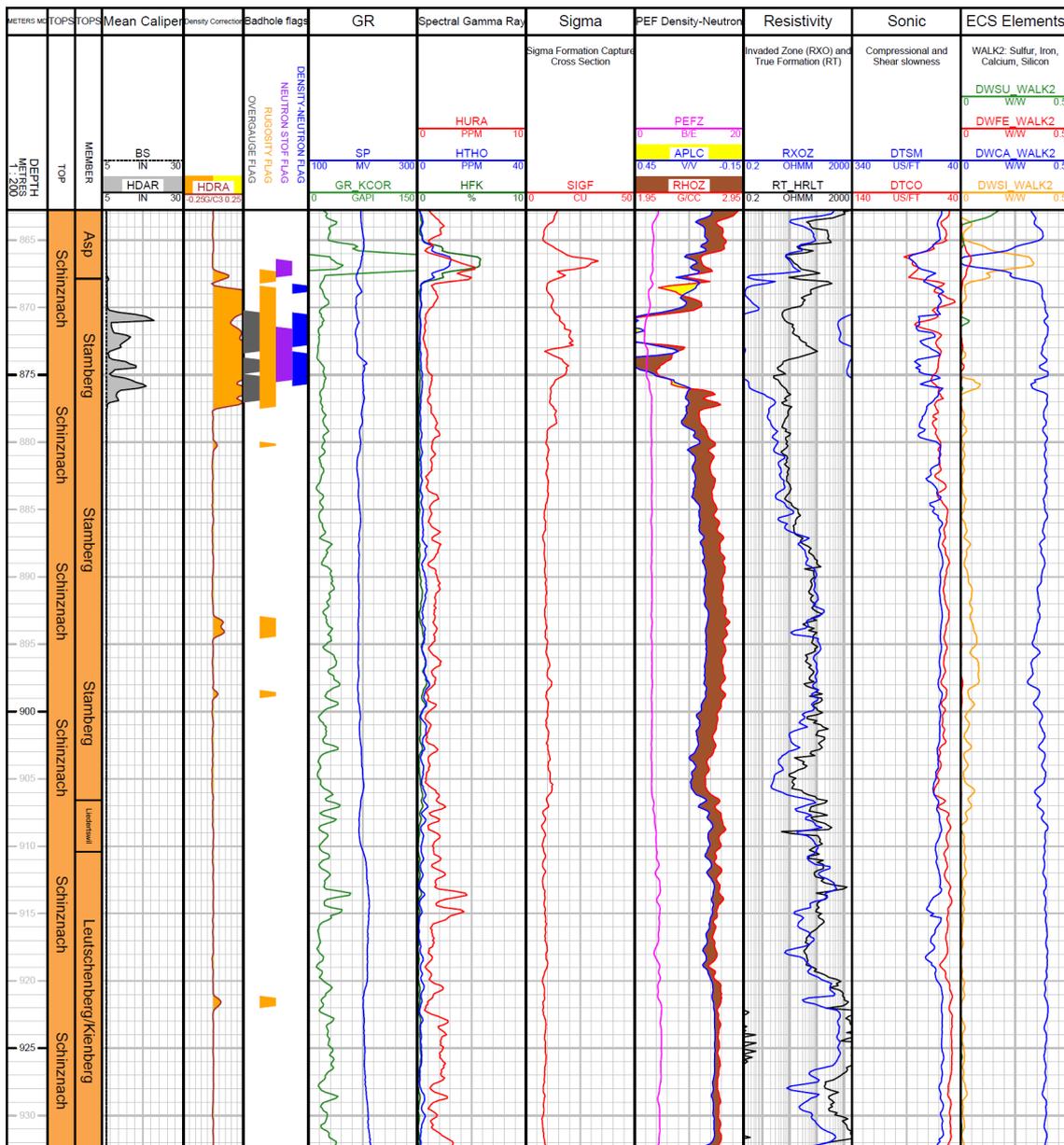


Fig. 3-7: Main logs of the composite dataset in the Schinznach Formation

3.4.9 Zeglingen Formation (932.47 to 993.97 m MD)

The top of the Zeglingen Formation corresponds to a decrease in calcium content (DWCA), an increase of silicon content (DWSI) and a reduction in the photoelectric factor (PEFZ).

Hole conditions were good except in a short interval in the upper formation (from 937.2 to 944.1 m MD), where there were washouts and rugosity. Outside this zone, logs responded well to borehole lithology. The Zeglingen Formation is characterised by the following (Fig. 3-8):

- Low to moderately high clay content: total GR (GR_KCOR: 2 to 129 GAPI), sigma (SIGF: 8.9 to 45.1 CU) and thorium (HTHO: 0.3 to 13.0 ppm).
- Density (RHOZ) is often greater than 2.9 g/cm³ suggesting the presence of anhydrite. This is supported by the photoelectric factor (PEFZ) that is close to the value in pure anhydrite (5.05 B/E) and the significant sulphur content (DWSI: up to 0.24 W/W; value in anhydrite: 0.236 W/W).
- From the top of the Zeglingen Formation to 951.7 m MD, logs indicate less anhydrite, and dolomite is the main mineral component: the photoelectric factor values are close to that of pure dolomite (3.1 B/E) and calcium content (DWCA) ranges from 0.18 to 0.39 W/W.

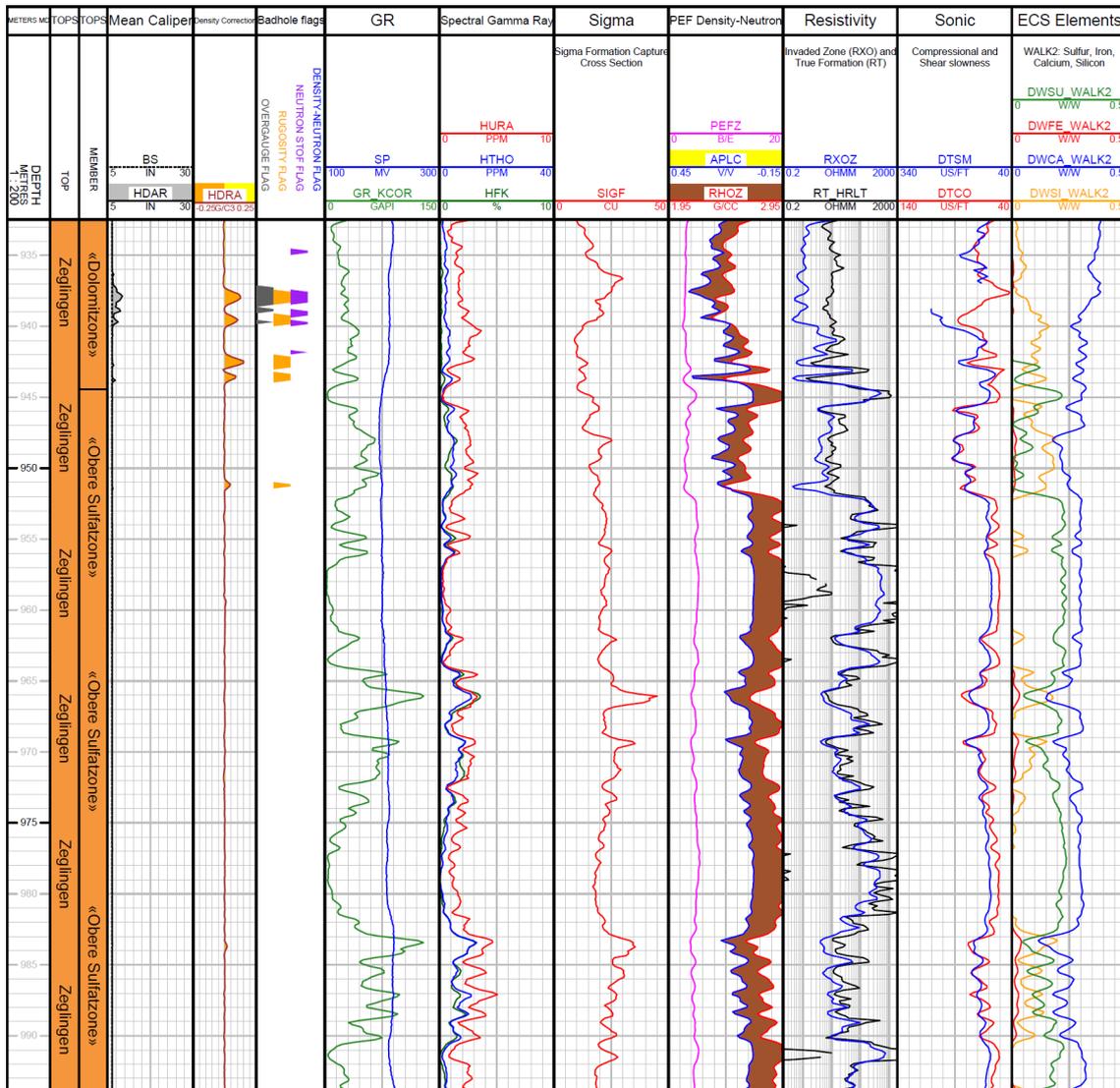


Fig. 3-8: Main logs of the composite dataset in the Zeglingen Formation

3.4.10 Kaiseraugst Formation (993.97 to 1'029.95 m MD)

The top of the Kaiseraugst Formation is difficult to identify because the wireline logs do not show any obvious markers. Nevertheless, a gradual increase in clay indicators (e.g., GR_KCOR) is observed between 994 and 998 m MD.

Due to the good-hole conditions, log responses reflect the borehole lithology well (Fig. 3-9). Logs in the Kaiseraugst Formation have the following attributes:

- Intermediate to high clay content as shown by the total GR (GR_KCOR: 37 to 159 GAPI), sigma (SIGF: 14.2 to 35.3 CU) and thorium (HTHO: 3.4 to 16.6 ppm), except in a short interval from 998.6 to 1'000.8 m MD that is rich in anhydrite.
- The anhydrite layer is characterised by its high sulphur content (DWSU: up to 0.23 W/W; pure anhydrite: 0.236 W/W), low total GR (GR_KCOR: up to 36 GAPI) and high resistivities (e.g. RT_HRLT).
- Below the anhydrite layer (from 1'000.8 m MD) to the base of the «Wellenmergel» (1'022.8 m MD), logs show relatively homogeneous values, e.g. an intermediate density-neutron separation in the limestone compatible scale, intermediate sonic (DTCO: 64 to 101 μ s/ft) and consistent iron concentrations (DWFE: 0.01 to 0.06 W/W). These suggest intermediate to moderately high clay content as is common in marlstone. The photoelectric factor (PEFZ) values are intermediate between those of pure dolomite (3.1 B/E) and pure calcite (5.1 B/E), which suggests dolomitic carbonates.
- Matrix mineralogy indicators such as silicon (DWSI), calcium (DWCA) and the photoelectric factor (PEFZ) are variable and not consistent with clay indicators suggesting that the matrix mineralogy is composed of both carbonates and siliciclastics.

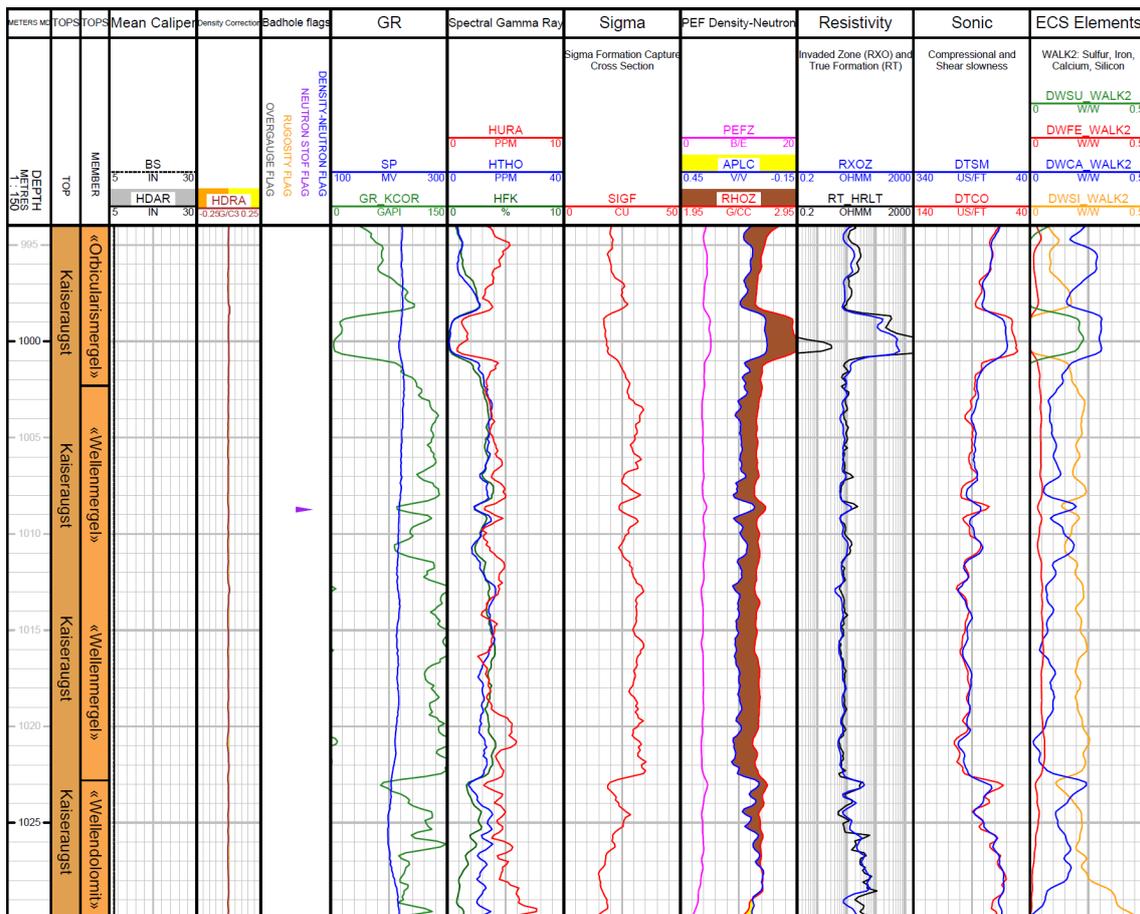


Fig. 3-9: Main logs of the composite dataset in the Kaiseraugst Formation

3.4.11 Dinkelberg Formation (1'029.95 to 1'038.23 m MD)

The top of the Dinkelberg Formation corresponds to the bottom of a progressive transition from carbonates to sandstones from 1'027.9 m to 1029.8 m MD, which is represented in the logs by an increase in the silicon content (DWSI) and a decrease in calcium (DWCA), as well with a very distinctive change in the density-neutron separation, where the density log shifts to the left of the neutron log ("crossover" in a limestone-compatible scale, shaded yellow).

Logs respond well to lithology in this formation because hole conditions were good and are characterised by the following attributes (Fig. 3-10):

- Logs often show a high corrected total GR (GR_KCOR) ranging from 41 to 133 GAPI, despite the crossover in the density-neutron separation that is indicative of low clay content and mineralogy dominated by siliciclastics. This is typical for siltstones and sandstones that contain slightly radioactive minerals such as K-feldspar and mica (and are better quantified by the stochastic, multiminerall analysis described in Dossier X). The relatively high potassium concentrations (HFK), ranging from 1.0 to 2.2%, also suggest the presence of radioactive minerals.
- Photoelectric factor values (PEFZ) are close to that of pure quartz (1.8 B/E) in the upper Dinkelberg Formation down to 1035.2 m MD, averaging at 2.4 B/E. The silicon content (DWSI) also suggests the presence of significant quartz, ranging from 0.41 to 0.45 W/W (pure quartz: 0.467 W/W). Below 1035.2 m MD, the calcium contents increase to 0.26 W/W and siliciclastics decrease, suggesting a change in the matrix mineralogy to carbonates.
- The large separation between the shallow (RXOZ) and deep (RT_HRLT) resistivities indicate a permeable formation that has been invaded by the mud filtrate.

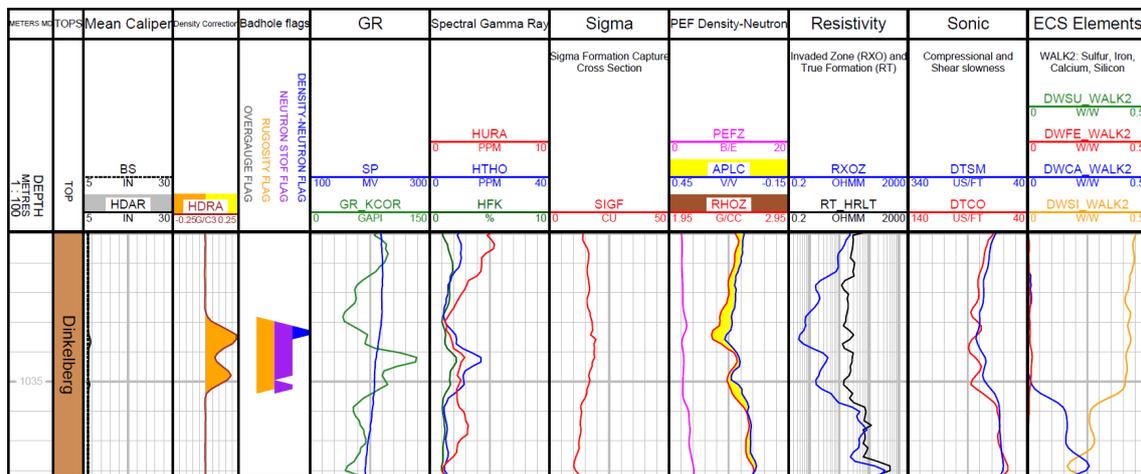


Fig. 3-10: Main logs of the composite dataset in the Dinkelberg Formation

3.4.12 Weitenau Formation and Crystalline basement (1'038.23 to 1'099.25 m MD)

The top of the Weitenau Formation is characterised by sharp increases in the clay indicators such as total GR (GR_KCOR) and sigma (SIGF).

Logs respond well to lithology in this formation because hole conditions were good (Fig. 3-11). Logs in the Weitenau Formation have the following attributes:

- A high total GR, ranging from 83 to 145 GAPI, with a low density-neutron separation in the limestone compatible scale, indicate relatively low clay contents. This is typical for siltstones and sandstones that contain slightly radioactive minerals such as K-feldspar and mica.
- In a few zones, "crossover" is observed in the density-neutron separation (shaded yellow) indicating the presence of siliciclastic minerals such as quartz (and feldspars). This observation is supported by the high silicon content (DWSI: 0.28 to 0.41 W/W) and the low photoelectric factor (mean PEFZ: 2.8 B/E).
- Log characteristics are fairly homogeneous, which is best shown by the low variations in spectral GR contributions (potassium: HFK; thorium: HTHO; uranium: HURA).
- A limited suite of logs were acquired in the lower Weitenau Formation due to the loss zones encountered in Section III.

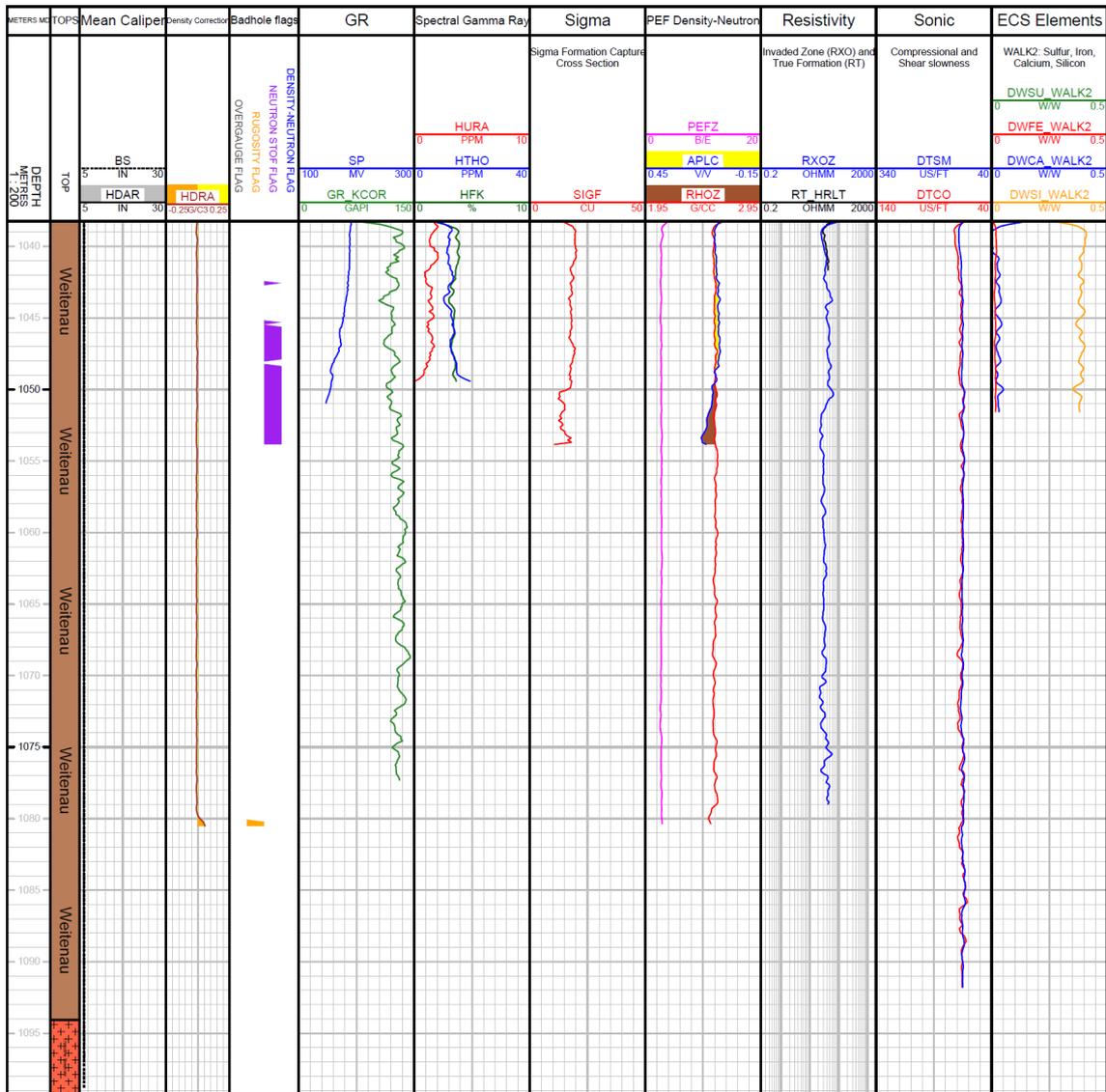


Fig. 3-11: Main logs of the composite dataset in the Weitenau Formation

3.5 Post-completion mud temperature

A temperature log was acquired by Schlumberger post-completion (in cased hole) on 10.07.2021 (Run 3.7.1) to measure the undisturbed temperature of the mud after the last mud circulation on 14.07.2020. Temperature was measured using the EMS tool, which has an accuracy of $\pm 1\text{ }^{\circ}\text{C}$ and resolution of $0.1\text{ }^{\circ}\text{C}$. In Fig. 3-12, only the downlog from Run 3.7.1 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. Maximum temperature of $48.29\text{ }^{\circ}\text{C}$ was recorded at 890.02, 890.93 and 892.91 m MD, while the minimum of $11.21\text{ }^{\circ}\text{C}$ was at 68.43 m MD. In the Opalinus Clay, the temperature varies between $31.09\text{ }^{\circ}\text{C}$ – $39.46\text{ }^{\circ}\text{C}$ and the average geothermal gradient is $\Delta T/\Delta D = 0.071\text{ }^{\circ}\text{C/m}$ (slightly less than for Bülach1-1 and Trüllikon1-1: $0.073\text{ }^{\circ}\text{C/m}$). The overall temperature gradient is higher in the clay-rich units of the Dogger compared to the calcareous units of Malm and Muschelkalk.

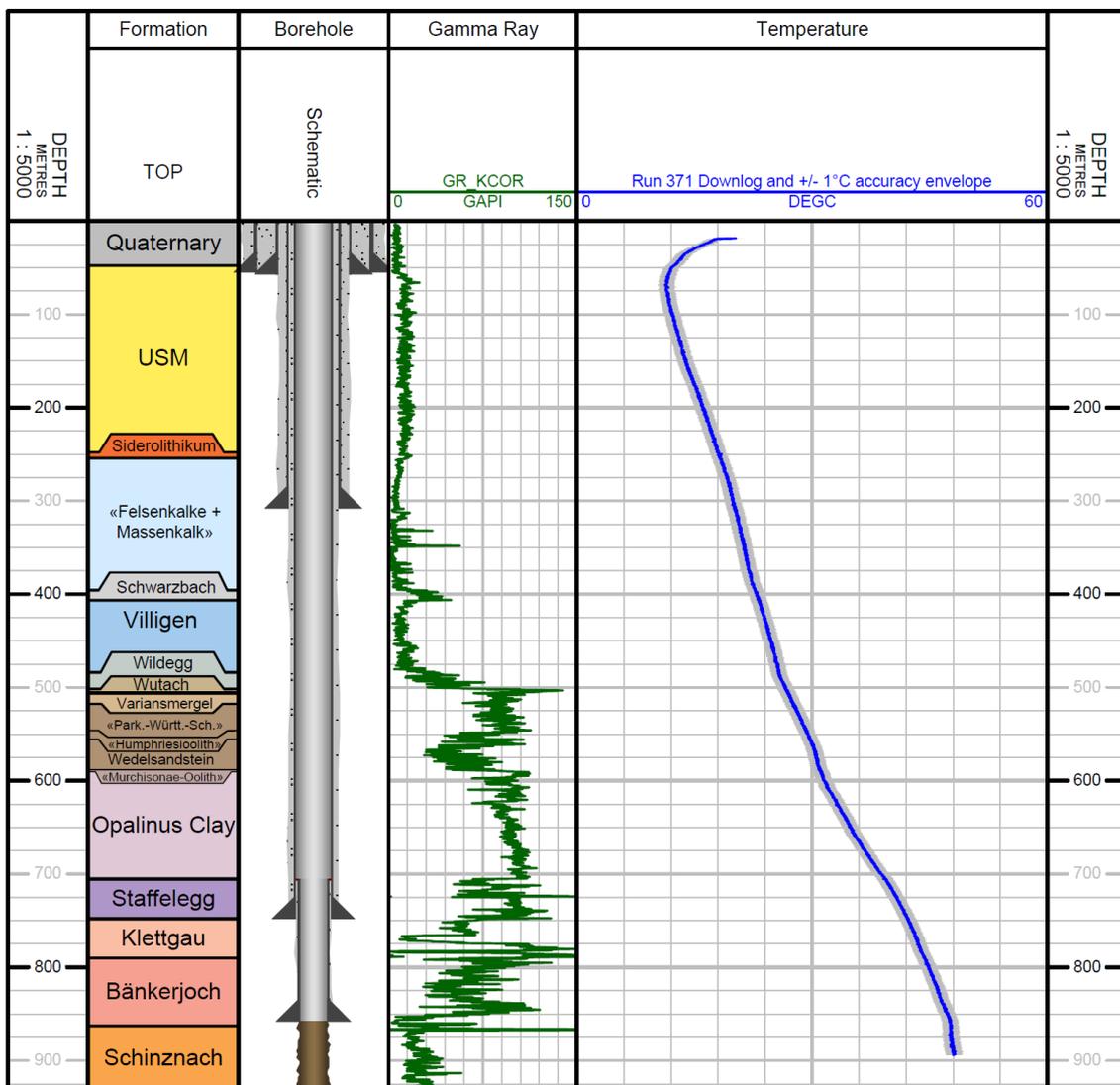


Fig. 3-12: Post-completion temperature log from the downlog pass of Run 3.7.1 (10.07.2021)
A $\pm 1\text{ }^{\circ}\text{C}$ accuracy envelope is drawn in grey around the temperature log

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 MAR1-1 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 a 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 testing 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 stations immediately after BHI log acquisition and prior to MHF testing. 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).

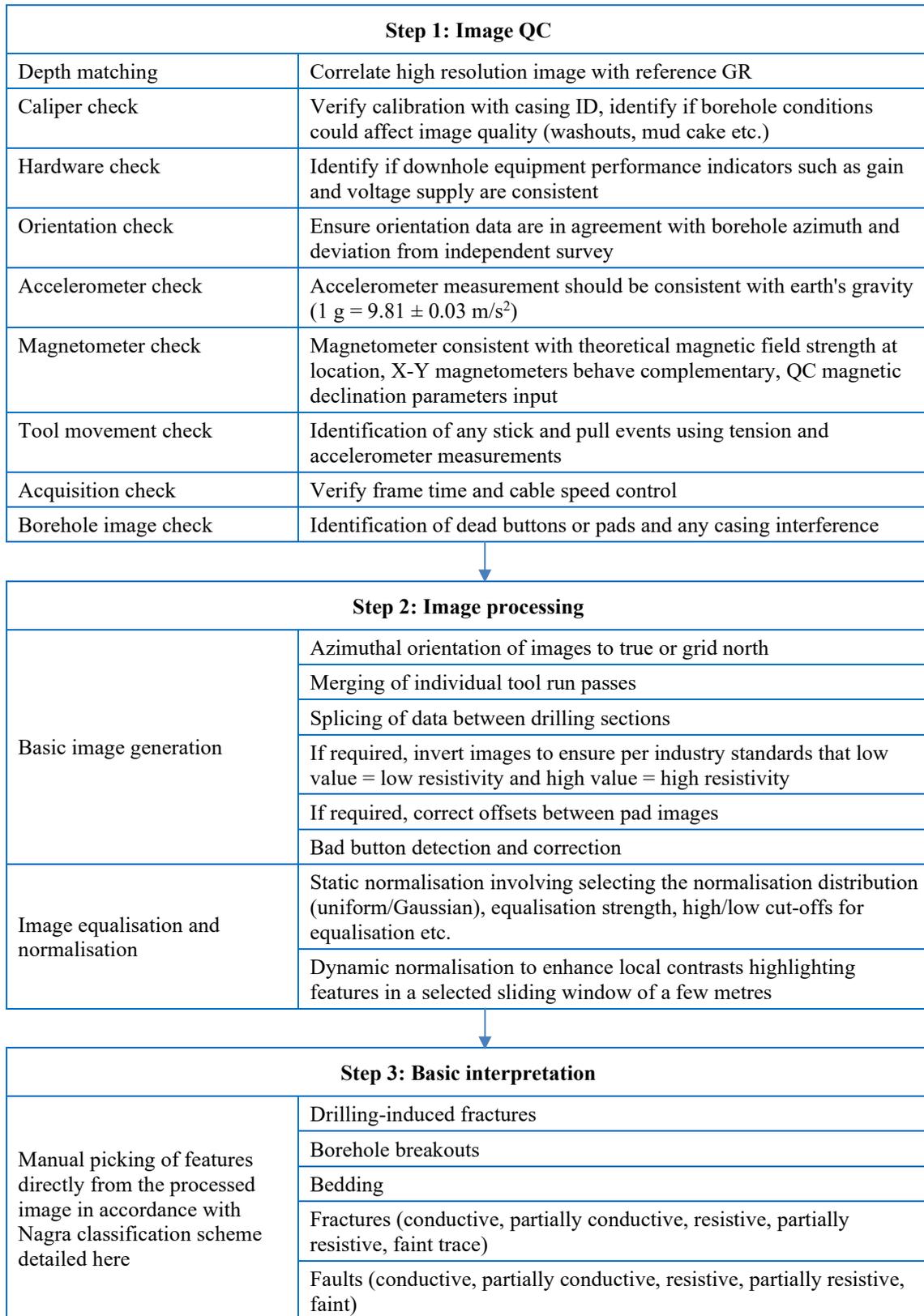


Fig. 4-1: Borehole image processing workflow

5 Micro-hydraulic Fracturing (MHF)

5.1 Introduction and objectives

A series of stress measurements were performed in Section II of the MAR1-1 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).

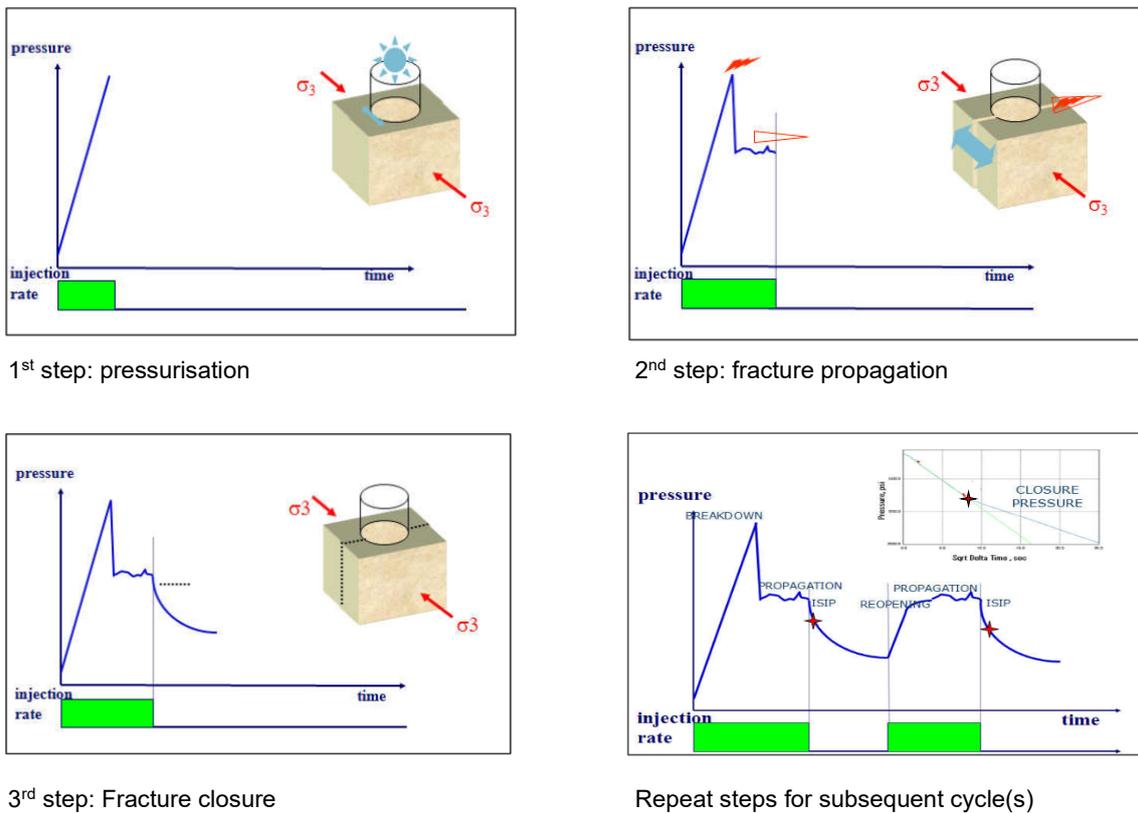


Fig. 5-1: Schematic showing the response of the interval pressure to fluid injection in the interval as a function of time during an MHF test and associated formation response (courtesy of SLB)

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.
- 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 MAR1-1 borehole is presented (Station 1-2, Run 2.1.8). Fig. 5-2a shows the pressure in the interval, Fig. 5-2b the fluid injection rate as a function of time, 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 11. 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, 10 and 11 are reopening tests, cycle 9 is a step-rate test (cycle 8 is absent from interpretation because it is a packer inflation cycle). A slamback / rebound test was performed at the end of cycle 9. 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, 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 MAR1-1 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.

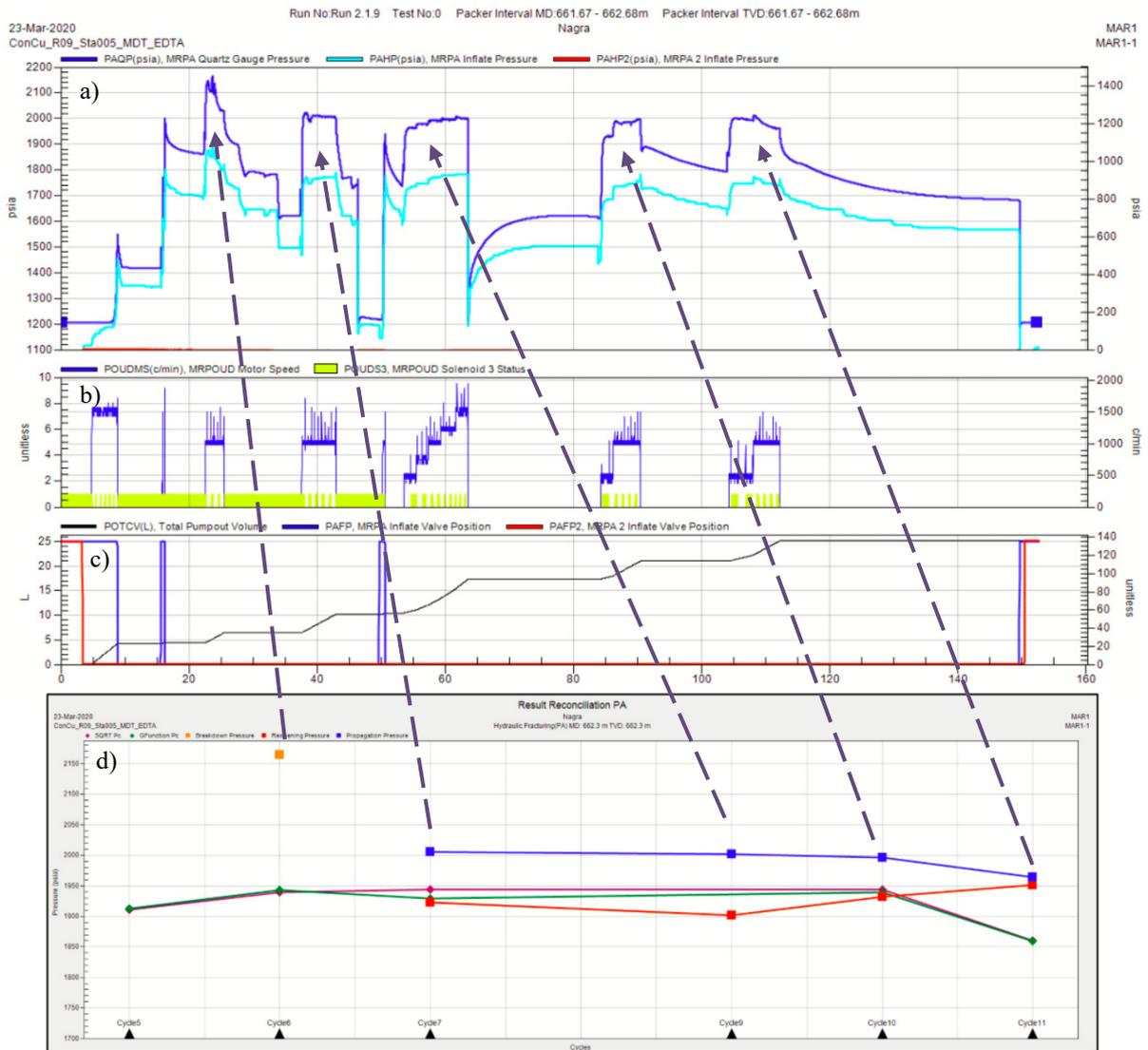


Fig. 5-2: Example of pressure record for MHF test from MAR1-1 (Station 1-2, Run 2.1.9)
 Pc stands for closure pressure, ISIP stands for Instantaneous Shut-in Pressure.

Tab. 5-1: Summary of MHF station locations and operations carried out in Section II of the MAR1-1 borehole

| Phase / Section | Station | Formation / unit | Middle interval depth [m] | Sleeve fracturing cycles | Breakdown cycles | Reopening cycles | Slamback / rebound tests | Step-rate tests | Sleeve reopening cycles |
|-----------------|---------|---------------------------------------|---------------------------|--------------------------|------------------|------------------|--------------------------|-----------------|-------------------------|
| II (Run 2.1.8) | 0-1 | Wildeggen Fm. | 486.6 | 2 | 1 | 3 | 1 | 2 | 2 |
| | 1-1 | Opalinus Clay | 659.8 | 2 | 1 | 2 | 1 | 3 | 2 |
| II (Run 2.1.9) | 1-2 | Opalinus Clay | 662.15 | 2 | 1 | 2 | 1 | 1 | 2 |
| | 1-3 | Opalinus Clay | 651.1 | 2 | 1 | 3 | 1 | 2 | 2 |
| | 3-1 | Villigen Fm. | 402.95 | 2 | 1 | 0 | 3 | 1 | 2 |
| | 4-1 | «Felsenkalk» + «Massenkalk» | 397.9 | 2 | 1 | 3 | 2 | 1 | 2 |
| II (Run 2.4.2) | 1-1 | Staffelegg Fm. | 706.65 | 3 | 1 | 3 | 1 | 1 | 3 |
| II (Run 2.4.3) | 1-2 | Staffelegg Fm. | 726.3 | 2 | 1 | 2 | 1 | 2 | 2 |
| | 2-1 | Wedelsandstein Fm. | 585.5 | 3 | 1 | 2 | 1 | 2 | 2 |
| | 2-2 | «Parkinsoni-Württembergica-Schichten» | 532.4 | 2 | 1 | 1 | 2 | 2 | 2 |
| | 3-1 | «Felsenkalk» + «Massenkalk» | 387.2 | 2 | 1 | 3 | 0 | 2 | 2 |
| | 4-1b | Opalinus Clay | 602.3 | 2 | 1 | 3 | 0 | 2 | 2 |
| | 4-3 | Opalinus Clay | 618.9 | 2 | 1 | 0 | 2 | 2 | 2 |

5.4 MHF results

13 tests were attempted, with 13 of them being successful, from the «Felsenkalke» + «Massenkalk» unit (254 m) down to the Stafflegg Formation (747.83 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. 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.

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).

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 1-1 (Runs 2.1.8). New fracture segments induced by the MHF test are highlighted in yellow on the rightmost track. Note that there were no pre-existing fractures on the pre-MHF images. The MHF test led to the creation of slightly inclined conductive fractures at the wellbore, which cover the entire length of the straddle packer arrangement (and even extend away from it). 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.

Tab. 5-2: Quicklook interpretation of MHF results for Section II of the MAR1-1 borehole

| Run Diameter | Station | Formation | Depth [m] | Breakdown pressure [MPa] | Closure stress range [MPa] | Comments |
|--|---------|---|-----------|--------------------------|----------------------------|---|
| Run 2.4.3 8½" bit size | 3-1 | «Felsenkalke» + «Massenkalk» | 387.2 | 19.5 | 12.0 – 15.17 | Shmin likely |
| Run 2.1.9 6¾" bit size | 4-1 | Schwarzbach Fm. | 397.9 | 13.0 | 8.89 – 10.75 | Highest part of the range: Shmin likely; lowest part of the range: Sv likely |
| Run 2.1.9 6¾" bit size | 3-1 | Schwarzbach Fm. | 402.95 | 12.1 | 8.73 – 9.5 | Shmin likely |
| Run 2.1.8 6¾" bit size | 0-1 | Wildeggen Fm. | 486.6 | 13.9 | 9.0 – 11.2 | Stress assignment unclear |
| Run 2.4.3 8½" bit size | 2-2 | «Parkinsoni- Württembergica- Schichten» | 532.4 | 13.75 | 11.15 – 12.25 | Shmin likely |
| Run 2.4.3 8½" bit size | 2-1 | Wedelsandstein Fm. | 585.5 | 19.45 | 11.4 – 12.6 | Shmin likely |
| Run 2.4.3 8½" bit size | 4-1b | Opalinus Clay | 602.3 | 18.1 | 11.7 – 12.9 | Shmin likely |
| Run 2.4.3 8½" bit size | 4-3 | Opalinus Clay | 618.9 | 17.4 | 11.58 – 12.75 | Shmin likely |
| Run 2.1.9 6¾" bit size | 1-3 | Opalinus Clay | 651.1 | 14.2 | 9.65 – 12.82 | Shmin likely |
| Run 2.1.8 6¾" bit size | 1-1 | Opalinus Clay | 659.8 | 14.7 | 10.9 – 13.24 | Shmin likely |
| Run 2.1.9 6¾" bit size | 1-2 | Opalinus Clay | 662.15 | 14.9 | 11.17 – 13.65 | Shmin likely |
| Run 2.4.2 8½" bit size | 1-1 | Staffelegg Fm. | 706.65 | 18.25 | 13.1 – 15.1 | Shmin likely |
| Run 2.4.3 8½" bit size | 1-2 | Staffelegg Fm. | 726.3 | 19.52 | 13.45 – 16.55 | Shmin likely |
| Total number of tests | | | | | | 13 |
| Total number of successful tests | | | | | | 13 |
| Success rate (actual vs. attempted) & (actual vs. desired from initial plan) | | | | | | 100% & 118% |

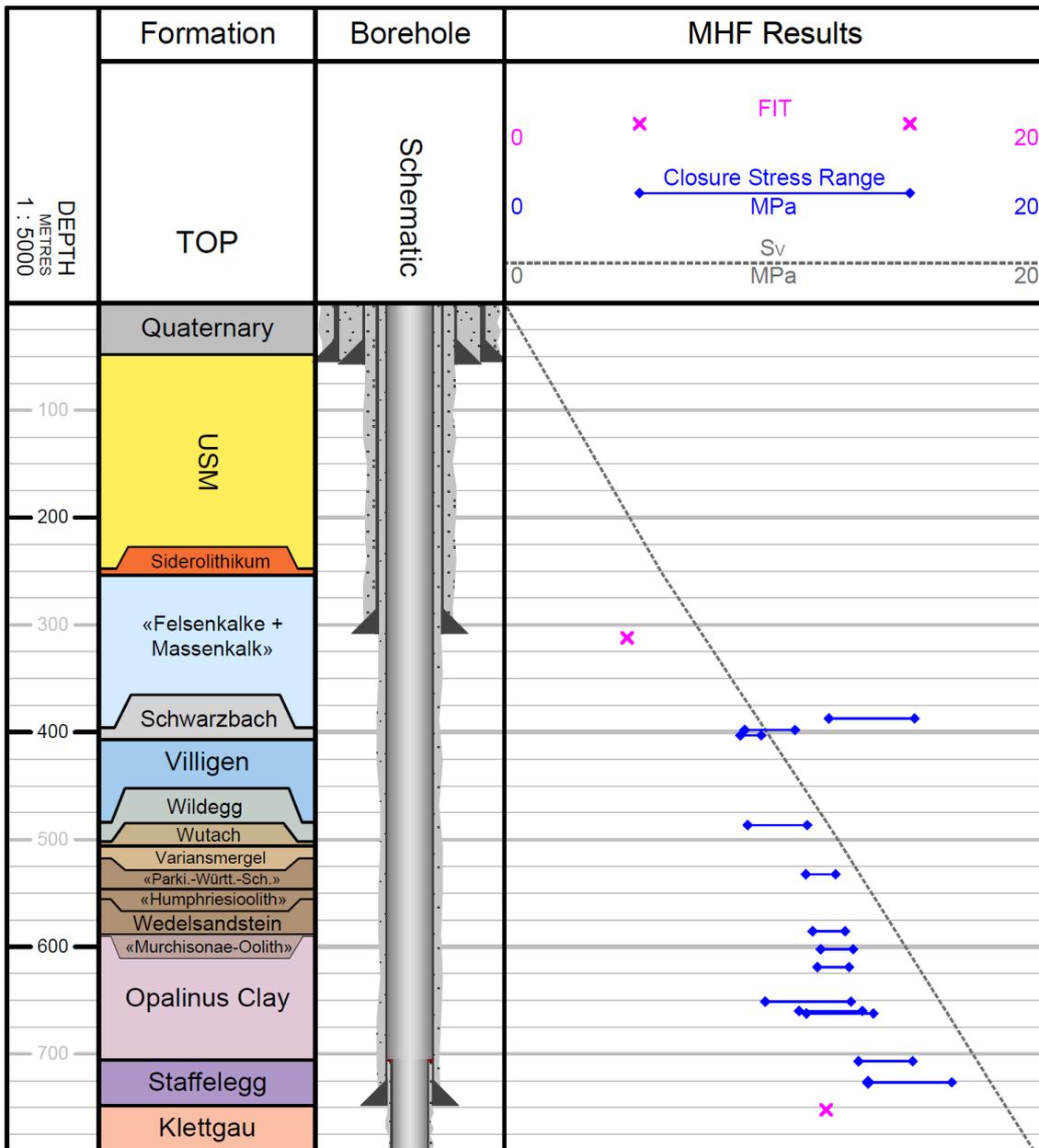


Fig. 5-3: Comparison of the quicklook closure stress range obtained from the MAR1-1 MHF tests with the overburden vertical stress (S_v) from the integration of density over depth and the maximum pressures attained during the formation integrity tests (FIT)

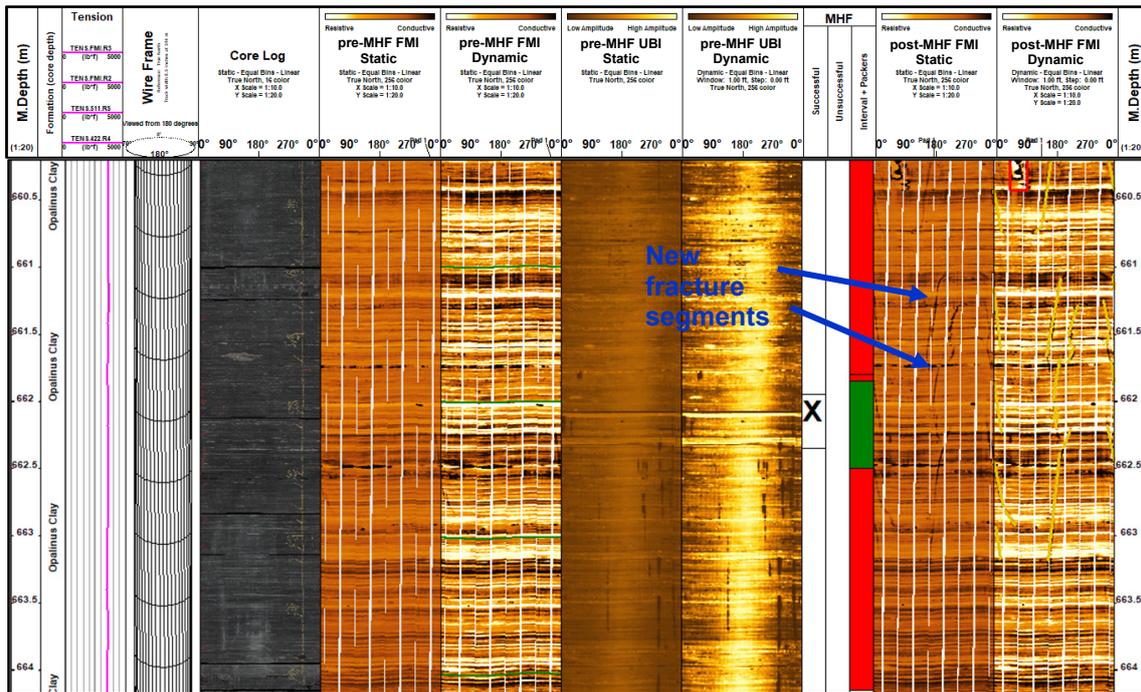


Fig. 5-4: Example of pre- vs. post-MHF images from MAR1-1 (Station 1-2 from run 2.1.9, Section II)

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 with blue arrow on the post-FMI static image; the features picked by NiMBUC Geoscience are shown in yellow on the post-FMI dynamic image.

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